MONITORING OF EVAPOTRANSPIRATION AND INFILTRATION IN RAIN GARDEN DESIGNS

By

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NOMENCLATURE

ET_o	Daily reference evapotranspiration [mm/day]
ET_{sz}	Standardized reference evapotranspiration [mm/day]
ET_L	Lysimeter evapotranspiration [mm/day]
Δ	Slope of the vapor pressure curve [kPa/°C]
R_n	Net solar radiation on the crop surface [MJ/m^2/day]
G	Soil heat flux density [MJ/m^2/day]
γ	Psychometric constant based on altitude [kPa/°C]
T	Average daily temperature at 2 meters from ground level [°C]
u_2	Average daily wind speed at 2 meters from ground level [m/s]
e_s	Saturation vapor pressure [kPa]
e_a	Actual vapor pressure [kPa]
$(e_s - e_a)$	Vapor pressure deficit [kPa]
K_c	Crop coefficient [dimensionless]
K_s	Water stress coefficient [dimensionless]
C_n	Numerator coefficient that relates to time step [dimensionless]
C_d	Denominator coefficient that relates to the crop height [dimensionless]
ET	Actual evapotranspiration [mm]
P	Precipitation inflow [mm]
O	Percolate outflow [mm]
ΔS	Change in storage [mm]
θ	Volumetric moisture content [vol/vol]
w	Gravimetric moisture content [%]
ρ_d	Bulk dry density [g/cm^3]

ABSTRACT

Stormwater control measures (SCMs) mitigate the runoff from increased urbanization. One common SCM is a rain garden that consists of a depressed vegetated area that captures runoff from surrounding impervious area, holding and treating the non-point source pollutants in stormwater. Stored water can exit via infiltration and evapotranspiration. Evapotranspiration (ET) is the combined effort of evaporation and transpiration to remove water from the soil and vegetation. Although ET comprises an important component in the hydrologic cycle, over 50% in the natural environment (Sloto 2005), it is often neglected as a volume reduction mechanism in SCM design.

The need to quantify the rates of ET and infiltration in SCMs is to properly accredit the systems' volume reduction to optimize ecosystem benefits. At Villanova University, weighing lysimeters have been constructed to represent three different rain garden configurations in a side-by-side comparison of their ET and infiltration volume reduction capability. Two different soil media were investigated, as well as two different drainage regulation devices. Three lysimeters were constructed to compare how different outflow and media systems affect water availability for infiltration and ET. A controlled outflow temporarily stores water within the rain garden's soil to slow percolation rates and increase the opportunity for ET. The controlled outflow was implemented in two lysimeters with different media: typical engineered media and a soil native to Villanova's campus. A third lysimeter contains engineered media with an internal water storage (IWS) zone, a permanent reservoir created by an upturned drainage pipe. The three lysimeters consist of native plants in a lined soil media basin.

Flow into the system is measured by a rain gage, soil moisture is measured through the soil column, and flow out via ET and infiltration is measured to provide a comprehensive view of how water is moving through each of the systems. The monitoring system includes soil moistures meters located at 10 cm, 35 cm, and 65 cm (4 in, 14 in, and 26 in) depths in each lysimeter. Evapotranspiration loss is determined by a system mass balance via a tension load cell that measures the systems weight at 5 min intervals and precipitation and drainage measurements. Each lysimeter's drainage regulation system is monitored for exfiltration with a custom-made flow rate device. To simulate the volume of rainfall a rain garden would obtain from the runoff of the surrounding catchment area, a distribution system that provides for a 5:1 and 10:1 impervious area: SCM area rainfall event was developed.

ET and percolation amounts were determined for storms under 40 mm (1.6 in) at a 1:1 loading ratio for July 2013 to March 2014. This analysis yields 7:1, 5:1, and 10:1 ET to outflow ratio for lysimeters 1, 2, and 3, respectively. The average water budget are as follows, lysimeter 1: 67% ET, 10% percolation, and 23% storage, lysimeter 2: 63% ET, 13% percolate, and 24% storage and lysimeter 3: 75% ET, 8% percolate, and 17% storage. During the storm simulations lysimeters 1, 2, and 3 operate on average at a 1.5:1, 1:1 and 2.5:1 ET to percolation ratio. Soil moisture meters show potential to provide a viable and cost effective proxy to measure the change in storage in rain garden designs. This analysis concludes that selection of media and drainage configurations have the potential to increase ET and decrease outflow to fit site specific goals.

CHAPTER 1: INTRODUCTION

The most precious resource to society is water. We consume it, we clean with it, we develop near it, and we harness its power for energy. For millennia, civilizations developed around waterways for fresh drinking water, travel, and energy. Civilization's outward spatial expansion from waterways was reliant on developed technology to direct water from reservoirs, like surface water or groundwater, to taps in our homes.

Water is governed by the hydrologic cycle. The hydrologic cycle is a balance of different processes such as precipitation, evaporation, transpiration, infiltration, surface runoff, ground water, and water body storage. One of these components cannot be altered without affecting one or all of the others to maintain equilibrium. The extraordinary rate of urbanization, the process in which natural landscapes, such as forest and agricultural areas, are converted into urban and suburban areas, has severely affected the way in which water moves above and below ground both during and after rainfall events (NRC 2008). Urbanization has introduced impervious surfaces (e.g. rooftops and roadways) and topographic change (e.g. leveling, alteration and compaction of soil) to the natural system. Urbanization destroys vegetation and soil, both of which hold the potential for transpiration and evaporation. Development of impervious surfaces also covers soil, which holds the potential for infiltration to water body storage and groundwater recharge. Therefore, water from precipitation events on impervious surfaces primarily becomes surface runoff.

In the recent past, projects in civil engineering have not kept stormwater runoff that impervious areas create on site. Instead, surface runoff is handled by quickly directing the water away from the structure to protect the structure's lifespan and to ensure public safety. Then, the runoff travels through the sewer and is discharged into nearby surface waterways. The discharge erodes and pollutes streams by increasing their temperature and introducing nutrient and sediment loads that disrupt the ecologic health of the stream (EPA 2005).

The Clean Water Act (CWA) oversees the National Pollutant Discharge Elimination System (NPDES) program to manage the water quality in the nation's water bodies (EPA 2005). To do this, the NPDES first focused to reduce point source pollution from industrial process wastewater and municipal sewage discharges (NRC 2008). These point source discharges are relatively easy to regulate since the outfalls into the receiving water body can be identified to a known location. However, point source pollutants are only part of the solution to improve the health of our lakes, rivers, and streams. In 1987, the NPDES extended its reach to the control of stormwater as a non-point source pollution (EPA 2005). Now that stormwater is acknowledged as a major pollutant, managing agencies are turning to treat non-point source pollution with creative and sustainable solutions.

Non-point source pollution control presents a challenge for both design and regulation alike. Stormwater control measures (SCMs) aim to help treat non-point source pollution in both quantity and quality. These SCM devices may also be referred to as best management practices (BMPs) in current and past literature. Stormwater control measures can be structural or nonstructural. Nonstructural SCMs include the reduction of overall impervious area for new development. Already developed areas present another issue as they have already established the amount of impervious area with no SCMs to offset the stormwater capture. Therefore, structural SCM design has to be retrofitted into the system's available space. The quantity control of SCMs refers to the reduction of the amount of stormwater degrading nearby water bodies. This quantity reduction is obtained by other hydrologic processes, such as infiltration to water body storage and groundwater recharge, transpiration, and evaporation. Structural SCMs are small and there may be need for multiple to capture site specific runoff volume to offset the water budget. In water quantity control, SCMs help to mitigate the peak flow of the storm and reduce the overall volume of water to be discharged into receiving water bodies.

Presently, water quality benefits of SCMs are taken into account by some state regulations by percent removal of the key nutrients, nitrogen and phosphorus, and total suspended solids (TSS) typically found in stormwater runoff (PA DEP 2006). Percentage removal is inherently flawed when considering the inflow concentration. Water with high pollutant concentration coming into the system will have a higher potential for removal. The same is true for the opposite; water with low pollutant concentration coming into the system will have less potential for removal. Therefore, the SCM may not meet the design criteria, but still function to meet the overall goal.

The complicated nature of water quality benefits are out of the scope of this paper, but are important to SCM design. Instead the focus will be on water quantity control function of SCMs. Overall, if the amount of stormwater is being reduced, then water quality is improving as less of the pollutants are able to reach the discharging area. Therefore, stormwater volume quantity reduction by mechanisms of ET and infiltration is the focus of the present study. This will be done by equipping a site with all necessary instrumentation to observe the water budget of a rain garden system. Quantification of

ET, infiltration, and soil moisture change in three types of rain garden designs will be observed.

Stormwater control measures are a new practice that seek to mimic the natural or before construction hydrology. EPA (2008) acknowledges that uncertainties in performance, longevity, and regulation come with this new practice. The present research attempts to clarify one aspect of an SCM design to understand evapotranspiration's potential to reduce sizing and economic impacts of SCMs.

1.1 CURRENT SCM DESIGN

Stormwater management and control is involved with every civil engineering application as the addition of impervious area disrupts the natural hydrologic cycle. As

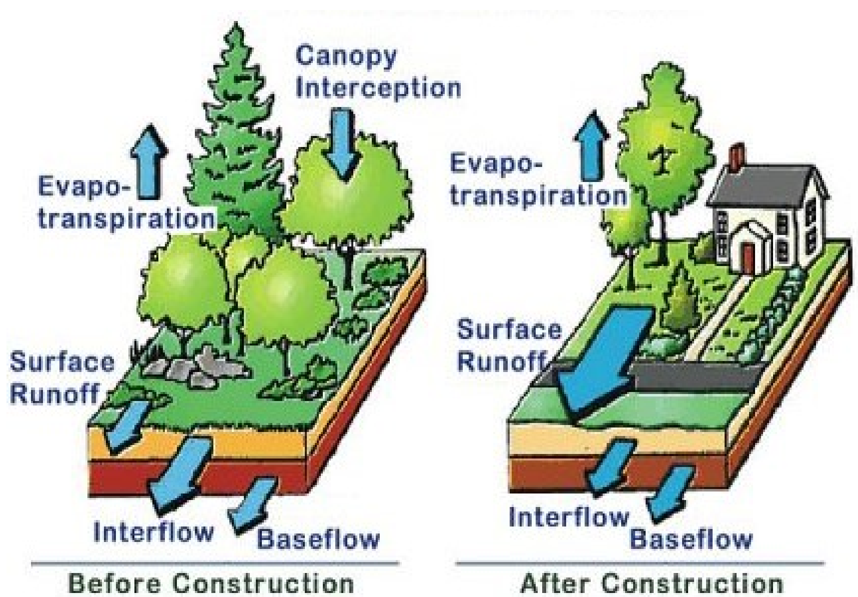

Figure 1.1: Local Hydrologic Cycle (MD DES 2011)

seen in Figure 1.1, the post-construction developed phase has much more water contributing to surface runoff (larger arrow). Only recently have engineers shifted their view of stormwater management to include a low impact development (LID) approach. This approach allows for the developed hydrologic cycles to move closer to pre-construction conditions by encouraging more evapotranspiration and infiltration/groundwater flow. Low impact development consists of reducing and mitigating the stormwater runoff from urbanization with structural and nonstructural SCMs. The goal of a nonstructural SCM design lies with the planning behind the new construction, such as reduction of overall pervious surfaces that are associated with the proposed development. This can be done by reducing pavement in a development plan by improved site selection, shortening driveways, eliminating curbs and sidewalks, one-sided parking, or one-way streets. Structural SCMs are a technology within a development plan. There are many types of structural SCMs and their selection depends on site specific restrictions. These devices are also selected based on water quantity and water quality concerns and include rain gardens, infiltration beds, stormwater wetlands, and detention ponds.

1.2 CURRENT RAIN GARDEN DESIGN

Rain gardens are presently a popular type of SCM design that is used to mitigate peak flow and non-point source pollution associated with runoff. Rain gardens improve both quantity and quality functions while satisfying economical and aesthetic concerns. A rain garden consists of a vegetated, depressed basin consisting of a lightly compacted soil media. Plant life in the media can range from trees to shrubs to small plants and is determined by the size of the basin, climate and geographic area. Another attractive trait of these SCMs is the flexibility of the physical dimensions, and incorporation of it into the natural landscape.

The basin is generally placed in a lower elevation point within a drainage area, which allows for this gravity driven system to collect stormwater runoff and infiltrate it through the profile of the lightly compacted soil basin (Figure 1.2). The depth of the soil

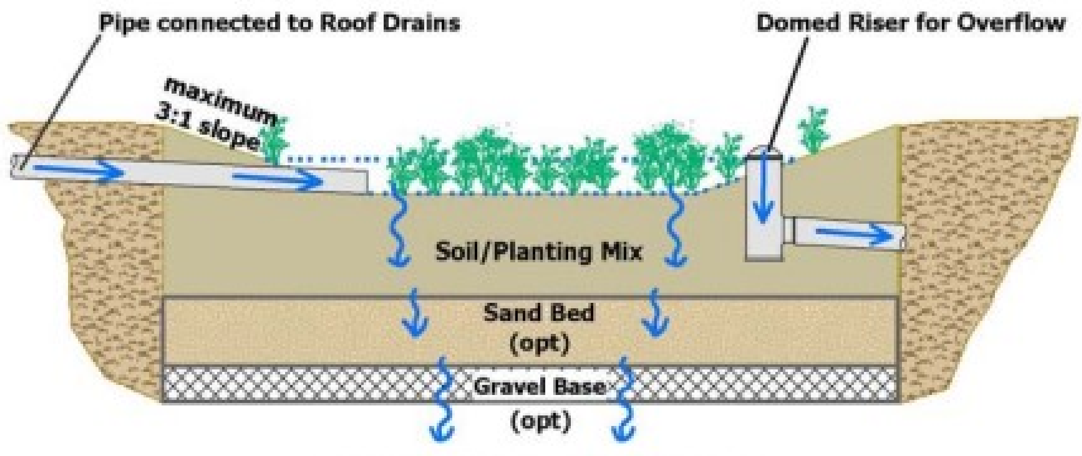

Figure 1.2: Typical Bioinfiltration Rain Garden Design (PA DEP 2006)

profile varies with site specific conditions, and can be designed with optional sand or gravel beds to increase infiltration. A positive outflow is needed for overflow in the case of a large storm event. In Pennsylvania, it is recommended that the base of the final basin layer that overlies the indigenous soil should have an infiltration rate greater than or equal to 0.1 in (2.5 mm) per hour (PA DEP 2006). For infiltration rates less than that, a

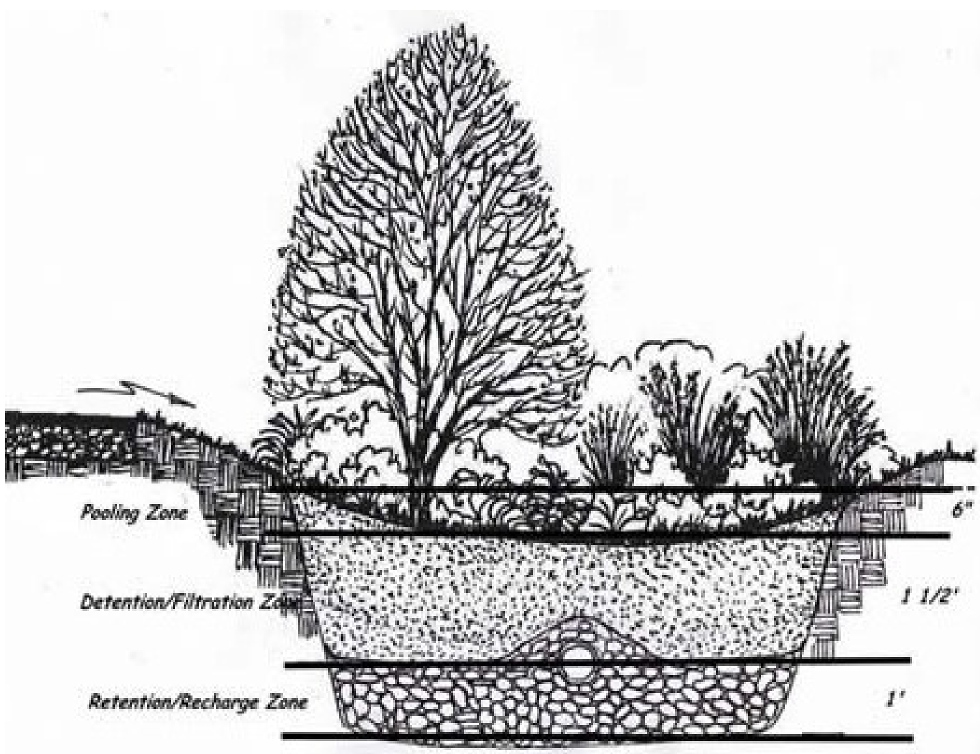

Figure 1.3: Bioretention Rain Garden (University of CT 2011)

bioretention design is recommended (Figure 1.3). The bioretention design consists of a lined depressed basin with a perforated underdrain pipe that ties into existing stormwater lines; this design alters from a bioinfiltration design (Figure 1.2) that allows stored water to infiltrate into the native soils. The gravel around the underdrain can vary in size, ranging from 20 to 30 cm (8 to 12 in) so long as clogging of the drain from fine particles is avoided (PA DEP 2006; VA DCR 2011; MD DES 2007; NC DENR 2009). Bioretention systems retain runoff for delayed outflow to the storm sewer. Evapotranspiration may reduce the stored runoff volume, although current design and permitting practices only account for stormwater volume reduction by infiltration to drain the 15 cm (6 in) surface ponding depth within 72 hours for the design storm for Pennsylvania and areas with similar climates (PA DEP 2006). The design storm is based off of 2.5 cm (1 in) of precipitation, which was chosen on a statistical basis. Based on historic information, 85% of the annual storms in Pennsylvania were found to be 2.5 cm (1 in) or less (Prokop 2003). Therefore, a design storm of 2.5 cm (1 in) allows for the SCM to treat up to 85% of the storms for their corresponding runoff area.

Rain gardens are flexible in size and shape (PA DEP 2006; VA DCR 2011; MD DES 2007; NC DENR 2009). Guidelines on the depth of media are provided in many state guidance manuals, but can be altered depending on site-specific requirements. Larger basins that incorporate deeply rooted vegetation, such as trees, may have a 1.5 m (5 ft) depth of media, while shallower basins may have a minimum depth of 0.76 m (2.5 ft) depth (PA DEP 2006; NC DENR 2009). Deeper basins could be required to reach a soil with an acceptable infiltration rate and shallower basins may be employed in areas of seasonally high water tables. The basin may be comprised of just soil media, or a combination of soil and an underlying gravel layer (PA DEP 2006; VA DCR 2011; MD DES 2007; NC DENR 2009). Gravel layers are incorporated to provide an area with greater void space for more volume capture as well as protecting bioretention underdrains from clogging.

Although depth and shape can vary in rain gardens, there are still limitations to the calculated volume that the bowl can hold in a static state. As these are dynamic systems, a more dynamic approach should be used in calculations such that processes such as ET and infiltration rates can be accounted fully. Chapter 2: Literature Review will delve into more specifics of rain garden design that can be modified to enhance the site specific volume reduction.

CHAPTER 2: LITERATURE REVIEW

2.1 RAIN GARDEN DESIGN ASPECTS

Rain gardens have many aspects of their design that can be altered to maximize their water quantity and quality control. These features include the sizing criteria, soil media mix, and drainage outflow design. Two types of soil media and two drainage systems, i.e. controlled valve outflow and internal water storage, are discussed.

2.1.1 Sizing Criteria

Sizing criteria for rain gardens function on an area ratio. This ratio is defined as the impervious runoff area or drainage area to infiltrating SCM area. The PA BMP manual (2006) indicates that rain gardens not exceed a loading ratio of 5:1 or an 8:1 ratio if considering total drainage area with pervious areas. The loading ratios are based on risk assessment of infiltrating SCMs failure due to clogging over 20 years and should be considered a “rule of thumb” (Rocco 2009). However, the Bioinfiltration Traffic Island

Figure 2.1: BTI Rain Garden in June 2012 (Lord 2013)

(BTI) rain garden on Villanova Campus (Figure 2.1) has a 10:1 loading ratio and has performed well over the last 12 years. The BTI has been functioning as a volume control and nutrient removal device (Jenkins et al. 2010; Lord 2013; Isaac-Ricketts 2008).

The loading ratio maximum is enforced to prevent failure due to clogging, concentration of pollutants, and adverse groundwater mounding effects. Analysis of groundwater monitoring wells surrounding the BTI basin demonstrates the effect of this loading ratio on groundwater mounding (Nemirovsky et al. 2014). Results indicate that precipitation greater than 2.3 cm (0.91 in) causes increased mounding at wells adjacent to the site and can be felt 23 m (75 ft) away from the BTI. For a rainfall amount of less than 2.3 cm (0.91 in) the groundwater mounding effect remains localized to the rain garden and does not extend a significant distance down-gradient (Nemirovsky et al. 2014; Machusick 2009). The BTI is monitored for water quality via pore water samplers at the surface of the bowl, at the bottom of the bowl depth and 1.2 m (4 ft) below the bottom of the bowl depth.

Analysis of these water quality samples reveal possible denitrification. Adjacent to the BTI, under a grassed non-SCM area, a profile of pore water samplers were also installed. Comparison of water samples from the adjacent, non-SCM area yielded higher overall nitrogen levels than directly beneath the BTI (Lord 2013). A study on sediment accumulation on the BTI 9 years after construction revealed that small sporadic deposition was found but did not hinder the overall infiltration rates (Jenkins et al. 2010). In the present study, two loading ratios will be evaluated: the 5:1 ratio recommended by PA DEP (2006) and the 10:1 ratio employed at the BTI site.

2.1.2 Soil Media

Studies have shown variations in soil mixture can impact pollutant removal in bioretention rain gardens (Sickles et al. 2007; Carpenter 2010; Barrett et al. 2013). A media mix comparison typically had the greatest solids removal from sand (100% sand, washed though No. 40 Sieve), however one commercial top soil mix (61% sand, 16% silt, and 23% clay) performed better for overall contaminant removal as the organic matter filtered pollutants (Sickles et al. 2007). The PA BMP manual recommends a soil mix in rain gardens to be comprised primarily of sand with a layer of topsoil and a clay content under 10% (PA DEP 2006). This composition allows for the water to flow relatively quickly through the media and enhances nutrient removal.   The minimum infiltration rate that acts as the borderline to determine if a lined or unlined system should be used is 2.5 mm (0.1 in) per hour (PA DEP 2006). Other states, such as Maryland and North Carolina, recommend infiltration to be greater than 13.2 mm (0.52 in) per hour as this borderline (MD DES 2007; NC DENR 2009). Infiltration rates are inversely related to the amount of fine particles (passes through No. 200 sieve) that are in the media (Hinman 2009). Larger infiltration rates will typically have less fines and smaller infiltration rates will have more silt and clay particles. For infiltration dependent designs, a large percentage of fines is avoided to increase the infiltration capacity. Vegetated bioinfiltration column studies showed columns with higher clay contents allowed for more water holding capacity and produced healthier plants during dry spells (Barrett et al. 2013). Medias with more clay particles and greater potential to retain water longer shift some of the volume reduction mechanism from infiltration to ET. Designs that favor quick infiltration may prohibit ET because they move water through the system so quickly. Delaying the infiltration process provides more time for available water to be lost to ET. The use of natural soils may enhance the natural ET process, while reducing costs and decreasing the negative effects of construction (Benson 2012).

2.1.3 Drainage Designs

Current rain garden drainage design relies upon infiltration to control runoff volume and are often referred to as infiltrating systems (PA DEP 2006). Infiltration is the phenomenon of water percolating through soil media via gravity. Infiltration occurs in the soils beneath the rain garden basin or the underdrain pipe for bioretention design. There are site locations where infiltration is not recommended to occur, such as karst areas, sites with poorly infiltrating underlying media, urban areas, and other sites where typical media depth cannot be obtained (Wadzuk 2013; PA DEP 2006; MD DES 2007; NC DENR 2009). If the goal is to prevent infiltration, lined bioretention systems are used or rain gardens are avoided all together. Karst areas are those with an underlying media comprised of carbon rock (e.g. limestone or dolostone) that is subject to dissolution which forms small to large voids. When the flow path is disturbed in this media, it can often lead to sink holes. Infiltration SCMs are usually not recommended in karst. However, the goal should be not to change the amount of water reaching the karst voids, as drying out of these areas may also lead sinkhole formation (Browne 2013). Poorly infiltrating underlying soil is defined as a soil with an infiltration rate less than 2.5 mm (0.1 in) per hour. Poorly infiltrating soils typically have higher silt and clay content; the fine particles reduce the hydraulic conductivity (Sickles et al. 2007).

All of these situations described above present a challenge to SCM design. Bioretention technology is recommended to accommodate the needed volume capture in these challenging situations. Bioretention requires a perforated pipe that ties into the existing stormwater pipe lines to move infiltrated runoff off site. This research investigates two types of drainage systems that are not currently included in the PA BMP manual. These drainage systems consist of an internal water storage (IWS) zone system and a controlled valve outflow system. A controlled valve outflow allows user interference to provide a customized IWS.

2.1.3.1 Internal Water Storage

The internal water storage (IWS) is a design that implements an available zone for saturation at the bottom of the bioretention basin. This saturated zone is established by adding an upturned elbow to the perforated outlet pipe in a bioretention basin. A comparison of an IWS and conventional connections is shown in Figure 2.2. The IWS

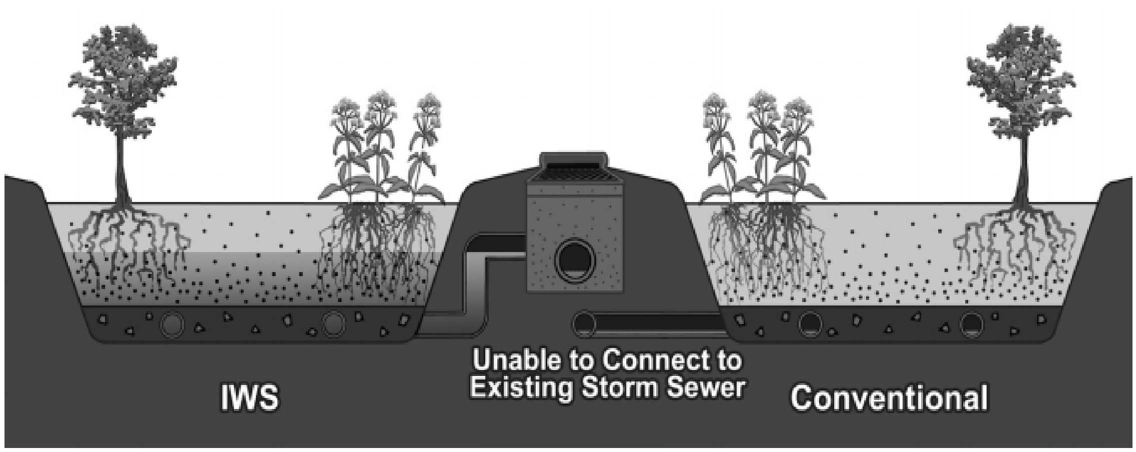

Figure 2.2: Internal Water Storage vs. Conventional Drainage (Brown et al. 2009)

provides many water quality benefits, such as nitrogen removal, as well as prolonged water storage for plants to draw on during dryer periods and reduce stored stormwater volume via ET (Brown et al. 2009; Davis et al. 2009; Hunt et al. 2006).

The availability of water will allow the plants to retain their health, leading to more ET production over the long-term. Without healthy plants, transpiration greatly deceases, which is the leading component in ET (Allen et al. 1998). Case studies have shown that hydraulic performance can be increased with the use of an IWS by eliminating outflow for the design storm capture amount (Brown et al. 2009). A comparison study of two 1.2 m (4 ft) media depth rain gardens in Greensboro, NC showed that the rain garden with a conventional underdrain was twice as likely to overflow then the rain garden with a 0.6 m (2 ft) IWS zone (Sharkey 2006). The absence of overflow means that the main volume reduction mechanism is ET. However, this performance is lost when considering back-to-back large storm events, as there is not ample time for the ET to take effect. According to a 10 year period of rainfall data analysis associated with the Villanova BTI site, which is located about 760 m (2500 ft) from the weighing lysimeters, the likelihood of back to back storms is not a concern. For a storm event larger than 81 mm (3.2 in), there is only a 15% chance of a storm larger than 44.5 mm (1.75 in) beginning within 2 days or longer (Appendix A, Figure A.1). For design storm events of 25 mm (1 in) there is only a 3% to 20% chance of a storm of the same magnitude to occur within 2 days to 4 days after (Appendix, Figure A.2).

Focusing on water quality, rain gardens with an IWS system that creates a saturated zone have been shown to provide water quality benefits, such as denitrification (Hunt et al. 2006; Hunt et al. 2012). The saturated area provides anaerobic conditions for nitrate to produce harmless nitrogen gas, which comprises 78% of the gaseous environment (Brown et al. 2009). Various case studies of rain gardens with IWS have shown nitrogen removal in the forms of both total nitrogen and total Kjeldahl nitrogen (Dietz et al. 2006; Davis et al. 2006; Hunt et al. 2006; Hunt et al. 2008; Hunt et al. 2012).

The present study will determine if systems with an IWS are a viable SCM solution to account for volume reduction. Most IWS case studies have been done in North Carolina and have provided the scientific background to show an increase in pollutant removal for a rain garden with an IWS (Dietz et al. 2006; Davis et al. 2006; Hunt et al. 2006; Hunt et al. 2008) in the North Carolina BMP manual (2009). North Carolina has a mild climate (during the fall and spring) and rainfall patterns similar to that of PA (PA BMP 2006; NC DENR 2009). Pennsylvania has a typical range of 94 to 114 cm (37 to 45 in) of rain annually (PA BMP 2006), while NC rainfall varies based on the mountainous, Piedmont, and coastal regions, but has a typical range of 94 to 127 cm (37 in to 50 in) per year (NC DENR 2009). The design capture of SCMs in NC are 2.5 cm (1 in) in the Piedmont and mountainous areas and 3.8 cm (1.5 in) in coastal areas (NC DENR 2009), similar to that of PA design capture. Therefore, the findings from the NC case studies on IWS systems are most likely applicable in the southeastern PA region; these case studies will be used to verify the results herein.

