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Monitoring and Modeling the Hydrological Performance of Extensive Green Roof Systems

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MONITORING AND MODELING THE HYDROLOGICAL PERFORMANCE OF EXTENSIVE GREEN ROOF SYSTEMS

by

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ABSTRACT

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The University of Wisconsin-Milwaukee, 2015
Under the Supervision of Professor Dr. Qian Liao

Urban stormwater runoff causes many problems for watersheds located within large metropolitan areas, including such detrimental effects as flooding, erosion, pollution, and the increased risk of combined sewerage overflows. Increased amounts of impervious areas resulting from urban sprawl have also been shown to escalate stormwater flows, which exacerbates water management issues in these metropolitan areas. Water resource engineers have progressively turned toward green infrastructure to solve stormwater problems, and green roof systems represent one type of this green infrastructure. As of current, however, green roof systems are largely underused in as an effective stormwater management tool.

The major factor limiting the installation of green roof systems is the unpredictable hydrological response of green roofs to individual storm events. Currently, many municipalities use the Soil Conservation Service model or rational method and associated curve numbers to estimate stormwater flows, with green roofs typically receiving an assigned value ranging from 75-90 within these models. However, these simple models do not accurately predict the hydrological response of green roof systems, where the overall performance is determined by many supplementary factors including geometry, soil media type and depth, initial conditions, and the individual storm hyetograph. The accurate monitoring of green roof stormwater runoff and the

use of data to create models are critical to measuring hydrological response, as well as to assess the benefits of the green roof installation to the local watershed.

In this study, four 15 m^2 test plots were constructed on the roof of the Milwaukee Metropolitan Sewerage District headquarters located in downtown Milwaukee, Wisconsin. An ET 107 weather station manufactured by Campbell Scientific was installed onsite. Stormwater flows were monitored for each plot using a "WeirBox", a tipping gauge and v-notch weir combination which was developed and calibrated specifically for this project. Three extensive green roof systems manufactured by Vegetal i.D. were tested, including Hydropack, a standard modular extensive green roof, and Hydro Active Smart Roof (HSRP) and Hydro Active Smart Roof Active (HSRA), both of which are extensive green roof systems with additional water storage basins. A control bare roof plot was also monitored to confirm and compare hydrological performance.

The WeirBox flow monitoring equipment displayed impressive results with water budget error typically less than 7% for individual storm events when comparing total runoff volume from the control plot to onsite precipitation data. All three of the tested green roof systems exhibited significant hydrological performance in terms of total runoff retention, peak runoff rate reduction, and peak runoff rate delay. However, depending mostly on rainfall characteristics, the responses to individual storm events varied widely. Total runoff retention for the 8 month monitoring period was calculated to be 64%, 87%, and 91% for Hydropack, HSRP and HSRA respectively. In general, both HSR systems with greater water capacities outperformed the standard extensive green roof system, which suggests that optimization through an integrated storage basin can be achieved to improve overall green roof performance.

A conceptual simple bucket model was created for the Hydropack and HSRP green roof systems. Data from 6 individual storm events was used to validate the model. While "simple", the

conceptual bucket model successfully reproduced the hydrological response of the green roof systems to individual storm events. Synthesized storm events with return periods ranging from 1 to 100 years were then analyzed using the calibrated models. Hydrological performance diminished with larger storm events, mirroring results from monitoring and literature review. Both monitoring and modeling showed that the integration of extensive green roofs with storage basins greatly improves performance.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

BMPs	Best Management Practices
C	Runoff Coefficient
CN	Curve Number
C_e	Weir Coefficient
CR	Capillary Rise
CSO	Combined Sewerage Overflows
c_1 & c_2	Ultrasonic Sensor Calibration Curve Parameters
DP	Deep Percolation
EDPM	Ethylene Propylene Diene Terpolymer
EPA	Environmental Protection Agency
EQ	Equation
ET	Evapotranspiration
GI	Green Infrastructure
H	Height
H_w	Water Depth
H_{le}	Adjusted Water Depth
HSRP	Hydro Active Smart Roof
HSRA	Hydro Active Smart Roof Active
Hydropack	Extensive Modular Green Roof System
i	Rain Intensity
L	Length
MATLAB	Mathworks Numerical Computing Environment Software
MMSD	Milwaukee Metropolitan Sewerage District

P	Precipitation
PRR	Peak Runoff Rate
Q	Runoff Rate
Q_{tip}	Tipping Gauge Flow rate
Q_{weir}	V-notch Weir Flow rate
RO	Runoff
S	Maximum Storage Depth
SCS	Soil Conservation Service
SWMM	Stormwater Management Model
SWMS-2D	Simulating Water and Solute Movement
T	Time
T_{peak}	Time of Maximum Runoff Rate
US_{ave}	Average Ultrasonic Signal
UWM	University of WI-Milwaukee
V	Runoff Volume
WeirBox	Tipping Gauge V-notch Weir Combination Flow Monitoring Equipment
w_1 - w_4	V-notch Weir Calibration Coefficients
Θ	N-notch Weir Angle
ΔSF	Change in Subsurface Flow
ΔSW	Change in Soil Water content

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dashboard to display our work. Your dedication, experience and expertise were essential for this project's success. As a teacher, you showed me what it means to struggle, and how to learn and grow through the process. As a friend, you always showed patience and support. All of these traits make you a great advisor, but your ability to perpetually conduct yourself with unconditional kindness makes you an even better person, and I consider myself fortunate to call you a friend.

Thank you all. I dedicate this paper to you.

I. INTRODUCTION

Stormwater Problems

Global population growth and urban sprawl have resulted in increased quantities of impervious surfaces in metropolitan areas (Nawaz et al., 2015; Hakimdavar et al., 2014; Locatelli et al., 2014). Impervious surfaces cause detrimental effects to both the quality of the surrounding watershed and local stormwater infrastructure. By inhibiting natural infiltration, impervious areas increase surface runoff, which results in erosion, urban flooding, and decreased water quality (Berndtsson, 2010; Li and Babcock, 2014). Increased stormwater runoff rates require larger sewer pipe diameters to convey escalating flows, and the implementation of updated stormwater infrastructure can have astounding costs in developed areas (Hakimdavar et al., 2014). Furthermore, the advancement of intense rain events caused by climate change will likely exacerbate local stormwater problems (Larsen et al., 2009).

The problems associated with urban stormwater become amplified in cities, such as Milwaukee, WI, which have a combined sewerage system as intense rain events can result in combined sewerage overflows (CSOs) (Roldin et al., 2012; Hakimdavar et al., 2014). Milwaukee's Deep Tunnel System, a series of 6 – 12 meter diameter tunnels located at a depth of 100 meters below the ground surface, was first constructed in the 1980s to reduce CSOs (Royer 2012). The now finished system has a capacity of over 1.5 billion liters and has successfully reduced CSOs from an average of more than 60 per year to less than 3; however, this has come at a staggering cost of more than 1.5 billion taxpayer dollars (Behm, 2013). Similar to other municipalities, Milwaukee is moving away from large projects such as the Deep Tunnel System toward green infrastructure (GI) to further reduce CSOs and to solve local stormwater issues.

In the past 25 years, urban stormwater infrastructure has shifted from simply conveying surface runoff away from metropolitan areas towards dealing with rain water where it falls with GI (Berndtsson, 2010; Lamera et al., 2014). The United Stated Environmental Protection Agency (EPA) has recognized several forms of GI as Best Management Practices (BMPs) including riparian buffers, detention basins, rain gardens, bio-swales, permeable pavement and vegetated or green roofs (Carter and Ramussen, 2006). In general, stormwater BMPs act to detain runoff water on-site and to increase infiltration in order to decrease surface runoff, which results in improved water quality and reduced urban flooding by mimicking a predevelopment hydrologic cycle (Li and Babock, 2014). Unfortunately, in urban areas where space is limited, many GI solutions are not practical (Hilten et al., 2008). In contrast, green roofs represent an underutilized opportunity for urban stormwater management (Palla et al., 2009; Berndtsson, 2010; Locatelli et al., 2014).

The major obstacle facing green roof installations is inconsistent hydrological performance, namely in terms of total runoff retention, peak runoff rate reduction, and peak runoff delay. In general, the scientific community agrees that green roofs act to detain and delay runoff and to mitigate peak runoff rates through absorption, infiltration, and evapotranspiration (Figures 2.3 – 2.5). However, because exact values for individual storm events vary significantly, it is difficult to quantify the benefits of green roof installations and potential impacts on the urban water cycle (Lamera et al., 2014).

Project Goals

The main objective of this research project is to qualify and quantify the hydrological benefits of modular extensive green roof systems in order to gain a better understanding of their response to individual storm events. To accomplish this task, a series of sub-goals were created to benchmark progress. These sub-goals included 1) the set-up of a reliable experimental design; 2) accurately monitoring runoff from plots under all runoff conditions; 3) monitoring plot runoff, plot temperature, and meteorological data continuously over the monitoring period; and 4) using data to create working models to predict hydrological response. Furthermore, our ultimate goal was to use the collected data to assess the ability of modular green roof systems to mitigate local urban stormwater problems.

Project Scope

The size of our study was determined by the specific project goals and constraints resulting from limiting funding. In order to accomplish goals (1) and (2), a pilot-sized approach was chosen to allow greater control of critical parameters such as slope, area, and drainage patterns while still providing enough space to mimic a subsection of a typical green roof installation. Furthermore, this allowed us to use a single drainage outlet for each plot, which reduced costs in flow monitoring equipment. After surveying the roof of the Milwaukee Metropolitan Sewerage District (MMSD) headquarters which served as the location for this project, a 3 x 5m plot size was selected. The roof slopes generally remained consistent over these size intervals, which diminished possible error from ponding and irregular draining. Plot size in this project is comparable to that reported in similar studies. Palla et al. (2009) and Hilten et al. (2008) reported test plot areas of 180 m^2 and 37 m^2 respectively, while researchers in the United Kingdom were able to collect data to monitor green roof performance and to validate models from a single 3 m^2 plot (Kasmin et al., 2010; Stovin et al., 2012). One additional advantage of a smaller plot size is that it allowed for three separate test plots to be monitored along with an onsite control. This means that onsite weather data collected is applicable to all plots in real time. Additionally, the onsite control plot allowed us to validate flow monitoring equipment performance and to assess hydrological benefits of test green roof systems.

Research Partners

This project represents a partnership between the University of WI-Milwaukee (UWM), MMSD, and Vegetal i.D., with additional funding provided by the Fund for Lake Michigan. UWM was responsible for engineering and design, along with flow monitoring equipment, data collection and analysis. Vegetal i.D., the green roof manufacturer, provided and installed the test green roof systems, oversaw the project budget, and subcontracted work such as plot construction as needed. MMSD provided the project site at the roof of their headquarters located in downtown Milwaukee, as well as technical support and equipment.

Figure 1.1 Green Roof Pilot Project, Milwaukee WI

II. LITERATURE REVIEW

History

The concept of a green roof is a well-established idea; however, this concept's original purpose was not related to stormwater management. The first recognized green roof systems originated in ancient Babylon, where hanging gardens were erected purely for aesthetic reasons. Scandinavian cultures have been using sod roofs for several centuries to waterproof and insulate homes during the harsh winter months (Osmundson, 1999). H. Koch inadvertently created green roofs while covering flammable tar roofs with soil media with the intention of reducing fire hazards in late 19th century Germany (Magill et al., 2011). The origin of the modern green roof is attributed to 1970s Germany, where rapid industrialization and urban growth resulted in stormwater problems and the ability of green roofs to mitigate these issues was first realized. Today, Germany is recognized as the leader of green roof development and implementation. An estimated 14% of flat roofs in Germany have green roofs installations (Getter et al., 2006; Stovin et al., 2012).

Green Roofs

Modern green roofs are roofs covered with growing media and vegetation installed with the purpose of storing rain water, thus reducing stormwater runoff (Osmundson, 1999). While individual green roof systems differ significantly, all are comprised of four basic layers (Figure 2.1). These layers include drainage material to allow excess water to leave the system, a filter membrane which prevents soil substrate loss, soil media to provide space for plant growth, and a vegetation layer which allows water capacities to be replenished through evapotranspiration (ET) (Berndtsson, 2010; Voyde et al., 2010; Hakimdavar et al., 2014).

Green roofs are typically classified into two major groups: intensive and extensive. Intensive green roofs are deeper, typically more than ~15 cm, and can support larger, deep- rooted

Figure 2.1: Cross Section of Hydropack Green Roof System

vegetation and higher water capacities (Gregoire and Clausen, 2011; Morgan et al., 2013). However, intensive green roofs tend to be heavy, as well as harder to maintain, which limits the potential for installation. Alternatively, extensive green roofs, which are shallower and have less capacity, are easier to install and maintain (Gregoire and Clausen, 2011; Locatelli et al., 2014). In the past decade, engineers have improved extensive green roofs, creating hybrid modular tray systems with high water capacity and simple installation procedures. These systems integrate a shallow soil media and vegetation top layer with a water storage basin. The stormwater management complement referred to as the Hydroactive Smart Roof (HSR) currently sold by Vegetal i.D. is an example of these new hybrid green roof systems (Vegetal i.D. 2015a).

Hydrological Performance

To date, numerous studies have been conducted to quantify the hydrological performance of green roof systems in terms of total runoff retention, peak runoff rate reduction, and peak runoff delay (Figures 2.3, 2.4 and 2.5). These studies generally agree that green roofs act to detain and delay runoff and mitigate peak runoff rates; however, exact values for individual storm events vary significantly (Carter and Rasmussen, 2006; Stovin et al., 2012; Lamera et al., 2014).

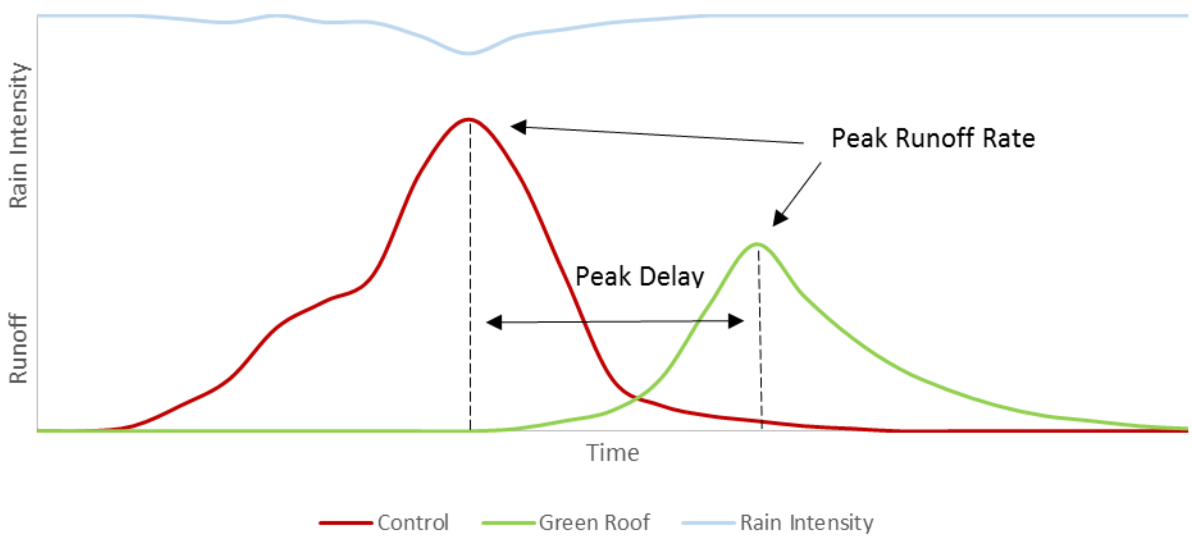

Figure 2.2: Example Storm Event Hydrograph

Total Runoff Retention

Total runoff retention is defined as the precipitation water depth compared to the runoff volume of the green roof normalized by the area of the plot.

$$Total\ Runoff\ Reduction = \frac{rainfall\ depth - runoff\ depth}{rainfall\ depth} \times 100\% \quad (2.1)$$

The runoff volume (V) is calculated by integrating the runoff rate (Q) over the time interval that runoff was measured (Carpenter et al., 2011).

$$V = \int_0^t Q(t)dt \quad (2.2)$$

Calculating the total runoff volume in our study was straightforward due to the constant 5 minute time interval using a discretized version of equation (2.2).

$$V = \sum_{i=1}^{n} Q_i t_i \quad (2.3)$$

Total runoff retention is the most common characteristic used to quantify GI performance. When precipitation falls on impervious areas such as conventional roofs, a high percentage (>90%)

is turned into runoff as only a fraction of water is retained by interception and evaporation. In contrast, green roofs can retain much of the precipitation through ET and storage in soil media. (Voyde et al., 2010; Stovin et al., 2012). Stormwater reduction has several benefits to both surrounding ecosystems and downstream property owners, including increased water quality, reduced flooding and erosion, and reduced water treatment volumes (Li and Babcock, 2014).

