RAIN GARDEN EVAPOTRANSPIRATION ACCOUNTING

By

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NOMENCLATURE

$ASCE$	American Society of Civil Engineers
C_d	Denominator coefficient that relates to the crop height
C_n	Numerator coefficient that relates to time step
CRM	Coefficient of residual mass
CWA	Clean water act
D	Difference between the observed and predicted data
E	Coefficient of efficiency
e_a	Actual vapor pressure [kPa]
e_s	Saturation vapor pressure [kPa]
$(e_s - e_a)$	Vapor pressure deficit [kPa]
ET	Evapotranspiration
ET_a	Actual evapotranspiration
ET_{HG}	Modified evapotranspiration by Hargreaves equation [mm/d]
ET_p	Potential reference evapotranspiration
ET_{PM}	Modified evapotranspiration by Penman-Monteith equation [mm/d]
ET_{sz}	Potential reference evapotranspiration by Penman-Monteith equation [mm/d]
FC	Field capacity [vol/vol]
G	Soil heat flux density [MJ/m^2/d]
HG	Hargreaves
I	Inflow [mm]
IWS	Internal water storage
K_c	Crop coefficient
K_{int}	Initial season crop coefficient

K_{end}	Ending season crop coefficient
K_{mid}	Middle season crop coefficient
K_s	Water stress coefficient
K_{sat}	Saturated hydraulic conductivity [cm/d]
LAI	Leaf area index [mm/mm]
MVG	Malum van Genuchten soil water relation equation
n	Shape parameter for MVG
N	Sample size
$NPDES$	National pollutant discharge elimination system
O	Outflow percolate [mm]
O_i	Observed value is at time step *i*
$\bar{O}$	Mean of observed values
P_i	Estimated value is at time step *i*
$\bar{P}$	Mean of estimated values
PET	Potential reference evapotranspiration by Hargreaves equation [mm/d]
PM	Penman-Monteith
R_a	Extraterrestrial radiation [MJ/m^2/d]
R_n	Net solar radiation on the crop surface [MJ/m^2/d]
R^2	Coefficient of determination
$RMSE$	Root mean square error
S	Standard error [mm]
SCM	Stormwater control measure
SM_{10}	Daily change in soil moisture at 10 cm depth from weighing lysimeters
SM_{35}	Average daily change in soil moisture at 35 cm depth in weighing lysimeters

SM_{65}	Daily change in soil moisture at 65 cm depth from weighing lysimeters
$SMEF$	Soil Moisture Extraction Function
SMC	Soil moisture capacity [vol/vol]
SMT	Actual or current soil moisture [vol/vol]
$SWAP$	Soil, Water, Atmosphere, and Plant
$SWCC$	Soil water characteristic curve
T	Average daily temperature at 2 meters from ground level [°C]
TR	Difference between the mean daily maximum and minimum temperature [°C]
$UNSODA$	United States Department of Agriculture's Unsaturated Soil Database
UO	Unconstricted outflow
$USDA$	United States Department of Agriculture
W	Daily change in weight from weighing lysimeter systems
WP	Wilting point [vol/vol]
α	Shape parameter for MVG
$\alpha - level$	Significance level for statistical test taken at 0.05
Δ	Slope of the vapor pressure curve [kPa/°C]
ΔS	Change is storage [mm]
θ	Volumetric moisture content [vol/vol]
θ_r	Residual volumetric moisture content [vol/vol]
θ_s	Saturated volumetric moisture content [vol/vol]
ρ_d	Bulk dry density [g/cm^3]
γ	Psychometric constant based on altitude [kPa/°C]
ψ	Suction head [MPa]

ABSTRACT

Quantifying evapotranspiration (ET) and infiltration from vegetated stormwater control measures (SCMs), such as rain gardens, is necessary to properly assess their volume reduction potential. A standard model equation in most states or regulatory entities is used for rain garden design which only includes static processes and excludes the dynamic functions of infiltration during an event and ET during the time between events. Accreditation of rain gardens' volume capture cannot be fully realized unless dynamic processes are studied and included into design. The guiding research question is "**How can ET be incorporated into rain garden design and permitting?"** To achieve the goal of quantifying the impact of design on rain garden hydrologic performance, tools based on experimental performance are developed and provided within to reliably accredit volume reduction attributed to ET.

Weighing lysimeters at Villanova University mimic rain garden designs and measure water budget parameters to determine how design elements impact ET and infiltration and to quantify how these processes are continuously occurring over time. A set of three 66 cm deep rain garden continuous weighing lysimeters enable comparison of two soil media with the same unconstricted drainage systems, a sandy loam and sand, and two drainage systems with the same media (sand), an unconstricted outflow (UO) and internal water storage (IWS). A bench scale study of 46 cm deep discrete weighing lysimeters compare five types of soil media (i.e. loamy sand, sandy loam, loam, silt loam, clay loam). These devices were studied for a one year period (2015-2016).

Evapotranspiration rates from the large continuous weighing lysimeters are in annual, seasonal, and monthly averages, which reveal that the IWS has statistically higher ET rates on average (4.4 ± 3.4 mm/d) compared to the UO systems (2.9 ± 2.2 mm/d for sandy loam and 2.7 ± 2.3 mm/d for sand). Evapotranspiration comprises 30%, 31%, and 53% of the water budget for sandy loam UO, sand UO and sand IWS systems, respectively. Statistics on cumulative ET between storm event sizes greater than 6 mm revealed that the UO systems can evapotranspire an equivalent storm volume of 15 mm or less and the IWS can evapotranspire an equivalent storm volume of 40 mm, on average. Comparisons of the UO systems indicate that the additional fines in the sandy loam media do not inhibit ET rates and are not statistically different from sand media.

Soil moisture at three depths within the soil column is compared to lysimeter weight readings and was found that it can be a suitable proxy to determine cumulative storm ET for all lysimeter types (R^2 of 0.88, 0.87, and 0.77 for sandy loam UO, sand UO, and sand IWS, respectively). Soil moisture tracking at the bottom of the root zone is most correlated to weight on a storm basis (i.e. days after a storm) as a suitable proxy to calculate ET, however tracking soil moisture at the top and bottom of a rain garden soil column is recommended to determine cumulative storm ET.

The Hargreaves and ASCE Penman-Monteith reference ET equations with and without modifications for water availability and crop presence are calibrated on a daily and storm basis. Hargreaves equation provides an adequate estimate for rain garden ET for all systems without modification on a daily basis (efficiencies are approximately 0 or greater for all cases). On a yearly scale, Hargreaves equation overpredicts ET in the UO systems and underpredicts the IWS. Modifications to Hargreaves equation through crop factors and a soil moisture extraction function are able to reduce the root mean square error (RMSE), increase R^2 and efficiency for all weighing lysimeter types over the study period. On a storm basis, Hargreaves without modification performs similarly to the daily basis but with higher R^2 and efficiency (R^2 of 0.89, 0.79, and 0.91 for sandy loam UO, sand UO, and sand IWS, respectively). With modification, even higher R^2 and efficiency values can be obtained (R^2 of 0.95, 0.85, and 0.91 for sandy loam UO, sand UO, and sand IWS, respectively).

The ASCE Penman-Monteith equation provides an adequate estimate of rain garden ET for the UO systems but not the IWS without modification (efficiencies of 0.14, 0.29, and -0.14 for sandy loam UO, sand UO and sand IWS, respectively). Generally, ASCE Penman-Monteith equation estimates the UO systems well but underestimates the IWS system. Modifications to Penman-Monteith reference ET through crop factors and a soil moisture extraction function are able to reduce RMSE, increase R^2 and efficiency for all weighing lysimeter types. On a storm basis, ASCE Penman-Monteith equation proves an adequate estimation (all efficiencies greater than 0) for all lysimeters types without modification (R^2 of 0.83, 0.78, and 0.92 for sandy loam UO, sand UO, and sand IWS, respectively), and with modification even higher R^2 and efficiency values can be obtained (R^2 of 0.94, 0.89, and 0.92 for sandy loam UO, sand UO, and sand IWS, respectively). For both equations, crop coefficients were found in an expected range for the UO systems (0.5 to 1.5) but were high in the IWS system (1.6-2.0); soil moisture extraction functions were not needed in calibration of IWS on a storm basis.

A 1-D Richards equation simulator, Soil Water Atmosphere and Plant (SWAP), uses the calibrated Penman-Monteith equation and its results are verified using the weighing lysimeter and bench scale study cumulative ET and outflow data on days after events greater than 25 mm. SWAP was then used as a tool for rain garden design void space credit. Soil media, depth of rooting and media, crop coefficients, ponding depth, and lower boundary condition (bioretention, bioretention with IWS, and bioinfiltration with hydraulic soil types A, B, and C) are varied to provide a wide range of rain garden design and the ET rates to be expected within 6 days and 12 days after a storm event.

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 affected the way in which water moves above and below ground during and after rainfall events (NRC 2008). Urbanization has introduced impervious surfaces (e.g. rooftops and roadways) and topographic change (e.g. leveling and 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, stormwater runoff from impervious areas on site was not a priority. Instead, surface runoff is handled by quickly directing the water away from the structure (e.g. a roadway or building) to protect the structure's lifespan and ensure public safety. Then, the runoff travels through the sewer and is discharged into nearby surface waterways. The discharge causes erosion 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) created the National Pollutant Discharge Elimination System (NPDES) program to manage the water quality in the nation's water bodies (EPA 2005). To manage water quality, the NPDES first focused on the reduction of 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 are identifiable. However, control of point source pollution is only part of the solution to improve the health of lakes, rivers, and streams. In 1987, the NPDES extended its reach to the control of stormwater as 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 stormwater pollution in both quantity and quality. Stormwater control measures can be structural or nonstructural. Nonstructural SCMs include the reduction of overall impervious area for new development thus reducing volume and potential pollutant load. Structural SCMs can be incorporated into new development or retrofitted into areas previously developed if available space allows. Structural

SCMs include vegetated systems like rain gardens, green roofs, swales, wetlands and ponds and non-vegetated systems such as infiltration beds overlain with porous media.

The quantity control of SCMs refers to the reduction of the amount of stormwater leaving a watershed and degrading receiving water bodies. This quantity reduction is obtained by other hydrologic processes, such as infiltration to surface and groundwater, transpiration (if vegetated), and evaporation. Structural SCMs are typically small and there may be a need for multiple measures to capture site specific runoff volume to restore balance to 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 key nutrients, nitrogen and phosphorus, and total suspended solids (TSS) typically found in stormwater runoff (PADEP 2006). Percentage removal is inherently flawed as it is dependent on the inflow concentration. Water with high pollutant concentration coming into the SCM 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. Due to the large uncertainty and variety of SCM performance, better tools to assess SCM's function are needed to portray SCM's efficiency in site specific conditions.

The complicated nature of water quality benefits are out of the scope of the present study, but are important to SCM design. Overall, if the amount of stormwater is being reduced, then water quality is improving as less of the pollutants reach the receiving water body. The focus of this research is on water quantity control function of SCMs, specifically stormwater volume quantity reduction by mechanisms of evapotranspiration (ET) and infiltration. This study uses a site equipped 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 part of a new practice that seek to mimic the natural or before construction hydrology; the EPA (2008) acknowledges there are uncertainties in SCM performance, longevity, and regulation. 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.

CHAPTER 2. LITERATURE REVIEW

2.1 SCM BACKGROUND

Stormwater control measures (SCMs) are used to manage stormwater runoff from increased urbanization by using smaller, more dispersed techniques to restore the hydrologic cycle. One common SCM is a rain garden (also referred to as bioretention or bioinfiltration) that mitigates peak flow and volume and non-point source pollution associated with runoff. In Pennsylvania, current design and permitting practices for rain gardens only account for static stormwater volume storage by bowl depth and a portion of media void space during a rain event (PADEP 2006; PWD 2015), similar to other state design guidelines (e.g. VADCR 2011; NCDENR 2009; MDDES 2013). Recent updates to the Philadelphia Stormwater Manual rank SCMs, placing rain gardens at the top; this encourages rain garden use over other SCMs (PWD 2015). The implementation of rain gardens is likely to increase in the near future (Davis et al. 2009), and this increase in usage requires that these systems have improved efficiency to create cost-effective designs. To date, rain garden design focuses on specification of infiltration rates to use as a volume reduction mechanism and neglects evapotranspiration's (ET's) role in restoring water holding capacity within a rain garden. Present design tools are also not capturing infiltration dynamics well and are missing a substantial portion of a system's hydrology. Infiltration rates are typically taken conservatively as the saturated hydraulic conductivity (Jarrett 2017). Infiltration rates vary spatially and temporally such that it is difficult to find a representative value or describe seasonal variation (Ritzema 1994). The purpose of the proposed research is to create tools that incorporate ET and infiltration dynamically into rain garden design ranging from a simple approach requiring little input information with conservative volume reduction to a more robust approach requiring more information with high volume reduction potential.

2.1.1 EVAPOTRANSPIRATION IN SCMS

Many state manuals only mention ET insofar as it is recommended to add plants to enhance ET from rain gardens (VADCR 2011; NCDENR 2009; MDDES 2007; NYDEC 2015). The literature is limited in showing the role of ET in rain gardens, but there is some evidence that ET can be a substantial factor in a system's water balance (Li et al. 2009; Denich and Bradford 2010; Culbertson and Hutchinson 2004; Wadzuk et al. 2015). Li et al. (2009) measured 19% of the annual precipitation was evapotranspirated in a lined rain garden with an underdrain and a 4.5:1 drainage area to surface area ratio. Denich and Bradford (2010) measured 4.2 mm/d to 7.7 mm/d of ET in the summer in an unconstrained draining sandy soil rain garden lysimeter in Canada. Culbertson and Hutchinson (2004) measured 2.7 mm/d of ET for fall to 7.8 mm/d for summer for rain garden lysimeters in the same region of Canada as Denich and Bradford (2010). Wadzuk et al. (2015) found that 50% of precipitation was evapotranspirated in a freely draining, sandy soil rain garden lysimeter (3.1 mm/d on average). Wadzuk et al. (2015) also showed that the drainage structure did affect ET rates and volumes; a rain garden lysimeter with an internal water storage layer, which increased available water, had 6.1 mm/d of ET on average (78% of the precipitation). Evapotranspiration (ET) is a significant component of a watershed's water balance, ranging from 10% of the annual precipitation in the temperate oceanic climate of the US northwest region to 100% in the desert and semi-arid climates of the US southwest and central regions during drought (Hanson 1991; Sanford and Selnick 2013). In the Delaware River Basin watershed-wide ET can account for 50% or greater of the annual water budget (Sloto and Buxton 2005). Although ET has been heavily studied in agriculture (Allen et al 2006; Allen et al 1998; Doorenbos and Pruitt 1977; Tolk et al. 2005), it remains largely unaccounted for in the design of SCMs.

2.1.2 SOIL MIX DESIGN

Current rain garden designs are primarily specified with "engineered sandy soils" due to their low hydraulic retention time to expedite infiltration (Emerson and Traver 2008; Brown and Hunt 2011). As such, research has focused on rain garden systems with soils that are primarily sand (Brown and Hunt 2011; Carpenter et al. 2010; Davis et al. 2006; Dietz and Clausen 2005). While sandier soils may lend themselves better to infiltration, soils with lower hydraulic conductivities may lend themselves better to ET. Soils with a lower hydraulic conductivity, such as fine-grained soils, retain more water near the surface making more water available for ET. Theoretically, the total water available for ET can be taken as the difference between a soil's field capacity and wilting point (Allen et al. 1998; Wadzuk et al. 2013). When designing for ET in a bioretention system, it may not be desired that the water move quickly through the soil media as previous designs specified. Higher fines content has been shown to produce healthier plants, less percolation, and more ET (Hess et al. 2014; Whiting et al. 2015), in addition to increased pollutant concentration removal (Sickles et al. 2007). Often native soil is not homogenous and can have a higher percentage of fines than the typically engineered sandy soils for rain gardens. Benefits of utilizing a site's native soils include lessening the disturbance of the natural hydrologic cycle and perhaps increasing the amount of ET (Benson and Bareither 2012). Utilizing native soil would also provide a cost savings to the project and reduce the environmental impact of construction as the need for quarrying and hauling borrow pit soil is eliminated (Flynn and Traver 2013).

Rain garden performance is a function of soil mix design and more technical research is needed (Lee et al. 2016) to determine the best soil mixes for optimum volume (ET and infiltration) and pollutant removal from stormwater (Brown et al. 2009; Carpenter et al. 2010; Sickles et al. 2007). The variation and range in soil mix design characteristics among different federal, state and private agencies is vast, and it was found that at least 27 different rain garden mix designs have been published (Carpenter et al. 2010). The planting media composition specified by each state varies with recommended percentages of sand ranging from 35-65% and percentages of topsoil ranging from 20-80%. Some states do not provide proportions for soil mixes at all or are very vague on technical soil type. The term “topsoil” appears in many of the recommended soil mix compositions, yet this is a broad term lacking any technical classification. In one study by Sickles et al. (2007), topsoil was used to refer to both native soil as well as commercial topsoil. Commercial topsoil has no uniform USDA or USCS classification. It may refer to silty loams, sandy loams, loams, etc.; therefore, using the term topsoil in design criteria is highly unspecific. Commercial topsoil typically incorporate fine particles for water holding capacity and organics for nutrients that are desirable for plant growth (Whiting et al. 2015). When referring to native soils, topsoil is defined by its location in the soil profile (the top layer) and not by its gradation.

2.1.3 DRAINAGE DESIGN

Many design details about rain garden systems are still being investigated; these include when it is appropriate to use underdrains and the use and depth of an internal water storage layer (Davis et al. 2009; Lee et al. 2015). Since rain gardens systems inherently use ET for soil storage recovery and can even increase the amount of ET activity by increasing available water, it is vital to continue to study rain gardens with different drainage configurations. In the present study, the two drainage systems are an unconstricted outflow (UO) underdrain and an internal water storage (IWS) zone with an elevated drain. The IWS is a design that implements a semi-permanent saturated zone at the bottom of the bioretention basin. This is accomplished by adding an upturned elbow or elevated outlet to the underdrain pipe that is exiting the rain garden and connecting to the stormwater sewer pipe line. The IWS provides increased hydrologic performance via less outflow volume, prolonged water storage for plants to draw on during dryer periods, reduced stored stormwater volume via ET, as well as water quality benefits (Davis et al. 2009; Hunt et al. 2006; Brown et al. 2009).

2.2 RESEARCH QUESTION

Accounting for ET in rain garden design has its challenges. Evapotranspiration is a continuous process and does not easily fit into the existing static design equation for rain garden sizing. The current volume reduction calculation is based mostly on bowl depth but also accredits a volume reduction from the minimum of void space or infiltration rate based calculations (Figure 2.1; PADEP 2006). The guiding research question is **"How can ET be incorporated into rain garden design or permitting?"** This research provides methods that incorporate ET and infiltration

Volume Reduction Calculations

The storage volume of a Bioretention area is defined as the sum total of 1. and the smaller of 2a or 2b below. The surface storage volume should account for at least 50% of the total storage. Inter-media void volumes may vary considerably based on design variations.

1. Surface Storage Volume (CF) = Bed Area (ft^2) x Average Design Water Depth

2a. Infiltration Volume = Bed Bottom area (sq ft) x infiltration design rate (in/hr) x infiltration period (hr) x 1/12.

2b. Volume = Bed Bottom area (sq ft) x soil mix bed depth x void space.

Figure 2.1: Volume reduction calculation from PADEP 2006 bioretention manual

dynamically into rain garden design. A combination of statistical data from rain garden lysimeters, predictive ET equations, and a 1-D Richards equation solver is used to answer this question.

2.3 LYSIMETER BACKGROUND

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 and have been established in agriculture to predict when and how much water to irrigate to a specific crop (Allen et al. 1998). 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 measure, it is the unknown of the system, and can be derived from a mass balance of the remaining variables. The lysimeter design for agricultural typically involves a sunken monolithic soil column that rests on compression load cells. The lysimeter requires a system to measure outflow percolate, sensors to measure desired parameters, 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. Outflow percolate may be collected in a passive or active fashion. Passive outflow collection allows the water to percolate through the system and then is collected at the bottom (Figure 2.2). Active outflow collection requires a device that applies suction to the bottom boundary of the lysimeter (Rivera 2013).

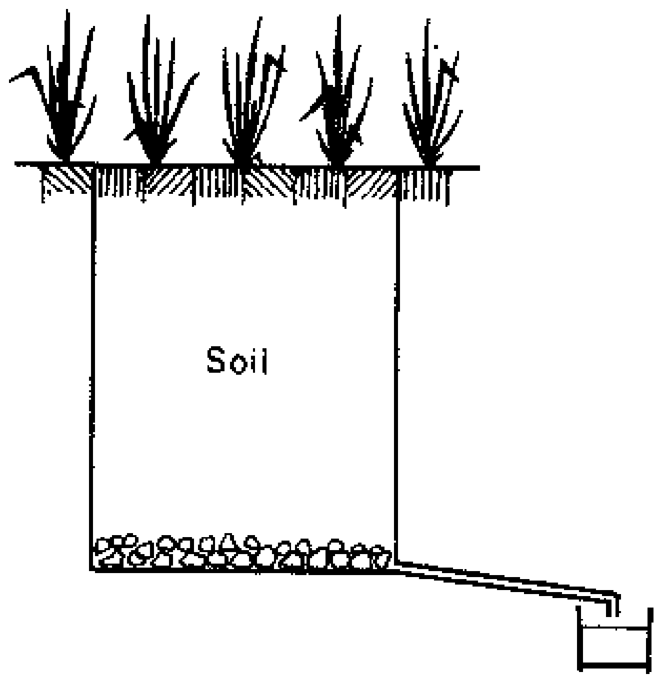

Figure 2.2: Freely draining lysimeter schematic (Allen et al. 1998)

The advantage of active outflow collection over passive collection is that it attempts to mitigate the influence of the bottom boundary but also requires knowledge of the suction value and application of suction in a constant or variable mode. The bottom boundary condition of a passive collecting lysimeter creates a capillary break. This capillary break will then cause water to gather on the soil above the bottom boundary until it reaches a soil moisture content that will overcome the force of the soil suction. After the soil suction is overcome, the water will flow out as percolate outflow. The outflow collection of the lysimeters used in this study is passive.

2.4 LYSIMETER APPLICATION IN SCMS

Lysimeter technology has many applications, including using it to evaluate vegetated stormwater controls including green roofs and rain gardens (DiGiovanni et al. 2010, Wadzuk et al. 2015, Dench and Bradford 2010, Wadzuk et al. 2013). The drainage design of lysimeters can influence ET performance and may cause differences between ET observed from a lysimeter compared to ET observed by the total vegetated SCM (Wadzuk et al. 2013). Rain gardens include bioretention (with underdrain and liner) and bioinfiltration (no underdrain or liner) designs. Bioretention design includes an underdrain (typically surrounded by gravel) and liner or a soil of very different hydraulic conductivity (e.g. compacted clay). These systems are important areas where infiltration is not possible or preferred such as over or near utility lines, basements, karst, poorly infiltrating soils, and contaminated soils (brownfields redevelopment).

