The Design and Implementation of a Green Roof Shelter Research Site

By

Margaret M. Chase

Thesis
Submitted to Department of Civil and Environmental Engineering
College of Engineering
Villanova University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

In

Water Resources and Environmental Engineering

December, 2015

Villanova University, Pennsylvania

The Design and Implementation of
a Green Roof Shelter Research Site

By
Margaret M. Chase

Approved: ______________________________
Bridget Wadzuk, Ph.D.
Associate Professor of Civil and Environmental Engineering
Primary Advisor

Approved: ______________________________
Robert Traver, Ph.D., P.E., D.WRE
Edward A. Daylor Chair in Civil Engineering
Professor of Civil and Environmental Engineering
Co-Advisor

Approved: ______________________________
David Dinehart, Ph.D.
Chairman, Department of Civil and Environmental Engineering

Statement by Author

ACKNOWLEDGEMENTS

I would like to thank Dr. Bridget Wadzuk for creating this unique research project, for bringing me on board and for being knowledgeable, helpful and enthusiastic along the way. Additionally, I would like to thank Dr. Traver and all the VUSP professors for providing constructive guidance and insight. Finally, thanks to the EPA Urban Waters Small Grant program and the VUSP partners for providing funding for these green infrastructure projects.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

A green roof living laboratory space was created for stormwater performance research, with additional benefits of providing stormwater education for the surrounding community. The research focus in this initial stage of the project was to design and build a green roof structure, constructed with an overflow collection and monitoring system to facilitate green roof research.

The field laboratory site is a green roof with an area of 160 ft^2 (14.9 m^2) located on a shelter over a picnic table on campus at Villanova University. The shelter is a custom-designed steel structure with a modular, semi-intensive (8-in media depth) green roof. Construction of the foundation, construction of the shelter and installation of the green roof modules was completed in August 2015. The green roof is separated into two halves with separate drainage collection systems to enable research through runoff comparison. Upon installation, each half of the roof was planted with two different hardy vegetation types; one with sedum species and one with non-sedum species (primarily grasses). The monitoring equipment is set up to enable measurement of meteorological data, media moisture, media temperature, and overflow. Data from the monitoring equipment is collected and recorded with a low-cost logging system including an Arduino microcontroller and logging shield. The data logging system incorporates more than 15 sensors and costs up to ten times less than traditional data logging equipment. The system is currently in operation, collecting data during dry periods and storm events to evaluate the interactions between soils, plants, atmosphere and water and their effects on stormwater performance.

1. Introduction

1.1 Stormwater and Stormwater Control Measures

Nationwide, stormwater runoff is one of the great challenges of modern water pollution control, as it is a principal contributor to the impairment of waterbodies. Impervious surfaces in the urban environment, including roadways and buildings, prevent important water cycling processes for stormwater, primarily infiltration and evapotranspiration, and increase runoff relative to a natural environment (Figure 1.1). During storm events, runoff collects and transports chemical and biological contaminants as it runs over impervious surfaces, posing a threat to surface water quality. In highly urbanized areas, the excess rainfall runs off at higher volumes and velocities than would naturally occur, causing flooding and ecological degradation. Aquatic habitats and stream functions are degraded by erosion of downstream channels and deposition of sediment and pollutants caused by the force of this runoff. (Walsh 2005)

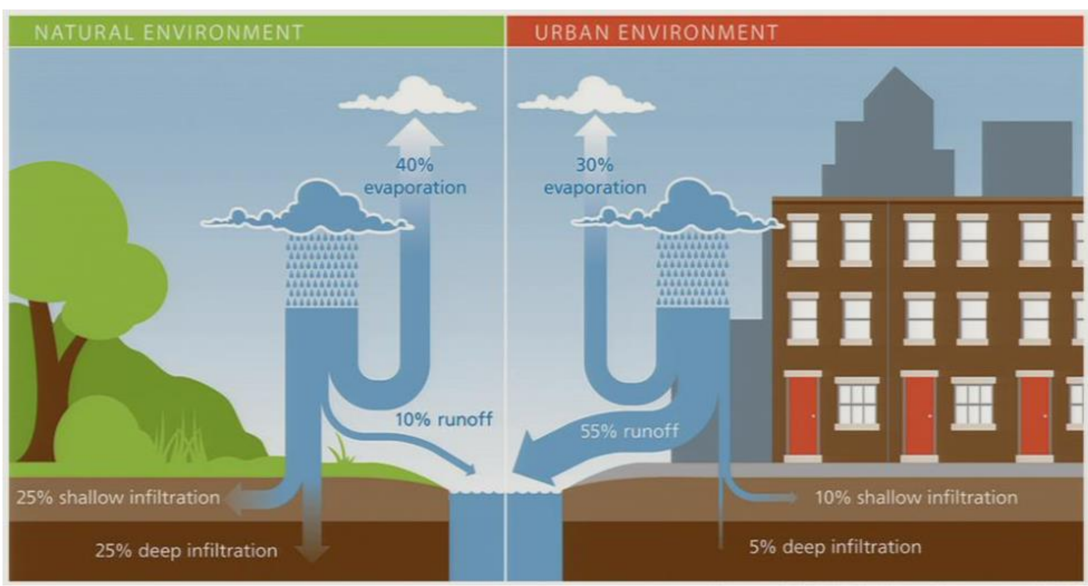


Figure 1.1 Schematic of the hydrologic pathways before and after urban development. The percentages represent examples of the changes in magnitude of the different elements of the hydrologic cycle, although conditions vary between individual catchments. Adapted from the US EPA (Philadelphia Water Department 2015).

In addition to the problems caused solely by stormwater runoff, many older cities (including many of the largest cities in the United States) have combined sewage and stormwater in the same pipe. In communities with combined sewers, the surplus stormwater volume results in sewer overflows, which pose a serious risk to public health and water quality of receiving waterbodies. The effects of stormwater runoff and combined sewer overflows (CSOs) have been consistently observed to include flashier hydrographs, elevated concentrations of nutrients and contaminants, altered channel morphology and reduced biotic diversity (Walsh 2005). With population increases and continuous development, land area in the United States is becoming increasingly urbanized (NJDEP 2013). The magnitude of urban stormwater management problems is expected to grow.

Traditionally, cities have attempted to manage increased volumes entering stormwater systems by separating combined sewers, expanding treatment capacity, increasing the system storage, or by replacing broken pipes. Implementation of these traditional gray infrastructure practices can be expensive and time consuming, sometimes taking decades to complete. The management of individual runoff sources often does not consider watershed-scale impacts. This disconnection can result in significant alteration of the hydrologic balance, such as stormwater being displaced from the watershed of origin (Hall 2010).

Throughout the past few decades, the strategy for stormwater management has been to collect and convey runoff away from a developed area as quickly as possible. Designs aimed for the most efficient conveyance systems often utilized peak-flow stormwater management devices like detention basins. These basins were designed to reduce the peak flow rate on a given site for large events (e.g. 100 year storm event) resulting in localized control, however did not demonstrate watershed-wide effectiveness, nor did they provide any mitigation for the frequent, smaller events. (Emerson 2005; McCuen 1979) As an alternative to grey infrastructure, many municipalities have recognized that stormwater can be diverted upstream of the sewer system and directed into areas where it can be infiltrated, evapotranspirated or re-used. This methodology has the benefit of retaining stormwater within the watershed and enabling control over a wide range of rainfall event sizes. These approaches are called green infrastructure because soil and vegetation is used as opposed to (or in conjunction with) pipes, storage basins, and other 'hard' infrastructure. The individual structural features used to mitigate the effects of increased runoff are referred to synonymously as low impact development (LID) features, Best Management Practices (BMPs,) or stormwater control measures (SCMs.) The spectrum of SCMs include green roofs, bioswales, bioretention and bioinfiltration basins, pervious pavements and constructed wetlands.

Green infrastructure approaches have a range of benefits, including improvement of social, environmental, and economic conditions of a community at the watershed scale, as well as at the neighborhood scale. Green stormwater infrastructure provides opportunities for urban areas to reduce localized flooding, reduce stormwater system overflows, improve water quality and add to aesthetic appeal of infrastructure. Many major cities are taking this innovative approach to reduce stormwater pollution entering combined sewer systems, including New York City, Chicago, Portland and Philadelphia. The municipal programs have included a wide range of local stormwater regulations that focus on both public and private properties.

While there has been a movement to adopt green infrastructure as a viable stormwater management solution strategy, there is still resistance to widespread application. Some of this resistance is due to concerns on the reliability of performance, maintenance needs, and cost. To address these concerns, research must be done and the results must be disseminated in an accessible way for municipal engineers and planners, as well as community residents, who are integral to the success of a green infrastructure focused stormwater management plan.

1.2 Green Roofs in Urban Areas

Green roofs (also called living roofs, vegetated roofs or ecoroofs) provide several distinct advantages as SCMs including source control, ability to capture frequently-occurring rainfall events and ability to utilize otherwise un-used space (Fassman-Beck et al. 2013). In dense urban centers, on-site retention through ground-level SCMs can be difficult and expensive. Space restrictions, subsurface utility infrastructure, and poor infiltration are all common barriers for ground-level SCMs, including rain gardens and infiltration trenches. The ability to retrofit sites with green roofs is ideal for ultra-urban areas with a lack of pervious space. The dual use of roofs for building footprint and stormwater management can save more highly valued ground space for alternate purposes. For example, at Evergreen State University in Washington, a green roof was added to offset new parking spaces on campus (Hall 2010).

Green roofs provide additional benefits outside of stormwater including air quality improvements, carbon sequestration, roof longevity, and building energy conservation (Castleton 2010; USEPA 2000). With careful site selection, the implementation of green roofs can result in visible changes to a community's landscape. A key benefit to vegetative roof systems is the ability to provide a thermal barrier for the roof surface. The barrier function serves to extend rooftop durability and as insulation to reduce building energy costs. The vegetation barrier reduces heat transfer through the roof structure, and cools the surrounding air through the effects of shading and evapotranspiration. (Huang 2008; Teemusk 2010; Wong and Jim 2015)

Stormwater regulations are increasingly focusing on runoff peak flow mitigation or volume control. In response, several cities have embraced green roofs as a part of their green infrastructure portfolio. Portland, Oregon has implemented an “Ecoroof Floor Area Ratio (FAR) Bonus” which increases a building’s allowable area in exchange for adding a green roof, or ecoroof. This program resulted in more than 120 ecoroofs added to the city. (City of Portland 2015) Chicago’s Green Roof Grants are $5,000 awards for residential and small commercial buildings that meet specific criteria. Through grants, residents have added over 2.5 million ft^2 of green roofs across the city. Chicago has collected data from the green roof on its City Hall, and the data indicates that the roof reduces stormwater runoff by 50%, and also saves the city approximately $5,500 annually on heating and cooling expenses. (City of Chicago 2015) In 2013, the Green Roof Tax abatement program in New York City was renewed for an additional five years with amendments to further incentivize green roof construction in the private sector (City of New York 2014). In 2013, the Philadelphia installed the city’s first green roof bus shelter to serve as a highly visible demonstration project (Bauers 2013). These cities, and a growing number of cities across the nation, depend on green roofs as key stormwater management tools.

As with all SCMs, questions arise about the reliability and effectiveness of green roofs. As green roofs are often atop a building, they are often not seen as much as other SCMs, such as a rain garden, so are more difficult for the design and residential community to observe. Bringing a green roof closer to eye-level will enable educational opportunities on their function and usefulness.

1.3 Research Objectives

The goal of the present project is to create green roof living laboratory spaces used for stormwater performance research with additional benefits of community and STEM education and product development for green roof technology companies. The sites are designed for research with monitoring of stormwater performance data, as well as centers of stormwater education for the surrounding community. The research focus in this initial stage of the project was to design and build two green roof structures, including the implementation of overflow collection and monitoring system. This initial project stage also highlighted the interdisciplinary nature of stormwater management and community engagement.

Several design goals combined to create the optimal research site. The shelter and related equipment was designed for structural integrity, direct rainfall capture, water storage and drainage, accurate overflow quantification, environmental monitoring and an affordable monitoring system. The sensors were chosen to collect a wide range of performance data to provide flexibility and opportunity for future research. The monitoring system was designed to be simultaneously innovative, robust and cost-effective, providing data including weather, soil moisture, and overflow measurement. To accurately measure the range of design overflows, a custom, cost-effective Orifice Restricted Device (ORD) was developed. The monitoring equipment, including the data logging equipment and ORD, was carefully chosen to be easily replicated at a future site (e.g. educational institution) with limited engineering expertise. The low-cost design approach is intended to create a feasible research opportunity on a small budget, for public or private groups to monitor the performance of green roofs, and contribute to the growing knowledge base about green roof performance. The designed green roof living laboratory system and accompanying monitoring plan could also be used in STEM education to provide opportunities for a variety of educational disciplines, including the basic sciences, engineering, mathematics, and horticulture.

2. Literature Review

2.1 Green Roofs as Stormwater Control Measures

Stormwater retention is a well-studied benefit of green roofs, including the ability to mitigate total runoff volume, reduce peak flow rate and frequency of runoff when compared to a standard roof surface (Alfredo 2010; Bengtsson 2005; Fassman-Beck et al. 2013; Mentens 2006; Speak et al. 2013; VanWoert 2005; Villarreal 2007). The peak flow rate reduction is a result of the ability of green roofs to delay the start of runoff, characterized by elongating the hydrologic flow path of rainfall (DeNardo 2005; Moran et al. 2005).

At the individual site scale, stormwater capture performance of a green roof is a function of several roof design and site characteristics. The physical roof characteristics determine the roof's ability to capture water, including substrate depth, moisture capacity, and plant type (Fassman and Simcock, 2012). In particular, the design and function of the drainage layer on a green roof is significant to the continued success of the system. Vegetation growth and health is entirely dependent on the system's ability to remove excess water from the roof, while simultaneously storing some water for use by the plants (Wingfield 2005). Additionally, climatological factors influence the stormwater performance, including rainfall depth and intensity, antecedent dry period, solar radiation, and temperature (Wong and Jim 2015).

Ideally, green roofs should be accompanied by other means of water retention to further reduce runoff impacts. For example, rooftop disconnection can be easily integrated into green roof design. Directing green roof runoff to nearby vegetated areas allows the runoff to be collected and managed on site, effectively decreasing stormwater volumes entering into combined or separate sewer systems (PADEP 2006). At the watershed scale, conceptual hydrological models applied on a large time series have seen results that widespread green roof implementation results in significant reduction of urban runoff in terms of reduced peak runoff discharge, total volume and CSO events (Deutsch 2005; Versini et al. 2015).

Water quality results on green roof performance are highly site-specific and generally inconclusive. Reported results for total suspended solids (TSS), phosphorus, nitrogen and heavy metals capture have varied. Mendez et al. (2011) identified that a first flush effect was not seen on green roofs, as it is consistently seen on conventional roofs. Green roofs have been found to sometimes be sinks or sometimes sources of nutrients. When designed to receive primarily direct rainfall, inflows to green roofs are relatively clean compared to overland flow. As elevated structures, the sources of incoming pollutants are limited to atmospheric deposition, and components derived from the green roof system itself. Peak nutrient-retention performance is typically seen after a minimum of five years of establishment (Hall 2010). It has been concluded that established green roofs do not substantially impair water quality (Fassman-Beck et al. 2013). Although green roof water quality performance is not consistent, conventional rooftops do not provide water quality improvement, and have even been shown to pollute runoff with copper, zinc and pathogens (Clark et al. 2008; Lamprea and Ruben 2011; Timperely et al. 2005). The following have been identified as key parameters effecting green roof quality performance: substrate composition, fertilization, roof age, presence or absence of vegetation, and system disturbance (Fassman-Beck et al. 2013).

Design and construction costs are significant barriers to widespread implementation of green roofs. Compared to other SCMs, green roofs are generally more expensive. Extensive vegetated covers range between \$8 and \$15 per ft^2, including design and installation (PADEP 2006; Peri et al. 2012). Compared to other SCMs, green roofs direct construction cost estimates are much higher than bioretention/subsurface infiltration and street trees (Table 2.1). The redevelopment project cost for a green roof (stormwater management costs that are marginal beyond the cost of already-occurring development) is 50% lower than a retrofit, however are still generally the most expensive for SCMs. In relation to other SCMs, green roof installations require expensive investments up-front, and realize results in the long-term (Getter and Rowe 2006). Furthermore, there is a lack of consistent, quantified data detailing the benefits that green roofs provide to the building owners, occupants, and the community. To fill the gap, data is needed from varying climates to address the design questions of choosing plant species, and substrates, and predicting water retention and water quality treatment (Getter and Rowe 2006).

Table 2.1. Mean and median direct construction cost estimates in 2008 dollars. (Vanaskie 2010)

Control	Type	Median Cost ($ / impervious acre)	Mean Cost ($ / impervious acre)
Bioretention / Porous Pavement / Subsurface Infiltration	Retrofit	$120,000	$160,000
	Redevelopment	$90,000	$110,000
Green Roof	Retrofit	$500,000	$500,000
	Redevelopment	$250,000	$250,000
Street Trees	Retrofit	$18,000	$18,000
	Redevelopment	$15,000	$15,000

2.2 Green Roof Design Standards

The majority of existing American green roof standards have been published relatively recently. Often, the German Forschungsgesellschaft, Landschaftsentwicklung and Landschaftsbau (FLL) guidelines are referenced for standard design. There has been a movement to standardize green roofs nationally in the United States, including publications from American

Society of Testing and Materials (ASTM), American Society of Civil Engineers (ASCE), and American National Standards Institute (ANSI)/ Single Ply Roofing Industry (SPRI).

ASTM convened a Green Roof Task Force to further the advancement of green roof standards, which has published several standards to establish a common basis for comparing green roof fundamental properties (Roofmeadow 2015). The ASTM standards include methods of testing granular media for permeability and water retention, determining dead and live loads, evaluating performance of drain layers, selecting and maintaining plants all relative to green roof design (ASTM 2015). These ASTM standards provide media testing procedures and test quality assurance. They have been recommended for testing substrates' physical characteristics to ensure consistency with the international best practice. Each of these specific standards are included in the comprehensive guide published as ASTM E2400/E2400M "Standard Guide for Vegetative (Green) Roof Systems." In summary, this document includes discussion of "technical requirements for vegetative (green) roof systems pertaining to the following categories: plants, media, wind scour resistance, soil reinforcement, separation or filter layers, drain layers, water retention layers, protection layers, and root penetration barriers." (ASTM 2014) This guide also references the ASCE/SEI 7 standard for methodologies for determining uplift pressures.

The "Pennsylvania Stormwater Best Management Practices Manual", published in 2006, includes a "Vegetated Roof" section. The section describes primarily extensive roofs, general design considerations and the stormwater benefits. The primary benefits acknowledged are runoff volume and rate control. Other acknowledged benefits include water quality improvements, habitat creation and peak rate control through combination with infiltration measures. The bulk of the specifications are references to the FLL guidelines and ASTM standards. The manual also includes descriptions of plant selection, maintenance, cost, and construction sequence. Overall, this manual functions as a reference for the implementation of green roofs as SCMs, however is not a primary source of design specifications. (PADEP 2006)

The Auckland manual “Living Roof Review and Design Recommendations for Stormwater Management” is comprehensive and includes a review of several design standards. Each design component discussed is reviewed thoroughly and it thoroughly references the exiting design standards and manuals. Although the manual does include specific design recommendations for the Auckland area, a majority of advice and information is helpful to the design of a living roof in any location. The manual includes design of waterproofing, leak detection, edging, testing procedures for living roof components, drainage layers, substrate design, water holding capacity, and plants.

The FLL guidelines cover all aspects of green roof design, including specifications for the substrate, plant selection, and drainage design and maintenance considerations. These guidelines are available in English, and are universally referenced as a primary source of design standards for green roofs. The guidelines include several exclusive items, not replicated by any U.S. standards, including a certification test for root-barriers, and methods for measuring saturated hydraulic conductivities of various media assemblies (PADEP 2006).

ANSI and SPRI in cooperation with Green Roofs for Healthy Cities (GRHC) have published three design standards: wind uplift design standard, fire design standard and resistance to root penetration for vegetated roofing systems. As their names imply, these standards are used for designing green roofs with wind uplift resistance, external fire resistance and resistance to root and rhizome penetration for green roofs. The wind design standard references many other publications on wind uplift for both vegetated and non-vegetated roofs, including the FLL guidelines, a previous wind design standard published by SPRI and ASCE standards. (GRHC

2010) The abundance of related references reflects that wind uplift resistance is generally a well-researched topic. The relative lack of references in the fire design standard reflects that this topic has less related information, and that fire resistance is perhaps less of a concern to the green roof design community. (GRHC 2010) The root penetration resistance procedure is based on the FLL "Procedure for Investigating Resistance to Root Penetration at Green Roof Sites" (GRHC 2011).

2.3 Green Roof Hydrologic Performance Research

Most commonly, the purpose of green roofs is to mitigate the effects of rainfall events characterized by a return period of lower than 10 years. Beyond a certain point, the percentage of large storms that are retained on green roofs may be insignificant. Specifically, the rainfall volume over a green roof's designed storage volume is not retained so events larger than the design event result in runoff (Fassman-Beck et al. 2015). The hydrologic response from a green roof (peak runoff volume and total volume) has been shown to vary based on substrate depth for smaller precipitation events, for which a thicker substrate produces less runoff due to the porosity within the substrate providing storage for precipitation. For runoff from varying substrate depths during larger precipitation events, both peak discharges and runoff volumes have been seen to be of the same order. For example, Versini et al. (2015) studied two vegetated plots with a substrate depth of 3 cm and 15 cm, which produced volumetric runoff coefficients of 0.17 and 0.11 respectively. In areas where small, frequent rainfall events account for the majority of annual rainfall volume, a larger substrate depth may be most useful to eliminate green roof runoff as there is more soil storage capacity. Larger substrate depths provide greater retention, however the relationship is not linear and requires further investigation (Fassman-Beck et al. 2013).