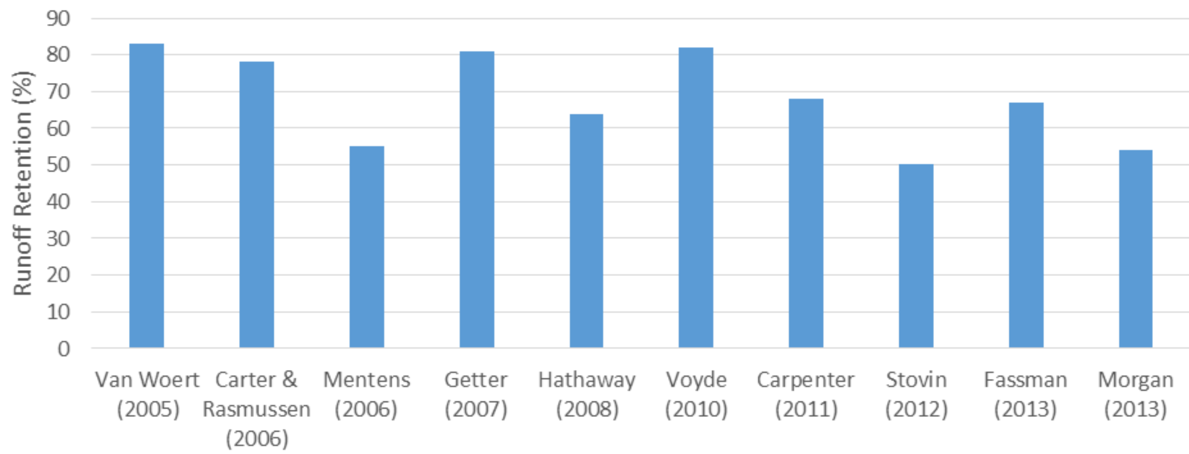

Figure 2.3: Total Runoff Retention from Literature

Total runoff retention values obtained from literature review prove green roofs can be a viable stormwater management tool (Figure 2.3). All of the reviewed studies showed a significant percentage of overall runoff retention ranging from 50% (Stovin et al., 2012) to 82% (Voyde et al., 2010). In a summary of German green roof studies from 1987 to 2003, Mentens et al., (2006) reported extensive green roof total runoff retention ranging from 27-81% of the total annual precipitation. Unfortunately, overall retention values based on individual storm or annual averages are inherently skewed higher as more numerous, smaller events have greater weight than infrequent, larger events. These figures are worsened by the fact that large storms are significantly more important for stormwater management purposes as they cause the majority of urban flooding issues and the associated detrimental effects. Therefore, analyzing individual storm events or classifications of storm events is often a better evaluation of hydrological benefits. For example, Carter and Rasmussen (2006) reported green roof runoff retention ranging from 39 to 100% for individual storm events. After classifying these storm events into categories based on total precipitation depth, these reports showed green roofs exhibited significantly less runoff retention in larger storms ($P > 7.62$ cm), 48% than their smaller ($P < 2.54$ cm) counterparts, which have 88% retention (Carter et al., 2006). In a similar study, Stovin et al. (2012) analyzed only significant storms, defined by a return period of over one year and observed runoff retention ranging from 0 to 100% for the 22 individual storms monitored. The average runoff retention of these more intense storm events was determined to be 30%, significantly less than the 50% retention calculated on a cumulative basis. Other studies mirrored the wide range of runoff retention experienced by individual storm events. Simmons et al. (2008), and DeNardo et al. (2005) reported individual storm runoff retention ranging from 16 – 88% and 19-98% respectively. All studies showed a correlation between the total rainfall and the volume of runoff retained. Smaller events showed the highest runoff volume retention and often absorbed all rainfall, while large events displayed a reduction in runoff retention.

Peak Runoff Rate Reduction and Delay

Along with total runoff retention, studies demonstrate that green roofs have the ability to reduce peak runoff rates and to delay the timing of peak flows compared to conventional roofs (Figure 2.4). The magnitude of the peak runoff rate or largest runoff rate exhibited on a storm event hydrograph is a critical factor in determining the potential benefits of green roofs and other GI on the urban water cycle. The peak runoff rate (PRR) reduction was calculated using an equation similar to total volume reduction.

$$Peak\ Runoff\ Rate\ Reduction = \frac{PRR\ control - PRR\ green\ roof}{PRR\ control} \times 100\% \quad (2.4)$$

Urban flooding and erosion commonly correspond to peak flows (Li and Babcock, 2014). Furthermore, stormwater infrastructure such as sewer systems is designed for peak flows so any mitigation can potentially reduce pipe sizing and the associated costs. Peak runoff rate reduction also relieves stress on water treatment facilities, which can reduce the size and frequency of CSOs (Alfredo et al., 2010). The timing of the peak runoff rate is also important as any delay compared to impervious areas acts to alleviate cumulative downstream peak flows (Li and Babcock 2014). Because this study provided distinct peak runoff rates and times for both control and test plots, the peak runoff rate delay was defined as

$$Peak\ Runoff\ Rate\ Delay\ = T_{peak}\ green\ roof - T_{peak}\ control \quad (2.5)$$

where T_{peak} is the time corresponding of the peak flow rate.

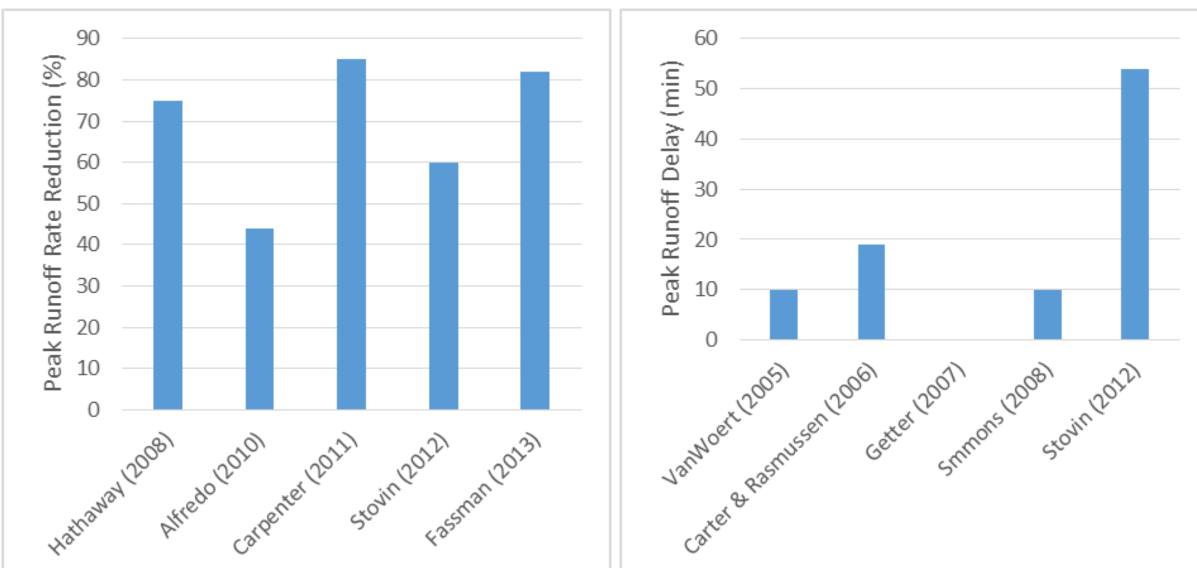

Figure 2.4:Literature Values-Peak Runoff Rate Reduction (L) & Peak Runoff Rate Delay (R)

Similar to total runoff retention, studies reviewed in literature have shown a wide range of peak runoff rate reductions (Figure 2.4) with average values ranging from 45% (Alfredo et al., 2010) to 85% (Carpenter et al., 2011). Furthermore, individual storm events within studies exhibited a greater variation of peak runoff rate attenuation. Stovin et al. (2012) and Carter and

Rasmussen (2006) reported peak runoff rate reductions ranging from 20% – 99.9% and 0 to 100% respectively. Likewise, literature review showed average peak runoff delays (Figure 2.4) ranging from 0 to 55 minutes (Getter et al., 2007; Stovin et al., 2012). Carter and Rasmussen reported that 57% of storm peak runoff rates were delayed between 0 and 10 minutes and an average delay of 17 minutes, which agrees well with the 10 minute delay stated by Simmons et al. (2008). In contrast, Getter et al. (2007) observed minimal peak runoff delay, where DeNardo et al. (2005) observed an average 2.0 hour delay in peak runoff rates.

Factors Influencing Hydrological Performance

The large variance of hydrological performance is likely due to two factors: first, the differences in green roof systems studied; and second, the random nature of rainfall events. As these studies encompass a wide variety of green roof types, with different soil depths, plants, and soil holding systems, hydrological performance will differ. Several studies designed to better understand how specific green roof characteristics influence performance have been completed in the past decade. In an analysis of 18 individual studies, Mentens et al. (2006) showed a correlation between both soil media depth and type and the total runoff retention. Extensive green roofs (average soil media depth 10 cm) displayed significantly less total runoff retention than deeper intensive green roofs (average media depth 15 cm), 45% and 75% respectively, while shallow gravel roofs showed only 25% retention (Mentens et al., 2006). Studies performed by Getter et al. (2007) and Villareal and Bengtsson (2005) investigated the influence of roof slope and found that total runoff retention and peak runoff rate reduction both decreased with increased slope. Vegetation type was also found to have an effect on green roof hydrological performance, albeit to a lesser extent than soil media depth and roof slope. Morgan et al. (2013) studied runoff retention in green roofs with varying amounts of plant cover and found that 25% coverage was required to raise retention compared to bare soil media alone. Plants act to absorb water through root systems and use this water via ET, which ultimately increases water capacity preceding rain events. Plant type and size can have a significant impact on ET rates. Ouldboukhitine et al. (2012) investigated the ET rates of grasses and sedums and compared results to bare soil media. Grasses were found to have significantly higher ET rates, which supports findings by Nagase and Dunnet (2012) in which total runoff retention from different plant types was compared. Nagase and Dunnet also used lab experiments to show that grasses exhibited greater runoff retention than both sedum and forbs (Nagase and Dunnet, 2012). While plant type does affect overall hydrologic performance, green roof vegetation is typical chosen for ease of maintenance. Therefore, drought resistant sedums are most common (Li and Babcock, 2014).

Most importantly, the unpredictable nature of storm events will dominate how any green roof system will respond, which creates a difficult problem when quantifying the potential benefits of green roofs to manage stormwater runoff (Morgan et al., 2013; Fassman-Beck et al., 2013; Li and Babcock, 2014). The advancement of green roof systems with the integration of storage basins obscures this problem. More studies need to be completed to not only monitor green roofs, but to also use data to develop accurate models which can predict hydrological performance in the wide range of conditions they experience.

Modeling

Over the past several years, a trend has evolved in green roof research which shows a distinct shift away from the simple quantification of green roof hydrological performance towards further development of accurate computer models which can predict responses to individual storm events. The methods used to simulate green roof hydrographs are diverse, ranging from standard software programs including SWMM, SWMS-2D, and HYDRUS to conceptual models created and calibrated by researchers for specific studies.

The widely used stormwater management model (SWMM) uses Soil Conservation Service (SCS) curve numbers (CN) to approximate the rainfall-runoff response of watersheds with empirical relationship

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (2.6)$$

where (P) is the storm precipitation depth, and (S) is the maximum storage depth defined by the following approximation.

$$S = \frac{CN}{1000} - 10 \quad (2.7)$$

Green roofs and other GI are modeled by estimating CN's or placing storage nodes to capture runoff. For example, Carter and Jackson (2007) calculated a CN number of 86 from a green roof test plot and assessed the benefits of potential green roof installations by applying this to all impervious roofs (nearly 30%) in a specific local water shed. They found green roofs can have a significant impact on the urban water cycle, especially for smaller events. In their simulation, Jackson and Carter (2007) calculated a 37% total runoff reduction for a 1 year event; however, this performance diminished for larger storm events. A study completed by Alfredo et al. (2010) calibrated SWMM models for green roofs of different depths using simulated precipitation. A storage node approach faired significantly better than calibration by varying CN values to match observed runoff. While the SWMM models did show hydrological benefits of green roofs as well as the rough approximations of total runoff retention and peak runoff rates, it also suggested that the simplicity of SWMM is insufficient for accurately predicting the rainfall-runoff relationship of individual green roof installations to complex storm events. However, the ubiquitous and simple nature of SWMM and the associated SCS model permits engineers and city planners to quickly assess the impacts of green roof installations to watersheds.

In contrast to the largely empirical SWMM, the U.S Salinity Lab's simulating water and solute movement software (SWMS-2) and PC-Progress' HYDRUS software models use Richards Law and Genuchten-Mualem relations to calculate saturated and unsaturated water flow in porous media, which in turn can be used to simulate green roof runoff hydrographs. Both SWMS-2D and HYDRUS use a water balance approach (EQ. (2.8)) to solve for water fluxes.

$$P - ET - RO - DP + CR \pm \Delta SF \pm \Delta SW = 0 \quad (2.8)$$

Precipitation (P) and meteorological data are used as inputs to calculate ET, runoff (RO) deep percolation (DP), capillary rise (CR), changes in subsurface flow (ΔSF), and changes in soil water content (ΔSW). Both of these models are more intricate and require more input variables and data, including geometry and soil properties, than their empirical counterparts. The complexity of SWMS-2D and HYDRUS has limited their use to mostly academic research, but the ability of these models to consider all relevant water balance interactions has yielded promising results in green roof modeling. Palla et al. (2009) monitored the runoff from a 170 m^2 intensive green roof and used data from 8 individual storm events to calibrate a SWMS-2D model with impressive results. Simulated hydrographs accurately depicted observed counterparts even for complex storm events with multiple runoff peaks. Moreover, model total runoff volumes and peak runoff rates were similar to observed values with maximum errors of 33% and -35% respectively cited for the 8 individual storm events modeled (Palla et al. 2009). Hilten et al. (2008) and Hakimdavar et al. (2014) both used HYDRUS 1-D software to mimic green roof runoff. In contrast to calibrating models with runoff data, both studies used measured or estimated model parameters from experiments or educated assumptions. For example, Hakimdavar et al. (2014) conducted lab experiments to calculate hydraulic conductivity and water retention curve parameters, but estimated 10% antecedent soil moisture content for modeling purposes. Similarly, Hilten et al (2008) also used 10% initial moisture content which was calculated as an average from observed data, and also assumed soil characteristics to be that of sand as it most closely matched the high water conductivity and low retention typical of green roof soil media. Simulated hydrographs likely suffered from these assumptions, but still provided reasonable estimates of green roof performance. Hakimdavar et al. reported that 17 of 38 storms were deemed acceptable using the Nash-Sutcliffe efficiency (NSE) index. Hilten et al. (2008) cited a 0.92 correlation when comparing total runoff volumes from observed and modeled storm events. After validation, Hilten et al. (2008) used simulated storm events to show how green roof hydrological performance decreased with increased precipitation depths.

Several reviewed studies created conceptual models unique to their specific research projects. Lamera et al. (2014) developed and calibrated a simplified bucket model which used few parameters but was still able to successfully reproduce green roof runoff hydrographs with great accuracy. All seven modeled storms displayed acceptable NSE values when compared to observed data, with maximum total runoff volume and peak runoff rate relative errors of -40% and -16% respectively (Lamera et al. ,2014). A MATLAB model was written using a conceptual water balance and a non-linear reservoir approach by Locatelli et al. (2014) and was then validated using data from 3 separate green roof sites. This model accurately predicted individual storm runoff hydrographs and was used to run long term simulations using 22 years of meteorological data to better estimate green roof performance in terms of total runoff retention. In a similar study, Kasmin et al. (2010) created a runoff storage/routing model with an associated ET module based on the Thornthwaite formula that allowed researchers to run long term simulations. ET lab experiments and data from a green roof test plot was used to calibrate this model, which effectively predicted restored water capacities in soil media during antecedent dry weather conditions (Kasmin et al., 2010; Stovin et al., 2012).

While a complete green roof model has yet to be developed, this literature review not only illustrates the evolution of green roof modeling from simple empirical models towards sophisticated computer programing and accurate conceptual models, but also displays the potential benefits which accurate simulations can have. Precise GI modeling will allow engineers to predict the impact of installations while also providing the ability to use simulations to optimize design and performance.

III. EXPERIMENT DESIGN

Plot Construction

Test plot construction was a critical element in creating a precise experiment. In order to collect accurate data and comparable results, the test plots required: 1) uniform plot shape and area; 2) collection of all rainfall that fell over the plot area; 3) conveyance of all runoff to a single outlet; and 4) similar slope and minimal ponding. Furthermore, the test plots needed to be raised approximately 0.5 m above the roof surface to allow space for the flow monitoring equipment.

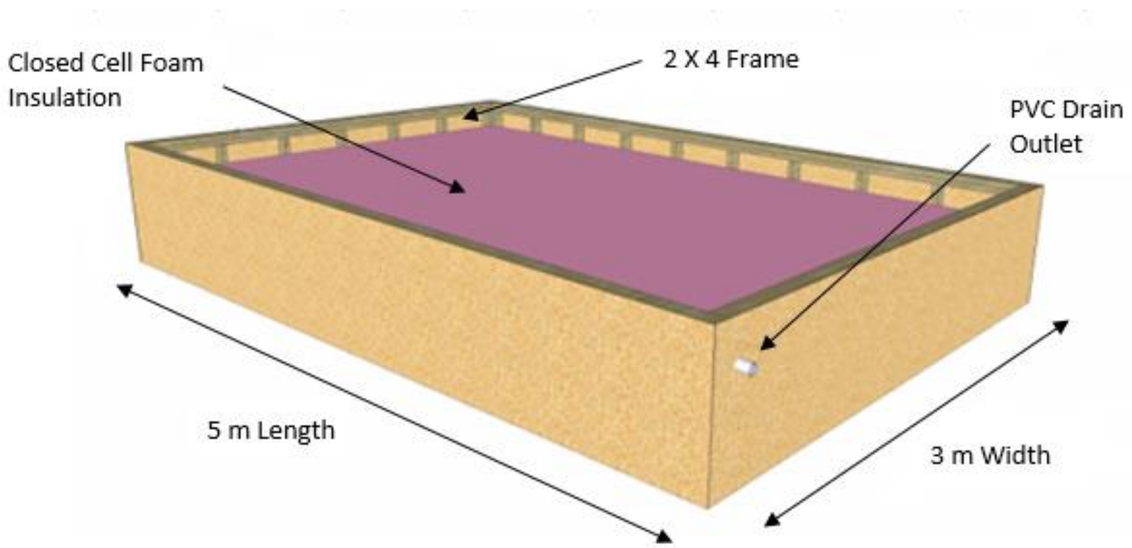

Figure 3.1: Plot Construction Diagram

These requirements were achieved by first constructing 2" x 4" wood frames to the determined 3 by 5 meter plot size (Figure 3.1 and 3.2). Rigid closed cell foam insulation was then used to raise the interior of the plot to the desired height. Plot slope and drainage were controlled by cutting and manipulating the foam insulation as needed. A 3 inch PVC drainage pipe and an ethylene propylene diene terpolymer (EDPM) roofing membrane were then professionally installed by Skyline of Milwaukee, a local roofing company. Following construction, all plots were tested for drainage and ponding using a simple water volume test. This test found that all plots were acceptably exhibiting greater than 98% return rates for 100 liter water volumes.