A rain garden lysimeter with a passive collection system is most comparable to bioretention design as there is an inherent capillary break in the system. Bioinfiltration design is preferred when infiltration is possible and adequate (Lee et al. 2015). The PADEP (2006) manual recommends infiltration rates greater than 6.1 cm/day for bioinfiltration design. Typically there will be a difference in hydraulic properties between rain garden media and the underlying media in a bioinfiltration design. However, hydraulic properties of a soil to soil interface that are both above 6.1 cm/day (bioinfiltration design) can be expected to be more similar than that of a soil to gravel interface, which is necessary for bioretention design (PADEP 2006). Some state manuals recommend the use of gravel as an underlying layer in bioinfiltration (PADEP 2006; VADCR 2011; MDDES 2013). The use of gravel is incentivized in PA as the manual allows 40% void space attributed to the gravel layer and only 20% void space to the soil layer (PADEP

2006). Bioinfiltration with a gravel layer will cause a similar capillary break as seen in bioretention designs thus making the results from the lysimeter setup comparable to this design.

Due to the bottom boundary condition of the rain garden lysimeter, the direct results from the lysimeters are probably more representative of bioretention or bioinfiltration design with a gravel layer. For this same reason, ET estimated from the rain garden lysimeters may be different than ET occurring from a bioinfiltration with no gravel layer rain garden design. The 1-D Richards equation solver has the capability to simulate various bottom boundary conditions which are able to represent that of a bioinfiltration and bioretention (with and without an IWS) design. The simulations performance can be verified with the observed data from the bioretention designs. The 1-D Richards equation solver can then be used to determine ET estimates in various bioinfiltration scenarios.

2.5 PREDICTIVE EVAPOTRANSPIRATION EQUATIONS

With the limited study on ET in rain garden systems, there is also limited study on estimation methods or mathematical models of ET for SCMs. The present study is a comparison of ET measured from three lysimeters and predicted by the American Society of Civil Engineers (ASCE) modified Penman-Monteith equation and Hargreaves equation. These two equations are commonly used in agricultural practice. The ASCE Penman-Monteith equation is the accepted method for predicting ET in agriculture (Allen et al. 2005). This method can factor in modifications for plant health and water stress, but it uses multiple weather parameters that may be more difficult to obtain. The Hargreaves equation only requires temperature and global position, which are easily obtained, but the equation tends to overestimate ET (Weiß and Menzel 2008; Trajkovic 2007; Fooladmand and Haghighat 2007). The Hargreaves equation can be modified with a soil moisture extraction function to incorporate water stress into the prediction (Zhao et al. 2013). Wadzuk et al. (2015) found that neither the ASCE Penman-Monteith or Hargreaves equations predicted observed ET rates well without modification for plant use or soil moisture availability.

The Hargreaves equation is a simple method to estimate potential ET (Hargreaves and Allen 2003):

Equation 2.1:

$$\boldsymbol{PET = 0.0023R_a(T + 17.8)(TR^{0.50})}$$

Where PET is potential ET [mm/d], R_a is extraterrestrial radiation [MJ/m^2/d], T is average daily temperature at 2 meters from ground level [°C], and TR is difference between the mean daily maximum and minimum temperature [°C]. Equation 2.1 assumes adequate water supply.

The ASCE Penman-Monteith equation is the recommended equation for ET estimates (Walter et al. 2000):

Equation 2.2:

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

where ET_{sz} is standardized potential reference ET [mm/d], Δ is slope of the vapor pressure curve [kPa/°C], R_n is net solar radiation on the crop surface [MJ/m^2/d], G is soil heat flux density [MJ/m^2/d], γ is the psychometric constant [kPa/°C], T is average daily temperature at 2 meters from ground level [°C], e_s is saturation vapor pressure [kPa], and e_a is the actual vapor pressure [kPa]. A numerator coefficient, C_n, relates to the time step and is taken at 900 for daily calculations. A denominator coefficient, C_d, relates to crop height and is estimated as 0.34 for 0.12 m tall crops. Equation 2.2 assumes that there is adequate water available.

Water availability and plant health affects the amount of ET that is actually produced, causing discrepancy between potential ET and actual ET. Both ASCE Penman-Monteith and Hargreaves equations may include a reduction factor for water availability (i.e. soil moisture). Crop ET is calculated from potential evapotranspiration (both ASCE Penman-Monteith and Hargreaves equations) by applying crop coefficients that coincide with the duration of crop development stages and can be found in tabulated form (Allen et al. 1998).

The modified Hargreaves equation is as follows:

Equation 2.3:

$$\boldsymbol{ET_{HG}} = (\boldsymbol{SMEF})(\boldsymbol{K_c})(\boldsymbol{PET})$$

Where ET_{HG} is modified Hargraves ET [mm/d], $SMEF$ is soil moisture extraction function and K_c is the crop coefficient.

The modified ASCE Penman-Monteith equation is as follows:

Equation 2.4:

$$\boldsymbol{ET_{PM}} = (\boldsymbol{SMEF})(\boldsymbol{K_c})(\boldsymbol{ET_{sz}})$$

where ET_{PM} is modified ASCE Penman-Monteith ET [mm/d], and $SMEF$ is used instead of a soil moisture reduction factor, $\mathrm{K_s}$.

2.6 RICHARDS EQUATION SOLVER

The continuous simulation model that was chosen for this study is Soil Water Air Plants (SWAP) by Altera. The simulation solves the one dimensional (1-D) Richards equation for unsaturated soil flow (similar to HYDRUS). This program was chosen as it is equipped to handle multiple years of data quickly and allows for a simulation of an internal water storage layer. A 1-D software is chosen as it is very applicable to lysimeter design as lateral flow is not allowed in both scenarios. Two dimensional (2-D) models are more representative of rain gardens as there is lateral flow in these systems and they have better ability to describe scenarios with soil interfaces or high groundwater tables. However, the addition of the extra dimension largely increases complexity of model, requiring more assumptions and longer run time. The primary movement of water in rain gardens is vertical, such that SWAP and similar 1-D models are acceptable to estimate rain garden performance (Aravena and Dussaillant 2009; Lee et al. 2016).

SWAP calculates surface ponding and runoff, water fluxes in soil, and bottom boundary fluxes or drainage (Kroes et al. 2009). The SWAP program uses Mualem van Genuchten relations, with a modification near saturation to describe the soil water relationship. SWAP models ET by computing the Penman-Monteith equation via meteorological input or allowing for the input of reference ET values ideally with crop factors (the latter option is used in this study). SWAP splits up the potential ET into evaporation and transpiration fluxes for partly covered soils and then finds actual evaporation based on the soils ability to transport water to the surface (Kroes et al. 2009). Actual transpiration is dependent on soil moisture in root zone and root density. SWAP offers many bottom boundary conditions. In this study a soil-air interface represents the bottom boundary of the UO systems and bench scale study while a bottom flux of zero in combination with a basic drainage routine represents the IWS.

3.1 RAIN GARDEN WEIGHING LYSIMETERS

Weighing lysimeters use a mass balance, where evapotranspiration is determined if precipitation, percolation from the rain garden and change in soil moisture storage are known (Figure 3.1). Three lysimeters were constructed at Villanova University, which is located about

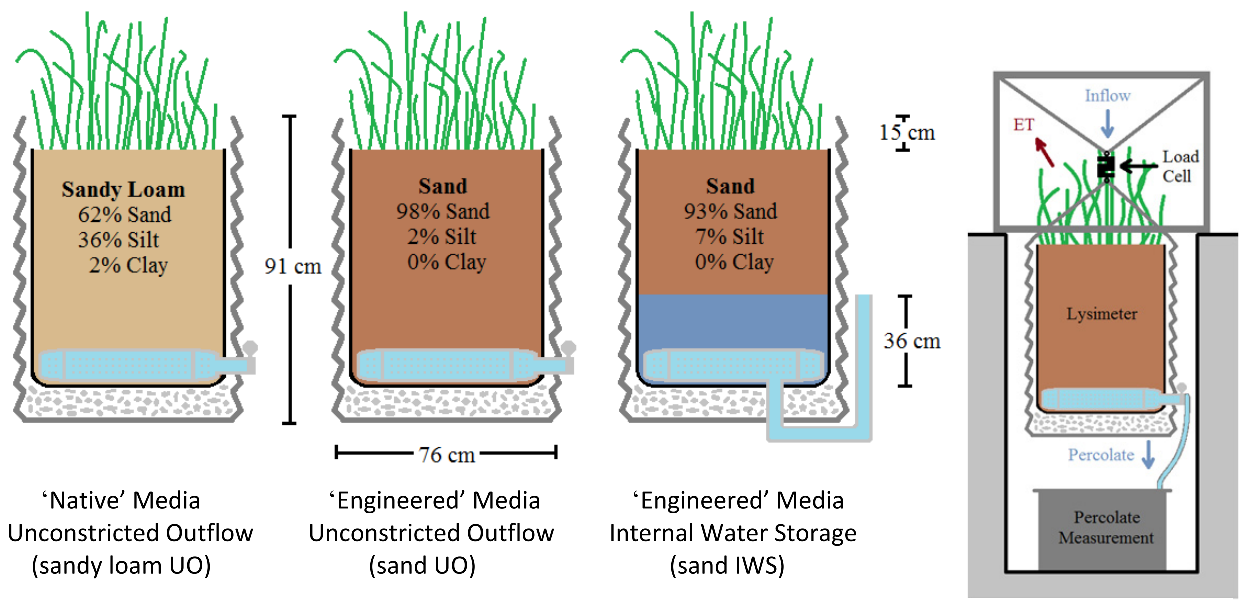

Figure 3.1: Rain garden weighing lysimeters dimensions and constituents (left), and mass balance (right).

24 km outside of Philadelphia, PA. The three lysimeters are: unconstricted valve (UO) underdrain with native sandy loam (62% sand, 36% silt, 2% clay) media, UO underdrain with engineered sand (95% sand, 5% silt, 0% clay) media, and an internal water storage (IWS) zone with elevated drain and engineered sand (93% sand, 7% silt, 0% clay) media (Figure 3.1). The UO underdrain can be used to temporarily store water within the rain garden's soil to slow percolation rates and increase the opportunity for ET; in this study the valve was left half open,

which did not inhibit underdrain flow so the system functioned similarly to a rain garden with an underdrain design and it is referred to herein as an unconstricted outflow (UO). Each lysimeter is a 760 mm diameter container 910 mm high filled with approximately 660 mm of media. An overflow capture device is installed should the ponding exceed a 150 mm depth. switch grass (*panicum virgatum*), seaside goldenrod (*solidago sempervirens*), and Black Chokeberry (*photinia melanocarpa*) were planted in each lysimeter in the summer of 2013 with a thin layer of commercial mulch topsoil for nutrients. These plants are indigenous to the New Jersey coast and are resistant to saline environments. These plants are currently in use in a rain garden located on Villanova's campus (Welker et al. 2010). Rain garden plant inspections are performed monthly in winter and bimonthly for summer.

Climatological parameters such as wind speed (014A), temperature (HMP60), relative humidity (HMP60), and solar radiation (LI200X) are collected on site (Figure 3.2). Each lysimeter uses a

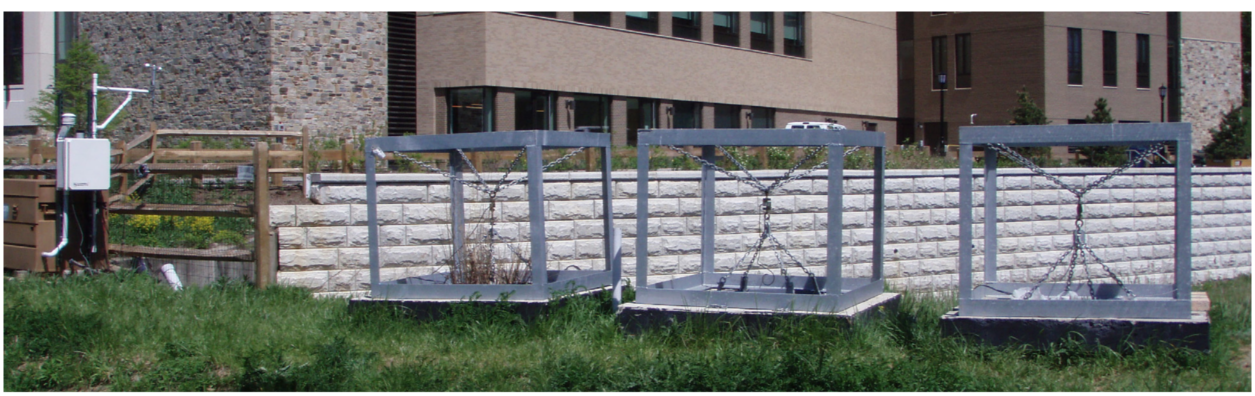

Figure 3.2: Weighing lysimeter site with weather instrumentation.

Sentran S-Beam tension load cell (ZB1-2.5K) to measure the change in weight, which served as a proxy to the change in storage. Precipitation was measured by an on-site American Sigma Model 2149 tipping rain gage from July 13th 2013 to September 30th 2014 and then by a Met-

One Model 375 heated tipping bucket rain gage from September 30th 2014 onwards. Both rain gages have the same resolution (0.25 mm/tip) and similar accuracies (1% for rainfall between 2.5 and 7.6 cm/h). The outflow percolate is measured through a custom-made percolate measurement collection system. This system consisted of a container of known size where collected water depth was measured with a Senix Toughsonic ultrasonic (TSPC-30S1) distance level with an accuracy of 0.5% of the range with a minimum of 0.76 mm. With the inflow (I), outflow percolation (O), and the change in weight of the lysimeter measured (used as a proxy for change in storage; ΔS), the difference is attributed to ET (Equation 3.1).

Equation 3.1: $$\boldsymbol{ET = I - O - \Delta S}$$

Soil moisture monitoring is implemented throughout the profile of the three weighing lysimeters. Steven's Hydraprobe II soil moisture sensors are placed at 10 cm, 35 cm, and 65 cm depth, with a duplicate sensor at 35 m depth. The duplicate sensors have been found to function within the manufacturers' variability (Hess et al. 2014), such that an average of soil moisture meters at 35 cm depth is allowable. The actual soil moisture of the system was found using a weighted average of all three depths.

3.1.1 LYSIMETER SENSITIVITY

Evapotranspiration rates may range from 0 to 9 mm/d (Allen et al. 1998), thus it is necessary to have a system adequately sensitive to detect these small daily changes. The tension load cell model has a combined error of ±0.02% of full scale output of 2500 lbs which equates into ±0.50 mm of water. The rain gage has an error of 1% for 25 to 76 mm/h of rainfall equating to a ±0.25 mm of water. When rainfall intensities are above 25 mm/h, the daily ET rate for that day is excluded from the data. The ultrasonic distance level error is taken as the greater of ±0.76 mm or 0.1% of the range. In this case, the 0.1% of the 609 mm range equates to ±0.61 mm, which is less than ±0.76 mm.

Table 3.1: Lysimeter sensitivity of mass balance parameters

Parameter	Change in Storage	Inflow	Outflow
Instrumentation	Sentran S-Beam tension load cell (ZB1-2.5K)	Met-One heated tipping bucket rain gage (Model 375)	Senix Toughsonic ultrasonic distance level (TSPC-30S1)
Instrument Error	±0.02%	±0.1%	±0.76 mm
Error (mm water)	±0.50	±0.25	±0.33

The total expected error in this system is equal to ±1.1 mm if all components of the water budget are required to calculate the ET (i.e. outflow producing rainfall days). This cumulative error is more significant when it comes to lower ET rates observed in the winter and fall seasons. Therefore, excluding days when rainfall above 25 mm/h intensity and outflow occur from the dataset, the system error is reduced to ±0.50 mm. The dates excluded and reasons for exclusion from the three year data set for the weighing lysimeters are found in APPENDIX C.

3.1.2 LYSIMETER SOIL PROPERTIES

The soil water characteristic curve (SWCC; Figure 3.3) for each soil was estimated to better understand the behavior and properties of the soil in each lysimeter to guide in predicting the movement of water related to infiltration and ET in these systems. The measured data for each SWCC was found using two devices: UMS's HYPROP and Decagon's WP4C Dewpoint PotentiaMeter. The HYPROP uses tensiometers to measure the tension from a saturated condition until an air dried condition is reached (UMS 2015). This method yields the high moisture content, low tension part of the SWCC. The WP4C Dewpoint PotentiaMeter uses the chilled mirror dewpoint method to find the low moisture content, high tension part of the curve (Decagon Devices 2015).

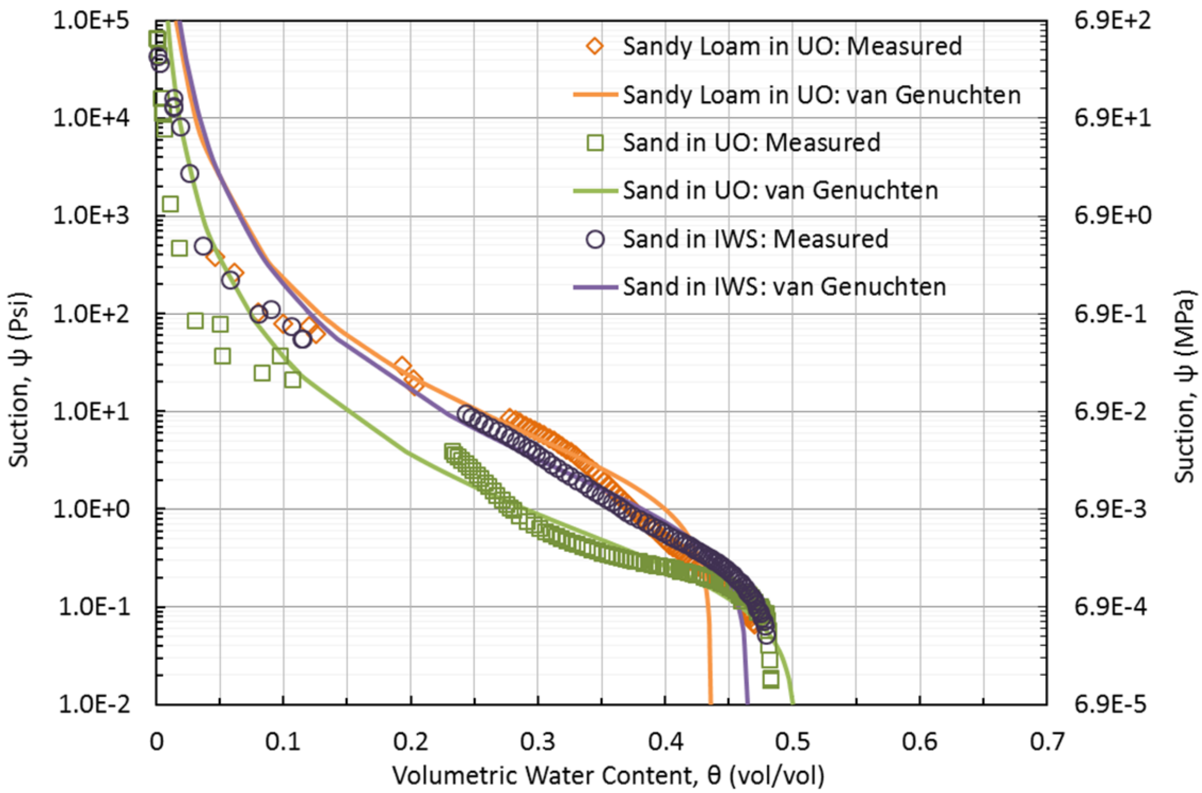

Figure 3.3: SWCC for three weighing lysimeter soils

The Mualem van Genuchten (MVG) model was fit to the HYPROP and WP4C Dewpoint PotentiaMeter data using a SWCC curve fitting program (Seki 2007). Mualem van Genuchten was chosen due to popularity of the method and closeness of fit. The SWCC is used as input into the SWAP model.

Field capacity (FC) and wilting point (WP) are important soil moisture contents that determine the soil moisture capacity (SMC). The SMC serves as input into the Soil Moisture Extraction Functions (SMEFs) used in conjunction with the Hargreaves and Penman-Monteith predictive ET equations (Section 3.7.1). Field capacity is the soil moisture content at which the water has drained out of the soil from a higher saturated state via gravity. Wilting point is a soil moisture content, lower than field capacity, where plants can no longer remove the water from the soil. The difference between FC and WP is the SMC of the media or ET available soil moisture. The difference between saturation and FC is the gravity available soil moisture.

The FC and WP for each soil type is found using judgment based on a combination of information from average literature values based on soil type, the MVG model, and soil moisture meter readings (Table 3.2).

Table 3.2: Field capacity and wilting point of weighing lysimeter media

Rain Garden Weighing Lysimeter	Average (Saxton and Rawls 2006) [vol/vol]		MVG Fit [vol/vol]		Soil Moisture Meter Readings [vol/vol]		Chosen Value [vol/vol]		ET Available Soil Moisture, Soil Moisture Capacity [vol/vol]
	FC	WP	FC	WP	FC	WP	FC	WP	FC – WP, SMC
Sandy Loam in UO	0.18	0.08	0.31	0.07	0.20	0.08	0.21	0.07	0.18
Sand in UO	0.10	0.05	0.22	0.03	0.15	0.04	0.16	0.04	0.12
Sand in IWS	0.10	0.05	0.25	0.05	0.15	0.04	0.16	0.04	0.12

The FC and WP are taken at a suction of 1.5 MPa (218 psi) and 33 kPa (4.8 psi), respectively, for the MVG relationship (Saxton and Rawls 2006; Dane and Toppe 2002). Average soil moisture meter readings 3 days after a storm event were used to find FC and the lowest soil moisture reading was taken for the WP (Decagon Devices 2015). Due to the light compaction of the rain garden soil (bulk density, ρ_b range: 1.18-1.31 g/cm^3) the field capacities are notably larger than literature values for these soils (Table 3.2; Saxton and Rawls 2006), however rain gardens are designed with low compaction so in-line with what is expected in the field. There are large variabilities of soil properties for each of the USDA classification types (Lee et al. 2016), which can further lead to differences in observed and cited field capacities and wilting points. The chosen value for field capacity and wilting point based on the average of the values determined by MVG fit and literature.