2.3.1 Semi-intensive Green Roofs

Green roofs are typically categorized into two types: extensive roofs (substrate depth less than 6 in, 150 mm) designed to perform most environmental management functions, and intensive roofs (substrate depth greater than 6 in, 150 mm) providing conditions suitable for a wider range of plants, and more flexibility to be aesthetically pleasing. Intensive green roofs can be used for recreational space where people can interact directly with the roof, whereas extensive green roofs are often not designed to support the same magnitude of live loads. Semi-intensive roofs have an intermediate depth, typically 5 to 8 in (130-200 mm) and are described by the FLL guidelines with the term “simple intensive greening…involving the use of grass, shrubs and coppices as ground cover” (FLL 2002). The rainfall-runoff relationship is strongly determined by the depth of the substrate (media) layer. Intensive green roofs have been shown to produce less runoff than extensive green roofs, gravely roofs and traditional roofs (Figure 2.1) (Alfredo 2010; Buccola 2011; Mentens 2006). For a given site design, the green roof depth can be limited by site conditions, including structural integrity and climate, and the depth is chosen depending upon the design goals and limitations. Previous studies have noted increased green roof depth beyond minimum requirements for stormwater mitigation may provide multiple benefits, including the ability to have healthy and diverse plants in the absence of irrigation or shade (Fassman-Beck et al. 2013). Lu et. al. (2015) indicated a deeper substrate ensures better drought tolerance performance of plants on green roofs, although the ability of the roots to distribute into reservoir in drainage layer should be considered.

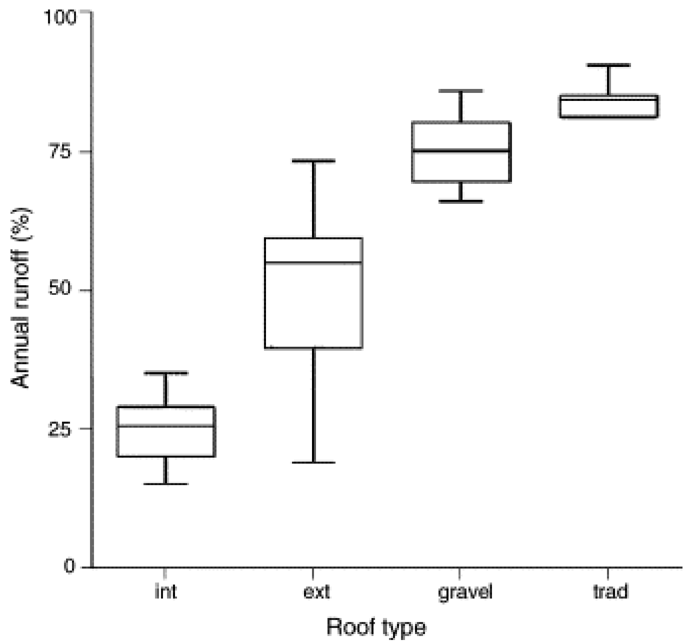


Figure 2.1. Annual runoff as a percentage of the total annual rainfall for various green roof types; respectively for intensive green roofs (n=11), extensive green roofs (n=121), gravel-covered roofs (n=8) and traditional, non-greened roofs (n=5). The box plots show the total range of the data (after removal of outliers), the 25 and 75 percentiles and the median. (Mentens 2006)

2.3.2 Green Roof Plants

A significant proportion of the hydrological benefits of green roofs can be attributed to the biological function and physical properties of green roof vegetation (Oberndorfer et al. 2007). In some cases, the plant health can directly affect the green roof performance. For example, unhealthy or very shallow root structures have been shown to export more phosphorus into green roof runoff (Alfredo 2010).

Research has consistently shown that plant species affect the amount of runoff from a green roof. Grasses are generally the most effective for reducing runoff, when compared to forbs and sedums (Nagase 2012; Whittinghill et al. 2015). However, grasses may require more maintenance and may not have as much tolerance for drought as sedums. In addition to the species, the size and the structure of plants significantly influenced the amount of water runoff.

Plant species with taller heights, larger diameters, larger shoots and root biomass were more effective in reducing water runoff from simulated green roofs. Species diversity did not have an effect on water runoff (Lundholm 2010).

As an important part of evapotranspiration, plant transpiration is estimated to account for between 20% and 48% of moisture lost to the atmosphere on green roofs (Voyde et al. 2010). Transpiration rates vary among plant species. Crassulacean Acid Metabolism (CAM) plants tend to have less evaporative loss than plants that transpire during the day. Sedums are a hardy, drought tolerant CAM species that have been widely studied on green roofs. Alternatively, many grasses utilize the C4 pathway for photosynthesis, which reduces photorespiration and increases the photosynthetic efficiency in hot, dry conditions. (Nave 2012) The variables related to plant type include ET rates, capacity for interception, foliage density, drought tolerance and plant size (Lundholm 2010; Poë 2015). The effects of various plant types on ET rates and overall roof runoff from is not widely known.

Plant health is important to water retention and media stability, however roof ecologies are dynamic and are expected to change over time from the original planting design. Often, new or emergent species that were not included in the original planting are found on a roof landscape. The vegetative dynamics can change according to weather, architecture, maintenance activities or other external factors. As plant communities change and evolve, the roof is ideally growing in resiliency and diversity (KieranTimberlake 2015). Due to the complex nature of plant-soil-water interactions, further study on plant types, plant health variations and their effect on green roof performance is necessary for the improved engineering of green roof systems.

2.3.3 Modular Green Roof systems

Modern green roof technology offers a variety of vegetated covers for impervious surfaces. Green roof types are generally divided into two groups: layered systems (with granular drainage or a drainage board/cup layer) (Figure 2.2a) and newly developed tray or modular systems (Figure 2.2b). The purpose of layered systems and modular systems are generally the same, however the systems differ in physical implementation. Layered systems are continuous, and are typically installed by media and plants (as plugs or seeds) being arranged directly on the roof. The typical layers include a waterproofing membrane to protect the underlying structure, a drainage layer such as an expanded plastic board or a porous media (e.g. gravel), and a geotextile to prevent media and root migration. Modular systems are self-contained within a lightweight module (usually high-density polyethylene- HDPE) of varying dimensions. The three main components of green roofs (waterproof membrane, drainage layer, filter fabric) are contained in the module. When interlocked, they offer nearly continuous roof drainage and coverage (Velazquez 2003). The modules can be planted prior to installation, then transported on to the roof. Due to the novelty of modular green roof systems, further research is necessary to properly determine the most suitable conditions and effects of choosing a modular tray system.

(a)  (b) 

Figure 2.2. Green roof types including (a) layered systems (image from pinstake.com) (b) modular, tray systems (image of GreenGrid ® system)

2.4 Flow Measurement from a Green Roof

Across hydrologic and hydraulic engineering, flow measurement is critical to tracking flow into or out of a system. Flow measurement devices range from quite simple to quite complex. All flow measurement techniques hinge on the concept of a velocity of water moving through a known area. Throughout water resources engineering there is widespread use of weirs and orifices, which provide a known area and can be designed such that the effective head that drives flow can be correlated to the discharge (and velocity), characterized by well-known equations (Sturm 2010). Weirs and orifices can measure flow over a wide range, although accuracy may be compromised as the range increases. While there are commercially available weir and orifice devices available for some water resources applications, the theory can be applied in custom devices to target the specific range and accuracy for a more unique application.

In a brief survey of green roof performance research, it was found that various types of flow measurement devices were used, including many devices utilizing level sensors, weirs and orifices. In pilot scale laboratory experiments, there is often a relatively small range of possible outflow volumes and sometimes only the total runoff volume is measured (Alfredo 2010; Nagase 2012). Moran et al. (2005) measured outflow using a weir box and level sensor. Carson et al. (2013) designed a custom runoff monitoring weir device, with a weir and level sensor. Zaremba et al. (2015) utilized a two-stage system that included a weir and level sensor for larger flows and a tipping-bucket rain gage for smaller flows. At the University of Auckland, an orifice restricted device (ORD) was custom-designed to enable measurement of flows 0.0002 L/s to 1 L/s (Voyde et al. 2010). The small pipe diameter and long pipe length created a greater depth increase for a corresponding increase in inflow than previous weir systems. This reduces potential measurement error from the pressure transducer, especially at low flows which result from small rainfall events. This design produced measurement accuracy for the wide range of flows expected from small green roofs. (Voyde et al. 2010)

3. Site Design and Construction

3.1 Project Locations

The two site locations for this project within the Delaware River Basin were selected as Villanova University (Radnor Township) and Upper Darby High School (Upper Darby Township) (Figure 3.1). Considering educational opportunities and visibility, the locations for the shelter sites were chosen by a committee of community leaders, primarily the Eastern Delaware County Stormwater Collaborative. Within each property, the specific project site was selected based on available land space, visibility and accessibility to the community. The Villanova University site was originally planned to be in the Darby-Cobbs Creek watershed, however due to building restrictions a location in the Mill Creek watershed, a tributary to the Schuylkill River watershed, was selected. The Upper Darby High School site is in the Darby-Cobbs Creek watershed. The possibility of retro-fitting an existing roof was explored on both properties, however not feasible due to lack of structural records and difficulty of structural reinforcements. The construction of a new structure was necessary to provide certain structural support for the green roof and associated monitoring equipment and serve as a community gathering place and stormwater educational demonstration. The new structures will provide a shelter: the Villanova University site consists of a picnic area along a highly-used walking path and the Upper Darby High School site is a bus stop shelter in the main parking lot. For both sites, municipal construction permits were obtained, and the associated permit fees were disbursed.

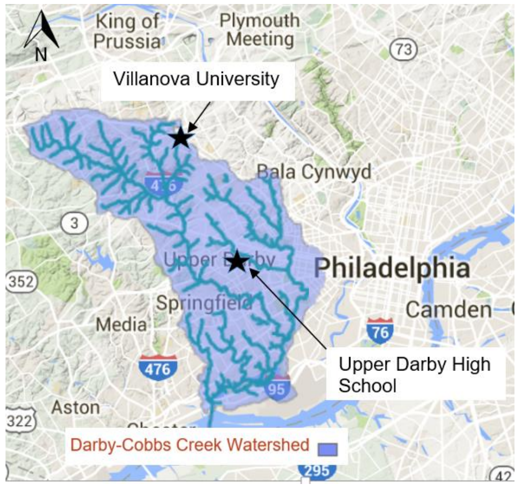


Figure 3.1. Site locations in the Darby Creek watershed in relation to Philadelphia.

The Upper Darby High School shelter location drains to a northern tributary of the Cobbs Creek. The Darby-Cobbs watershed drainage area is 77 mi^2 (200 km^2) and contains approximately 135 mi (217 km) of streams. The watershed is home to about 460,000 residents, with the highest population density near the City of Philadelphia. Within the watershed, impervious cover is estimated at 45%. (PWD 2015) As a result, this impaired urban watershed receives stormwater runoff pollution that results in erosion, siltation, flow variability, and aquatic habitat modification. The Cobbs Creek sub-watershed has combined sewers and several locations that regularly overflow, sometimes with over 50 CSOs each year. Throughout the Darby Creek, there are areas that regularly flood. Since the 1970s, the National Flood Insurance Program has paid out approximately $9 million in losses to two boroughs on the Darby Creek alone (Wood 2012). Citizens in the commonly flooded areas incur additional undocumented costs associated with flood damage. As development continues, the flooding and CSO issues are expected to persist and worsen.

In 2004, the Philadelphia Water Department (PWD) published the Cobbs Creek Integrated Watershed Management Plan (CCIWMP), which identified several watershed issues, including degraded aquatic and riparian habitat, little volume control of stormwater flows in separate-sewered areas, and limited public awareness and sense of stewardship for Cobbs Creek. The municipalities involved are older, highly urbanized, mostly small communities that have technical and financial constraints in dealing with stormwater regulatory requirements. The Eastern Delaware County Stormwater Collaborative was created by the Southeastern Pennsylvania Resource Conservation and Development Council to assist municipalities in working together to address issues identified in the CCIWMP within watershed boundaries, since there is no centralized entity responsible for undertaking stormwater issues in a coordinated fashion (SEPA RC&D 2011). This green roof shelter project serves as an SCM and educational resource for stormwater and green infrastructure within the Darby-Cobbs watershed.

The green roof shelter on Villanova University's campus is part of the VUSP SCM Research and Demonstration Park, which includes a variety of SCMs including a constructed stormwater wetland, bio-infiltration and bio-retention rain gardens and swales, pervious concrete/porous asphalt, infiltration trenches and a retro-fit green roof. The inclusion of this shelter into the VUSP SCM Research park facilities enables an enhanced opportunity for partnership with the University during construction, monitoring and throughout the life of the project. The location benefits include visibility by University visitors, inclusion in the frequent on-campus SCM tours, and accessibility for operation, maintenance and future improvements.

3.2 Structural Design and Construction

Since this project is not a traditional SCM nor a traditional bus or picnic shelter, no existing standard design options for green roof shelters of this scale were available. The structure chosen is a steel frame manufactured by Dugouts USA. As the name implies, the structure is designed as a baseball dugout, and was modified for this project. The dugout structure was chosen because it was a commercially available, standard design with durable steel materials (Appendix A), and the ability to customize structural features and aesthetic features. The alternative option was a completely custom fabrication, which was not feasible for the project budget. The dugout structure included all the necessary structural elements at an affordable price (approximately 30% of the custom-design cost). Dugouts USA manufactured the structure to the partially-custom specifications, including a powder coated paint in two colors, and the structure was shipped disassembled.

Consequently, the structural design was primarily a modification of an existing available dugout structure (Appendix A), with additional precautions taken to ensure the support of the green roof. At the Villanova campus site, prior to the structure construction six concrete footings were installed by a contractor using concrete forms 2 ft (0.61 m) in diameter and 3.5 ft (1.07 m) deep (Appendix B), as engineered by Dugouts USA. The foundation or footings design must take into account the frost line and soil characteristics on site. Alternatively, a concrete slab could function as the foundation for the shelter.

The structural analysis was completed in conjunction with Villanova University's Structural Engineering department and in accordance with ASCE 7-10 (American Society of Civil Engineers 2013). The analysis included an evaluation of the green roof loading and the necessary modification of the commercially available dugout design (Appendix C). The green roof design loading was determined for a maximum eight inch media depth, allowing for the flexibility of roof design with a smaller media depth. The design dead load included roof decking materials, beams, monitoring equipment, vegetated trays and additional loading (4 psf) for future equipment additions, including solar panels. Using industry-standard media, the saturated weight (dead load) of a green roof is about 6.75 lbs per in of media per ft^2, following the ASTM E2397 method for estimating wet and dry weights. The structure is designed for a snow load of 25 psf (1.2 kPa) and a wind load up to 115 mph (185 km/h). The sizes of beams and columns of the commercially available dugout were increased to accommodate the additional green roof loading (Table 3.1). All structural members and features were designed with the goal of creating a durable, attractive and affordable shelter for this project.

Table 3.1. Structural details of the original and customized Dugouts USA shelter, including beams, columns and roof characteristics.

Structure Parameter	Original Detail	Custom Detail
Lateral beam quantity	3	4
Beams size	A500, HSS 4in x 4in x 1/8 in	A500, HSS 4in x 4in x 1/4 in
Columns size	A500, HSS 4in x 4in x 1/8 in	A500, HSS 4in x 4in x 1/4 in
Column base plate	A36 steel, 1/2in thickness	A36 steel, 1/2in thickness
Roofing material	26 gauge metal	26 gauge metal
Roof slope	2:12 pitch, 9.5^o	1:12 pitch, 4.8^o
Roof height	8 ft	8 ft

The shelter roof slope (8.3%) was the flattest slope offered by the manufacturer. The slope helps to promote free drainage and prevent standing water during rainfall events, while maintaining a gentle gradient to minimize erosion. To compensate for slopes greater than 5%, the FLL guidelines recommend a “superstructure with a fairly high water-storage capacity and poor drainage, or vegetation which does not require a great deal of water” (FLL 2002). The intensive depth of Rooflite media and GreenGrid ® trays with built-in storage cups provide a high water-storage capacity. The vegetation was selected to survive and grow with little to no irrigation after establishment. For protection against slipping and shearing for roofs with slopes of 36% or less, the FLL guidelines indicate “there is usually no need for any costly measure to prevent the structure from shearing.” The National Roofing Contractors Association suggests that generally with less than a 2:12 roof pitch no significant slippage of the growth medium is expected (Barista 2007).

The Villanova shelter is 24 ft roof length and roof width of 8 ft (Figure 3.2). The Upper Darby shelter will be a 15 ft roof length and a roof width of 8 ft (Figure 3.3). The roof height of 8 ft allows for visibility from ground level. Additionally, this site is along a graded walking path so a passerby is able to view the roof. To minimize media disturbance, the roof level is accessed only during maintenance situations, therefore maintaining the permeability of the media and avoiding compaction. The primary access to roof components is by ladder from any of the four sides.

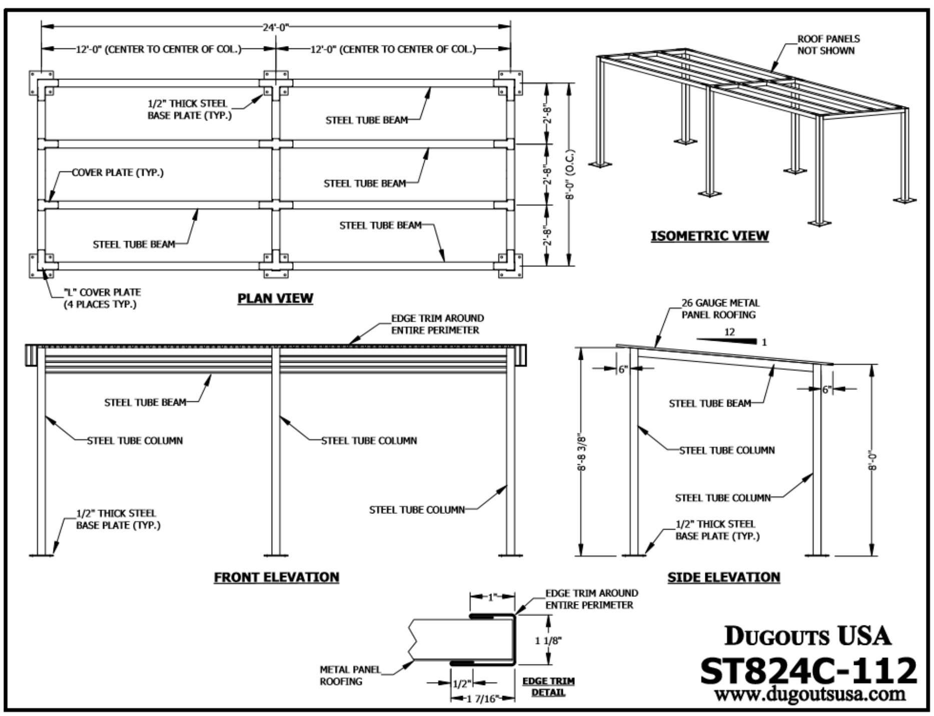


Figure 3.2 Structural details for the Villanova University shelter manufactured by Dugouts USA.

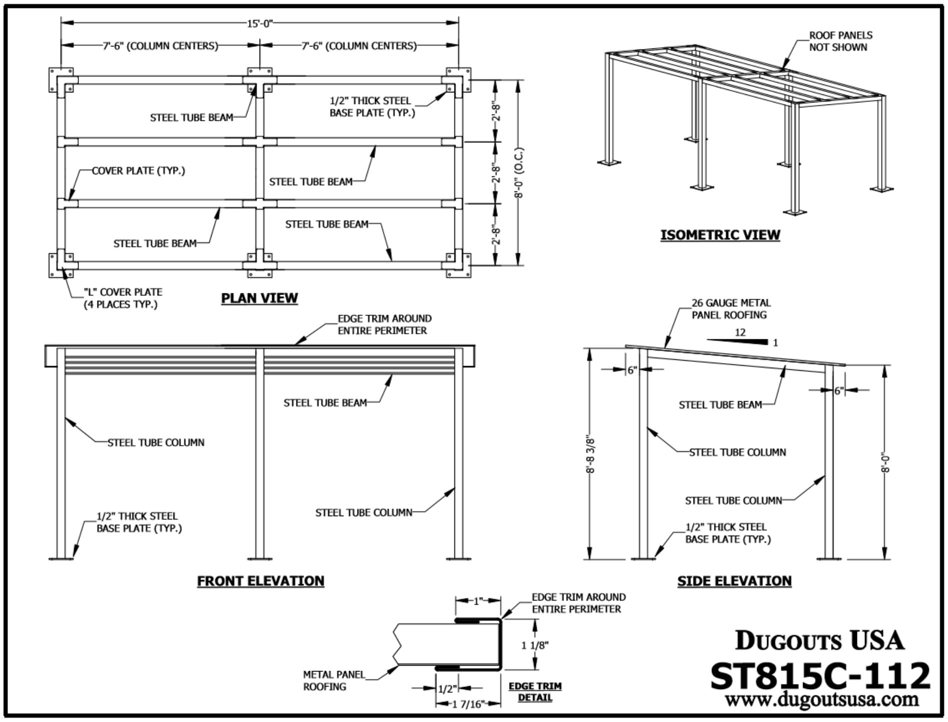


Figure 3.3 Structural details for the Upper Darby High School shelter manufactured by Dugouts USA.

The Upper Darby High School structure has not been constructed as of December 2015. The subsequent sections focus on the Villanova University site, although design and installation elements are transferrable. For the Villanova University structure, installation was completed in April 2015 (Figure 3.4). The duration of installation was approximately two days with three people. To secure the structure to the ground, the column base plate (pre-fabricated welded connection between the base plate and column) was bolted into the footings (Figure 3.5a). All connections are bolted. The metal roof material was included in the order from Dugouts USA and pre-cut. For the roof installation, ensure that the ribs of the roof material are oriented vertically so that runoff is directed downslope on the roof (Figure 3.5b).

Figure 3.4 Structure installation complete including roofing material.

(a)  (b) 

Figure 3.5 (a) Support columns electrically welded to ½” thick steel base plate, and bolted to footings. (b) Roof ribbing directed downslope.

The overflow collection system was designed to capture drainage leaving the GreenGrid modules, entering the gutter system and exiting through the downspout (which houses the flow measurement device). There are two gutters on the down-slope edge of the roof, angled with the higher elevation at the center of the roof and a slope downwards to the corners in order to compare the two halves of the roof. As such, there are two outflow collection systems receiving runoff from equal roof areas. In the current configuration, one gutter system is collecting the runoff from the grasses section, and one gutter section is collecting runoff from the sedums section. In both gutters, a mesh filter is installed to serve as protection from incoming debris for the flow measurement device (Figure 3.6). In this way, the runoff is filtered to remove large solids to prevent a blocked drain, and the subsequent standing water and increased structural load. The gutters are vinyl for durability and are attached to the structure with screws into pressure treated wood sections. The wood sections are secured into the steel beams on the downslope of the roof.