Figure 3.2: Control Plot Photograph

Weather Station

Accurately monitoring green roof performance requires dependable onsite meteorological data. Therefore, an ET 107 weather station manufactured by Campbell Scientific was installed at the experiment site. The ET 107 model measures precipitation, air temperature, humidity, wind speed, and direction. In addition, CS655 soil moisture and temperature sensors manufactured by Campbell Scientific were installed for each of the green roof test plots. Using Campbell Scientific's LoggerNet software, a program was written that collected and averaged all data over five minute time intervals which was then stored in the internal CR1000 data logger. A Python code was written which sent the meteorological data to a PHP database for analysis.

Figure 3.3: ET 107 Weather Station (left); Experiment Site (right)

Vegetal i.D. Green Roof Systems

All of the green roof systems tested in this project were manufactured by Vegetal i.D., the American branch of the French company Le Prieure which operates globally. Vegetal i.D. has been installing green roofs throughout the United States for over 20 years. Hydropack, an extensive modular green roof system designed and patented by Vegetal i.D. in 1993, now has over 5 million square feet of green roof installations worldwide (Vegetal i.D. 2015c). While Hydropack has proven to be successful as a stormwater management tool, Vegetal i.D. has continued to develop new green roof solutions. By incorporating Hydropack with a water reservoir (Hydrostock50) Vegetal i.D. created the Hydroactive Smart Roof system (HSR), which optimizes water storage capacity while minimizing weight (Vegetal i.D., 2015a). Hydropack and HSRP represent two green roof systems studied in this project. A third test system was created by attaching a control valve to the HSR system, thus creating the Hydroactive Smart Roof Active (HSRA). Currently, this valve is controlled by manual means. Decisions were made to drain water in the trays based on water depths and weather forecasting. Work is also being conducted to replace the manual valve with a control valve operated by microcontrollers, thus creating a “smart” green roof. We hypothesize that a "smart" green roof with the ability to react to weather forecasting and to control initial conditions will further optimize performance. This technology is in its infancy, and much work will still need to be conducted in order to troubleshoot problems as well as to assess potential benefits.

Product Description

In this study, three separate extensive green roof systems were tested: Hydropack, HSRP and HSRA. Hydropack is a modular tray system made of high density polyethylene with individual tray dimensions of 60 x 40 x 9 cm (L,W,H). All three systems use FLL-compliant growing media and vegetation designed for longevity. Drainage holes and a polyester filter membrane allow Hydropack to slowly drain rainwater without washing away growing media. Hydropack has a maximum water capacity of 28 mm, with dry and fully saturated weights of 56 and 85 Kg/m^2 respectively (Vegetal i.D., 2015b).

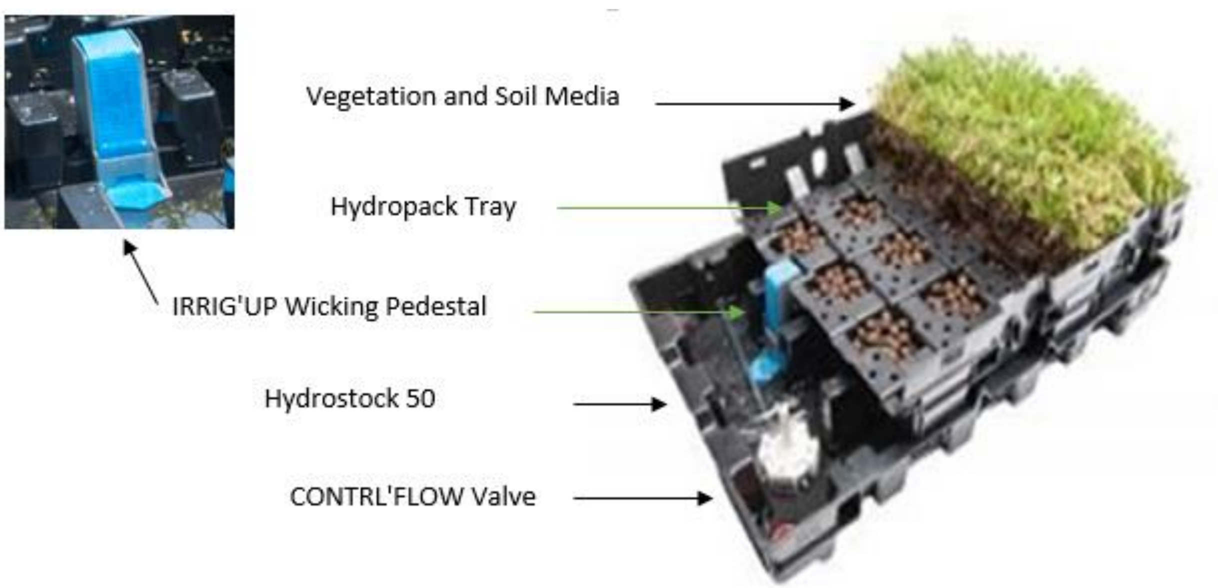

Figure 3.4. Hydropack and HSR Modular Green Roof Systems

The HSR system integrates Hydrostock50, a reservoir capable of storing an additional 85 mm of water with Hydropack. Additional features include IRRIG'UP, a sub-irrigation system that wicks water from the reservoir to the plants to increase ET, and CONTROL'FLOW, a flow control system designed to regulate flow rates out of each tray. HSR has a fully saturated weight of 150 Kg/m^2 (Vegetal i.D. 2015b).

Functionality

Both the HSRP and HSRA systems have similar functionality in how they respond to individual storm events. All rainfall is initially absorbed by the plants and soil media in the Hydropack tray. Once saturated, rainwater filters through the vegetation and soil media where it is captured by the Hydrostock50 reservoir. During dry conditions, water in the Hydrostock50 reservoir is pulled up into the soil media via the IRRIG'UP wicking pedestals, which allows plants to use water via ET. During more extreme rain events, water levels in the Hydrostock50 reservoir will rise to a point where water is drained by either the CONTROL'FLOW valve for the HSRP system or manually for the HSRA system (Vegetal i.D. 2015a).

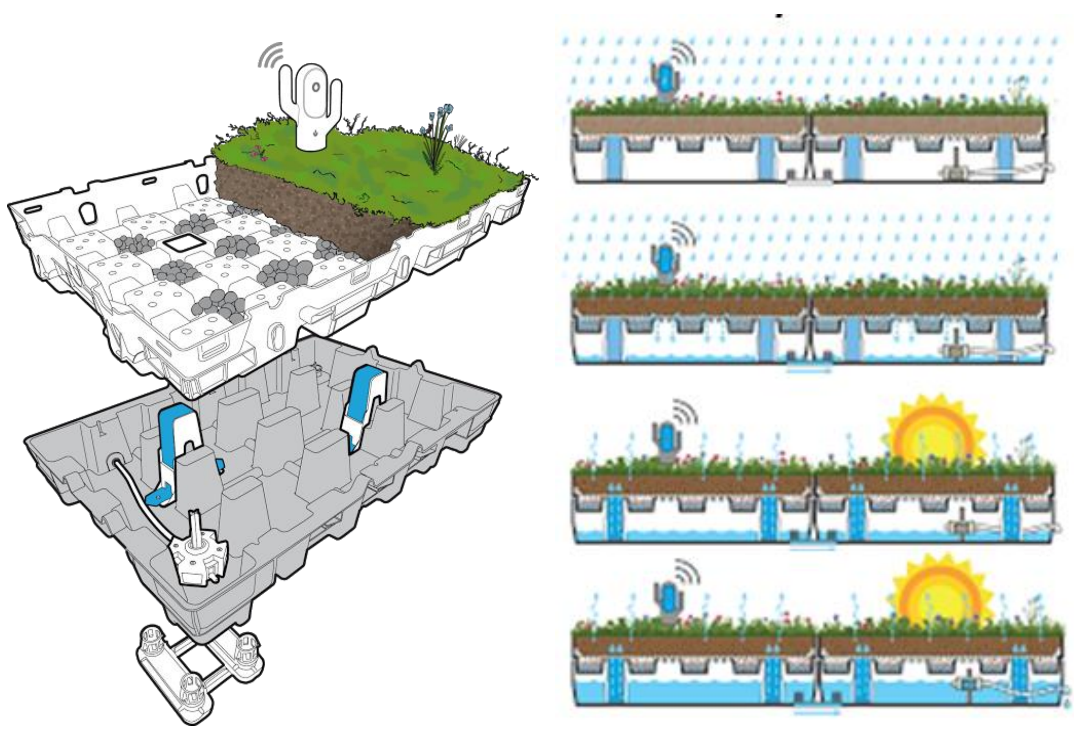

Figure 3.5: Diagram of HSR System (left); HSR Functionality (right)

IV. WEIRBOX FLOW MONITORING EQUIPMENT

Design

The second major obstacle of this project was the design and construction of the flow monitoring equipment, which was dubbed a “WeirBox”. Because green roofs experience a wide variety of runoff rates which range from dripping while draining to heavy flows during downpours, it is difficult to accurately measure stormwater runoff with a single device. We chose to build our own flow monitoring equipment after commercially available options were ruled infeasible based on target error tolerance and budget limitations.

The first step in the design process was to estimate the range of flows that the test plots would experience. The lower limit dripping flows were estimated to be in the order of several mL per minute. Maximum flow rates during extreme rain events were calculated using the rational method.

$$Q = CiA \quad (4.1)$$

A runoff coefficient (C) of 0.98 was selected due to its correspondence to a conventional roof and a rainfall intensity (i) from a 100 year storm with a 5 minute duration from the point rainfall intensity-duration frequency curve specific for Milwaukee provided by South Eastern Wisconsin Planning Regional Commission (SEWRPC) (Loucks, 2000). Substituting an area (A) of 15 m^2 yielded a maximum design flow rate of approximately 40 liters per minute.

In order to accurately measure the calculated range of flow rates, a combination of a tipping rain gauge and v-notch weir was used which is similar to that described in Palla et al. (2009). The tipping rain gauge selected was Model 6011 manufactured by All Weather Inc. To measure the water depths associated with the v-notch weir, an ultrasonic sensor Model 7569 manufactured by MaxBotix was chosen because of its external temperature and humidity compensation, and high resolution of 1 mm. A 7.5º v-notch weir was used, machined from 20 gauge stainless steel manufactured by C R Industries Inc. The 7.5º v-notch was chosen over larger, more traditional 30º and 45º sizes, as it acted to optimize resolution and ultimately increased accuracy.

Construction

The two sensors were housed in an acrylic box with dimensions 15 x 60 x 45 cm (Figure 4.1). Baffles were used to moderate water level irregularities caused by the tipping gauge. A diversion funnel (Figure 4.2) was designed with SolidWorks software and 3-D printed using Makerbot Industries' Replicator. The funnel was essential to the overall design as it acted to divert all the water from smaller flow rates into the tipping gauge while still allowing larger flows to bypass the tipping mechanism and enter the WeirBox.

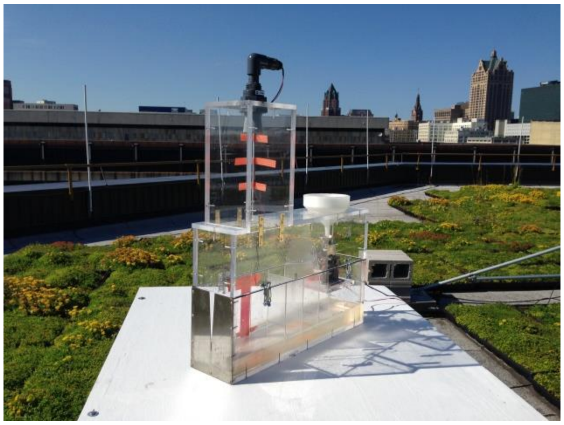

Figure 4.1: WeirBox Photo

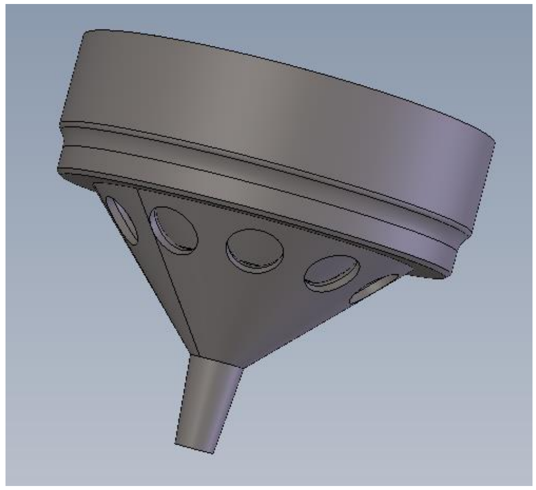

Figure 4.2: Diversion Funnel Design

Code

Arduino microcontrollers (Arduino Mega 2556) were used to process signals from the sensors and to perform associated calculations. A software program was written to measure the flow rate at one minute intervals and to average values over the five minute collection time. Programming code was written as a series of loops for both the tipping gauge and v-notch weir. The tipping gauge code counts the number of tips every minute and calculates a tipping gauge flow rate (Q_{tip}) by referencing a calibration curve for the corresponding tip volume.

$$Q_{tip} = Tip\ Count\ \times Tip\ Volume \quad (4.2)$$

The code for the v-notch weir is more complicated. Ultrasonic sensor signals were collected every 1.5 seconds and stored in an 11 number array. A mode filter was then applied to the array to reduce signal noise. Every minute, three mode filtered signal values were averaged (US_{ave}) and that value was used to calculate a water depth (H_w) by referencing a calibration curve which determined coefficients c_1 and c_2.

$$H_w = c_1 US_{ave} + c_2 \quad (4.3)$$

Subsequently, the water depth was used to calculate the v-notch weir flow rate (Q_{weir}) with the equation

$$Qweir = w_1 H_w^3 + w_2 H_w^2 + w_3 H_w + w_4 \quad (4.4)$$

where w_1,w_2 ,w_3 and $w_4$are coefficients derived from calibration.

In order to calculate the overall flow rate (Q) over the 5 minute interval, a master loop was created that selected the relevant flow rates (Q_{tip} or Q_{weir}) every minute using the water level for decision criteria.

$$If \;\; H_w < \; H_c \; then \; Q = \; Q_{tip} \quad (4.5)$$

$$If \;\; H_w \; \geq \; H_c \; then \; Q = Q_{weir}$$

The critical depth (H_c) was defined as the depth just before the tipping gauge mechanism reached its specific maximum calibrated flow rate. A separate program was written using Python script which collected all the data from the Arduino microcontrollers and posted values onto a PHP database for storage and analysis.

Calibration

All Weather Inc. cites a volume of 8.6 mL per tip for the model 6011 tipping gauge, but because of our specific application, flow rates higher than the tipping gauge's intended use were processed. This resulted in significant spillage and under-estimation of flow rates calculated using the cited tip volume alone. Therefore, the tipping gauge mechanism needed to be calibrated for our specific application. The tipping gauge was calibrated to a maximum flow rate of approximately 1.5 L/min by collecting data from known flow rates measured via graduated cylinders and stop watches similar to the method described in (Zhao et al., 2001). A calibration curve was created by plotting the tip count per minute versus the corrected tip volume calculated from the known flow rates (Figure 4.3). The software program referenced this curve to effectively calculate the flow rate from the tipping gauge.

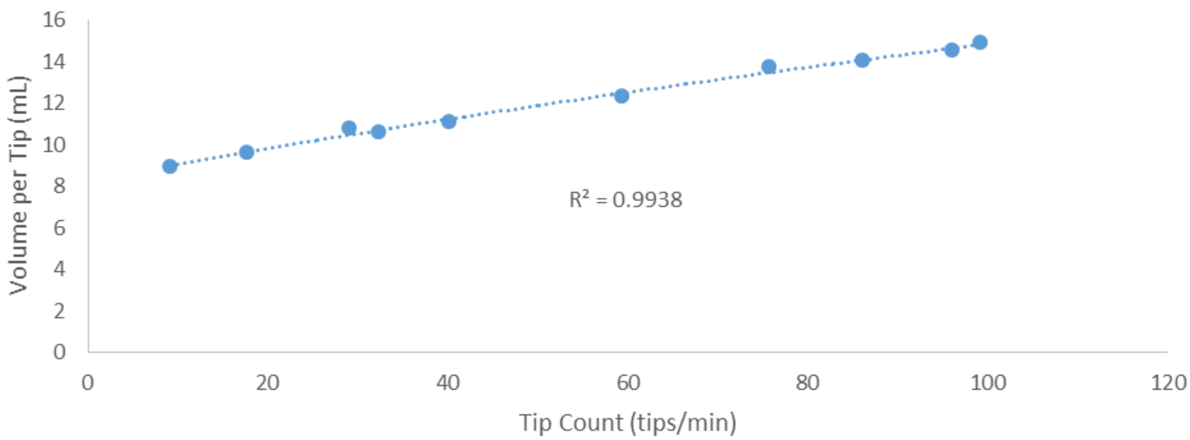

Figure 4.3: Tipping Gauge Calibration Curve

A 7.5º v-notch weir was used to measure larger flow rates greater than 1.5 L/min. The calibration of the v-notch weir was done by measuring the water level depths associated with known flow rates measured with graduated cylinders and a stop watch. Curves were then created for ultrasonic signals versus observed water depth (Figure 4.4) and water depth versus flow rates (Figure 4.5). The software program referenced these calibration curves to first convert the ultrasonic signal into a water depth and to then calculate a flow rate from that water depth.