Saturated hydraulic conductivity was found by a UMS KSAT device that measures conductivities values in the range of 10,000 - 0.1 cm/d based on the inversion of Darcy's Law. One constant head and two falling head tests were performed on each soil. Since all tests for each soil type were in the same order of magnitude, the tests produced an average saturated hydraulic conductivity, K_{sat}, of 60 cm/d for sandy loam and 240 cm/d for sand normalized at 20^{o}C. Literature values agree with the experimental K_{sat}. Saturated hydraulic conductivity for sandy loam soils are on average 47.2 cm/d, with a range from 20.7-134.1 cm/d (Rawls et al 1998). Similarly, K_{sat} for sand soil, on average, is about as 316.4 cm/d with a range of 230-602.1 cm/d. According to a filtered version of the U.S. Department of Agriculture's Unsaturated Soil Database, an average K_{sat} for the sandy loam and sand soils is 42.7 cm/d and 186.9 cm/d, within the range of 18.5-120.1 cm/d and 86.7-536.7 cm/d, respectively (Lee et al. 2015).

Table 3.3: Soil parameter inputs of rain garden lysimeter media for SWAP

Rain Garden Weighing Lysimeter	Mualem van Genuchten Parameters				Saturated Conductivity at 20^{o}C, Ksat [cm/d]
	Residual Moisture, θr [vol/vol]	Saturated Moisture, θs [vol/vol]	Shape Parameter		
			α	n	
Sandy Loam in UO	0.000	0.436	0.539	1.306	50
Sand in UO	0.000	0.460	5.687	1.303	90
Sand in IWS	0.000	0.460	1.380	1.273	90

The summary of the MVG fit parameters and saturated hydraulic conductivity can be found in Table 3.3, which serve as soil input properties for the 1-D Richards equation simulator (Section 3.8). The 1-D Richards equation simulator input K_{sat} values (Table 3.3) are lower than the experimentally determined values as they are used to calibrate the simulation to observed data. The chosen input K_{sat} values are within the range of literature values and in the same order of magnitude as those values determined experimentally.

3.1.3 LYSIMETER PLANTS

A gallon pot of each switch grass (*panicum virgatum*), seaside goldenrod (*solidago sempervirens*), and black chokeberry (*photinia melanocarpa*) were planted in the UO systems. Seaside goldenrod and black chokeberry were planted in the IWS lysimeter in 2013. The sand IWS lysimeter is the oldest of the three lysimeters and had previously been studied in 2010 (Wadzuk et al. 2015). The plant inspections on the lysimeters include quantitative measurements such as leaf count and plant height, as well as qualitative pictures (APPENDIX A) and comments.

Leaf area index (LAI) is a useful characteristic for plant canopies and takes into account area of the individual leaves. There are many methods to find leaf area, destructive methods typically being more accurate but do not allow for continuous study (Marshall 1968). This study uses a non-destructive LAI estimation method to keep the integrity of the plants intact. Leaf area index is an input into SWAP crop file (Section 3.8.2).

3.2 RAIN GARDEN BENCH SCALE STUDY

Five discrete weighing lysimeters were filled with soils that span the lower portion of the USDA classification triangle (Figure 3.4). The bench scale study has five vertical 46 cm deep columns made from 10 cm diameter PVC pipe. The five different lysimeters have different soil types:

loamy sand, sandy loam (typical rain garden mix in PA), loam, silt loam, and clay loam. The percentages of sand, silt, clay can be found graphically Figure 3.4 or tabulated in Table 3.4.

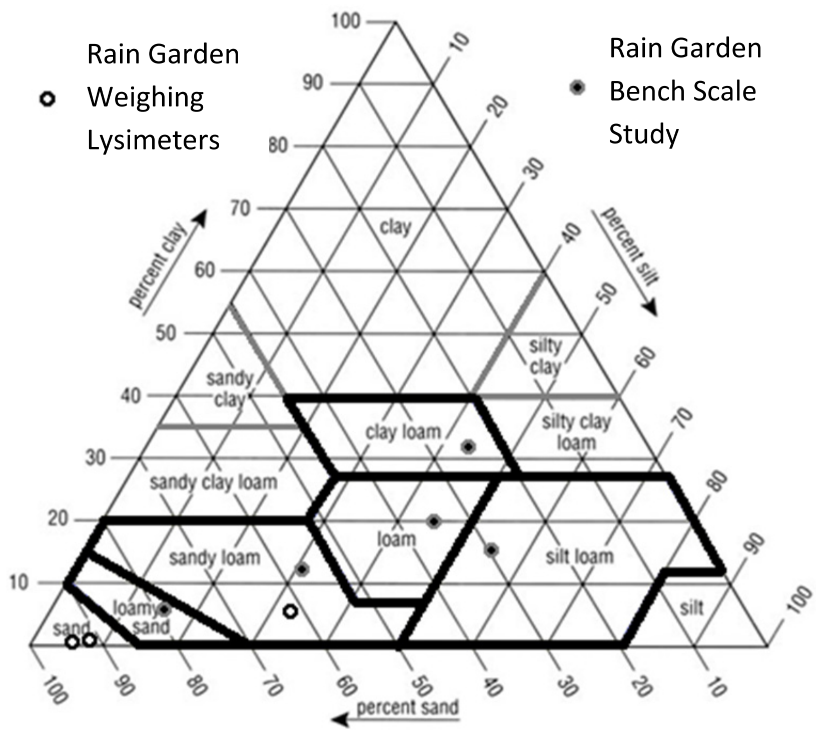

Figure 3.4: USDA soil classification triangle with studied soils

Table 3.4: USDA soil textural classification for bench scale study

USDA Classification	% Sand	% Silt	% Clay
Loamy Sand	80	14	6
Sandy Loam	56	32	12
Loam	37	44	19
Silt Loam	29	55	16
Clay Loam	26	44	30

Each discrete lysimeter was planted with switch grass (*panicum virgatum*) and allows for 7.5 cm of ponding (Figure 3.5). Daily weight measurements are taken manually by lifting the boxes onto a scale at approximately the same time each day. The weights are normalized to 12:00 pm eastern standard time via linear interpolation. The percolate volume and rate is measured by a tipping bucket rain gage and the volume is verified with a graduated cylinder (Figure 3.5). Similar to the weighing rain garden lysimeters, a passive bottom boundary is descriptive of the

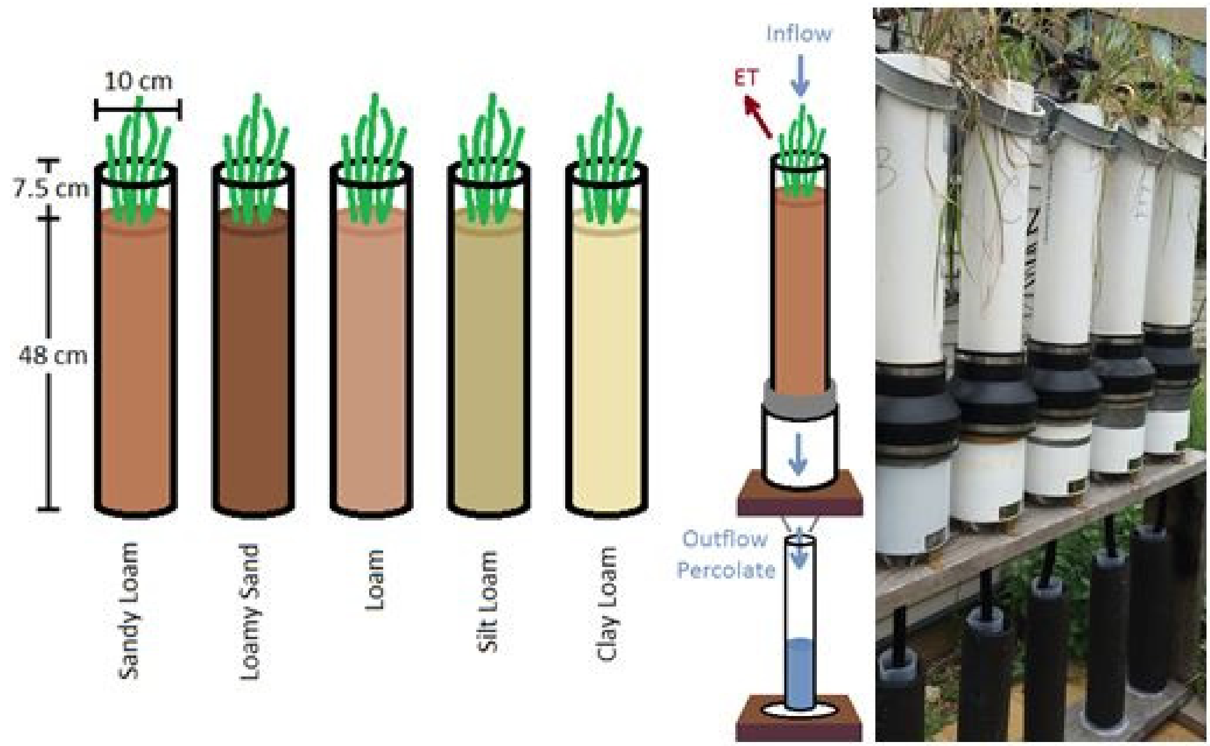

Figure 3.5: Rain garden bench scale dimensions and constituents (left) and mass balance (middle), bench scale study site (right)

bench scale outflow. Each discrete lysimeter works on a similar mass balance principle as the continuously weighing rain garden lysimeters (Equation 3.1). The bench scale study is located about 20 m away from rain garden weighing lysimeter site such that it is appropriate to use the same precipitation and weather instrumentation.

3.2.1 BENCH SCALE SENSTIVITY

The bench scale study uses the same precipitation and weather instrumentation as the rain garden weighing lysimeter site. The A&D Industrial Bench Scale (GP-61K) is used to measure the daily weight. The scale has a standard deviation error of ±0.2 g which equates into ±0.25 mm of water. Texas Electronics tipping bucket rain gage (TR-525I) is used to measure outflow from each rain garden bench scale box or column. The outflow rain gages are accurate for ±1% of outflow up to 2.5 cm/h which equates to ±0.25 mm. 1000 ml graduated cylinders with a 5 ml accuracy are placed under the outflow rain gages and are used as volume comparisons such that outflow rates higher than 2.5 cm/h can be excluded.

Table 3.5: Vertical bench scale lysimeter sensitivity of mass balance parameters

Parameter	Change in Storage	Inflow	Outflow
Instrumentation	A&D Industrial Bench Scale (GP-61K)	Met-One heated tipping bucket rain gage (Model 375)	Texas Electronics tipping bucket rain gage (TR-525I)
Instrument Error	±0.2 g	±0.1%	±1%
Error (mm water)	±0.03	±0.25	±0.25

The total expected error in this system is equal to ±0.53 mm if all components of the water budget are required to calculate the ET (i.e. outflow producing rainfall days; Table 3.5). This cumulative error is less than that of the larger rain garden weighing systems (±1.1 mm). Most ET measurements are taken during the growing season where ET values are typically greater than this cumulative system error. Also, the bulk of the ET values are taken during days with no rainfall or outflow such that system error is reduced to ±0.03 mm. Dates excluded and reasons for their exclusion from the one year data set for the rain garden bench scale study can be found in APPENDIX C.

3.2.2 BENCH SCALE SOIL PROPERTIES

The bench scale study is used primarily for simulation in the SWAP program, such that a SWCC and saturated hydraulic conductivity was found for each soil type (Figure 3.6). Similar methods that are discussed in Section 3.1.2 are used to determine the properties that influence water movement through soil. The summary of the Mualem van Genuchten (MVG) fit parameters and saturated hydraulic conductivity for the bench scale study can be found in Table 3.6 which serve as soil input properties for the SWAP program.

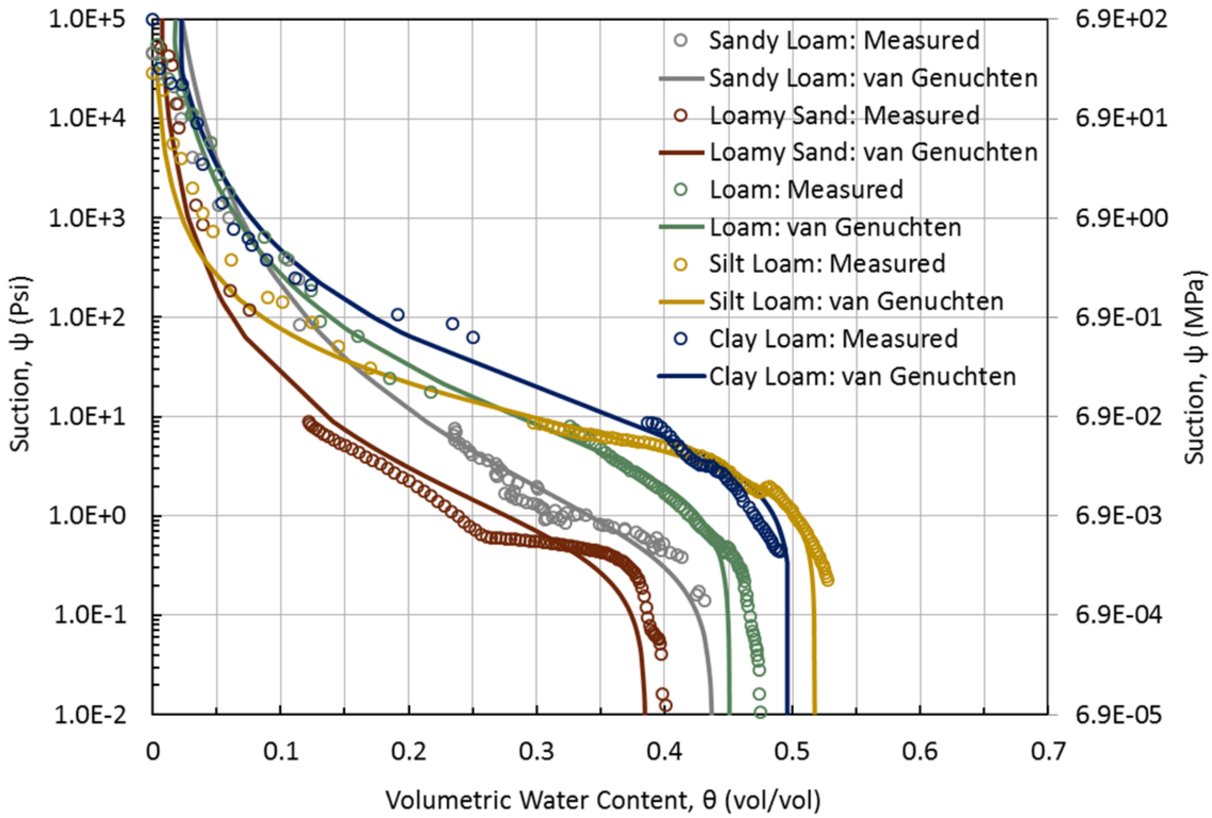

Figure 3.6: SWCC for bench scale lysimeter soils

Table 3.6: Soil parameter inputs of rain garden bench scale media for SWAP

Bench Scale Study Media	Mualem van Genuchten Parameters				Measured Saturated Conductivity at 20°C, Ksat [cm/d]
	Residual Moisture, θr [vol/vol]	Saturated Moisture, θs [vol/vol]	Shape Parameter		
			α	n	
Loamy Sand	0.000	0.438	2.158	1.241	90
Sandy Loam	0.000	0.385	2.077	1.343	24
Loam	0.000	0.451	0.351	1.330	12
Silt Loam	0.000	0.517	0.228	1.573	6
Clay Loam	0.000	0.499	0.200	1.353	4

For verification of the SWAP model, the K_{sat} values determined experimentally were adjusted slightly to calibrate the model as well as provide saturated hydraulic conductivity values that are more typical of the soil type based on literature values. Average K_{sat} for loamy sand, sandy loam, loam, silt loam and clay loam are experimentally found to be 95, 24, 12, 3, and 1 cm/d normalized at 20°C, respectively. The K_{sat} values measured experimentally are in the range of K_{sat} compared to literature values (Rawls et al 1998 and Lee et al 2015; Table 3.7). Saturated conductivity values for loamy sand (90 cm/d), silt loam (6 cm/d), and clay loam (3 cm/d) are chosen at a value that is slightly different from the experimentally determined K_{sat} but allowed for verification of the SWAP simulation. Chosen values are within the same order of magnitude as the experimentally determined values. For silt loam and clay loam, the chosen values are closer to typical range of K_{sat} for both soil types.

Table 3.7: Saturated hydraulic conductivity for bench scale compared to literature values

Bench Scale Study Media	Chosen K_{sat} at 20°C, [cm/d]	Measured K_{sat} at 20°C, [cm/d]	Rawls et al 1998 average K_{sat} [cm/d]	Rawls et al 1998 range of K_{sat} [cm/d]	Filtered UNSODA average K_{sat} [cm/d]	Filtered UNSODA range of K_{sat} [cm/d]
Loamy Sand	90	95	151.7	86.7-329.5	159.3	60.4-499
Sandy Loam	24	24	47.2	20.7-134.1	42.7	18.2-120.1
Loam	12	12	12.5	6.7- 48.2	23.2	10.9-68.2
Silt Loam	6	3	18.5	8.6-55	19.6	7.5-58.6
Clay Loam	4	1	2.9	0.7-16.8	6.6	4.4-18.7

Similar to the weighing lysimeters, the WP and FC based on SWCC is used to make an estimate of the two soil moisture contents and is compared to average values (Table 3.8; Saxton and Rawls 2006; Lee et al. 2015). In this case, the average FC values from literature are used to represent the loam, silt loam, and clay loam media in the rain garden bench scale study (Saxton and Rawls 2006), while the rest remain at their measured values. The loamy sand measured values for FC and WP are close to literature values and sandy loam measured values are close to that of the sandy loam in the weighing lysimeter device such that these were confirmed to provide adequate estimates. Since the other three soil types cannot be confirmed with another measurement, the FC were taken as literature values as they are much larger than expected.

Table 3.8: Field capacity and wilting point of bench scale media

Rain Garden Weighing Lysimeter	Average (Saxton and Rawls 2006) [vol/vol]		MVG Fit [vol/vol]		Chosen Value [vol/vol]	
	FC	WP	FC	WP	FC	WP
Loamy Sand	0.12	0.05	0.15	0.06	0.15	0.06
Sandy Loam	0.18	0.08	0.25	0.11	0.25	0.11
Loam	0.28	0.14	0.35	0.12	0.28	0.12
Silt Loam	0.31	0.11	0.41	0.08	0.31	0.08
Clay Loam	0.36	0.22	0.41	0.12	0.36	0.12

3.2.3 BENCH SCALE PLANTS

About 50 grams of switch grass (*panicum virgatum*) was planted in each of the bench scale lysimeters. Leaf count and plant height was recorded each month. Leaf area index was determined similar to the large rain garden lysimeters for the 2016 growing season based on the leaf count. Only leaf height and LAI are presented as they are to serve as the input parameters in the SWAP crop model (Section 3.8.2).

3.3 RUNOFF SIMULATIONS

The lysimeter systems accept direct rainfall (1:1 watershed area to SCM area); however, rain gardens typically collect runoff from the surrounding impervious area. In Pennsylvania's design manual, a loading ratio of impervious area to SCM area was recommended at 5:1 and was recently increased to 8:1 in Philadelphia (PADEP 2006, PWD 2015); similar loading ratios are specified in other state guidelines. A water distribution system was developed to mimic the runoff from surrounding impervious surfaces.

The distribution system was built and calibrated to handle a range of storm volumes from 19 mm to 76 mm over a 24 hour period at a loading ratio of 5:1. The 19 and 38 mm storms relate to typical design criteria for SCMs and the 76 mm storm relates to the 2 year storm for PA, which ranges from 61 to 84 mm across the state (PADEP 2006). The rain garden weighing lysimeters accept simulated runoff added at a constant rate during a rainfall event (Figure 3.7).

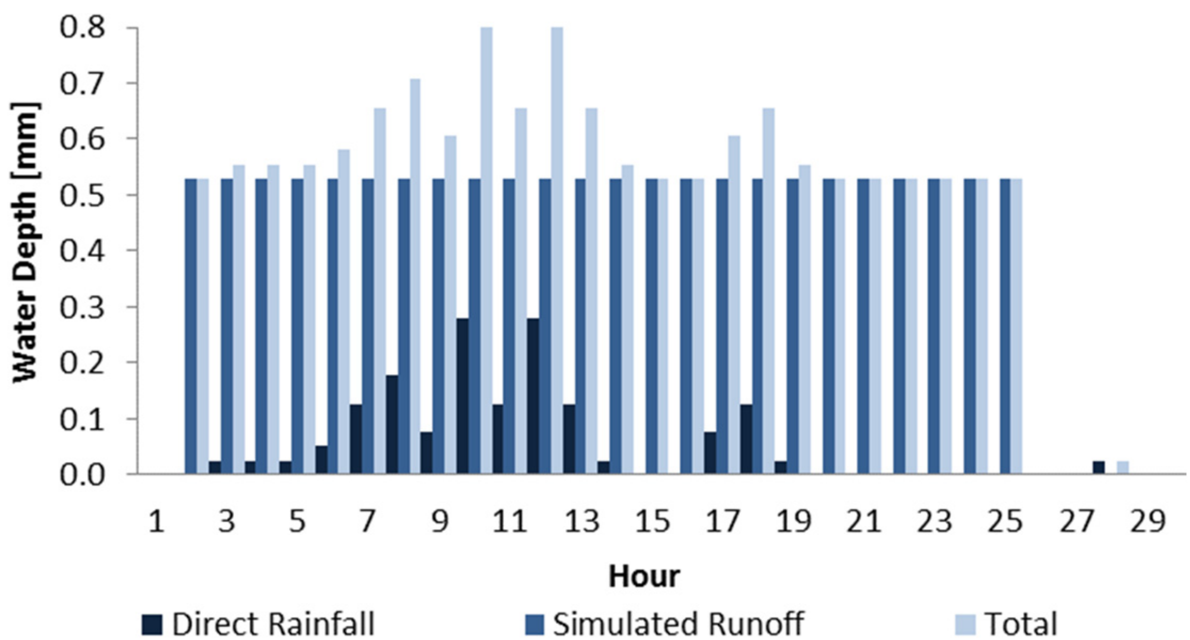

Figure 3.7: Example hyetograph of simulated runoff during rainfall events

The resulting total hyetograph accounts for the volume of runoff. The simulated runoff is delivered through a pump and showerhead that is suspended over each of the lysimeters (Figure 3.8). The showerhead and pump system for each of the three weighing lysimeters have been calibrated to provide the expected amount of total water over a 24 hour period (Hess et

Figure 3.8: Distribution heads for continuous weighing lysimeters (left), discrete weighing lysimeter vertical (middle), and discrete weighing lysimeter horizontal (right).

al. 2014). The rain garden bench scale experiment has a similar distribution system modeled after the large scale study. The bench scale distribution system utilizes balling light doser pumps that deliver the precise amount of water in hour intervals. Both rain garden lysimeter systems follow the 5:1 loading ratio.