Figure 3.6 Left: The drainage collection system on one corner of the roof including roof edging, roof ridges and orifice for flow to enter downspout. Right: the filter mesh used to block debris.

Edging on green roofs functions to keep media and vegetation in place while allowing water to freely discharge. Here, the edging provided structural support to keep the GreenGrid trays in place (Figure 3.7). The edging material is 7 ¼ in tall PVC boards, with the boards fastened together with stainless steel screws and straight brackets. The edging is attached to the roof with screws at the top and bottom of the roof to prevent movement of the trays and wind uplift on the trays. The ribbing of the roof material provides channels for overflow to enter the gutters underneath the edging. Additionally, flashing was installed to keep the gutters protected from precipitation on parts of the roof not covered by the green roof trays and damage (Figure 3.8). The module installation was completed by Villanova Facilities by lifting the fully planted trays onto roof with a forklift. This activity took approximately two days for three people.

Figure 3.7. Roof edging before and during tray installation.

Figure 3.8. Aluminum roof flashing functioning as a gutter cover and protection for the drainage collection system.

3.3 Green Roof Design

3.3.1 Modules

Green roofs sites are designed to reduce runoff by three mechanisms: plant interception and evapotranspiration, substrate detention and retention, and the storage. The design of this roof described herein aimed to maximize these removal mechanisms. The unique features of this roof include the modular trays and the semi-intensive depth with a relatively small green roof area.

Due to a generous donation from Weston Solutions, this project utilizes the GreenGrid® modular green roof system (Figure 3.9). The physical modularity allows for roof access during seasonal design changes, roof membrane repairs or other roof maintenance. If necessary, one or more of the modules can be removed with minimal disruption to other modular plantings. Compared to a layered design, the modular design is simplified since the modules are engineered to contain the drainage layer elements, including storage cups. The storage cup design is similar to common synthetic drainage mats used for green roofs, which are typically molded plastic in the shape of egg crates. These storage cups function to provide additional water retention capacity and to extend the volume of water and amount of time the water is available to the plants. This storage cup volume is the minimum expected retention volume, as discussed in section 3.3.4. As plants mature, fine roots grow into the cups, acting as wicks. When cups are filled, the water is available for removal through evapotranspiration (ET) instead of becoming runoff. The GreenGrid modules with integrated reservoirs follows the FLL guidelines on water storage in intensive greening:

> "Current knowledge indicates that in the context of intensive greening schemes, the form of water storage which offers the most reliable long-term performance and which caters most event-handedly

for all economic and ecological needs is a combined system in which water is stored in the vegetation support course and held in a reservoir formed in the drainage course."(FLL 2002)

Additionally, the modules act as a confinement system to hold the growth media in place, especially necessary during the early stages of development of vegetation.

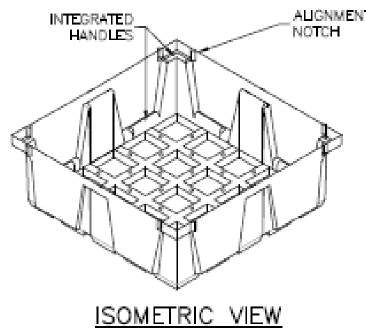


Figure 3.9. Weston Solutions GreenGrid module design of 2' x 2' x 8" module. U.S. Patents: 6,711,851 | 6,862,842 | 7,900,397 | 8,555,545

One way to maximize water storage volume is to maximize the depth of the media, as described in Section 2.2.1. For the GreenGrid® modules, the largest commercially available module depth (8 in, 20.3 cm) was chosen. Since the support structure was designed for the green roof, the structural capacity did not restrict the media depth. Compared to an extensive media depth, the semi-intensive depth allows for greater water storage volume and a wider variety of plant life.

This project takes advantage of the modular system by having two different plant types on the roof, separated and contained by the trays. Because the modules are easily removed, the site has greater flexibility and is open to future improvements for new research ideas. The site has potential to be dynamic, adapting to a new research goal or design. Many communities could benefit from the dynamic nature of the modular system. Since the trays can be handled individually, they could be used as a temporary way to mitigate stormwater issues, especially if a smaller media depth was used to limit the weight per tray. This flexibility lends itself well to a "pop-up" green infrastructure demonstration, which have been seen in major cities as a way to promote stormwater education. Urban communities use this concept to attract visitors by transforming a forgotten outdoor area into an attractive landscape (Pennsylvania Horticultural Society 2015).

For other modular green roof projects, there are additional features of the modules that can enable a simpler installation. The modules can be pre-planted off-site in a greenhouse environment, so that installation can occur with established mature plants. When designing a structure with a modular green roof, it is advised to take into consideration that the fully planted modules bulge and may exceed the specified width and length of two feet. Further design variations between each module could be employed including different substrates or soil mixes, different soil depths, different plant types.

3.3.2 Media

Green roof media is ideally a balance of lightweight, well-drained materials, and good water and nutrient holding capacity. The FLL guidelines do not include specific requirements for semi-intensive media, likely because the media has very similar requirements as extensive media. The media used for this project is rooflite ® semi-intensive engineered growth media, manufactured by Skyland USA LLC (Appendix D). Reported by the manufacturer, the dry weight is 0.70 – 0.85 g/cm^3 and the water-holding capacity is 45-65% of the volume. This blend is designed to support a range of plant life, including perennials, ornamental grasses and even small shrubs.

(Skyland USA 2015) In order to minimize nutrient export in the runoff, no fertilizer was added to the media.

The media water holding capacity and the tray volume are used to calculate the storage volume for the green roof. Because of the air space beneath the modules, the entire green roof can drain freely by gravity. This limits the maximum water holding capacity to about 42% for the rooflite extensive media blend, as investigated in a previous thesis at Villanova University (Schneider 2011). In the storage volume calculations for this roof, the water holding capacity was conservatively estimated at 40% of the media volume. The green roof capture volume is detailed in section 3.3.4.

3.3.3 Plants

The roof was divided into two halves to compare the performance of various plant types. The two groups of plants being compared are sedums and non-sedums (primarily grasses) (Figure 3.10). As described in Section 2.2.2, it has been proved that plant type significantly influences the runoff volume. Within the groups, the plant species were chosen based on drought tolerance and hardiness, demonstrated by success on previous green roof installations in the same general climate. Both vegetation groups were planted as plugs, and watered upon installation. As previously mentioned, no fertilizer was added and no consistent irrigation will occur after plant establishment, in order to minimize nutrient export and resource use. The two separate halves have separate collection systems to determine the differences in hydrologic performance between the grasses and the sedums.

A	M	F	PV	PV			DD	AS	SSS	JC	DD
A	M	F	PV	PV			DD	AS	SSS	JC	SA
A	M	F	MF	PV			DC	AS	SSS	SR	DC
A	PP	PS/MF	MF	PV			SA	AS	SSS	JC	SA
Grasses							Sedums				

A	Achillea Moonshine	DD	Delosperma Dyeri
M	Muhlenbergia reverchonii 'seep muhly'	DC	Delosperma Cooperi
PP	Opuntia humifusa 'Prickly Pear'	SSS	Sedum spurium. Schorbuser Blut
F	Festuca glauca	AS	Sedum spurium. Album Superbum
PS	Petrorhagia Saxifraga	JC	Sedum spurium. 'John Creech'
MF	Monarda Fistulosa	SR	Sedum reflexum S. Rupestre
PV	Panicum Virgatum 'switchgrass'	SA	Sedum Album F. Murale

Figure 3.10. Planting plan implemented in Fall 2015 with corresponding photographs of each vegetation group: non-sedums (left) and sedums (right.)

3.3.4 Water Retention

Since precipitation varies by location, the most efficient SCM design considers the local distribution of rainfall and event size frequency. When stormwater management only addresses large events (2-year storms and greater), the majority of actual rainfall and runoff are overlooked. Managing smaller storms that comprise the majority of annual rainfall is crucial. The Philadelphia area receives approximately 107 cm (42 in) of rainfall annually and a majority in small storm events (2.54 cm (1 in) or less). For Pennsylvania, 65% of storms are 2.54 cm (1 in) or less and 92% of storms are 5.08 cm (2 in) or less (Figure 3.11).

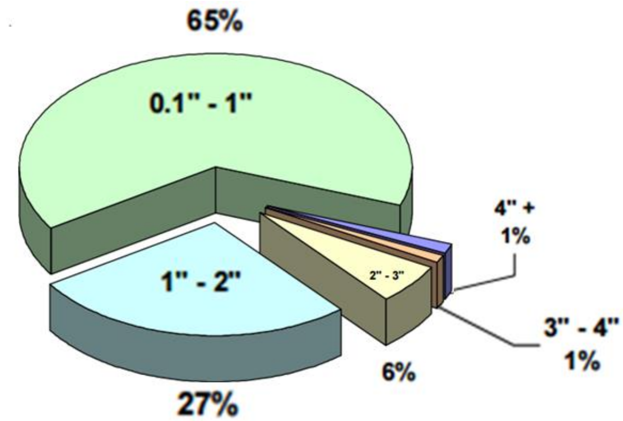


Figure 3.11. Distribution of precipitation by event magnitude for Pennsylvania, 1926-2003 *(PADEP 2006)*

The water retention calculations for the green roof were calculated using the available storage volume, considering the media depth and a conservative porosity estimate (40%). Media details are included in Section 3.3.2. With a media depth of 8 in (20 cm) and green roof area of 160 ft^2 (15 m^2), the Villanova green roof shelter has a maximum rainfall capture depth of 3.1 in, calculated using the entire storage volume of the media with zero antecedent moisture (Table 3.2). The minimum rainfall capture depth, 0.14 in, was calculated from the pore volume within the water retention reservoirs (storage cups) which are filled with media and do not freely drain. Assuming no antecedent moisture, the rainfall volume of the 2-year 12-hour storm (2.85 in) is less than the maximum storage capacity (3.1 in) of the green roof (Table 3.3). The 5-year 12-hour storm (3.57 in) exceeds the maximum storage capacity, however the resulting rate of overflow (0.053 gpm) is within the measurement range of the ORD, so overflow can be measured. It is expected that overflow will be observed before 3.1 in of rain due to draining by gravity through the module; the depth of rainfall that is the threshold to induce drainage will be investigated moving forward.

Table 3.2. Site specifications for the Villanova shelter and Upper Darby shelter.

Site Parameter	Villanova	Upper Darby
Green Roof area, ft^2 (m^2)	160 (14.9)	120 (11.1)
GreenGrid ® modules	40	30
Media Depth, in (cm)	8 (20.3)	8 (20.3)
Minimum Capture Volume, in (cm)	0.14 (0.35)	0.14 (0.35)
Maximum Capture Volume, in (cm)	3.1 (7.87)	3.1 (7.87)

Table 3.3. Precipitation frequency (PF) estimates in inches for Villanova, Pennsylvania compared to green roof shelter capture volume. Green indicates a value less than the maximum capture volume, yellow indicates a value greater than the maximum capture volume and within measurement range for ORD. PF estimates based on frequency analysis of partial duration series (PDS) from NOAA Atlas 14. (NOAA PFDS)

Legend
Less than maximum capture volume
Greater than maximum capture volume, less than ORD maximum flow

	PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)						
Duration	Average recurrence interval (years)						
	1	2	5	10	25	50	100
5-min	0.348	0.414	0.486	0.536	0.595	0.636	0.675
10-min	0.556	0.662	0.778	0.857	0.949	1.01	1.07
15-min	0.694	0.833	0.984	1.08	1.2	1.28	1.36
30-min	0.952	1.15	1.4	1.57	1.78	1.93	2.08
60-min	1.19	1.44	1.79	2.04	2.37	2.62	2.86
2-hr	1.42	1.73	2.15	2.48	2.91	3.25	3.59
3-hr	1.56	1.89	2.36	2.72	3.2	3.58	3.97
6-hr	1.94	2.35	2.92	3.39	4.04	4.56	5.11
12-hr	2.36	2.85	3.57	4.17	5.04	5.78	6.57
24-hr	2.72	3.28	4.12	4.81	5.82	6.67	7.59
2-day	3.14	3.79	4.77	5.56	6.69	7.63	8.63
3-day	3.31	3.99	5	5.83	7	7.97	9

The ongoing research aims to monitor and eventually predict the actual response of the green roof in terms of retention and drainage. To compare the expected overflow (drainage) to a more established SCM on the same campus, the CEER retrofit green roof on campus is 575 ft^2 (53.42 m^2) and has approximately 4 in of growing media. From the CEER roof, the overflows ranged from 2 mm – 152 mm (0.08 in – 6.0 in) for monthly recorded overflow from 2013- 2014

(Zaremba 2015). If normalized per media volume and scaled to the Villanova shelter size [160 ft^2 (14.86 m^2) and 8 in (20.32 cm) media depth], the expected monthly overflow range over the same two years would have been 1.1 mm – 85 mm (0.04 in – 3.3 in). In comparison, the Villanova green roof shelter is expected to have 55% less runoff than the CEER green roof.

3.4 Sensing and Monitoring

3.4.1 Monitoring Equipment

The monitoring equipment was chosen to provide the broadest range of data within the project budget. The goal of designing the monitoring system was to anticipate future research questions and prepare the laboratory space to quickly implement a project to collect data to answer a specific research question. The equipment will provide data for the following parameters: wind speed and direction, temperature, overflow rate and volume, soil moisture, solar radiation. The monitoring equipment is split into two groups: low-cost "minimal" sensing and high-end sensing. The low-cost sensors (Table 3.4) are placed in tandem with the research-grade sensors (Table 3.5) to discern the differences in performance, quality of measured data and accuracy of each sensor. The low-cost sensors may be appropriate for educational purposes or at demonstration sites. The high-end sensing includes research grade instruments intended to intensely monitor the meteorological conditions and green roof stormwater performance. The Villanova site is employing both the low-cost and research grade monitoring equipment. The data from each level of sensor will be compared to determine if the low-cost sensors are adequate for research grade monitoring. The accuracy and power requirements were reviewed to determine system compatibility (Appendix E).

Table 3.4. Low-cost monitoring equipment manufacturers, models and number of units.

Item	Unit Cost	Units	Total Cost
Atlas Scientific ENV-TMP Temperature Probe	$ 25.00	2	$ 50.00
Dallas DS18B20 Digital Temperature sensor	$ 10.00	2	$ 20.00
Vegetronix VH400-10M Soil Moisture Sensor	$ 54.00	2	$ 108.00
Hach Sigma 2459 Tipping Bucket Rain Gage	$ 200.00	1	$ 200.00
		TOTAL	$ 378.00

Table 3.5. Research-grade monitoring equipment manufacturers, models, and number of units.

Item	Unit Cost	Units	Total Cost
Campbell Scientific CS450 Pressure Transducer	$ 700.00	1	$ 700.00
Decagon DS-2 Sonic Anemometer- Wind Speed and Direction	$ 510.00	1	$ 510.00
Decagon EC-5 Soil moisture sensor	$ 110.00	4	$ 440.00
Stevens SP-212 Pyranometer with level plate AL100 and bracket AM110	$ 385.00	1	$ 385.00
		TOTAL	$ 2,035.00

The soil moisture sensors measure the moisture conditions of the media. Changes to the soil moisture measurements track the water flow through the media. The soil moisture sensors were installed at a depth of 4 in (10 cm). The Vegetronix VH400 sensors and the Decagon EC-5 sensors output an analog signal and determine volumetric water content (VWC) by measuring the dielectric constant of the media, and both sensors were calibrated to the green roof media. The VH400 (low-cost) and the EC-5 (high-end) were installed at identical depths to compare performance of the sensors.

The pressure transducers are used to measure the depth of water in the ORD flow meters. The pressure transducers are SDI-12 compatible with ± 0.1% accuracy with a 0 - 16.7 ft (0 – 5.09 m) depth range. The advantage of the SDI-12 output is the digital signal instead of the data unit interpolating a range of millivolts or amps to get a depth, eliminating a source of measurement error. As the error is related to the range measured, a smaller measurement range reduces error. If the pressure transducer is set to the smaller range of 0 to 6.7 ft (0- 2.0 m), the error is 0.1% of full scale, or within 0.007 ft.

Meteorological data is collected on-site to determine the site-specific climate. Detailed instrument specifications are included in Appendix E. Precipitation is measured by a Sigma Rain Logger, which is an automatic data-logging, tipping-bucket rain gauge. Air temperature, wind speed and wind direction are measured by a Decagon DS-2 sonic anemometer. The wind data analysis will include investigation of the influence of wind on soil moisture conditions, and consequently the ET rates on the roof, which is the most important process of runoff volume reduction. Soil temperature is measured by Atlas Scientific ENV-TMP probes and DS18B20 digital temperature probes. Soil temperature probes will be at four depths (2, 4, 6, and 8 inches below media surface) to provide a profile with depth to better understand the thermodynamics of the system. Like the soil moisture meters, two sensors (DS18B20- low-cost, ENV-TMP- higher-cost) are used to compare the utility of both sensors. Relative humidity data is available from a weather station approximately 500 ft (152 m) away. A monitoring system without on-site meteorological data could instead rely on local publicly-available weather data for precipitation, solar radiation and wind speed.

3.4.2 Orifice Restricted Device (ORD)

This project utilized a custom orifice restricted device (ORD) to address the unique challenge of accurately measuring a wide range of outflow volumes and rates. For any vegetated SCM, measuring low flows accurately in the field can be difficult. Custom solutions are often employed in green roof monitoring systems due to the absence of established techniques. As discussed in section 2.4, previous systems have utilized ORDs to measure green roof outflow

(Howell 2014; Voyde et al. 2010). A custom design provides the benefit that the instrument is tailored to the needs of the individual site. This project employed a custom ORD with a design based on previous instruments used in similar green infrastructure projects. The ORD was designed to optimize measurement accuracy and design simplicity with an affordable instrument that can be made with low-skilled labor and common equipment. The final ORD design consists of two concentric PVC pipes with reducer fittings between the 3 in (7.6 cm) diameter and 1 in (2.54 cm) diameter pipes (Figure 3.12). Water enters the interstitial space between the pipes, and flows out through the five orifices of varying diameters on the inner pipe. During calibration, the water depth inside the ORD is related to the volumetric inflow rate with a regression equation. In the field, the water depth is measured throughout a storm event and using the calibrated relationship, the inflow rate to the ORD (roof volumetric overflow rate) is determined.

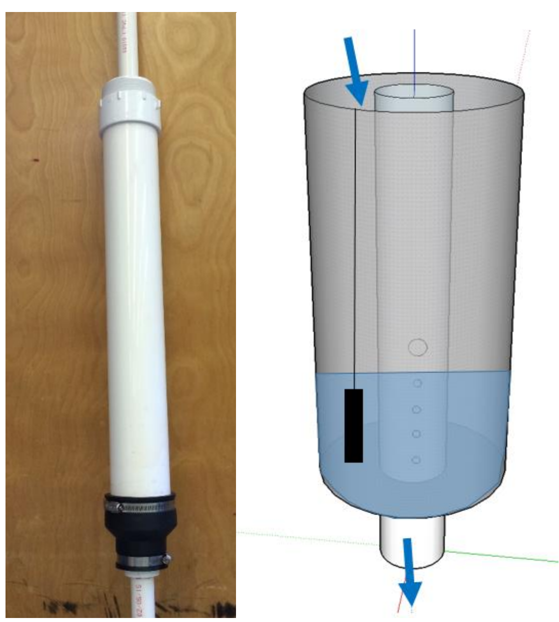


Figure 3.12. ORD photograph (left) and conceptual drawing (right) with inflow, outflow (blue arrows) and pressure transducer (black.)

The design of the orifice diameters and quantity was based on the expected ORD inflow rate (equivalent to the green roof overflow rate) from a standard design storm. The ORD capacity was designed to measure the 2yr-24hr storm (3.28 in, 0.125 in/hr), the 2yr-6hr storm (2.34 in, 0.35 in/hr), and low flows down to 0.06 gpm (0.004 L/s). The calculation of the roof overflow rate from these storms assumed 100% of the rainfall becomes runoff. Considering the rainfall intensity, rainfall depth and green roof area, the overflow rate was calculated to be 0.0017 cfs (0.049 L/s) for the 2yr-6hr storm and 0.0061 cfs (0.017 L/s) for the 2yr-24hr storm. The initial design flowrate 0.0353 cfs (1 L/s) was chosen to be greater than both of these two rates to conservatively estimate the capacity of the instrument. The orifice equation was used to calculate the orifice area required to discharge the design flowrate. The orifice equation only considered fully-submerged orifice discharge, and weir flow for partially-submerged orifices was not significant due to the small orifice diameters. The calculations assumed circular orifices, ORD height of 18 in and a discharge coefficient of 0.51. The total required orifice area was approximately 2.5 in^2 (16.13 cm^2).

To empirically determine the optimal orifice configuration (space between orifices, etc), several prototypes were constructed, tested and refined. The first prototype was a single-pipe ORD with a pipe diameter of 1.5 in, pipe length of approximately 2 ft, and 14 orifices with orifice diameters varying from 0.5 in to 1/10 in. The orifices were drilled by hand directly into PVC with a drill bit (Figure 3.13a). Upon testing with the pressure transducer inside the ORD, the device was determined to require alteration as it did not consistently have the same water depth for a given inflow rate.

(a)  (b) 

Figure 3.13. (a) The first ORD prototype with hand-drilled orifices, (b) One of the second generation prototypes with milled orifices

The next group of four prototypes had an additional PVC pipe. Another design improvement was using a mill to drill the orifices to improve the uniformity and consistency of the orifice edges (Figure 3.13b). These four prototypes were made with varying pipe diameters and orifice configurations. ORD 1 and ORD 2 both had 1 in and 3 in concentric pipes. ORD 3 and ORD 4 both had 2 in and 4 in concentric pipes. The ORD height was 27 in (69 cm) and the distance between each orifice is 1 in. Each ORD was calculated to have the discharge capacity to handle the design flowrate at minimum. The four ORDs had four different orifice configurations (Table 3.6) with orifice diameters increasing from the bottom to the top of the ORD.

Table 3.6. Four orifice configurations (quantity and diameter size) in the initial prototypes.