2.1.3.2 Controlled Valve Outflow

The controlled valve outflow would essentially be the same design as a conventional bioretention pipe system with the addition of a valve to regulate the flow after exiting the bioretention basin and prior to entering the stormwater sewer. Although a controlled valve outflow design requires more attention, it also provides flexibility and potential for enhanced hydrologic performance. The user is able to allow for full flow during rain events to achieve the immediate volume reduction via infiltration. The user is also able to close the valve completely to allow for a permanent water storage system for a temporary, or user defined, amount of time. The controlled valve can be thought of as a customized IWS, where the height of the upturned elbow can vary as needed. A study utilizing a float controlled discharge regulator on a stormwater detention basin was effective in controlling the discharge rate despite storage depth (Higgins 1995). In the urban setting, a controlled outflow allows for collection and slow release of impervious runoff to prevent erosion, flooding, or combined sewer overflows (Higgins 1995).

At the time of writing, the process for sizing of the IWS is still uncertain (Davis et al. 2009). The recommended height of the upturned elbow is generally 0.3 m (1 ft) or greater for a media depth of 0.9 m (3 ft) or greater (Brown et al. 2009). However, this design has flexibility so long as it provides a 30.5-45.7 cm (12 to 18 in) unsaturated zone above the saturated zone. The controlled valve outflow has the opportunity to challenge these constraints.

Gate valves and other types of valves that allow for partially constricted flow allows the user to operate in the range between fully open and fully closed. The controlled valve also offers a much more dynamic system to complement the dynamic environment in which it functions, both in terms of before, during and after a rain event and seasonally. The drawbacks of the controlled valve outflow system is the incorporation of moving parts that will likely need maintenance and informed persons to operate the valve.

2.2 EVAPOTRANSPIRATION

Evapotranspiration (ET) is the combined effort of water loss to evaporation from surfaces and transpiration from plant life. Evaporation consists of any water that is returned to the atmosphere from the soil surface, depression storage, or intercepted storage. Evaporation is governed by climate and driven mainly by the solar energy required to convert water from a liquid to a gas phase. The latent heat of vaporization is the amount of energy needed for evaporation and is a function of the vapor pressure deficit. The rate of evaporation is dictated by climatological parameters as well as soil water availability (Allen et al. 1998; Feller 2010). Actual evaporation can be estimated as close to 90% of potential evaporation (evaporation based on climatological parameters) for a saturated surface (Ward et al. 2004). The case of a constant saturated surface is not often met in stormwater applications, thus evaporative rates are dictated by the available surface water quantities (Allen et al. 1998).

Transpiration consists of any water that leaves through the vegetated surface via plant stomata and plant root uptake from the soil to return to the atmosphere. The plants leaf structure and aperture of stomata allows for the evaporation to occur from the leaf surface and by a vapor pressure gradient (Allen et al. 1998; Feller 2010). Once the vapor leaves the leaf, more water is drawn up from the underlying root system bringing with it nutrients to sustain the plant (Ward et al. 2004). The available amount of water is limited by the soil moisture content of the underlying soil. Transpiration rates are dictated by the same parameters as evaporation: the available water and climatological factors such as solar radiation, temperature, wind speed, and relative humidity. Transpiration rates will vary by plant, growth stage, season, and environment (Allen et al. 1998).

The dominating part, evaporation or transpiration, in the combined term of ET is dependent on the amount of foliage present. In the case of bare soil, evaporation governs ET. As the density of the vegetation increases transpiration governs ET as the vegetation will shade the soil below (Allen et al. 1998). In practice, evaporation and transpiration are combined into one term: evapotranspiration, because of the difficulty in distinguishing between the two simultaneous processes (Ward et al. 2004). Evapotranspiration is a known component of the water balance and can account for up to 50% of the annual water budget for some Delaware River Basin watersheds (Sloto 2005), for example.

The goal of the present research is to equip and monitor weighing lysimeters to quantify ET and infiltration in different rain garden media and drainage configurations. Ultimately, the goal is to quantify the amount of ET so that rain gardens of similar configurations may take credit for ET as a means to reduce stormwater volume. This quantification of ET has the potential to be incorporated into industry practice to give rain gardens of similar configurations ET accreditation. Quantifying ET is not a new concept in and of itself; it has been heavily studied in agriculture (Allen et al. 1998; Ward et al. 2004) and for landfill caps (Benson 2012), but remains unaccounted for in rain garden SCMs as a volume reduction mechanism. Monitoring with soil moisture meters sensors in agricultural use aid in estimating ET to maximize irrigation (Fares et al. 1999). At the time of writing there are no known studies quantifying ET in rain garden systems; there have been some studies on green roofs, but the dynamics are different than rain gardens.

Currently, the state of the practice allows designers to take volume credit for only the water that infiltrates through a rain garden (PA DEP 2006; VA DCR 2011; MD DES 2007; NC DENR 2009). Allowing designers to use the volume reducing mechanism of ET will help to reduce the size and therefore the cost of rain gardens, as well as enable implementation where infiltration is not recommended. Evapotranspiration has been a topic of great discussion in academia and the public and private sectors of industry.

Conferences, such as the World EWRI Congress and LID Symposium, have sessions devoted to ET in recent years. During the PA Stormwater Symposium 2013, great interest was shown for the best methods to account for green roof ET (Wadzuk 2013) and was a popular topic during plenary talks. The importance of this component is of obvious interest to professionals currently working in the field. Yet, much research remains before including ET as a design element is adopted in practice.

2.3 LYSIMETER DESIGN

Lysimeters are devices that are built to assess the water balance budget of a vegetated or non-vegetated soil column. The use of lysimetry technology dates back to 1640 with the work done by Philippe de Hire for use in agriculture (Rivera 2013). Lysimeters assess the water balance by attempting to monitor all or most of the water into or out of the system. Since ET is the hardest to capture, it is the unknown of the system, and can be derived from a mass balance of the remaining variables. The lysimeter design

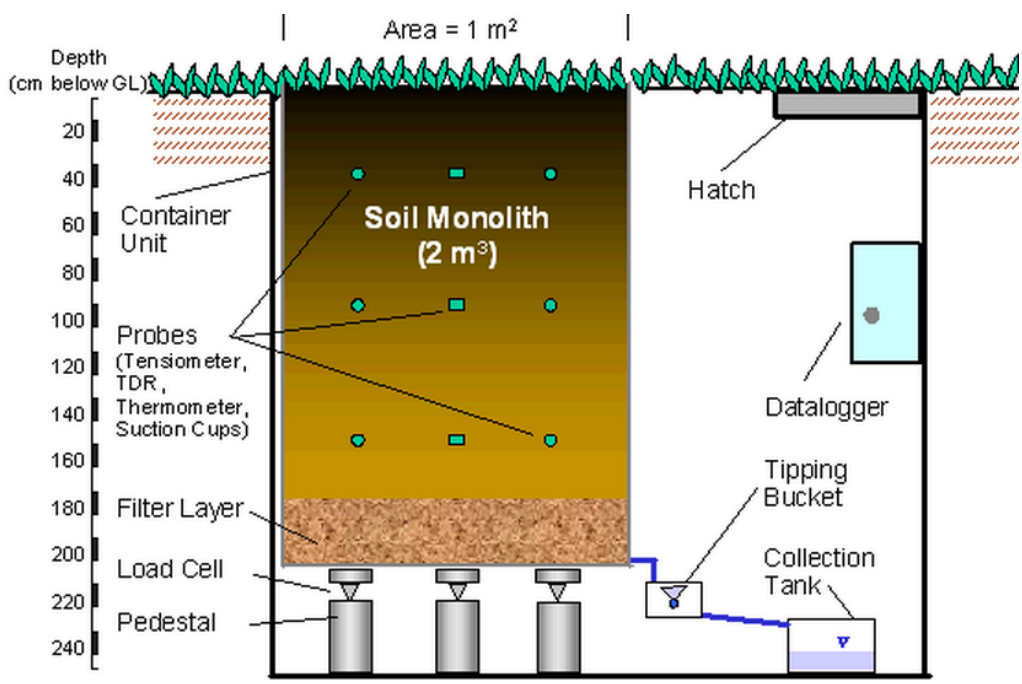

Figure 2.3: Compression Weighing Lysimeter Schematic (Meissner 2004)

for agricultural typically involves a sunken monolithic soil column that rests on compression load cells (Figure 2.3). The lysimeter requires a system to measure outflow percolate, sensors to measure desired parameters, a hatch for maintenance access, and a data logger collecting the necessary parameters. The inflow via tipping bucket or other rain gage is necessary to complete the mass balance in which these systems operate. These types of systems have been established in agriculture to predict when and how much water to irrigate to a specific crop (Allen et al. 1998).

2.4.1 Rain Garden Lysimeter Design

Lysimetry technology has many applications, including using it to evaluate rain garden design. Tension load cell weighing lysimeters have been previously studied at Villanova University (Hickman 2011). Two rain garden designs with different medias and drainage designs were monitored (Figure 2.4). One lysimeter was built to mimic the expected ET loss from a free flowing outflow with a similar soil mix to a Bioinfiltration

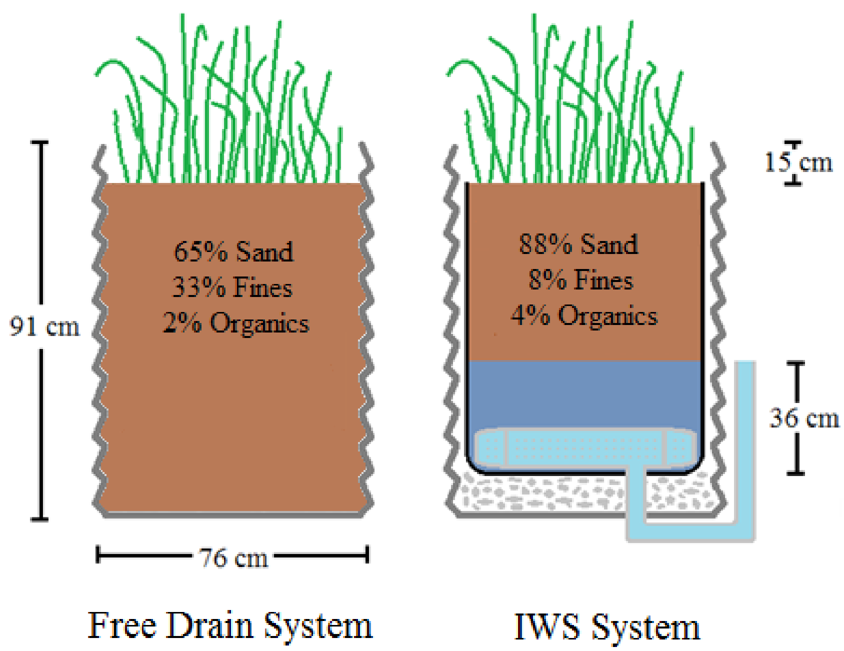

Figure 2.4: Previously Studied Lysimeters

Traffic Island (BTI) rain garden located at Villanova University. This soil mix was developed by mixing half of the "native" Glenelg Loam and half concrete sand (Hickman 2011), for more soil specific information consult Section 3.3.4.2. The second lysimeter consists of a lined sandy media mix with an IWS drainage layer of 36 cm (18 in). For a 10 month period, 35% and 63% of the contributing precipitation was removed by ET for the freely draining infiltrating design and bioretention design with an IWS, respectively (Hickman 2011). The results of Hickman (2011) work revealed that both rain gardens were effective at producing considerable amounts of ET that can contribute to overall stormwater volume reduction. Many details about bioretention systems are still to be determined; these include when it is appropriate to use underdrains and depth of the IWS layer (Davis et al. 2009). Since bioretention technology increases the amount of ET activity, it is vital to continue to study this technology under different configurations.

2.4.2 Predictive ET Equations

In 1948, the Penman equation was first developed to quantify evaporation off of surfaces by combining energy and mass balance of the system (Penman 1948). Monteith added aerodynamic and surface resistivity factors to account for vegetation to create the Penman-Monteith (PM) equation to account for transpiration (Monteith 1965). The PM equation served as the basis for the Federal Agriculture Organization (FAO) to establish a standardized equation for reference ET (Doorenbos and Pruitt 1975). The FAO56 manual presented a modified PM equation to standardized it to a 0.12 m (0.4 ft) crop height, a surface resistance of 70 s/m, aerodynamic resistance of $\frac{208}{u_2}$ s/m, and an albedo (refection coefficient) of 0.23, where u_2 is the average daily wind speed at 2 m (6.5 ft) from ground level in m/s (Allen et al. 1998; Equation 2.1)

$$\textbf{Equation 2.1: } ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where ET_o is reference ET in mm/day, Δ is the slope of the vapor pressure curve in kPa/°C, R_n is the net solar radiation on the crop surface in MJ/m^2/day, G is the soil heat flux density in MJ/m^2/day, γ is and altitude based psychometric constant in kPa/°C, T is the average daily temperature at 2 meters from ground level in °C, e_s is the saturation vapor pressure in kPa, e_a is the actual vapor pressure in kPa, and the vapor pressure deficit is defined as $(e_s - e_a)$ in kPa. The reference ET equation assumes that there is adequate water available. Water availability has the biggest effect on the amount of ET that can actual be produced and the potential ET that this equation is computing. Crop coefficients, K_c, and stress coefficients, K_s, can be applied to the reference ET to provide a closer estimate to the actual ET produced. Crop coefficients are based off of the physical properties of the crop and have been established for a variety of crops. Furthermore, K_c values can be further broken down in to initial, middle, and ending season stages (Allen et al. 1998). Crop coefficient values can increase or decrease ET_o to provide reliable ET estimates (Allen et al. 1998). The stress coefficient K_s is a reduction factor that depends on the availability of water. To obtain K_s, a daily water balance computation for the root zone must be performed (Allen et al. 1998). Although stress produced from lack of available water is important and directly effects amount of ET, it is much harder to determine an accurate estimate of this value.

The American Society of Civil Engineers (ASCE) have accepted a modified FAO56 PM equation that calculates a standardized potential reference ET, ET_{sz} (Walter et al. 2000; Equation 2.2).

$$\textbf{Equation 2.2: } ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

Where ET_{sz} is standardized reference ET in mm/day, C_n is the numerator coefficient that relates to time step, C_d is the denominator coefficient that relates to the crop height. These coefficients are fixed in FAO56 PM to 900 for a time step of a day and 0.34 for a crop height of 0.12 m (0.4 ft). For this application, these assumptions are appropriate, therefore the ASCE modified PM equation (ASCE-PM) will be the same as the equation presented in FAO56 equation (Equation 2.1). The predictive ASCE-PM (or FAO56) ET equations presented here have been found to most closely predict ET off of crop weighing lysimeters when compared so other available equations (Lopez et al. 2006).

Hickman (2011) made a comparison between reference ET, ET_o, and the observed lysimeter ET, ET_L, produced from the lysimeter based on load cell weight change. He reported that the ET_o most likely predicts the ET_L for the months of May, October, November, and December for the free flowing lysimeter and for the months of October and November for the bioretention lysimeter. During these months, the lysimeters where closest to mimicking the criteria that governs the predictive ET equations, mainly that the lysimeters had an adequate supply of water. The free flowing lysimeter actual ET was severely over predicted in the warmer months of August and September by more than twice predictive equations due to moisture deficit. Using the ASCE-PM equation in an SCM application, such as a rain garden or green roof, has had variable results, but still remains the most closely predicting of available equations (Feller 2010; Hickman 2011).

CHAPTER 3: METHODOLOGY

3.1 SITE AND LYSIMETERS

The weighing lysimeters are located at the northern end of campus near the Villanova School of Law, adjacent to the Stormwater Wetland Site (Figure 3.1). The

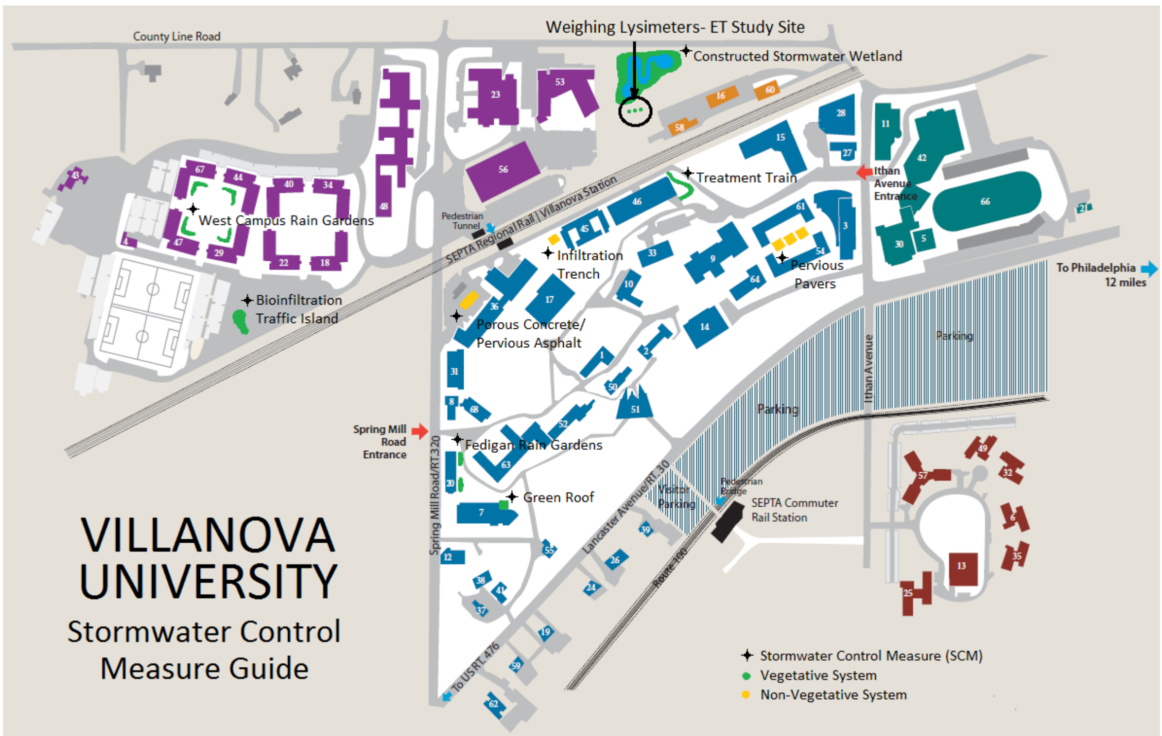

Figure 3.1: Villanova University Evapotranspiration Site

Villanova University ET study site is geographically located at latitude 40° 2' N and longitude 75° 20' W at an elevation of approximately 120 m (390 ft) above sea level in Villanova, Pennslyvania.

The site consists of three identical lysimeter housings. Each lysimeter is housed inside of a concrete well 1.83 m (6 ft) deep and 1.22 m (4 ft) square. There is a concrete ceiling with a 1.07 m (3.5 ft) diameter hole through which a 0.76 m (2.5 ft) diameter and 0.91 m (3 ft) deep galvanized steel weighing bucket hangs from an open 1.22 m (4 ft)

Figure 3.2: Weighing Lysimeters

cube galvanized steel structure (Figure 3.2). This ratio of diameter to depth of the lysimeter meets the design recommendation that a lysimeter must be at least as deep as its diameter (Marek et al 1998). The soil column fills approximately 0.76 m (2.5 ft) of the cylinder depth, leaving 0.15 m (0.5 ft) of free space at the surface to allow for ponded water within the lysimeters. The ponding depth is in compliance with the recommended range of 0.15 to 0.3 m (0.5 to 1 ft) stated in the PA BMP Manual (PA DEP 2006).

Weighing lysimters work on the principle of a mass balance, where the evapotranspiration (ET) is equal to the precipitaiton (P) minus the outflow (O) and change in storage (ΔS). This can be seen in Equation 3.1.

$$\textit{Equation 3.1: } ET = P - O - \Delta S$$

The S-Beam tension load cell measures the change in weight and is used as a proxy to the change in storage. Stevens Water Monitoring Systems Hydraprobe II soil moisture and salinity sensors measure soil moisture changes over time through the soil profile, which helps to better understand the storage and transport of water within the media column.

Precipitation is measured by an American Sigma rain gauge tipping bucket located approximately 5.5 m (18 ft) from the lysimeters. A weather station is located approximately 4.5 m (15 ft) away equipped with an anemometer for wind speed, a relative humidity and temperature sensor, and a solar radiation sensor (Figure 3.3). These climatological parameters are collected in 5 minute intervals and are necessary in estimation equations of ET. The outflow percolate is measured through a custom made

Figure 3.3: On-site Weather Station

percolate measurement collection system that is elaborated on in Section 3.3.2. Refer to Figure 3.4 for a cross section schematic of this overall mass balance. The three lysimeters

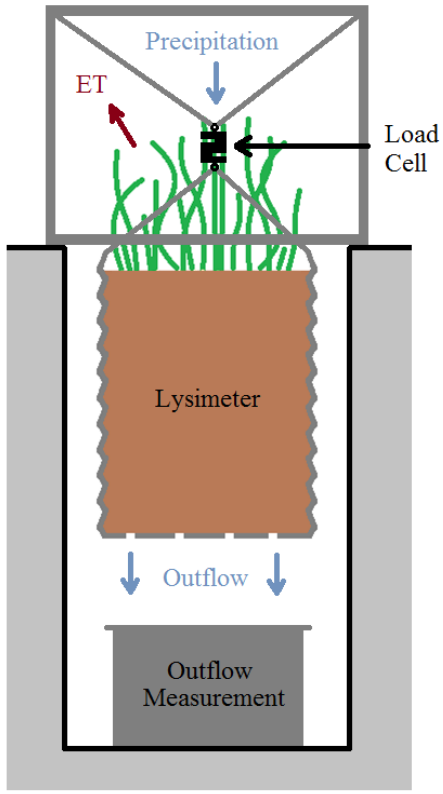

Figure 3.4: Mass Balance of Weighing Lysimeters

are built to mimic three different rain garden configurations (Figure 3.5). The first, labeled 1, is a “native” soil with a controlled valve outflow system. The second, labeled 2, is an “engineered” soil with the same controlled valve outflow. The third, labeled 3, is

Figure 3.5: Labeling of Weighing Lysimeters

an “engineered” soil with an internal water storage zone. Figure 3.6 provides a detailed cross sectional view of each lysimeter.

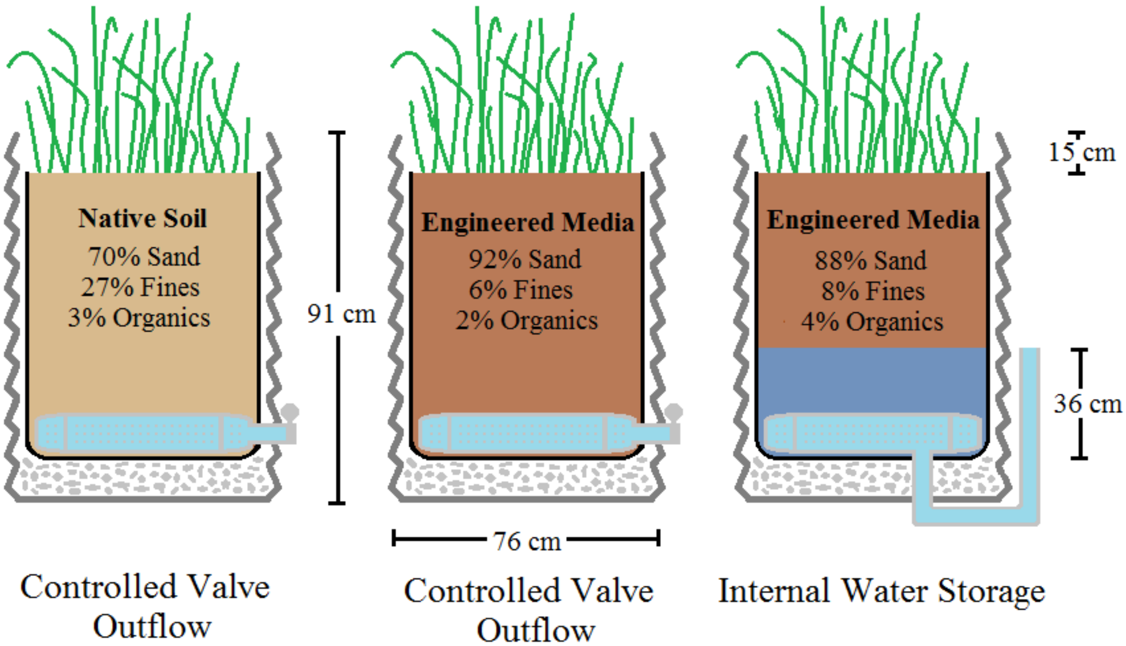

Figure 3.6: Overview of Weighing Lysimeters

3.1.1 Lysimeter 1- Native Soil with Controlled Valve Outflow

Lysimeter 1 is comprised of a “native” soil media that had been taken from Villanova’s campus in 2012; construction of this lysimeter was completed in the summer of 2013. Soil specific information is found in Section 3.3.4.2. The outflow system is comprised of a 5.1 cm (2 in) gate valve that connects to a 10.2 cm (4 in) perforated plastic pipe. This perforated pipe represents the underdrain. The underdrain system rests on 10.2 cm (4 in) of 2 cm (0.75 in) coarse gravel, on top of the coarse gravel and directly under the 4 in (10.2 cm) slotted PVC pipe. Wrapped around the slotted PVC pipe is more 2 cm (0.75 in) diameter clean coarse gravel. Gravel placement under the liner is done so for sturtural purposes, whereas gravel placement around the underdrain prevents clogging of the underdrain and mimics recommended bioretenion designs (PA DEP 2006). The valve handle is secured along the curved side of the corrugated metal conduit to allow for access to valve (Figure 3.7) that can be opened fully, partially opened or closed to

Figure 3.7: Valve and Handle Configuration

manually regulate percolate flow out of the system. During dryer months the valve may be completely closed to act as a temporary internal water storage zone for plants. Whereas wetter months the valve may be full open to allow for maximum storage during a rain event. This flexible design will allow for future studies on the outflow rate and its impact on storm water quantity mitigation. However, the present study the valve will remain at half full flow capacity. This half open configuration allows for an area of flow of 4.0 cm^2 (1.57 in^2). A hose attachment is placed on the outflow side of the gate valve to funnel percolate into the collection system.

There is a 45 mil (1.14 mm) ethylene propylene diene monomer (EPDM) liner, typically used for ponds, around the inside of the bucket (Figure 3.8). This type of EDPM

Figure 3.8: Liner and Clean Out Pipe Installation

liner is used in other SCM sites on campus, such as a rain garden comparison site of a lined and unlined system. This is in compliance with the recommended thickness of 30 mil (0.76 mm) or greater for bioretention technology (MD DES 2007). There is a 3.8 cm (1.5 in) cleanout pipe attached to the perforated underdrain pipe (Figure 3.8) to release accumulated sediment trapped in the underdrain. Soil moisture meters were installed at specific depths during the placement of the soil (Section 3.3.4).

The hanger arrangement is optimized to improve the amount of solar radiation and rainfall reaching the buckets to better simulate the actual conditions without sacrficing structural support. Four chains attach the bucket to the upper corners of the cube and converge at a Sentran S-beam tension load cell, as in seen in Figure 3.9.

Figure 3.9: Tension Load Cell

3.1.2 Lysimeter 2- Engineered Media with Controlled Valve Outflow

Lysimeter 2 has essentially the same set up as lysimeter 1, however the media is comprised of a more "typical" rain garden soil mix. The valve configuration, clean out pipe, underdrain design, soil mositure meter placement, liner, and contruction time line remained consistant between lysimeter 1 and 2. The “engineered” media placed in lysimeter 2 was designed to match the existing media is lysimeter 3.

3.1.3 Lysimeter 3- Engineered Media with Internal Water Storage

Lysimeter 3 consists of an “engineered” soil and a permanent water storage zone. Consult Section 3.3.4.2 for soil specifc information. For this design, instead of a valve, an upturned elbow is connected to the underdrain device. The 10.2 cm (4 in) underdrain drains to a 5.1 mm (2 in) outflow pipe that angles around the side of the bucket with two 90 degree turns. A ball check valve was also placed on the bottom of the upturned elbow for future maintenance (Figure 3.10). The purpose of the upturned elbow is to create an

Figure 3.10: Upturned Elbow with Valve

internal water storage (IWS) layer for plants to draw moisture from during periods of low rainfall, as well as to create an anaerobic zone similar to bioretention designs of Hunt et al. (2006).

The upturned elbow has a total height of 46 cm (18 in) up the side of the lysimeter bucket; this creates the upper boundary of the IWS layer. Due to the structural gravel support, this leaves an approximately 36 cm (14 in) layer of saturated soil to house denitrifying bacteria and acts as a reservoir for plants to draw from during dry periods. The top of the upturned elbow is attached to a hose, as seen in Figure 3.11. This hose is

Figure 3.11: Upturned Elbow with Hose Attachment

used to funnel the percolate into the outflow measurement system, simlar to that of lysimeter 1 and 2.

This lysimeter was established in 2010, but was alterated in the summer of 2013. The upturned elbow diameter was changed from 3.8 cm (1.5 in) to 5.1 cm (2 in), the lysimeter was de-weeded and re-planted, soil mositure meters were installed, and an ouflow measurement device was incorporated.

3.2 PLANTS

The plant selection was informed by the plants selected for the Bioinfiltration Traffic Island (BTI), as well as recommendations from the horticulturalist from Villanova's Facilities and Maintenance Department. The quantity and names can be found in Table 3.1 and pictured in Figure 3.12.

Table 3.1: Plant Selection and Quantity

Type	**Common Name**	**Scientific Name**	**Quantity (gallon buckets)**			
			Lysimeter 1	**Lysimeter 2**	**Lysimeter 3**	**Total**
Herb	Seaside Goldenrod	Solidago Sempervirens	2	2	2	6
Woody	Black Chokeberry	Photinia Melanocarpa	1	1	1	3
Grassy	Switch Grass	Panicum-virgatum	1	1	0	2

The selected plants are indigenous to the New Jersey coast and are resistant to saline environments. Salt resistivity is necessary for rock salt accumulation in rain gardens from de-icing of pavements during the winter months. Since lysimeter 1 and 2 were completely reconstructed, there were no previous plants inhabiting the soil. Lysimeter 3 had plants in the soil media previously and contained invasive species. This lysimeter was weeded and new plants were planted, however this lysimeter is especially prone to presence of invasive species as the seed bank remains, thus weeding occurs periodically. All lysimeters were planted on June 13th 2013 with a layer of topsoil for nutrients. A monthly plant inspection is performed such that correlations between plant health and ET production can be assessed to the fullest.