A total of 23 storm simulations were performed from July 13 2013 to August 24 2016 (Table 3.9). Of this, 22 storm simulations are accounted for in the three year study (July 13 2013-2016) for the large scale rain garden weighing lysimeters. The bench scale study came online on August 24 2015 such that the one year of study (August 24 2015-2016) includes 15 storm simulations. The same time period of August 24 2015-2016 is used for comparisons of performance between the large scale rain garden weighing lysimeters and the bench scale study.

Table 3.9: Storm simulations for all rain garden lysimeters

Date	Rainfall [mm]	Simulated Rate [mm/h]	Simulated Volume [mm]	Total Inflow [mm]	
				5:1 Ratio	10:1 Ratio
Mar 29-30 2014*†	73.7	12.70	304.82	75.69	37.85
Apr 3-4, 2014*	8.6	7.94	190.49	39.82	19.91
Apr 15-16, 2014*	59.2	3.18	76.22	27.08	13.54
Aug 7-8, 2014*	0.5	3.97	95.24	19.15	9.57
Aug 21-22, 2014*	27.2	3.97	95.24	24.48	12.24
Sep 24-25, 2014*	0.0	5.29	126.99	25.40	12.70
Oct 22-23, 2014*	18.3	5.29	126.99	29.05	14.53
Oct 29-30, 2014*	0.8	7.94	190.49	38.26	19.13
Aug 24-25, 2015	0.0	5.29	126.99	25.40	12.70
Sep 10-11, 2015	20.3	5.29	126.99	29.46	14.73
Sep 29-30, 2015	50.3	3.97	95.24	29.11	14.55
Oct 12-13, 2015	0.0	3.97	95.24	19.05	9.52
Oct 20-21, 2015	0.0	8.65	207.51	41.50	20.75
Mar 8-9, 2016	0.0	5.29	126.99	25.40	12.70
Mar 21-22, 2016	0.2	5.29	126.99	25.44	12.72
Apr 6-7, 2016	4.3	5.29	126.99	26.26	13.13
Apr 19-20, 2016	0.0	7.94	190.49	38.10	19.05
May 10-11, 2016	0.0	7.94	190.49	38.10	19.05
May 30-Jun 1, 2016	10.9	7.94	190.49	40.28	20.14
Jun 12-13, 2016	0.0	7.94	190.49	38.10	19.05
Jun 22-23, 2016	1.0	7.94	190.49	38.30	19.15
Jul 6-7, 2016	3.0	7.94	190.49	38.71	19.35
Jul 25-26, 2016‡	57.7	5.82	139.72	39.47	19.74

*Bench scale study not online until August 2015, †ET data from this event excluded due to overflow
‡Not considered for 3 year study on continuous weighing lysimeters

Monthly summations of rainfall and total inflow that results from the inclusion of the storm simulations are seen in Figure 3.9. Figure 3.9 displays 13 months as the first July contains summations from the 13th to the 31st and the last July contains summations from the 1st to the 13th, all other monthly summations are over the entire month. The first year of July 13 2013-2014 shows simulations occurring after the winter season, where the second year of Jul 13 2014-2015 show storm simulations are occurring before winter the season. The third year of July 13 2015-2016 has storm simulations occurring during all time except winter.

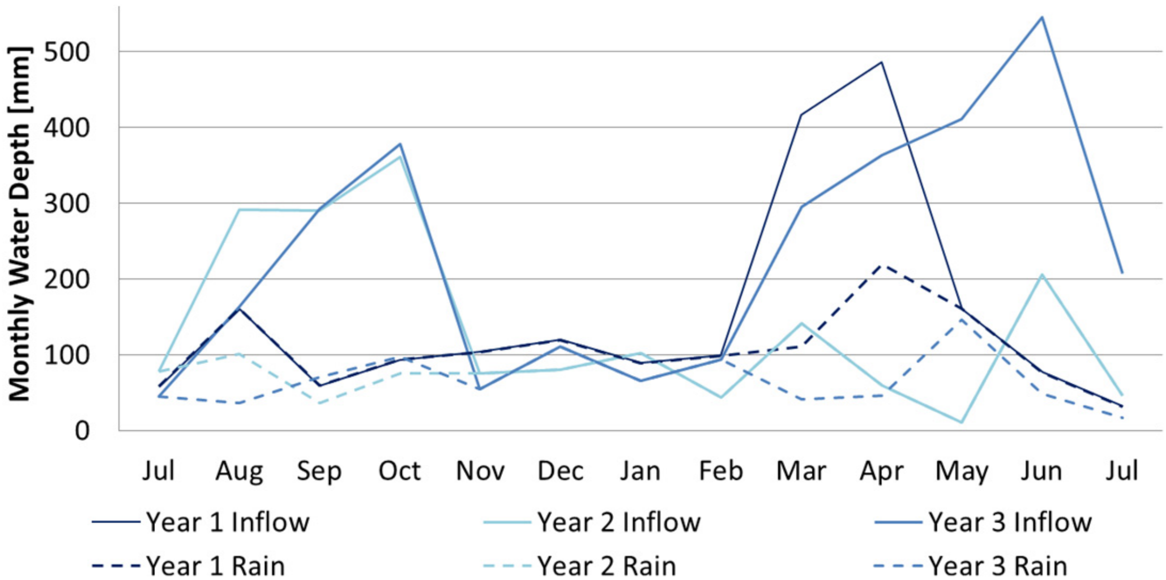

Figure 3.9: Total inflow and rainfall patterns for 3 year study

Cole Parmer Masterflex L/S Variable Speed low-flow peristaltic pumps (#EW-7553-75) are used for the distribution of the runoff simulations in the continuous weighing rain garden lysimeters, which has an accuracy of ±2% speed control, which equates to ±0.20 mm of water for the largest storm simulation performed (Table 3.10; Hess et al. 2014). Since the error in the distribution systems are less than that of the rain gage and days during storm simulations are vetted from the data, only rain gage error is considered in the sensitivity of each system.

The GHL light dosing pumps (Fauna Marin Balling) are used for the bench scale study distribution system, which have an accuracy of ±1 ml which equates to ±0.01 mm and ±0.12 mm in the vertical and horizontal systems, respectively (Table 3.10).

Table 3.10: Sensitivity of distribution systems for storm simulations

Instrumentation	Met-One heated tipping bucket rain gage (Model 375)	Inflow: Storm Simulations	
		Cole Parmer peristaltic pump (#EW-7553-75)	GHL light dosing pump (Fauna Marin Balling)
Instrument Error	±0.1%	±0.2%	±1 ml
Error (mm water)	±0.25	±0.2	±0.01

The error in the distribution systems are less than that of the rain gage and days during storm simulations are vetted from the data such that only rain gage error is considered in the sensitivity of each system.

3.4 STATISTICAL METHODS

The rain garden weighing lysimeter site has been functioning since July 2013; data from July 13 2013 to July 13 2016 are analyzed. Data from the rain garden lysimeter sites are processed as daily, monthly, seasonally, and annually averaged ET rates to provide a baseline of ET values in rain garden design. All measurements were taken at 5 minute intervals for the study period, although ET was calculated daily. Daily calculations were performed by taking the midnight to midnight change in weight and total precipitation and percolation over that period. These daily values provide the basis data for all following analysis.

Monthly, seasonal, and annual analysis is based on the calculated daily ET values. The meteorological seasons are divided into spring (March through May), summer (June through August), fall (September through November) and winter (December through February). The ET data presented in winter months are mostly from direct rainfall. The 22 storm simulations are included for the sand UO and sand IWS lysimeters in the summer, fall and spring season. Nineteen storm simulations are included for the sandy loam UO lysimeter. Over the study period there were rare days that were omitted from analysis because of equipment malfunctions; the load cell on the sandy loam UO was not functional for a four month period from October 2014 through January 2015 (APPENDIX C).

Statistical methods, such as mean, 95% confidence intervals, and t-tests, were used to analyze the data. Average daily ET rates are presented over different time periods. The confidence interval takes into account uncertainty due to the standard deviation and sample size of the data set. Two sample t-tests were used to determine if the data sets are statistically different from one another for an α-level of 0.05 (95% confidence). Paired t-tests were also used as they are more robust; comparing each daily measured ET value, rather than summary parameters. Both sand lysimeters have a total of 775 days of measured ET whereas the sandy loam had 688 days of measured ET over the three year period.

Days when it rained and the average soil temperature at 10 cm depth read below freezing (0°C) were excluded from winter as it indicates that there is snow at ground level. It is expected that more error is associated with the winter data, and the lower 95% confidence interval may be more appropriate to apply to rain garden design. For the winter of 2013-2014, there was a non-heated rain gage such that the melting times were more realistic, but the volume is less accurate. In the case of 2014-2015 and 2015-2016 winters, the volume was accurate but the heated rain gage records faster melting times than the lysimeters experience. In all cases, the lower 95% confidence interval can be seen as a conservative or minimum estimate of ET rate.

3.5 STORM BASED ANALYSIS METHODS

3.5.1 6 MM STORM BASED METHOD

The 6 mm storm based analysis defines a storm event with a total daily inflow greater than 6.35 mm (0.25 in). Once 6.35 mm or greater daily inflow occurs, inflow, percolation, and ET are accumulated until another event of 6.35 mm or greater occurs. This results in each storm having a different number of days in which inflow, percolation, and ET are accumulated and ranges from 2 to 35 days. For this analysis, the summations of ET, percolation, and inflow were capped at 15 days between storm events. Storms occurring in winter months are not used such that the following analysis is representative of a combination of summer, spring, and fall storms (i.e. growing season). Under these criteria, 80 storms are analyzed with a total storm inflow volume range from 7 to 200 mm. The larger storm inflow volumes occur by way of runoff simulation.

3.5.2 25 MM STORM BASED METHOD

The 25 mm storm based analysis defines a storm event with a total daily inflow greater than 25 mm (1 in). There are 45 storms (40 storms for sandy loam UO due to equipment issues) that meet this criterion during the summer, fall, and spring months through direct rainfall storms and storm simulations over the three year study. The daily ET and percolate amount for the first day after each 25 mm storm event is averaged; this process is continued until 12 days after the storm event. The sample size (N) of ET and outflow are different based on lysimeter type and data availability (Table 3.11).

Sample sizes generally decrease as the days after 25 mm (or greater) event has occurred as dry time between events is variable. Due to the sensitivity of the lysimeter, data when it is raining and outflowing is not used to calculate ET such that there is no sample size for ET on day 0 of 25 mm or greater event. Sample size for ET does not reach its maximum until day 4 as there may have been rain or outflow on the first, second or third day after the 25 mm or greater storm.

Sample size for outflow for all lysimeter systems is largest on the day of the storm event, but outflow can occur days later due to small (< 25 mm) rain events occurring between events of 25 mm or greater. The UO systems outflow at a similar frequency and the sand IWS outflows about half as frequently for storms greater or equal to 25 mm of daily inflow volume.

Table 3.11: Sample sizes for 25 mm storm based method

Days after Events >25 mm	N for ET			N for Percolate		
	Sandy Loam	Sand UO	Sand IWS	Sandy Loam	Sand UO	Sand IWS
0	--	--	--	40	38	19
1	32	34	34	2	2	9
2	38	42	42	2	3	6
3	39	44	44	0	1	5
4	40	45	45	0	2	4
5	37	42	42	0	0	3
6	38	41	41	2	3	3
7	32	35	35	1	2	4
8	32	35	35	0	1	2
9	32	35	35	2	3	2
10	29	32	32	2	0	3
11	26	29	29	3	1	4
12	17	20	20	1	3	1

3.6 SOIL MOISTURE COMPARED TO WEIGHT

In the following section, an alternative method to calculate observed ET via the mass balance method is explored. Lysimeters rely on the change in weight as a proxy for change in storage. Since water is the mass of interest, soil moisture meters provide tracking of the change in water and thusly the change in storage. Change in soil moisture meter readings distributed throughout the soil column are compared to change in overall weight, which is the current change in storage proxy. In a lysimeter, ET is observed from the recession limb of weight readings after a storm (using 6 mm storm based method), provided outflow is not occurring.

Similar recession limbs after storms are seen in soil moisture readings after a storm event (Figure 3.10). Winter data are excluded from this analysis as the soil moisture readings can act unpredictably in cold temperatures (Stevens 2007).

Daily changes in weight (midnight to midnight readings) are compared to daily changes soil

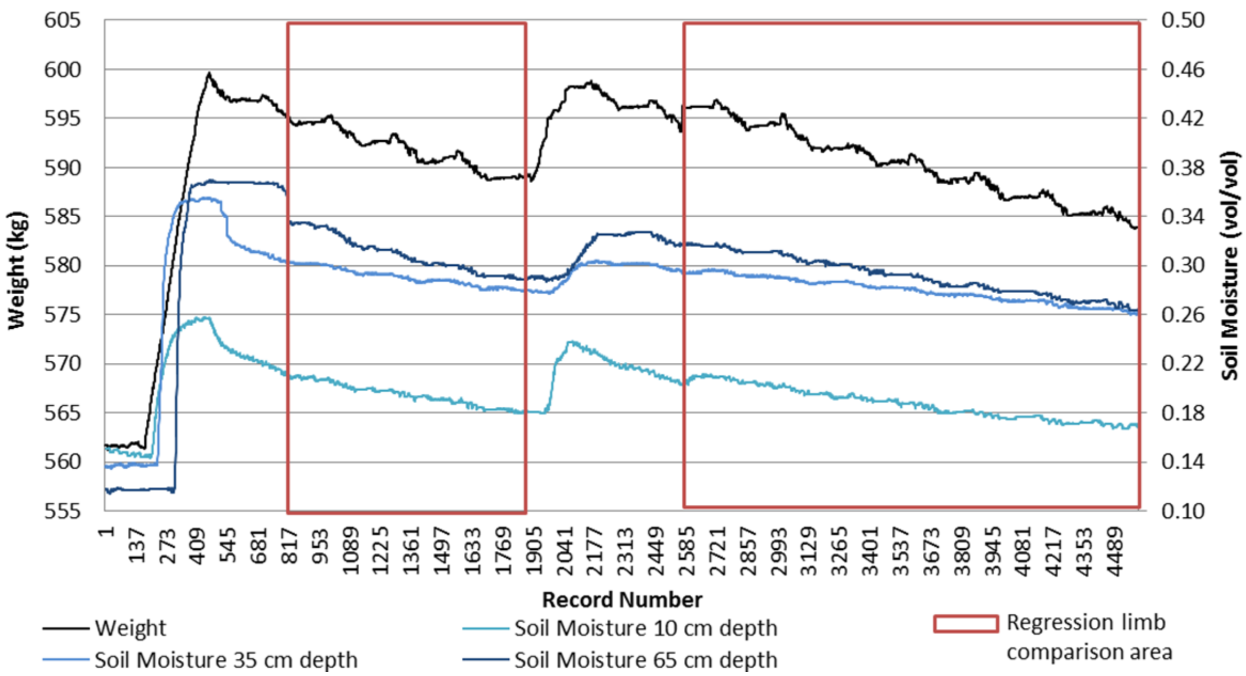

Figure 3.10: Example of weight and soil moisture vs time for sandy loam UO

moisture (midnight to midnight readings) at each depth (10 cm, 35 cm, 65 cm). Midnight to midnight readings are utilized for ET calculations due to the diurnal variations of the weight readings as seen in the black line in Figure 3.10. The diurnal variations are conjectured to occur based on temperature effects on the load cell where small peaks occur based on higher temperatures during the day and the flat lines or low points occur during the lower temperature of the night.

Days of rainfall, simulated runoff, or outflow are excluded such that the change in weight is a better comparison to the change in soil moisture. The incremental changes of weight and soil moisture are accumulated over the dry time duration. Multiple linear regressions are performed for each weighing lysimeter with the three soil moisture readings as the continuous predictors and the weight as the response variable. The regression model is evaluated by the coefficient of determination and standard error. The coefficient of determination, R^2, measures the degree of correlation between the response and predictors which ranges from 0 to 1; a value close to 1 represents a strong correlation. The standard error, S, represents the average distance that the observed values fall from the regression line such that smaller values indicate that observations are closer to the fitted line.

3.7 PREDICTIVE EVAPOTRANSPIRATION EQUATION MODIFICATION METHODS

3.7.1 SOIL MOISTURE EXTRACTION FUNCTIONS

Soil moisture extraction functions (SMEF) have been developed and used to correct for water availability in the soil and work well when paired with the Hargreaves equation (Zhao et al. 2013). Five SMEFs are explored here for predictive ET calibration, but there are a variety of SMEFs that exist to correct for soil moisture deficiency. Allen et al. (1998) recommends the water stress (e.g. K_s) as a linear reduction after the soil has reached a threshold under field capacity between wilting point for the ASCE Penman-Monteith. This recommended K_s relationship is described by SMEF Equation 3.2. However, all SMEFs that are explored for the Hargreaves equation will also be used for the ASCE Penman-Monteith soil moisture reduction factor, K_s. The following SMEFs (Equation 3.2-Equation 3.6) were selected as the possible relationship between actual daily ET and potential daily ET calculated as follows:

Equation 3.2: $$SMEF = \frac{SMT}{SMC}$$

Equation 3.3: $$SMEF = \left(\frac{SMT}{SMC}\right)^2$$

Equation 3.4: $$SMEF = 2\left(\frac{SMT}{SMC}\right)\left[\frac{1}{1+\left(\frac{SMT}{SMC}\right)^{SMT/SMC}}\right]$$

Equation 3.5: $$SMEF = 2\left(\frac{SMT}{SMC}\right)^2\left[\frac{1}{1+\left(\frac{SMT}{SMC}\right)^{SMT/SMC}}\right]$$

Equation 3.6: $$SMEF = \left(\frac{SMT}{SMC}\right)^2 / \left(\left(\frac{SMT}{SMC}\right)^2 + \left(1-\left(\frac{SMT}{SMC}\right)\right)^2\right)$$

Where SMT is the current soil moisture [vol/vol] and SMC is the soil moisture capacity [vol/vol] (i.e. the difference between field capacity and wilting point). The SMEFs limit the maximum amount of evapotranspiration based on available water within the system and are a relationship between current water content and the maximum water holding capacity.

Current soil moisture (SMT) was determined by a weighting of soil moisture meter readings at three different depths of 10 cm, 35 cm, and 65 cm within the soil column. The weighted soil moisture reading was taken as the sum of 25% of 10 cm reading, 50% of 35 cm reading, and 25% of 65 cm reading for all lysimeter types. This weighting is based on the physical position of the soil moisture meters throughout the column, as 10 cm soil moisture reading will represent the top 16.5 cm of the soil column, the average 35 cm soil moisture reading represent the middle 33 cm, and the bottom 65 cm soil moisture reading represent the bottom 16.5 cm. It should be noted that this weighting is different and not related to weighting of soil moisture vs the load cell readings in Section 4.3 as this analysis is concerned with the value of soil moisture rather than the change in soil moisture.

The behavior of the SMEF equations only determines soil moisture reduction on potential ET until the current soil moisture is greater than or equal to the field capacity of the soil (Figure 3.11). When actual soil moisture is below field capacity, then the SMEF is applied. The behavior

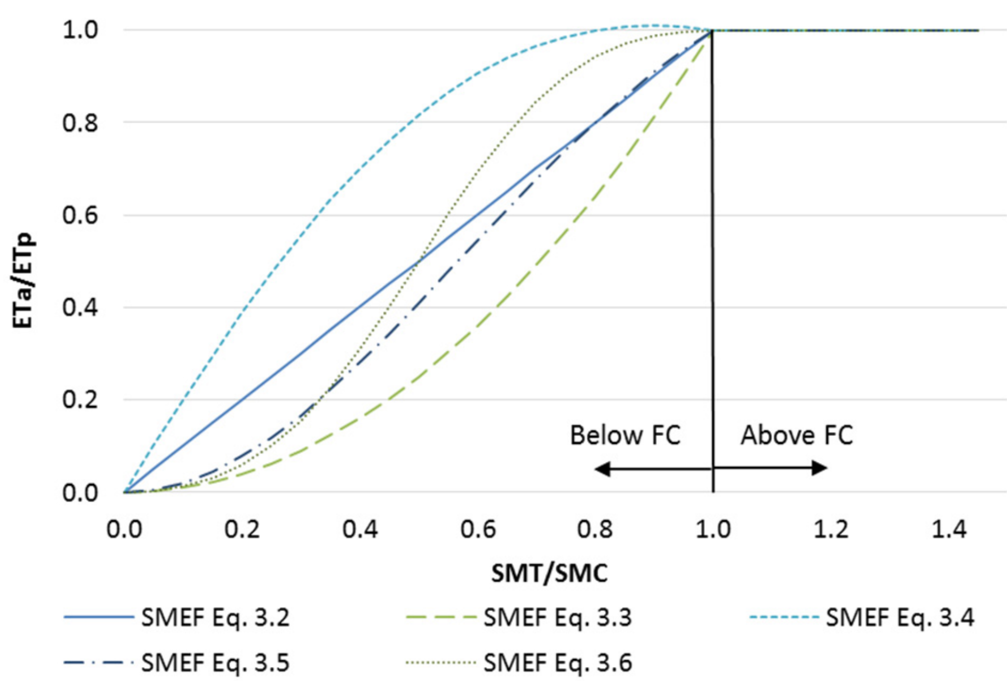

Figure 3.11: Soil moisture extraction functions

of Equation 3.2 is a linear relationship between actual over potential ET ratio and actual soil moisture over soil moisture capacity ratio; this relationship can be seen as the baseline understanding for the other SMEFs. Equation 3.3 describes a relationship that will reduce actual ET more dramatically than Equation 3.2 at the same soil moisture deficit. Oppositely, Equation

3.4 compared to Equation 3.2 will provide a relationship that sustains a higher actual ET at same soil moisture deficit, and actually peaks slightly above 1, at 1.01. Equation 3.5 reduces actual ET values compared to Equation 3.2 less severely than Equation 3.3, and reduces actual ET more at lower actual soil moisture to soil moisture capacity ratios. Lastly, Equation 3.6 is a combination of higher actual ET values at higher actual soil moisture to soil moisture capacity ratios and lower actual ET values at low actual over soil moisture capacity ratios (producing the same actual ET at an actual over soil moisture capacity ratio of 0.5) compared to Equation 3.2. The SMEF relationship that provides the most optimal model performance results for crop ET will be chosen for each lysimeter type.

3.7.2 CROP COEFFICIENTS

Crop ET is calculated via modifications to potential ET equations that include crop coefficients to simulate stages of plant growth. Agricultural crop coefficients range from 0.30 (e.g. initial season berries) to 1.25 (mid-season sugar cane; Allen et al. 1998). The applicable durations of the crop coefficients are divided by initial, development, middle, and late seasons (Figure 3.12).