	Orifice quantities				
	ORD 1	ORD 2	ORD 3	ORD 4	Orifice Diameter (in)
	0	0	2	2	0.75
	5	2	5	2	0.5
	5	18	5	18	0.25
	5	0	5	0	0.125
Total #	15	20	17	22	

Each of the four ORD prototypes was tested and a polynomial regression equation was created to represent the relationship between the inflow and water depth. The sum of the squared residuals between the calibration data and the corresponding polynomial equation was chosen to represent the fitness of the model. The sum of the squared residuals was lower for the 1 in ORDs than for the 2 in ORDs (Table 3.7). This lead to refining the design to use the 1in/3in concentric pipe diameters. Further calibration data for these initial prototypes are included in Appendix F.

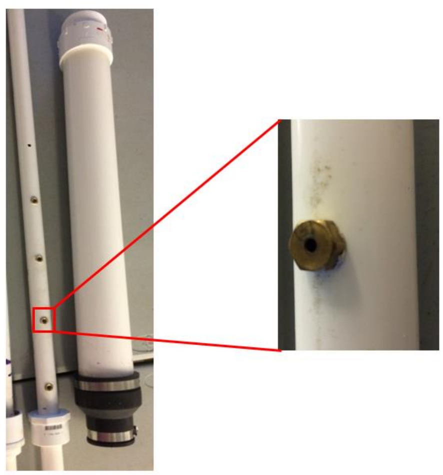
Table 3.7. The sum of squared residuals between regression equation and calibration data for the four initial ORD prototypes.

ORD, internal pipe diameter	Sum of Squared Residuals
ORD1 1 in	0.23
ORD2 1 in	0.13
ORD3 2 in	0.60
ORD4 2 in	1.83

In this design, the pressure transducer is housed in the interstitial space between the two pipes. The smaller ORD with pipe diameters (1 in and 3 in) has just enough space to fit the CS450 pressures transducer used; some other pressure transducers are thicker and did not fit. Pipes of alternate diameters can be used to handle a larger or smaller flow volume, or larger measurement equipment. The pipe lengths can also be adjusted to accommodate structure dimensions or flow capacity. The length of the 1 in pipe will depend on the expected measurement range. The 1 in pipe should be about 1 ft longer that the 3 in pipe to allow vertical space for the connection.

Because testing thus far determined that fewer and smaller orifices increases the ability to accurately model the inflow-depth relationship, the third generation prototype decreased the quantity and diameter of the orifices to two orifices (Figure 3.14a). Four out of the five orifices were drilled and tapped orifice plugs instead of mill- or hand-drilled orifices to maintain consistency when constructing future ORDs (Figure 3.14b). Additionally, the orifice plugs provide the ability to interchange the plugs with alternate orifice diameters without physically altering the PVC pipe. The fifth, drilled orifice with the largest diameter was included to provide additional flow capacity. Testing of the third generation prototype revealed a long lag-time between a drop in inflow rate and a drop in the ORD water depth due to the small amount of orifices. This prevented a consistent relationship between inflow and water depth, and necessitated additional orifices be added to the final ORD design.

(a) 

(b) 

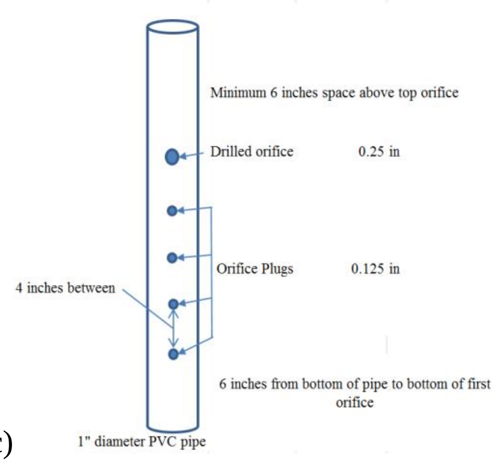
(c) 

Figure 3.14. Orifice plugs used for production consistency and ability to interchange orifice sizes on the (a) third generation ORD prototypes with two orifice plugs, (b) final ORD with enlarged orifice plug and (c) drawing of final ORD design.

The final ORD design (Figure 3.14c) has five total orifices: four are orifice plugs with diameter of 0.125 in (0.3175 cm) and the uppermost orifice is mill-drilled with an orifice diameter of 0.25 in (0.635 cm). The 1 in diameter pipe length is 4 ft and the 3 in diameter pipe length is 3 ft. Two of the final ORDs have been constructed and calibrated for use on the green roof shelter site.

The ORD materials were available for purchase at a local hardware store with the exception of the orifice plugs, which were ordered online through O'Keefe Control Co. in Trumbull, Connecticut and Datum-A-Industries in Maple Plain, Minnesota. The cost of the ORD materials (Table 3.8) for this specific device is approximately $50, which does not include taxes, pressure transducer, calibration equipment or adhesives (PVC cement) used in assembly.

Table 3.8. Itemized material and price list of ORD materials

Item	Number	Unit Cost	Total Cost
PVC pipe 1in x 10ft Schedule 40	1	$ 4.30	$ 4.30
PVC Pipe 3in x 2ft Schedule 40	1	$ 8.98	$ 8.98
Fernco Flexible Coupling 3in to 2in	1	$ 6.68	$ 6.68
PVC Flush Bushing 2in to 1 ½ in	1	$ 0.85	$ 0.85
PVC Bushing 1 ½ in to 1in	1	$ 1.32	$ 1.32
Orifice Plugs 0.125 in diameter	2	$ 6.26	$ 12.52
Orifice Plugs 0.113 in diameter	2	$ 6.26	$ 12.52
3 in PVC Snap-in Drain	1	$ 2.94	$ 2.94
		TOTAL	$ 50.11

If possible, using a mill is highly recommended so the orifices are sized and aligned properly. Once the holes are drilled in the smaller PVC pipe, the two pipes are connected. The connection should be water-tight to ensure all flow is measured. This construction included two separate PVC bushings (1 in to 1 ½ in and 1 ½ in to 2 in) due to the commercially available sizes, however it is simpler to have one bushing (1 in to 2 in). The bushings are attached approximately an inch below the bottom orifice, permanently with PVC cement. These pieces function to create a connection between the 1” pipe and the Fernco coupling. The Fernco flexible coupling is available in standard sizes and enables the connection to be removable to enable separation of the two pipes for maintenance purposes. The space beneath the first orifice is left to account for the low accuracy of the pressure transducer at very low depths (depths less than approximately 1 in). This can be adjusted depending on the instruments used and required measurement flow rate. A PVC drain was modified to fit between the two pipes to center the inner pipe vertically and to prevent any kind of large debris from entering the ORD (Figure 3.15). Depending on the location of the inflow, a PVC cap may need to be added on the inner pipe to prevent inflow from directly flowing through the system without being measured. Further details on construction steps are included in Appendix G.

Figure 3.15. Modified PVC drain between the concentric pipes.

The measurement range was determined by the maximum inflow rate that did not cause the ORD to overflow. The maximum inflow rate was limited by the storage capacity between the two pipes. The measurement range of the ORD is 0.06 - 1.75 gpm. Comparing the maximum measurement intensity to design storms, the ORD has the capacity to measure the 2-year 10-min storm (Table 3.9)

Table 3.9. Precipitation frequency (PF) estimates in inches per hour for Villanova, Pennsylvania compared to maximum ORD measurement intensity. Green indicates a value less than the ORD maximum intensity. Yellow indicates a value greater than the ORD maximum intensity. PF estimates based on frequency analysis of partial duration series (PDS) from NOAA Atlas 14. (NOAA PFDS)

Less than ORD maximum intensity
Greater than maximum intensity

PDS-based precipitation frequency estimates with 90% confidence intervals (in inches/hour)							
Duration	Average recurrence interval (years)						
	1	2	5	10	25	50	100
5-min	4.18	4.97	5.83	6.44	7.16	7.66	8.15
10-min	3.34	3.98	4.67	5.15	5.71	6.1	6.47
15-min	2.78	3.33	3.94	4.34	4.82	5.15	5.45
30-min	1.9	2.3	2.8	3.15	3.57	3.88	4.17
60-min	1.19	1.44	1.79	2.05	2.38	2.63	2.88
2-hr	0.712	0.865	1.08	1.24	1.46	1.63	1.8
3-hr	0.519	0.629	0.788	0.909	1.07	1.2	1.33
6-hr	0.324	0.392	0.489	0.567	0.677	0.765	0.858
12-hr	0.196	0.237	0.297	0.347	0.42	0.481	0.548
24-hr	0.113	0.137	0.172	0.201	0.243	0.279	0.318
2-day	0.065	0.079	0.099	0.116	0.14	0.16	0.181
3-day	0.046	0.055	0.07	0.081	0.097	0.111	0.125

Once fully constructed, each protoype was tested by fitting a regression model to the calibration data to correlate the inflow with the water depth between the pipes. Detailed calibration instructions are included in Appendix H. The pressure transducer used was the Campbell Scientific CS450, calibrated according to the Villanova Urban Stormwater Partnership's (VUSP) Laboratory Standard Operating Procedure VUSP-SOP-J1.

The orifice equation was used to calculate the predicted relationship between inflow and depth for a given ORD design (Equation 3.1). Flow through multiple orifices was computed as the sum of flow through the submerged individual orifices. Since the orifice diameter is less than 0.3 m (1 ft), headwater and tailwater effects were not considered (ConnDOT 2001).

$$Q = \Sigma\,[C_{oi}A_{oi}(2gH_{oi})^{0.5}] \qquad \text{(Equation 3.1)}$$

where: Q = the orifice flow rate, m^3/s (ft^3/s)
C_o = discharge coefficient (0.40 - 0.60)
A_o = area of orifice, m^2 (ft^2)
H_o = effective head on the orifice measured from the centroid of the opening, m (ft)
g = gravitational acceleration, 9.81 m/s^2 (32.2 ft/s^2)

Statistical analysis was performed in Microsoft Excel and MiniTab. The regression models were adjusted to maximize the adjusted R-squared value and p-values were evaluated to determine statistically significant predictors. The model was evaluated with polynomial terms, reciprocal terms, log transformations and with the orifice equation. The design which produced the model with the lowest prediction error was chosen. The orifice equation was determined to be the best fit equation with the least error. The orifice equation is piece-wise, as the total flow is the sum of flow from multiple submerged orifices. In the orifice regression equation, the discharge coefficient was optimized for each orifice based on calibration data. The Villanova site has two ORDs (ORD 1 and ORD 2) and each is calibrated separately to ensure model accuracy. The regression models are similar but slightly different for the two ORDs (Figure 3.16, Figure 3.17, Figure 3.18, Figure 3.19). The error in the regression model is 0.0911 gpm for ORD 1 and 0.1305 gpm for ORD 2 (Table 3.10). For both ORDs, the sum of squared residuals (deviations of predicted from actual empirical values) is small enough to indicate a tight fit of the model to the data. Given the complexity of each set of ORD equations, field data processing is done with a Matlab program.

Table 3.10. Statistics for the regression models for ORD 1 and ORD 2 including the sum of squared residuals (SSR, mean and standard deviation of the residuals, and error.

	ORD 1	ORD 2
SSR	0.1053	0.1732
Residuals- Mean	0.0006	0.0003
Residuals- StDev	0.0450	0.0642
Error (+/-)	0.0911	0.1305

ORD 1

Cd1	0.896
Cd2	0.419
Cd3	0.816
Cd4	0.493
Cd5	0.697

When H < 4.057”:

$Q = 7.64E\text{-}05*(64.35*(h-0.063))^{0.5}$

When H < 8.057”:

$Q = 7.64E\text{-}05*(64.35*(h-0.063))^{0.5} + 2.92E\text{-}05*(64.35*(h-4.057))^{0.5}$

When H < 12.063”:

$Q = 7.64E\text{-}05*(64.35*(h-0.063))^{0.5} + 2.92E\text{-}05*(64.35*(h-4.057))^{0.5} + 5.68E\text{-}05 * (64.35*(h-8.057))^{0.5}$

When H < 16.125”:

$Q = 7.64E\text{-}05*(64.35*(h-0.063))^{0.5} + 2.92E\text{-}05*(64.35*(h-4.057))^{0.5} + 5.68E\text{-}05 *(64.35*(h-8.057))^{0.5} + 4.20E\text{-}05*(64.35*(h-12.063)^{0.5}$

When H >= 16.125”:

$Q = 7.64E\text{-}05*(64.35*(h-0.063))^{0.5} + 2.92E\text{-}05*(64.35*(h-4.057))^{0.5} + 5.68E\text{-}05 *(64.35*(h-8.057))^{0.5} + 4.20E\text{-}05*(64.35*(h-12.063)^{0.5} + 2.37E\text{-}04*(64.35*(h-16.125)^{0.5}$

Figure 3.16. ORD 1 regression equation and discharge coefficients

ORD 2

Cd1	0.542
Cd2	1.000
Cd3	0.612
Cd4	1.000
Cd5	0.638

When H < 4.057”:

$Q = 4.62E\text{-}05*(64.35*(h-0.063))^{0.5}$

When H < 8.057”:

$Q = 4.62E\text{-}05*(64.35*(h-0.063))^{0.5} + 6.96E\text{-}05*(64.35*(h-4.057))^{0.5}$

When H < 12.063”:

$Q = 4.62E\text{-}05*(64.35*(h-0.063))^{0.5} + 6.96E\text{-}05*(64.35*(h-4.057))^{0.5} + 4.62E\text{-}05*(64.35*(h-8.057))^{0.5}$

When H < 16.125”:

$Q = 4.62E\text{-}05*(64.35*(h-0.063))^{0.5} + 6.96E\text{-}05*(64.35*(h-4.057))^{0.5} + 4.62E\text{-}05*(64.35*(h-8.057))^{0.5} + 8.52E\text{-}05*(64.35*(h-12.063)^{0.5}$

When H >= 16.125”:

$Q = 4.62E\text{-}05*(64.35*(h-0.063))^{0.5} + 6.96E\text{-}05*(64.35*(h-4.057))^{0.5} + 4.62E\text{-}05*(64.35*(h-8.057))^{0.5} + 8.52E\text{-}05*(64.35*(h-12.063)^{0.5} + 2.18E\text{-}04*(64.35*(h-16.125)^{0.5}$

Figure 3.17. ORD 2 regression equation and discharge coefficients

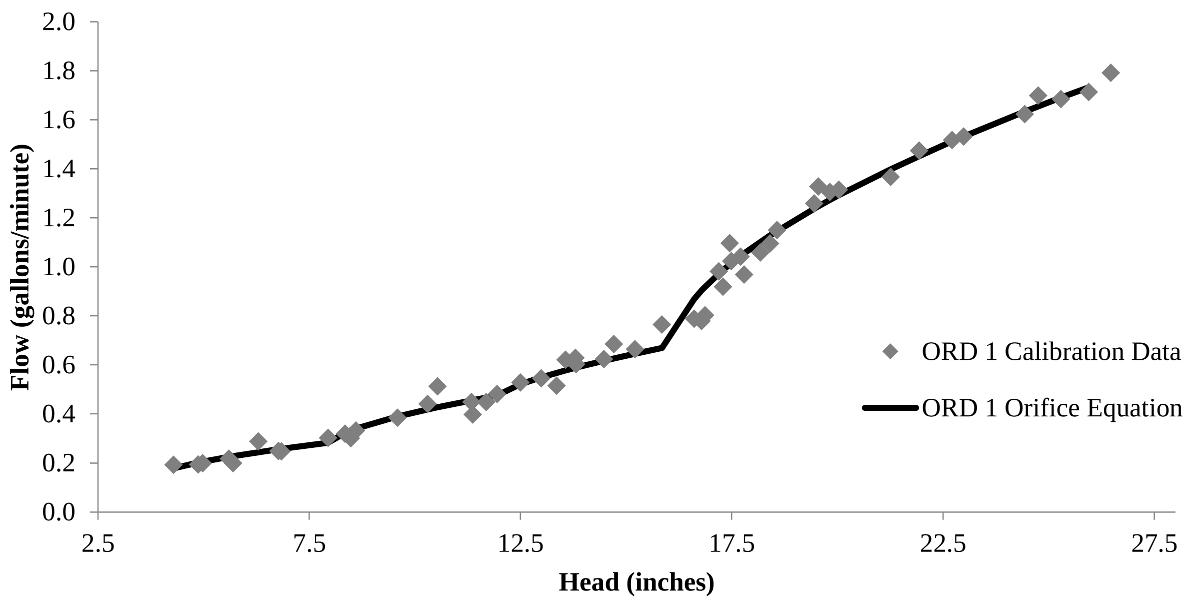


Figure 3.18. ORD 1 calibration data and regression equation.

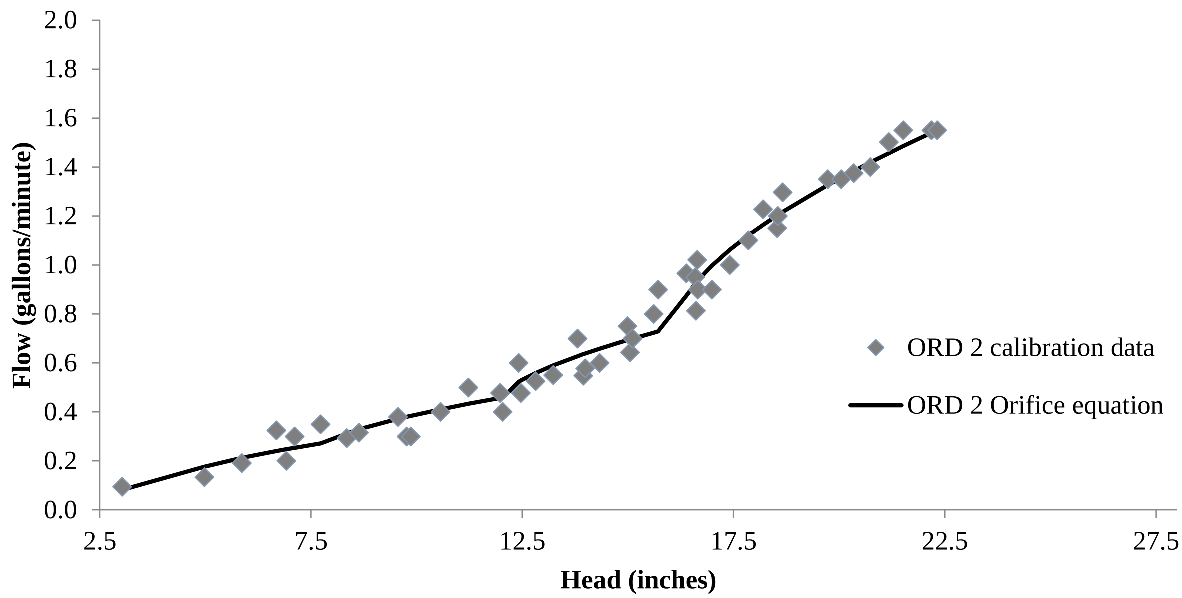


Figure 3.19. ORD 2 calibration data and regression equation.

3.4.3 Arduino Data Logging

The advantage of the Arduino system is primarily price-driven. The prices of Arduino data loggers are 90% less than of the cost of more traditional data logging equipment (Table 3.11). In comparison, a CR800 data logger costs more than $1,000. The price for traditional monitoring systems can be prohibitive, especially for non-profit and/or educational institutions or organizations performing low-level monitoring. The Arduino can be used with a variety of sensor types, including both digital and analog. The learning curve can be significant for a first time user, however the Arduino system has a lot of available code and libraries online for free.

Table 3.11. Data logging equipment for one research site

Item	Units	Cost
Arduino Mega 2560	1	$ 25.00
Screw terminal shield for Arduino	1	$ 15.00
Data logging shield for Arduino	1	$ 20.00

The data logging shield includes a clock that provides a consistent timestamp. This clock has a battery that will continue to run even if the Arduino loses power and the battery guaranteed for 5 years. The consistent timestamp is necessary to maintain data integrity during unexpected or unknown power outages. In many cases, data is useless without any time reference. The screw terminal shield for the Arduino is optional but recommended for ease of use and secure electrical connections in the field. Depending on whether pre-assembled shields are purchased or not, other accessories will be necessary including a soldering iron, jumper wires, solder, pins, USB A/B cable for connecting the Arduino to a computer for initial programming. Many items are available online preassembled for a higher cost.

The Arduino Mega is a microcontroller that handles communications between the sensors and Arduino. It does not have any memory, so anytime the Arduino loses power, it is reset, requiring a logging shield or alternative memory; for the present work, the logging shield was selected. The Arduino programming software is available for free and enables users to write code and upload it to the board. When programming each sensor, it is necessary to evaluate the required measurement time and the frequency of data collection. Many sensors have code available online compatible with Arduinos. As opposed to analog or digital sensors, SDI-12 or similar serial data interfaces will be more complex to program, however have the benefit of sharing communication ports with a unique address for each sensor.

The power source for the monitoring system is hardwired from a university light pole nearby. The Arduino Mega is powered by a 9 VDC power adapter. Since Arduinos can only power 3- 5 volts, any 12 volt sensors will require an alternative power supply (battery or converter from outlet). If on-site power is not available, a battery system can be used.

For this site, data will be collected manually by retrieving an SD card from the site bi-monthly. All data is recorded at 1 minute intervals. With a similar frequency of data collection, the SD card can be sized at 1 GB or smaller. As an example, a file containing data from 17 instruments each with 5800 data points was 720 KB in size. The Arduino with both shields will be stored in a watertight equipment box on site. An additional case is preferred for protection against dust deposition and water.

Within the Arduino program, a consideration was taken to restart the data logging after the removal of the SD card or a power interruption. Although the power is hardwired, ideally the logging program can continue to operate after a power outage without any manual adjustments required. The program for this site continues logging after a power outage or power reset, utilizing the real-time clock as an absolute time stamp reference. The Arduino program was primarily written by Dr. Ryan Lee from Villanova University Civil and Environmental Engineering and Kellen Pastore from Villanova University Mechanical Engineering. Sample code for many of the sensors is publically available online at no cost. The data output type (e.g. analog or digital) and Arduino code for each sensor is detailed in Appendix I.