Figure 3.12: Switch Grass (top right), Seaside Goldenrod (bottom right), and Black Chokeberry (right)

3.3 INSTRUMENTATION

Total rainfall, relative humidity, solar radiation, temperature, and wind speed were measured and recorded by a Campbell Scientific CR1000 data logger in 5 minute intervals. The control box is located approximately 4.5 m (15 ft) from the weighing lysimeters at the Stormwater Wetland site. The instrumentation associated with the mass balance includes a tipping bucket rain gage for inflow, distance sensor for percolate, tension load cells and soil moisture meters for change in storage; all measured in 5 minute intervals.

3.3.1 Rain Gage Inflow

The 20 cm (8 in) American Sigma Tipping Bucket Rain Gage is used to measure rainfall. The rain gauge is located on a level base by the control beam. It has a resolution of 0.25 mm (0.01 in) and an accuracy range from 1% to 5% (American Sigma 2001; Heasom et al. 2006). According to the manufacturer, at the 0.5% accuracy range, a total of 12.7 mm/hr (0.5 in/hr) can be recorded (American Sigma 2001). Over the 5 minute record interval, a total of four tips can be accurately accounted (American Sigma 2001).

3.3.2 Percolate Outflow Measurement Device

Below each lysimeter there is an outflow measurement bucket to capture the percolate from the rain garden microcosm. This device consists of a constant diameter bucket, with the following attachments: a ToughSonic Senix ultrasonic measurement device, the percolate hose, and a solenoid outflow valve (Figure 3.13). In the field, the

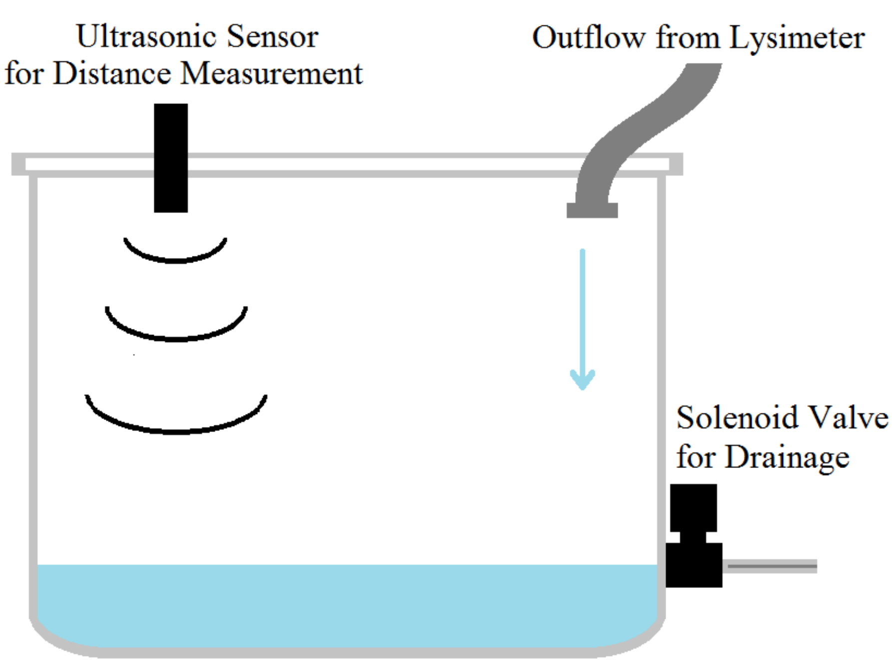

Figure 3.13: Percolate Measurement Schematic

outflow hose is placed opposite to the distance measure sensor to avoid detecting high ripple effects from the hose (Figure 3.14). The bucket is emptied by gravity to its zero

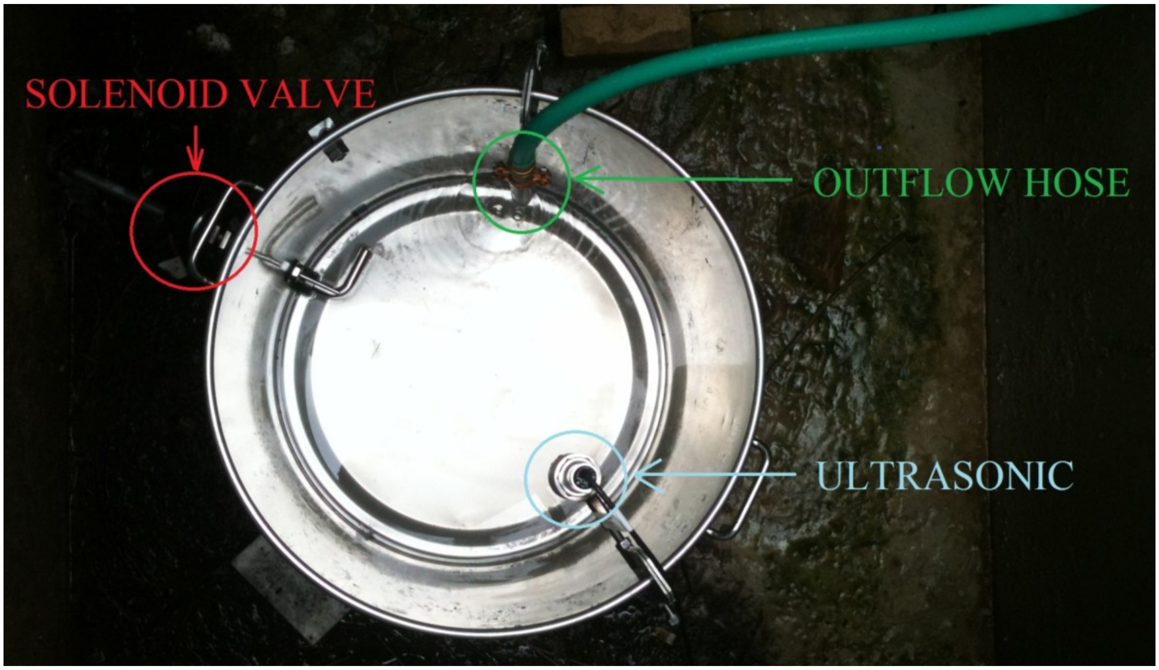

Figure 3.14: Field Percolate Measurement System

point via the solenoid valve prior to overfilling and every storm simulation.

The ultrasonic outflow measurement device monitors water height level within the bucket. The distance sensor is optimized to operate within the depth of the bucket and internally compensated for temperature. This particular sensor functions on the speed of light, which varies in relation to temperature. The water level reading is converted to the infiltration rate of the soil column through a relationship between the diameter of the bucket and the diameter of the soil column. The ultrasonic setup allows for recording large to very small flows that is necessary to capture the peak of the storm simulations to the dripping of percolate hours after the rain event.

3.3.3 Load Cell Calibration

The bucket is mounted on a Sentran S-Beam (ZA1) tension load cell to measure the weight over time. A tension load cell is used over the compression type due to the increased accuracy it provides. The Sentran S-Beam tension load cell has a combined error of 0.025% of the rated output compared to the 0.030% of the rated output given for the comparable compression model. Each has a capacity of 11 to 907 kg (24 to 2000 lb), with a maximum lysimeter weight measurement of 770 kg (1700 lb). The load cells are subject to diurnal fluctuations; this variability becomes significant, especially when tracking ET fluctuations in weight as small as 2 or 3 mm (0.08 to 0.12 in) of water per day, which is equivalent to 0.9 to 1.4 kg (2 to 3 lb) in these lysimeters (Hickman 2011). Previously, one of three lysimeters remained empty as to provide as a control weight. However, since the results from those studies provided that the load cells were reliable, the control lysimeter was repurposed into a soil carrying lysimeter to provide another comparison rain garden design.

Load cell calibration was still performed to confirm the design is reliable. To verify the lysimeter weight measurements, known weights of 4.5 kg (10 lbs) were added to each lysimeter for a 26 hour period in fall and spring. The weight of the lysimeter the day prior and after were compared to that of the day during the test, such that dew effects would not be present. The difference between the daily readings should correlate the ET and load cell weight. The verification was performed during late October 2013. The ASCE Penman-Monteith equation calculates ET_{sz}, the standardized reference ET, based on climatological parameters and was used as an estimate of expected ET. These climatological parameters were collected from the on-site weather station for October

22nd and October 23rd yielded a daily ET_{sz} of 1.17 mm (0.046 in) and 1.28 mm (0.05 in), respectively. These calculations utilized a crop height of 0.12 m and all other assumptions stated in Section 2.4.2. The results of the load cell calibrations for the tension load cell on Lysimeter 1 can be seen in Table 3.2.

Table 3.2: Load Cell Verification for Lysimeter 1

Day	Hr	Min	Day Prior (kg)	Added Weight (kg)	Weight Removed (kg)	Difference in Weight (kg)	ASCE-PM Daily ET (mm)	ASCE-PM Daily ET (kg)	Derived Added Weight (kg)
22	8	0	565.3	568.4	-	3.18	+1.17	+0.54	3.72
22	8	5	565.3	568.6	-	3.27			3.80
22	8	10	565.5	568.7	-	3.14			3.67
23	10	35	-	567.9	562.9	5.06	-1.28	-0.58	4.47
23	10	40	-	568.1	562.9	5.27			4.69
23	10	45	-	568.4	562.9	5.54			4.95

Lysimeter 2 and 3 were calculated in a similar manner (Appendix B). The daily ET predicted by the ASCE PM Equation pre and post the addition of the known weight is shown to be similar to each other, which is expected as the weather conditions were relatively the same between the two days (Appendix B). The ET was converted into a weight using the density of water at the mean temperature of the day over the surface area of the lysimeter. The weight from the ET is added to the difference in weight for the day prior and subtracted for the day after. The derived load cell weight should be similar to that of the known weight (4.5 kg or 10 lb) added to the system. A similar analysis for the same period for lysimeters 2 and 3. A comparison of the derived load cell differences and the known load added is seen Table 3.3. The percent difference associated with the load cells the day prior ranges from 9-23% and the day after from 5-7% (Table 3.3). The day prior reading was taken at 8:00 am on October 22nd and the range in error can be attributed to morning dew formation. The readings taken the day after at 10:00 am on October 23rd are less likely to have a discrepancy because of added moisture. There is also inherent error with the calculated ET from the ASCE PM Equation, as assumptions are made and computed based on climate alone and is not truly representative of the actual ET produced by the lysimeters. The calibration revealed that the load cell accuracy is adequate.

Table 3.3: Average Difference Load Cell Comparison

Date	Derived Added Weight-1 (kg)	Derived Added Weight-2 (kg)	Derived Added Weight-3 (kg)	Known Weight (kg)	Difference for Load Cell 1	Difference for Load Cell 2	Difference for Load Cell 3
22-Oct	3.72	4.42	3.67	4.54	20%	3%	21%
	3.80	4.15	3.59	4.54	18%	9%	23%
	3.67	3.94	3.54	4.54	21%	14%	25%
	Average Error:				**19%**	**9%**	**23%**
23-Oct	4.47	4.60	4.52	4.54	1%	1%	0%
	4.69	4.73	4.73	4.54	3%	4%	4%
	4.95	5.26	5.08	4.54	9%	15%	11%
	Average Error:				**5%**	**7%**	**5%**

3.3.4 Soil Moisture Monitoring

Soil moisture monitoring was implemented throughout the profile of the three weighing lysimeters, as well as in the adjacent in situ soil. Steven's Hydraprobe II soil moisture sensors are placed at 10 cm (4 in), 35 cm (14 in), and 65 cm (26 in) depth, with a duplicate sensor at 35 m (14 in) depth (Figure 3.15). The placement of these sensors were selected to be at the top, middle and bottom of each lysimeter to get a full profile of the water path. The 10 cm (4 in) placement will be in the dense root zone, the 35 cm (14 in) is approximately placed at the interface of the top of the water reservoir in lysimeter 3

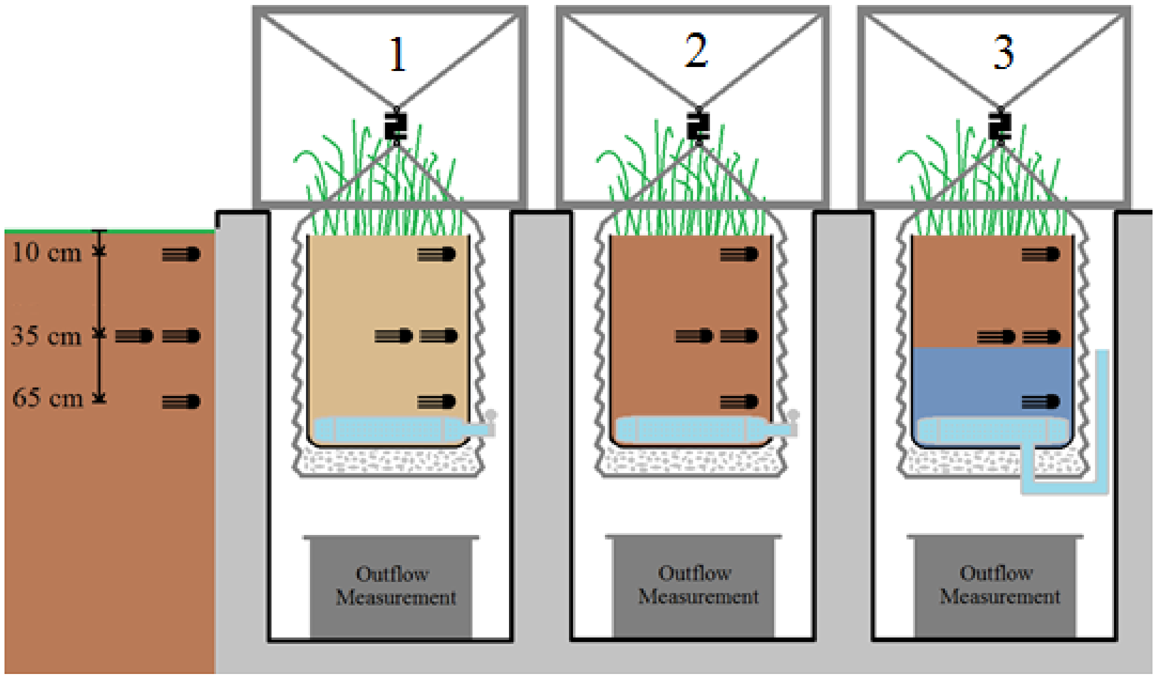

Figure 3.15: Soil Moisture Meter Placement

and the 65 cm (26 in) was the deepest that the moisture meters could feasibly be placed without conflicting with the drainage pipe. A duplicate sensor was placed at the 35 cm (14 in) mark for quality assurance purposes.

3.3.4.1 Soil Moisture Meter Selection

The two soil moisture meter probe candidates were the Hydraprobe II developed by Steven's and the GS3 probe developed by Decagon. Both probes have their flaws and assets depending on the probe's environment. The sensors were studied for a two-month side-by-side comparison at two different depths in a rain garden media (23 cm or 9 in and 91 cm or 36 in). Both probes remained uncalibrated for soil type during this study and were left as the defaults in which the probes are manufactured. The results for a two week section where all four probes were operating successfully incorporates two storm events

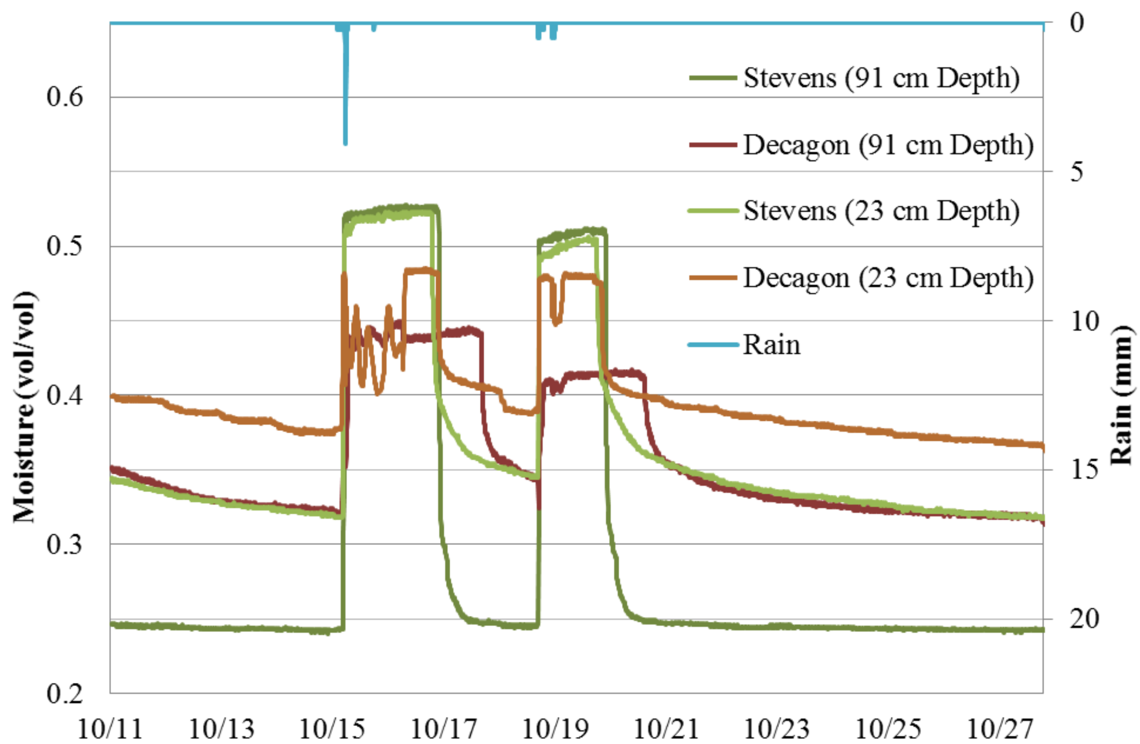

Figure 3.16: Soil Moisture (vol/vol) Reading Comparison for Two Devices at Two Depths. The red and orange lines are Decagon devices at 91 cm and 23 cm depth, respectively. The dark green and light green lines are Steven's devices at 91 cm and 23 cm depth, respectively. Rain (mm) is on the secondary axis.

and the four probes response to each of the events (Figure 3.16). The Decagon probes produce an acute variation on the soil moisture, whereas the Steven's probes seem to react extremely.

The overall trends are similar, however, the Decagon device at 23 cm (9 in) depth produces a fluctuation from the response of the first storm event on October 16th, 2012, and even makes a seemingly erroneous dip in moisture during the October 19th 2012 event. A notable difference between the two devices is observed at a depth of 91 cm (36 in). The Decagon device recorded high soil moisture readings for almost a day longer than that of the Stevens device, which may, in part, be attributed to the default equations used in the factory calibrations of each device. The main difference between the two is what the probe is reading. They both utilize dielectric permittivity as the measurement that is taken through the soil media, but Stevens utilizes the real component and Decagon utilizes the combination of both the real and imaginary to find the apparent dielectric permittivity. Dielectric permittivity relates charge separation to the applied electric field and is the technology used in many current soil moisture meters (Wightman 2003). The appropriateness of which component of the dielectric permittivity for soil moisture determination is beyond the scope of this work, however, it is important to know what is being measured to understand that a true comparison of probes cannot be made.

Decagon GS3 sensor is better for use in a greenhouse environment, and durability of the device during the winter months was of concern. Since the Hydraprobes had been installed in another monitored site at Villanova, the Bioinfiltration Traffic Island (BTI) rain garden, they were selected for programming familiarity and installation feasibility. Steven's Hydraprobe II had sufficient literature containing the wiring feasibility aspect related to the site specific data logger system and the total number (sixteen) of the meters needed. Ultimately, Steven's Hydraprobe II devices were selected for the study, given the performance during the test period, ease of calibration and user familiarity from another study site.

3.3.4.2 Soil Testing

Soil testing was completed on the different lysimeter media, the in situ profile adjacent to the lysimeters, and the Bioinfiltration Traffic Island (BTI) media, and a comparison rain garden. The "native" media placed in lysimeter 1 was taken from the corner of Ithan Avenue and Lancaster Avenue in Villanova University's campus during a campus reconstruction effort. The media was taken at a profile from the top of grass to about 1 m (3 ft) down. The adjacent in situ media provides a “native” control profile with no SCM design. The engineered media in lysimeter 2 was purchased from the same company and ordered with the same specifications known in the existing lysimeter 3. The goal of these tests are to better understand the behavior and properties of the soil to guide in predicting the movement of water related to infiltration and evapotranspiration in these systems.

This analysis included grain and particle size distribution (sieve and hydrometer ASTM D 422), specific gravity (ASTM D 854-00), bulk dry density (ASTM D 2937-00), moisture contents (ASTM D 2216), organic content (ASTM D 2974) such that required properties and USDA classification are determined (Table 3.4).

Table 3.4: Soil Properties and USDA Classification

Averaged Item	**BTI**	**In Situ**	**Lysimeter 1**	**Lysimeter 2**	**Lysimeter 3**
Bulk Dry Density (g/cm^3)	1.16	1.24	1.02	1.03	1.03
Specific Gravity	2.65	2.58	2.58	2.65	2.65
Sand (%) (2-0.05 mm)	66	72	72	96	92
Silt (%) (0.05-0.002 mm)	23	27	27	4	8
Clay (%) (>0.002 mm)	11	1	1	0	0
USDA Classification	Sandy Loam	Loamy Sand	Loamy Sand	Sand	Sand

A minimum of two sieve tests and one hydrometer test was performed for each soil type and the averages are presented (Figure 3.17). The native media placed in lysimeter 1 was assumed to have the same grain and particle distribution as the in situ profile with a different bulk dry density. Rain gardens are typically much less compacted than that of

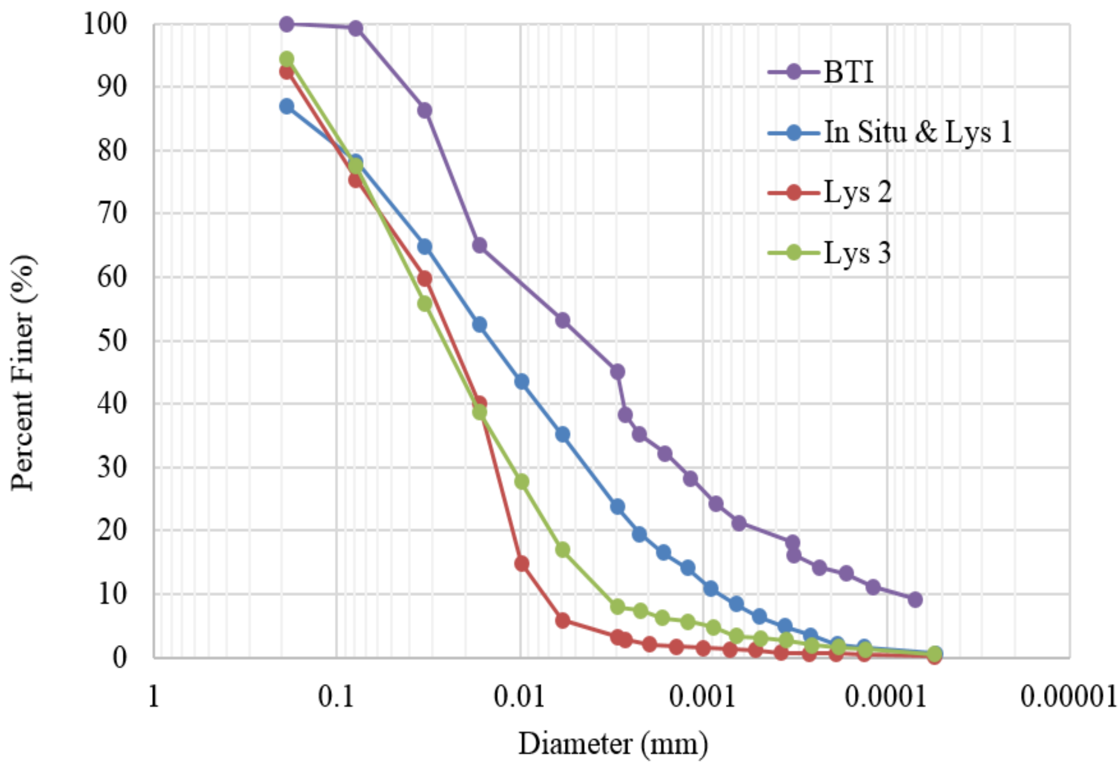

Figure 3.17: Grain and Particle Size Distribution. Purple line is BTI, blue line is In Situ and lysimeter 1, red line is lysimeter 2 and green line is lysimeter 3.

the non-SCM in situ soil. Bulk dry density of the soil is used to convert gravimetric to volumetric soil moisture by Equation 3.2.

$$\textit{Equation 3.2: } \theta = w\rho_d$$

Where θ is the volumetric soil moisture in volume per volume, w is the gravimetric soil moisture in percent water, and ρ_d is the bulk dry density of the soil in g/cm^3. Specific gravity tests results were utilized in determination of the saturated moisture content (ASTM D 854-00). Bulk dry densities were determined by a soil core and the moisture content of the soil. The bulk dry density is vital for the conversion of gravimetric to volumetric moisture contents for soil moisture meter calibration (ASTM D 2937-00; ASTM D 2216). The BTI media had been previously analyzed (Isaac-Ricketts 2008;

Gilbert Jenkins et al. 2010; Lord 2013) and that data is presented in Table 3.4 for comparison.

With the inclusion of the organic matter, these soils were classified by the Unified Soil Classification System (USCS) (Table 3.5). For this classification fines are defined as particles less than the No. 200 sieve (0.075 mm) opening.

Table 3.5: USCS Classification with Organics

Average	BTI	In Situ	Lysimeter 1	Lysimeter 2	Lysimeter 3
% Sand (2-0.75 mm)	65	70	70	92	88
% Fines (>0.075 mm)	33	27	27	6	8
% Organics	2	3	3	2	4
USCS Classification	SM (silty sand)	SM (silty sand)	SM (silty sand)	SP (poorly graded sand)	SP (poorly graded sand)

The organic content of the soil was determined by a mass difference method; this value will be important for determining a base line for future organic matter tests for root growth (ASTM D 2974).

Soil water characteristic curves (SWCC) were developed for each soil based on the given grain and particle size distribution with the saturated moisture content using the Fredlund and Xing model (1994) with a pedotransfer function (Fredlund et al. 2002). A soil water characteristic curve is used to predict the soil suction at various moisture contents including the theoretical field capacity and wilting point of the media (Figure 3.18). An estimation of these parameters are taken at, or close to, the negative suction values of 33 kPa and 1550 kPa, respectively (Van Genuchten 1980; Karkanis 1983; Decagon 2014). Field capacity can also be defined at a different suction value on the

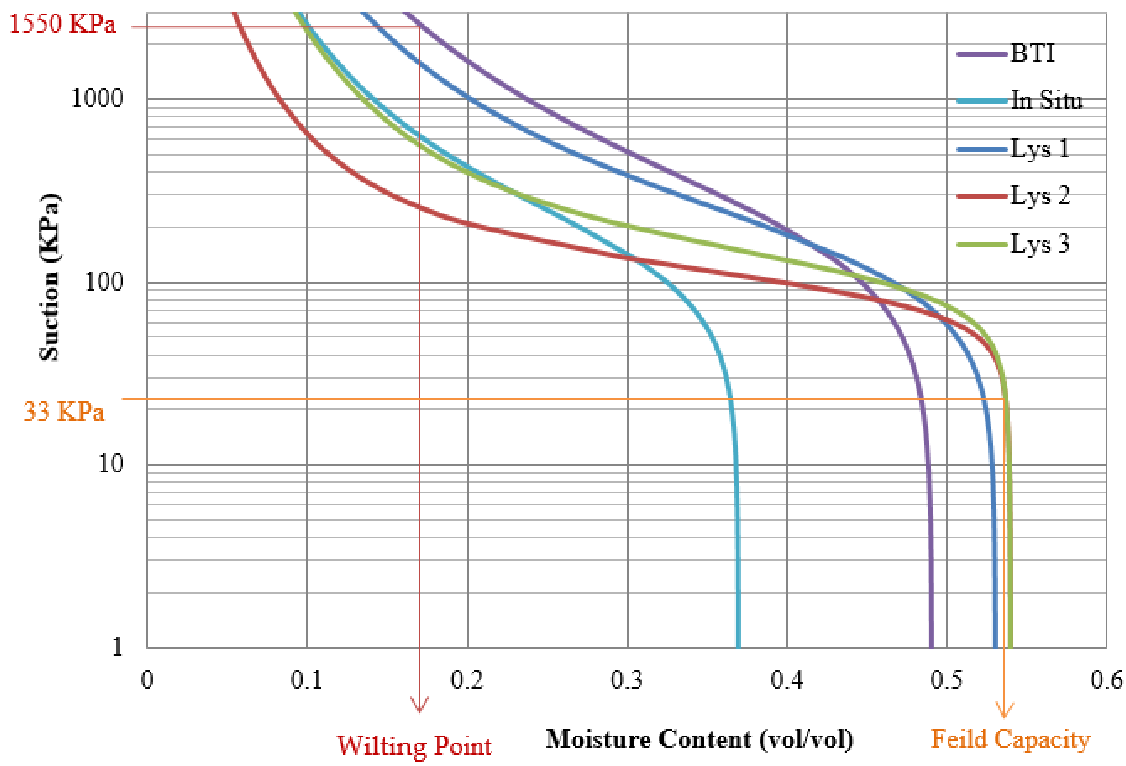

Figure 3.18: Soil-Water Characteristic Curves. Purple line is BTI, light blue line is In Situ, dark blue line is lysimeter 1, red line is lysimeter 2 and green line is lysimeter 3. Red and orange arrows indicate estimated wilting point and field capacity, respectively.

SWCC visually corresponding to the inflection point, related to a lower moisture content in these cases (Twarakavi 2009). The field capacity parameter of the soil is not well defined and varies with compaction of the soil (Twarakavi 2009; Tinjum 1997). Tabulated field capacity based on soil type recommend a value of 18% for Sandy Loams, according to Saxton and Rawls (1986), with higher moisture contents relating to soils with greater percent fines.

Soil specific values are always preferable to assumed values, thus a field capacity test was designed and performed on each soil type, then confirmed with the visual inflection point of the SWCC. This test consists of a sample in a known volume compacted to that of the matching bulk dry density. The sample was then flooded with water until saturation and allowed to drain for 24 hours, 2 days, and 3 days. Field capacity can be reached anywhere between 24 hours to 3 days after a rain event, and will be related to the depth of the column. The field capacity test utilized for the 15 cm soil column. The change in mass was measured for 24 hours, 2 day, and 3 day, and yielded similar results each time, due to the relatively small sample column. The experimentally determined volumetric moisture contents related to the field capacity and the wilting point are compared with that of literature established values (Table 3.6).