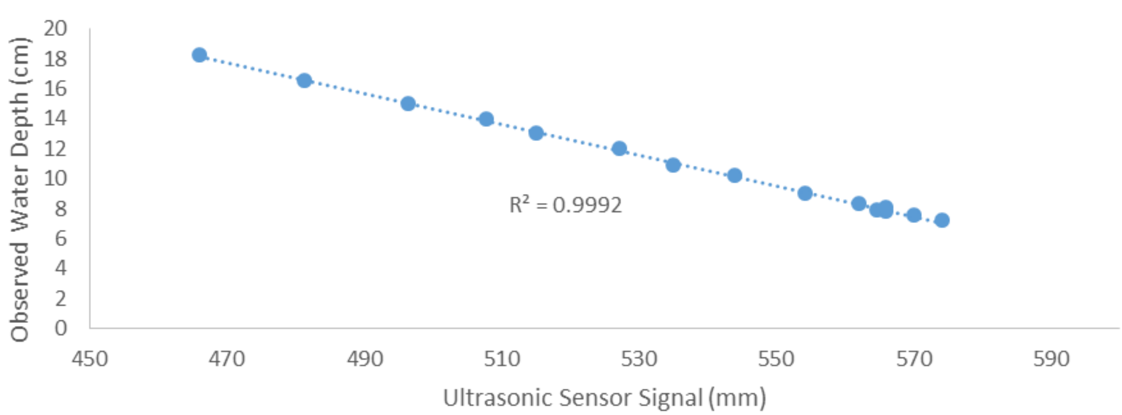

Figure 4.4: Ultrasonic Sensor Calibration Curve

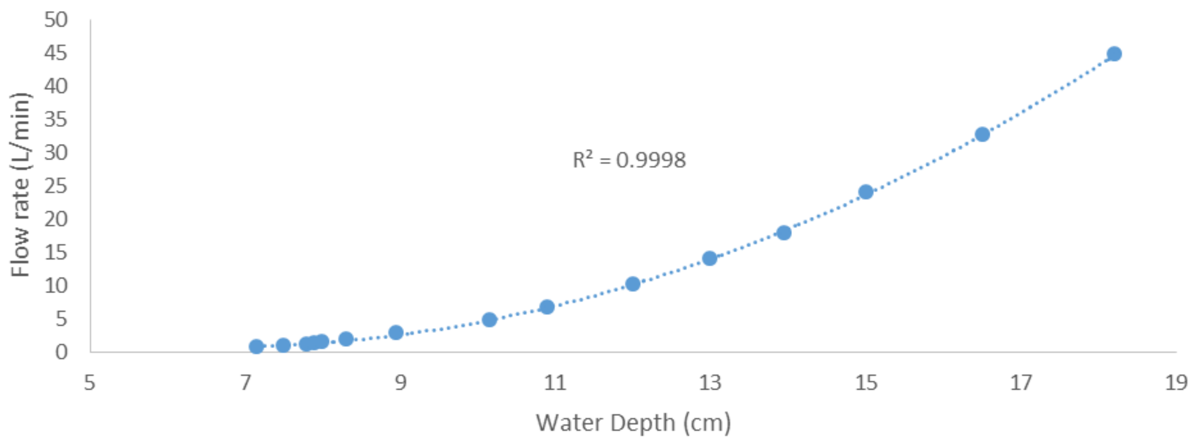

Figure 4.5: V-notch Weir Calibration Curve

Each of the four WeirBoxes were calibrated independently. High R^2 values of over 0.99 for all of the calibration curves led to precise flow rate measurements, with error rates typically less than 7%. The tipping gauge calibration curve was best characterized using a 2^{nd} order polynomial. A linear relationship was found between the ultrasonic signal and water depth, parallel to that reported by the manufacturer. The v-notch weir calibration curve was best described as a 3^{rd} order polynomial and was similar to curves calculated using the Kindsvator-Shen weir equation (EQ (4.6)).

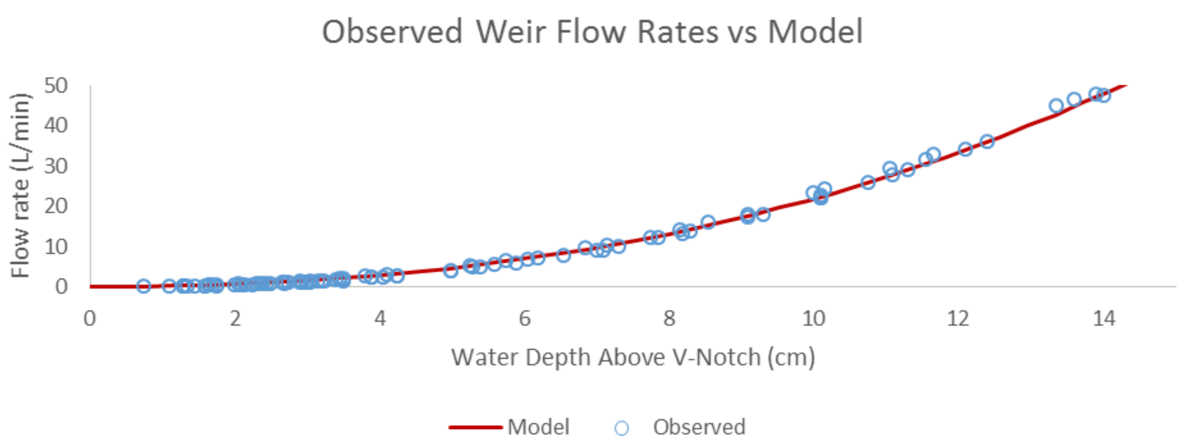

Figure 4.6: Kindsvator-Shen Model and Collected Data Comparison

$$Q = 0.121 C_e \tan\left(\frac{\theta}{2}\right) H_{le}^{2.5} \quad (4.6)$$

Figure (4.6) plots weir flow rate data for the four calibrated WeirBoxes (blue circles) and modeled flow rate (red line) using the Kindsvator-Shen equation.

Installation

After calibration in the lab and exhaustive testing to ensure accuracy, the WeirBoxes were installed at the experiment site on the roof of the MMSD headquarters. Leveling platforms were built to level each individual WeirBox. After observing initial incorrect water depth measurements, it was found that sunlight was having a significant effect on the accuracy of the external ultrasonic temperature sensor. To repair this issue, a wooden box cover was installed over each WeirBox with the purpose of blocking direct sunlight and protecting the face of the weir from possible interferences of rain and wind. After applying this solution, the WeirBoxes performed similarly to controlled laboratory conditions, specifically with water depth values within +/- 2 mm of observed values.

After installation, error analysis was performed on each individual WeirBox. Error testing was conducted over the entire flow rate range by comparing known values to those provided from the Arduino program. The maximum errors associated with the tipping gauge and v-notch weir error were less than 10 and 15% respectively.

V. RESULTS

Milwaukee Weather

Milwaukee weather observed for the 2015 year has been largely normal (Figure 5.1), with slightly dryer than average conditions (U.S. Climate Data, 2015). As of October, Milwaukee is experiencing a 13 mm precipitation deficit, resulting in part from a dry winter.

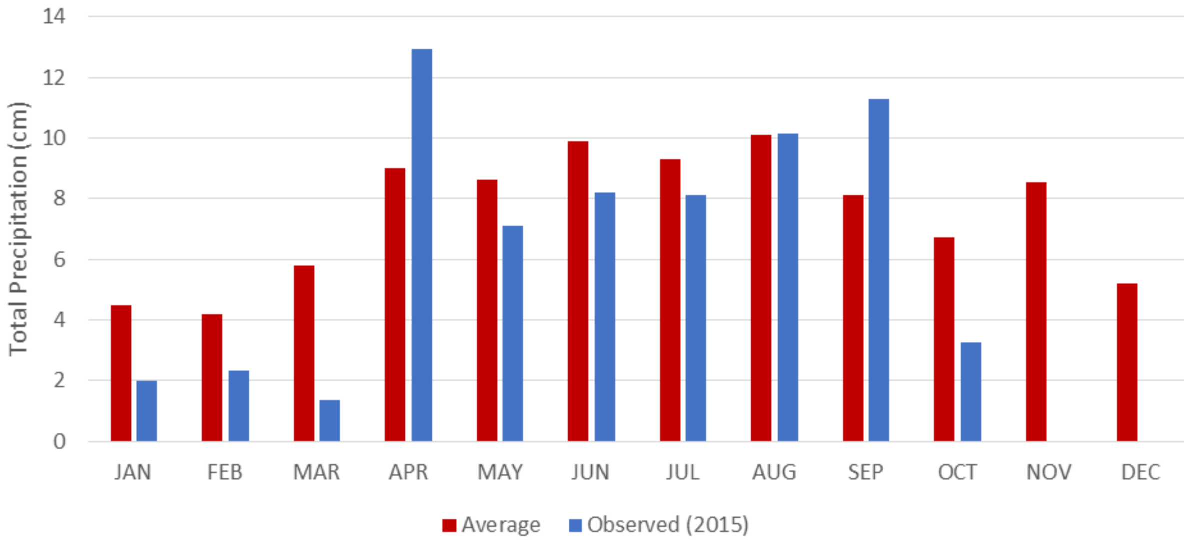

Figure 5.1: Milwaukee Monthly Precipitation

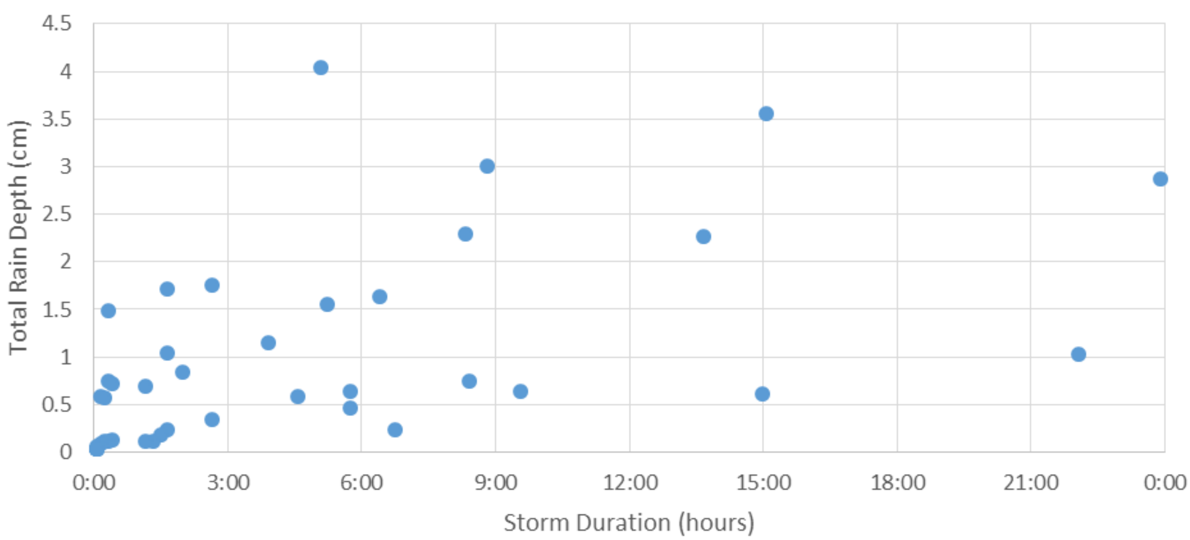

Figure 5.2: 2015 Observed Storm Events

Since monitoring began in mid-April, 54 individual storm events were observed (Figure 5.2) having total rain depths ranging from 0.0254 cm (1/100th inch) to 4.04 cm (1.6 inch). All storm events were typical for Wisconsin's yearly weather patterns with the lone exception being August 10th, which was the largest storm captured this year. The August 10th event had a peak 15 minute rain intensity of slightly over 10 cm/hr (4inch/hr), corresponding to a storm with a 5 year return period.

Individual Storm Hydrographs

Eight individual storm hydrographs are presented on the following pages to demonstrate the wide range of hydrological responses experienced by the green roof plots (Figures 5.3-5.10). Predictable storm properties, including total rain depth, peak rainfall intensity, and the individual storm hyetograph, determined the observed runoff rates.