Because this site is located on Villanova's campus, thanks to the help of Villanova Facilities department, there is a direct power connection and easy access for data collection. The site is easy to access and in close proximity to students, so the travel time to the site is minimal. On a more remote site with more difficult access, the need for transmission of data over wi-fi may be possible. In this case, a more powerful device like a Raspberry Pi, may be used to store and send data. The Raspberry Pi is similarly low-cost, although will add complexity to the system and requires further knowledge of software programming. If direct power is not available at a site, the Arduino can alternatively be powered from a battery. The battery enables the ability to electronically log data in disconnected sites, although will require charging periodically.

3.4.4 Research Questions and Initiatives

As green roofs grow in use for stormwater management, there are several aspects that require further research. The shelter living laboratory with monitoring equipment aims to create a site where interactions between soils, plants, atmosphere and water can be quantified to analyze their effects on green roof stormwater performance. There are many different questions that could be asked; the following list are a few ideas that will be examined in the short-term.

One research goal is to quantify the effect of weather parameters on vegetation health and rainfall capture. The ability to predict the extent of the effect of weather parameters is useful to understand the system functioning. According to one study, amongst the studied environmental factors, solar radiation and wind speed contributed notably to green roof stormwater retention (Wong and Jim 2015). The analysis of meteorological data can inform the design of irrigation systems, as well as site assessments in cities with complex topographical features to ensure a site is appropriate for a green roof. While measuring evapotranspiration directly is typically difficult and costly, these common meteorological elements can be monitored conveniently and inexpensively and used in models to estimate evapotranspiration.

Temperature will be analyzed at various media depths and compared to other green roof sites to more fully understand the thermal flux on green roofs. Compared to a roof over a building, or adjacent to walls, the green roof shelter is more exposed to weather elements. The greater exposure could affect the roof temperature, and subsequently plant health and growing cycle and the stormwater capture performance. Higher maximum temperatures enhance evapotranspiration and subsequent retention (Wong and Jim 2015). Dvorak and Volder (2013) previously determined that in hot, dry summer conditions, modular green roofs experienced consistent temperature reductions both on the soil surface and at the bottom of the soil profile when compared to a standard roof surface. The modules were unirrigated, succulent based landscapes that experienced mean daily temperature reductions of 27.5 degrees Celsius when the bottom of the module was compared with a standard roof surface (Dvorak and Volder 2013). This Villanova site is unique in that the semi-intensive roof does not have insulation underneath by a building. The temperature profile at the shelter site will be directly compared to the nearby CEER roof, which is atop a building and also has two side walls for protection, to reveal the effect of exposure to weather conditions.

The effect of vegetation on water capture has been integrated into the site design presently. The roof was divided into two sections: sedums and non-sedums. The outflow from the sedums and non-sedums are expected to illustrate how each general species affect and utilize the capacity of the semi-intensive trays. Sedums have been widely studied and favored when it comes to rooftop plantings because they are hardy and drought-resistant. However, it is anticipated that a diversity of species may better utilize water stored within the media, increasing evapotranspiration rates. Grasses have been used on green roofs before, but are not as drought-tolerant as sedums and often require irrigation on extensive roofs. Given that the site is presently semi-intensive and not irrigated, the plant health will be evaluated to determine if there is enough natural moisture available for these species. Due to the roofs positioning below the tree line, the introduction of non-planted (volunteer) species will inevitably arrive; this will be monitored and charted. Plants will be monitored with photographs to provide a qualitative measure of well-being.

The evaluation of the SCM monitoring system will continue throughout the life of the project. The data logging cost is up to 10 times less than more a traditional data logger and processer. The affordability of this system is expected to expand access to SCM monitoring to educational institutions and non-profits, or even private or public entities that want to demonstrate performance for stormwater crediting, who would be able to collect and analyze local stormwater data on a small budget. This type of system could lower the cost barrier to collecting stormwater performance data. In addition to data logging systems, sensors continue to improve in accuracy and reduce in price. Low-cost vs. high-cost sensors will be evaluated (e.g. soil moisture meters and thermometers) to compare and contrast the benefits of each sensor. As the study continues, low-cost sensing and data collection will be explored to make recommendations for designing and implementing monitoring plans.

The comparison of the data collected on this green roof shelter site will be evaluated in relation to other green roof configurations to inform design standards. The existing Villanova extensive retrofit green roof on the CEER building has been monitored for more than a decade, and will provide a good basis for comparison to this green roof site. The parameters of temperature and soil moisture on each roof can be analyzed and related to the benefits of various media depths, roof footprints, and protection.

3.5 Maintenance

General inspections will occur during site visits for data collection. The visual inspections can be conducted from ground-level, and will include a review of the drainage system, edging, and monitoring equipment. In general, the ease of access and visibility of the site will make obvious any significant necessary maintenance. The maintenance for vegetation will include occasional irrigation in times of drought if necessary to sustain the plant populations. In the case of invasive species establishment, the modules can be weeded. During spring, the plant populations will be evaluated and additional seeds, plugs or cuttings may be added. The majority of the roof is accessible by ladder from any of the four sides.

A site-specific Quality Assurance Project Plan (QAPP) was submitted to US EPA Region III regarding quality control of data generation and acquisition, analytical methods, and instrument testing and calibration, and is awaiting approval. As detailed in the QAPP, sensors will be inspected quarterly and cleaned as necessary. The pressure transducer will be calibrated biannually according to the VUSP's SOP. During the pressure transducer calibration, the downspout is removed and the ORD is detached. This also enables the clean-out of the ORD in the case of any accumulation of fine particles. To protect the longevity of the monitoring equipment, certain sensors including the pressure transducers are removed during expected frost.

3.6 Project Costs

The total project cost for the steel structure, media, modules, vegetation, edging, gutters, ORD, monitoring and data logging equipment is $11,632 (Table 3.12). This table separately tallies research grade equipment, such as a depth sensor for the ORD since pressure transducers are generally very expensive. Alternatively, an ultrasonic sensor or another liquid level sensor can be used. The price of the research-grade meteorological instruments and pressure transducer is about $2,000. If a picnic shelter is not desirable, other functions for similar, small-scale green roof structures include baseball dugouts or bus shelters. Compared to this intensive site, the cost for an extensive (thinner) green roof would be less, potentially reducing the structure cost, module cost and media cost.

Table 3.12. Summary of the project costs for (a) minimal and (b) research-grade monitoring equipment configurations.

Structural materials and minimal sensing equipment

Item	Cost
Structure	$ 6,250.00
Media	$ 1,356.00
GreenGrid® modules	$ 2,290.00
Plants	$ 489.00
Edging	$ 478.00
Gutters & accessories	$ 209.00
ORD	$ 50.00
Monitoring Equipment (Soil moisture, temperature, precip.)	$ 428.00
Data logging Equipment (Arduino)	$ 82.00
TOTAL	$ 11,632.00

Research-grade sensing monitoring equipment

Item	Cost
Campbell Scientific CS451 Pressure transducer	$ 695.00
Decagon EC-5 Soil Moisture Sensors - 2 @ $110, 2 @ $125.30	$ 471.00
Decagon DS-2 Sonic Anemometer	$ 529.00
Stevens SP 212 Pyranometer	$ 315.00
TOTAL	$ 2,010.00

Prices include delivery costs, does not include taxes or structure footings

3.7 Preliminary Data

Since the Villanova University green roof shelter was constructed and instrumented in autumn of 2015, two storm events have occurred at the site to provide data to confirm that the monitoring equipment is functioning in the field, particularly the overflow measurement. Soil moisture data was not available for these events. The data collected, weather and ORD output, should be considered preliminary.

The event on November 19th, 2015 was 1.64 in with a duration of 11.4 hours, with an average intensity of 0.14 in/hr. There were six antecedent dry days. Precipitation volume is calculated from the rainfall depth over the drainage area (half of total green roof area). The temperature data showed an increase in media temperature during the storm event (Figure 3.20). The two temperature sensors (ENV-TMP and DS18B20) recorded very similar temperatures, although the ENV-TMP had more variability around an average than the DS18B20. There was a lag in the media temperature relative to the air temperature. During the rainfall event, the media temperatures were about 2°C below air temperatures. After the rainfall ceased, the media temperatures matched up closely with the air temperatures reported by the nearest reporting weather station run by the National Oceanic and Atmospheric Administration (NOAA) at the Philadelphia International Airport.

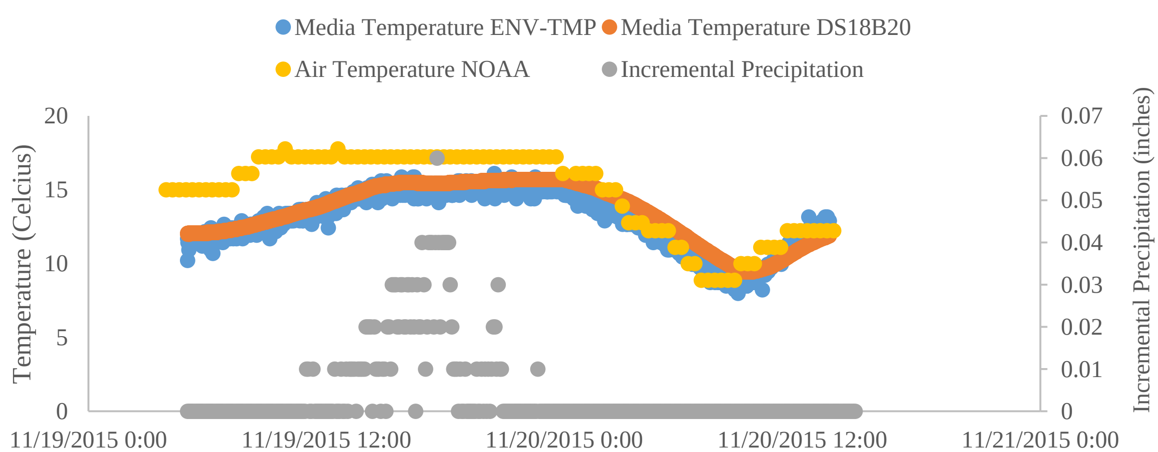


Figure 3.20. The precipitation, air temperature and media temperature for the 11/19/15 storm event. The media temperature was recorded by two sensors (ENV-TMP and DS18B20) at duplicate media depths within the same module. Media temperature data was recorded at 30 second intervals.

The overflow is represented by the water depth inside the ORDs for each roof half. As this preliminary data has not been fully processed, the flow has not been directly calculated. The overflow data indicates that the runoff was captured by the drainage collection and measured by the ORD (Figure 3.21). The overflow for both plant species follows the patterns of the storm event (increase in precipitation caused increase in overflow). The peak of the rainfall occurred at 17:35 on 11/19/2015 and the peak overflow for both ORDs occurred at about 18:10 on 11/19/2015, resulting in a lag time between the peak inflow and peak outflow of 35 minutes. Comparing the total water depth measured in each ORD, overall the non-sedums half of the roof measured less outflow volume, indicating more water retention may have occurred. The sedum side of the roof shows steady overflow starting after approximately 0.03 inches of rainfall. The non-sedum side of the roof shows steady runoff overflowing after approximately 0.27 inches of rainfall. The early runoff volumes from the sedum side suggest the drainage collect system on that side that may have received direct rainfall. The sedums side had a greater peak overflow than the non-sedum side. Both ORD depths level off above the zero point, which is anticipated as a part of the ORD design since the pressure transducer sits below the lowest orifice. When compared to the calibration tests, the ORD depth at the end of the storm is larger than expected, suggesting the pressure transducer may have shifted vertically during the storm. Future inspections and design alterations will occur to address this issue. The results function to show that the monitoring system is recording data and captures the sensitivity of the outflow from the green roof.

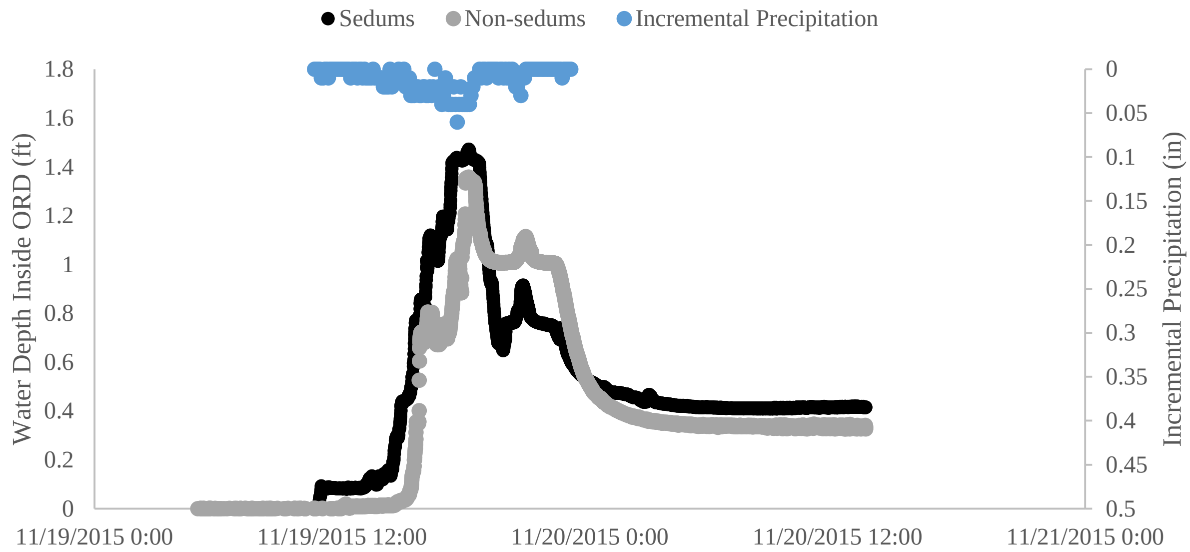


Figure 3.21. The incremental precipitation and water depth inside the two ORDs from the 11/19/15 storm event. Depth data was recorded at 30 second intervals.

The event starting on November 30th, 2015 storm was 1.1 in with a duration of 45.17 hours, with an average intensity of 0.024 in/hr (Figure 3.22). There were 0 antecedent dry days, with 0.05 in of rain falling within the previous 36 hours. The raw collected data for the 11/30/2015 storm (Appendix J) indicated that the vertical position of the pressure transducer was altered during the storm, so during processing, the data was adjusted to account for the altered position. This observation will inform future inspections and design alterations. Compared to the previous storm, the precipitation was a smaller volume and less intense. The precipitation was at constant intensity with no clear peak intensity since the incremental precipitation depth did not exceed 0.01 in throughout the storm. The time of peak overflow for the sedums was 8 minutes before the time of peak for the non-sedums; the time of peak overflow for the sedums occurred 15.75 hours after the start of the event. Comparing the total water depth measured, overall the non-sedums measured less outflow volume, indicating more water retention may have occurred, which is congruent with the previous storm finding.

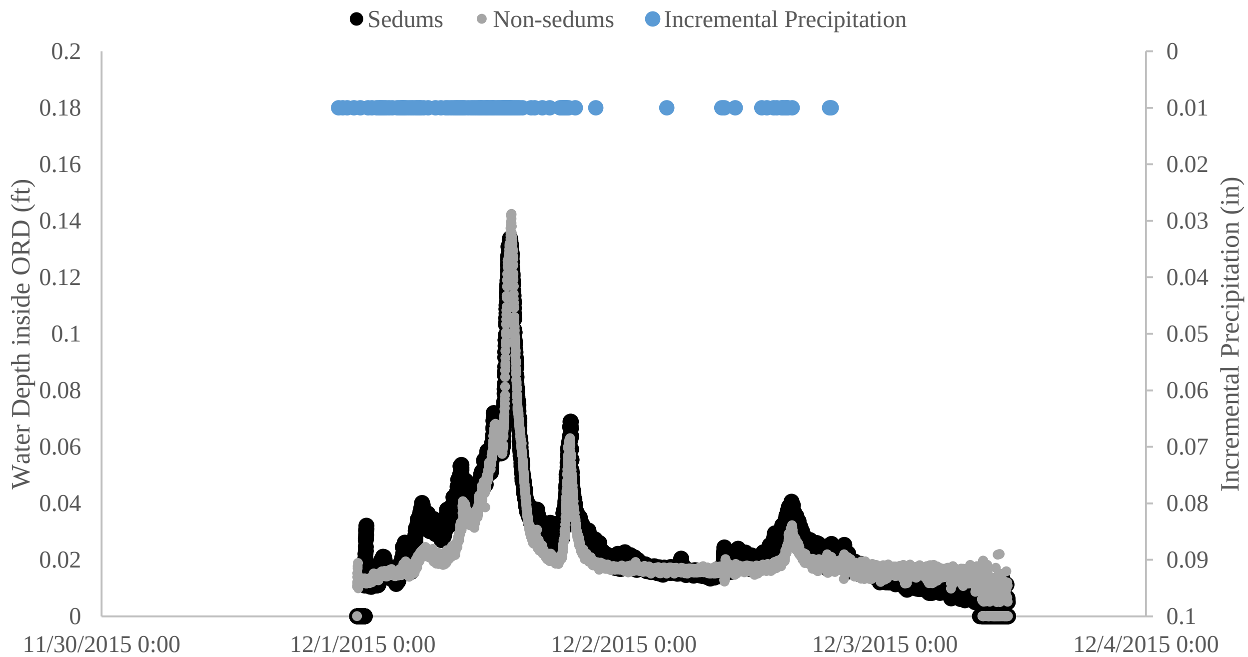


Figure 3.22. The incremental precipitation and water depth inside the two ORDs from the 11/30/15 storm event. Depth data was recorded at 30 second intervals.

Additionally, these two initial events enabled us to understand the quality of the data obtained from this site. For these events, the sampling frequency of the depth collected by the pressure transducers in the ORDs was every 30 seconds. While this resulted in high resolution of the outflow depth in the ORD, it also generated a great amount of data points. Relatively, at many other SCM research sites on campus at Villanova, the sampling frequency is 5 mins. These events demonstrated that a 5 min sampling frequency may be too infrequent to get the small peaks and for the future a 1 min sampling frequency will be employed for the ORD pressure transducers. Comparison of this data to future storm events will enable the verification of the monitoring system physical and electrical set up.

4. Community Outreach and STEM Education

The lack of locally relevant design, operation and maintenance information is considered a barrier to uptake and widespread implementation of living roof technology for stormwater control (Fassman-Beck et al. 2013). This project serves as a test-bed and a resource for community education on green roofs. The site locations have been chosen to be included on educational tours, posted with informational signage and highly visible to community members.

The Villanova site is integrated into the VUSP's SCM research and demonstration park, which provides exposure to the local and visiting stormwater engineering community. The Pennsylvania Municipal Workshop and Stormwater Symposium was held on Villanova's campus in October 2015 and was attended by municipal and industry engineers. The symposium focused on the state-of-the-art in the practice of SCMs and included campus tours and research presentations from the VUSP students and faculty. This green roof shelter site was included on the tour and will continue to be included in the future. The university enables the connection with area engineers, as well as higher education students, to integrate the site into education and research programs. There is also opportunity for this site to be used directly in the undergraduate curriculum.

Upper Darby has 10,520 people per square mile (Holm 2011) and the high school hosts year-round community activities, which increase visibility and educational opportunities. In order to engage community members, the Upper Darby High School site is planned to be integrated into the curriculum of many subjects including horticulture, mathematics and environmental science. In April 2015, representatives from the VUSP presented in the A.P. Environmental Science class at Upper Darby High School about green stormwater infrastructure. Over two days and approximately 3.75 hours, the presentations reviewed stormwater management, hydrographs, combined sewer systems, and green infrastructure with two classes. The final project for both classes included the evaluation of green infrastructure technologies for implementation on the Upper Darby High School campus.

The educational relationship has been established with the faculty at the school for future activities. Once the green roof structure is in place, the monitoring data will become available for the faculty to integrate into curriculum and students will be able to get hands-on experience with the green roof. It is anticipated that the green roof structure can be incorporated into basic science classes, including environmental science. Data analysis of the site output could be performed in a mathematics course. The development of sensor technology and data logging systems, such as the Arduino programming and constructing, can be incorporated in to the engineering classes offered. Upper Darby High School also has a successful horticultural program and greenhouse classroom, so the green roof structure can be an extension of the classroom where students can learn about different types of green roof plants, perhaps provide new vegetation propagated in the green house and learn about maintenance of a green roof site.

The long-term goal of the project is to encourage townships within impaired watersheds, like the Darby Creek watershed, to develop creative methods for preserving natural corridors, manage floodplains, connect natural and human-made resources, improve community aesthetics, and educate community members on the benefits of incorporating green space into the landscape. This specific project is an alternative application of an SCM that is flexible, effective and appropriate for deployment in densely developed urban areas. The presence of the green roof is intended to encourage the idea that reducing small amounts of stormwater runoff throughout the watershed can have a significant effect on runoff volumes and other associate pollutant loads downstream.

5. Future Research

Monitoring and data collection began in November 2015 at the Villanova University shelter site and the initial phase has been set up to answer research questions, including:

- A comparison of overflow from the 8 in media depth at the shelter to 4 in media depth at the layered green roof system installed at Villanova University's CEER building
- A temperature study through the soil media to determine thermodynamic properties and behavior, to accompany data collected at the CEER green roof
- A comparison of low-cost and research-grade temperature and soil moisture sensors
- A comparison of overflow from two groups of vegetation: sedums and non-sedums
- An assessment of vegetation species success given the climate and modular, semi-intensive environment

Additionally, there are many future research questions that could be investigated at this site using data from established sensors.

5.1 Green Roof Runoff Water Quality

There is a need for more research into the quality of the runoff water from green roofs (Hashemi et al. 2015). Such research could include an investigation of the leaching phenomenon and the effects of vegetation on the quality of storm water runoff. The addition of a filtration mechanism (e.g. natural zeolite, activated carbon filter) is identified as a potential reduction in water quality of runoff. The characteristics of the filtration system should be suitable for application to both private and commercial. Research could also define and predict the effects of various media mixtures for improvement of runoff water quality.

5.2 Hydrologic Performance Modeling and Prediction

In conjunction with Villanova University's other SCM research locations, the green roof site will provide the data necessary to aid in prediction of green roof performance. The site specific meteorological data can be paired with the overflow volumes to aid in the search for patterns to predict green roof performance. Modifications to the green roof can be implemented to improve the stormwater capture, including adjustments to the drainage system, media depth, media type, media amendments. As the local knowledge base grows in each community, features of green roof media can be adjusted to suit their specific climate and native plants. These local adjustments can further enhance the stormwater performance and maintain healthy plants (Fassman-Beck et al. 2013).