Table 3.6: Field Capacity and Wilting Points

Media Type	**USDA Classification**	**Experimental Values**		**Average Values (Rawls et al. 2006)**	
		FC (vol/vol)	**WP (vol/vol)**	**FC (vol/vol) [(%)]**	**WP (vol/vol) [(%)]**
BTI	Sandy Loam	35	20	21 [18]	9 [8]
In Situ	Loamy Sand	29	12	15 [12]	6 [5]
Lysimeter 1	Loamy Sand	32	17	12 [12]	5 [5]
Lysimeter 2	Sand	31	7	10 [10]	5 [5]
Lysimeter 3	Sand	31	11	10 [10]	5 [5]

The moisture contents for field capacity were estimated by the field capacity tests and confirmed with the inflection point of the SWCC. The wilting point was taken as the moisture content that relates to the suction pressure of 1550 kPa on the SWCC.

3.3.4.3 Soil Moisture Meter Calibration

In recent years, soil moisture monitoring technology has significantly improved, but still only provides an estimate of soil moisture. Therefore, calibration based on soil parameters is recommended to get more meaningful results. It is important to keep in mind that the soil moisture is not the actual measurement that the probe reading.

Dielectric permittivity is the parameter that is being read, and it has both a real and imaginary component. Real and imaginary numbers occur when dealing with the mathematical square root function. In the Stevens Hydraprobe, only the real component is taken into account when the square root is determined (Stevens 2007). This signal is then used in either a square root function (semi linear polynomial function) or a third power polynomial function to obtain the soil moisture (Bellingham 2007). The default calibration for Hydraprobe II is the square root function utilized for loam soil type seen in Equation 3.3.

$$\textbf{\textit{Equation 3.3:}}\ \boldsymbol{\theta = A\sqrt{\varepsilon_R} + B}$$

Where θ is the volumetric soil moisture measured in volume per volume, ε_R is the real dielectric permittivity, and A and B are coefficients found by the curve of best fit. Sand, silt, and clay soil types are calibrated with the Equation 3.4.

$$\textbf{\textit{Equation 3.4:}}\ \boldsymbol{\theta = A + B\varepsilon_R + C{\varepsilon_R}^2 + D{\varepsilon_R}^3}$$

Where A, B, C, and D are the coefficients found by the polynomial line of best fit. The clay, silt, and sand calibrations require different coefficients to mimic the behavior of the soil type. Figure 3.19 shows the various media on the USDA soil classification triangle. The shaded area in Figure 3.19 represents the soils that are recommended for the default loam calibration (Stevens 2007). Since the soil types that are of interest are mostly in the loam and sand range, the manufacturer's default clay and silt calibrations were not considered. The lysimeter 2 and 3 soil was determined to be primarily sand. The manufacturer's default sand calibration was satisfactory for these two soils. Due to this,

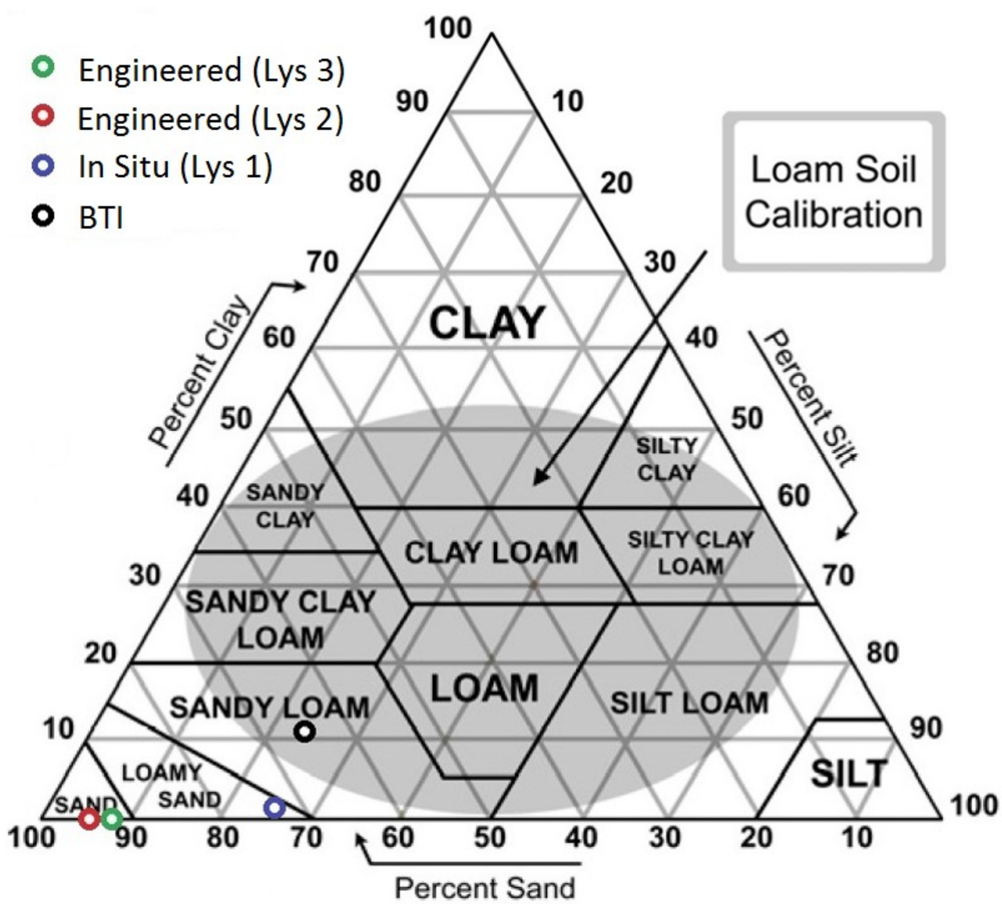

Figure 3.19: USDA Classification Triangle with Relevant Soils

only lysimeter 1, In Situ, and BTI media will be considered for custom calibrations. As mentioned previously, lysimeter 1 and the in situ profile were assumed to have the same grain size distribution, but their compaction will cause the two media to have unique calibrations.

To calibrate the system, a combination of moisture content tests along with experimentally determined soil properties were utilized. The ε_R was back calculated for the reading that corresponded to the time at which either the moisture content sample was taken or when the system was conjectured to be demonstrating wilting point and field capacity. Field capacity read from the soil moisture meters was taken at 2 and 3 days after the peak of a rain event over five different rain events. The 2 and 3 day readings were typically very similar, so they were averaged. Wilting point was determined by the SWCC and compared to the theoretical moisture deficit in which the device operates (Appendix C). Gravimetric moisture content tests were performed as mentioned previously and converted to volumetric via the bulk dry density (Equation 3.2) (Appendix C). The results of these determinations were plotted and the line of best fit was determined (Table 3.7). The square root function was deemed more appropriate for the in situ and BTI soils, whereas the third order polynomial equation was more fitting to lysimeter 1 soil. The coefficients of each calibration can be seen in Table 3.7.

Table 3.7: Soil Moisture Meter Calibration Coefficients

Soil Type	**Equation Type**	**Equation No.**	**Coefficients**			
			A	**B**	**C**	**D**
Default	Loam	3.3	0.102	-0.179	-	-
Recommended	Sand	3.4	-8.63	3.216	-0.0954	0.00158
BTI	Loam	3.3	0.0848	-0.136	-	-
In Situ	Loam	3.3	0.111	-0.219	-	-
Lysimeter 1	Sand	3.4	-8.70	3.216	-0.0954	0.00180
Lysimeter 2	Sand	3.4	-8.63	3.216	-0.0954	0.00158
Lysimeter 3	Sand	3.4	-8.63	3.216	-0.0954	0.00158

These soil calibrations will be applied to each of the systems to gain more accurate soil moisture meter readings based off of the individual soil media’s properties.

3.4 DISTRIBUTION SYSTEM

Rain gardens typically collect runoff from surrounding impervious area. The PA BMP Manual (2006) indicates suitable loading ratios for rain gardens range from 5:1 or 10:1. A loading ratio is defined as impervious runoff area to SCM area. Since there only exists a 1:1 loading on each lysimeter, a water distribution system was developed to mimic the runoff quantity from surrounding impervious surfaces. The distribution system was built and calibrated to handle a range of storm volumes and intensities. Storm events of 19, 38, and 76 mm (0.75, 1.5, and 3 in) over a 24 hour period were chosen, as they mimic design criteria for PA (PA DEP 2006). The 19 and 38 mm (0.75 and 1.5 in) storms relate to typical design critera for SCMs and the 76 mm (3 in) storm relates to the 2 year storm for PA, which ranges from 61 to 84 mm (2.4 to 3.3 in) across the state (PA DEP 2006). The smallest storm intensity, that of a 19 mm (0.75 in) storm at an 5:1 ratio yields a loading rate of 30 ml/min (0.008 gpm). The largest storm intensity is 241 ml/min (0.064 gpm) for the 76 mm (3 in) storm at a 10:1 loading ratio. The distribution system was design and calibrated to produce flow rates between 30 and 241 ml/min.

The location of the site adjacent to the Constructed Stormwater Wetland (CSW) provides for a supply of water for the distribution system. A 12.7 l/min (3.35 gpm) delivery pump is utilzed to overcome the height differentinal between the lysimters and the base of the sediment forebay of the CSW. The 1.91 cm (0.75 in) suction tube is elevated about 45 cm from the base covered with a mesh filter to avoid suspeneded soilds. Another easily accessable 150 micron (No. 100) mesh filter is in place before the delivery pump to ensure longveity of the pump as recommended by the manufacturer

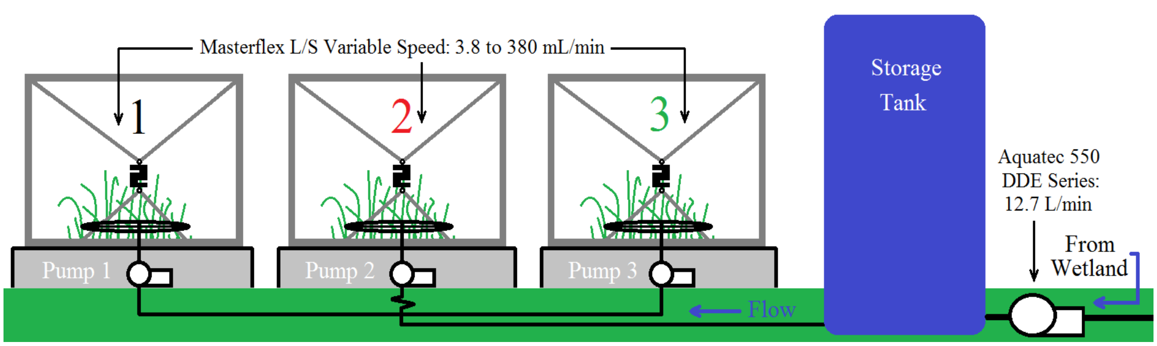

Figure 3.20: Distribution System Schematic

(Aquatec 2009). This set up provides the 380 liter (100 gal) storage tank with a reservoir of water (Figure 3.20). The storage tank provides water to a distribution head regulated by a peristaltic pump. The peristaltic pumps are able to produce variable flows of 3.8 ml/min to 380 ml/min (0.001 to 0.1 gpm), which incorporates the goal simulation range of 30 to 241 ml/min (0.008 to 0.064 gpm). The distribution head is made from 9.5 mm (0.37 in) flexible plastic tubing formed into a circle and preforated with approximatly twenty 1 mm (0.04 in) holes. The tubing is supported by 12.7 mm (0.5 in) PVC pipe (Figure 3.22).

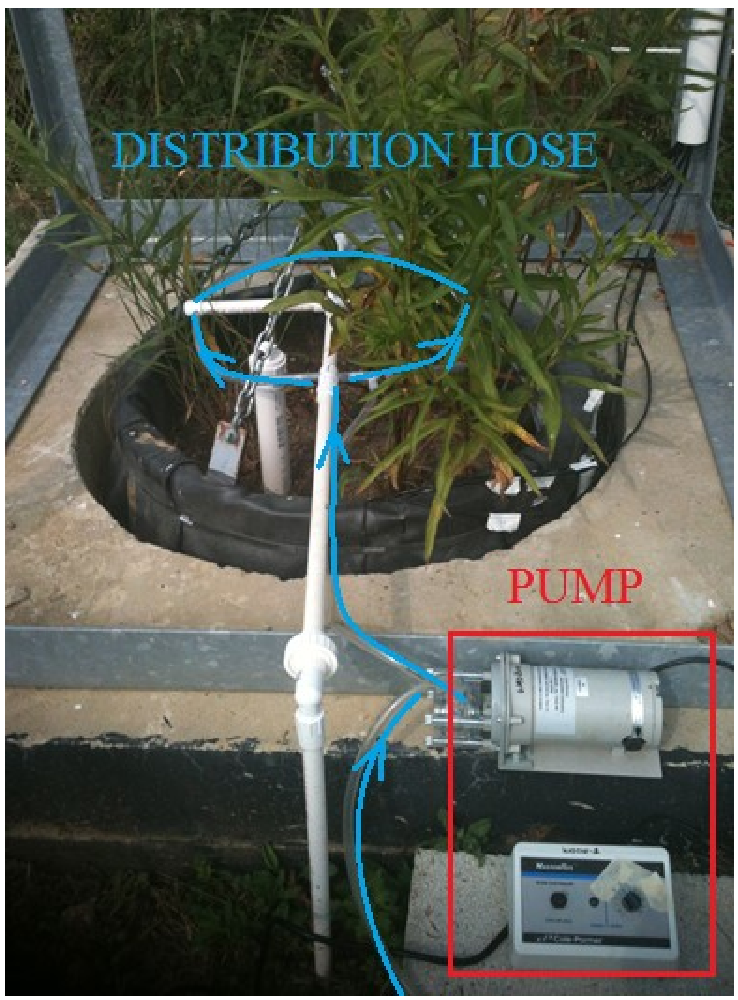

Figure 3.21: Flow (ml/min) to Calibrate for Pump Speed for Distribution System. Blue is lysimeter 1, red is lysimeter 2, and green is lysimeter 3 data.

Each of the three rain garden lysimeters has their own distribution system. Each distribution head and pump were calibrated together to account for any minor losses specific to the system. Calibration of the distribution system consisted of short and long flow testing. The short term testing provided a relationship of flow to pump speeds. Each of the three systems were tested twice for speeds 1 through 8 and averaged. The pump speed goes up to 10, however was not needed as the highest flow rate of 241 ml/min (0.064 gpm) that was achieved around a speed of 7 (Figure 3.21).

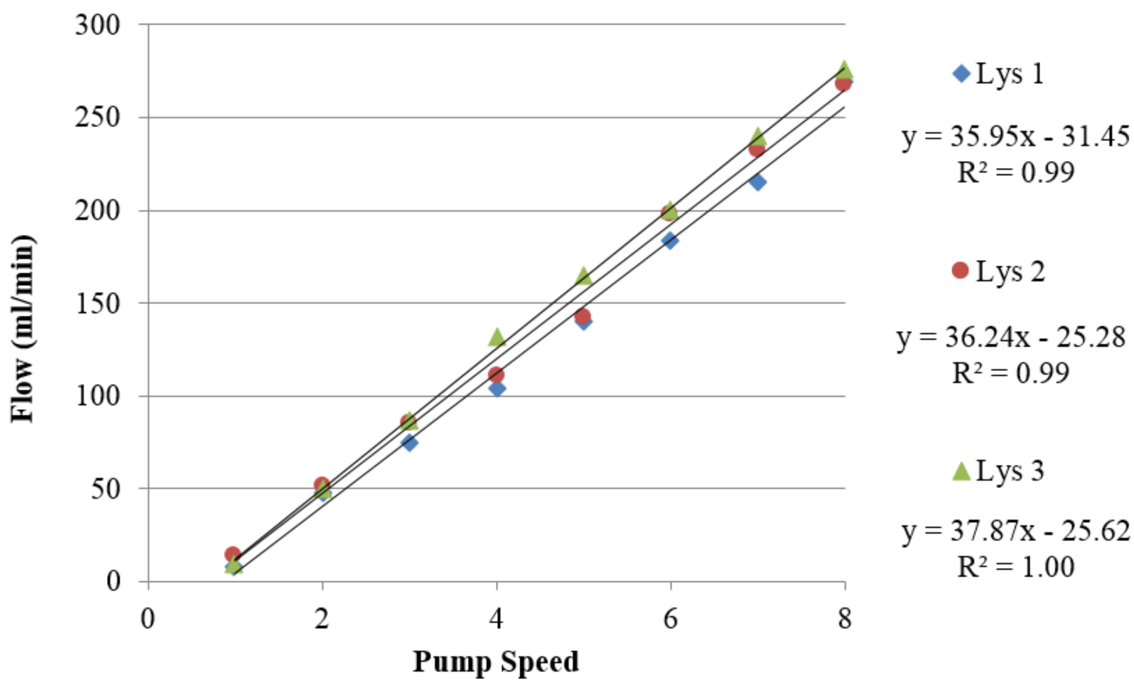

Figure 3.22: Distribution Hose and Pump over Lysimeter

The experimental data was determined by capturing the mass of the water released from the system for a known period of time (approximately 10 minutes). The mass of the water was then related to volume and a flow rate with time. The line of best fit was taken and the exact speed at which the pump needed to remain for the differing flows was interpolated. To verify these interpolated speeds, a long duration testing round was performed, the long duration ranged between 2 to 3 hours. Measurements were taken at known intervals within the time span to confirm that the rate was consistent. Some durations were held longer, almost up to 6 hours if no adjustments needed to be made. The adjustments consists of correcting the pump speed in case the flows were too fast or slow. An example of the median flow calculations for lysimeter 3 is shown in Table 3.8.

Table 3.8: Long Duration Flow Calculation Example

Flow- Medium (ml/min)	Interpolated Pump speed	Duration (hrs)	Goal Volume (ml)	Achieved Volume (ml)	Percent Error (%)
121	4	1.5	10859	10700	1.5
		3	21719	21580	0.6

Table 3.9: Error in Long Duration Distribution Verification

Flow Rate	**Lysimeter 1**	**Lysimeter 2**	**Lysimeter 3**
Low	5%	0%	5%
Medium	0%	5%	2%
High	7%	3%	1%
Average:	4%	3%	3%

The greatest percent error from each flow was determined and can be seen in Table 3.9. For very low flows, a slight incline to the distribution head could produce inaccurate flow amounts, so it is important that the distribution heads remain level over the duration of the test. To properly mimic weather conditions, as they affect ET, storm simulations will be performed during actual rainfall events. The inflow of the natural event will be added to the total volume of the storm simulation via the rain gage tipping bucket.

CHAPTER 4: RESULTS AND DISCUSSION

The following section is roughly divided into two sections: soil moisture and evapotranspiration (ET). The influence of media and drainage type is observed and compared for each of these sections. The soil moisture readings were first verified such that the soil moisture behavior through each lysimeter depth profile could be observed. Slope and lag time analysis of soil moisture reading responses to assess influence of media and drainage configuration on soil moisture readings. Minimum rainfall amount required to cause a reaction in soil moisture readings for both shallow and deep depths were determined.

The ET and percolation rates are calculated by the change in load cell and the percolation collection system, respectively. Performance of each lysimeters for ET and percolation is compared based on media and drainage type. The water budget distribution for all lysimeters for rainfall amounts under 40 mm (1.6 in) at a 1:1 loading ratio will be addressed. Minimum rainfall amounts to generate percolation will also be quantified. Comparison of data from the change in weight and soil moisture perspective will be done to verify the proxy to the change in storage parameter that is needed in the mass balance of the water budget.

The ET and percolation for storm simulations (i.e. 5:1 and 10:1 loading ratios) is also quantified and compared with that of the storms operating on a 1:1 ratio. Preliminary plant data will also be presented.

4.1 SOIL MOISTURE VARIABILITY

Two soil moisture meters were installed at a 35 cm (14 in) depth, which represent mid-depth in each lysimeter. For lysimeter 3, the depth of 35 cm (14 in) is at the top of the internal water storage zone. The soil moisture meters in the lysimeters were duplicated at this depth and installed side by side to quantify the reliability of the readings. For this analysis, mid-July of 2013 through mid-January of 2014 data was used for lysimeters 2 and 3 (Figure 4.1). Due to instrument issues, lysimeter 1 data from the

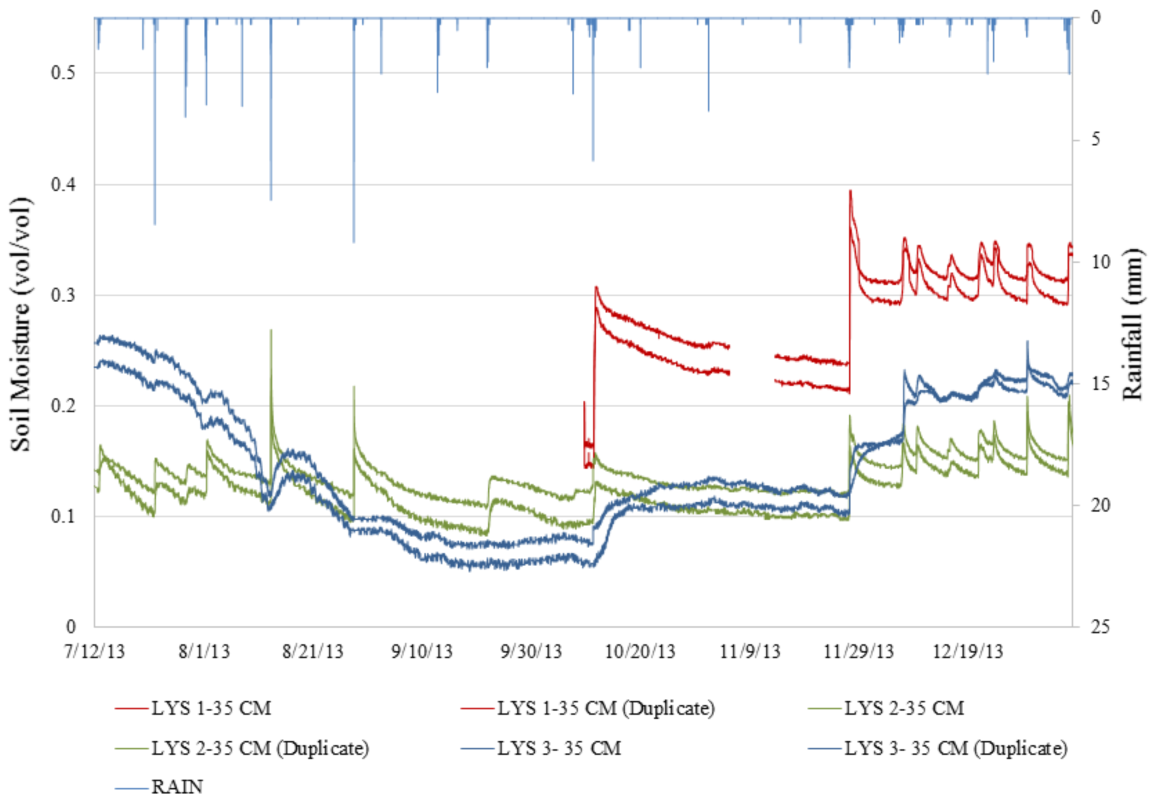

Figure 4.1: Soil Moisture Variability. Soil moisture readings (vol/vol) for an observation period demonstrate small variation of duplicates (meters at same depth). The red lines are Lysimeter 1, the green lines are lysimeter 2, and the blue lines are lysimeter 3. Rain (mm) is shown on the secondary axis.

beginning of October to January is presented. The soil moisture meters in situ profile adjacent to the lysimeter site were not functioning properly during for this observation period and are not analyzed here. The uncalibrated raw data is used for this purpose as it seeks to find the variability within the soil moisture probes themselves.

The standard deviation for each five minute interval over the entire analysis period of the two adjacently placed probes was found. The maximum of the standard deviation from this record period was then determined for each lysimeter and presented with the average for that % minute time interval. The mean moisture contents with the maximum standard deviation are 0.324±0.026, 0.247±0.031, and 0.210±0.030 vol/vol for lysimeters 1, 2, and 3, respectively, which corresponds to 2.6%, 3.1%, and 3.0% variability in the readings of raw soil moisture data. The manufactured specifications state the accuracy of the soil moisture meters is ±0.01 vol/vol for most soils and ±0.03 vol/vol maximum for fine textured soil (Stevens 2007). The maximum deviation experimentally determined on the raw soil moisture meter readings in the conforms quite well with the out of factory variability meaning that the soil moisture meters are operating as optimal as the technology will allow.

The calibration of these devices (Section 3.3.4.3) were done based on soil specific properties, which allow for the range of soil moisture to be more descriptive of the site specific soil. The most extreme variability of soil moisture readings is 3.1%, which is adequate for these systems. This variability could be caused by installation, even though the moisture meters were installed at the same depth, or soil settling after installation, which could have made a differential distance between the meters.

4.2 SOIL MOISTURE BEHAVIOR

The soil moisture data has been calibrated and based on individual soil type (Section 3.3.4.3). This data was processed by removal or smoothing of outlying erroneous measurements. These erroneous measurements most likely caused by connection error and not representative of actual soil moisture behavior. Since the discrepancy between the duplicate soil moisture meters was found to be acceptable and within the manufactured specified values, the average values for the duplicate sensors at 35 cm (14 in) depth will be presented.

4.2.1 Lysimeters 1 and 2

Overall behavior of the soil moisture meters through the entire profile of the soil columns is examined. Lysimeter 1 and 2 differ by the soil media and have the same controlled valve outflow. For this study, the outflow valve remains at half open with no alteration of the flow rate over time. Lysimeter 1 and 2 correspond to the red and green profiles, respectively, where a darker color indicate a deeper depth (Figure 4.2). The period of observation extends from the middle of July to end of October 2013. Soil moisture results were not reported past November, as there were complications with a few probes in

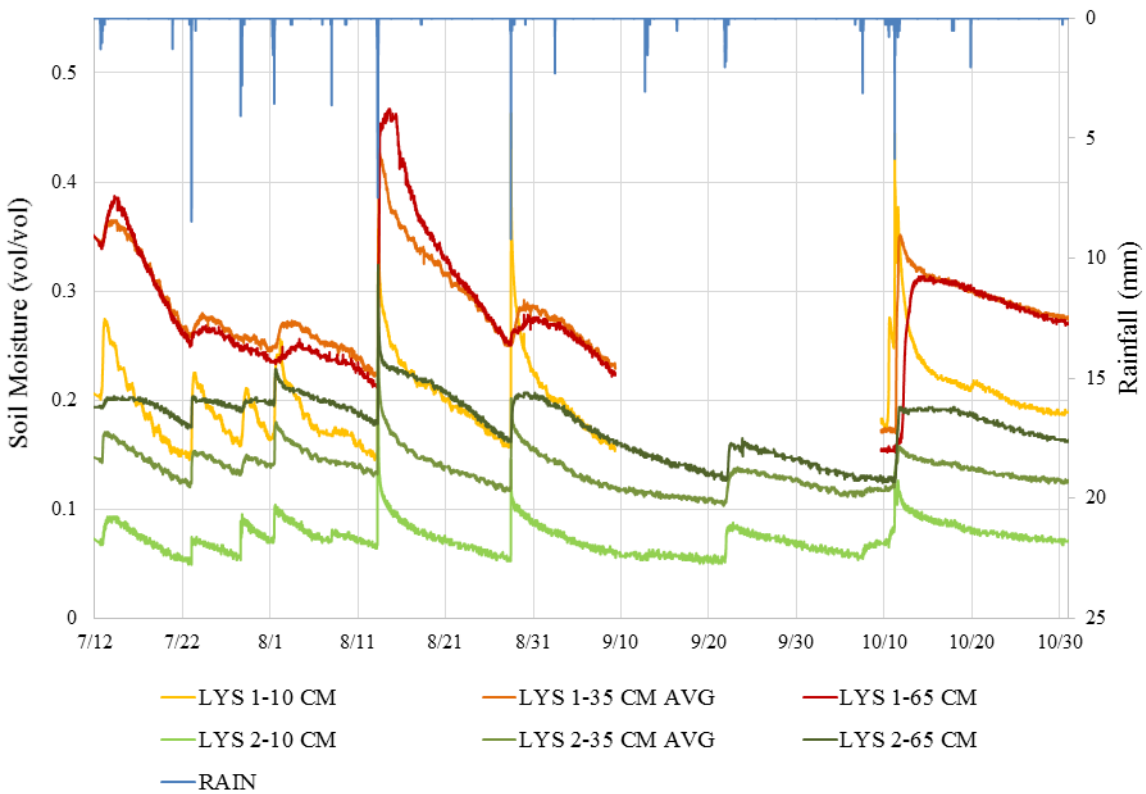

Figure 4.2: Soil Moisture Meter Readings (vol/vol) for Observation of Behavior for Lysimeter 1 and 2. Lysimeter 1 is the red (65 cm depth), orange (averaged 35 cm depth) and yellow (10 cm depth). Lysimeter 2 is the dark green (65 cm depth), medium green (averaged 35 cm depth) and light green (10 cm depth). Rain (mm) is shown on the secondary axis.

lysimeter 1 and one in lysimeter 2. In December into February, although all probes were functioning, the average ambient temperature for that time was 2°C (36°F) with a range of 19°C to -8°C (66°F to 18°F). These probes do not operate below freezing temperatures (0°C or 32°F) in soil, thus they will provide questionable results in the winter months (Stevens 2007).

In both lysimeters, the soil moisture meters at deeper depths read higher moisture contents than that of the shallower placed soil moisture meter readings. This trend is seen throughout the soil moisture analysis and is expected as root mass and density will decrease through the depth of the column such that water reduction via ET will decrease through the column. Also, since gravity is constantly at work, during a rain event water will percolate down through the column, where it would accumulate until the gravitational forces will exceed the soil suction forces and begin to outflow.

A typical response of the soil moisture meter readings to a rain event are displayed by a sudden increase, or spike, in soil moisture followed by a slower decline. For this outflow configuration, those reactions track down through the depth of the column. Lysimeter 1, consisting of the “native” soil with more fine material (loamy sand), has an overall wetter profile when compared to the sand media in lysimeter 2. This is expected as water does not flow as freely in finer materials when compared with well-draining media. Most of lysimeter 2 is comprised of sand, where the soil retains less water and water flows relatively quickly through the media when compared to lysimeter 1 soil.