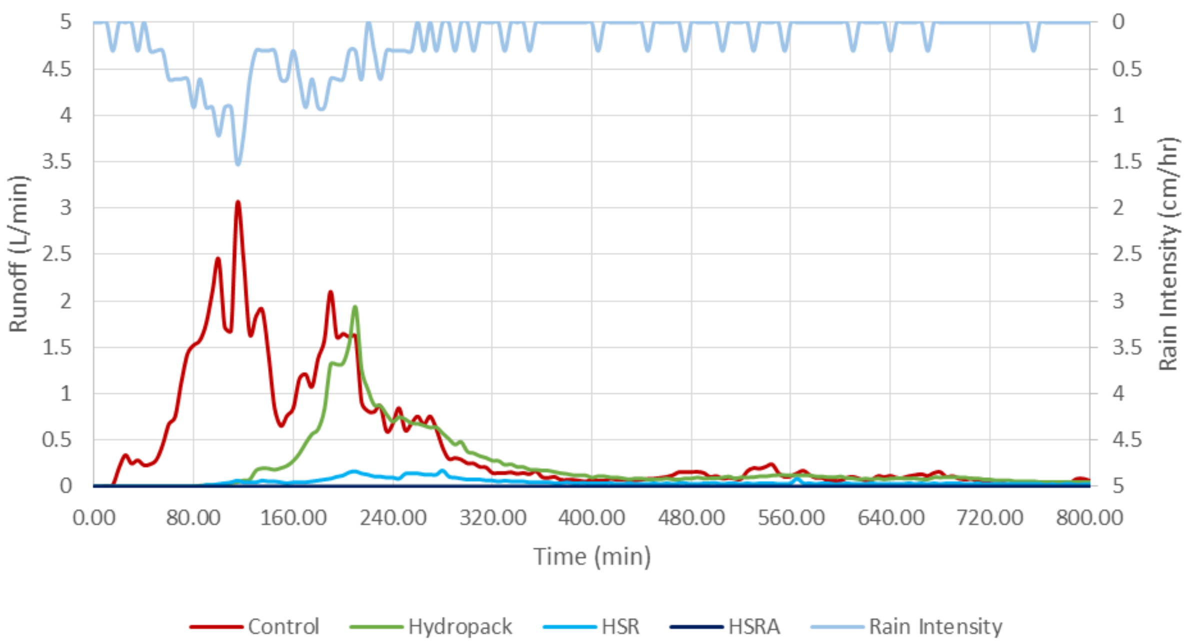

Figure 5.3: 4/19/15 Storm Event Milwaukee, WI

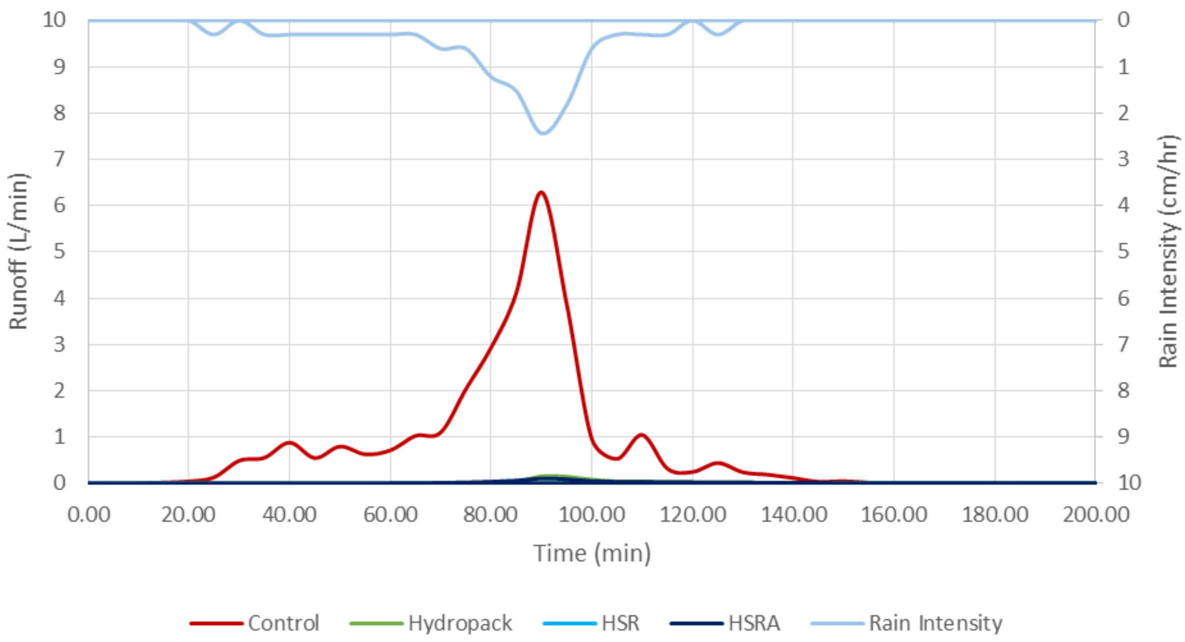

Figure 5.4: 5/26/15 Storm Event Milwaukee, WI

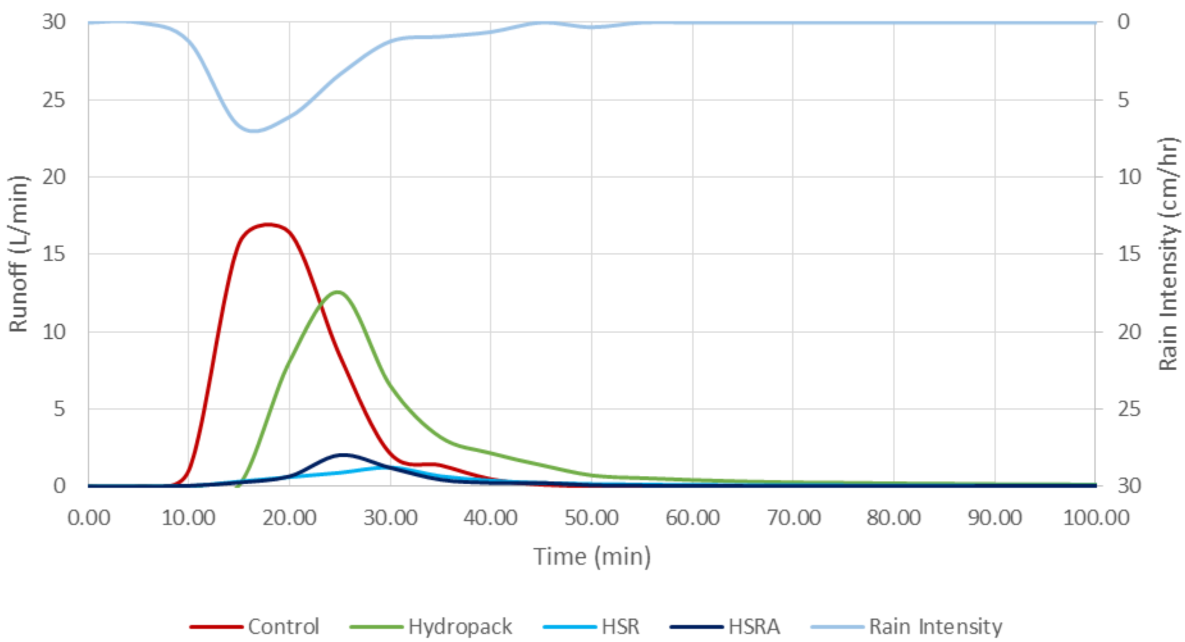

Figure 5.5: 7/18/15 Storm Event Milwaukee, WI

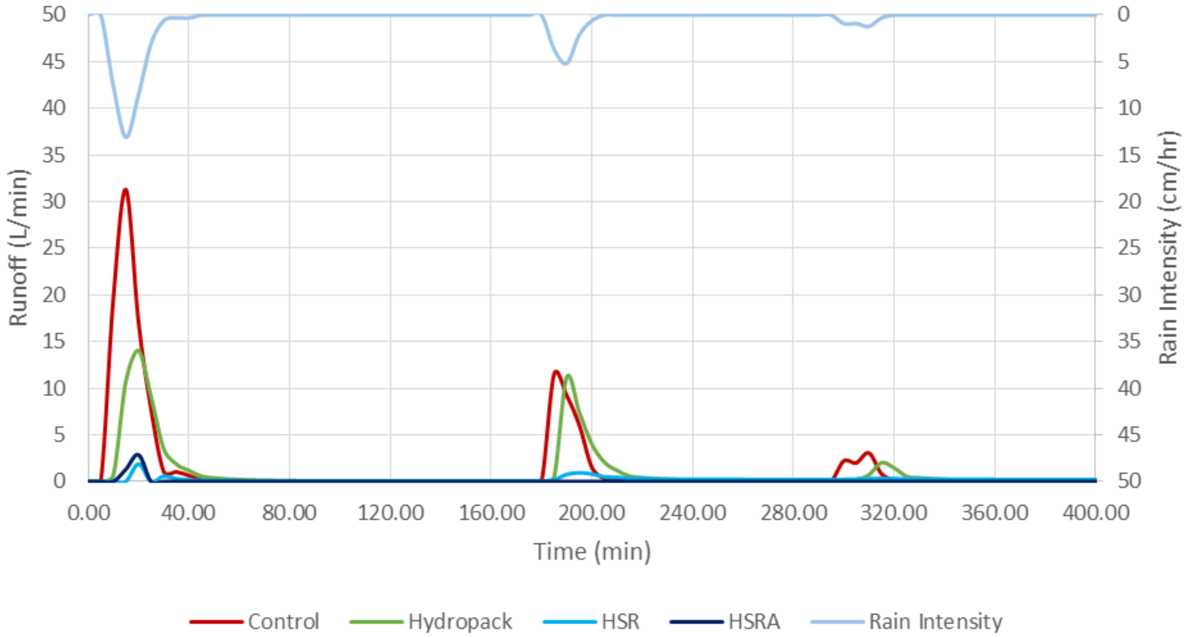

Figure 5.6: 8/10/15 Storm Event Milwaukee, WI

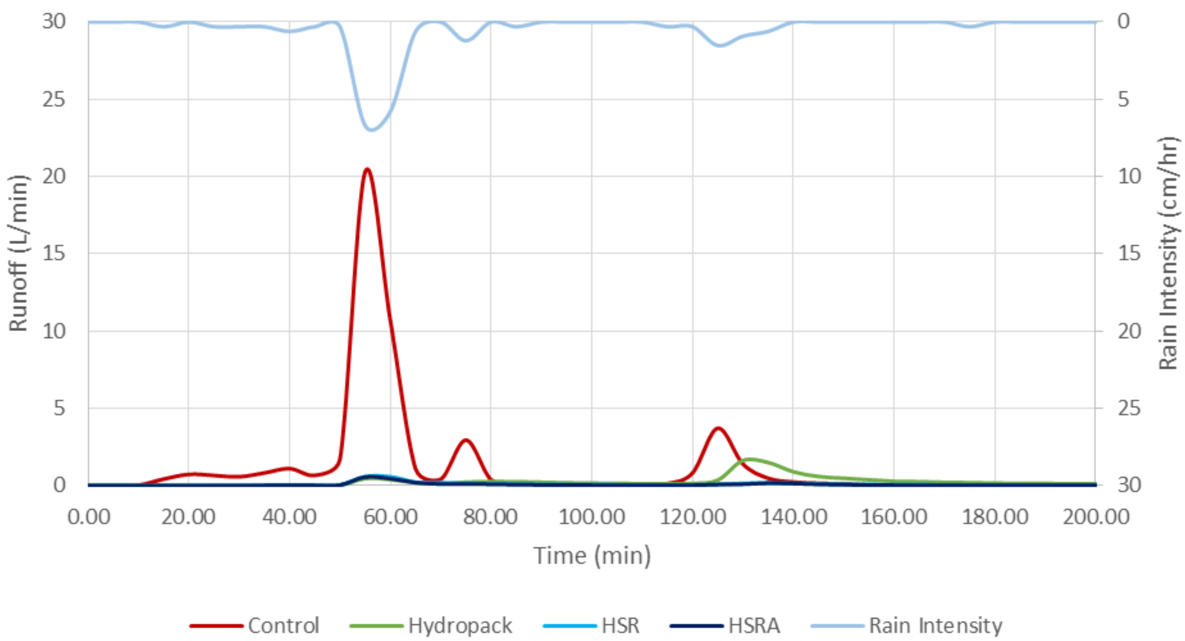

Figure 5.7: 8/18/15 Storm Event Milwaukee, WI

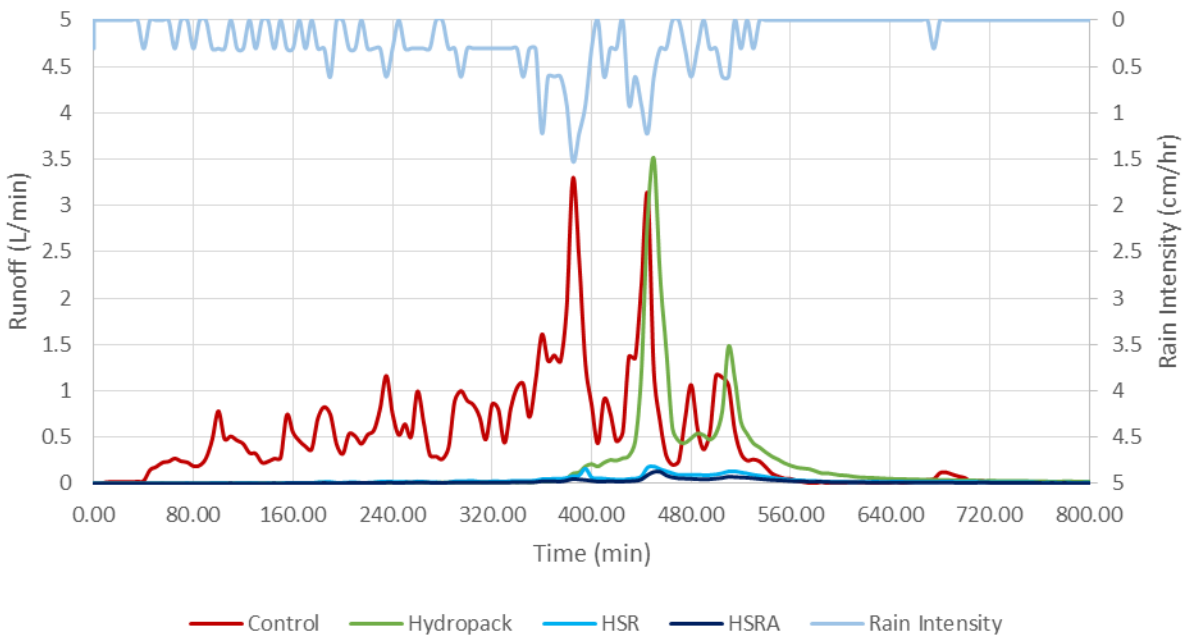

Figure 5.8: 8/28/15 Storm Event Milwaukee, WI

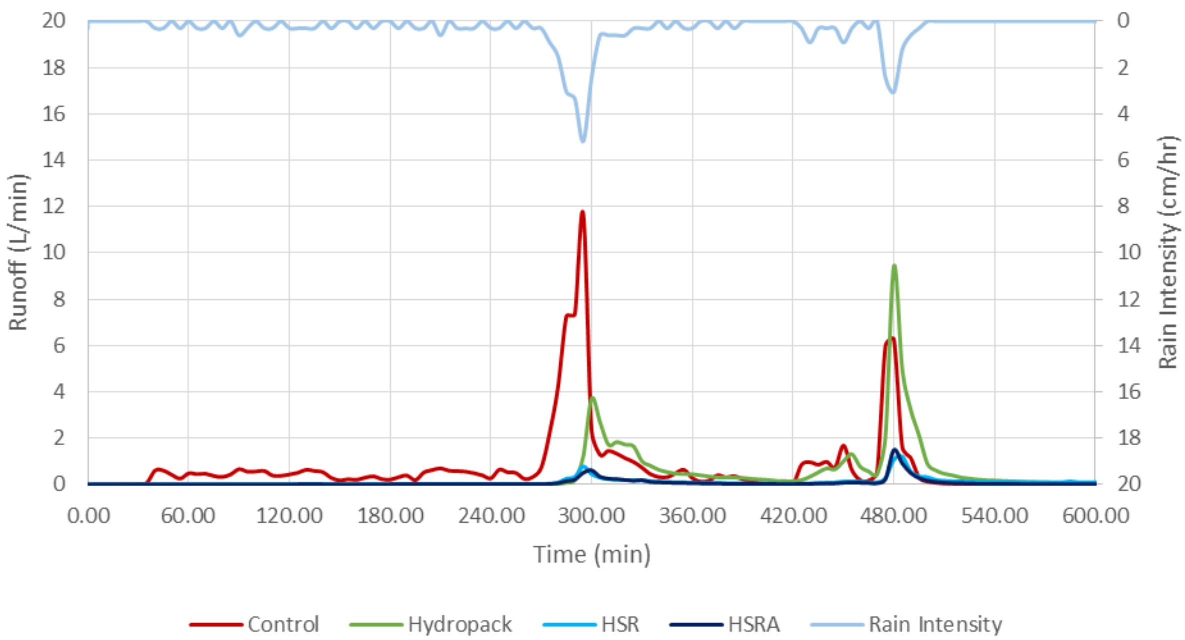

Figure 5.9: 9/18/15 Storm Event Milwaukee, WI

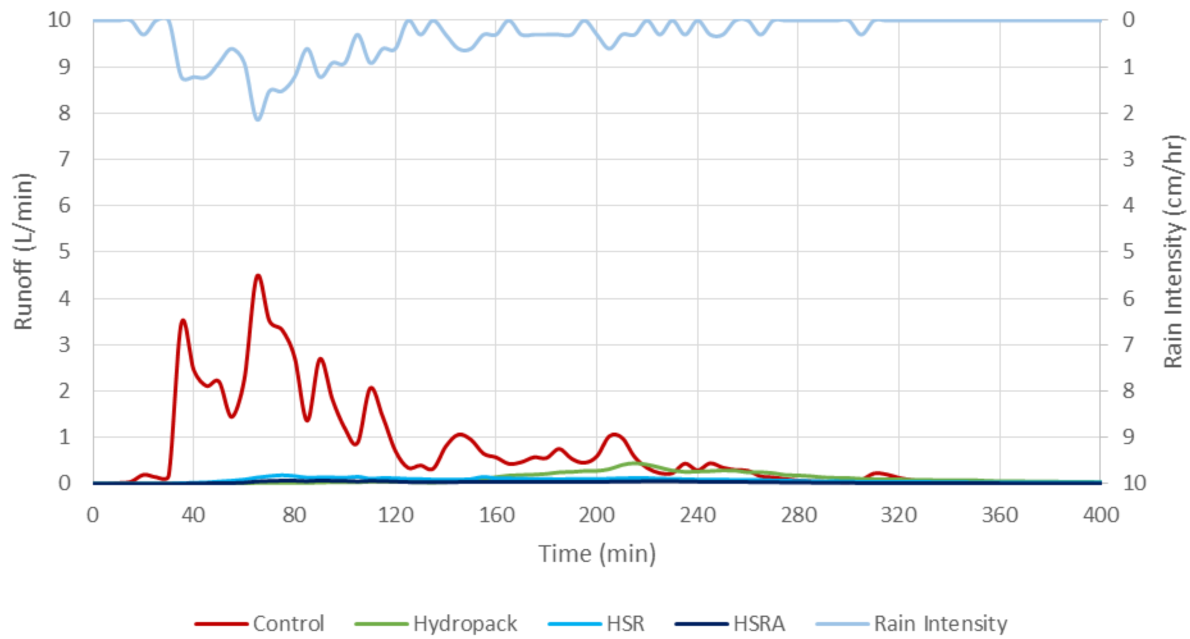

Figure 5.10: 9/29/15 Storm Event Milwaukee, WI

Seven of the storms displayed had a total rain depth of over 1.5 cm, as smaller storms typically showed negligible runoff for the green roof systems and essentially absorbed all precipitation. The 5/26/15 event (Figure 5.4) with a total rain depth of 1.04 cm is an example of this, having total runoff retention of over 97% for both the Hydropack and HSRA plots. In storm events with slightly larger rainfall totals (1.5 – 2.5 cm), the Hydropack green roof system began to develop a significant runoff response which can be viewed in the 8/18/15 (Figure 5.7) and 8/28/15 (Figure 5.8) storm events. In large storm events (greater than 2.5 cm) the Hydropack green roof system became completely saturated, displaying runoff characteristics similar to the control plot after reaching water capacity. The 4/19/15, 8/28/15, and 9/18/15 storm events (Figures 5.3, 5.8, and 5.9) are examples of this phenomenon, displaying total volume retention of 48.3%, 63.4% and 40.3% respectively. The peak runoff rate reduction was similarly reduced in these storm events (36.6%, -6.6%, 19.3%).

Storm Event	*Total Rain Depth (cm)*	*Hydropack*	*HSR*	*HSRA*
4/19/2015	2.59	48.3	85.1	- - -
5/25/2015	1.04	97.0	- - -	97.8
7/18/2015	1.70	14.0	75.0	86.4
8/10/2015	4.04	30.7	79.9	96.4
8/18/2015	1.75	75.3	92.3	94.2
8/28/2015	2.87	63.4	88.8	96.2
9/18/2015	3.66	40.3	83.4	90.5
9/29/2015	2.21	82.4	83.0	95.6

Table 5.1: Total Runoff Retention (%)

The initial water content of the soil media also strongly affected the runoff rates of the Hydropack green roof system. While the 7/18/15 storm event was relatively small (total rain depth 1.7 cm), the Hydropack system essentially displayed no hydrological benefits, resulting in the retention of only 14% of the runoff volume and reducing the peak runoff rate by 23.5%. This can be explained by the three smaller events that occurred earlier in the week and saturated the soil media prior to the start of the 7/18/15 storm event.

In contrast to the Hydropack green roof system, the HSRP and HSRA systems exhibited impressive hydrological benefits in all of the storms observed to date. In the storms displayed, total runoff retention ranged from 75-92% and 90.5 -97.8% for the HSRP and HSRA systems respectively. Similarly, the peak runoff rate reduction was greatly mitigated, ranging from 89.7-97.1% for the HSRP system and 86.4-97.8% for the HSRA system. The differences in hydrological performance can best be observed in the large 8/10/15 storm event. During the initial downpour, the Hydropack system quickly reached rainfall capacity and displayed negligible hydrological benefits thereafter. Alternatively, both HSR systems having larger rainfall capacities were able to absorb much of the runoff and greatly reduce the peak runoff rates.

The ability of the three green roof systems to delay the peak runoff rate was difficult to observe and quantify. Values for individual storm events ranged widely for all three systems from 0 to over 3 hours and were determined by the individual storm hyetograph. Typically larger, long duration storms with relatively low rainfall intensities experienced longer runoff rate delays (4/19/15, 8/28/15, and 9/29/15 storm events). In contrast, storms with high rainfall intensities over 5 cm/hr displayed little or no peak runoff rate delay (7/18/15, and 8/10/15 storm events). This is likely caused by significant overland flow which primarily occurs during heavy downpours where rainfall is instantly discharged to the outlet instead of being absorbed and filtered through soil media. Moreover, it must be noted that in some storms (8/18/15, 8/28/15, 9/29/15) the HSR systems displayed insignificant peak runoff rates (less than 5% of the control) and therefore the resulting peak runoff rate delays could likely be ignored.