5.3 Solar Panels on Green Roofs

To enhance the community value of the green roof structure, proposed future additions to the site include a rooftop photovoltaic (PV) system, and a subsequent study of the interactions between the solar system and the health of the green roof. The energy harnessed by the proposed PV system would be made available for public use. The goal is to provide visitors the ability to charge small electronic devices at the shelters, where educational material will be displayed. For this project, the structural design included capacity for the additional loading of solar panels. Integrating additional loading capacity into the design of this small structure did not significantly burden the structural design or structure manufacturing cost. Research would explore the effect of this addition of a PV system and the establishment of a new type of microclimate on the roof. With the monitoring and understanding of this microclimate, the combination of vegetated roofs with a PV system can be fully evaluated.

The effects of a vegetated layer on a PV system have only recently been studied, with very few studies reporting experimental results. The few published studies have suggested that the plant characteristics lead to an improvement in photovoltaic output and the solar panels protect vegetation from high irradiances. In a Mediterranean climate, it was found that a green roof (planted with sedums) compared to the gravel roof had a lower average daily temperature on a sunny day with no wind, with an average reduction of 7.7° C. Additionally, for a sunny, five-day time period, there was an average increase in the maximum power output of the PV system, ranging from 1.29% to 3.33% depending on the plant species. (Chemisana and Lamnatou 2014) In Hong Kong, on a sunny day in summer, a 4.3% PV output increase was found for a 3-hr period on a sedum roof with respect to a bare roof (Hui and Chan 2011). In Pittsburgh on a commercial warehouse over a 16 month period, it was found that the green roof increased PV panel efficiency 0.8-1.5% compared to black roofs in temperatures above 25° C (77° F) (Nagengast 2013). In New York City during the month of June, a sedum green roof obtained a PV performance increase of 2.56% with respect to a PV gravel roof. (Perez et al. 2012) In Portland, when PV-green roof system was compared to PV-black roof system, 1.0 – 1.2 % increase in performance on the green roof. (Ogaili 2015) These studies demonstrate the positive synergy of combining PV with vegetation on rooftops.

6. Lessons Learned and Summary

Several lessons were learned throughout this project that may be useful in future activities. Initially, identifying and engaging all appropriate stakeholders is essential to the project success. At the Villanova University site, the understanding of building covenants and local township requirements was essential in the initial stages of siting this project. Villanova University is quite supportive of sustainability and research practices, but as this project was the first of its kind, there was some hesitancy to put the structure in extremely visible places due to uncertainty of how the structure would be perceived from an aesthetic perspective. Aesthetics was also a concern at Upper Darby High School. Having descriptive images or previous examples of the proposed project can be extremely useful in helping the community to visualize the project and gain acceptance. When working with Upper Darby High School, there was also a great deal of support. Many people collaborated to make this project possible, including teachers, administration, governing board and the parent's association, and information was often passed via email or through third-party communication. At the beginning, a clear, detailed, visual plan with benefits, concerns and costs clearly delineated to ensure everyone understands the goal can significantly aid in the success of the project. Additionally, this plan could be helpful in detailing an apparent and feasible path for necessary project funding. The interactions encountered in this small project are similar to any interactions in an engineering design project, thus building community engagement and consensus from the beginning is critical.

In meeting both stormwater research and community education goals, the site location can affect its success as much as, if not more than, the site design itself. If the site goals are community education and aesthetic appeal, these benefits are only realized if the site is located in a visible, utilized space. Ideally, the green roof is sited to cover impervious area so the precipitation managed is preventing runoff. Runoff prevention is important in urbanized areas, especially those with sewage and stormwater combined into the same pipes. Green roofs are designed to reduce the quantity of runoff, so ideally overflow is directed into an infiltrating area which could potentially provide water quality treatment or filtration, and further volume reduction. Also, siting the project to allow for a hard-wired connection to a power supply will increase the reliability of the data supply. An advantage of siting this kind of SCM at an academic institution (e.g. university) enables access to interdisciplinary personnel. Access to a wide range of skillsets is necessary since the project involves horticulture, structural engineering, electronics wiring, computer programming, and much more. Additionally, the ability to ensure continuous inspection, maintenance, and improvement of the site will enhance the value of the site in the future. In section 3.6, costs for personnel or labor were not included so students and volunteers may be of best use to both learn from, and contribute to the function of the site.

In summary, a small green roof research site provides many benefits to the stormwater research practice and the surrounding community for a relatively low cost. The project can be implemented for under $12,000 (see section 3.6). The site provides an urban living laboratory to research and illustrate the performance of green roof designs, while engaging the community on urban water issues. As the need for improved knowledge of stormwater management grows, this site will serve as a community asset for students, teachers, municipal officials, engineers and residents.

7. Bibliography

Alfredo, K., Montalto, F., and Goldstein, A. (2010). "Observed and Modeled Performances of Prototype Green Roof Test Plots Subjected to Simulated Low- and High-Intensity Precipitations in a Laboratory Experiment." *Journal of Hydrologic Engineering*, 15(6), 444-457.

American Society of Civil Engineers (2013). "Minimum Design Loads for Buildings and Other Structures (7-10, Third Printing)." *ASCE/SEI 7-10*www.asce.org.

ASTM (2014). "Standard Guide for Vegetative (Green) Roof Systems." ASTM International, West Conshohocken, PA.

ASTM (2015). "Standard Test Method for Saturated Water Permeability of Granular Drainage Media [Falling-Head Method] for Vegetative (Green) Roof Systems." ASTM International, West Conshohocken, PA.

Barista, D. (2007). "5 Tips on Building a Sloped Green Roof." *Building Design and Construction*www.bdcnetwork.com.

Bauers, S. (2013). "Green roofs: That bus stop shelter is only the beginning." *philly.com*.

Bengtsson, L. (2005). "Peak flows from thin sedum-moss roof." *Nordic Hydrology*, 36, 269-280.

Buccola, N., Spolek, Graig. (2011). "A Pilot-Scale Evaluation of Greenroof Runoff Retention, Detention, and Quality." *Water, Air, & Soil Pollution*, 216(1), 83-92.

Carson, T. B., Marasco, D. E., Culligan, P. J., and McGillis, W. R. (2013). "Hydrological performance of extensive green roofs in New York City: observations and multi-year modeling of three full-scale systems." *Environmental Research Letters*, 8(2), 024036.

Castleton, H. F., Stovin, V., Beck, S.B.M., Davison, J.B. (2010). "Green roofs; building energy savings and the potential for retrofit." *Energy & Buildings*, 42(10), 1582-1591.

Chemisana, D., and Lamnatou, C. (2014). "Photovoltaic-green roofs: An experimental evaluation of system performance." *Applied Energy*, 119, 246-256.

City of Chicago (2015). "Green Permit." <http://www.cityofchicago.org/city/en/depts/bldgs/provdrs/green_permit.html>. (August 9, 2015, 2015).

City of New York (2014). "PlaNYC Progress Report 2014." <http://www.nyc.gov/html/planyc2030/downloads/pdf/140422_PlaNYCP-Report_FINAL_Web.pdf>.

City of Portland (2015). "Title 33 Planning and Zoning." B. o. P. a. Sustainability, ed.Portland, OR, 510-532.

ConnDOT (2001). "Drainage Manual." D. o. Transportation, ed.www.ct.gov.

DeNardo, J. C. (2005). "Stormwater mitigation and surface temperature reduction by green roofs." *Transactions of the American Society of Agricultural Engineers*, 48(4), 1491-1496.

Deutsch, B. W., Heather; Sullivan, Michael; Savineau, Anouk (2005). "RE-GREENING WASHINGTON, DC: A Green Roof Vision Based on Quantifying Storm Water and Air Quality Benefits ", 7-9.

Dvorak, B., and Volder, A. (2013). "Rooftop temperature reduction from unirrigated modular green roofs in south-central Texas." *Urban Forestry & Urban Greening*, 12(1), 28-35.

Emerson, C. H. W., Claire; Traver, Robert G. (2005). "Watershed-Scale Evaluation of a System of Storm Water Detention Basins." *Journal of Hydrologic Engineering*, 10(3), 237-242.

Fassman-Beck, E., Hunt, W., Berghage, R., Carpenter, D., Kurtz, T., Stovin, V., and Wadzuk, B. (2015). "Curve Number and Rational Formula Coefficients for Extensive Living Roofs." *Journal of Hydrologic Engineering*(accepted).

Fassman-Beck, E., Simcock, R., and Auckland (N.Z.). Council (2013). "Living roof review and design recommendations for stormwater management." *Auckland Council technical report TR2013/045*, <http://www.aucklandcouncil.govt.nz/>.

Fassman-Beck, E., Voyde, E., Simcock, R., and Hong, Y. S. (2013). "4 Living roofs in 3 locations: Does configuration affect runoff mitigation?" *J Hydrol*, 490, 11-20.

FLL (2002). "Guideline for the Planning, Execution and Upkeep of Green-Roof sites." *Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau*, Rep. No. 3253115.

Getter, K. L., and Rowe, D. B. (2006). "The role of extensive green roofs in sustainable development." *Hortscience*, 41(5), 1276-1285.

GRHC, S. I. (2010). "External Fire Design Standard for Vegetative Roofs." *American National Standards Institute*.

GRHC, S. I. (2010). "Wind Design Standard for Vegetative Roofing Systems."

GRHC, S. I. (2011). "New Root Repellant and Testing Standard Released."

Hall, A. (2010). "Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure." EPA Office of Wetlands, Oceans and Watersheds, 2.

Hashemi, S. S. G., Mahmud, H. B., and Ashraf, M. A. (2015). "Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review." *Renewable and Sustainable Energy Reviews*, 52, 669-679.

Holm, K. L. "Eastern Delaware County Stormwater Collaborative." *Proc., Philadelphia Low Impact Development Symposium*, Villanova University.

Howell, J. (2014). "Protoype-Downspout Primary Device." R. G. Traver, ed., Geosyntec Consultants.

Huang, L., Li, Jianlong., Zhao, Dehua., Zhu, Jiyu. (2008). "A fieldwork study on the diurnal changes of urban microclimate in four types of ground cover and urban heat island of Nanjing, China." *Building and Environment*, 43(1), 7-17.

Hui, S. C. M., and Chan, S. C. " Integration of green roof and solar photovoltaic systems." *Proc., Joint Symposium 2011: Integrated Building Design in the New Era of Sustainability*, 1.1-1.10.

KieranTimberlake (2015). "Green Roof Vegetation Study." <http://kierantimberlake.com/pages/view/31/green-roof-vegetation-study/parent:4>. (10/08/2015, 2015).

Lundholm, J. M., J. Scott; MacDougall, Zachary; Ranalli, Melissa (2010). "Plant Species and Functional Group Combinations Affect Green Roof Ecosystem Functions." *PLoS ONE*, 5(3), e9677.

McCuen, R. H. (1979). "Downstream Effects of Stormwater Management Basins." *ASCE Journal of the Hydraulics Division*, 105(11), 1343-1356.

Mentens, J. (2006). "Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?" *Landscape and Urban Planning*, 77(3), 217-226.

Moran, A., Hunt, W., and Smith, J. (2005). "Green Roof Hydrologic and Water Quality Performance from Two Field Sites in North Carolina." *Managing Watersheds for Human and Natural Impacts*, 1-12.

Nagase, A. D., Nigel (2012). "Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure." *Landscape and Urban Planning*, 104(3–4), 356-363.

Nagengast, A. L. (2013). "Energy Performance Impacts from Competing Low-slope Roofing Choices and Photovoltaic Technologies." Doctor of Philosophy (PhD), Carnegie Mellon University, www.repository.cmu.edu.

Nave, C. R. (2012). "Systems of Photosynthesis." *HyperPhysics*.

NJDEP (2013). "Land Use and Land Cover." *Stormwater Trends*, D. o. S. R. a. E. H. Department of Environmental Protection, ed.www.state.nj.us/dep/dsr/publications.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., Gaffin, S., KÖHler, M., Liu, K. K. Y., and Rowe, B. (2007). "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services." *BioScience*, 57(10), 823.

Ogaili, H. H. K. (2015). "Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in Combined Systems." ProQuest Dissertations Publishing.

PADEP (2006). "Pennsylvania Stormwater Best Management Practices Manual." Pennsylvania Department of Environmental Protection.

Pennsylvania Horticultural Society (2015). "PHS Pop Up Gardens." <http://www.visitphilly.com/events/philadelphia/pennsylvania-horticultural-society-pop-up-garden/>. (10/01/2015, 2015).

Perez, M., Fthenakis, V., Wight, N., and Ho, C. "Green-Roof Integrated PV Canopies—An Empirical Study and Teaching Tool for Low Income Students in the South Bronx." *Proc., WREF World Renewable Energy Forum*.

Peri, G., Traverso, M., Finkbeiner, M., and Rizzo, G. (2012). "The cost of green roofs disposal in a life cycle perspective: Covering the gap." *Energy*, 48(1), 406-414.

Philadelphia Water Department (2015). "Stormwater Management in Philadelphia."http://www.phila.gov/water/Pages/default.aspx, 2.

Poë, S. S., Virginia; Berretta, Christian (2015). "Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration." *J Hydrol*, 523, 356-367.

PWD (2015). "Watershed Issues: Darby-Cobbs." <http://phillywatersheds.org/your_watershed/darby_cobbs>. (10/01/2015, 2015).

Roofmeadow (2015). "Guidelines." <http://www.roofmeadow.com/details-specs-services/technical-information/guidelines/>. (August 5, 2015, 2015).

Schneider, D. (2011). "Quantifying Evapotranspiration from a Green Roof Analytically." Master of Science in Civil Engineering, Villanova University.

SEPA RC&D (2011). "5/25/11." *Current Projects*, <http://separcd.org/2011/05/eastern-delaware-county-stormwater-collaborative/>. (10/01/15, 2015).

Skyland USA (2015). "rooflite semi-intensive." <http://rooflitesoil.com/products/semi-intensive/>. (10/26/2015, 2015).

Speak, A. F., Rothwell, J. J., Lindley, S. J., and Smith, C. L. (2013). "Rainwater runoff retention on an aged intensive green roof." *Science of The Total Environment*, 461–462, 28-38.

Sturm, T. W. (2010). "Hydraulic Structures." *Open Channel Hydraulics*, D. B. Hash, ed., McGraw-Hill, New York, NY, 264-282.

Teemusk, A., Mander, Ulo. (2010). "Temperature regime of planted roofs compared with conventional roofing systems." *Ecological Engineering*, 36(1), 91-95.

USEPA (2000). "Vegetated Roof Cover, Philadelphia, Pennsylvania." O. o. Water, ed.Washington, DC.

Vanaskie, M., Myers, R., and Smullen, J. (2010). "Planning-Level Cost Estimates for Green Stormwater Infrastructure in Urban Watersheds." *Low Impact Development 2010*, 547-558.

VanWoert, N. D. (2005). "Green roof stormwater retention: Effects of roof surface, slope, and media depth." *Journal of Environmental Quality*, 34(3), 1036-1044.

Velazquez, L. S. "Modular Green Roof Technology: An Overview of Two Systems." *Proc., First Annual Greening Rooftops for Sustainable Communities Conference, Awards & Trade Show*.

Versini, P. A., Ramier, D., Berthier, E., and de Gouvello, B. (2015). "Assessment of the hydrological impacts of green roof: From building scale to basin scale." *J Hydrol*, 524, 562-575.

Villarreal, E. L. (2007). "Runoff detention effect of a sedum green-roof." *Nordic Hydrology*, 38(1), 99-105.

Voyde, E., Fassman, E., and Simcock, R. (2010). "Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand." *J Hydrol*, 394(3–4), 384-395.

Walsh, C. J. (2005). "The urban stream syndrome: current knowledge and the search for a cure." *Journal of the North American Benthological Society*, 24(3), 706-723.

Whittinghill, L., Rowe, D. B., Andresen, J., and Cregg, B. (2015). "Comparison of stormwater runoff from sedum, native prairie, and vegetable producing green roofs." *Urban Ecosyst*, 18(1), 13-29.

Wingfield, A. (2005). "The Filter, Drain and Water Holding Components of Green Roof Design." *Greenroofs.com*.

Wong, G. K. L., and Jim, C. Y. (2015). "Identifying keystone meteorological factors of green-roof stormwater retention to inform design and planning." *Landscape and Urban Planning*, 143, 173-182.

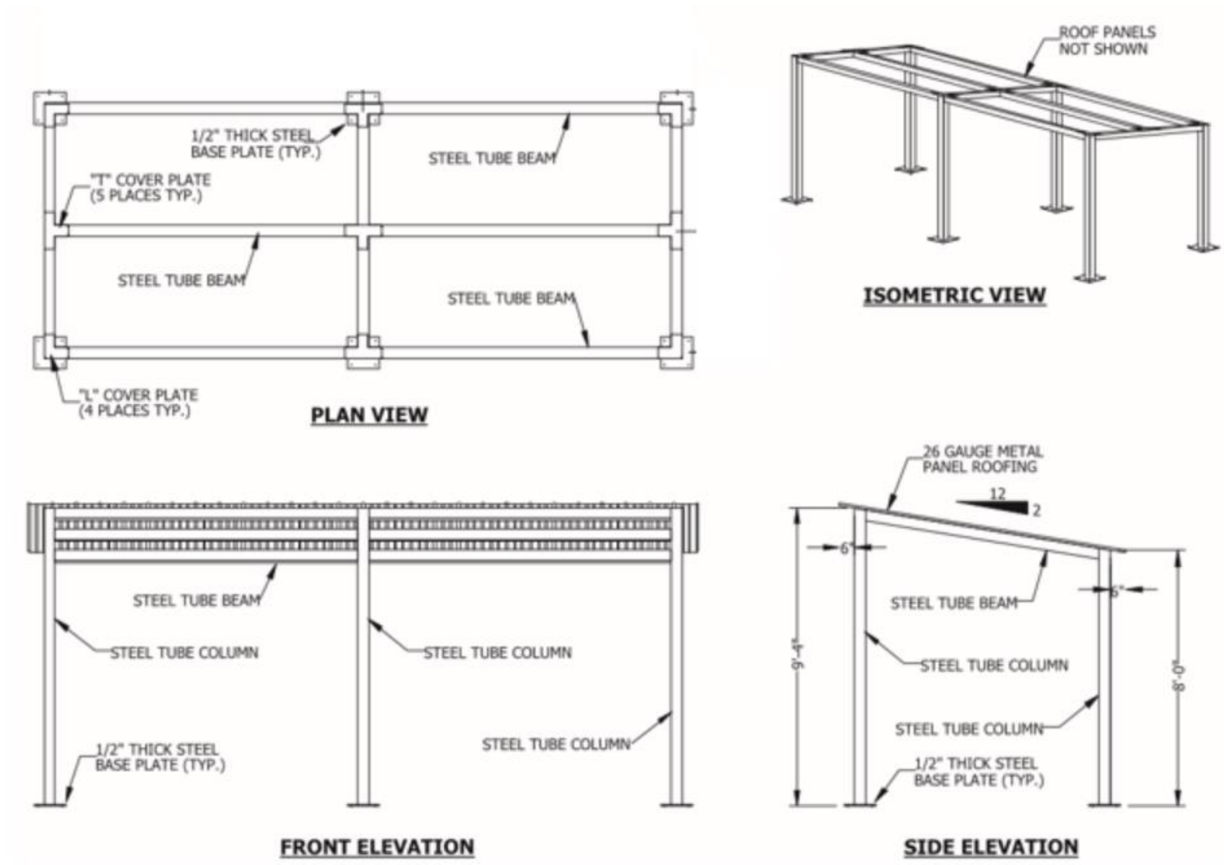
Wood, A. R. (2012). "Again, Darby Creek appears on the verge of flooding homes." *www.philly.com*.

Zaremba, G. (2015). "Evapotranspiration Measurement and Modeling for a Green Roof System." M.S., Villanova University, Villanova, PA.

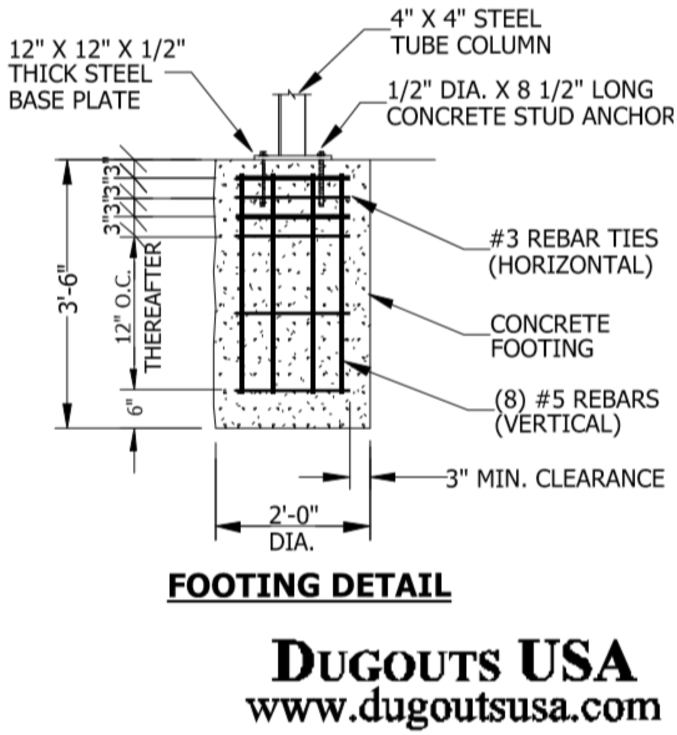
Zaremba, G., Traver, R. G., and Wadzuk, B. (2015). "The Impact of Drainage on Green Roof Evapotranspiration." *Journal of Irrigation and Drainage*, Under Review.