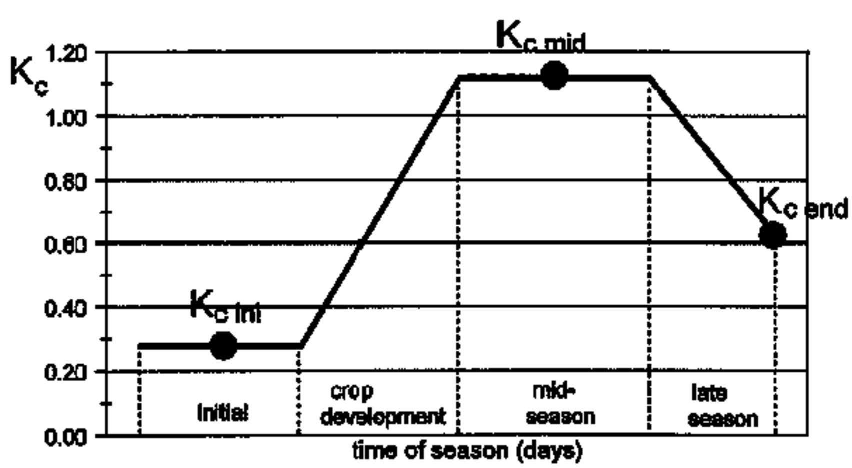

Figure 3.12: Crop coefficient seasons schematic (Allen et al. 1998)

The duration of these seasons will vary by crop type and climate. Length of crop stages (without cutting cycles) range from 5 days (e.g. initial season for radish) to 602 days (development of winter wheat; Allen et al. 1998). For plants and climate closer to that expected in this study, a more practical range of season length would be 5-160 days for initial stage, 10-75 days for development stage, 10-130 days for middle stage, and 10-103 days for late stage. This produces a range of 45-335 days for the total of the stages. The initial season was not used as the plants were transplanted and not grown from seed. The initial crop coefficient, K_{int}, is still needed as the development stage is a linear interpolation from initial to middle crop coefficient, K_{mid}, value. Similarly, during the late stage, the crop coefficient is a decreasing linear relationship between the middle and end crop coefficient, K_{end}. The middle stage is a constant value at the middle crop coefficient.

Allen et al. (1998) provides tabulated estimates on season durations and crop coefficients, but actual values will vary for site specific conditions. Data gathered in the plant inspections will be used to determine crop coefficient stage length with respect to the lysimeter plants. Each plant type present in each of the lysimeters had its leaves counted and the summation of all leaves is reported. It should be noted that this may not be the most representative way to cumulate leaf count, as each type of plant and more specifically each leaf on that plant will have different leaf areas. Similarly, each plant type present in each of the lysimeters had its height measured and the average of all heights is reported. The leaf count and plant height inspections show expected trends (Figure 3.13; Figure 3.12). For all lysimeters, the maximum total leaf count increases each growing season in accordance with the plant development. For each season, the lysimeter plant count increases during the growing phase and decreases toward winter. The

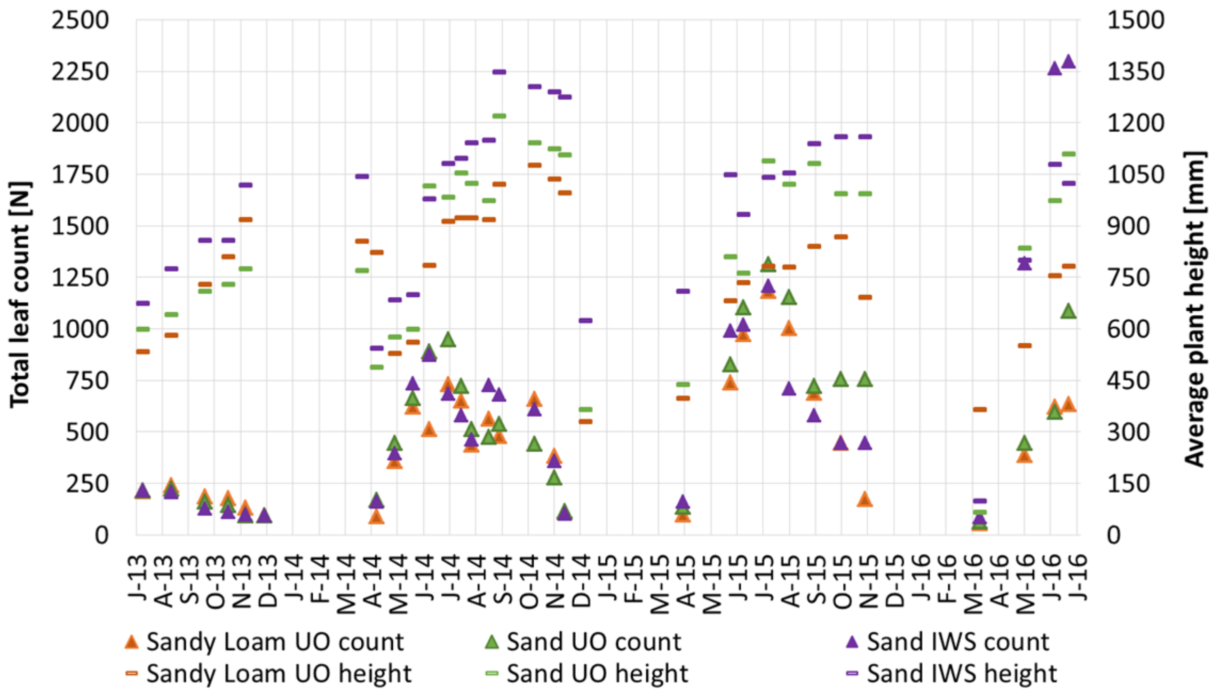

Figure 3.13: Leaf count and height for all lysimeter plants over three year study

height increases from the initial planting and during each growing season but reaches a maximum and evens out prior to dormancy during winter.

The area of three leaves of each plant in each lysimeter were estimated by tracing the outline of leaves on graph paper and counting boxes to find the area (Pandey and Singh 2011). This was done for the summer of 2015 and 2016, and the results are projected to the previous two growing season of 2013 and 2014. Samples of the same plants, no matter which lysimeter or season they came from were not statistically different from one another such that the areas were averaged for each plant type. The average leaf area was determined to be 16 cm^2 for the long, thin blades of switch grass, 47 cm^2 for the oblong and lance-shaped leaf of seaside goldenrod, and 18 cm^2 for small, elliptical shaped leaf of the black chokeberry. Average dimensions for a switch grass leaf are 10-60 cm long by 0.2–1.5 cm wide (GoBotany 2016), for a seaside goldenrod the average dimensions are 15-20 cm long by 1.3-3.8 cm wide (Sheahan 2014), and for black chokeberry the average dimensions are 5-10 cm long by 2.5-5 cm wide (Plumb 2009). Estimating the leaf area via an elliptical shape produces a range of leaf areas for switch grass of 11-23 cm^2, for seaside goldenrod of 30-60 cm^2, and black chokeberry of 10-40 cm^2. All the leaf area found for this study fall into these estimated ranges.

Actual leaf areas are in a constant state of flux, such that they will be constantly changing over the growing season as well as each growing season. Total leaf area can be found by the sum of all leaf areas times the number of total leaves. Leaf area index is the ratio of leaf area over total ground cover area. Due to availability of leaf area data, these parameters will be kept constant for each plant throughout the three years to obtain an estimate of LAI. As there is not significant difference among leaf areas for the sample sizes, a constant leaf area for LAI is reasonable. Applying the constant leaf area for each plant will weigh the total number of leaves to a representative area. The leaf count times the representative leaf area is then divided by the total surface area of the lysimeter to determine LAI (Figure 3.14). Similar to the trend in total leaf count, the LAI increases each growing season in accordance with the plant growth. All lysimeters have similar LAI overall with the exception of the last growing season from Jun 2016-July 2016 where the IWS lysimeter plants are seen to have very high LAI, which is consistent with visual plant inspections (APPENDIX A). The LAI is capped at 12 m^2/m^2 (SWAP also caps at this value). In the sand IWS lysimeter, LAI values are estimated just under 12 m^2/m^2 in June and July 2016. The lysimeter configuration is analogous to a potted plant, where the plant is able grow and spread outwards above a fixed sized soil surface. Leaf area index above 12 m^2/m^2 are most likely representing the leaves that are growing past the surface of the soil. These two months are a relatively small subset of the data and are not expected to influence comparisons overall. General mean LAI is variable, ranging from 1.31 ± 0.85 m^2/m^2 for deserts to 8.72 ± 4.32 m^2/m^2 for tree plantations (Scurlock 2001). Higher LAI typically describe dense tree cover, which is not descriptive of the lysimeter plants. The lysimeter plants LAI (except June and July 2016 for the IWS) are more comparable to that of crop LAI estimated at 3.62 ± 2.06 m^2/m^2.

Leaf area index for the lysimeters is used to determine timing of plant growth stages (Figure 3.14). Such that the time that coincides with leaf emergence is the start of the development

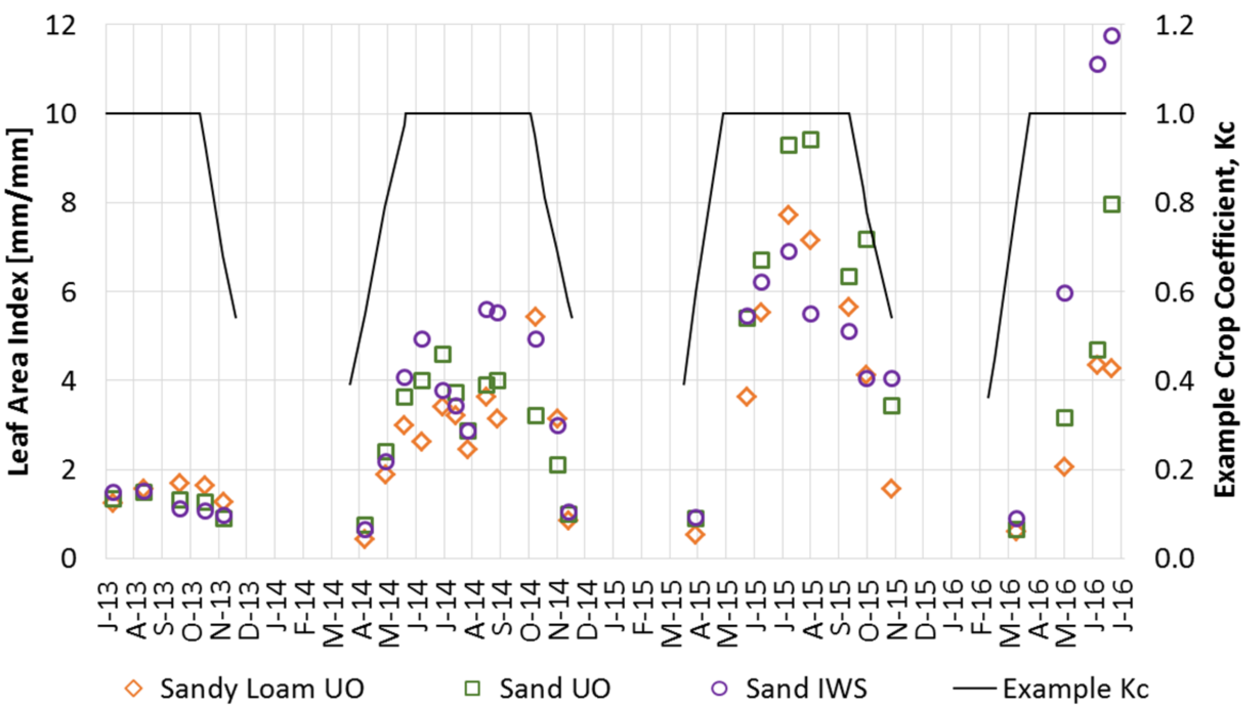

Figure 3.14: Leaf area index and crop coefficient trend for all lysimeter plants over three year study

stage. The end of the development stage (and start of the middle stage) is marked when the slope of the total leaf area stops increasing, found to be at the beginning of April. Similarly, when total plant count decreases drastically, the end of middle stage (and beginning of the late stage) is marked, found to be mid-October. Finally, the end of the late season is marked by the disappearance of leaves found at the end of November.

Durations of plant growth stages found via the leaf count data vary slightly year to year due to the ET data vetting process. The development stage ranges 39-45 days, the middle season is 154 days, and the late stage ranges 42-46 days (Table 3.12). All stages total to about 239-245 days. The development and late stages are within the expected duration whereas the middle season is longer than expected but still in the acceptable range for the total of the stages.

Table 3.12: Duration of plant growth stages (days)

Stage	2013	2014	2015	2016
Development	--	39	45	44
Middle	95*	154	154	60*
Late	42	46	46	--
Total	137*	239	245	104*

*Data starts July 13 2013 and ends July 13 2016 such that middle season is incomplete for these seasons

Sugarcane and grapes in low latitudes, onion seed in California, and sugar beet in California are similar to the stage duration based on total leaf count. These crops give a range of crop coefficients between 0.3-0.4 for initial, 0.85-1.25 for middle, and 0.45-0.8 for ending. However, the average maximum rain garden crop height is about 1.2 m, which is not descriptive of the previously mentioned crops. Sugar beet is the closest with an average height of 0.5 m. Therefore, these ranges will provide the lower boundary condition for optimization on rain garden crop coefficients, where the upper boundary is 2. The crop coefficients (K_{int}, K_{mid}, K_{end}) are allowed to change to optimize the criteria for model performance.

3.7.3 PERFORMANCE CRITERA

The model performance criteria are based on four approaches: the root mean square error (RMSE), coefficient of determination (R^2), coefficient of efficiency (E), and the overall difference between the observed and predicted data (D). The coefficient of residual mass (CRM) was also computed to determine the degree of under or overpredictions. The approaches are computed as follows:

Equation 3.7 $$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{n}}$$

Equation 3.8: $$\boldsymbol{R^2} = \frac{\left(\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})\right)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2 * \sum_{i=1}^{n}(P_i-\bar{P})^2}$$

Equation 3.9: $$\boldsymbol{E} = \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2}$$

Equation 3.10: $$\boldsymbol{D} = \sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i$$

Equation 3.11: $$\boldsymbol{CRM} = \frac{\left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i\right)}{\sum_{i=1}^{n} O_i}$$

Where O_i is the observed value is at time step *i*, P_i is the estimate value at time step *i*, $\bar{O}$ is the mean of the observed values, $\bar{P}$ is the mean of the estimate values, and *n* is the sample size.

The RMSE measures differences between the observed data and model estimations (Licciardello et al. 2007), exaggerating larger errors over smaller ones. The RMSE is a positive value and when close to 0 represents an accurate predictive model. The R^2 measures the degree of correlation between the observed data and model estimations. The range of R^2 is from 0 to 1 and when close to 1 represents a strong correlation. The E measures predictive power of hydrological models (Nash and Sutcliffe 1970; Moriasi et al. 2007) and is sensitive to extreme values. The range of E is from 1 to negative infinity and when close to 1 represents an accurate predictive model. This parameter is used in conjunction with the RMSE because E values that range from 0 and 1 are generally viewed as acceptable levels of performance as the predictor is estimating better than the mean of the observed data (Moriasi et al. 2007). The CRM measures the inclination of the model to overestimate or underestimate the observed values. The range of CRM is from −1 to +1, a negative value indicating model overestimation and positive indicating model underestimation (Loague and Green 1991; Chanasyk et al. 2003).

The goal of calibration includes the optimization of RMSE, R^2, E, and overall difference between the observed data and model estimations such that they are more desirable than the potential equations. The CRM is used to describe the model and observed relationship. The growing seasons (April through November) for the three years of study are used to calibrate predictive models with the observed daily ET on a daily basis; this includes a sample size of 549 for the sandy loam UO and 606 for sand UO and sand IWS. Daily observed values are influenced by rain events and often are higher the two or three days after an event and then decrease, whereas predictive ET model estimates do not take this observed phenomenon into account. Storm basis calibration is also performed, where the cumulative ET during dry times between events larger than 6.4 mm is compared to cumulative predicted ET for the same period. The storm based calibration approach is beneficial as the daily discrepancies described above will be lessened and can provide a more useful understanding of ET's role in rain gardens and other stormwater control measures. To understand the influence of the modifications on the predictive ET equations, the criteria for model performance is presented for both unmodified and modified forms, as well as on a daily and 6 mm storm basis.

3.8 RICHARD'S EQUATION SIMULATOR

To model surface water, water fluxes in the soil, outflow or drainage fluxes, Soil Water Atmosphere Plant (SWAP) requires inputs of rainfall, meteorological or ET values, a soil water relationship (e.g. SWCC), crop factors, and initial soil moisture conditions. The SWAP model simulation runs from July 13 2013-2016 to compare data on observed events greater than 25 mm for the large weighing lysimeters. A model of the bench scale study was developed and simulations run from August 24 2015-2016 to compare data on observed events greater than 25 mm. SWAP consists of four files: the main file (APPENDIX D), the crop file (APPENDIX E), the rainfall file (APPENDIX F), the meteorological file (APPENDIX G), and. In the case of the IWS, a drainage file (APPENDIX H) is also used.

SWAP's main file defines the initial moisture conditions, the Mualem van Genectuen (MVG) relationships, and computational tolerances. Initial soil moisture conditions were estimated using readings from the soil moisture meters for the continuous weighing lysimeters. The bench scale initial soil moisture values were estimated using the difference between weight reading on Aug 24th 2016 and dry weight. If initial soil moisture data is not available, primer rain events have been used to obtain a realistic soil moisture conditions before the simulating the event of interest (Lee et al. 2016).

Soil hydraulic functions are defined through MVG parameters (Section 3.1.2 for weighing lysimeters and Section 3.2.2 for bench scale) with no hysteresis or macropore flow. The fitting parameter that influences saturated hydraulic conductivity, h_e, was left at -0.1 cm for all systems (Lee et al. 2015). The saturated hydraulic conductivity, K_{sat}, were assigned at the values found in Section 3.1.2 for weighing lysimeters and Section 3.2.2 for bench scale with the exception of using 4 cm/d for clay loam and 6 cm/d for silt loam. These K_{sat} values were determined to be in the range of typical K_{sat} values for each soil type, within in the same order of magnitude, and more descriptive of each soil type for the SWAP program.

The numerical calculation of Richards equation was left at the default tolerances and sensitivities. Rainfall and simulated inflow was combined into the total inflow and those values were input in 15 minute intervals, the smallest interval allowed in SWAP. Meteorological data is input in daily intervals, where reference ET (to be used with crop factors) was specified. The bottom boundary condition was set at a soil air interface for all systems besides the IWS, where a bottom flux of zero was prescribed with a drainage file. The SWAP manual recommends this combination for a lysimeter with groundwater interaction with a low drainage resistance (Kroes et al. 2009). The drainage file for the IWS was chosen as a single drain tube with a dimensionless drainage resistance used as calibration factor, but this resistance should be on the lower end of the range of 10 – 100,000.

3.8.1 EVAPOTRANSPIRATION

Reference ET was calculated via the ASCE Penman-Monteith equation and input in daily intervals. SWAP portions out reference ET into transpiration, evaporation, and interception as each process is governed by different mathematical equations. For example, transpiration will occur throughout the rooting depth and soil evaporation occurs at the soil-air interface. Interception was ignored as simulated storms are applied to the base of the plants at the soil surface. Evaporation is portioned from reference ET based on the Darcy equation such that it is necessary to have the top portion of the soil surface to be split up into compartments that are less than or equal to 1 cm thick for an accurate simulation (Kroes et al. 2009). For all systems, the first 10 cm is comprised of compartments 0.5 cm thick. Plant transpiration is calculated using crop factors to convert the remaining portion of reference ET rate into actual plant transpiration by considering root depth and density. The rooting depth is estimated to reach the bottom of the lysimeters (i.e. 660 mm) and root density distribution is adapted from a SWAP example, based on grass, called Nature Grass. It is expected that rooting depth and density will change over the growing season which will affect rates of transpiration. However, change in roots was decided to be reflected in the crop coefficient which will limit ET in the developing and ending stages.

3.8.2 CROP FACTORS

SWAP recommends crop factors in conjunction with the ASCE Penman-Monteith reference evapotranspiration equation. When used with the Penman-Monteith equation, crop factors in SWAP are analogous with crop coefficients. The crop coefficients timing, based on LAI, found in the calibration of the Penman-Monteith equation on a storm basis (Section 4.4.2) are used for all the lysimeter simulations. Based on the LAI of the bench scales study, the timing of crop coefficients found from the weighing lysimeters is representative of the bench scale study (Figure 3.15). Similar to the weighing lysimeters, monthly leaf count and a representative leaf area was used to determine LAI of each bench scale lysimeter. Again, the LAI was capped at 12 mm/mm since this is the maximum allowed in the SWAP program and represents the leaves extending over the sides of the soil surface.

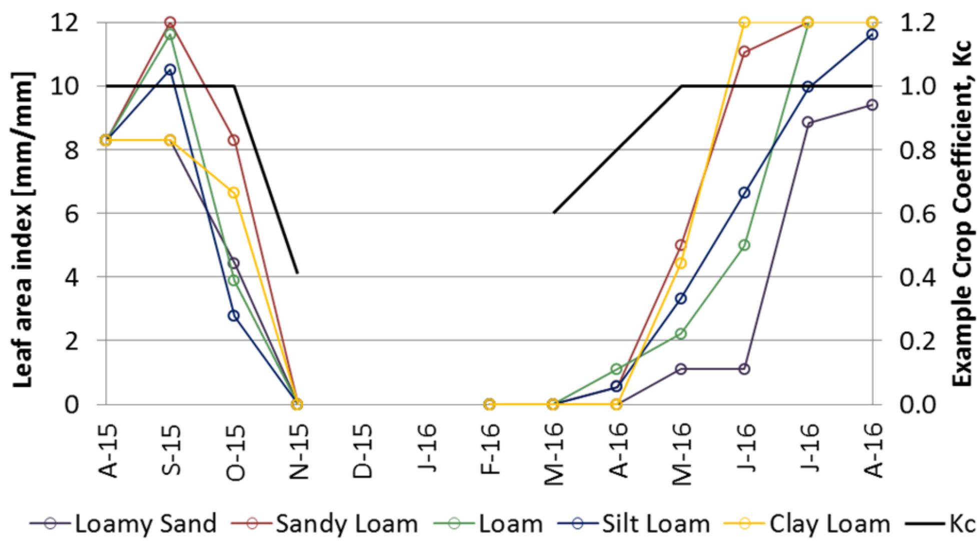

Figure 3.15: Leaf area index for bench scale study over one year

3.8.3 SIMULATION VARIABLES

Variables to the SWAP simulation include crop factors, soil type, lower boundary condition, depth of media, rooting depth, and ponding depth. The values of the crop factors (or crop coefficients) used in SWAP are based on the crop coefficients determined in the calibration of the Penman-Monteith equation on a storm basis (Section 4.4.2) for the UO weighing lysimeters. However, since the storm basis calibration of Penman-Monteith equation for the IWS did not have a SMEF associated with it, the crop coefficient values for the daily basis are used. A total of three different sets of crop coefficients are explored (Table 3.13).