All moisture meters have a similar trend of spiking when there is rainfall and slowly deceasing moisture during dryer times. The sensors at 10 cm (4 in) depth exhibit a greater sensitivity to the rain, as the moisture readings spike at the rainfall event very rapidly. The deeper sensors at 65 cm (26 in) depth tend to produce readings that exhibit a slower and rounder increase of moisture. Lysimeter 1 soil moisture meters at 35 and 65 cm (14 and 26 in) depths display a more rounded peak in comparison to the sharp spikes seen in Lysimeter 2 soil moisture meters at 35 and 65 cm (14 and 26 in) depths. The differences in soil media between lysimeters 1 and 2 is most likely responsible for the smoother response of deeper soil moisture meters from rainfall events, where the finer soil particles slow down the movement of water and dampen the response of the soil moisture meters.

There are minimum amounts of rainfall that are required to trigger reactions in the soil moisture meters throughout the profile. The probe reaction at shallow, 10 cm (4 in) depth, probes will be discussed separately from the reactions of deeper, 35 and 64 cm (14 and 26 in) depth, probes. This is done as the shallow probe can react independently and the deeper probes tend to react together. The soil moisture meters at 10 cm (4 in) is closest to the surface and within the root zone, thus making it the most likely to be influenced by small rainfall amounts and ET. The soil moisture meters responses at 35 and 64 cm (14 and 26 in) are deeper and can possibly be indicative of an outflow occurrence.

4.2.1.1 Minimum Soil Moisture Responses at Shallow Depth

The rain event on October 19th consisted of 4.6 mm (0.18 in) at an intensity of 3.92 mm/hr (0.15 in/hr) generated a small response to the soil moisture probe at 10 cm (4 in) depth in lysimeter 1 media, but no response in the deeper probes. This same phenomena was observed in the September 2nd storm with a rainfall of 5.6 mm (0.22 in) at an intensity of 3.53 mm/hr (0.14 in/hr). The intensities of all the storm over the observed time period (mid-July through October) range from 20.7 mm/hr to 0.69 mm/hr (0.81 in/hr to 0.03 in/hr) with an average of 4.5 mm/hr (0.18 in/hr). The minimum responses of each probe will try to be taken at the median intensity if the data is available, if not the storm that provides the more conservative estimate will be chosen. This concludes that the minimum response of the lysimeter 1 at 10 cm (4 in) depth is a rainfall of 4.6 mm (0.18 in) of moderate intensity.

The rain event on August 8th consisted of 8.6 mm (0.34 in) of rain at an intensity of 20.7 mm/hr (0.81 in/hr). This event was able to generate a small response to the soil moisture probe at 10 cm (4 in) depth in lysimeter 2 media. This same phenomena was observed in the September 12th storm with a rainfall of 15.3 mm (0.6 in) at an intensity of 1.12 mm/hr (0.04 in/hr). Since the intensity of the September storm is lower than average of 4.5 mm/hr (0.18 in/hr), the more extreme intensity will be chosen. The minimum response of the lysimeter 2 at 10 cm (4 in) depth can be obtained from a rainfall of 8.6 mm (0.34 in) at a high intensity.

4.2.1.2 Minimum Soil Moisture Responses at Deep Depth

The rain event on August 8th consisted of 8.6 mm (0.34 in) of rain at an intensity of 20.7 mm/hr (0.81 in/hr). This event was able to generate a small response to all soil moisture probes in lysimeter 1. Data is not available to observe the September 12th storm for lysimeter 1, so the July 28th event was utilized as it generates small responses in the deeper probes. This event consisted of 22.1 mm (0.87 in) at an intensity of 2.14 mm/hr (0.085 in/hr). The July storm was chosen to represent the lysimeter 1 as it consisted of a intensity that was deemed close enough to the median intensity of 4.5 mm/hr (0.18 in/hr).

A minimum response of the lysimeter 1 at 35 and 64 cm (14 and 26 in) can be obtained from a rainfall of 22.1 mm (0.87 in) at a moderate intensity.

The rain event on October 7th consisted of 17.4 mm (0.68 in) at an intensity of 3.92 mm/hr (0.15 in/hr) generated responses to all probes in lysimeter 2. This same phenomena was observed in the July 28th event consisting of 22.1 mm (0.87 in) at an intensity of 2.14 mm/hr. The October 7th event was delivered very close to the median intensity such that is was chosen to represent lysimeter 2. A minimum response of the lysimeter 2 at 35 and 64 cm (14 and 26 in) is 17.4 mm (0.68 in) at a moderate intensity.

Media in lysimeter 1 and 2 will retain water in the upper profile after 4.6 mm (0.18 in) and 8.6 mm (0.34 in) of rain, respectively. However, due to the intensity associated with the 8.6 mm (0.34 in) storm, it would be expected that a greater rainfall, up to 15.4 mm (0.6 in), at low intensity could have simulated a similar response in lysimeter 2. After 22.1 mm (0.87 in) and 17.4 mm (0.68 in) of rain for lysimeter 1 and 2, respectively, the lower depth of media shows moisture retention.

4.2.2 Lysimeter 3

Lysimeter 3 consisted of a sand media with the internal water storage (IWS) drainage system, providing a zone for saturation. The soil moisture response in lysimeter 3 is substantially different than lysimeter 1 and 2 because of the outflow structure (Figure 4.1). The same time period used for lysimeter 1 and 2 analysis is used for lysimeter 3 analysis (Figure 4.3). The sensors at 35 cm (14 in) depth are just above the interface of the internal storage zone, which is able to reach saturation if rainfall is abundant. The 65 cm (26 in) depth sensor is within the IWS zone. The behavior of the sensors show that in July the IWS was saturated with a maximum volumetric moisture content of about 52%. Following the sensor readings at 65 cm (26 in) depth, the IWS has an overall decline in

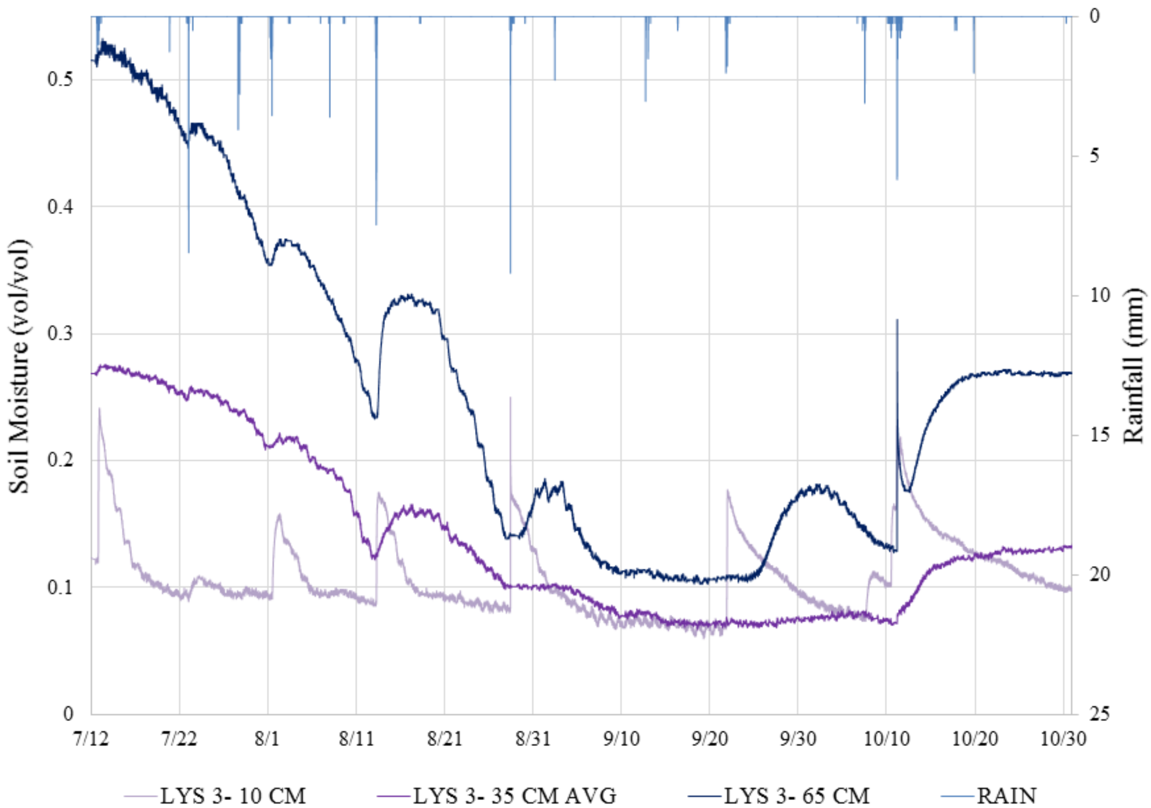

Figure 4.3: Soil Moisture Meter Readings (vol/vol) for Observation of Behavior of Lysimeter 3. The dark blue line is 65 cm depth, purple is averaged 35 cm depth, and light purple is 10 cm depth. Rain (mm) is shown on the secondary axis.

soil moisture and hits a minimum in September (10.5%). From July to September, about 313 mm (12 in) of rain had fallen, of this 91 mm of this was outflow. Historically, about 355 mm (14 in) of rainfall is average through these months. As this can be seen as a pretty average rainfall amount, the behavior of the saturated zone emptying during this time is to be expected. The soil moisture at 65 cm (26 in) has a rapid decrease at an intensity greater than that of the 35 cm (14 in) depth. This is evidence of root depth extending to this depth. Lysimeter 3 is unique as it was the only lysimeter to be planted in 2010; roots would have had ample time to establish in this lysimeter.

A rain event on August 8th consisted of 8.6 mm (0.34 in) of rain at an intensity of 20.7 mm/hr (0.81 in/hr) generated a small response to the soil moisture probe at 10 cm (4 in) depth in lysimeter 3 media, but no response in the deeper probes. A similar response was caused by the July 28th storm, but caused a small but notable reaction from the 35 cm (14 in) deep probe, was not considered. This concludes that the minimum response of the lysimeter 3 at 10 cm (4 in) depth is a rainfall of 8.6 mm (0.34 in) of high intensity.

The rain event on September 12th storm that consisted of 15.2 mm (0.6 in) at an intensity of 1.12 mm/hr (0.04 in/hr) generated responses to all probes in lysimeter 3. This same phenomena was observed in the July 22nd storm that consisted of 34.5 mm (1.36 in) at an intensity of 2.04 mm/hr (0.08 in/hr). The September storm event was chosen to represent lysimeter 3 as it is more conservative in rainfall amount rather than intensity. A minimum response of the lysimeter 3 at 35 and 64 cm (14 and 26 in) is 15.2 mm (0.6 in) at a low intensity.

4.2.3 Soil Moisture Comparison at Shallow Depth

Soil moisture at a shallow depth will be observed to compare all lysimeters and confirm calibrations. The shallow depth of 10 cm (4 in) was chosen for this comparison as it is the most descriptive for ET production as it is close to the surface and within the dense root mass zone (Figure 4.4). It can be seen that lysimeter 1 tracks an overall wetter profile compared to that of the lysimeter 2 and 3. This is due to the influence of the different soil types. Lysimeter 2 and 3 display similar moisture contents, as they are both sand medias. The influence of the IWS can be seen in lysimeter 3 by the slower recession limb of the soil moisture response to rainfall as compared to lysimeter 2. In some cases, such as the July 12th, August 1st, and October 10th events, lysimeter 1 display a similar response behavior to that of lysimeter 3, with larger peaks and slower decrease in soil

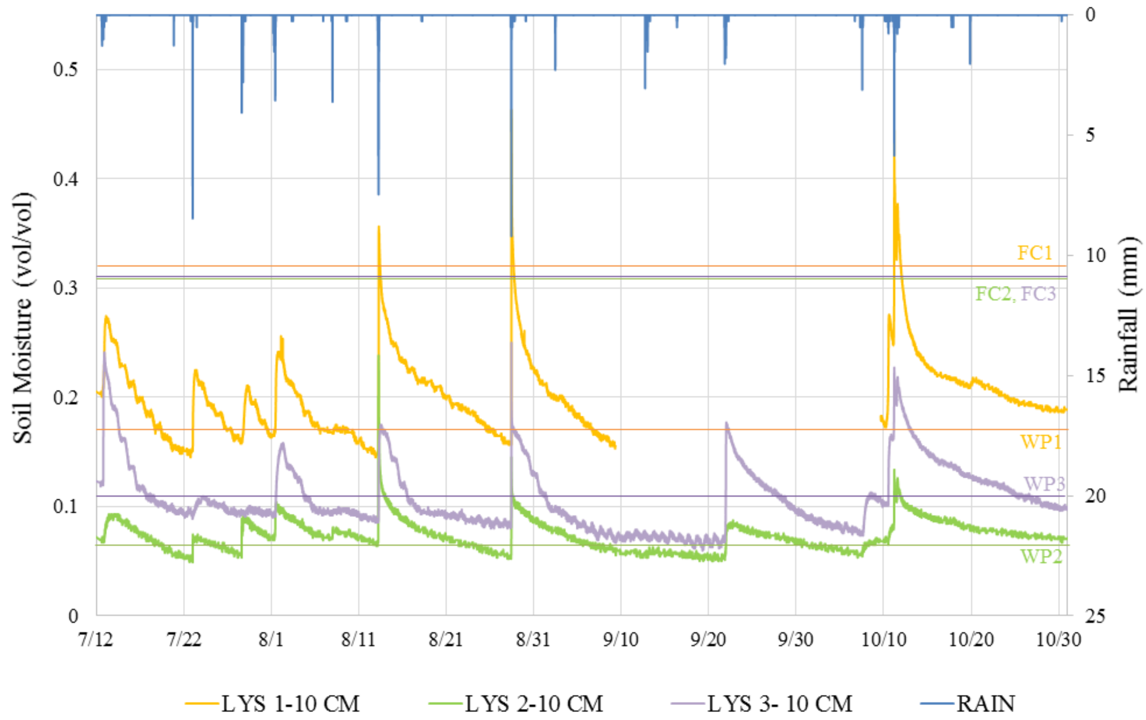

Figure 4.4: Soil Moisture (vol/vol) Vs Time at a 10 cm Depth. Experimental WP (wilting point) and FC (field capacity) is presented. Yellow is lysimeter 1, green is lysimeter 2 and purple is lysimeter 3.

moisture. However, there is most often a 0.5 vol/vol offset of soil moisture between lysimeter 1 and 2 soil moisture. This This indicates that amendment to media type and outflow type provide a longer duration of available water that can be lost to ET rather than outflow.

In order to confirm calibration, 10 cm (4 in) depth profiles were compared to wilting point and field capacity obtained from experiments and literature. The experimental field capacity and wilting points appear as they were determined previously (Section 3.3.4.2) in Figure 4.4. In general, each lysimeter operates within the experimentally determined wilting point to field capacity range. The soil moisture sometimes meets wilting point and is more often dropping below wilting point in each lysimeter during dry time between storms. As this is the shallowest moisture meter depth, it is expected that soil moisture is to come close to that of wilting point. In a stormwater application, where no irrigation occurs, it is not unrealistic that soil moisture will meet or drop below that of wilting point in times of water deficit. However, continual soil moisture decrease below that of wilting point is suspect.

Lysimeter 1 demonstrates how the sharp spike of soil moisture response would be expected to exceed field capacity and then be drained by gravity. Lysimeter 2 and 3 never display soil moisture values that meet or exceed field capacity. It would be more expected for field capacity to form at the inflection point of the response curves. This behavior could also be suspect, as drainage via gravity is not expected to occur until field capacity is met.

Areas of concern for include soil moisture dipping below that of the wilting point and not reaching field capacity. A possible reason for this disconnect was the use of factory calibrations as a base. The manufacture's calibrations were altered based on soil analysis in each lysimeter (Section 3.3.4.3). The underlying analysis behind the manufacture's calibrations is based on average literature values. It was determined that the site soils field capacity and wilting points were not represented by literature values as they were consistently greater than that of literature values (Table 3.6). Figure 4.5 displays the literature based field capacity and wilting point with respect to the soil moisture readings in each lysimeter at 10 cm (4 in) depth. The base equation's affiliation with the literature values are shifting soil moisture readings in Lysimeter 2 and 3 down in an attempt to operate within the theoretical wilting point and field capacity. Lysimeter 1, however does not agree with these theoretical values as it operates on an alternate version of the base equation (Section 3.3.4.3).

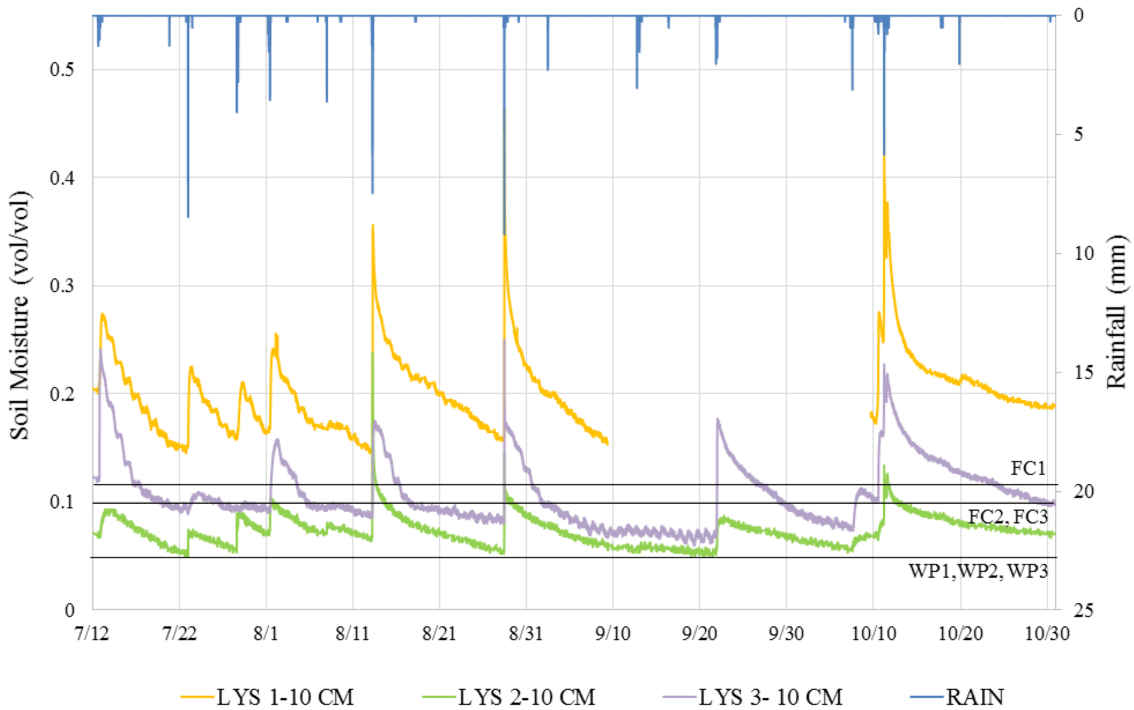

Figure 4.5: Soil Moisture (vol/vol) Vs Time at a 10 cm Depth. Literature WP (wilting point) and FC (field capacity) is presented in black. Yellow is lysimeter 1, green is lysimeter 2, and purple is lysimeter 3.

It is suspect that the downwards shift of the soil moisture readings would be caused by the use of factory calibrations. The basis of the factory calibrations are still rooted to average values presented in literature. The experimental soil moisture meter calibration in lysimeter 1 was successful in shifting the soil moisture readings in an attempt to mimic the experimentally determined soil properties. More soil moisture contents tests of lysimeter 2 and 3 should be performed such that the current calibration can be confirmed or altered as needed.

4.2.4 Soil Moisture Recession Slope and Outflow Comparison

Typically, the response of the storm from the soil moisture meters fall into two categories: a steep (greater than -0.005 hr^{-1}) or gradual response (less than -0.005 hr^{-1}). The examples in Figure 4.6 are from two actual storm events in lysimeter 2 at 10 cm (4 in) depth that occurred on August 1st 2013 (gradual) and August 13th 2013 (steep). Shape

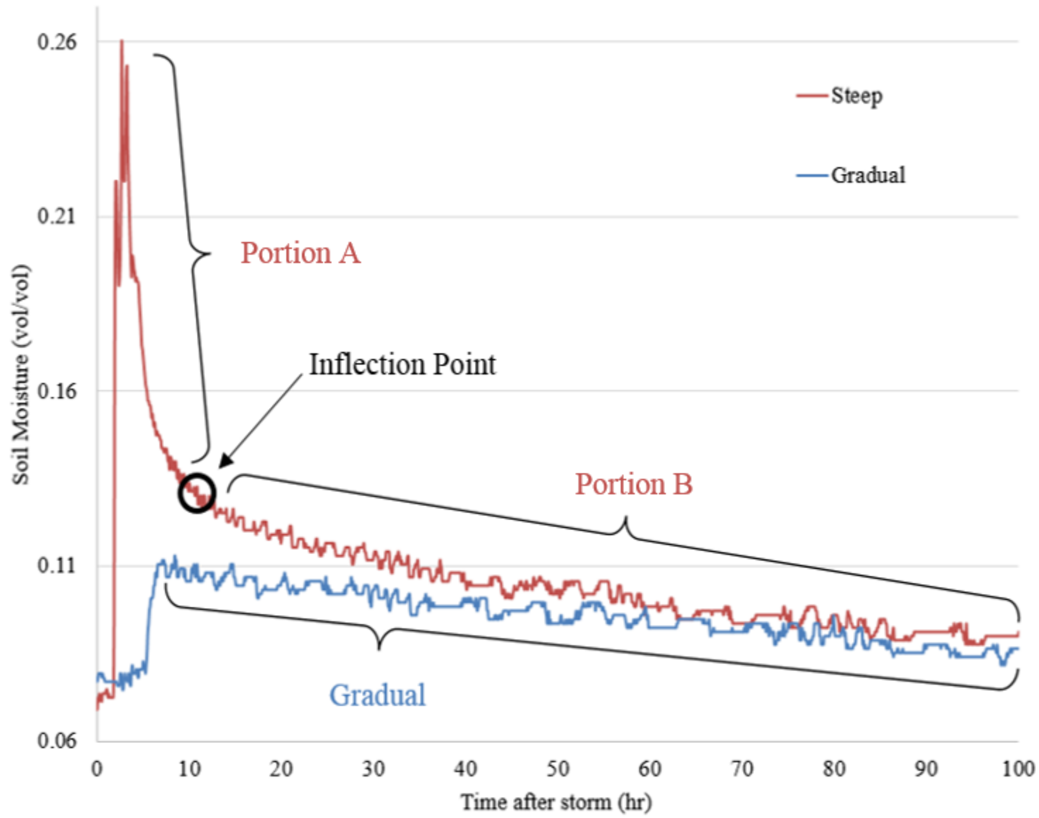

Figure 4.6: Gradual and Steep Slope Schematic

and inflection point will vary with storm rainfall amount and intensity and soil type. The steep sloped response can be bisected into two types of slopes, the large drop in the beginning, called portion A, and the gradual decrease after an inflection point, called portion B (Figure 4.6). If the response of the soil moisture meters mimicked a steep slope, the portion B was what was used to create the analysis in Sections 4.3.1 and 4.3.2 that discuss media and drainage comparisons. To see if this sharp decline, portion A, relates to the infiltration of the soil outflow amounts and soil moisture meter behavior for six storms was analyzed. Comparison of outflow amount and slope type was performed to attempt to understand if the steep portion of the slope relates to outflow occurrence (Table 4.1).

Table 4.1: Slope and Outflow Comparison of All Lysimeters. S indicates steep slope and G indicates gradual slope

Date	Rainfall (mm) (Intensity (mm/hr))	Lysimeter 1				Lysimeter 2				Lysimeter 3			
		Outflow (mm) (Percent Outflow)	Peak (10 cm)	Peak (35 cm)	Peak (65 cm)	Outflow (mm) (Percent Outflow)	Peak (10 cm)	Peak (35 cm)	Peak (65 cm)	Outflow (mm) (Percent Outflow)	Peak (10 cm)	Peak (35 cm)	Peak (65 cm)
7/12	27 (2.2)	0 (0%)	S	G	G	2.1 (8%)	G	G	G	2 (7%)	S	G	G
8/1	32 (2.1)	0 (0%)	G	G	G	9.9 (31%)	G	G	G	3 (9%)	G	G	G
8/13	82 (16.5)	5.3 (6%)	S	S	G	31 (38%)	S	S	S	5.4 (6%)	G	G	G
8/28	32 (2.9)	0.2 (1%)	S	G	G	1.2 (4%)	S	S	G	2.5 (8%)	S	G	G
9/22	36 (3.1)	0 (0%)	-	-	-	0 (0%)	G	G	G	1.3 (4%)	S	G	G
10/10	65 (1.7)	0 (0%)	S	S	G	10 (15%)	S	G	G	6.3 (10%)	S	G	G

Comparison of outflow amount and slope type was performed to attempt to understand if the steep portion of the slope relates to outflow occurrence (Table 4.1). Overall, lysimeter 1 tends to produce the least amount of outflow. In lysimeter 1, a steep slope was displayed at depths of 10 and 35 cm (14 and 26 in) for both August 13th and October 10th events while the first produced outflow and latter did not. A gradual slope displayed at 35 and 65 cm (14 and 26 in) depths were very unlikely to produce outflow, with outflow percentages less than 1% in three storm events.

Lysimeter 2 produces the most total outflow. A steep slope is displayed for all depths during the August 13th event, which produces an outflow that consists of 38% of the rainfall. The August 1st event has a similar outflow percentage of 31%, yet has a consistent gradual slope through the depths. Three events have gradual slopes through the entire profile produced a variety of outflow conditions, with 0 to 31% of rainfall contributing to outflow.

Lysimeter 3 produces outflow the most consistently with a percent outflow ranging from 4% to 10% of the rainfall. This lysimeter only shows gradual responses from the 35 and 65 cm (14 and 26 cm) depth, which was expected since these depths are close to or in the IWS, which tends to stay wetter. The steep versus the gradual slopes at 10 cm (4 in) depth seem to have no strong correlation to the amount of outflow produced. Only storms greater than 27 mm (1.06 in) were considered for this analysis, which will most likely produce outflow in this lysimeter.

The steep shape of the soil moisture slopes are not necessarily linked to that of infiltration such that outflow is produced. Instead, reactions of the soil moisture and outflow can act independently of each other and vary with the amount and intensity of the storm. Due to the limited amount of storms analyzed, it may be possible to establish a correlation with more data. However, since this analysis is limited to this data set, portion A will not be considered as a link to infiltration. Instead, portion B on the steep slopes will be taken to compare performance linked to that of ET.

4.2.5 Drainage Comparison

Two drainage outflow mechanisms are being considered in this study, the controlled valve outflow and the internal water storage (IWS) outflow. Lysimeter 2 demonstrates the behavior of the open valve outflow (at half open), and lysimeter 3 demonstrates the IWS behavior. Both lysimeters are comprised of similar media so an appropriate comparison can be made. Slopes and lag times of soil moisture meter readings to responses in rainfall events will be considered.

Slope was found by a linear best fit line through the gradual decrease of the soil moisture after a rain event. The slopes of the soil moisture at 10 cm (4 in) depth in Lysimeter 2 and 3 are going to be discussed to demonstrate how drainage devices govern the movement of water. The storms chosen were ones with rainfall amounts that produced a response in the soil moisture readings through all depths, 27 mm (1.1 in) of rainfall or greater.

The recession limb of the soil moisture graph was analyzed for six storm events (Figure 4.7). The average slope of these six storms is -0.0002 hr^{-1}. These events include

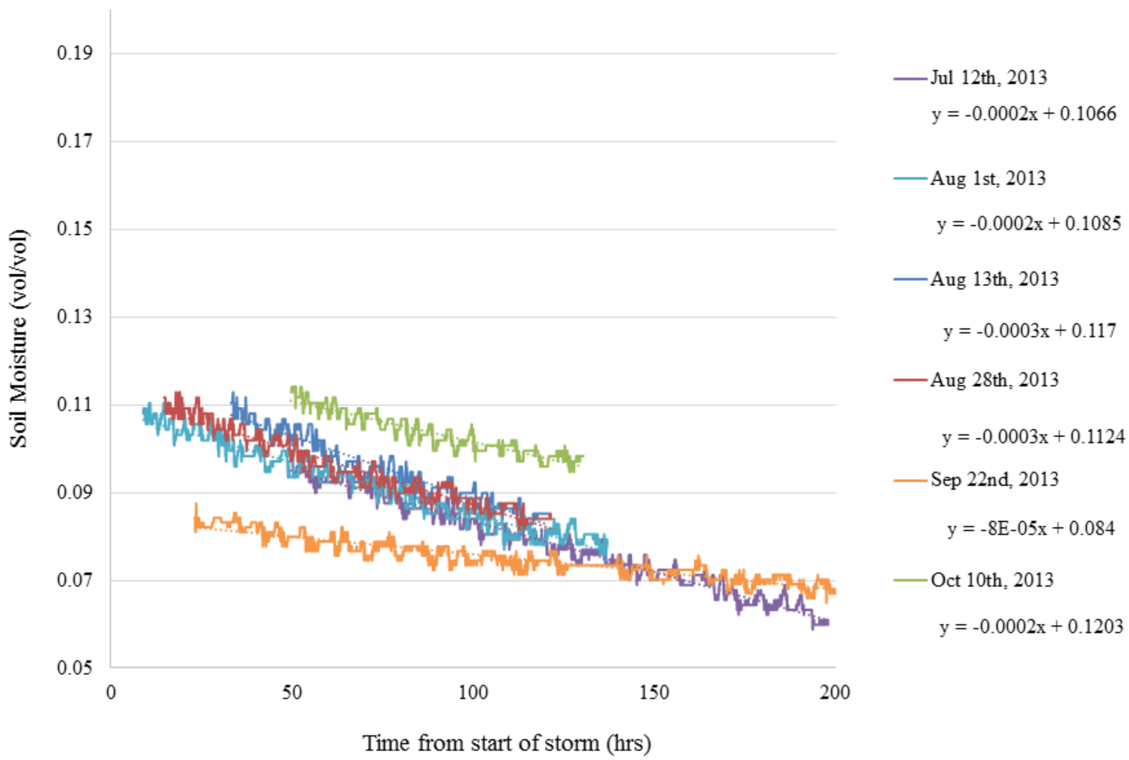

Figure 4.7: Lysimeter 2 Soil Moisture (vol/vol) at 10 cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple, August 1st is light blue, August 13th is dark blue, August 28th is red, September 9th is orange, and October 10th is green.

rainfall amounts greater than 27 mm (1 in) in all cases. These events happened on July 12th, August 1st, August 13th, August 28th, September 22nd, and October 10th during the year of 2013. Lysimeter 3 soil moisture recession at 10 cm (4 in) depth for the same six storm events (Figure 4.9) was determined to have an average slope -0.0005 hr^{-1}.