8. Appendices

Appendix A. Dugouts USA Pre-fabricated Steel Dugout Structure



Appendix B. Footing detail for structure foundation for Pennsylvania



Appendix C. Structural calculations for the shelter structure loading

Beams

STEEL PROPERTIES (HSS)		
E	29000	ksi
Fy	42	ksi

LOADS		
Dead Load	55.01	psf
	220	lb/ft
Live Load	0	psf
	0	lb/ft
Snow Load	25	psf
	84	lb/ft
Factored W	398	lb/ft
Approx Mu	7.17	kft
Approx Vu	2.39	kips
factored Load	99.612	psf

DIMENSIONS		
Span length	12	ft
Tributary width	4	ft

Appendix C. Structural calculations for the shelter structure loading

Columns

BEAM PROPERTIES (HSS)			
HSS 5x5x1/4			
t	0.233	in	
Weight	13.91	lb/ft	
A			
b/t	16.3		
h/t	16.3		
I	11.4	in4	
S	5.08	in3	
r	1.73	in	
Z	6.06	in3	
Workable Flat	3.375	in	
COMPACT/NONCOMPACT/SLENDER			
HSS Sections			
b/t	16.3		
			Table B4.1a
λr	36.79		Case 6
Therefore	NONSLENDER		
EFFECTIVE LENGTH FACTOR			
Gbot	1		
Gtop	0.6666667		
K (sidesway)	1.25		Fig C-A-7.2
NOMINAL COMPRESSIVE STRENGTH			
KL/r	78.03		
Fe	46.96	ksi	(E3-4)
4.71(E/Fy)^.5	123.8	ksi	
Fcr	28.88	ksi	(E3-2,3)
ϕPn	99.82	kips	(E3-1)
COMBINED FLEXURE AND AXIAL FORCE			
Pr	5.851	kips	STAAD
Mr	2.048	kft	STAAD
ϕMc	19.09	kft	
Pr/Pc	0.059		
Mr/Mc	0.107		
Pr/Pc+8/9(Mr/Mc*2)	0.249		(H1-1a)
Pr/2Pc+(Mr/Mc*2)	0.244		(H1-1b)
Use	0.244		
Check <1.0	OK		

DEFLECTION			
Approx Δ (DL+LL)	0.11	in	
L/240	0.45	in	
Check	OK		
Approx Δ (LL)	0.11	in	
L/360	0.30	in	
Check	OK		
SHEAR			
h	3.375	in	
tw	0.21669	in	
Kv	5		
h/tw	16.3		
1.10(kvE/Fy)^.5	64.6		(G2-3,4,5)
1.37(kvE/Fy)^.5	80.5		(G2-3,4,5)
Cv	1.0		(G2-3,4,5)
Aw	1.92	in2	
Vn	43.5456	kips	(G2-1)
Vu	1.54	kips	STAAD
Check	OK		

STEEL PROPERTIES (HSS)

E	29000	ksi
Fy	42	ksi
LOADS		
Dead Load	55.01	psf
	660	lb/ft
Live Load	0	psf
	0	lb/ft
Snow Load	25	psf
	252	lb/ft
Wind	20	psf
	240	lb/ft
Seismic	142	lb/ft
Factored W	240	lb/ft
Aprrox Mu	2.43	kft
Approx Vu	1.08	kips

DIMENSIONS

L	9	ft
Tributary width	12	ft

Appendix D. Semi Intensive Rooflite Media Specifications

rooflite® semi-intensive

A growing medium for semi-intensive green roof systems with a separate drainage course or a synthetic drainage layer. rooflite® semi-intensive is a precisely balanced blend of light weight mineral aggregates like HydRocks® or pumice and premium organic components like USCC STA approved compost complying with the following requirements:

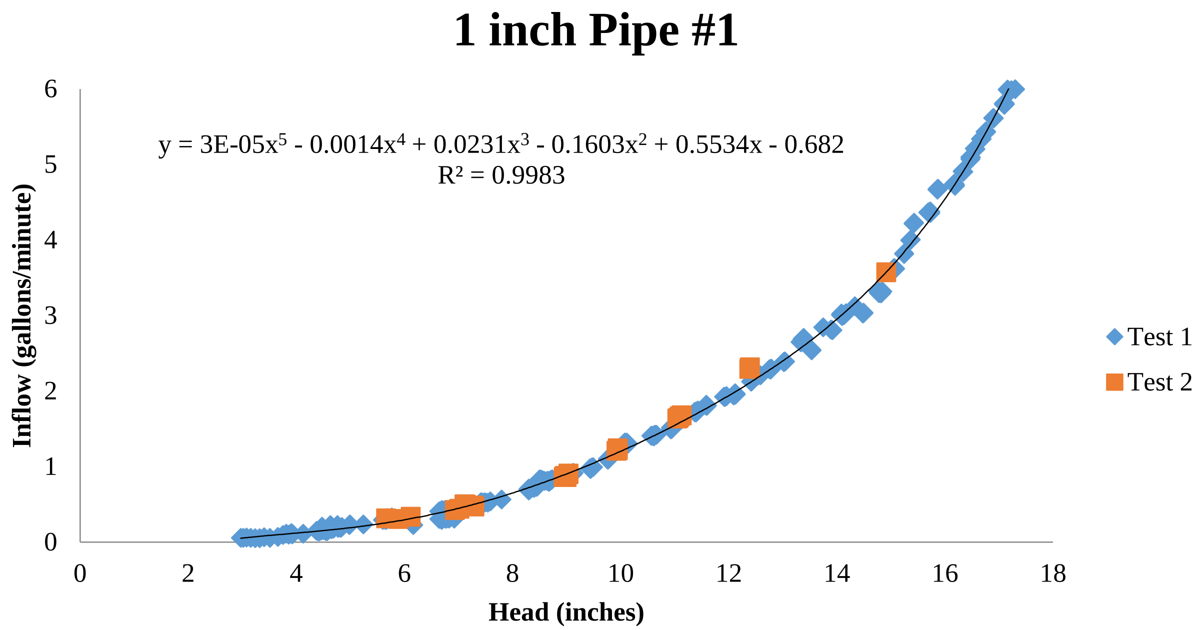
Particle Size Distribution		
Proportion of silting components < 0.063 mm	Mass %	≤ 15
Proportion of particles < 0.25 mm 60 mesh	Mass %	5 - 30
Proportion of particles < 1.00 mm 18 mesh	Mass %	10 - 50
Proportion of particles < 2.00 mm 10 mesh	Mass %	30 - 70
Proportion of particles < 3.20 mm 1/8 inch	Mass %	40 - 80
Proportion of particles < 6.30 mm 1/4 inch	Mass %	65 - 95
Proportion of particles < 9.50 mm 3/8 inch	Mass %	80 - 100
Proportion of particles < 12.50 mm 1/2 inch	Mass %	100
Density Measurements		
Bulk Density (dry weight basis)	g/cm^3	0.70 - 0.85
Bulk Density (dry weight basis)	lb/ft^3	44 - 53
Bulk Density (at max. water-holding capacity)	g/cm^3	1.15 - 1.35
Bulk Density (at max. water-holding capacity)	lb/ft^3	72 – 85
Water/Air Measurements		
Total Pore Volume	Vol. %	≥ 50
Maximum water-holding capacity	Vol. %	45 – 65
Air-filled porosity at max water-holding capacity	Vol. %	≥ 10
Water permeability (saturated hydraulic conductivity)	cm/sec	0.001 – 0.12
Water permeability (saturated hydraulic conductivity)	in/min	0.024 – 2.83
pH and Salt Content		
pH (in $CaCl_2$)		6.0 - 8.5
Soluble salts (water, 1:10, m:v)	g (KCl)/L	< 3.5
Organic Measurements		
Organic matter content	g/L	40 - 65
Nutrients		
Phosphorus, P2O5 (CAL)	mg/L	≤ 200
Potassium, K2O (CAL)	mg/L	≤ 700
Magnesium, Mg (CaCl2)	mg/L	≤ 200
Nitrate + Ammonium (CaCl2)	mg/L	≤ 80

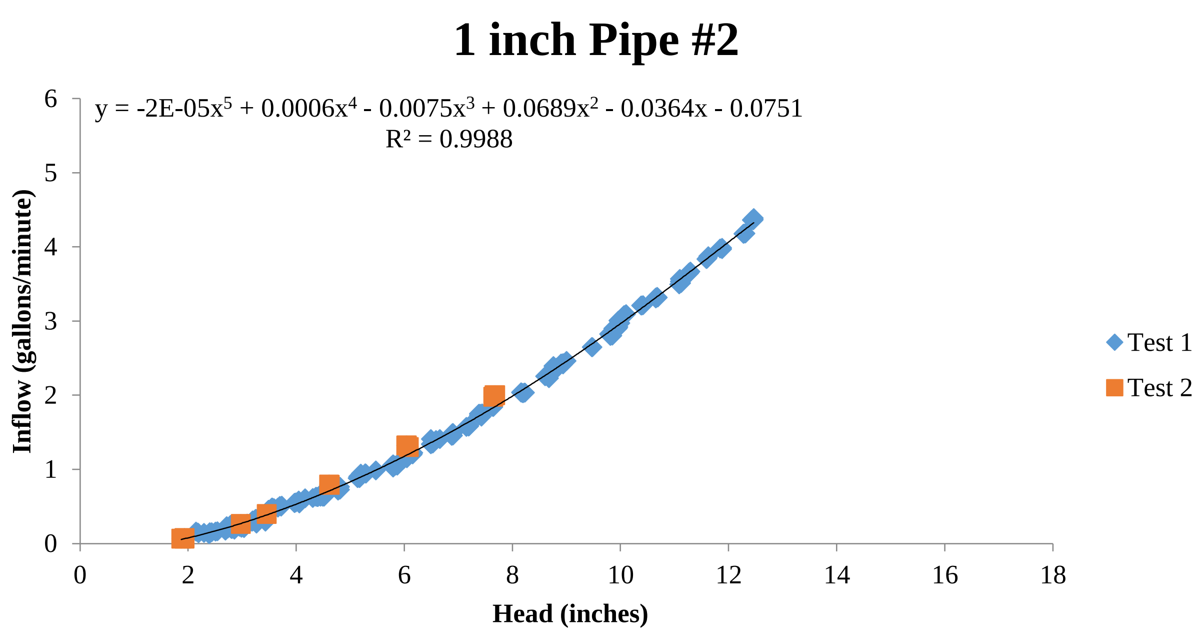
All values are based on compacted materials according to laboratory standards and testing methods defined by the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) Landscape Development and Landscaping Research Society, Guidelines for the Planning Construction and Maintenance of Green-Roofing, Green Roofing Guideline, 2008

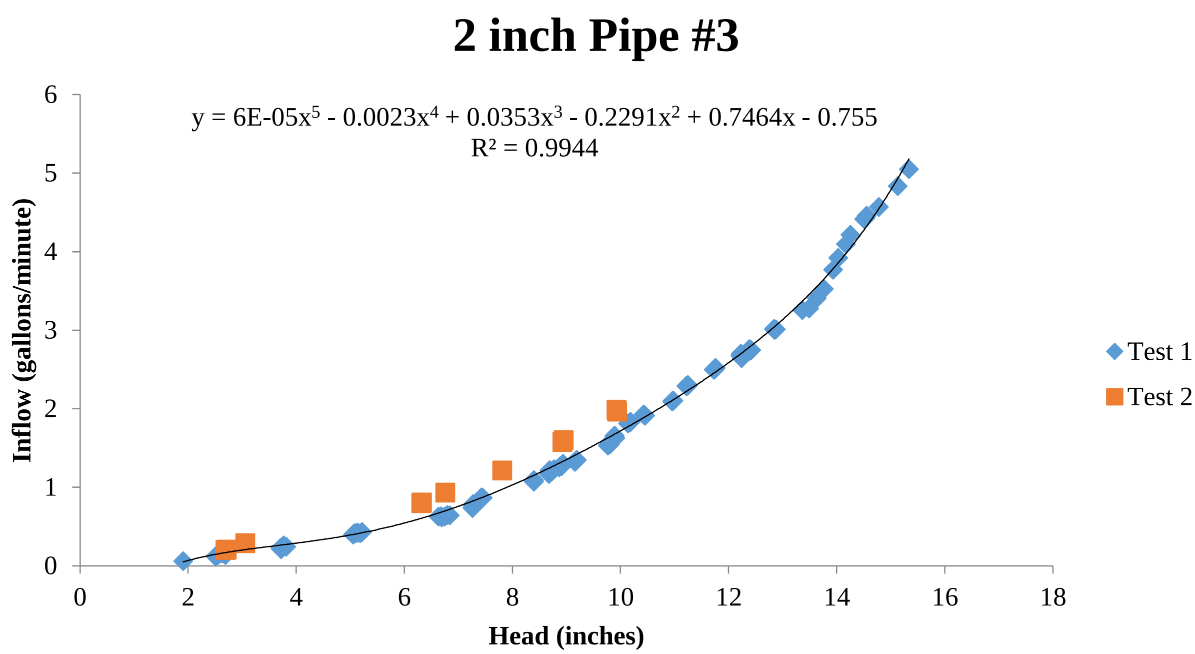
Appendix E. Instrumentation specifications

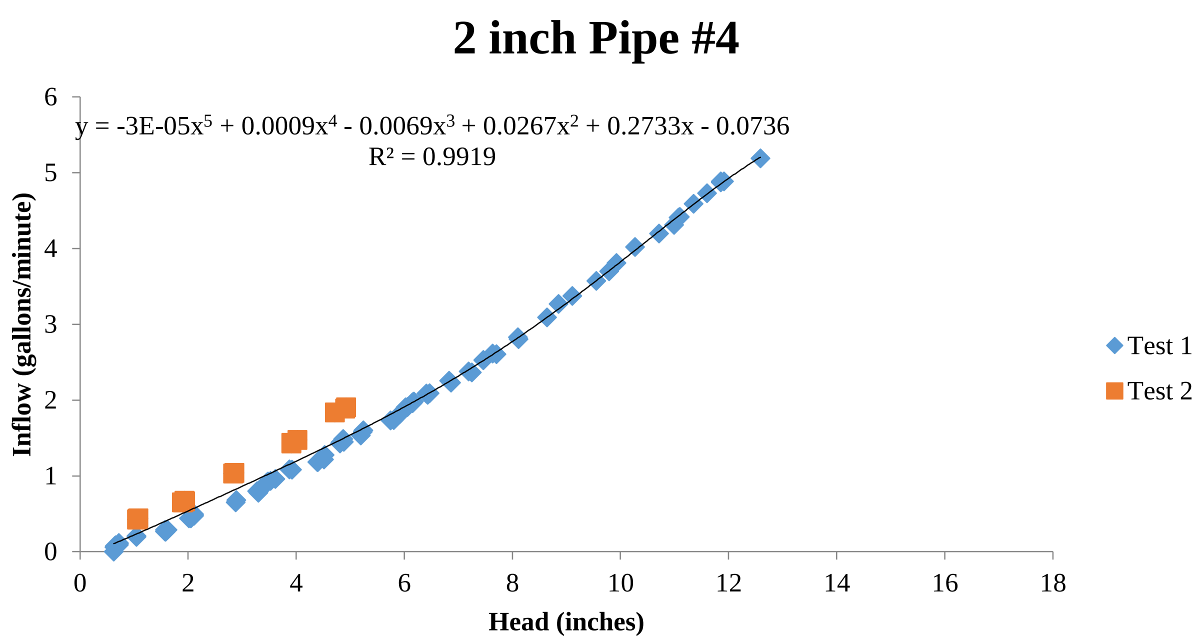
Item	Accuracy	Power Requirements
Atlas Scientific ENV-TMP Field Ready Temperature Probe	± 1°C	Operational voltage: 3.1V to 5.5V Current draw= 6 µA
Campbell Scientific CS450 Pressure Transducer	±0.1%	6 to 18 vdc
Decagon DS-2 Sonic Anemometer 5 m cable	Wind Speed Accuracy +/- 0.30 m/s or +/- 3% (whichever is greater) Wind Direction: Accuracy: +/- 3 degrees	Supply Voltage: 3.6 - 15 V
Decagon EC-5 Soil moisture sensor- 5m cable	±3% VWC, most mineral soils, up to 8 dS/m ±1-2% VWC with soil specific calibration	2.5 - 3.6 V DC @ 10 mA. Output proportional to input voltage.
Hach Sigma 2459 Tipping Bucket Rain Gage- 25 ft cable	0.5% at 0.5 in/hr	Power Requirements Replaceable 9 Vdc alkaline battery
Stevens SP-212 Pyranometer with level plate AL100 and bracket AM110	± 5 %	Power Supply: 5-24 VDC with a nominal current draw of 300 µA
Vegetronix VH400-10M Soil Moisture Sensor - 10 meter cable	2% at 25°C	Power Consumption: <7ma. Supply Voltage: 3.5V to 20VDC.

Appendix F. ORD calibration results from four initial prototypes design.






2 inch Pipe #3
y = 6E-05x5 - 0.0023x4 + 0.0353x3 - 0.2291x2 + 0.7464x - 0.755
R² = 0.9944
Inflow (gallons/minute)
Head (inches)
Test 1
Test 2


2 inch Pipe #4
y = -3E-05x5 + 0.0009x4 - 0.0069x3 + 0.0267x2 + 0.2733x - 0.0736
R² = 0.9919
Inflow (gallons/minute)
Head (inches)
Test 1
Test 2

Appendix G. Orifice Restricted Device (ORD) Construction

1. Purchase materials in table 1. The table includes approximate prices and the amount of material to make one Orifice Restricted Device (ORD.)
    a. Required items not included in the purchase table:
        i. Saw, permanent marker, rounded file (pictured below), drill with 0.25 inch drill bit, PVC cleaner and cement (pictured below), silicon sealant, and sealant gun (pictured below.)
    b. File

    c.
    d. Sealant

    e.
    f. PVC Cement & Cleaner

    g.

2. Cut the 1” PVC to a 4 ft. section using a saw.
3. **Drilling the Orifices**

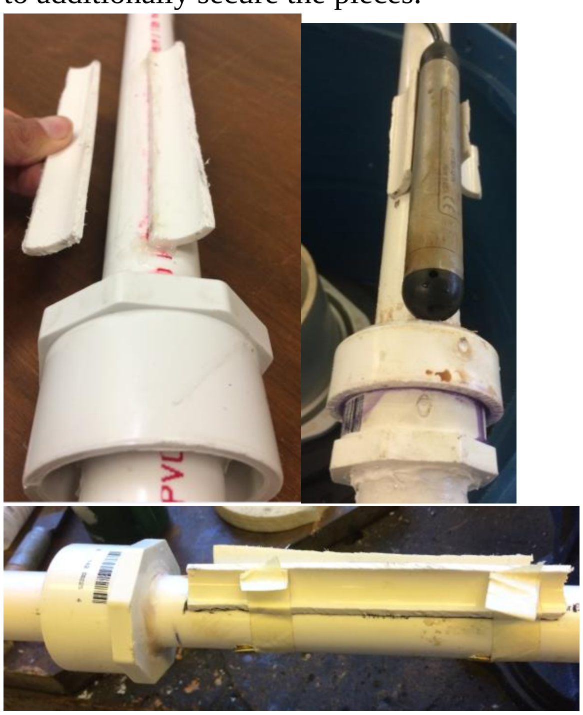
a. Mark the location of the orifice plugs on the 1” PVC pipe according to Figure 1. There are 5 total holes: 4 orifice plugs and 1 ¼” orifice drilled directly into the pipe.
b. Use a mill to drill and tap the orifice plugs into correct alignment.

4. Create connection between 1” PVC and 3” PVC

a. Take the 1 1/2” to 1” PVC bushing and use a file to remove the edge from the inside of the bushing. File the edge down until 1” PVC pipe can slide through the bushing.
b. Take the filed bushing from the previous step and the 2” to 1 1/2” PVC bushing. When connecting the 2 PVC bushings using PVC cement, follow all directions on the PVC cement. Start on a flat surface and cover with paper towels (or other disposable covering) to protect the work surface.
c. Coat both bushings first with PVC cleaner, then with PVC cement. Immediately after coating, push the two bushings together. Leave the bushings to dry for 3+ hours without disturbance.
d. Once the cement has dried, it is time to adhere the bushing piece to the 1” pipe. On the 1” pipe with orifice plugs, measure 1” below the bottom orifice plug and mark that distance.
e. 

f. Insert the 1” pipe with orifice plugs into the bushing piece, and position the bushing so the top of the piece is even with the mark from the last step. This is where the piece will be adhered to the pipe.
g. Move the bushing down about 1 inch. Coat the 1 inch pipe with PVC cleaner, then PVC glue. Immediately after coating, push the bushing upwards to be even with the measured mark. Leave the bushings to dry for 3+ hours without disturbance.

5. Pressure Transducer slot

a. The function of the pressure transducer slot is to ensure the pressure transducer is kept upright. The slot is made from scrap PVC pieces glued to the 1” ORD pipe. There are 2 pieces glued vertically parallel to each other.
b. Using a saw, cut 2 pieces of scrap PVC from a 1 inch pipe approximately 1 inch wide by 4-6 inches tall. The pieces will be curved. To create a straight line on one of the edges, use a file.
c. Measure the size of the pressure transducer to determine the distance between the pieces. Using the pressure transducer, mark the pipe with the locations of where the pieces will be glued. It may be helpful to use masking tape to hold the PVC piece in place before gluing.
d. With PVC cleaner & cement, glue the pieces to the 1 inch pipe and the bottom touching the bushing piece. Once the PVC glue has dried/set, add silicon sealant to additionally secure the pieces.
e. 