Table 3.13: Sets of crop coefficients for SWAP

Season	Low	Medium	Maximum
Development	0.6	0.8	1.8
Middle	1.2	1.5	2.0
Ending	0.9	1.2	1.8

It is expected that the low, medium, and maximum crop coefficient sets will provide the best simulated to observed data match for the sandy loam UO, sand UO, and sand IWS, respectively. For the bench scale study, all sets will be explored and the closest match is presented in Section 4.5.2.

Soil type will include sand, loamy sand, sandy loam (properties taken from the UO system), loam, silt loam, and clay loam for all systems. Bioretention design (with underdrain) or bioinfiltration with gravel layer is modeled using a lower boundary condition of an air-soil interface. Depth of media considered includes 20 cm, 46 cm, 66 cm, 90 cm, and 152 cm to encapsulate the range of media depth used in rain gardens, with the shallower depth perhaps representing green roof or the upstream side of a swale with a dam. Rooting depth will also vary with depth of media for a bioretention design. Ponding depths of 7.5, 15, and 30 cm are explored.

The bioinfiltration design is simulated with a deep groundwater table using a lower boundary condition of freely draining at 200 cm below ground surface. Bioinfiltration design explores various rain garden media depths (20 cm, 46 cm, 66 cm, 90 cm, and 152 cm) with several underlying soils to represent the soil hydrologic groups. The soil hydrologic groups are defined by their saturated hydraulic conductivities and are labeled A through D in order of decreasing hydraulic conductivity. Type A soil is defined as any hydraulic conductivity greater than 87 cm/d for deep groundwater levels and is represented by sand media (K_{sat}= 90 cm/d). Type B soil has a hydraulic conductivity between 87 cm/d to 35 cm/d for deep groundwater levels and is represented by sandy loam media (K_{sat}= 50 cm/d). Type C soil has a hydraulic conductivity between 35 cm/d to 4 cm/d for deep groundwater levels and is represented by loam media

(K_{sat}= 12 cm/d). Type D soil is not explored as SWAP is a 1-D program and does not model boundary conditions of the transition from high saturated hydraulic conductivity to low saturated hydraulic conductivity well. Also, for underlying D type soils, a bioinfiltration design is not recommended but rather a bioretention design (PABMP 2006).

3.9 EVAPOTRANSPIRATION ACCOUNTING METHOD

It is proposed to account for ET between storm events and add it into the static storage equation that is currently used in rain garden design in PA via a void space credit. Typically, only 20% of void space is allowed to be considered in rain garden design for soil media (PA BMP 2006). Recently, Philadelphia increased their void space accounting for sand only to 30% (PWD 2016). Gravel is attributed a 40% void space, which incentives the use of gravel layers in rain gardens but can increase the cost of rain gardens due to hauling and decrease the use of onsite soils. The static storage is modeling the worst case scenario of a 25 or 38 mm storm event where the bowl depth is full and the soil is saturated. It is not written explicitly what void space credit volume is representing but it is deduced that the soil is expected to be less than the saturated soil moisture by 20% (or 30% for sand) via some removal mechanism. This removal mechanism may be gravity as it can represent the change from saturation to field capacity or can be the combination of infiltration and ET. Volume of water removed via gravity (infiltration) from the soil void space is dictated by the difference between saturation and field capacity. Similarly, the volume of water removed via ET from the soil void space is dictated by the difference between field capacity and wilting point. Typical saturations, wilting points, and field capacities based on soil type with saturated moisture contents a presented alongside with those found from data (Table 3.14). Ultimately the data determined values are utilized in the analysis as they are similar to that of literature values based on average soil properties.

Table 3.14: Typical and measured saturations, wilting points, and field capacities

Soil Type	(Rawls et al. 1982)			(Rawls et al. 1998)			(Saxton and Rawls 2006)			Data		
	θ_s	FC	WP	n*	FC	WP	θ_s	FC	WP	θ_s	FC	WP
Sand	0.42	0.09	0.03	0.42	0.08	0.03	0.46	0.10	0.05	0.46	0.16	0.05
Loamy Sand	0.40	0.13	0.06	0.40	0.12	0.05	0.46	0.12	0.05	0.39	0.15	0.06
Sandy Loam	0.41	0.21	0.10	0.41	0.21	0.11	0.45	0.18	0.08	0.44	0.25	0.08
Loam	0.43	0.27	0.12	0.42	0.29	0.15	0.46	0.28	0.14	0.45	0.35	0.12
Silt Loam	0.49	0.26	0.13	0.45	0.32	0.14	0.48	0.31	0.11	0.52	0.41	0.08
Clay Loam	0.39	0.32	0.20	0.42	0.34	0.24	0.48	0.36	0.22	0.50	0.41	0.12

*Rawls et al. 1998 only provides porosity which includes residual moisture content

In this method, the void space credit is modified to a value that better represents removal of water from ET and removal of water from saturation to field capacity. To do this, the static rain garden design standard will incorporate a dynamic component: days between events. Historically in Philadelphia, PA (located about 20 km east of Villanova, PA) there are about 62 storm events greater than 2.5 mm per year (Driscoll et al. 1989). On average, this would provide a storm event about every 6 days. Data from a rain gage located about 2 km away from the weighing lysimeters confirmed this average over 12 years of data (Wadzuk et al. 2017). Six days is used for a benchmark time in between storm events to account for ET in rain gardens at Villanova, PA (located in between the Dfa and Dfb climate zone in Koppen Geiger; Kottek et al. 2006). Though there is variability as to when these events will occur in relation to one another, 6 days is an average for a very small event size of 2.5 mm. Rain garden design is typically concerned with storms about 25 to 38 mm, such that using 6 days between events can be seen as appropriate. Accounting for ET over 6 days between storm events is still very conservative as

25 mm events occur about 13 times a year (found from 12 years of data from rain gage 2 km away), averaging a storm event every 28 days (Wadzuk et al. 2017). However, 28 days between events greater than 25 mm does not provide an adequate sample size due to the frequency of simulated events. Therefore 12 days between storm events will also be considered as a benchmark time. Twelve days provides more days between events that is more representative of storms greater than 25 mm and also provides an adequate sample size of 23 events over the three years of data. Similarly, six days provides more days between events provides an adequate sample size of 40 events over the three years of data.

To fully understand this void space credit for a variety of rain garden design, the SWAP program will use the 3 years of rain and Penman-Monteith equation data for the weighing lysimeters to vary soil types, rooting and soil depths, ponding depth, underlying soils, and crop factors. The results obtained from the SWAP program will inform cumulative ET values for 6 and 12 days between storm events greater than 25 mm.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 ET STATISTICS

Summary statistics on the available ET rates from the three years of data (July 13 2013-2016) is used for media comparison and drainage comparison (Table 4.1). The mean ET rates are 2.86 mm/d, 2.72 mm/d, and 4.42 mm/d for sandy loam UO, sand UO, and sand IWS lysimeters, respectively. Both two sample t-tests showed that sandy loam UO is not statistically greater than sand UO within a 95% confidence. This means that the average ET rate is unaffected by the use of the native media. The sand IWS ET rates are statistically higher than sand UO by 1.70 mm. Similarly, the sand IWS ET rates are statistically higher than sandy loam UO by 1.56 mm.

Table 4.1: Summary statistics for 3 year study of total inflow

Lysimeter	Sandy Loam UO (n=689)	Sand UO (n=776)	Sand IWS (n=776)
Daily Mean [mm/d]	2.86	2.72	4.42
Standard Deviation [mm/d]	2.19	2.25	3.40
95% Confidence Interval [mm/d]	(2.69, 3.02)	(2.56, 2.88)	(4.18, 4.66)

Similar summary statistics are presented for only the growing season (i.e. excluding winter) of the 3 year period (Table 4.2). The mean ET rates are 3.02 mm/d, 2.96 mm/d, and 4.97 mm/d for sandy loam UO, sand UO, and sand IWS lysimeters, respectively. These averages are slightly greater than that of the average ET rates from July 2013-2016 (Table 4.1). Similarly, results from both two sample t-tests show for the growing season data that sandy loam UO is not statistically greater than sand UO within a 95% confidence and that sand IWS ET rates are statistically higher than sand UO and sandy loam UO by 2.01 mm/d and 1.95 mm/d, respectively. Distribution of the ET rates for all seasons and the growing seasons for each lysimeter are shown in Figure 4.1.

Table 4.2: Summary statistics for 3 year study of total inflow for growing season

Lysimeter	Sandy Loam UO (n=610)	Sand UO (n=667)	Sand IWS (n=667)
Daily Mean [mm/d]	3.02	2.96	4.97
Standard Deviation [mm/d]	1.99	2.11	3.10
95% Confidence Interval [mm/d]	(2.74, 3.29)	(2.68, 3.23)	(4.56, 5.38)

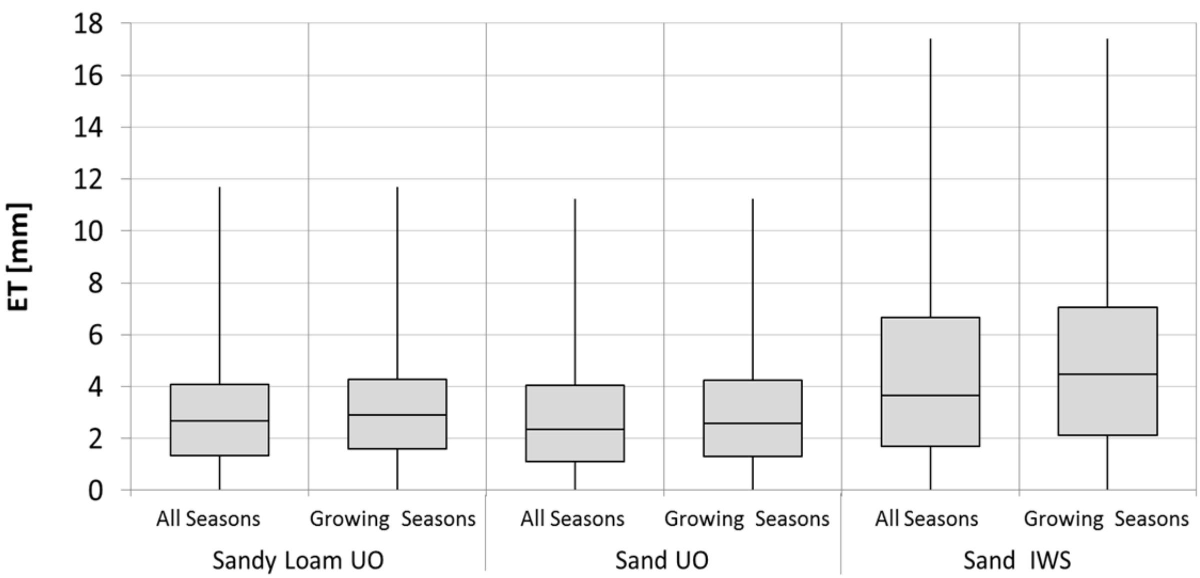

Figure 4.1: Box plot of daily ET rates for all seasons and growing seasons

There was 1835 mm of inflow for July 13 2013 – July 13 2014. Of that inflow, 625 mm were simulated, leaving 1210 mm of direct rainfall (Table 4.3). Between July 13 2014-2015, there was 1793 mm of inflow, of that 730 mm were simulated, leaving 1063 mm of direct rainfall. During this year, the sandy loam lysimeter was offline for a portion of time and thus has different summations of effective rainfall, simulated inflow, and total inflow. Between July 13 2015-2016, there was 3034 mm of inflow, of that 2154 mm were simulated, leaving 880 mm of direct rainfall. Please note that direct rainfall for these years is taken over a time period of July 13 to July 12 of the next year such that the summations may be different than what is typically expected for a traditional year (January 1 to December 31 in the same year) or a water year (October 1 to September 31 of the following year).

Table 4.3: Annual summations of ET as a percentage of inflow

Year	Rainfall [mm]	Simulated Runoff [mm]	Inflow [mm]	ET [mm]			ET [% Inflow]		
				Sandy Loam UO	Sand UO	Sand IWS	Sandy Loam UO	Sand UO	Sand IWS
2013-14	1210	625	1835	805	687	1243	44%	37%	68%
2014-15	1063 (691)*	730 (317)*	1793 (1009)*	483	743	1078	48%	41%	60%
2015-16	880	2154	3034	616	492	1044	20%	16%	34%

*Sandy loam lysimeters was offline from October 2014 through January 2015

All lysimeters had much less ET as percentage of rainfall in the third year (2015-16) than the previous two years (Table 4.3). This is due to the large amount of simulated inflow in the third year. When there is more direct rainfall than simulated runoff, the ET percentages of inflow are much higher and average 46% in the sandy loam UO, 39% in the sandy UO, and 64% in the sand IWS. When simulated runoff dominates, these percentages are reduced by a factor of two (i.e. 20% for sandy loam UO, 16% for the sand UO, and 34% for the sandy IWS). The sand IWS has the largest ET percentage of inflow in all years. On average, ET comprised 37, 32, and 54% of the total inflow for the sandy loam UO, sand UO, and sand IWS systems, respectively.

There is a substantially lower percentage of rain volume retained within and evapotranspirated from the UO lysimeters during simulated events than during direct rainfall events; this is because the applied water greatly exceeds the water holding capacity of the system and percolation dominates removal during and immediately after rain application. Ponding in the

UO systems would not exist for longer than a day, where ponding in the IWS had seen to last up to three days. The direct rainfall scenarios did not observe this flushing because the volume and rate applied at 1:1 typically did not overwhelm the water holding capacity of the UO lysimeters. The IWS zone provides a reservoir to retain excess rainfall so this system has a more equal balance between percolation and ET.

Table 4.4: Seasonal daily ET rates for 3 year study period of total inflow

Season	Lysimeter	Mean [mm/d]	Standard Deviation [mm/d]	Sample Size	Lower 95% Confidence [mm/d]	Upper 95% Confidence [mm/d]
Summer	Sandy Loam UO	4.00	2.01	227	3.74	4.27
	Sand UO	4.03	2.34	227	3.73	4.34
	Sand IWS	5.92	3.59	227	5.46	6.39
Fall	Sandy Loam UO	2.66	2.17	210	2.37	2.95
	Sand UO	2.66	2.05	210	2.39	2.94
	Sand IWS	5.87	3.42	210	5.41	6.33
Winter	Sandy Loam UO	1.34	1.59	78	0.99	1.69
	Sand UO	1.32	1.74	108	1.00	1.65
	Sand IWS	1.61	1.32	108	1.36	1.85
Spring	Sandy Loam UO	2.39	1.78	173	2.13	2.66
	Sand UO	2.17	1.95	230	1.92	2.42
	Sand IWS	3.11	2.30	230	2.81	3.41

Generally, the greatest ET rates occur in the summer, followed by the fall, spring, and winter (Table 4.4). A similar trend in seasonal ET was observed when looking at the monthly ET rates. On a monthly basis, the IWS lysimeter has elevated daily ET rates over the UO lysimeters (Table 4.5).

Table 4.5: Monthly presentation of daily ET rates for 3 year study period of total inflow

Mo.	Lysimeter	Mean [mm/d]	Standard Deviation [mm/d]	Sample Size	Lower 95% Confidence [mm/d]	Upper 95% Confidence [mm/d]
Jan	Sandy Loam UO	1.06	1.06	23	0.63	1.49
	Sand UO	0.60	1.01	26	0.21	0.99
	Sand IWS	1.87	1.55	26	1.27	2.46
Feb	Sandy Loam UO	1.45	1.48	20	0.80	2.10
	Sand UO	1.71	1.64	20	0.99	2.43
	Sand IWS	1.35	0.74	20	1.02	1.67
Mar	Sandy Loam UO	2.25	2.66	60	1.57	2.92
	Sand UO	1.98	2.04	60	1.46	2.49
	Sand IWS	3.59	2.59	60	2.93	4.24
Apr	Sandy Loam UO	2.25	1.71	73	1.86	2.65
	Sand UO	2.20	1.77	73	1.79	2.60
	Sand IWS	5.90	3.87	73	5.01	6.79
May	Sandy Loam UO	3.35	1.94	77	2.91	3.78
	Sand UO	3.67	1.91	77	3.24	4.09
	Sand IWS	7.20	2.57	77	6.63	7.78
Jun	Sandy Loam UO	4.03	2.22	89	3.57	4.49
	Sand UO	4.38	2.58	89	3.84	4.91
	Sand IWS	4.86	3.11	89	4.21	5.50
Jul	Sandy Loam UO	3.86	1.96	71	3.41	4.32
	Sand UO	3.46	1.96	71	3.01	3.92
	Sand IWS	5.96	3.43	71	5.16	6.76
Aug	Sandy Loam UO	4.15	1.75	67	3.73	4.57
	Sand UO	4.07	2.28	67	3.52	4.61
	Sand IWS	7.35	3.85	67	6.43	8.27
Sep	Sandy Loam UO	2.88	1.53	74	2.53	3.23
	Sand UO	2.96	1.98	79	2.53	3.40
	Sand IWS	4.10	2.22	79	3.61	4.59
Oct	Sandy Loam UO	2.33	2.44	51	1.66	3.00
	Sand UO	1.91	2.39	76	1.37	2.45
	Sand IWS	2.27	0.81	76	2.09	2.46
Nov	Sandy Loam UO	1.10	1.13	48	0.78	1.43
	Sand UO	1.36	1.80	75	0.95	1.76
	Sand IWS	1.93	2.01	75	1.47	2.38
Dec	Sandy Loam UO	1.34	1.89	35	0.71	1.96
	Sand UO	1.61	1.90	62	1.14	2.09
	Sand IWS	1.48	1.33	62	1.14	1.81

During the warmer months (April through August), the monthly averaged daily ET rates are generally more than 50% greater in the IWS lysimeter than the UO lysimeters. In the colder months (December through February), the ET rates for all lysimeter configurations are similar.

The summer data (Table 4.4) shows that UO systems had an average ET rate of 4.02 mm/d and the sand IWS of 5.92 mm/d, which are statistically different according to paired t-test. In the fall, the UO systems have an average ET rate of 2.66 mm/d and the IWS system has an average ET rate of 5.87 mm/d. For spring, there is no statistical difference between ET rates among the configurations and average 2.28 mm/d. The sand IWS lysimeter's fall season was statistically greater than the spring by 2.76 mm/d. There is no statistical difference between the fall and spring season for the sandy loam or sand UO rain garden lysimeters. In the winter the average ET rate is 1.42 mm/d with no statistical difference among the configurations. It is important to note there are observed ET rates that are greater than zero during the winter months. It is often assumed that ET would not be an active process in the winter and thus cannot be relied upon as a volume reduction mechanism in those months. While there is snow and freezing during the winter, there is still time when, at least for a portion of the day, ET is not only possible, but substantial.

Monthly data are summarized for a three year period in Table 4.5 and may be used to provide baseline data for climates similar to southeastern PA (located in between the Dfa and Dfb climate zone in Koppen Geiger; Kottek et al. 2006). Trends in the seasonal and monthly data are also provided visually in Figure 4.2.

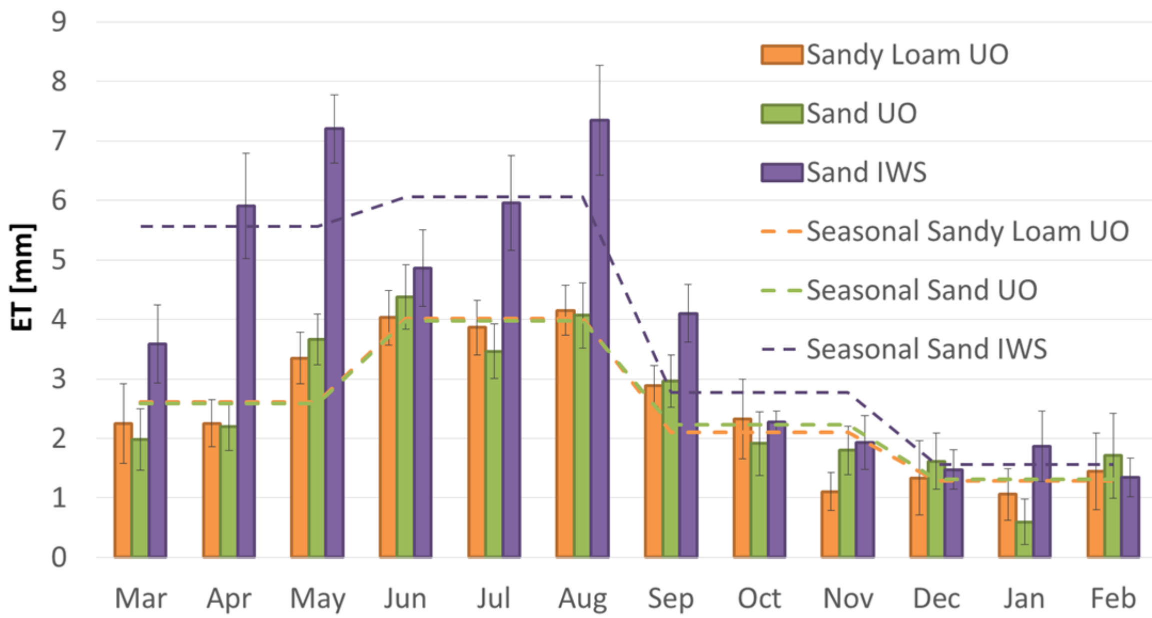

Figure 4.2: Monthly and seasonal daily ET rates

4.2 6 MM STORM BASED ANALYSIS

Over the three year study, 80 events are greater than 6 mm. The resulting storm summations were binned by inflow amount (i.e. 5-10 mm, 10-15 mm, 15-20 mm, 20-30 mm, 30-50 mm, 50-100 mm and 100-200 mm) and the average summation of ET is divided by total storm inflow to determine ET as percent of inflow. ET is summed over the days in between storm events (> 6 mm) up to 25 days. Figure 4.3 used a log based 10 scale on the x-axis to better show the range of inflow amount. As the amount of inflow increases, as expected, the percentage of ET as inflow decreases (Figure 4.3). Evapotranspiration as percentage of inflow greater than one means that there is more cumulative ET than rainfall during time in between events enabled by stored water. If this ratio is less than one, then the lysimeter has either outflowed, not had enough days between events to adequately remove inflow via ET, or a combination of the two scenarios.