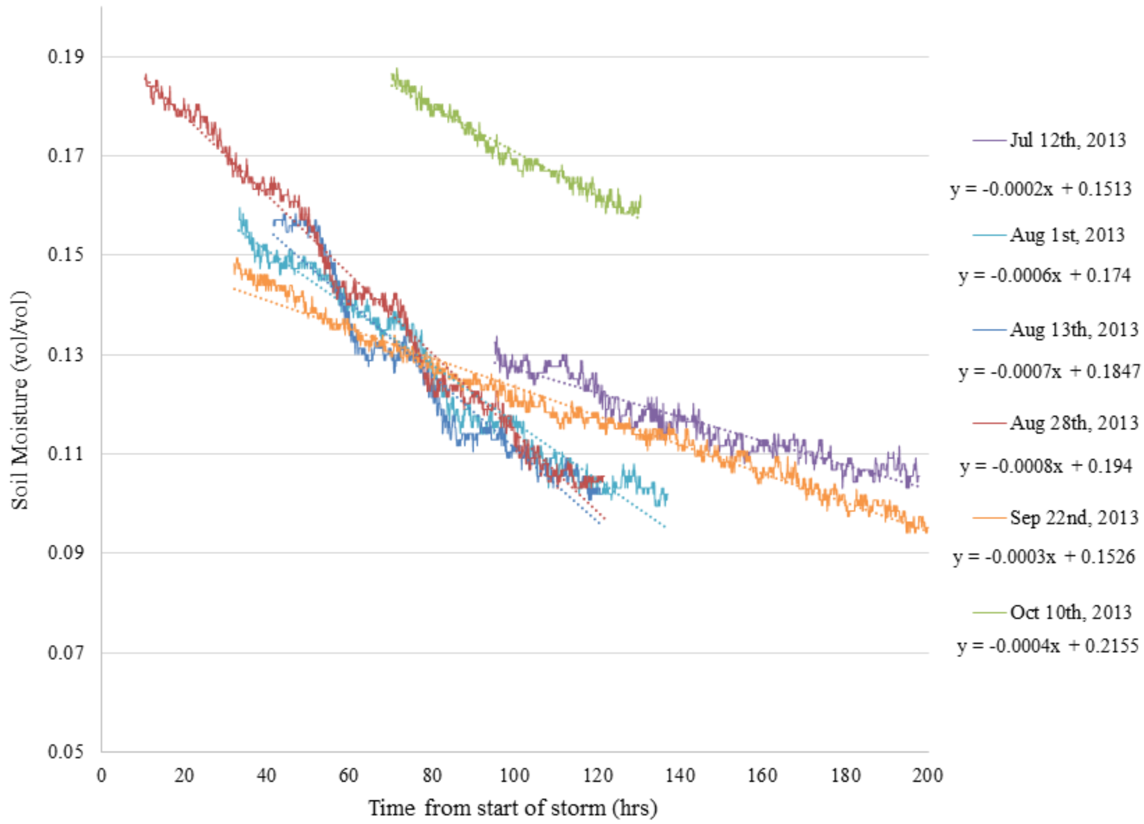

Figure 4.8: Lag Time Determination. Soil moisture (vol/vol) vs. yime from start of storm for lysimeter 3. Light purple line is 10 cm depth, dark purple line is average 35 cm depth, and dark blue line is 65 cm depth.

The lag time was found from the end of the rain event to start of the decrease of the gradual slope. The determination of lag times for lysimeter 3 during the August 13th storm is presented (Figure 4.8) as an example. Essentially, all of lysimeter 2 behaves similarly to the 10 cm (4 in) depth (light purple line in Figure 4.8), where the lag time can be found relatively easily from the sharp peak followed by a gradually decreasing slope. The slope and lag time values in Table 4.2 for the deeper depths (35 and 65 cm or 14 and 26 in) in lysimeter 3 for the August 13th to October 10th event were determined a slightly different way than the lysimeter 2. Lag time for the deeper soil moisture meters in

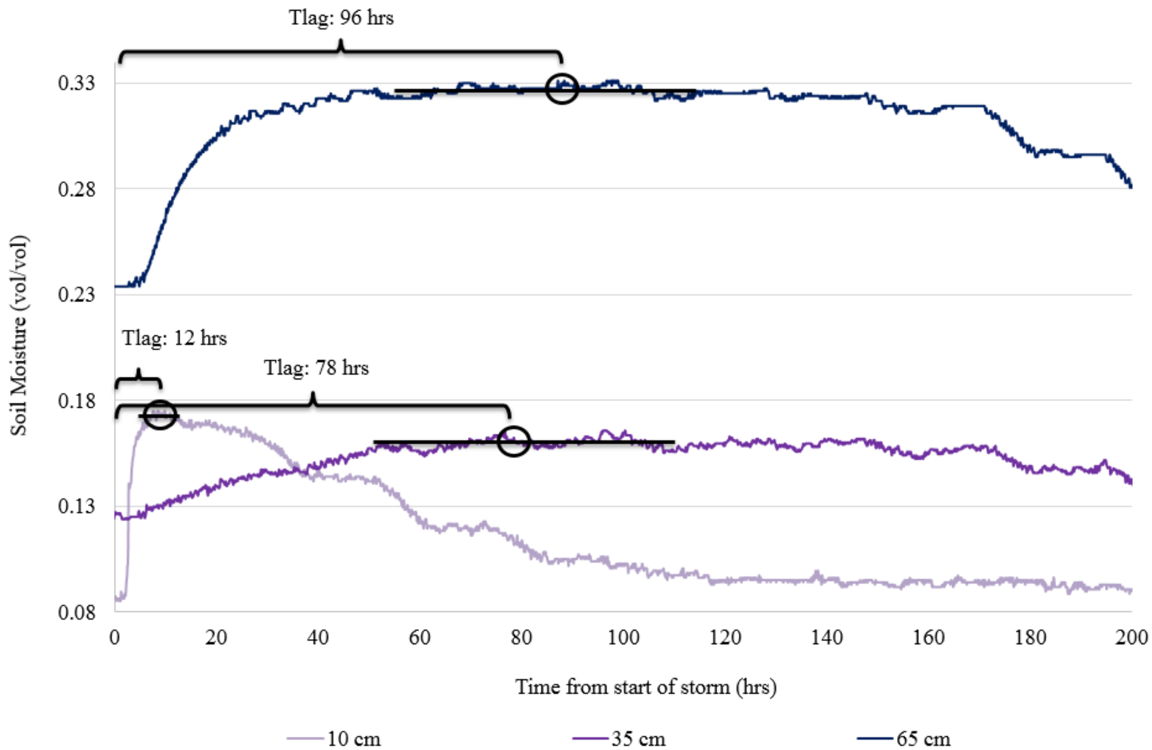

Figure 4.9: Lysimeter 3 Soil Moisture (vol/vol) at 10 cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple, August 1st is light blue, August 13th is dark blue, August 28th is red, September 9th is orange, and October 10th is green.

lysimeter 3 were determined when the rising response flattens out, to obtain a slope of zero and an approximate lag time in hours. For warmer months (July and August), when ET production is at a maximum, a decreasing slope was determined prior to the start of another storm event. However, due to the lagged response of the deeper soil moisture probes, it is unknown if the response came from only the storm analyzed or an accumulation of that storm event and other storm events that may have happened before the deeper moisture meters read a response. Therefore, an approximate lag time is reported when the soil moisture has reached a relative maximum (i.e. a slope of zero). The analysis of the soil moisture probes at all depths was for all six storms can be seen in Table 4.2 (Appendix E).

Table 4.2: Event Slope and Lag Times for Drainage Comparison

Date (Rain)	Parameter	Lysimeter 2			Lysimeter 3		
		10 cm Depth	35 cm Depth	65 cm Depth	10 cm Depth	35 cm Depth	65 cm Depth
7/12 (27 mm)	Slope (hr^{-1})	-0.0002	-0.0002	-0.0002	-0.0002	-0.0001	-0.0003
	Lag (hr)	49	50	83	95	128	128
8/1 (32 mm)	Slope (hr^{-1})	-0.0002	-0.0002	-0.0001	-0.0006	-0.0003	-0.0006
	Lag (hr)	9	25	26	33	46	58
8/13 (82 mm)	Slope (hr^{-1})	-0.0003	-0.0003	-0.0002	-0.0007	0	0
	Lag (hr)	25	40	40	12	78	96
8/28 (32 mm)	Slope (hr^{-1})	-0.0002	-0.0003	-0.0002	-0.0008	0	0
	Lag (hr)	15	23	42	11	72	138
9/22 (36 mm)	Slope (hr^{-1})	-0.00008	-0.00006	-0.00009	-0.0003	0	0
	Lag (hr)	23	23	54	32	85	202
10/10 (65 mm)	Slope (hr^{-1})	-0.0003	-0.0001	- 0.000007	-0.0004	0	0
	Lag (hr)	49	50	83	70	176	288
Avg. ± Std. Dev	Slope (hr^{-1})	-0.0002 ±0.00008	-0.0002 ±0.0001	-0.0001 ±0.00008	-0.0005 ±0.0002	-0.00007 ±0.0001	-0.0002 ±0.0003
	Lag (hr)	28±17	35±13	55±24	42±34	98±47	152±82

Focusing on the average slopes in lysimeter 2, it can be seen that the recession of the moisture remains relatively consistent through the depth. At 10 and 35 cm (4 and 14 in) depth, the average slope is essentially the same, -0.0002 hr^{-1}. There is a slight increase in lag time from this 10 cm (4 in) to 35 cm (14 in) of about 7 hours. The average 65 cm (26 in) depth slope is slightly smaller at -0.0001 hr^{-1}, but is to be expected as not all of these events produced outflow, September 22nd did not. However, since this decrease is not an order of magnitude of difference, it is not substantially different than the previous slopes derived from readings at 10 cm (4 in) and 35 cm (14 in). The lag time between 35 and 65 cm (14 and 26 in) depth is increased by about 20 hours in lysimeter 2.

Lysimeter 3 shows an average slope of -0.0005 hr^{-1} at the depth of 10 cm (4 in). The average slope at 35 cm (14 in) and 65 cm (26 in) is -0.00007 hr^{-1} and -0.0002 hr^{-1}, respectively. The influence of the IWS can be felt at 35 cm (14 in) as the decrease in the soil moisture recession rate from 10 cm (4 in) to 35 cm (14 in) implies. The lag time for lysimeter 3 at the 10 cm (4 in) depth (about 42 hrs) is nearly double that of lysimeter 2 at the same depth (about 28 hrs). For the deeper soil moisture probes (35 and 65 cm or 14 and 26 in), the lag time in lysimeter 3 (152 hr) is nearly triple that of lysimeter 2 (55 hrs).

Comparison of lysimeter 2 and 3 soil moisture recession rates is taken where the lag times are similar. In this case, 35 cm (14 in) depth and for lysimeter 2 is closest to 10 cm (4 in) depth in lysimeter 3 at average lag times of 35±13 hrs and 42±34 hrs, respectively. This situation yields a slope of -0.0002 hr^{-1} and -0.0005 hr^{-1} for lysimeter 2 and 3, respectively. The water in lysimeter 3 with the internal water storage is decreasing at a 2.5:1 rate faster than the water in lysimeter 2. This may indicate that the more rapid change in slope of lysimeter 3 is water that is lost to ET rather than infiltrating.

4.2.6 Media Comparison

Lysimeter 1 and 2 are governed by the same open outflow device and comprised of different media, such as loamy sand and sand, respectively. A similar analysis of slope and lag time as performed in the previous section is done for lysimeter 1 and 2 (Table 4.3) (Appendix E). All events were kept consistent between the drainage and media comparison, except the September 22nd data for lysimeter 1 was not available due to instrumentation complications. Lysimeter 2 shows an average slope of -0.0006 hr^{-1} at 10 cm (4 in), -0.0007 hr^{-1} at 35 cm (14 in), and -0.001 hr^{-1} at 65 cm (26 in). Lysimeter 2 behaves the same as discussed previously with an average slope of -0.0002 hr^{-1} at 10 cm (4 in), -0.0002 hr^{-1} at 35 cm (14 in), and -0.001 hr^{-1} at 65 cm (26 in).

Table 4.3: Event Slope and Lag Times for Media Comparison

Date (Rain)	Parameter	Lysimeter 1 10 cm Depth	Lysimeter 1 35 cm Depth	Lysimeter 1 65 cm Depth	Lysimeter 2 10 cm Depth	Lysimeter 2 35 cm Depth	Lysimeter 2 65 cm Depth
7/12 (27 mm)	Slope (hr^{-1})	-0.0006	-0.001	-0.0013	-0.0002	-0.0002	-0.0002
	Lag (hr)	46	56	58	49	50	83
8/1 (32 mm)	Slope (hr^{-1})	-0.0006	-0.0003	-0.0002	-0.0002	-0.0002	-0.0001
	Lag (hr)	27	69	74	9	25	26
8/13 (82 mm)	Slope (hr^{-1})	-0.0006	-0.0009	-0.0032	-0.0003	-0.0003	-0.0002
	Lag (hr)	32	60	66	15	40	40
8/28 (32 mm)	Slope (hr^{-1})	-0.0006	-0.0007	-0.0003	-0.0002	-0.0003	-0.0002
	Lag (hr)	48	56	58	15	23	42
9/22 (36 mm)	Slope (hr^{-1})	N/A	N/A	N/A	-0.00008	-0.00006	-0.00009
	Lag (hr)	N/A	N/A	N/A	23	23	54
10/10 (65 mm)	Slope (hr^{-1})	-0.0007	-0.0004	-0.00008	-0.0003	-0.0001	- 0.000007
	Lag (hr)	66	58	100	49	50	83
Avg. ± Std. Dev	Slope (hr^{-1})	-0.0006 ±0.00004	-0.0007 ±0.0003	-0.001 ±0.0013	-0.0002 ±0.00008	-0.0002 ±0.0001	-0.0001 ±0.00008
	Lag (hr)	44±15	60±5	71±17	28±17	35±13	55±24

Lag time for lysimeter 1 is, on average, about 44 hours after the storm at 10 cm (4 in). Lag time increases by 16 hours between 10 cm (4 in) and 35 cm (14 in) depths and by 11 hours from the 35 to 65 cm (14 to 26 in) depth. Comparison of lag time between lysimeters 1 and 2 indicate that lysimeter 1 lag time is increased by a factor of 1.5 in comparison to lysimeter 2 at all depths.

Comparison of lysimeter 1 and 2 soil moisture recession rates is taken where the lag times are similar. The lag time also have to be comparable to that of the drainage analysis, i.e. 35 to 42 hours after the storm. In this case, 10 cm (4 in) depth and for lysimeter 1 is closest to 35 cm (14 in) depth in lysimeter 2 at average lag times of 44±15 hrs and

35±13 hrs, respectively. This situation yields a slope of -0.0006 hr^{-1} and -0.0002 hr^{-1} for lysimeter 2 and 3, respectively. The water in lysimeter 1 with a loamy sand media is decreasing at a 3:1 rate faster than the water in lysimeter 2 with a sand media. This may indicate that the more rapid change in slope of lysimeter 1 is water that is lost to ET rather than infiltrating.

4.3 ET AND PERCOLATION ON EVENT BASIS

The following analysis looks at ET and percolation outflow of each lysimeter on a storm event basis. The percolation measurement is determined by the differential change in the ultrasonic reading. This differential change was then converted to a differential change in the lysimeter by a comparison of the area ratio of the two buckets to get percolation. The percolation was summed over the duration of the storm. For this analysis, a storm event was defined as a rainfall amount greater than 1.3 mm (0.05 in) as the start of the storm. The storm event ended when 6 hours of no rainfall occurred. The minimum dry time between rainfall events was set to 24 hours between rainfall events, however if this time could be exceeded until the criteria for another storm was met. The total rainfall was found by the summation of the rainfall over the entire storm event.

The storm ends when the criteria for a new storm is met, i.e. prior to 1.3 mm (0.05 in) of rainfall. However, the end time for this analysis had to be modified depending on the time in which the rainfall started. It was necessary to do this due to daily fluctuating behavior of the load cell. Figure 4.10 demonstrates the change in weight versus time from a storm simulation event during actual rainfall starting at 6:00 pm on August 3rd 2014. Overall, Figure 4.10 shows that the load cell, especially in the case of lysimeter 1 and 2, has a more constant change during the 0 to 12 hr, 24 to 32 hr, 48 to 60 hr, and 72 to 84 hr

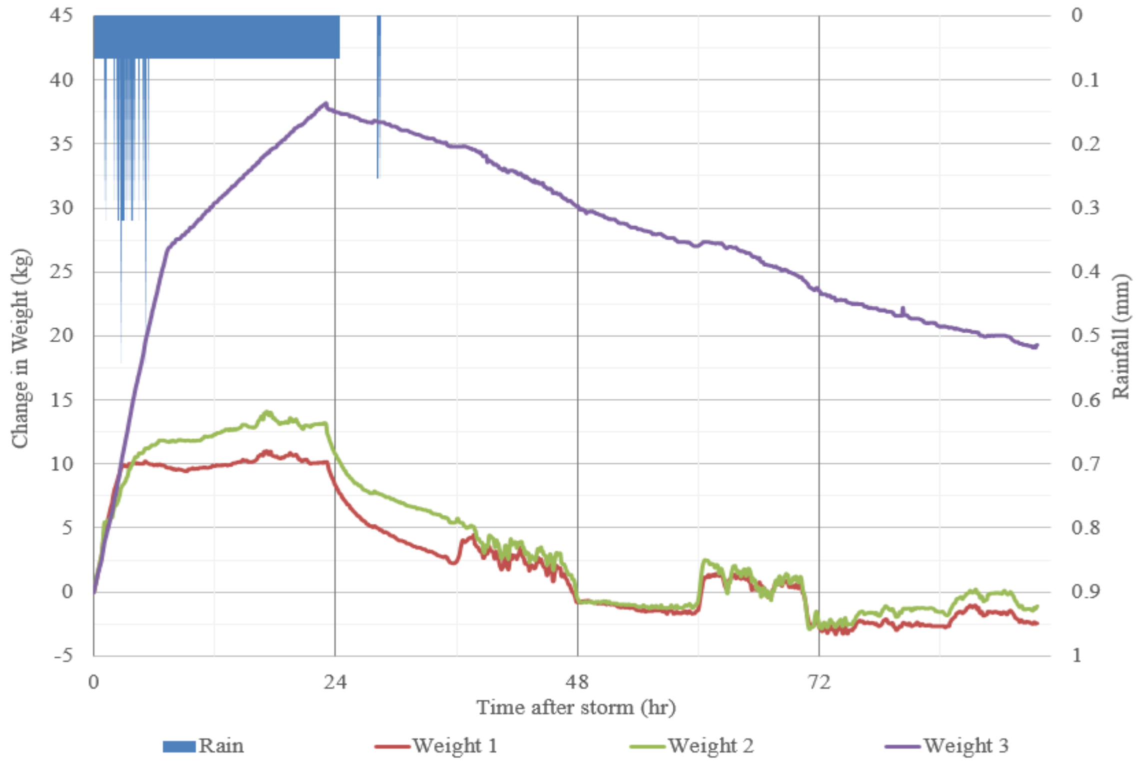

Figure 4.10: Daily Fluctuations of Load Cell Demonstrated by Change in Weight (kg) vs. Time after Storm. Red line is for lysimeter 1, green line is for lysimeter 2, and purple line is for lysimeter 3. Rain (mm) is displayed in blue.

(i.e. the 6 pm to 6 am) time slots. A more scattered trend is present during the 12 to 24 hr, 32 to 48 hr, 60 to 72 hr, and 84 to 96 hr (i.e. the 6 am to 6 pm) time slots. Based off of the starting time of the storm, the end time of the storm is back calculated from the start of another storm to reach a time that is a 24 hour interval away from the start of the storm. The start and end time of the storm is then used to find the corresponding load cell readings and determine the change in weight. Since all storms do not occur during the nightly time slot, where there is a less noise, a three point average of load cell weight readings are taken in an attempt to dampen possible noise.

Lysimeter 3 load cell is less prone to the daily variability (Figure 4.10), possibly because it is the heaviest of all lysimeters with an average weight of about 750 kg (1650 lb). Lysimeter 1 and 2 have an average weight of about 615 kg (1350 lb) and 550 kg

(1210 lb). This increase of weight decreases the amount of noticeable noise. Also, during July 2013 construction, lysimeter 3's load cell had to be sent back to the factory, making it the most recently maintained.

The ET was derived from the mass balance in Equation 3.1 with all the parameters determined as discussed previously. This analysis was done for each lysimeter from mid-July 2013 to the end of March 2014, with some exclusions due to instrumentation errors (Figure 4.11). Some events were discarded for if instrumentation

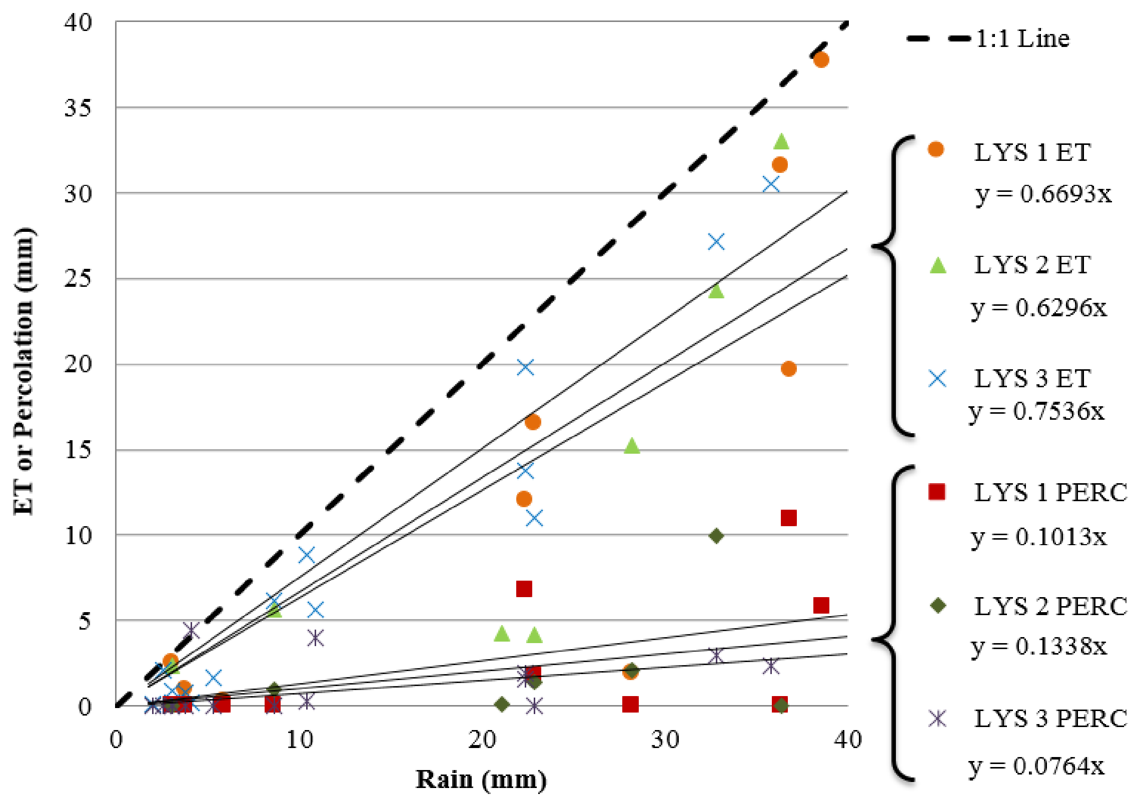

Figure 4.11: ET (mm) and Percolation (mm) Vs Rainfall Amount (mm) on Event Basis. Red and orange are lysimeter 1 percolation and ET, dark green and light green are lysimeter 2 percolation and ET, purple and blue are lysimeter 3 percolation and ET, respectively.

error was of suspect or the events occurring too close together, as a minimum of 24 hours of dry time was needed in between events. Even with this minimum in place, on occasion the mass balance was not completed if storms happened too close together and the effects from the prior storm were still 'felt' by the instrumentation. Data in tabulated form can be found in Appendix F.

All points rest below the 1:1 line of rain to ET or percolation, as ET or percolation cannot exceed the amount of available water (Figure 4.11). A best fit line was calculated and generally the ET data had stronger correlations than the infiltration data to the linear fit based on the R^2 values. The R^2 values for ET linear trend lines are 0.65, 0.88, and 0.92 for lysimeters 1, 2, and 3, respectively. The R^2 values for percolation linear trend lines are 0.33, 0.17, and 0.12 for lysimeters 1, 2, and 3, respectively. An R^2 value of 1 indicates a strong correlation, whereas 0 or less indicates a weak or no correlation. The weaker percolation relationship is most likely caused by the fact that percolate is dependent on both rainfall amount and intensity and only amount of rainfall is being compared.

This indicates that on a storm basis, about 67% goes to ET 10% goes to percolation, and the other 23% goes to storage in lysimeter 1. For lysimeter 2, about 63% ET, 13% percolate, and 24% storage. For lysimeter 3, about 75% ET, 8% percolate, and 17% storage. Precipitation makes up 100% of the water budget. Storage, percolation, and rain were measured directly and ET was calculated. It was expected that lysimeter 3 has the least holding capacity, as that aspect is hindered by the presence of the IWS. Lysimeter 1 and 2 have a similar holding capacity as they have the same valve drainage outflow. Lysimeter 1 has a greater outflow amount than lysimeter 1. The outflow from lysimeter 3 is less than both lysimeter 1 and 2. An IWS may cause percolation more often, but the overall amount of percolation produced is less in comparison with the controlled valve outflow systems. Lysimeter 3, as expected provides the most ET potential, followed by lysimeter 1 and then lysimeter 2. From this analysis on an event bases, ET to percolation amount ratios on an event rainfall basis are about 7:1, 5:1, and 9:1 for lysimeter 1, 2 and 3, respectively.

4.3.1 Media Comparison

To compare the media types with the same controlled outflow drainage configuration, lysimeter 1 and 2 will be the focus. From the event analysis above, it shows that lysimeter 1, on average, has 10% of the water budget dedicated to outflow and 67% dedicated to ET. Lysimeter 2 has 13% of the water budget dedicated to outflow and 63% dedicated to ET. The ET trend lines for lysimeter 2 and 3 have moderate to strong correlations of R^2=0.65 and R^2=0.88, respectively. This indicates that a change in media type from a sand media to a loamy media caused a 4% increase in ET production and a 3% decrease in outflow.

It is important to keep in mind the weak correlation that percolation has with the linear best fit line for lysimeter 1 (R^2=0.33) and lysimeter 2 (R^2=0.17). Despite this weak linear correlations, 10% and 13% outflow for lysimeters 1 and 2 are expected values as they are fairly similar due to the same outflow configuration, and a slight decrease attributed to the loamy sand in lysimeter 1. The storage capacities of both lysimeters were found to be very similar at 23% and 24% for lysimeter 1 and 2, respectively. This means the use of a media with greater fines does not greatly reduce the overall storage capacity of the lysimeter.

Lysimeter 1 produces outflow for events greater than 22.4 mm (0.88 in) whereas lysimeter 2 displays outflow for smaller events, such 9.1 mm (0.36 in) or greater. Since lysimeter 2 outflows for smaller events, the 3% increase in outflow percentage form this lysimeter was to be expected. The loamy sand media has more fine particles that allow for the containment of water to be available for ET without effecting the overall storage capacity of the lysimeter.

4.3.2 Drainage Comparison

To compare the drainage configurations with the same sand media, lysimeter 2 and 3 will be the focus. From the event analysis above, it shows that lysimeter 3, on average, has 13% of the water budget dedicated to outflow and 63% dedicated to ET. Lysimeter 3 has 8% of the water budget dedicated to outflow and 75% dedicated to ET. The ET trend lines for lysimeter 2 and 3 have strong correlations of R^2=0.88 and R^2=0.92, respectively. This indicates that a change in drainage outflow from an open flow to an IWS caused a 12% increase in ET production and a 5% decrease in outflow.

It is important to keep in mind the weak correlation that percolation has with the linear best fit line for lysimeter 2 (R^2=0.17) and lysimeter 3 (R^2=0.12). If this weak correlation causes the 8% outflow from lysimeter 3 not be accurate, it would assumed to error on the side of underestimation. This conjecture is based on the fact lysimeter 2 has a storage capacity of about 24%, and it is expected that IWS takes up about half of the available media, indication that a storage capacity of 17% errors on the side of overestimation.

According to the percolation data, for storm events less than 19.8 mm (0.8 in), lysimeter 3 did not produce a significant amount percolate outflow (greater than 1 mm or 0.04 in), whereas lysimeter 2 produces outflow for rain events of 9.1 mm (0.36 in) or greater. Since this analysis did not include events greater than 40 mm (1.6 in), 8% percolation from lysimeter 3 maybe correct in this range of rainfall data. Larger rainfall ranges may alter the water balance budget for all rain garden configurations involved, but is not a huge concern as they are not typically designed for greater than a 25.4 mm (1 in) capture.

4.3.3 Overall Comparison

Comparison and summation of the average performance via the mass balance using a change in weight proxy for all three rain garden design will now be assessed. The observation time incorporated data from mid-July 2013 to the end of March 2014. The average ET, outflow, and storage components amounts for storm events under 40 mm (1.6 in) in size is compared (Table 4.4).

Table 4.4: Average Water Budget for Rain Garden Designs for 40 mm Storm

Water Budget Parameter	Lysimeter 1	Lysimeter 2	Lysimeter 3
Rain (mm)	40	40	40
Outflow (mm)	4	5.2	3.2
ET (mm)	26.8	25.2	30
Change in Storage (mm)	9.2	9.6	6.8
Percent Outflow	10%	13%	8%
Percent ET	67%	63%	75%
Percent Change in Storage	23%	24%	17%
Percent Capture	90%	87%	92%
Adjusted Percent Outflow	13%	17%	10%
Adjusted Percent ET	87%	83%	90%

The average water budget for each lysimeter is presented in both rainfall amount and percentages of the rainfall amount that where the same as discussed previously. Percent capture is the percentage that which did not overflow. The rain garden designs that these lysimeters represent are performing with an 87-92% capture is seen for events up to 40 mm (1.6 in) at a 1:1 loading ratio. The adjusted ET and outflow percentages are redistributed such that they represent the percentage of the combined rainfall and storage component. Just considering the part of the water budget that is dedicated to water loss by either ET or outflow, for lysimeters 1, 2, and 3 about 87-13%, 83-17%, and 90-10% make up the ET to outflow precentages, respectively. Evapotranspiration to outflow ratios are similar as they were presented before of 7:1, 5:1, and 9:1 ET to outflow for lysimeters 1, 2, and 3, respectively. These adjusted ET to outflow percentages of storms under 40 mm (1.6 in) will be used in comparison to larger events of 134 mm (5.3 in) or greater achieved in the storm simulations in Section 5.2.4.