6. Drain attachment

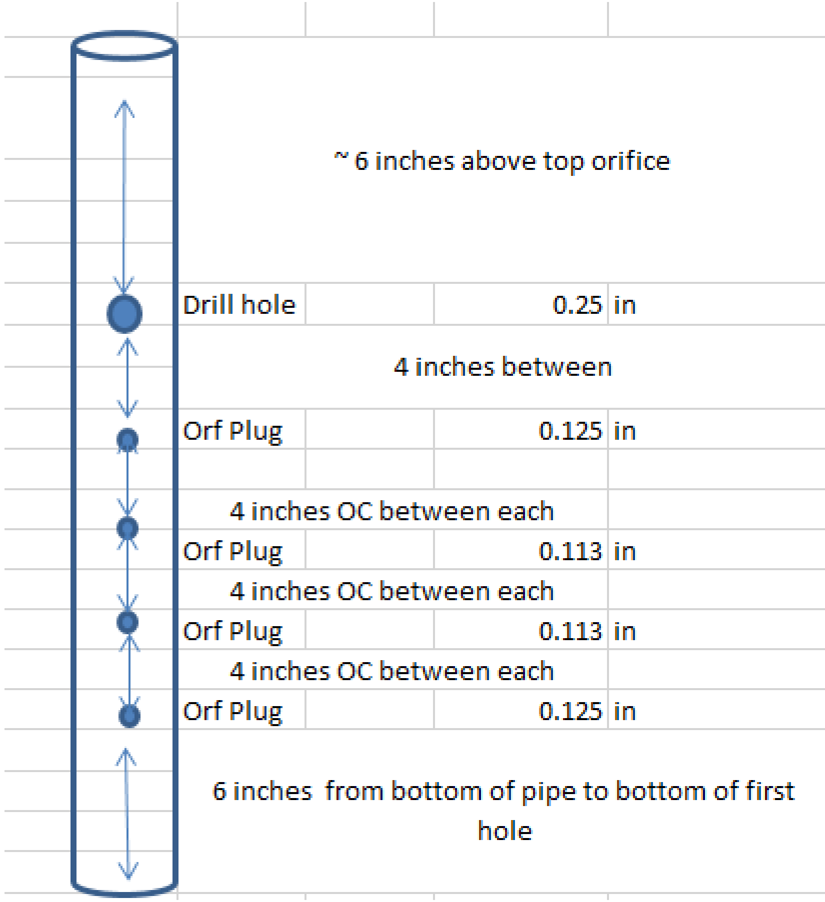
a. Take the 3 inch. PVC drain. Using a file, create a 1 inch hole in the middle of the drain. Make the hole sized so that a 1 inch pipe can slide through.

b. Once dry, insert the 1 inch PVC pipe and the 3 inch PVC pipe into the 3”/2” Fernco flexible coupling. Slide the PVC drain with the hole onto the top of the 1 inch PVC pipe so that the drain connects the 1 inch and 3 inch PVC pipe.



7. Attach a 1” PVC cap onto the top of the 1” pipe so that water can only enter through the orifices, and not fall directly into the top.
8. Drill a hole in the 3 inch pipe to allow the pressure transducer wire to exit the ORD.



Schematic of orifice plugs on 1 inch PVC pipe.

Appendix H. Orifice Restricted Device (ORD) Calibration

Equipment

- Data Logger
    - CR 1000
- Pressure transducer
    - Campbell Scientific 451
- Flow meter
    - IFM Flow Sensor SM 7001
    - Chosen due to accuracy at low flows (<1 gallon/minute)
- Hose

Calibration Instructions

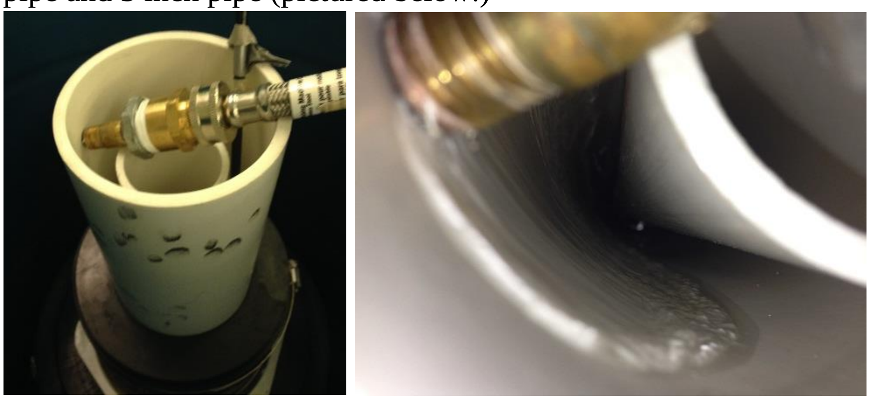
1. Set Up

a. Disassemble the ORD by removing the 1 inch pipe from the 3 inch Fernco coupling. Then place the pressure transducer in the slot on the 1 inch PVC (pictured below.) This can be done with the ORD assembled by dropping the pressure transducer into the slot from above.

b. Re-assemble ORD by securing the 1 inch pipe inside 3 inch pipe with the flexible coupling with the pressure transducer in between to create the assembled ORD.

c. 

d. The assembled ORD is situated vertically. A level can be used to ensure the ORD is vertical. The hose should be placed so that the water flows between the 1 inch pipe and 3 inch pipe (pictured below.)

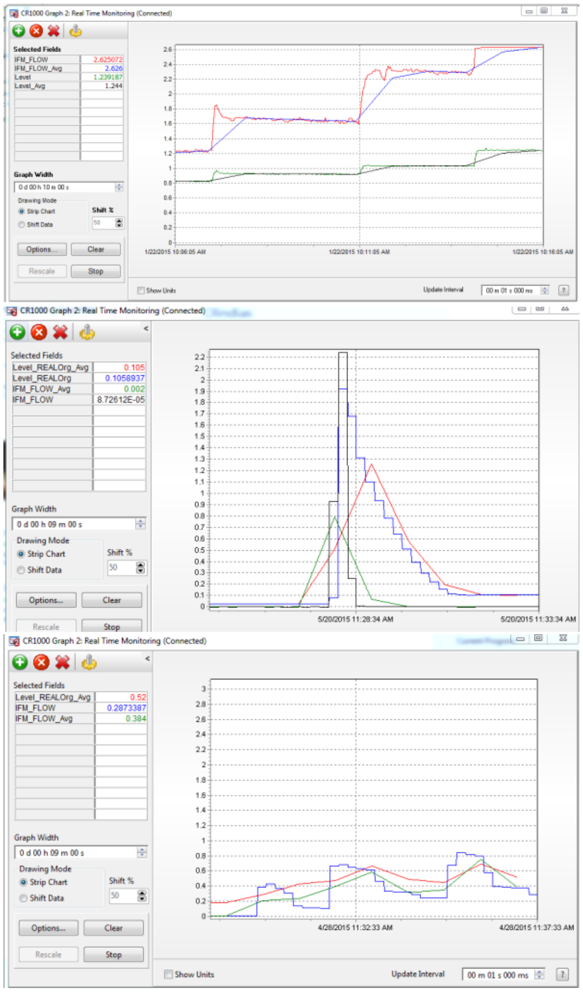
e. 

f. Before the beginning of data collection, the hose should be run for a minimum of 1 minute to fill the space below the first orifice with water. After this preparation, the ORD should be left without any water inflow for a minimum of 1 minute.

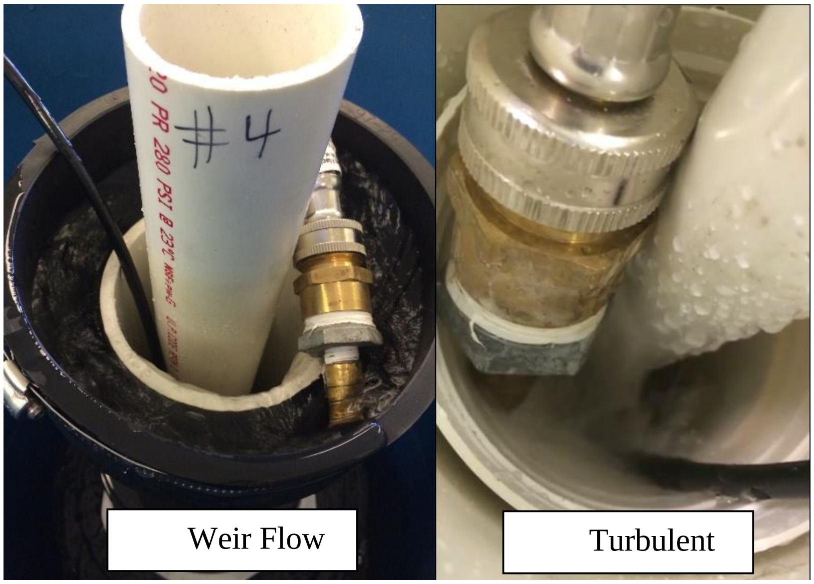
2. Data Collection

a. Collect data by simultaneously tracking the depth increase inside the ORD and the input flow rate. The calibration performed previously included the IFM Flow Sensor SM 7001 connected to a hose which acts as the input flow. The depth data was collected by a CS 450/1. A Campbell Scientific CR 1000 data logger was used to tabulate and store this data. If necessary, the data can be manually collected from the flow meter display screen.

b. The range of flow rates during calibration should reflect the range of flow rates expected at the field site. The input flow varied with different patterns with increments of approximately 0.2 gallons/minute (0.013 liters/second): steady increasing flow, steady decreasing flow and variable flow.

c. 

d. If the inflow may be turbulent in the field, include data with water entering as weir flow, in addition to directly from the hose (e.g. with a funnel or flexible coupling attachment.) Note the placement of the hose is either directly inside the ORD (turbulent flow) or directed into a coupling attachment (weir flow.) This is done to ensure that the inflow entry does not change the relationship between inflow and depth.

e. 

3. **Data Regression Analysis**
    a. The data should be a collection of data pairs of flow and depth. When the inflow is zero, the ORD depth won't be zero since there is space on the ORD below the first orifice. All data points should be normalized to the zero point. This is done by subtracting the zero-flow depth from the subsequent depths.
    b. When there are several data pairs in a row for approximately the same flow, the data is averaged. Example below. This ensures the data is independent from the surrounding data.

Time	Flow gpm	Level in	AvgF gpm	AvgD in
14:07	0.447	4.436	0.441	4.32
14:08	0.445	4.304		
14:09	0.432	4.22		

    c. The data was imported into Minitab for statistical analysis. In Minitab, the data was plotted with various regression lines. To evaluate the fit of a regression line, the residuals were plotted and examined. The residuals should be identically distributed and normal. The regression model with the least residuals shows it is the best fit.
    d. Choose the best fit model with least residuals. Consider ease-of-use of model. Can do piecewise regression if necessary. For example, if the data is much more variable at flows less than 1 gpm, there can be two separate regressions: one for flows below 1 gpm, one for flows above 1gpm.

Appendix I. Sensor Data Type and Arduino Code

Sensor	Output	Sample Arduino Code Available Online
Atlas Scientific ENV-TMP Field Ready Temperature Probe	Analog 0-3 V	Available http://atlas-scientific.com/_files/code/ENV-TMP-Arduino-Sample-Code.pdf
Campbell Scientific CS450 Pressure Transducer	SDI 12	Not Available
Dallas DS18B20 Waterproof Digital Temperature sensor	Digital	Available http://www.hobbytronics.co.uk/ds18b20-arduino
Decagon DS-2 Sonic Anemometer 5m cable	SDI 12	Not Available
Decagon EC-5 Soil moisture sensor 5m cable	Analog Voltage	Not Available
Hach Sigma 2459 Tipping Bucket Rain Gage- 25 ft cable	Self Logging	N/A
Stevens SP-212 Pyranometer with level plate AL100 and bracket AM110	SDI 12	Not Available
Vegetronix VH400-10M Soil Moisture Sensor - 10 meter cable	Analog 0-3 V	Not Available

Code Authors: Dr. Ryan Lee, Kellen Pastore, Villanova University

```
#include <SDISerial.h>
#include <SPI.h>
#include <Wire.h>
#include <RTClib.h>
#include <SD.h>
#include <DallasTemperature.h>
#include <OneWire.h>

#define ec5PinD 0
#define ec5PinA 0
#define atlasPinD 4
#define atlasPinA 1
#define vegPin1 2
#define vegPin2 3
#define SolarRadPin 9
#define DATALINE_PIN 3
#define INVERTED 1
#define ECHO_TO_SERIAL 1
#define redLEDpin 3
#define greenLEDpin 4
```

```
#define ONE_WIRE_BUS 5

//Change these for SDI-12 address (e.g. "1M1!" to "4M1!" if SDI12 address is now 4)
char* PT1cmd1="1M1!";
char* PT1cmd2="1D!";
char* PT2cmd1="6M1!";
char* PT2cmd2="6D!";
char* DS2cmd1="0M!";
char* DS2cmd2="0D0!";
// make sure the header names are in the same order that the sensors are measured in the main
loop
char*
header="TIMESTAMP,PHAtlasTemp,PHLevelPT1,PHTempPT1,PHLevelPT2,PHTempPT2,Wi
ndSpd,WindDir,AirTemp,PHSoilMoistEC5,PHSoilMoistVeg1,PHSoilMoistVeg2,Temp1,Temp2
,Temp3,Temp4,Temp5,PHSolarRad";
char filename[] = "PHUB00.CSV";
const int dt = 30; //time interval in seconds to record data
long lasttime = 0L;
const int chipSelect = 10;  // for the data logging shield, we use digital pin 10 for the SD cs
line

File logfile; // the logging file
RTC_DS1307 rtc;
SDISerial sdi_serial_connection(DATALINE_PIN, INVERTED);

// Setup a oneWire instance to communicate with any OneWire devices
OneWire oneWire(ONE_WIRE_BUS);

// Pass our oneWire reference to Dallas Temperature.
DallasTemperature sensors(&oneWire);

// Assign the addresses of your 1-Wire temp sensors.
// See the tutorial on how to obtain these addresses:
// http://www.hacktronics.com/Tutorials/arduino-1-wire-address-finder.html

DeviceAddress Thermometer1 =


void setup() {
  // put your setup code here, to run once:
  Serial.begin(57600);
  Serial.println();

  sdi_serial_connection.begin(); // start our SDI connection
  Wire.begin();
  if (!rtc.begin()) {
```

```
    logfile.println("RTC failed");
#if ECHO_TO_SERIAL
    Serial.println("RTC failed");
#endif  //ECHO_TO_SERIAL
  }

  pinMode(ec5PinD, OUTPUT);
  pinMode(atlasPinD, OUTPUT);

  // initialize the SD card
  Serial.print("Initializing SD card...");
  // make sure that the default chip select pin is set to
  // output, even if you don't use it:
  pinMode(10, OUTPUT);
  pinMode(11, OUTPUT);
  pinMode(12, OUTPUT);
  pinMode(13, OUTPUT);

  waitForSDCard();
  Serial.println("card initialized.");

  createNewFile();

  if (! logfile) {
    error("couldnt create file");
  }

  Serial.print("Logging to: ");
  Serial.println(filename);

  logfile.println(header);
  logfile.flush();
#if ECHO_TO_SERIAL
  Serial.println(header);
#endif

  // Start up the temperature library
  sensors.begin();

  // set the resolution to 10 bit (good enough?)
  sensors.setResolution(Thermometer1, 12);
  sensors.setResolution(Thermometer2, 12);
  sensors.setResolution(Thermometer3, 12);
  sensors.setResolution(Thermometer4, 12);
  sensors.setResolution(Thermometer5, 12);
```

```
  pinMode(redLEDpin, OUTPUT);
  pinMode(greenLEDpin, OUTPUT);

}

void loop() {
  // put your main code here, to run repeatedly:
  DateTime now;

  // start by checking the time, and looping around until "dt" has passed
  do {
      delay(1000);
     now = rtc.now();
  } while ((now.unixtime()-lasttime) < dt);

  digitalWrite(greenLEDpin, HIGH);

  // Real Time Clock Processing
  lasttime = now.unixtime();
  logfile.print(now.year(), DEC);
  logfile.print('/');
  logfile.print(now.month(), DEC);
  logfile.print('/');
  logfile.print(now.day(), DEC);
  logfile.print(' ');
  logfile.print(now.hour(), DEC);
  logfile.print(':');
  logfile.print(now.minute(), DEC);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(now.year(), DEC);
  Serial.print('/');
  Serial.print(now.month(), DEC);
  Serial.print('/');
  Serial.print(now.day(), DEC);
  Serial.print(' ');
  Serial.print(now.hour(), DEC);
  Serial.print(':');
  Serial.print(now.minute(), DEC);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  // Atlas Temperature
  float temp;
  temp = read_temp_atlas();
  logfile.print(temp, 2);
```

```
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(temp, 2);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  // CS450 PT
  float pt1Data[2];
  // the 2 specifies that there are 2 parameters to retrieve
  // 3000 is the ms delay
  getSDI12measurement(pt1Data, 2, PT1cmd1, PT1cmd2, 3000);
  //convert PSI to ft
  pt1Data[0]=pt1Data[0]*2.307;
  logfile.print(pt1Data[0], 4);
  logfile.print(',');
  logfile.print(pt1Data[1], 3);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(pt1Data[0], 4);
  Serial.print(',');
  Serial.print(pt1Data[1], 3);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  float pt2Data[2];
  // the 2 specifies that there are 2 parameters to retrieve
  // 3000 is the ms delay
  getSDI12measurement(pt2Data, 2, PT2cmd1, PT2cmd2, 3000);
  //convert PSI to ft
  pt2Data[0]=pt2Data[0]*2.307;
  logfile.print(pt2Data[0], 4);
  logfile.print(',');
  logfile.print(pt2Data[1], 3);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(pt2Data[0], 4);
  Serial.print(',');
  Serial.print(pt2Data[1], 3);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  // Decagon DS-2 anamometer
  float DS2Data[3];
  // the 3 specifies that there are 3 parameters to retrieve
  // 1000 is the ms delay
  getSDI12measurement(DS2Data, 3, DS2cmd1, DS2cmd2, 1000);
```

```
  logfile.print(DS2Data[0], 2);
  logfile.print(',');
  logfile.print(DS2Data[1], 0);
  logfile.print(',');
  logfile.print(DS2Data[2], 2);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(DS2Data[0], 2);
  Serial.print(',');
  Serial.print(DS2Data[1], 0);
  Serial.print(',');
  Serial.print(DS2Data[2], 2);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  //EC5 Soil Moisture Meter
  float ec5;
  ec5 = read_soilM_ec5();
  logfile.print(ec5, 4);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(ec5);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  //Vegetronix soil moisture meters
  float vegSoilM1;
  vegSoilM1 = analogRead(vegPin1);
  logfile.print(vegSoilM1*.0049);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(vegSoilM1*.0049);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  float vegSoilM2;
  vegSoilM2 = analogRead(vegPin2);
  logfile.print(vegSoilM2*.0049);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(vegSoilM2*.0049);
  Serial.print(',');
#endif //ECHO_TO_SERIAL

  //Dallas temperature
  //Getting Dallas temp ready for Measurement
```

```
  sensors.requestTemperatures();
  float t1 = sensors.getTempC(Thermometer1);
  float t2 = sensors.getTempC(Thermometer2);
  float t3 = sensors.getTempC(Thermometer3);
  float t4 = sensors.getTempC(Thermometer4);
  float t5 = sensors.getTempC(Thermometer5);
  logfile.print(t1);
  logfile.print(',');
  logfile.print(t2);
  logfile.print(',');
  logfile.print(t3);
  logfile.print(',');
  logfile.print(t4);
  logfile.print(',');
  logfile.print(t5);
  logfile.print(',');
#if ECHO_TO_SERIAL
  Serial.print(t1);
  Serial.print(',');
  Serial.print(t2);
  Serial.print(',');
  Serial.print(t3);
  Serial.print(',');
  Serial.print(t4);
  Serial.print(',');
  Serial.print(t5);
  Serial.print(',');
#endif //ECHO_TO_SERIAL


  int SolarRad;
  SolarRad = analogRead(SolarRadPin);
  logfile.print(SolarRad*0.5);
  logfile.println(); // last entry don't add a comma, print newline instead
#if ECHO_TO_SERIAL
  Serial.print(SolarRad*0.5);
  Serial.println();
#endif //ECHO_TO_SERIAL

  logfile.flush();
  digitalWrite(greenLEDpin, LOW);
}

float read_soilM_ec5(void){
  float v_out;
  float soilM;
```

```
  digitalWrite(ec5PinD, LOW);
  digitalWrite(ec5PinD, HIGH);
  delay(10);
  v_out = analogRead(ec5PinA);
  digitalWrite(ec5PinD, LOW);
  v_out*=.0029;
  v_out*=1000;
  soilM= 0.00119*v_out -0.4;
  return soilM;
}


float read_temp_atlas(void){
  float v_out;
  digitalWrite(atlasPinD,HIGH);
  delay(2);
  v_out = analogRead(atlasPinA);
  digitalWrite(atlasPinD,LOW);
  v_out*=.0048;
  v_out*=1000;
  float temp= 0.0512*v_out -20.5128;
  return temp;
}

// get SDi12 measurement
void getSDI12measurement(float* Desired_Data, int numParams, char* cmd1, char* cmd2,
int delayms){//Takes in an array to store results, and the address to store the data in
  char* service_request = sdi_serial_connection.sdi_query(cmd1,2000);//Ask for
measurement to be made
  delay(delayms);
  char* Raw_Data = sdi_serial_connection.sdi_query(cmd2,2000);//Request Data
  float Processed[numParams];
  parser(Raw_Data,Processed,numParams);
  for (int i=0; i<numParams; i++) {
    Desired_Data[i] = Processed[i];
  }
}

// parser used to process the SDI-12 string into numbers
void parser(char* dataString, float* parsed, int numParams){//You need string to be parsed,
and float array with elements equal to the number of data points being stored
  String temp="";
  temp += dataString;
  int strLength = temp.length();
  temp = "";
```

```
  int paramIndex=0;//which parameter are you on
  int i=1;  // dataString[0] should be the sensor address
  int sign=1;//Sign of the Float being converted, 1 being +, -1 being -

  for (paramIndex; paramIndex<numParams; paramIndex++) {
    if (dataString[i]=='+') {
        sign = 1;
    } else if (dataString[i]=='-') {
        sign = -1;
    }
    i++;
    do {
      temp += dataString[i];
      i++;
    } while (dataString[i]!='+' && dataString[i]!='-' && dataString[i]!= '\0');
    parsed[paramIndex]=temp.toFloat()*sign;
    temp="";
  }
}

// error message and halt
void error(char *str) {
  Serial.print("error: ");
  Serial.println(str);

  // red LED indicates error
  digitalWrite(redLEDpin, HIGH);

  while(1);
}

void waitForSDCard() {
  // see if the card is present and can be initialized:
  digitalWrite(redLEDpin, HIGH);
  while (!SD.begin(10, 11, 12, 13)) {
    delay(1000);
  }
  digitalWrite(redLEDpin, LOW);
}

void createNewFile() {
  // create a new file
  // Note: filename cannot exceed 8 characters + 3 extension chars
  filename[4] = '0';
  filename[5] = '0';
  for (uint8_t i = 0; i < 100; i++) {
```

```
    filename[4] = i/10 + '0';
    filename[5] = i%10 + '0';
    if (! SD.exists(filename)) {
      // only open a new file if it doesn't exist
      logfile = SD.open(filename, FILE_WRITE);
      break;  // leave the loop!
    }
  }
}
```

Appendix J. Raw collected runoff data from the 11/30/15 storm.