Storm Event	*Peak Storm Intensity (cm/hr)*	*Hydropack*	*HSRP*	*HSRA*
4/19/2015	1.5	36.6	94.3	- - -
5/25/2015	2.4	97.6	- - -	98.3
7/18/2015	6.7	23.5	92.5	87.6
8/10/2015	13.1	55.1	94.0	90.8
8/18/2015	6.7	92.0	97.1	97.3
8/28/2015	1.5	-6.6	94.4	96.2
9/18/2015	5.2	19.3	89.7	87.2
9/29/2015	2.1	90.0	95.9	98.4

Table 5.2: Peak Runoff Rate Reduction (%)

Storm Event	*Hydropack*	*HSRP*	*HSRA*
4/19/2015	1:35	2:45	- - -
5/25/2015	0	- - -	0
7/18/2015	0:05	0:10	0:05
8/10/2015	0:05	0:05	0:05
8/18/2015	1:15	0	0
8/28/2015	1:05	1:05	1:00
9/18/2015	3:05	3:10	3:05
9/29/2015	2:30	0:10	0:25

Table 5.3: Peak Runoff Rate Delay (hr:min)

Overall Runoff Retention

Total runoff retention was calculated by the summation of runoff from all successfully monitored storm events and then by comparing runoff volumes to the calculated possible runoff from on-site precipitation data. All three of the test green roof systems displayed significant total runoff retention. As expected, the Hydropack system, which has the smallest water storage capacity, displayed the lowest water retention at 64% of the total rainfall. The HSRP and HSRA systems with larger rainfall capacities exhibited improved performance, having total runoff retention of 87% and 91% respectively.

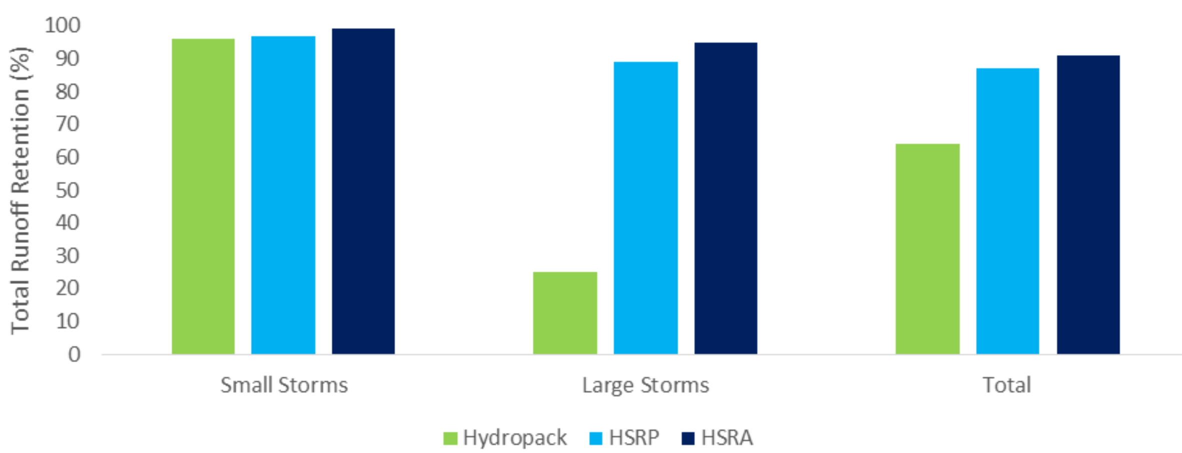

Figure 5.11: Total Runoff Retention

Hydrological Performance of Individual Storm Events

The overall runoff retention numbers are misleading as the green roof systems typically absorbed all water during small storm events (less than 1.5 cm) but had diminished water retention during larger storm events (Figure 5.12). However, the HSRP and HSRA systems did show significant improvement compared to the Hydropack system. Specifically, both HSR systems retained over 75% of runoff during all storms with the lone exception being HSRP, where a small storm occurred after a larger rain event and the green roof plots were still draining from the previous event.

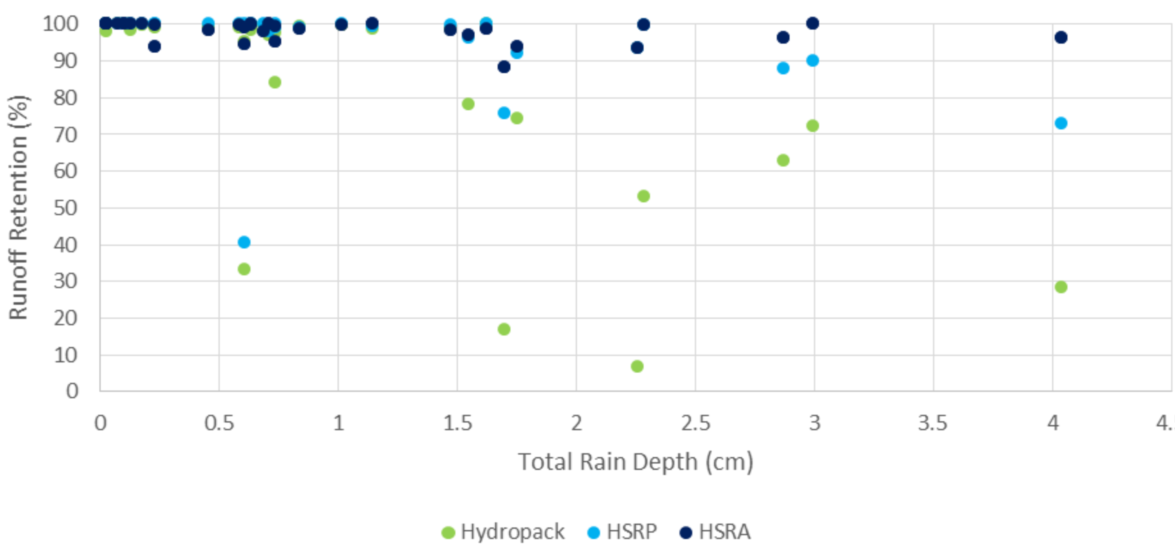

Figure 5.12: Individual Storm Runoff Retention

Similar to total runoff retention, peak runoff rate reduction varies significantly with individual storm events, and hydrological benefits are skewed for small events where runoff is minimal (Figure 5.13). After reaching saturation (~1.5 cm total rain depth) the Hydropack system displayed marginal peak runoff rate reductions ranging from -6 to 55%. In contrast, both the HSR systems exhibited impressive peak runoff rate reductions typically higher than 85%. Moreover, like total runoff retention, peak runoff retention was dominated by the individual storm hyetograph. Short, intense storm events generally exhibited higher peak runoff reductions than their longer, less intense counterparts. For example, the 5 year return period storm which occurred on 8/10/15 corresponds to a 55% peak runoff rate reduction for the Hydropack system, where the longer, more moderate 8/28/15 storm displayed a higher peak runoff rate than the control plot.

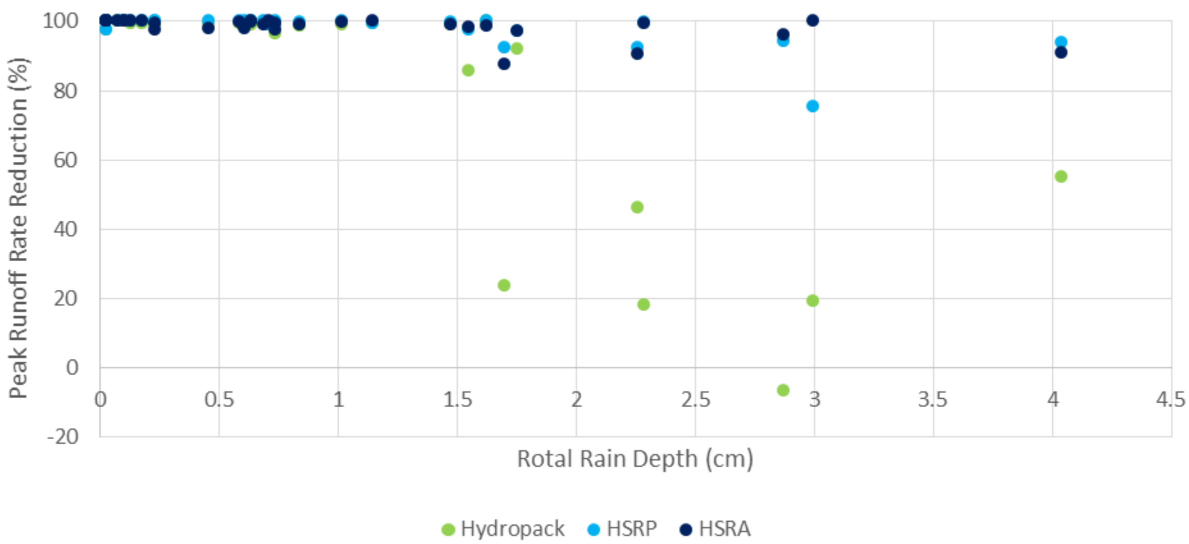

Figure 5.13: Individual Storm Peak Runoff Rate Reduction

Summary of Results

The hydrological performance of the Hydropack green roof system mirrored findings from previous studies in terms of total runoff retention, peak runoff rate reduction, and peak runoff rate delay. Total runoff retention for Hydropack (64%) falls within the range determined by Stovin et al. (2012) to be 50%, and by Voyde et al. (2010) to be 82%. The Hydropack system also exhibited the wide range of hydrological performance from individual storm events described in the literature review (Carter and Rasmussen, 2006; Stovin et al., 2012; Lamera et al., 2014). While both the HSRP and HSRA systems displayed similar variance in hydrological response to individual storms, the performance of these systems was significantly better than the Hydropack system, with total runoff retention of 87% and 91% respectively. This suggests that extensive green roof systems with added water reservoirs can optimize performance.

VI. MODELING

Conceptual Bucket Model

A conceptual model was built in an effort to recreate the hydrological response of the tested green roof systems. This simple model incorporated all significant runoff occurring from different sources in both the Hydropack and HSR systems. Similar to Kasmin et al. (2010) and Lamera et al. (2014), a 1-D bucket model was created in Microsoft Excel with linear reservoir drainage. Utilizing 1-D geometry, all inputs and calculations are in terms of length with units of mm. This model assumes that the green roof acts like a leaking container (Figure 6.1). Precipitation fills up the container, which will only start draining once the water level reaches the level of the leak. Once at capacity, all precipitation becomes runoff.

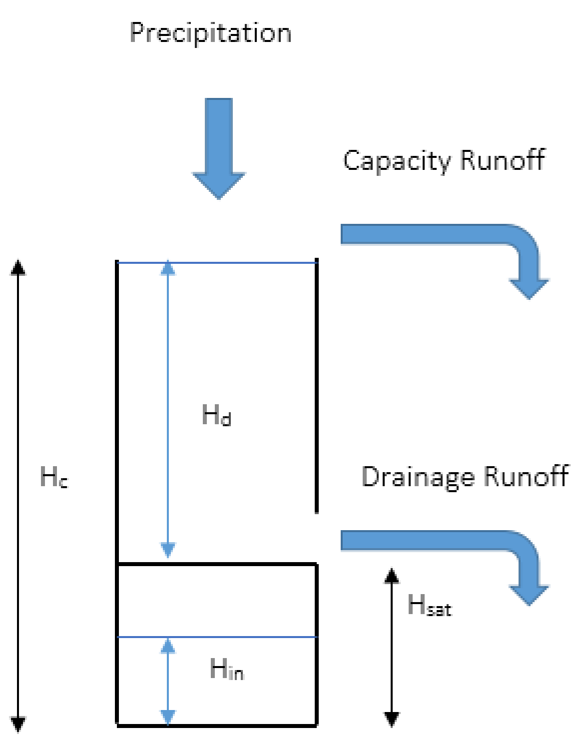

Figure 6.1 Conceptual Bucket Model Diagram

Figure 6.2 displays the flow chart of the model and the routing of the resulting runoff for both the Hydropack and HSR systems.

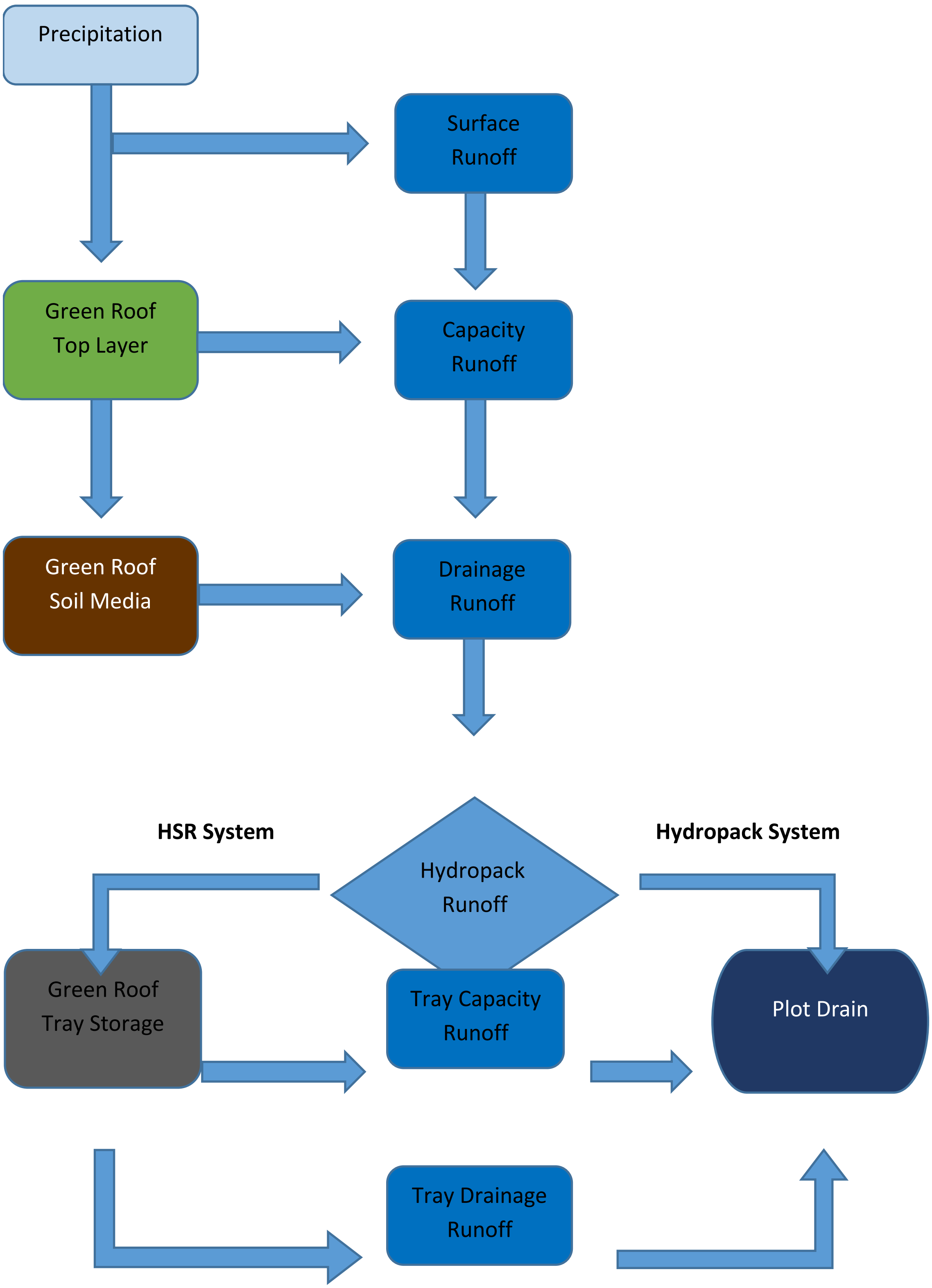

Figure 6.2 Conceptual Model Flow Chart

Model Assumptions

The actual processes involved in green roof runoff are highly complex and include ET, infiltration, drainage, storage, and overland flow, all of which depend on a myriad of factors. While engineers have previously modeled each of these individual aspects accurately, attempting to include all of these factors with even rudimentary mathematics would be challenging and time consuming.

While the simple bucket model oversimplifies the processes governing green roof runoff, several of the assumptions made have sound logic and will therefore produce an accurate overall model. For example, soil and plant interactions are disregarded entirely, and instead are modeled in terms of water capacity and reservoir drainage. However, because of relatively long time intervals of 5 minutes as well as the fact that green roof soil media is characterized by high porosity and hydraulic conductivity, these assumptions prove to be valid. Likewise, ET can be neglected, as ET rates during the storm event and subsequent drainage are negligible when compared to overall precipitation. Further, the model's 1-D geometry dictates that there can be no overland flow, but the small plot size studied, as well as the 5 minute time interval, diminishes the effects it has on modeled runoff rates.