4.4 SOIL MOISTURE AND WEIGHT PROXY COMPARISON

Comparisons of the drainage and the media types have been analyzed two ways: soil moisture meter slope and lag time responses and a mass balance of the change in weight and percolate outflow systems for direct rainfall. From the mass balance perspective, lysimeter 1, 2 and 3 was able to function on a 7:1, 5:1, and 9:1 ET to percolation ratio, respectively. Comparison of these ratios for media type yield a 1.5:1 increase in ET production of the loamy sand (lysimeter 1) to sand (lysimeter 2). Comparison of these ratios for drainage type yield a 2:1 increase in ET production of the IWS (lysimeter 3) to controlled valve outflow (lysimeter 2).

Soil moisture meter slope and lag time analysis yielded a possible ET activity ratio of 3:1 for the performance of the media type of a loamy sand (lysimeter 1) to sand (lysimeter 2) in the controlled valve outflow type. An ET activity ratio of 2.5:1 for the performance of the drainage configuration of IWS (lysimeter 3) to open controlled valve (lysimeter 2) in the same media type was determined. Both methods agree that amended designs, such as lysimeter 1 and 3, are able to produce more ET and less percolation compared to a typical design of lysimeter 2. However, the mass balance with the load cell indicates that alterations to the drainage design provides a greater ET increase than the alteration of soil media whereas the soil moisture slope results indicate the opposite. The disconnect lies with the fact that the soil moisture analysis is limited to six storm events (five in the case of lysimeter 1). The weight mass balance analysis incorporated more events and seasonal variation than the soil moisture slope and lag time analysis.

Focusing on outflow events, the soil moisture meters at the deepest depth in the controlled valve outflow drainage systems may be able to display those events. From soil moisture meter readings, minimum responses were able to be 'felt' by storms greater than 22.1 mm (0.87 in), 17.4 mm (0.68 in), 15.2 mm (0.6 in) of rain for lysimeter 1, 2, and 3, respectively. Outflow of greater than 1 mm from the percolation collection system was able to be quantified for storms greater than 22.4 mm (0.88 in), 9.1 mm (0.36 in), and 19.8 mm (0.8 in), or greater for lysimeter 1, 2, and 3 respectively. Despite some discrepancy of the outflow comparison to the soil moisture meter change, they follow the same trend with lysimeter 2 producing outflow at smaller rainfall amounts and lysimeter 1 and 3 producing outflows at greater rainfall amounts. Further work with soil moisture meters may provide a viable and cost effective proxy to measure the change in storage in rain garden designs. If the change in storage of the rain garden is known, then ET accreditation for the rain garden could be established.

4.5 STORM SIMULATIONS

Storm simulations were performed during rainfall events to mimic the proper storm weather conditions. Storm simulations were attempted to mimic a range of extreme to design storm conditions. The following storms will be investigating using the change in weight as a proxy in the mass balance.

The first simulation was performed on March 29th 2014 during a 64 mm (2.5 in) storm for a 76 mm (3 in) at a 4:1 loading area ratio over 24 hours. The loading ratio was decreased to 4:1, as a heavy storm was expected and would provide the volume to achieve a 5:1 storm. A total of 368 mm (14.5 in) rain was collected over the system. The results of this simulation were inconclusive as the drainage valve on the percolation collection system malfunctioned for lysimeter 1 and 2, not providing ample space in the percolation collection system. Overtopping was seen on the lysimeter 3, but not in lysimeter 1 or 2. This was a very extreme event and may have been too great of volume for these systems to handle as these lysimeters are not set up to account for overflow. It exceeds traditional rain garden design and typical rain garden design are limited to 25.4 mm (1 in) capture at a 5:1 ratio. However, even though ET and outflow cannot be determined, it is important to note this event since it is setting up the successive storm simulations with recently saturated conditions. However, in every other case, ponding of the third lysimeter had been alleviated by the system before another storm simulation was performed.

The second trial was performed on April 3rd 2014 during a 14 mm (0.55 in) storm. A rainfall of 38 mm (1.5 in) at a 5:1 loading area ratio over 24 hours was added to the 14 mm (0.55 in) storm. The total rainfall for this event is 204 mm (8.05 in) and the mass balance was performed over 4 days after the event began. Utilizing the total rainfall, this storm more accurately describes a 41 mm (1.6 in) storm at a 5:1 ratio or a 20 mm (0.8 in) at a 10:1 ratio. This storm was analyzed from a mass balance perspective using rain gage for inflow, load cell for change in storage, and ultrasonic data for percolation (Table 4.4). The results of the April 3rd simulation from the mass balance perspective yielded 50-50%

ET to outflow for lysimeter 1 and 47%-53% ET to outflow for lysimeter 2. Lysimeter 3 showed a 72%-28% ET to outflow ratio. These percentages are adjusted to such that they represent the percentage of the combined rainfall and storage component. However, since lysimeter 3 overtopping was not able to be quantified it is suspect that the percentage lost to ET maybe overestimated for this lysimeter.

Table 4.5: Storm Simulation Mass Balance for April 3rd 2014

Water Budget Parameter	Lysimeter 1	Lysimeter 2	Lysimeter 3
Rain (mm)	204	204	204
Outflow (mm)	97	101	68
ET (mm)	95	91	171
Change in Storage (mm)	13	12	-35
Overflow (mm)	0	0	N/A
Percent Capture	52%	50%	67%
Adjusted Percent Outflow	50%	53%	28%
Adjusted Percent ET	50%	47%	<72%

The third storm simulation was performed on April 15th 2014 during a 59 mm (2.3 in) storm. A rainfall of 19 mm (0.75 in) at a 4:1 loading area ratio over 24 hours was simulated. The loading ratio was reduced from that of 5:1 as it was suspected that the storm would match or exceed 19 mm (0.75 in). The total rainfall for this event is 134 mm (5.3 in) and the mass balance was performed over 6 days after the event began. Utilizing the total rainfall, this storm more accurately describes a 27 mm (1.0 in) storm at a 5:1 ratio or a 13 mm (0.5 in) at a 10:1 ratio. This storm was analyzed from a mass balance perspective using rain gage for inflow, load cell for change in storage, and ultrasonic data for percolation (Table 4.6). The results of this simulation by the mass balance perspective yielded 62%-38% ET to outflow for lysimeter 1 and 50%-50% ET to outflow for lysimeter 2. Lysimeter 3 percolation collection system malfunctioned for this event, so data for this lysimeter is not presented as outflow could not be accurately determined. Again, overtopping occurred during this event in lysimeter 3.

Table 4.6: Storm Simulation Mass Balance for April 15th 2014

Water Budget Parameter	Lysimeter 1	Lysimeter 2	Lysimeter 3
Rain (mm)	134	134	134
Outflow (mm)	52	70	N/A
ET (mm)	85	70	N/A
Change in Storage (mm)	-2	-5	-35
Overflow (mm)	0	0	N/A
Percent Capture	61%	48%	N/A
Percent Outflow	38%	50%	N/A
Percent ET	62%	50%	N/A

The change in storage is determined separately via the load cell, such that change in storage is determined in lysimeter 3. Lysimeter 3 has the same change in storage over both storm simulations and had the same fully saturated behavior for the two extreme storms. It is unknown what the ponding depth conditions were when the mass balance was completed, i.e. 4 days for April 3rd and 6 days for April 15th. Soil moisture readings at 10 cm (4 in) reveal that lysimeter 3 was fully saturated when the mass balance was closed after both simulations. This indicates that the IWS in lysimeter 3 has about 35 mm (1.4 in) of water storage capacity with some ponding.

Percentage capture is defined as the percentage of the rainfall that did not outflow or overflow. The April 3rd event represented a 41 mm (1.6 in) storm at a 5:1 ratio or a 20 mm (0.8 in) at a 10:1 ratio and was able to produce percent capture of 52%, 50% and 67% in lysimeters 1, 2, and 3, respectively. However, since overflow was unaccounted, this actual percent capture is expected to be lower in lysimeter 3. The April 15th event represented a 27 mm (1.0 in) storm at a 5:1 ratio or a 13 mm (0.5 in) at a 10:1 ratio and was able to produce percent capture of 61% and 50% n lysimeters 1 and 2, respectively. For the April 15th storm, capture rates were slightly lower than expected. Lysimeters are only providing a 50% or greater capture rate where as 85% capture rate was specified in literature review for a 27 mm (1.0 in) storm. However, it can be seen that the percent capture can be altered and increased with media and drainage design amendments. Evapotranspiration and percolation percentages at a 1:1 ratio for storms under 40 mm (1.6 in) was found to be 7:1, 5:1, and 9:1 for lysimeters 1, 2 and 3. During the storm simulations, lysimeters 1, 2, and 3 operate on average at a 1.5:1, 1:1 and 2.5:1 ET to percolation ratio. It is important to note this phenomenon as ET to percolation ratio are not a stationary value and change with storm type and intensity.

4.6 PLANTS

Since planting in July, each plant type height has increased steadily until winter. Seaside golden rod showed the largest growth from an average height of 50 cm (1.6 ft) in July to 120 cm (4 ft) in November before dormancy. A height of 120 cm (4 ft) indicates that the ET_{sz} values from the ASCE-PM predictive equation become more reliable as it calculated based on the assumed crop height of 120 cm (ft). Black chokeberry (i.e. a woody plant) grew 5-10 cm (2-4 in) since planting and remained around 80-85 cm (2.6-2.8 ft) height in all lysimeters for most of the duration of study. Leaves were lost in September to October and gone in November for black chokeberry and seaside goldenrod. Switch grass was able to grow from 40 cm (1.3 ft) to 60 cm (2 ft) before dormancy in November. A monthly plant inspection will continue to be performed such that colorations from plant health and ET production can be assessed more fully in future study. Higher clay content and IWS have shown to produce healthier plants, less percolation, and more ET. As the plants establish over a few growing seasons, a fuller analysis may be presented as to what effects plant establishment has on ET.

CHAPTER 5: SUMMARY

Many details governing evapotranspiration (ET) in bioretention technology have yet to be determined. Vital information quantifying ET from a bioretention rain garden with a controlled outflow versus a bioretention rain garden with an IWS can be obtained from this pending work, which will influence our understanding of the role of ET and how to best include it as a design parameter. It is also imperative to compare the native soil with that of a typical bioretention mix to determine the significance of the soil on ET production. This could potentially reduce the need for borrow pit soils, saving money and resources. Three weighing lysimeters were constructed and equip to measure the water balance of each configuration. Lysimeter 1 consisted of a controlled valve outflow that remained half open for the observation period with a loamy sand media. Lysimeter 2 consisted of the same outflow device as lysimeter 1 with a sand media. Lysimeter 3 consisted of an Internal Water Storage (IWS) zone with a sand media. The objective of this paper was to determine if different elements of design, such as drainage configuration and media selection can shift the amount of ET and outflow that is produced such that a rain garden design can be better suited for site specific goals. Analysis of these rain garden designs was done via mass balance. Change in weight is a surrogate for the change in storage. Soil moisture meter behavior and responses to rainfall events were also investigated to determine the potential of soil moisture meters as the proxy for change in storage.

5.1 CONCLUSIONS

ET and percolation amounts were determined for storms under that of 40 mm (1.6 in) at a 1:1 loading ratio for July 2013 to March 2014. This analysis yields 7:1, 5:1, and 9:1 ET to outflow ratio for lysimeters 1, 2, and 3, respectively. The average water budget are as follows, lysimeter 1: 67% ET, 10% percolation, and 23% storage, lysimeter 2: 63% ET, 13% percolate, and 24% storage and lysimeter 3: 75% ET, 8% percolate, and 17% storage. ET makes up 87%, 83%, and 90% of the water budget available for loss via outflow or ET in lysimeters 1, 2, and 3, respectively. Percent captures (percentage that did not lead to overflow) of the same storms over the same analysis period, on average, are 90%, 87%, and 92% for the respective lysimeters.

Storm simulations to increase the SCM to impervious area ratio were performed for events at 41 mm (1.6 in) at 5:1 or 20 mm (0.8 in) at 10:1 and 27 mm (1.0 in) at 5:1 or 13 mm (0.5 in) at 10:1 over a 24 hour interval. The larger storm of 41 mm (1.6 in) at 5:1 yielded percent 52%, 50% and 67% in lysimeters 1, 2, and 3, respectively. The smaller storm of 27 mm (1.0 in) at 5:1 yielded percent 61% and 50% for lysimeters 1 and 2, respectively. Lysimeter 3 was unable to be fully analyzed for this event. During large storm events, lysimeters 1, 2, and 3 operate on average at a 1.5:1, 1:1 and 2.5:1 ET to percolation ratio.

This analysis concludes that selection of media and drainage configurations have the potential to increase ET and decrease outflow to fit site specific goals. Introduction of a loamy sand with more fines will provide more ET and less outflow without hindering storage capacity in a controlled valve outflow. An IWS zone will provide more ET when compared to the controlled valve drainage in the same media. ET from IWS outperformed the ET production in the controlled valve outflow with the loamy sand media. The tradeoff is that there is less short term storage capacity with an IWS during storm events.

Drainage and the media types have been assessed two ways: soil moisture meter slope and lag time responses and a mass balance of the change in weight and percolate outflow systems for direct rainfall. From the mass balance perspective via change in weight, ratios for media type yield a 1.5:1 increase in ET production of the loamy sand to sand. Comparison of these ratios for drainage type yield a 2:1 increase in ET production of the IWS to controlled valve outflow drainage. Soil moisture meter slope and lag time analysis yielded a possible ET activity ratio of 3:1 for the performance of the media type of a loamy sand to sand and 2.5:1 for the performance of the drainage configuration of IWS to open controlled valve drainage. Both methods agree that amended designs such as lysimeter 1 and 3 are able to produce more ET and less percolation compared to a typical design of lysimeter 2. The difference is attributed to the different time scales of each analysis. The soil moisture analysis time span is limited to six storm events where as the weight mass balance analysis incorporated more events and possible seasonal variation.

Outflow of greater than 1 mm from the percolation collection system was quantified for storms greater than 22.4 mm (0.88 in), 9.1 mm (0.36 in), and 19.8 mm (0.8 in) for lysimeter 1, 2, and 3 respectively. Soil moisture meters responses were able to predict outflow occurrence at 22.1 mm (0.87 in), 17.4 mm (0.68 in), 15.2 mm (0.6 in) of rain for lysimeter 1, 2, and 3, respectively. Despite some discrepancy of the outflow comparison to the soil moisture meter change, further work with soil moisture meters may provide a viable and cost effective proxy to measure the change in storage in rain garden designs. This study concludes that design can shift the infiltration to ET ratio for site specific design and that soil moisture meters may provide viable option to complete the mass balance to predict ET from rain garden designs.

5.2 FUTURE WORK

Much of this work was a set up for continued study to be done on the site. Some future direction that can be taken explore the use of soil moisture as a proxy of change in storage: replacing the need for a weighing device, controlled valve outflow adjustments, comparison of ET via predictive equations versus actual ET.

5.2.1 Soil Moisture Proxy

Weighing lysimeters are weighed to complete the mass balance by finding the change in storage. The change in weight of the load cell will be compared with the soil moisture reading over a height of the column to see if a relationship develops. This relationship can then be used to account for change in storage via soil moisture monitoring. Since soil moisture monitoring is something that can be implemented relatively easily in a rain garden system along with precipitation, the mass balance can be completed and ET can be potentially reliability estimated.

Two more sites that were instrumented and calibrated with soil moisture meters at the same depth profiles are that of the BTI and the in situ non-SCM area. The same analysis can be attributed to these sites to gain the entire mass balance to back calculate out the ET. This can show how much ET to expect from a rain garden and a non-SCM area, as to demonstrate the role of ET by adding a SCM such as rain garden. Quantifying the amount of ET is crucial to receive ET accreditation in rain garden designs. Soil moisture meters are an easier device to install in the field that may be able to provide the user with a better way to accredit the system with water loss by ET.

5.2.2 Controlled Valve Outflow

The controlled valve outflow was kept at a half open configuration for the present work; variation of the opening size with storm simulations of the same controlled size would allow for a slope comparison of soil moisture recession. With understanding of how each rain garden device reacts at a different allowance of flow, automated systems of the valve can be equipped. Future applications may incorporate the use of flow meters or rain gages to control the valve's opening and closing timings, eliminating on site operation. There is still uncertainty with IWS depth. With proper monitoring, a controlled valve outflow may be able to mimic the same storage that you would get with an IWS, but has flexibility to which to potentially clarify IWS height. Closing the valve, and utilizing soil moisture readings to estimate the depth of saturation, the valve can be opened when the capacity is reached. Repeating this fore different depths and evaluating the results could provide recommendations on IWS height or ratio of IWS height to rain garden depth that is optimal for both a sand and loamy sand soil type.

5.2.3 Predictive Equations

Utilization of predictive equations has its flaws in a stormwater control system as it is dependent on soil moisture availability and crop type. However, more comparison of actual ET from weighing lysimeters with on-site weather parameters can help to establish a "rain garden crop coefficient".

5.2.4 Storm Simulations

Now that the distribution has been constructed and established, more storm simulations should be performed. Prior, a device for capturing overflow of lysimeter 3 should be constructed. Ideally, storm simulations would occur for every rainfall event as rain gardens function on an impervious are ratio. Automated setup could be achieved and triggered by the rain gage tipping bucket.

REFERENCES

ASTM D 2974 – Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Organic Soils

ASTM D 2216 - Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures

ASTM D 2937-00 - Standard Test for Density of Soil in Place by the Drive-Cylinder Method

ASTM D 854-00 – Standard Test for Specific Gravity of Soil Solids by Water Pycnometer

ASTM D 422 - Standard Test Method for Particle-Size Analysis of Soils

Allen, R. G., Pruitt, W., Wright, J., Howell, T., Ventura, F., Snyder, R., Itenfisu, D., Steduto, P., Berengena, J., and Yrisarry, J. (2006). " A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method." *Agricultural Water Management*, 81, 1-22.

Allen, R.G., Luis S. Pereira, Dirk Raes, and Martin Smith. (1998). “Crop evapotranspiration - Guidelines for computing crop water requirements” Food and Agriculture Organization of the United Nations (FAO). *FAO Irrigation and drainage paper 56*. Rome.

American Sigma. (2001). Sigma 2149 Rain Gauge Brochure. *Automatic Data Logging Rain Gauges Specifications.*

Aquatec. (2009). Installation Procedure “DDP” Series. Delivery/Demand Pumps Series 550, 5800 & 7800. *IMI-104.*

Benson, Craig H. and Christopher A. Bareither (2012). “Designing Water Balance Covers For Sustainable Waste Containment: Transition State-of-the-Art to State-of-the-Practice.” *Geotechnical engineering state of the art and practice: keynote lectures from GeoCongress.* Oakland, California, 1-33.

Browne, F.X. (2013). CEE 8508: Urban Stormwater Management Course. *Villanova University*.

Brown, Robert A, William F. Hunt, and Shawn G. Kennedy. (2009) “Designing Bioretention with an Internal Water Storage (IWS) Layer: Design guidance for an innovative bioretention feature.” *Urban Waterways.* Department of Biological and Agricultural Engineering.

Carpenter, Donald D. and Laura Hallam. (2010).“Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance.”*J. Hydrol. Eng*. 15, 404-416.

Davis, A. P., Hunt, W. F., Traver, R. G., and Clark, M. (2009). "Bioretention technology: Overview of current practice and future needs." *J. Environ. Eng.*, 135(3), 109–117.

Davis, A. P., Shokouhian, M., Sharma, H., and Minami, C. (2006). "Water quality improvement through bioretention media: Nitrogen and phosphorus removal." *Water Environ. Res.*, 78(3), 284–293.

Davis, A. P., Shokouhian, M., Sharma, H., and Minami, C. (2001). "Laboratory study of biological retention for urban stormwater management." *Water Environ. Res.*, 73(1), 5–14.

Davis, A. P. (2008). "Field performance of bioretention: Hydrology impacts." *Journal of Hydrologic Engineering*, 13(2): 90-95.

Davis, A. P. (2007). "Field performance of bioretention: Water quality." *Journal of Hydrologic Engineering*, 13(2): 90-95.

Decagon Devices, Inc. (2014). "Plant Available Water: How do I determine Field Capacity and Permanent Wilting Point?" Pullman WA 99163.

Decagon Devices, Inc. (2012). GS3 Operators Manual. Pullman WA 99163.

Denich, Chris and Andrea Bradford. (2010)."Estimation of Evapotranspiration from Bioretention Areas Using Weighing Lysimeters."*J. Hydro. Eng.* June.15, 522-530.

Dietz, M. E. and J. C. Clausen. (2006). "Saturation to improve pollutant retention in a rain garden." *Environmental Science and Technology*, 40(4): 1335-1340.

Doorenbos, J., and Pruitt, W. O. (1975). Guidelines for predicting crop water requirements, Irrigation and Drainage Paper 24, *Food and Agriculture Organization of the United Nations*, Rome.

Environmental Protection Agency (EPA). (2005). National Management Measures to Control Nonpoint Source Pollution from Urban Areas. Washington, DC.

Fares, A and A. K. Alva. (1999). "Estimation of Citrus Evapotranspiration By Soil Water Mass Balance." *Soil Science,*164(5), 302-310.

Feller, Meghan. (2010). "Quantifying Evapotranspiration in Green Infrastructure: A Green Roof Study." *MS Thesis, Villanova University.*

Fredlund, D.G., and Anqing Xing. (1994). "Equations for the soil-water characteristic curve." *Canadian Geotechnical Journal* 31:521-532, 10.1139.

Fredlund, Murray D, G Ward Wilson, and Delwyn G Fredlund. (2002) "Use of the grain-size distribution for estimation of the soil-water characteristic curve." *Canadian Geotechnical Journal,* 39(5): 1103-1117, 10.1139.

Hankins, K., Welker, A.L., and Mandarano, L. (2008). "An Integrated Monitoring Plan for BioInfiltration BMPs" *The Proceedings of GeoCongress*, New Orleans, LA, March 9-12.

Heasom, William, Robert G. Traver, and Andrea Welker. (2006). "Hydrologic Modeling of a Bioinfiltration Best Management Practice." *JAWRA.* 42(5), 1752-1688.

Hickman, J.M. (2011). "Evaluating the Role of Evapotranspiration in the Hydrology of Bioinfiltration and Bioretention Basins Using Weighing Lysimeters." *MS Thesis,* Villanova University.

Hickman, John and Dominik Scheider. (2010). "Determination of Evapotranspiration in SCM's Using a Weighing Lysimeter: An Experimental Approach." *World Environmental and Water Resources Congress: Challenges of Change*. 3990-3999.

Hinman, Curtis. (2009). "Bioretention Soil Mix Review and Recommendations for Western Washington." Washington State University.

Higgins, P.J. (1995). "Performance testing of a flow controller for at source BMP's" *International Conference on New Technologies in Urban Stormwater Lyon*, France. pp. 627-630.

Hunt, William F., Allen P. Davis, and Robert G. Traver. (2012). "Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design." *Journal of Irrigation and Drainage Engineering*, Vol. 138, pp. 698-707.

Hunt, W., A. Jarrett, J. Smith, L Sharkey. (2006). "Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina." *J. Irrig. Drain Eng*. 132:600-608.

Isaac-Ricketts, Keisha. (2008). "A Soil Profile Characterization of a Bioinfiltration BMP." *MS Thesis,* Villanova University.

Gilbert Jenkins, J., Wadzuk, B., and Welker, A. (2010). "Fines Accumulation and Distribution in a Storm-Water Rain Garden Nine Years Postconstruction." *J. Irrig. Drain Eng*., 136(12), 862–869.

Karkanis, P. G. (1983). "Determining Field Capacity and Wilting Point Using Soil Saturation by Capillary Rise." *Can. Agric. Eng.* 25: 19-21.

Lee, Ryan. (Personal communication, March 19, 2014).

López-Urrea, R, F. Martín de Santa Olalla, C. Fabeiro, and A. Moratalla. (2006) "Testing evapotranspiration equations using lysimeter observations in a semiarid climate." *Agricultural Water Management.*, 85(16), 15-26.

Lord, Laura. (2013). "Evaluation of Nitrogen Removal and Fate within a Bioinfiltration Stormwater Control Measure." *MS Thesis, Villanova University.*

Machusick, M., Welker, A., and Traver, R. (2011). "Groundwater Mounding at a Storm-Water Infiltration BMP." *Journal of Irrigation and Drainage Engineering*, Vol. 137, No. 3, pp. 154-160.

Machusick, Matthew Damien. (2009). "The Observed Effects of Stormwater Infiltration on Groundwater." *MS Thesis*, Villanova University.

Marek, Thomas H., Arland D. Schnieder, Terry A. Howell, and Lynn L. Ebeling. (1988). "Design and Construction of Large Weighing Monolithic Lysimeters." *ASAR Paper No. 86-2525.* Vol. 31(2).

Meissner, Ralph and Manfred Seyfarth. (2004). "Measuring water and solute balance with new lysimeter techniques." *The Regional Institute Ltd*, Supersoil.

Monteith, J. L. (1965). "Evaporation and the Environment. The State and Movement of Water in Living Organisms." *Proc., Symposium of the Society of Experimental Biologists*, 205-224.

National Research Council (NRC). (2008). Urban Stormwater Management in the United States. *Stormwater Report.* Washington, D.C.

Nemirovsky, Evgeny M, Ryan S. Lee, and Andrea L. Welker. (2014). "Vertical and Lateral Extent of the Influence of a Rain Garden on the Water Table." Print pending.

North Carolina Department of Environment and Natural Resources (NC DENR). (2009). Stormwater Best Practices Management Manual.

Pennsylvania Department of Environmental Protection (PA DEP). (2006). Stormwater Best Management Practices Manual.

Penman, H. L. (1948). "Natural evaporation from open water, bare soil and grass." Proceedings of the Royal Society of London. *Series A, Mathematical and Physical Sciences*, 193, 120-145.

Prince George's County, Maryland: Environmental Services Division Department of Environmental Resources (MD DES). (2007). Bioretention Manual.

Prokop, M. (2003). "Determining the effectiveness of the Villanova bio-infiltration traffic island in infiltrating annual runoff." *Dept. of Civil and Environmental Engineering*, Villanova University.

Rivera, Leo. (2013). "Advances in Lysimetry: Lighting up the Black Box." *Decagon Devices Inc. Virtual Seminar.*

Rocco, Domenic. (2009). "A Risk-Based Approach for Sizing Stormwater Infiltration BMPs." *Watershed Management Program PA DEP Southeast Region.*

Saxton K.E. and W.J. Rawls. (2006). "Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions." *Soil Sci. Soc. Am. J.* 70, 1569-1578.

Saxton K.E., Rawls W.J., Romberger J.S., Papendick R.I. (1986). "Estimating generalized soil-water characteristic curves from texture." *Soil Sci. Soc. Am. J.* 50, 1031-1036.

Scott, D. and N.G. Bayfield. (2002). "Use of a weighing lysimeter system to assess the effects of trampling on evapotranspiration of montane plant communities." *NRC Research Press*.

Sharkey, L.J. (2006). "The performance of bioretention areas in North Carolina: A field study of water quality, water quantity, and soil media." *M.S. Thesis*, North Carolina State University.

Sickles, L., N. Parker, J.S. Wu, and H. Hilger. (2007). "Evaluation of Regionally Appropriate and Cost Effective Bioretention Media Mixes." *World Environmental and Water Resources Congress*, ASCE, 1-10.

Sloto, R.A., and Buxton, D.E. (2005). "Water budgets for selected watersheds in the Delaware River Basin, eastern Pennsylvania and western New Jersey." *U.S. Geological Survey Scientific Investigations Report*, p. 37.

Stevens Water Monitoring System, Inc. (2007). The Hydra Probe II Soil Sensor. Comprehensive Stevens Hydra Probe User's Manual 92915.

Tinjum, J., Benson C., and Blotz, L. (1997). "Soil-Water Characteristic Curves for Compacted Clays." *Journal of Geotech. and Geoenviron. Eng*. Vol. 123, No. 11: pp. 1060-1069.

Tolk, J. A., T. A. Howell, and S. R. Evett. (2005). "An Evapotranspiration Research Facility for Soil-Plant-Environment Interactions." *Applied Engineering in Agriculture*. 21(6), 993−998.

Twarakavi, Navin K. C., Masaru Sakai and Jirka Šimůnek. (2009). "An objective analysis of the dynamic nature of field capacity." *Water Resour. Res*. 45(10), 1944-7973.

Virginia Department of Conservation and Recreation (VA DCR). (2011). Stormwater Design Specifications: Bioretention. Version 1.8.

Wadzuk, B. (2013). “How Best to Take Credit for ET in Green Roofs – A Roundtable Discussion” *PA Stormwater Symposium*, Villanova University. 17 October.

Walter, I. A., R. G. Allen, R. Elliott, M. E. Jensen, D. Itenfisu, B. Mecham, T.A. Howell, R. Snyder, P. Brown, S. Echings, T. Spofford, M. Mattendorf, R. H. Cuenca, J.L. Wright, and D. Martin . (2000). "ASCE’s standardized reference evapotranspiration equation." *Proc. of the Watershed Management Conference*, June.

Ward, A. W. and S. W. Trimble. (2004). “Environmental Hydrology.” CRC Press.

Welker, Andrea L. and Bridget M, Wadzuk. (2011). “Development of a Stormwater Control Measure Microcosm to Measure Evapotranspiration.”*Geo-Frontiers*, ASCE, 3068-3076.

Wightman, W. E., Jalinoos, F., Sirles, P., and Hanna, K. (2003). “Application of Geophysical Methods to Highway Related Problems.” Federal Highway Administration, Central Federal Lands Highway Division, Lakewood, CO, *Publication No. FHWA-IF-04-021*.

Van Genuchten, M. Th. (1980). “A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils.” *Soil Sci. Soc*. *Am. J*. 44:892–898.