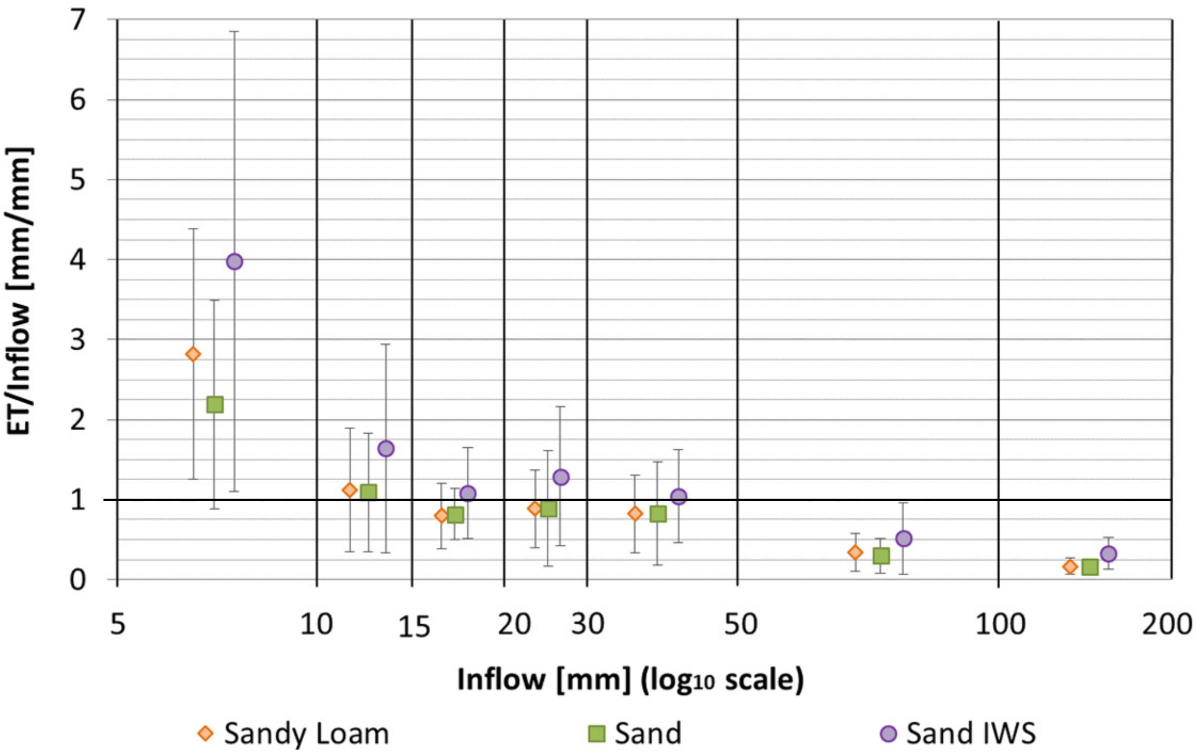

Figure 4.3: Cumulative storm ET as percentage inflow versus inflow

For storms less than 10 mm in all the lysimeter types, the average ET as percent inflow are above 1, meaning ET is removing 10 mm of water as well as some water in soil pore spaces. The storms less than 10 mm have the largest standard deviations of ET as portion of inflow for all lysimeter types due to the variable time between storm events. However, within this bin size, the standard deviations on the ET/Inflow parameter are greater than or close to one indicating that inflow can be lost by ET during the days that follow an event less than 10 mm. On average, the UO lysimeters ET to inflow percentage remains above one for events less than or equal to 15 mm. Similarly, this limit for the IWS is 40 mm. It should be noted that the average ET to inflow ratio for the UO lysimeters remains close to 0.9 until 40 mm of inflow as well. In extreme and runoff simulated events (i.e. 100-200 mm), the ET as percentage inflow becomes smaller but still remained at an average of 17% for the UO lysimeters and 33% for the IWS lysimeter.

For the same storms 80 storms, those events which produced outflow are used in the following analysis along with average soil moisture on the day before each event (Figure 4.4). The UO

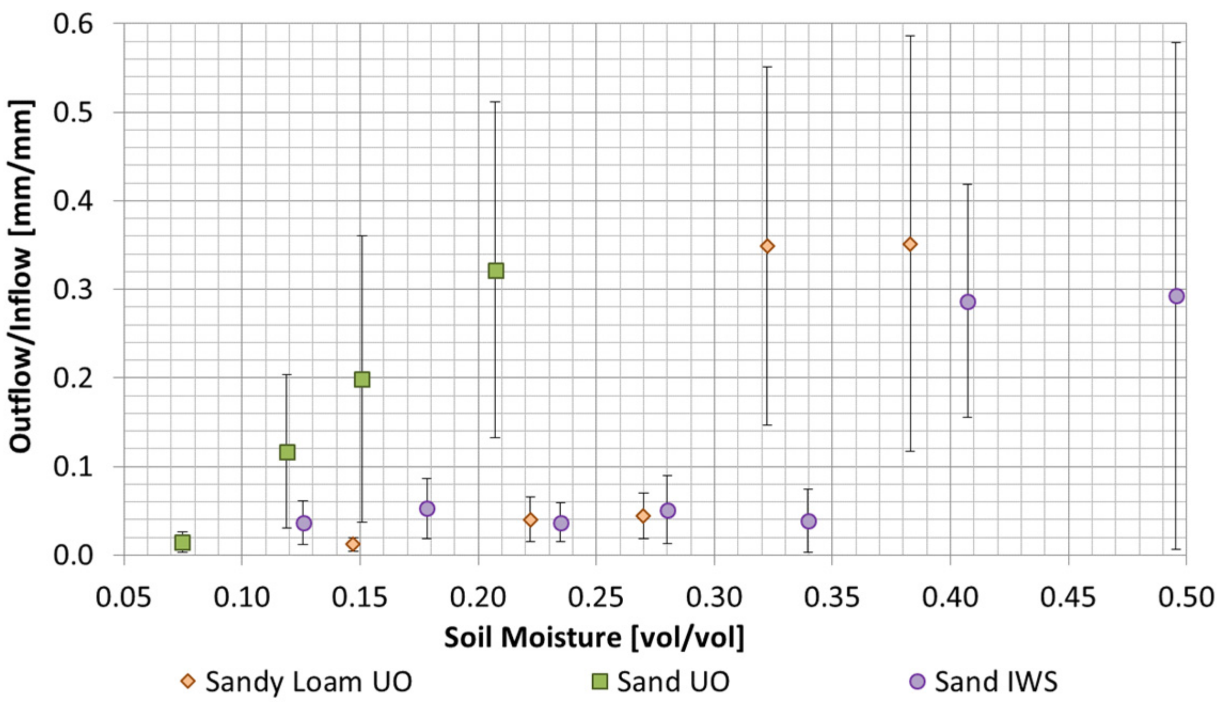

Figure 4.4: Outflow as percentage inflow versus antecedent soil moisture

lysimeters have a sample size of 40 events and the IWS lysimeter a sample size of 60, as only the outflow producing events are applicable. Outflow is divided by inflow to normalize for storm volume and produce an outflow to inflow ratio on the y-axis in Figure 4.4. The sandy loam UO lysimeter outflows in a soil moisture range of 0.15 to 0.38 vol/vol, but does not produce a large portion of outflow as portion of inflow until the antecedent soil moisture reaches between 0.27 and 0.32 vol/vol, which mimics the range of field capacity of the sandy loam soil (Section 3.1.2). The sand UO lysimeter outflows at a lower antecedent soil moisture range (0.06 to 0.21 vol/vol) than compared to the other two configurations. The range of this antecedent soil moisture range for sand UO surrounds the field capacity found for sand in UO in Section 3.1.2. The sand IWS lysimeter outflows over a soil moisture range from 0.13 to 0.5 vol/vol. It is not until a soil moisture of 0.41 vol/vol that the sand IWS lysimeter sees larger outflow as portion of inflow. The sand IWS soil moisture range is much larger than that of its UO counterpart, 0.47 vol/vol difference in soil moisture range compared to a 0.15 vol/vol difference in soil moisture range. The larger range of soil moisture that the sand IWS is experiencing complements the larger amount of ET as portion of inflow that is being observed from this lysimeter configuration. This observation is most likely due to the continuous saturation levels that the IWS lysimeter has because of the reservoir of water created by the IWS.

4.2.1 STORMS GREATER THAN 25 MM

Storm simulations and large storms (25 mm or greater) during the non-winter months were analyzed and a cumulative ET and outflow chart for each rain garden system was developed (Figure 4.5). The average parameter is presented surrounded by the 95% confidence intervals. The confidence intervals are based on incremental change, not cumulative change. The cumulative ET rates are surrounded closely with their 95% confidence intervals for all lysimeters. The ET rates have steady confidence intervals, indicating that average ET rate is a suitable proxy for spring, summer and fall performance. The bulk of the outflow volume for the UO systems occurs quickly, within 24 hours after the storm has accumulated to 25 mm (day 0).

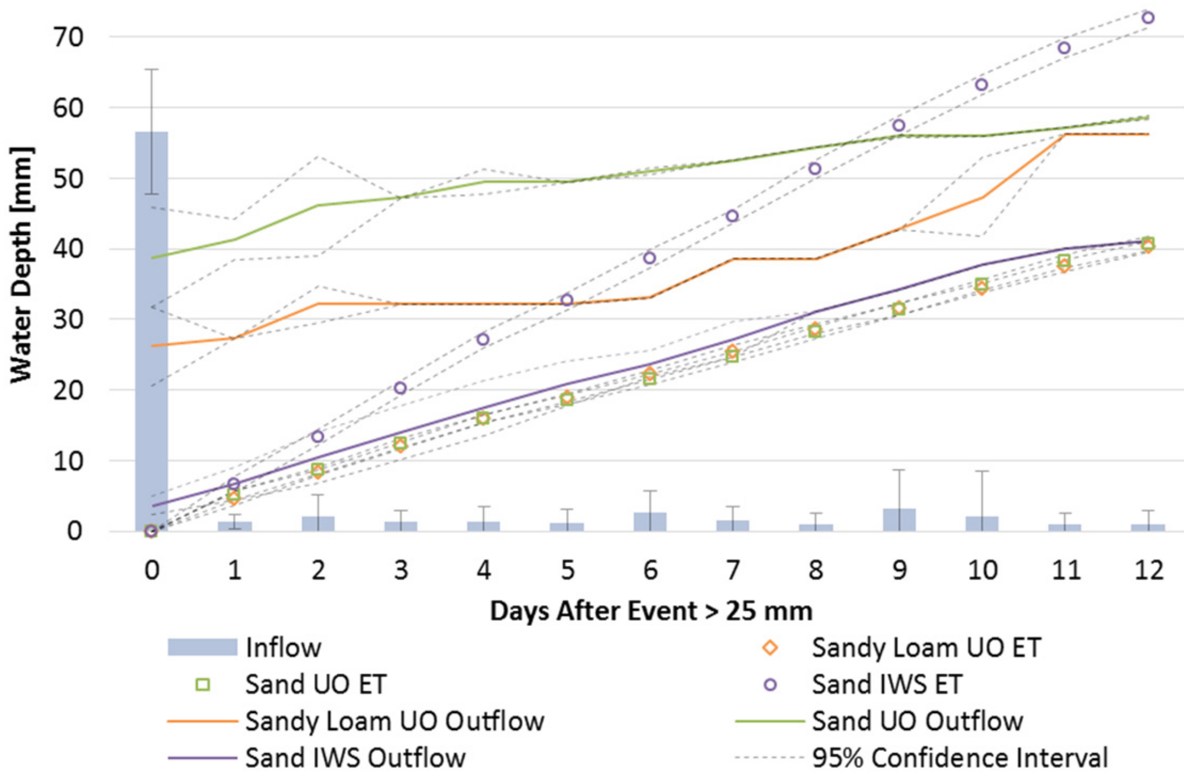

Figure 4.5: ET and outflow for days after storm events of 25 mm or greater

The sandy loam outflow rises to about 30 mm on average on day 2 after an event and stays flat until day 6, when there is a presence of some rainfall under 25 mm, by day 12 the total outflow rises to about 57 mm, again due to influence of rain events under 25 mm. The sandy loam configuration outflow and ET produces a total volume loss after 6 days of about 54 mm (32 mm to outflow and 22 mm to ET) and after 12 days of about 95 mm (55 mm to outflow and 40 mm to ET).

Outflow from the UO systems have similar volumes at the end of 12 days, however the pathway for the outflow is different due to different saturated hydraulic conductivites. Initially, the volume of outflow from sandy loam UO is about 15 mm lower than sand UO (about 25 mm vs 40 mm, respectively). Interestingly, at the end of 12 days the outflow volumes from both UO systems are similar values, around 55 mm. The IWS outflow is much lower compared to the UO system, but occurs more frequently as it is constantly increasing over the 12 days reaching about 40 mm. Due to the IWS slowing down the outflow rate, the ET from the IWS is about double than that of UO systems at the end of 12 days (70 mm of ET from IWS system vs 40 mm of ET from the UO systems).

Similar to the weighing rain garden lysimeters, storm simulations and large storms (25 mm or greater) during the non-winter months cumulative ET and outflow chart for the bench scale study was developed (Figure 4.6). The 95% confidence intervals are not presented on this graph

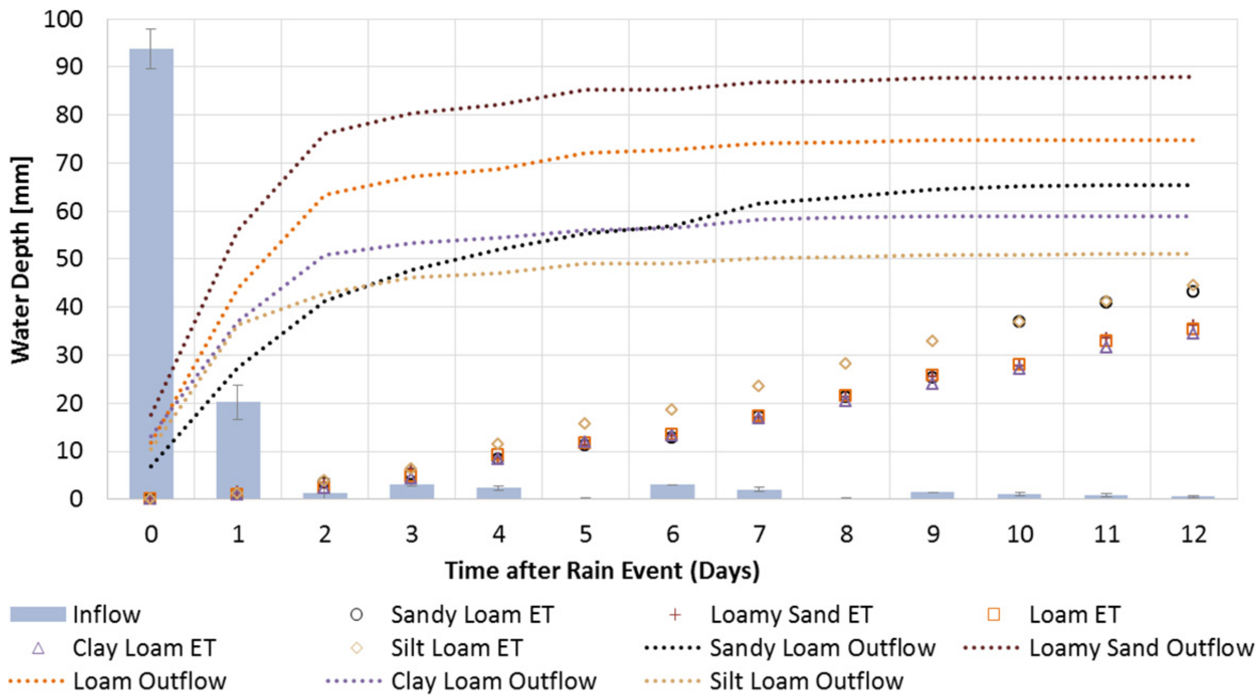

Figure 4.6: Bench scale ET and outflow for days after storm events of 25 mm

for visual clarity but can be seen in Section 4.5.2. Volume of outflow is largest from loamy sand followed by loam, sandy loam, clay loam, and silt loam. Cumulative ET rates over the 12 days are similar between the loamy sand, sandy loam, loam, and clay loam with the exception of sandy loam having higher rates between days ten through twelve. The silt loam is observed to have consistently higher ET rates from the fifth to the twelfth day compared to the other soil types. Cumulative ET and outflow on days after event greater than 25 mm for both the weighing lysimeters and bench scale study and are used to calibrate the SWAP program in Sections 4.5.1 and 4.5.2, respectively.

Sandy loam soil is a common soil type between the weighing lysimeters and bench scale study lysimeters. Cumulative outflow on day 1 is about 25 mm for both devices, the outflow for the bench scale study is larger overall than the sandy loam UO weighing lysimeter as outflow is a function of inflow; the average inflow is larger in the bench scale (about 95 mm; Figure 4.6) than the weighing lysimeters (about 58 mm; Figure 4.5).

4.3 SOIL MOISTURE COMPARED TO WEIGHT

4.3.1 WEIGHT VS ALL SOIL MOISTURE DEPTHS

A regression model was developed to describe the relationship between the soil moisture meters and the lysimeter weight. The regression model for the sandy loam UO results in the following equation:

Equation 4.1: $$W = 3.9 + 159 * SM_{10} + 40 * SM_{35} + 211 * SM_{65}$$

Where W is the daily change in weight, SM_{10} is daily change in soil moisture meter reading at 10 cm depth, SM_{35} is daily change in soil moisture meter reading at 35 cm depth, and SM_{65} is daily change in soil moisture meter reading at 65 cm depth. This regression model for sandy loam UO shows a strong correlation between soil moisture and weight with an R^2 of 0.88 and S of 4.63 mm for all seasons under consideration (Figure 4.7). The regression model is an average of summer spring, and fall data over the three years of study (July 13 2013-2016).

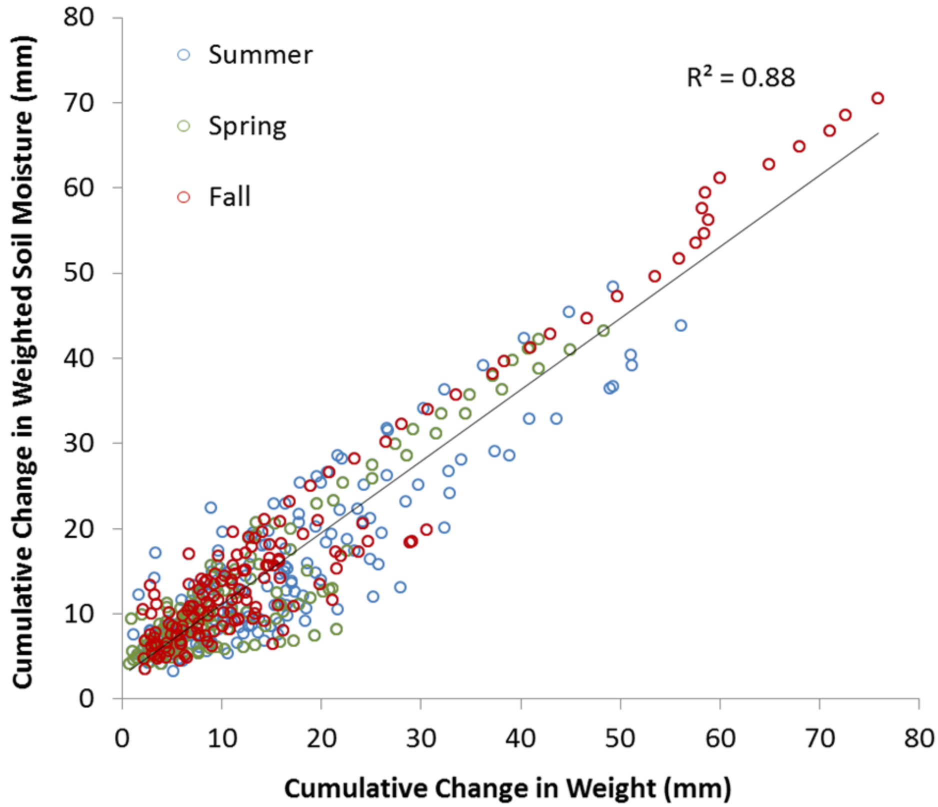

Figure 4.7: Soil moisture vs weight for sandy loam UO

Similarly, the regression model for the sand UO results in the following equation:

Equation 4.2: $$W = 5.4 - 0.5 * SM_{10} + 116 * SM_{35} + 523 * SM_{65}$$

The sand OU regression shows a strong correlation between soil moisture and weight with an R^2 of 0.87 and an S of 5.13 mm (Figure 4.8).

The regression model for the sand IWS results in the following equation:

Equation 4.3: $$W = 7.8 + 137 * SM_{10} + 27 * SM_{35} + 557 * SM_{65}$$

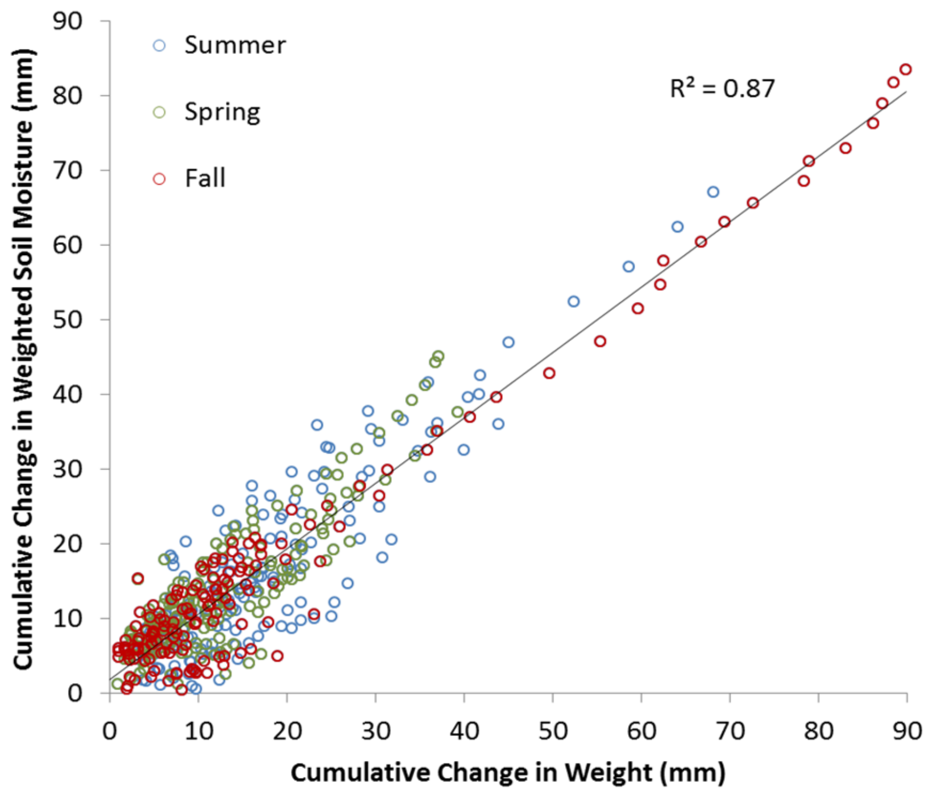

Figure 4.8: Soil moisture vs weight for sand UO

The sand IWS regression shows a correlation between soil moisture and weight with an R^2 of 0.77 and an S of 10.1 mm (Figure 4.9).