Conceptual Model Mathematics

The Hydropack system was modeled first as it was used to generate the input needed for the HSR system. The Hydropack model applies a mass balance approach (EQ (6.1)) where precipitation (P) is the input hyetograph and surface runoff ($RO_{Surface}$), capacity runoff ($RO_{Capacity}$), drainage runoff ($RO_{Drainage}$), and change in storage (ΔH) are calculated for each time interval.

$$P - RO_{Surface} - RO_{Capacity} - RO_{Drainage} = \Delta H \quad (6.1)$$

It was observed that heavy downpours almost always caused runoff regardless of the capacity of the green roof system, and therefore a surface runoff was calculated as

$$If\ P\ >\ P_{critical}\ then\ RO_{Surface} = P - P_{critical} \quad (6.2)$$

where ($P_{critical}$) is the critical precipitation depth, which was determined to be approximately 5 mm. Any precipitation which was not transformed into surface runoff but still entered the container with a water depth (H) was calculated as

$$H = P_{in} + H_{in} \quad (6.3)$$

where (P_{in}) is the precipitation that entered the container and (H_{in}) is the water depth from the previous time interval. Once at capacity, all additional precipitation will become runoff. Capacity runoff was calculated as

$$If\ H\ > H_C\ then\ RO_{Capacity} = H - H_C \quad (6.4)$$

where (H_C) is the depth associated with the maximum capacity of the container. Similarly the drainage runoff was calculated as

$$If\ H > H_{sat}\ then\ RO_{Drainage} = LRC_{soil} \times H_d \quad (6.5)$$

where (H_{sat}) is the depth associated with soil saturation, (LRC_{soil}) is the linear reservoir coefficient of the soil, and (H_d) is the drainage depth calculated with EQ (6.6).

$$If\ H > H_{sat}\ then\ H_d = H - H_{sat} \quad (6.6)$$

By solving the aforementioned set of equations for each time increment, the model successfully calculated the runoff from the Hydropack green roof system with EQ (6.7).

$$RO_{Hydropack} = RO_{Surface} + RO_{Capacity} + RO_{Drainage} \quad (6.7)$$

The HSRP system was then modeled through the addition of a second water reservoir to represent the Hydrostock50 tray and routing runoff generated from the Hydropack system

($RO_{Hydropack}$) as input. Three separate runoff types, including spill runoff (RO_{Spill}), tray capacity runoff ($ROT_{Capacity}$), and tray drainage runoff ($ROT_{Drainage}$), were used to calculate the overall runoff from the HSR system and tray water storage (ΔHT) using the mass balance EQ (6.8).

$$RO_{Hydropack} - RO_{Spill} - ROT_{Capacity} - ROT_{Drainage} = \Delta HT \quad (6.8)$$

Because the water capture in the Hydrostock50 tray was found to be less than 100% efficient, a spill coefficient (C_{spill}) was used to generate both spill runoff and water depth in the tray using EQ (6.9) and EQ (6.10) where the initial tray depth is defined as (HT_{in}).

$$RO_{Spill} = C_{spill} \times RO_{Hydropack} \quad (6.9)$$

$$HT = (1 - C_{spill}) \times RO_{Hydropack} + HT_{in} \quad (6.10)$$

Similar to the Hydropack system, capacity and drainage runoff were calculated for the Hydrostock50 reservoir using EQ (6.11) and EQ (6.12), where (HT_C), (HT_{sat}), and (LRC_{Tray}) are defined as the tray capacity depth, saturation depth, and linear reservoir coefficient respectively.

$$If\ HT > HT_C\ then\ ROT_{Capacity} = HT - HT_C \quad (6.11)$$

$$If\ H > HT_{sat}\ then\ ROT_{Drainage} = LRC_{Tray} \times HT_d \quad (6.12)$$

Finally, the overall runoff of the HSR system was calculated as the sum of the separate runoffs EQ (6.13).

$$RO_{HSR} = RO_{Spill} + ROT_{Capacity} + ROT_{Drainage} \quad (6.13)$$

The simple nature of the equations governing the runoff from the Hydropack and HSR green roof systems resulted in straightforward programming in Microsoft Excel.

Model Calibration

The simple bucket model required several parameters to be calibrated in order to optimize the runoff hydrographs produced for both the Hydropack and HSRP systems. Fortunately, a number of the parameters could be accurately estimated or measured directly from the green roof systems or through their hydrological response to the monitored storm events. Initial conditions for the Hydropack water depth (H_{in}) and Hydrostock50 tray water depth (HT_{in}) were calculated using soil moisture content data and water level sensor data respectively. The critical precipitation depth ($P_{critical}$) and spill coefficient (C_{spill}) were estimated from observations of heavy downpours in storm events and determined to be approximately 5 mm and 0.10 respectively. For the Hydropack system, the capacity depth (H_C) and saturation depth (H_{sat}) were calculated by weighing the trays during supersaturated, saturated, and dry conditions, and then normalizing the mass of the water by the area of the tray. The capacity depth (HT_C) and saturation depth (HT_{sat}) of the Hydrostock50 reservoir were measured directly from tray dimensions. Lastly, the linear drainage coefficients for the soil media (LRC_{soil}) and Hydrostock50 tray (LRC_{Tray}) were estimated from plot draining hydrographs.

	$P_{critical}$	H_C	H_{sat}	LRC_{soil}	C_{spill}	HT_{sat}	HT_C	LRC_{Tray}
Estimated	**5**	20.5	16.2	95	0.10*	25	75	50
Calibrated	6.2	20.6	16.8	185	0.11*	25	75	23.3

*Table 6.1 Estimated and Calibrated Model Parameters (mm) *Spill Coefficient (no units)*

	Hydropack		*HSRP*	
	Total Volume	Peak Runoff Rate	Total Volume	Peak Runoff Rate
Calibration				
4/19/2015	6.6	-18.1	19.6	0.0
8/10/2015	-16.8	-5.3	4.6	-23.1
8/17/2015	16.7	-19.3	-29.8	67.3
9/18/2015	9.2	-8.7	11.1	-22.3
Observation				
10/27/2015	16.5	12.0	5.5	-37.5
11/17/2015	-19.9	13.7	-3.5	-23.5

Table 6.2: Calibration and Observation Model Relative Error (%)

Calibration of critical model parameters (Table 6.1) was done using the Microsoft Excel Solver add-in. An analysis was performed to minimize error in terms of total runoff volume and peak runoff rates when comparing modeled and observed hydrograph values of 4 large storm events (Table 6.2). The maximum error for the Hydropack model was less than 20% for both the total runoff volume and peak runoff rate. The HSRP model had maximum errors of -28.9% and 67.3% for total runoff volumes and peak runoff rates respectively. While the error displayed in the HSRP system is relatively high, it must be noted that the error corresponds to relatively small flow rates where the error calculation is volatile. Two large events outside the calibration period further validate model parameters.

The measured and calibrated parameter values successfully reproduced observed runoff hydrographs for both the Hydropack and HSRP green roof systems (Figures 6.3 – 6.5). While “simple”, the bucket model accurately replicated the time and magnitude of peak flows. The modeled hydrograph of the large and complex 11/17/15 storm event (Figure 6.5a) is particularly impressive as the model precisely depicts both drainage and capacity runoff of the Hydropack system with parameters calibrated from previous storm events.

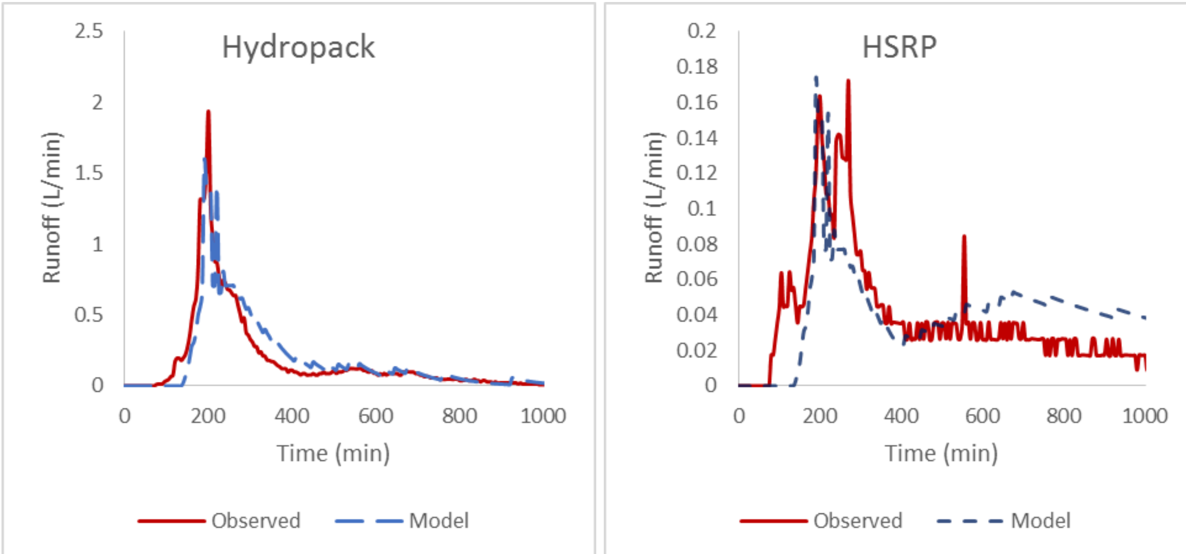

Figure 6.3 4/19/15 Storm Event Observed and Model Hydrographs

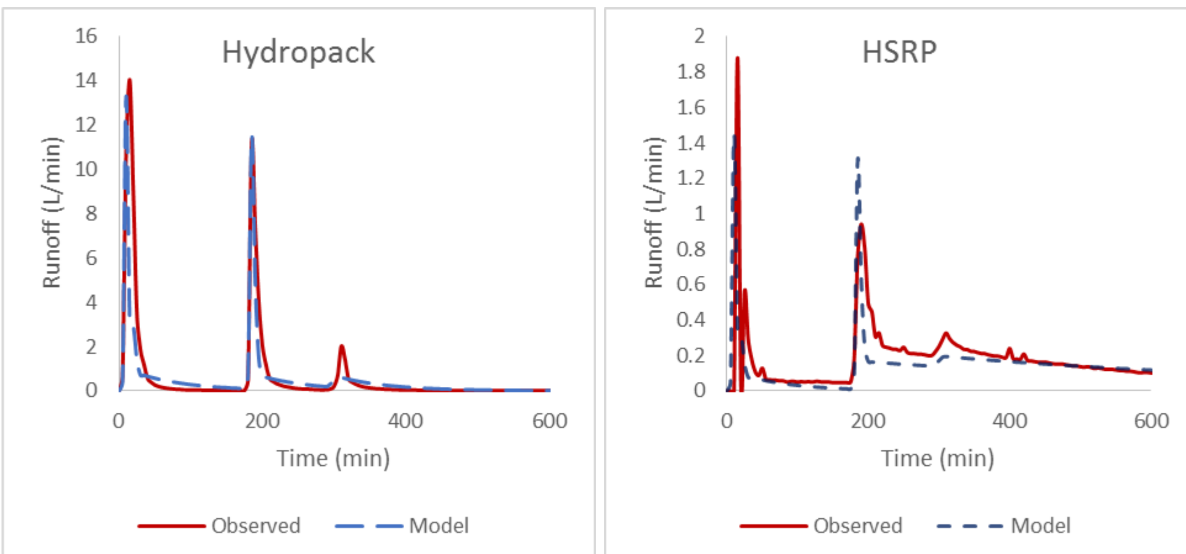

Figure 6.4 8/10/15 Storm Event Observed and Model Hydrographs

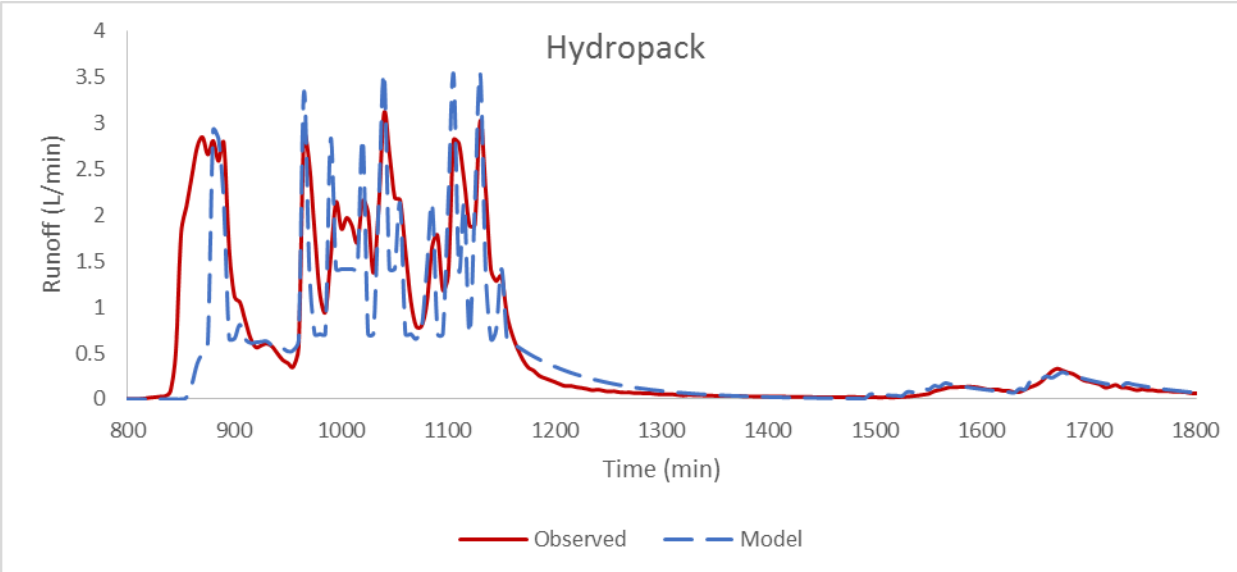

Figure 6.5a 11/17/15 Storm Event Observed and Model Hydrographs

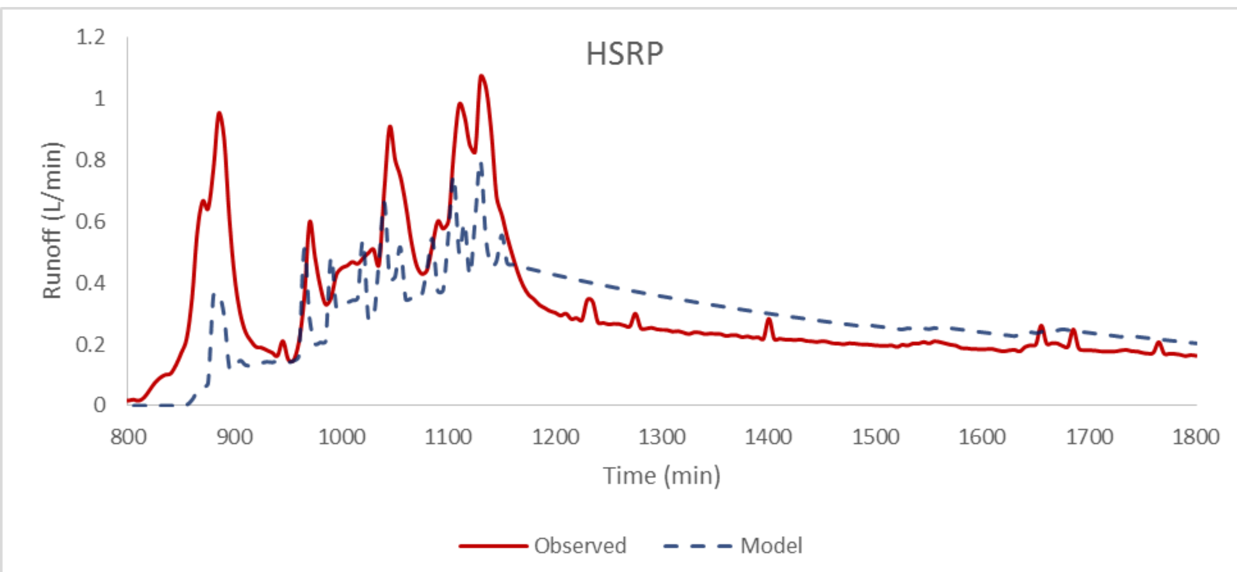

Figure 6.5b 11/17/15 Storm Event Observed and Model Hydrographs

Synthetic Storm Analysis

Using the calibrated models, 24-hour duration synthetic storms were analyzed to gain a better understanding of the performance of green roof systems in correlation to large storm events. Synthetic storms were created using 24-hour storm totals specific for the Milwaukee area and SCS type II rainfall distributions. Hydrographs are displayed for 1, 10, and 100 year storm events

(Figures 6.6-6.8). A reference conventional roof model (black roof) was created using the rational method and a runoff coefficient of 1, which allowed for total runoff volume retention and peak runoff rate reduction values to be calculated. Runoff for all models was normalized by the plot size area for this study (15m^2) for better comparison to monitored hydrographs.

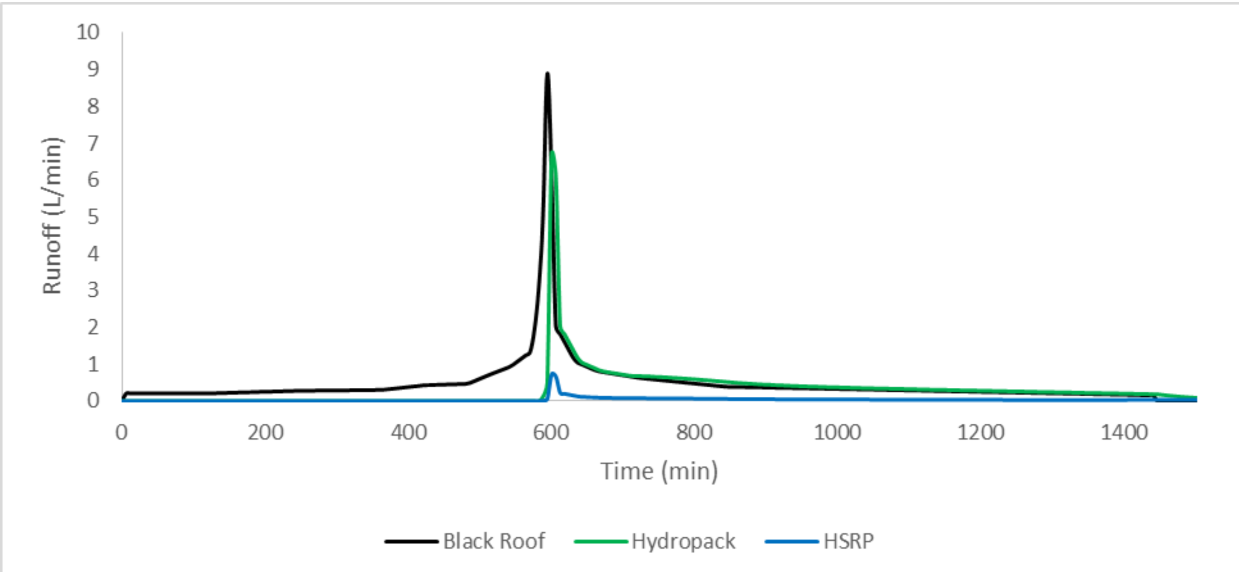

Figure 6.6 1 year Storm Event (P=50.8 mm)