APPENDIX

APPENDIX A: Probablity of Back to Back Storms

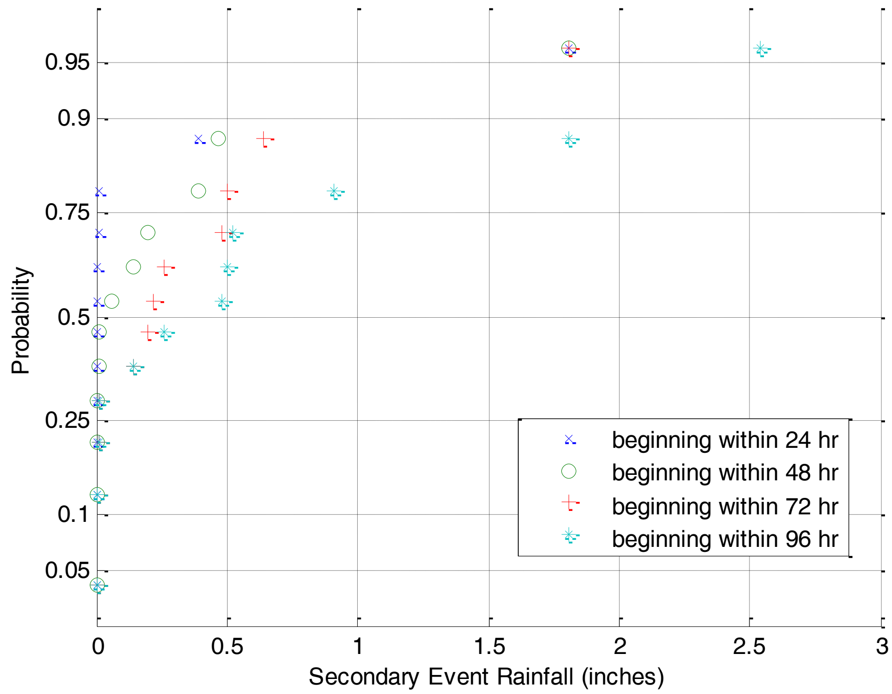

Figure A.1: Probability of second events given 81.3 mm (3.2 in) or greater event from BTI site rainfall data from 2003 to 2012 with an average of 1.3 events per year. Courtesy of Lee (2014).

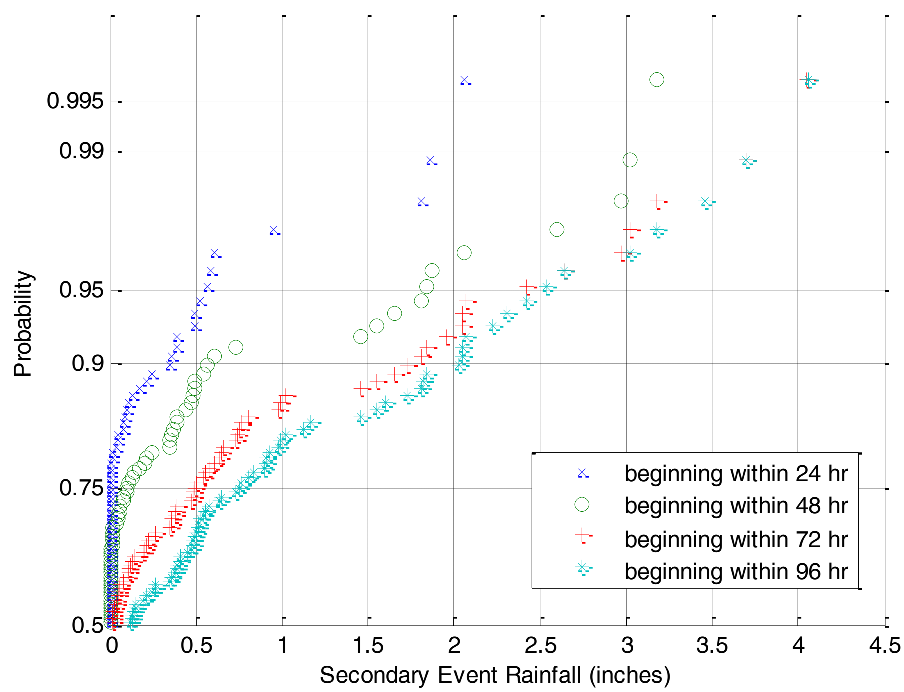

Figure A.2: Probability of second events given 25.4 mm (1 in) or greater event from BTI site rainfall data from 2003 to 2012 with an average of 14.9 events per year. Courtesy of Lee (2014).

APPENDIX B: Load Cell Calibration Calculations

Table B.1: ASCE-PM Daily ETsz Calculation for October 22nd 2013

Input Parameters	Input Values	Calculated Parameters	Calculated Values
Maximum Temperature, Tmax (°C)	17.5	Mean Temperature, Tmean (°C)	11.8
Minimum Temperature, Tmin (°C)	6.2	e(Tmax)	2.0
Maximum Relative Humidity, RHmax (%)	93.2	e(Tmin)	0.95
Minimum Relative Humidity, RHmin (%)	43.8	Slope Vapor Pressure Curve, Δ (kPa °C^{-1})	0.06
Daily Solar Radiation (MJ)	2.40	Actual Vapor Pressure, ea (kPa)	1.01
Area of Lysimeter (m^2)	0.46	Net Solar Radiation, Rns (MJ m^{-2} d^{-1})	4.05
Daily Solar Radiation (MJ m^{-2} d^{-1})	5.26	Clear Sky Solar Radiation, Rso (MJ m^{-2} d^{-1})	16.5
Daily Ra (MJ m^{-2}) (Allen et al. 1998)	22	Net Long Wave Radiation, Rnl (MJ m^{-2} d^{-1})	-1.00
Average wind speed at 2 m height, u2 (m s^{-1})	0.31	Net Radiation, Rn (MJ m^{-2} d^{-1})	5.05
Daily ASCE-PM ET, Etsz (mm)			1.17

Table B.2: ASCE-PM Daily ETsz Calculation for October 23rd 2013

Input Parameters	Input Values	Calculated Parameters	Calculated Values
Maximum Temperature, Tmax (°C)	14.9	Mean Temperature, Tmean (°C)	10.1
Minimum Temperature, Tmin (°C)	5.3	e(Tmax)	1.7
Maximum Relative Humidity, RHmax (%)	74.5	e(Tmin)	0.89
Minimum Relative Humidity, RHmin (%)	43.5	Slope Vapor Pressure Curve, Δ (kPa °C^{-1})	0.06
Daily Solar Radiation (MJ)	2.51	Actual Vapor Pressure, ea (kPa)	0.73
Area of Lysimeter (m^2)	0.46	Net Solar Radiation, Rns (MJ m^{-2} d^{-1})	4.2
Daily Solar Radiation (MJ m^{-2} d^{-1})	5.51	Clear Sky Solar Radiation, Rso (MJ m^{-2} d^{-1})	16.5
Daily Ra (MJ m^{-2}) (Allen et al. 1998)	22	Net Long Wave Radiation, Rnl (MJ m^{-2} d^{-1})	-1.01
Average wind speed at 2 m height, u2 (m s^{-1})	0.40	Net Radiation, Rn (MJ m^{-2} d^{-1})	5.25
Daily ASCE-PM ET, Etsz (mm)			1.28

Table B.3: Load Cell Verification for Lysimeter 2

Day	Hr	Min	Day Prior (kg)	Added Weight (kg)	Weight Removed (kg)	Difference in Weight (kg)	ASCE-PM Daily ET (mm)	ASCE-PM Daily ET (kg)	Derived Added Weight (kg)
22	8	0	521.3	525.2	-	3.88	+1.17	+0.54	4.42
22	8	5	522.0	525.6	-	3.62			4.15
22	8	10	522.5	525.9	-	3.40			3.94
23	10	35	-	523.9	518.7	5.19	-1.28	-0.58	4.60
23	10	40	-	524.0	518.7	5.32			4.73
23	10	45	-	524.3	518.4	5.84			5.26

Table B.4: Load Cell Verification for Lysimeter 3

Day	Hr	Min	Day Prior (kg)	Added Weight (kg)	Weight Removed (kg)	Difference in Weight (kg)	ASCE-PM Daily ET (mm)	ASCE-PM Daily ET (kg)	Derived Added Weight (kg)
22	8	0	557.7	560.9	-	3.14	+1.17	+0.54	3.67
22	8	5	557.9	561.0	-	3.05			3.59
22	8	10	558.1	561.1	-	3.01			3.54
23	10	35	-	560.2	555.1	5.10	-1.28	-0.58	4.52
23	10	40	-	560.4	555.1	5.32			4.73
23	10	45	-	560.6	554.9	5.67			5.08

APPENDIX C: Soil Moisture Meter Calibration Data

Table C.1: Soil Property Data for Soil Moisture Meter Calibration

Soil Type	Soil Property Value	Soil Property Value	Source of Soil Property	Probe Reading	Probe Signal
BTI	Wilting Point:	0.2	SWCC	0.24	16.97
	Moisture Content:	0.284	Moisture Content Test	0.338	25.84
	3 day Field Capacity:	0.33	Field Capacity Test	0.348	26.85
	2 day Field Capacity:	0.35	Field Capacity Test	0.363	28.40
	Moisture Content:	0.425	Moisture Content	0.548	51.10
	Maximum Saturation:	0.535	Calculated	0.58	55.70
IN SITU	Wilting Point:	0.12	SWCC	0.153	10.66
	Moisture Content:	0.225	Moisture Content Test	0.229	16.09
	Avg Field Capacity:	0.235	Field Capacity Test	0.27	19.49
	Moisture Content:	0.239	Moisture Content Test	0.259	18.55
	Realistic Saturation:	0.407	Calculated `	0.396	31.97
	Maximum Saturation:	0.513	Porosity	0.5	44.58
LYSIMETER 1	Wilting Point:	0.17	SWCC	0.132	9.35
	Moisture Content:	0.122	Moisture Content Test	0.156	10.85
	Moisture Content:	0.176	Moisture Content Test	0.175	12.12
	Avg Field Capacity:	0.33	Field Capacity Test	0.28	20.37
	Realistic Saturation:	0.5	Calculated	0.362	28.30
	Maximum Saturation:	0.54	Porosity	0.41	33.54

APPENDIX D: Distribution System Calibration Calculations

Table D.1: Long Duration Flow Calculation for Lysimeter 1

Flow (ml/min)	Interpolated Pump speed	Duration (hrs)	Goal Volume (ml)	Achieved Volume (ml)	Percent Error (%)
80	3	2.17	10010	10457	4.3%
		0.6	2740	2896	5.4%
121	3.9	3.5	24000	25339	5.3%
		2	14208	14479	1.9%
263	7.9	3.2	51000	50503	1.0%
		3	47700	47347	0.7%

Table D.2: Long Duration Flow Calculation for Lysimeter 2

Flow (ml/min)	Interpolated Pump speed	Duration (hrs)	Goal Volume (ml)	Achieved Volume (ml)	Percent Error (%)
80	3	1.5	7250	7240	0.1%
		3	13700	14479	5.4%
121	4	2	13800	14479	4.7%
		3.5	25900	25339	2.2%
263	8.1	1.4	23900	22095	8.2%
		1.87	30400	29460	3.2%

Table D.3: Long Duration Flow Calculation for Lysimeter 3

Flow (ml/min)	Interpolated Pump speed	Duration (hrs)	Goal Volume (ml)	Achieved Volume (ml)	Percent Error (%)
80	3	1.5	7240	6900	4.7%
		3	14479	13900	4.0%
121	4	1.5	10859	10880	0.19%
		3	21719	21580	0.64%
263	7.8	2.73	43138	46300	7.3%
		3	50500	47346.9	6.7%

APPENDIX E: Soil Moisture Slope Analysis Determination

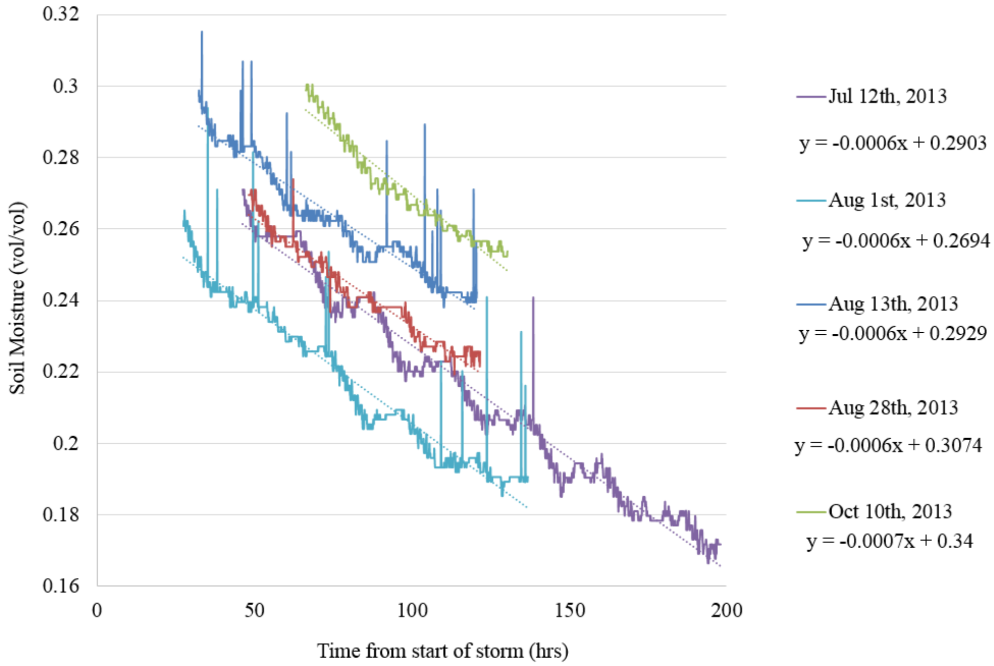

Figure E.1: Lysimeter 1 Soil Moisture (vol/vol) at 10 cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple, August 1st is light blue, August 13th is dark blue, August 28th is red, and October 10th is green.

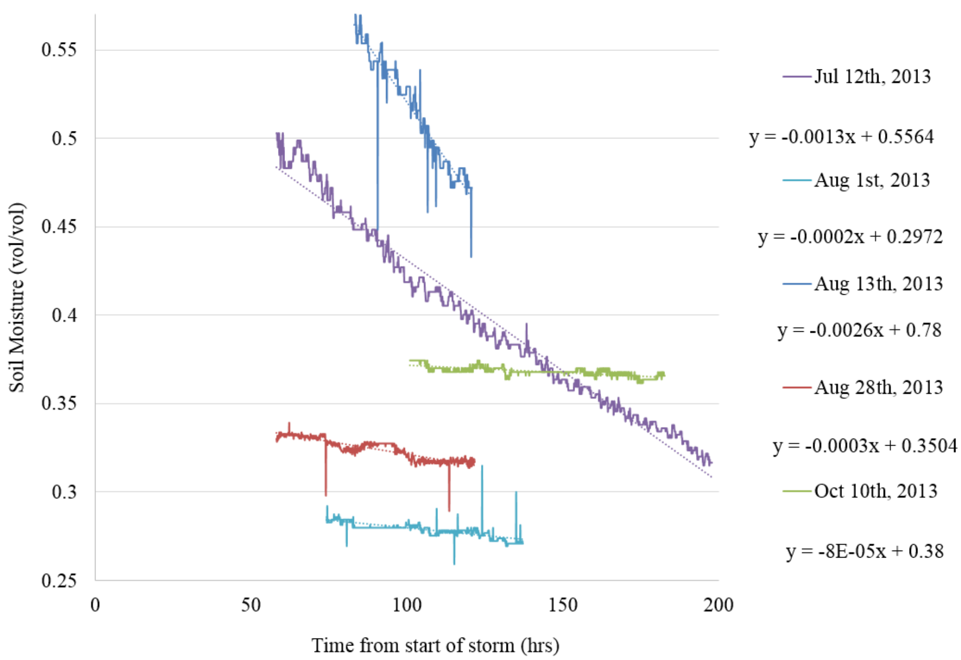

Figure E.2: Lysimeter 1 Soil Moisture (vol/vol) at 35 cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple, August 1st is light blue, August 13th is dark blue, August 28th is red, and October 10th is green.

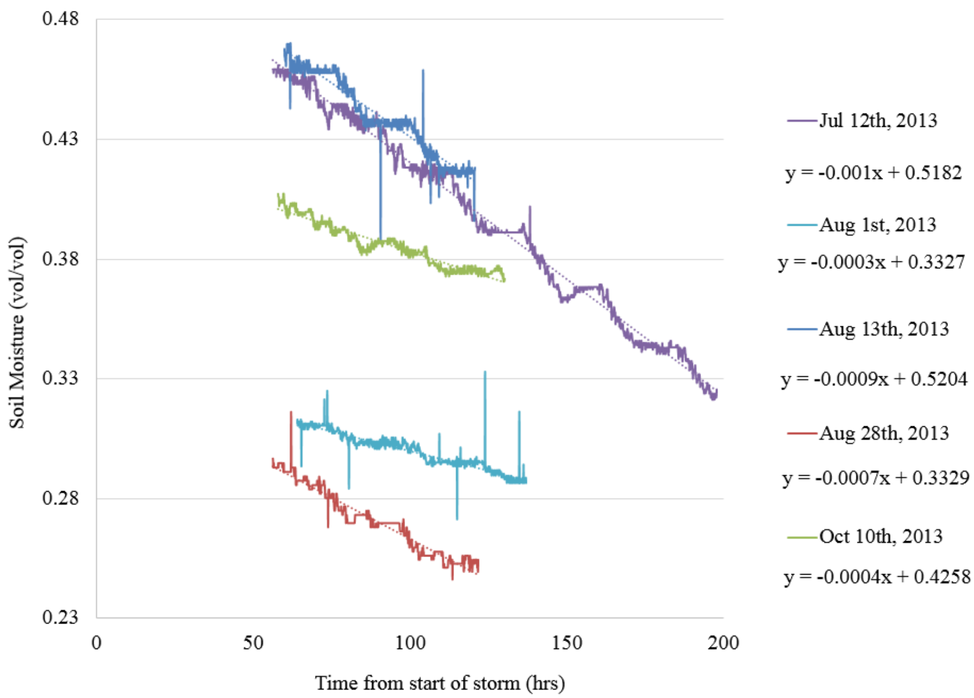

Figure E.3: Lysimeter 1 Soil Moisture (vol/vol) at 65 cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple, August 1st is light blue, August 13th is dark blue, August 28th is red, and October 10th is green.

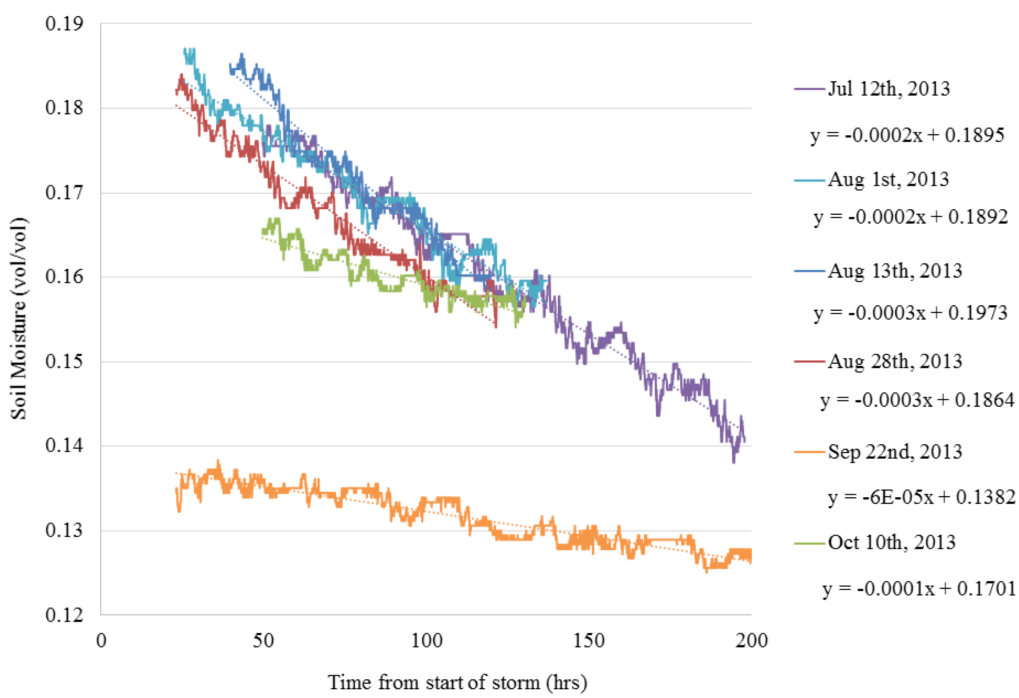

Figure E.4: Lysimeter 2 Soil Moisture (vol/vol) at 35cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple, August 1st is light blue, August 13th is dark blue, August 28th is red, September 9th is orange, and October 10th is green.

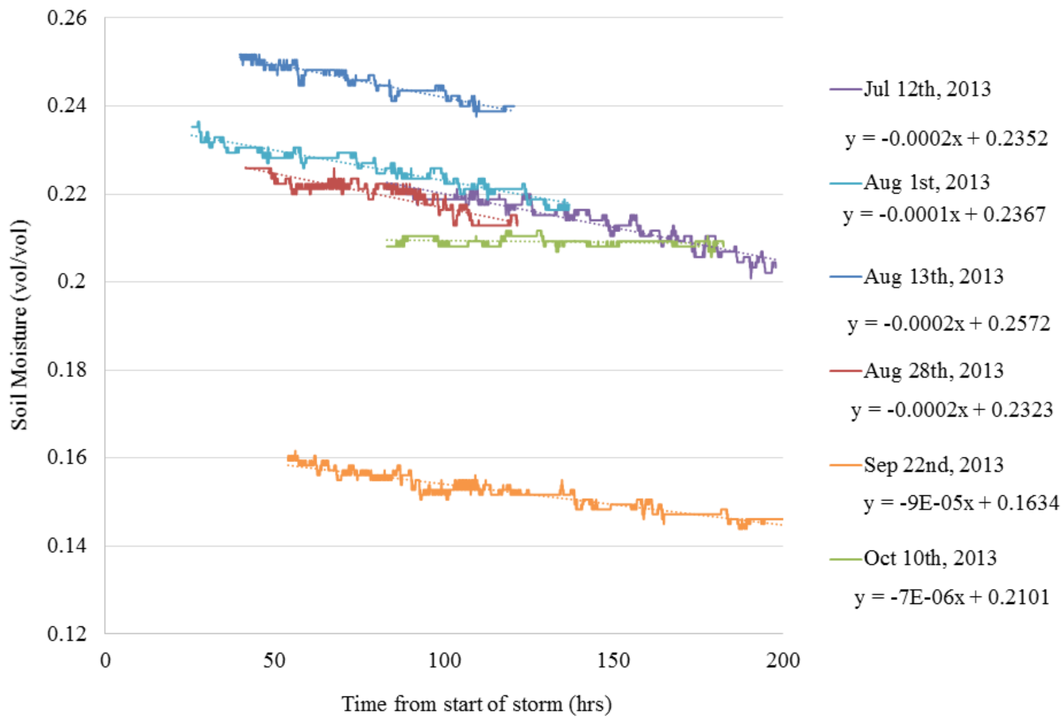

Figure E.5: Lysimeter 2 Soil Moisture (vol/vol) at 65cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple, August 1st is light blue, August 13th is dark blue, August 28th is red, September 9th is orange, and October 10th is green.

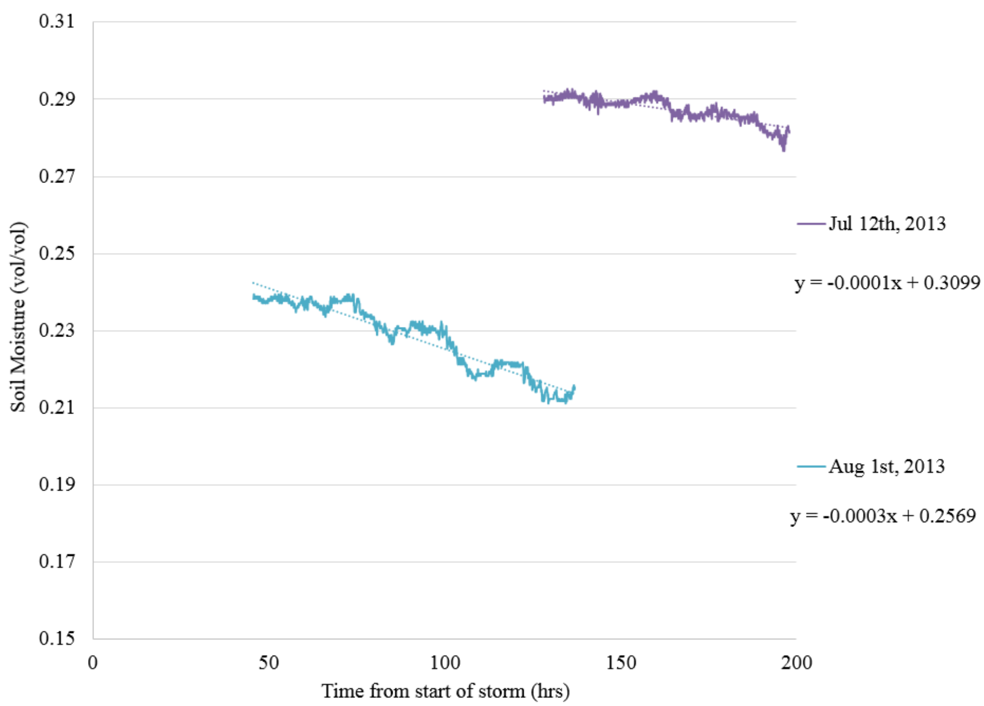

Figure E.6: Lysimeter 3 Soil Moisture (vol/vol) at 35cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple and August 1st is light blue.

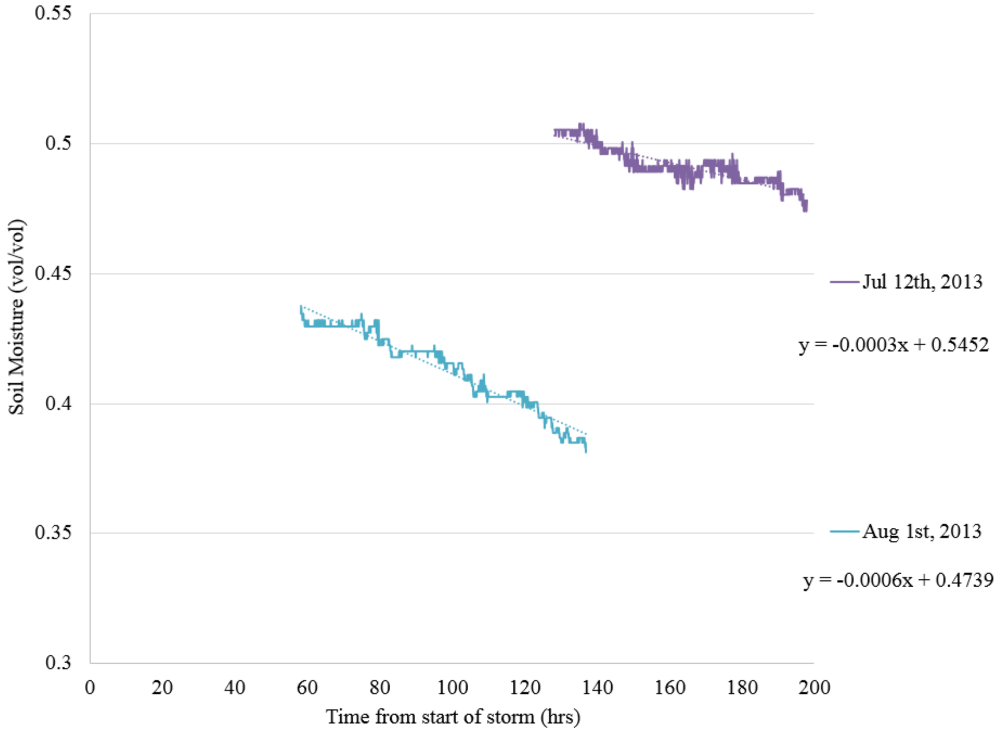

Figure E.7: Lysimeter 3 Soil Moisture (vol/vol) at 65cm depth versus time after storm start to show recession rates for six storm events in 2013. July 12th is purple and August 1st is light blue.

APPENDIX F: ET and Percolation Data

Table F.1: Lysimeter 1 Water Budget Data to Calculate Actual ET

Date	Date ID	Rain Total (mm)	Change in Weight (mm)	Percolation (mm)	ET (mm)
7/12/2013	1307121	28.2	26.3	0	1.9
9/21/2013	1309211	36.3	4.8	0	31.5
10/17/2013	1310171	3.0	0.5	0	2.6
11/18/2013	1311181	3.8	2.8	0	1.0
12/22/2013	1312221	22.4	3.5	6.8	12.1
1/5/2014	1401051	36.8	6.3	10.9	19.7
1/10/2014	1401101	38.6	-5.0	5.8	37.7
1/26/2014	1401261	5.8	5.6	0.0	0.3
2/5/2014	1402051	22.9	4.6	1.7	16.6

Table F.2: Lysimeter 2 Water Budget Data to Calculate Actual ET

Date	Date ID	Rain Total (mm)	Change in Weight (mm)	Percolation (mm)	ET (mm)
7/12/2013	1307121	28.2	10.8	2.1	15.2
8/1/2013	1308011	32.8	-1.5	9.9	24.3
9/21/2013	1309211	36.3	3.3	0.0	33.0
10/17/2013	1310171	3.0	0.7	0.0	2.4
10/31/2013	1310311	8.6	2.0	1.0	5.7
2/5/2014	1402051	22.9	17.2	1.4	4.2
2/17/2014	1402171	21.1	16.7	0.1	4.2

Table F.3: Lysimeter 3 Water Budget Data to Calculate Actual ET

Date	Date ID	Rain Total (mm)	Change in Weight (mm)	Percolation (mm)	ET (mm)
7/12/2013	1307121	28.2	2.9	2.4	30.6
7/28/2013	1307281	22.4	7.0	1.6	13.8
8/1/2013	1308011	32.8	2.6	3.0	27.2
9/16/2013	1309161	3.0	2.9	0.0	0.2
11/18/2013	1311181	3.8	2.2	0.0	0.9
10/19/2013	1310191	5.3	3.7	0.0	1.7
10/31/2013	1310311	8.6	2.5	0.0	6.1
11/18/2013	1311181	3.8	3.0	0.0	0.8
12/18/2013	1312181	10.4	1.3	0.3	8.8
12/22/2013	1312221	22.4	0.6	1.9	19.8
2/5/2014	1402051	22.9	11.8	0.0	11.0
3/2/2014	1403021	2.5	0.4	0.0	2.1
3/4/2014	1403041	4.1	-0.6	4.4	0.2
3/12/2014	1403121	10.9	1.3	4.0	5.6
3/17/2014	1403171	2.0	1.9	0.0	0.1