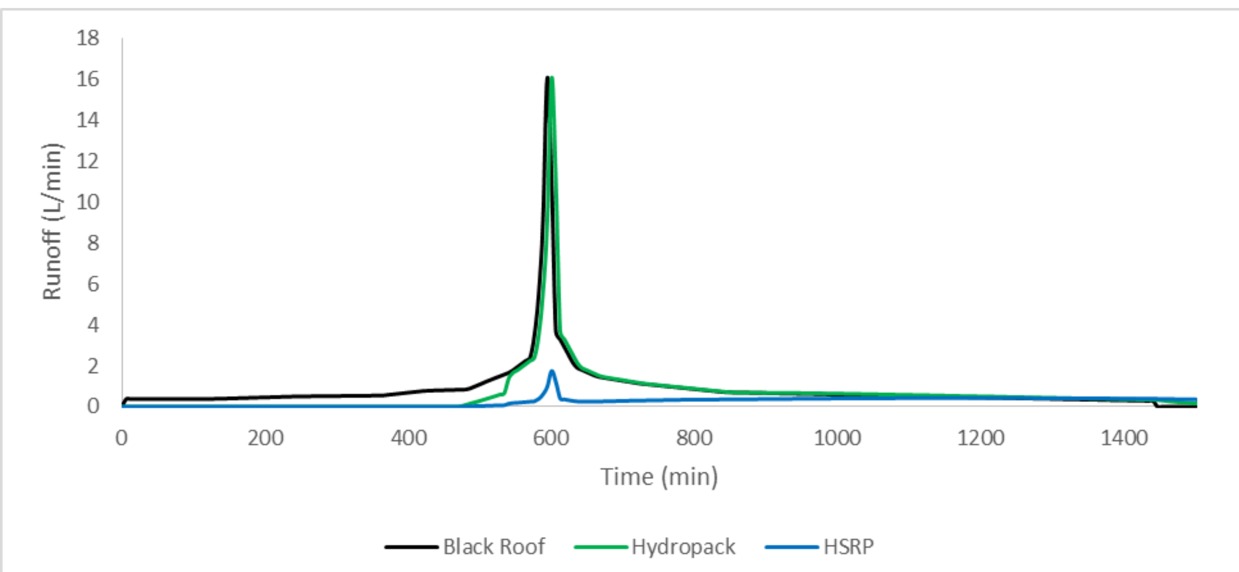

Figure 6.7 10 year Storm Event (P=91.9 mm)

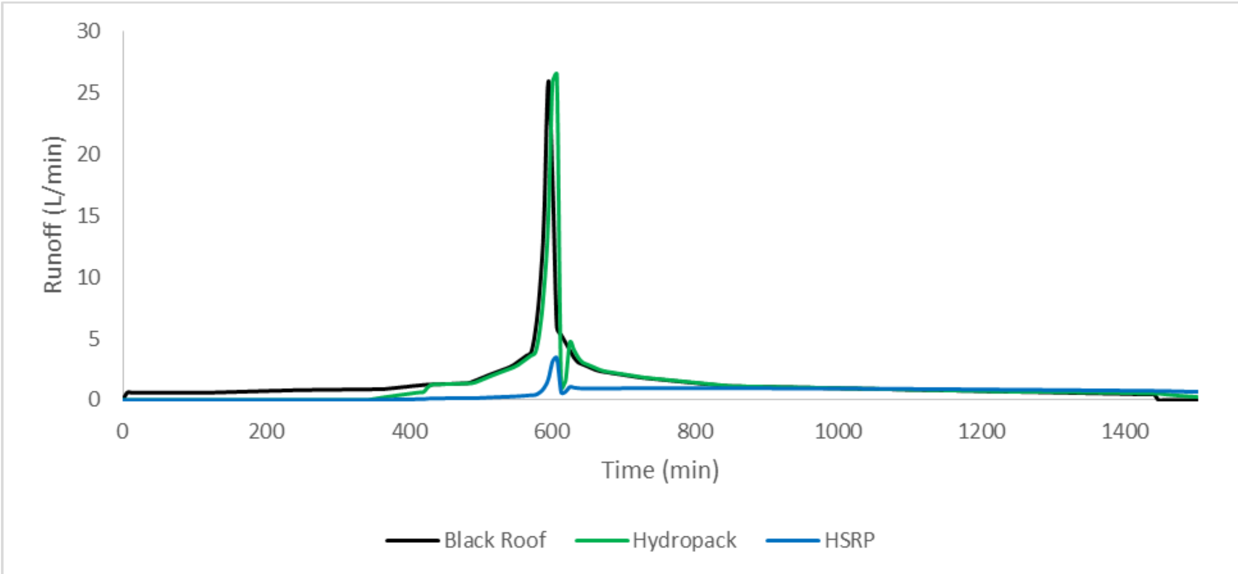

Figure 6.8 100 year Storm Event (P=149.4 mm)

The synthetic storm simulations match the hydrological response of the extensive green roof systems monitored in this study and through literature review. These simulations show that extensive green roofs exhibit decreased hydrological benefits in terms of total runoff retention and peak runoff rate reduction as precipitation depth increases (Table 6.3). Extensive green roofs with relatively small rainfall capacities have a limited ability to deal with large storm events as they quickly become saturated and thereafter act as a black roof. The Hydropack system displayed reduced total volume retention ranging from 33.2% to 11.4% for 1 and 100 year storm events. Similarly, peak runoff rate reduction decreased from 24.7% to -2.7% for 1 and 100 year storms respectively. In contrast, the HSRP green roof system with additional water storage displayed significant hydrological benefits for all simulated storms. Even for a 100 year storm, the model shows 37.8% and 86.8% reductions in total volume and peak runoff rates.

	Hydropack		*HSRP*	
	Total Runoff	Peak Runoff	Total Runoff	Peak Runoff Rate
1 year	33.2	24.7	91.8	89.7
10 year	18.4	0	54.5	89.1
100 year	11.4	-2.7	37.8	86.8

Table 6.3 Synthetic Storm Total Runoff Retention and Peak Runoff Rate Reduction (%)

Discussion

The creation of accurate runoff models and the use of simulations as a tool to predict performance of green roof systems is the most important aspect of this study. Models allow water resource engineers to not only assess the benefits of green roofs and other GI installations, but also to use these findings to optimize performance. For example, a simple analysis was applied to the Hydropack system using 24 hour type II rainfall distributions to show the development of the runoff hydrograph with increased precipitation depth (Figure 6.9).

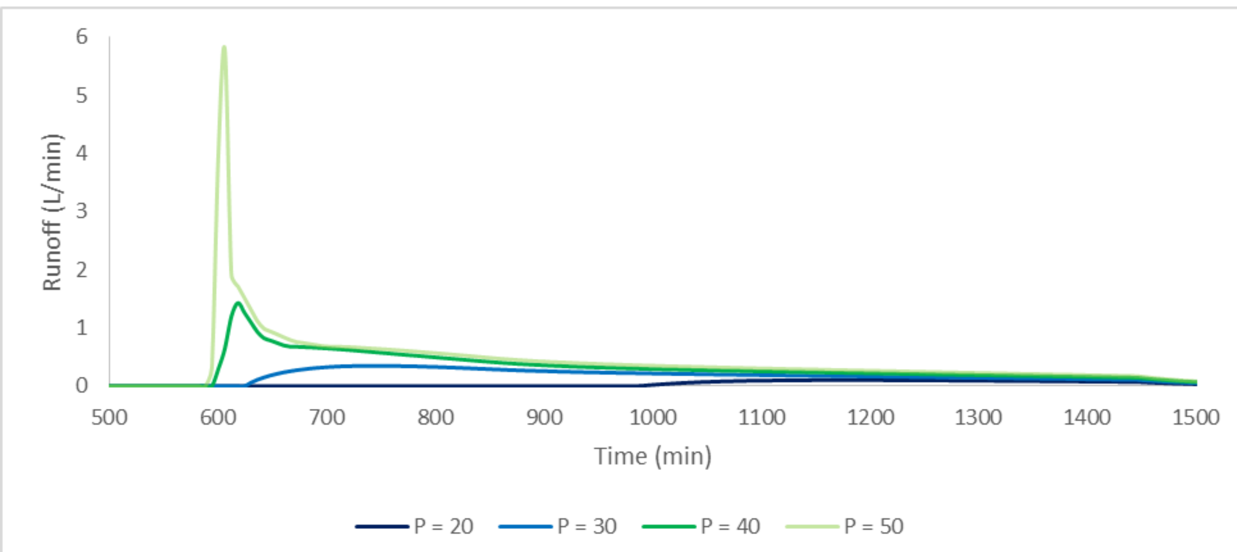

Figure 6.9 Modeled Hydropack Hydrograph with Increased Precipitation (mm)

Furthermore, analysis could be conducted to change critical parameters including water capacity and drainage coefficients to optimize performance, which would also aid in product design. Likewise, historical data can be applied to models to predict how green roof installations would mitigate urban runoff problems caused by previous events. Using model generated figures, engineers and city planners can assess the benefits of green roof installations to local watersheds and use these findings to more effectively appropriate taxpayer dollars towards GI.

VII. CONCLUSION

Summary

Overall, this project was deemed successful as all objectives defined at the onset were completed. Our experiment design and construction of pilot-sized test plots effectively conveyed runoff to our flow monitoring equipment. The WeirBoxes accurately monitored runoff during storm events and the subsequent drainage, validated by water budget error analysis, which was typically less than 7%. The data collected was used to develop a simple yet precise model that could recreate runoff hydrographs. Furthermore, the models were used to simulate 24-hour synthetic storms which proved that extensive green roofs, particularly systems with integrated water storage, can effectively alleviate the quantity and magnitude of stormwater flows and therefore reduce associated detrimental effects.

Suggested Further Work

While successful, there is still much work that needs to be conducted not only for this specific project, but for GI monitoring studies in general. While this project focused on the hydrological performance of green roofs, the ability of green roofs to reduce the heat island effect attributed to conventional roofs was not analyzed. However, reliable temperature data was collected for both the test plots and control roof, along with onsite meteorological data, so the thermal effects of extensive green roofs could be analyzed and modeled with current datasets. Furthermore, runoff quality data was not collected, which is a critical factor influencing the overall effect of green roof installations on local watersheds. Subsequent studies could investigate the water quality aspect by analyzing samples taken during runoff conditions. Because models are only as good as the data sets used to create them, it is recommended that the WeirBox monitoring equipment be reexamined to optimize data accuracy through design, calibration, and software updates.

The previous suggestions all assume that this project continues to a second year of monitoring, and it is imperative that this study and related studies continue. The models created require further validation and improved counterparts that can only be done through continued data collection. It is my hope that this study not only continues, but expands to monitor a full-sized green roof installation so the effects of size and layout can be further explored. Finally, although the simple bucket model which was built for this study successfully recreates runoff hydrographs, it has proven to be an inadequate model as it cannot predict the antecedent conditions preceding storm events. More accurate models will need to be created which utilize both runoff and meteorological data, resulting in long-term simulations which can then be generated to ultimately increase our overall understanding of green roof performance.

Concluding Remarks

Simply put, green roofs installations will not solve urban stormwater issues alone. Conversely, green roofs are a small part of a larger solution that incorporates all types of GI. Therefore, the responsibility lies on water resource engineers and city planners to optimize the installation of GI and other water management tools in order to protect watersheds and their inhabitants from escalating stormwater problems. Optimization can only be achieved through a more thorough understanding of these systems, and therefore it is critical that monitoring studies continue, modeling efforts improve, and the application of acquired knowledge continues to evolve to ultimately allow full advantage of all the stormwater management tools available.

VIII. REFERENCES

Alfredo, K., Montalto, F. & 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.

Behm, D. (2013). Milwaukee's deep tunnel turns 20 on Thursday. Journal Sentinel. Retrieved from http://www.jsonline.com/news/milwaukee/milwaukees-deep-tunnel-turns-20-on-thursday-b9970010z1-218696891.html

Carpenter, D. D. & Kaluvakolanu, P. (2011). Effect of roof surface type on storm-water runoff from full-scale roofs in a temperate climate. Journal of Irrigation and Drainage Engineering-ASCE, 137 (3), 161–169.

Berndtsson, J. C. (2010). Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering, 36, 351-360.

Carter, T. L. & Rasmussen, T. C. (2006). Hydrologic behavior of vegetated roofs. Journal of the American Water Resources Association, 42 (5), 1261–1274.

Carter, T. L., and Jackson, C. R. (2007). Vegetated roofs for stormwater management at multiple special scale. Landscape and Urban Planning, 80(1-2), 84-94.

DeNardo, J. C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J. & Berghage R.D. (2005). Stormwater mitigation and surface temperature reduction by green roofs. Transactions of the American Society Agriculture Engineers, 48(4), pp. 1491–1496

Fassman-Beck, E., Voyde, E., Simcock, R. & Hong, Y. S. (2013). 4 living roofs in 3 locations: does configuration affect runoff mitigation? Journal of Hydrology, 490, 11–20.

Getter, K. L., Rowe, D. B. & Andresen, J. A. (2007). Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering, 31 (4), 225–231.

Hakimdavar, R., Culligan, P., Finazzi, M., Barontini, S. & Ranzi, R. (2014). Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrological performance. Ecological Engineering, (73), 494-508.

Hathaway, A. M., Hunt, W. F. & Jennings, G. D. (2008). A field study of green roof hydrologic and water quality performance. Transactions of the Asabe, 51 (1), 37–44.

Hilten, R. N., Lawrence, T. M. & Tollner, E. W. (2008). Modeling stormwater runoff from green roofs with HYDRUS-1D. Journal of Hydrology, 358 (3–4), 288–293.

Lamera, C., Becciu, G., Rulli, M. C., Rosso, R. (2014). Green roof effects on the urban water cycle components. Procedia Engineering, (70), 988-997.

Larsen, A.N., Gregersen, I.B., Christensen, O.B., Linde, J.J., Mikkelsen, P.S., (2009). Potential future increase in extreme one-hour precipitation events over Europe due to climate change. Water Science and Technology, 60 (9), 2205–2216.

Li, Y. & Babcock, R. W. (2014). Green roof hydrologic performance and modeling: a review. Journal of Water Science and Technology, 69(4), 727-738.

Locatelli, L., Mark, O., Mikkelsen, P. S., Arnbjerg-Nielsen, K., Jensen, M. B. & Binning P. J. (2014). Modelling of green roof hydrological performance for urban drainage applications. Journal of Hydrology, (519), 3237-3248.

Loucks, E., Rodgers, C., Potter, K. and Hahn, M. G. (2000). Rainfall frequency in the southeastern Wisconsin region. (Technical report no 40). Retrieved from http://www.sewrpc.org/SEWRPCFiles/Publications/TechRep/tr-040_rainfall_frequency.pdf

Kasmin, H., Stovin, V. R., Hathaway, E. A. (2010). Towards a generic rainfall-runoff model for green roofs. Water Science and Technology, 62(4), 898-905.

Kohlor, M. (2003). Plant survival research and biodiversity: lessons from Europe Conference proceedings Greening Rooftops for Sustainable Communities, 2003, Chicago (2003)

Magill, J. D., Midden, K., Groninger, J., and Therrell, M. (2011). A History and Definition of Green Roof Technology with Recommendations for Future Research. *Research Papers.* Paper 91. http://opensiuc.lib.siu.edu/gs_rp/91

Mentens, J., Raes, D. & Hermy, M. (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.

Morgan, S., Celik, S. & Retzlaff, W. (2013). Green roof storm-water runoff quantity and Quality. Journal of Environmental Engineering-Asce, 139 (4), 471–478.

Nagase, A. & Dunnett, N. (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. 737

Nawaz, N., McDonald, A. & Psotoyko. (2015). Hydrological Performance of a full-scale extensive green roof located in a temperate climate. Ecological Engineering, (82) 66-80.

Ouldboukhitine, S. E., Belarbi, R. & Djedjig, R. (2012). Characterization of green roof components: Measurements of thermal and hydrological properties. Building and Environment, 56, 78–85.

Osmundson, T. (1999). Roof gardens: History, design and construction: London, UK: W.W. Norton and Company Ltd.

Palla, A., Gnecco, I. & Lanza, L. G. (2009). Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof. Journal of Hydrology, 379 (1–2), 193–204.

Roldin, M., Fryd, O., Jeppesen, J., Mark. O., Binning, P. J., Mikkelsen, P. S., & Jensen, M. B. (2012). Modelling the impact of soakaway retrofits on combined sewerage overflows in a 3km^2 urban catchment in Copenhagen, Denmark. Journal of Hydrology, 452-453, 64-75.

Royer, Scott. (2012). Deep tunnel deep clean: Managing water infrastructure 300 feet underground. Waterworld. http://www.waterworld.com/articles/print/volume-29/issue-02/urban-water-management/deep-tunnel-deep-clean.html

Simmons, M. T., Gardiner, B., Windhager, S. & Tinsley, J. (2008). Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosystems, 11 (4), 339–348.

Stovin, V., Vesuviano, G. & Kasmin, H. (2012). The hydrological performance of a green roof test bed under UK climatic conditions. Journal of Hydrology, 414, 148–161.

U.S. Climate Data. (2015). Weather history Milwaukee. Retrieved from http://www.usclimatedata.com/climate/milwaukee/wisconsin/united-states/uswi0455

VanWoert, N. D., Rowe, D. B., Andresen, J. A., Rugh, C. L., Fernandez, R. T. & Xiao, L. (2005). Green roof stormwater retention: effects of roof surface, slope, and media depth. Journal of Environmental Quality, 34 (3), 1036–1044.

Vegetal i.D. (2015a). Hydroactive smart roof: Blue and green roof solution with cloud monitoring. [Brochure] Batavia, NY: Vegetal i.D.

Vegetal i.D. (2015b). Hydroactive smart roof specifications. Retrieved from http://www.vegetalid.us/green-roof-solutions/stormwater-management/300-hydroactive-smart-roof-specifications.html

Vegetal i.D. (2015c). Specializing in green roofs since 1993! Retrieved from http://www.vegetalid.us

Villarreal, E. L. and Bengtsson,L. (2005). Response of a Sedum green-roof to individual rain events. Ecological Engineering, 25 (1), 1–7.

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

U.S. Climate Data. (2015). Weather history Milwaukee. Retrieved from http://www.usclimatedata.com/climate/milwaukee/wisconsin/united-states/uswi0455

Zhao, S. L., Dorsey, E.C., Gupta, S. C., Moncief, J. F., and Huggins D. R. (2001). Automated water sampling and flow devices for runoff and subsurface drainage. Journal of Soil and Water Conservation 56(4), 299-306.