Although the coefficients of determination represents a correlation, there is still variability, especially for the sand IWS and values less than 30 mm cumulative change in weight for the sandy loam UO and sand UO. The standard error in each of the systems are larger than their average daily ET values for the same seasons (4.63 mm > 3.02 mm for sandy loam UO, 5.13 mm > 2.96 mm for sand UO, and 10.1 mm > 4.97 mm for sand IWS). This indicates that change in soil moisture as proxy for change in weight may not be useful on a daily scale. However, for storm based cumulative ET, the change in soil moisture is a possible useful proxy. For example,

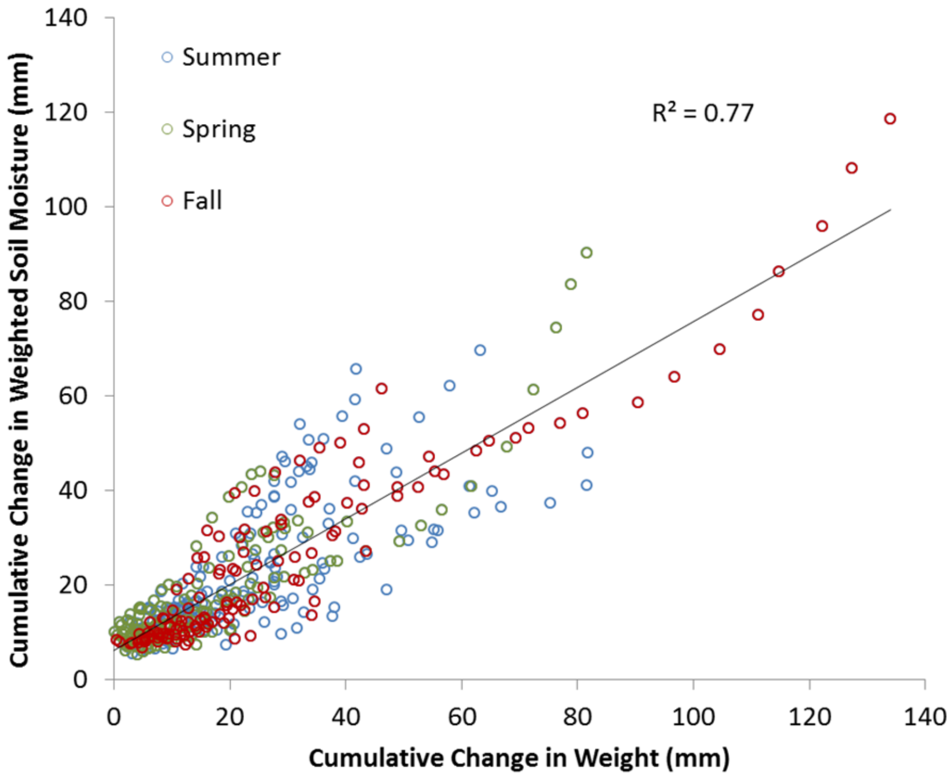

Figure 4.9: Soil moisture vs weight for sand IWS

cumulative ET for 6 days after a storm would be on a closer magnitude of 25 mm in the UO lysimeters and 50 mm in the IWS lysimeter (Section 4.2.1), where a deviation of about 5 mm in the UO systems and 10 mm in the IWS system is less impactful. It should also be noted that the largest cumulative change in the UO systems weights is about 80-90 mm, unlike the IWS where the maximum cumulative change in weight is 140 mm. The larger range of weight readings complements the function of the storage system and the IWS elevated ET rates compared to that of the UO systems.

In the pursuit of understanding this variability in relation to seasonal effects: summer, spring, and fall are represented in blue, green, and red, respectively (Figure 4.7-Figure 4.9). However, it seems that there is no clear distinction among the seasons. Each season has its own variability, with summer possibly showing the largest spread for all lysimeter configurations. Some variability is attributed to the instruments themselves, as both weight measurements and soil moisture measurements have error associated with the readings. Other reasons for variability in the soil moisture readings can be due to temperature that will affect the rate of water flow through the soil. The load cell, as it is exposed to the climate, is also affected by forces such as temperature and winds that will cause variability in weight readings. The weight also measures more than just fluctuations due to water movement, as there will be changes in plant growth over time and other effects due to outside exposure.

The IWS has more fluctuation as the storage system makes the water movement more complex than the UO systems where water flows through the column relatively unimpeded. However, in the case of the UO systems, the soil moisture change seems to have a strong relationship to change in weight therefore utilizing Equation 4.1 and Equation 4.2 for a bioretention design of the same media and depth may be applicable in cumulative ET over dry time.

4.3.2 WEIGHT VS VARIOUS SOIL MOISTURE DEPTHS

To further decrease the cost of measurements and increase understanding of monitoring methods, the use of one or two soil moisture meter depth combinations are explored to determine if any correlation exists (Table 4.6).

For each lysimeter, seven different cases are explored. The first case is the regression of all soil moisture depths as continuous predictors, the same as the regression models presented in

Table 4.6 Summary of weight vs soil moisture regression models

		Predictors	Equation	S [mm]	R^2
Sandy Loam UO Weight	1	$SM_{10}, SM_{35}, SM_{65}$	$W = 3.9 + 159 * SM_{10} + 40 * SM_{35} + 211 * SM_{65}$	4.63	0.88
	2	SM_{10}, SM_{35}	$W = 1.7 + 176 * SM_{10} + 311 * SM_{35}$	6.50	0.76
	3	SM_{10}, SM_{65}	$W = 2.5 + 209 * SM_{10} + 224 * SM_{65}$	4.63	0.88
	4	SM_{35}, SM_{65}	$W = 5.8 + 176 * SM_{35} + 210 * SM_{65}$	5.68	0.82
	5	SM_{10}	$W = 0.5 + 430 * SM_{10}$	8.09	0.63
	6	SM_{35}	$W = 4.5 + 447 * SM_{35}$	7.02	0.72
	7	SM_{65}	$W = 7.5 + 310 * SM_{65}$	6.12	0.79
Sand UO Weight	1	$SM_{10}, SM_{35}, SM_{65}$	$W = 5.4 - 0.5 * SM_{10} + 116 * SM_{35} + 523 * SM_{65}$	5.13	0.87
	2	SM_{10}, SM_{35}	$W = 5.1 + 7.3 * SM_{10} + 548 * SM_{35}$	9.13	0.60
	3	SM_{10}, SM_{65}	$W = 5.9 + 33 * SM_{10} + 581 * SM_{65}$	5.29	0.86
	4	SM_{35}, SM_{65}	$W = 5.4 + 115 * SM_{35} + 523 * SM_{65}$	5.13	0.87
	5	SM_{10}	$W = 8.8 + 285 * SM_{10}$	12.1	0.28
	6	SM_{35}	$W = 5.1 + 554 * SM_{35}$	9.13	0.60
	7	SM_{65}	$W = 6.3 + 602 * SM_{65}$	5.34	0.86
Sand IWS Weight	1	$SM_{10}, SM_{35}, SM_{65}$	$W = 7.8 + 137 * SM_{10} + 27 * SM_{35} + 557 * SM_{65}$	10.1	0.77
	2	SM_{10}, SM_{35}	$W = 12.6 + 145 * SM_{10} + 148 * SM_{35}$	17.6	0.30
	3	SM_{10}, SM_{65}	$W = 6.9 + 163 * SM_{10} + 618 * SM_{65}$	10.3	0.76
	4	SM_{35}, SM_{65}	$W = 11.8 + 127 * SM_{35} + 594 * SM_{65}$	12.7	0.63
	5	SM_{10}	$W = 14 + 185 * SM_{10}$	18.4	0.23
	6	SM_{35}	$W = 17.5 + 223 * SM_{35}$	19.1	0.17
	7	SM_{65}	$W = 13.9 + 646 * SM_{65}$	13.6	0.58

Section 4.3.1. Case 2 is change in weight regressed to change in soil moisture readings from 10 and 35 cm depths. Similarly, case 3 is change in weight regressed to change in soil moisture readings from 10 and 65 cm depths. Case 4 offers the change in weight regressed to change in soil moisture readings from 35 and 65 cm depths. Case 5 is change in weight regressed to change in soil moisture readings from just the 10 cm depth. Similarly, cases 6 and 7 are change in weight regressed with soil moisture readings at 35 cm and 65 cm, respectively.

Case 1 for all lysimeters provide the highest R^2 and lowest S values, indicating the strongest relationship exists between soil moisture and weight when all soil moisture depths are considered (i.e. all continuous predictors of SM_{10}, SM_{35}, and SM_{65} are used). For sandy loam UO, the R^2 and S parameters are able to remain the same as case 1 in case 3 (R^2 of 0.88 and S of 4.63 mm) indicating that soil moisture readings at 10 and 65 cm depths in the sandy loam are most important to make correlations to the weight readings. Sand UO has the same R^2 and S parameters in case 1 as in case 4 (R^2 of 0.87 and S of 5.13 mm) thus the soil moisture readings at 35 and 65 cm depths are the most important in correlating weight readings. However, it should be noted that case 3 produces very similar R^2 and S parameters to case 1 (R^2 of 0.86 and S of 5.29 mm vs R^2 of 0.87 and S of 5.13 mm) such that soil moisture readings at 10 and 65 cm depths is also well correlated to the sand OU weight readings. Cases 3 and 1 for sand IWS have very similar R^2 and S parameters (R^2 of 0.76 and S of 10.3 mm vs R^2 of 0.77 and S of 10.1 mm) such that soil moisture readings at 10 and 65 cm are most vital. These conclusions are supported by the case 1 equations themselves, were the larger coefficients are associated with the more impactful soil moistures, 10 and 65 cm. For example, sandy loam UO case 1 weights soil moisture at 10, 35, and 65 cm depths with coefficients of 159, 40, and 211, respectively. These coefficients give indication of which soil moisture values are most critical to correlate to weight.

Cases 5, 6, and 7 are regressions of a single soil moisture depth to weight readings. In all lysimeter configurations, the soil moisture at 65 cm depth is most correlated to weight. Sandy loam UO weight regression to soil moisture at 65 cm depth (case 7) yields an R^2 value of 0.79 and an S value of 6.12 mm. Similarly, case 7 for sand UO and sand IWS yield R^2 values of 0.86 and 0.58 and S values of 5.34 mm and 13.6 mm, respectively.

All the sandy loam UO lysimeter regressions provide a decent fit, ($R^2 > 0.60$). However, tracking moisture at the top and bottom of the soil column may be most critical to provide a closer relationship to change in weight for the sandy loam UO as demonstrated by case 3 results. For the sand UO, the most critical relationship to weight is the change in soil moisture at the bottom of the soil column as demonstrated in case 7. A second sensor at the top of the column or in the middle may help but do not play heavily into increasing the R^2 and lowering S values as seen in cases 3 and 4 for sand UO. To maintain the IWS weight relationship, change in soil moisture at the top and bottom of the soil column are most critical to be tracked (case 3). However, since the IWS weight and soil moisture relationship is not as strong as the UO systems, correlations may benefit from more soil moisture depths or piece-wise relationship.

If only one soil moisture meter is to be used, the most meaningful relationship is formed from the change in moisture at the bottom of the soil column with regards to change in weight for all lysimeters. A possible reason for the bottom boundary soil moisture relationship being the strongest of all soil moisture depths is that it is usually the wettest of the soil moisture readings and provides the roots with the place of least resistance to draw on during dry time. Soil moisture at the top of the soil alone provides the poorest correlation to weight as evaporation is expected to influence the moisture content in the top 10 cm and possibly drying out quicker than deeper depths and become less representative of the whole soil column. This evaporation may be beneficial to consider when using more than one soil moisture meter, but the lower boundary soil moisture change provided the most correlated relationship to a weight relationship for the growing seasons. The change in weight for this analysis is equal to ET since the data excludes days when there is outflow and inflow. Since the lower boundary soil moisture change is related to ET and provides evidence of rooting depth reaching the bottom of the soil column for each lysimeter.

4.4 PREDICTIVE EVAPOTRANSPIRATION EQUATIONS

The observed meteorological data were used to calculate the ASCE Penman-Monteith equation (Equation 2.2) and the Hargreaves equation (Equation 2.1) without any modifications for soil moisture or crop health. Since the observed ET data have some days excluded from its dataset due to instrumentation malfunctions or heavy rainfall days where error might be large, the concurrent predictive ET data have the same days excluded for a fair comparison. The Hargreaves equation mostly overpredicts the measured ET from the UO systems and more closely predicts the IWS system measured ET. The ASCE Penman-Monteith equation mostly underpredicts the IWS system measured ET and most closely predicts the UO systems (Figure 4.10). The IWS system stored more water due to the large amount of rain in spring 2014. This availability of water led to more observed ET and underprediction of ET from both equations

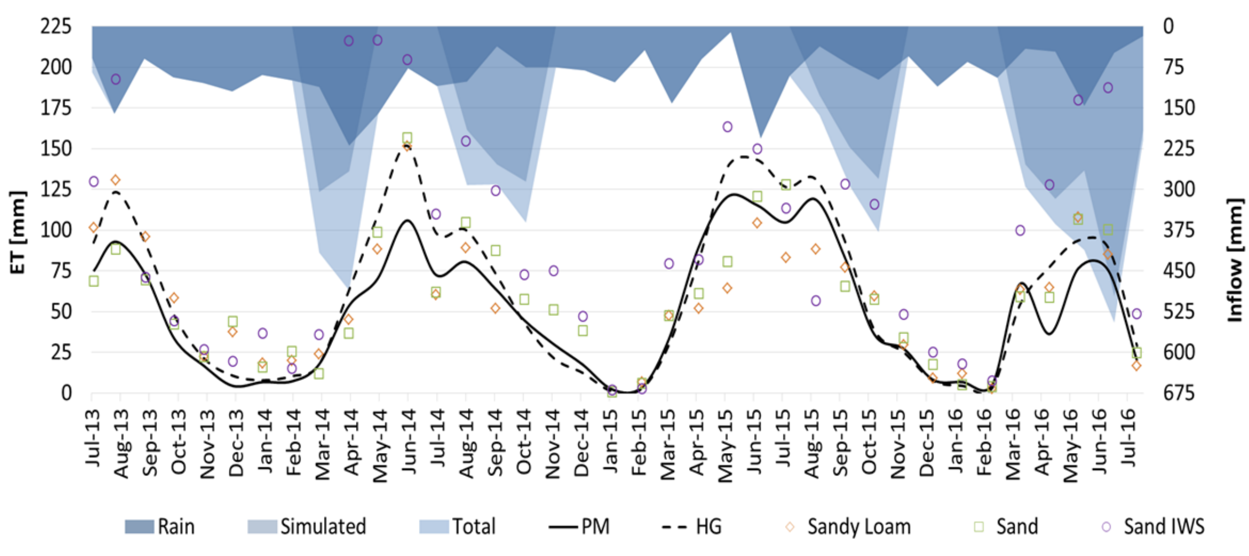

Figure 4.10: Monthly summations of daily Rain and ET for the 3 year period

for the IWS system. The opposite effect is seen in spring 2015, when there was much less inflow. The lack of inflow caused all the lysimeter configurations to be water stressed such that the ET equations overpredicted the observed amount of water removed. Neither equation accounts for rainfall, which causes the large discrepancy between the predictive equations and observed ET.

Although the predictive equations do not predict the lysimeter ET exactly, both equations verify that the observations in the lysimeter systems yield reasonable values for ET. The Hargreaves equation provides an upper limit of practical ET volumes, where the ASCE Penman-Monteith equation provides a lower limit for the measured lysimeter ET volumes. Modified versions of both equations will be explored for closer estimations of ET.

4.4.1 HARGREAVES EQUATION

The resulting performance criterion on a daily scale for the unmodified Hargreaves equation (Equation 2.1) confirms that Hargreaves equation mostly overpredicts ET in the UO system (CRM of -0.31 and -0.23 and D of -538 mm and -421 mm, respectively; Table 4.7). In the IWS, Hargreaves equation is mostly underestimating observed ET values (CRM of 0.26 and D of 784 mm). All efficiencies are greater than or equal to 0, such that the unmodified Hargreaves equation would be generally an acceptable model for the observed data as it provides a better proxy to observed ET than the average of the observed data. With modification to the Hargreaves equation (Equation 2.3), improvements in model prediction are found as there is slight decrease in RMSE, increase in R^2 and E, and an overall difference (D) and CRM of 0. The D and CRM is reduced to 0 as a part of calibration method (Section 3.7.3).

Table 4.7: Performance of Hargreaves equation on daily basis

Observed	Hargreaves equation	RMSE (mm/d)	R^2	E	D (mm)	CRM	K_{int}	K_{mid}	K_{end}	SMEF
Sandy Loam UO	Unmodified	2.07	0.17	0.00	-538	-0.31	-	-	-	-
	Modified	1.91	0.22	0.15	0	0.00	0.30	0.99	0.35	Equation 3.6
Sand UO	Unmodified	2.19	0.17	0.05	-421	-0.23	-	-	-	-
	Modified	1.99	0.25	0.21	0	0.00	0.40	1.08	0.39	Equation 3.2
Sand IWS	Unmodified	3.38	0.24	0.04	784	0.26	-	-	-	-
	Modified	2.57	0.46	0.69	0	0.00	1.96	2.01	1.96	Equation 3.2

It should be noted that the R^2 values in all cases are low, less than 0.5, indicating that there is not a strong correlation between daily Hargreaves equation rates and daily observed rates. The unmodified to the modified Hargreaves equation in the sand IWS system shows the largest increase in R^2 value from 0.24 to 0.46, the UO systems modified Hargreaves equation remain below a R^2 of 0.25.

Equation 3.6 for sandy loam UO and Equation 3.2 for sand UO and sand IWS are found to be the most representative SMEFs on a daily calibration. The crop coefficients, used as variables for calibration were found to be in an acceptable range for the UO systems, where initial crop coefficients are 0.30 and 0.40, middle crop coefficients are 0.99 and 1.08, and end crop coefficients are 0.35 and 0.39 for sandy loam and sand, respectively. As for the IWS system, the crop coefficients are above the expected range, with 1.96 as the initial and end crop coefficient and 2.01 as the middle crop coefficient. The observed sand IWS is greatly underestimated by the unmodified Hargreaves equation such that high crop coefficients are expected to reduce the difference between the observed and estimated values. Cumulative ET for the modified Hargreaves equation on a daily basis is compared to the observed cumulative ET in Figure 4.11.

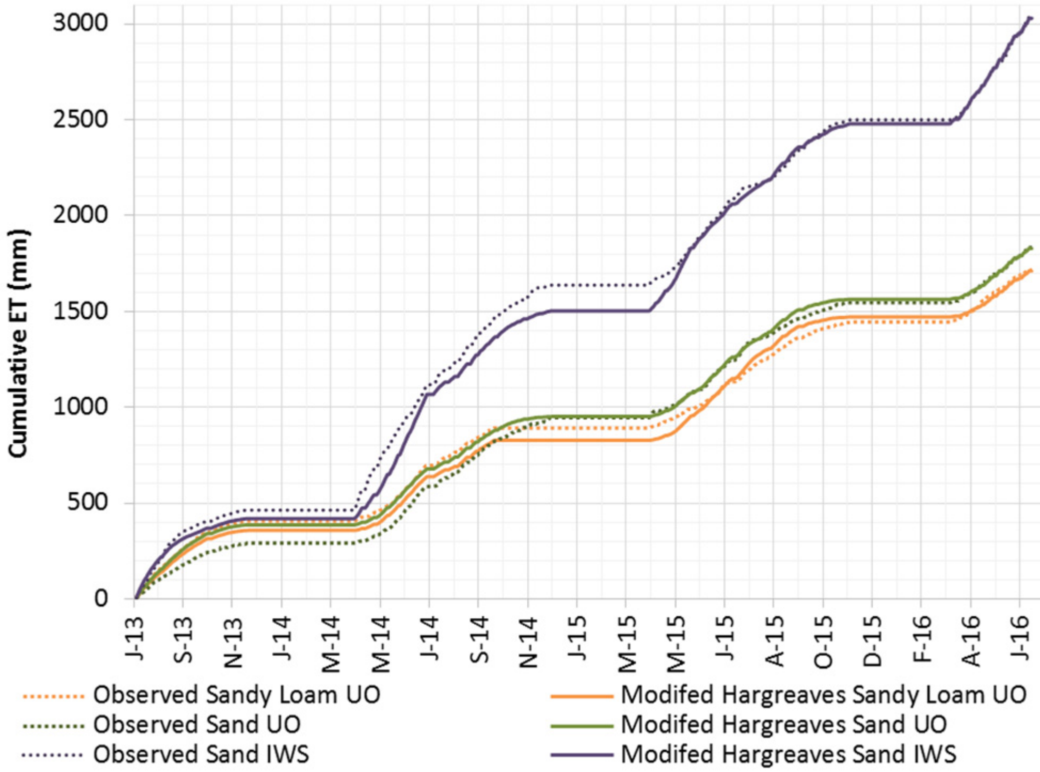

Figure 4.11: Cumulative ET of observed and modified Hargreaves equation

The resulting performance criterion on a storm basis for the unmodified Hargreaves equation shows strong correlations (R^2 of 0.89, 0.79, 0.91 for sandy loam UO, sand UO, and sand IWS), all of which are improved or stay the same by the use of modifications compared to the daily based calibration (Table 4.8). The root mean square error is increased from the daily scale, as the range of ET has increased. The daily ET rate has a range from 0 to about 12 mm for the UO systems (3 mm on average) and a maximum of 17 mm in the IWS system (4 mm on average). Storm scale has a range from 0 to 70 mm for the UO systems (16 mm on average) and a maximum of 130 mm in the IWS system (30 mm on average). With modification, the RMSE is able to decrease ET significantly from 5.79 mm/d to 3.35 mm/d for sandy loam UO, 10.6 mm/d to 6.61 mm/d in sand UO, and 12.4 mm/d to 4.62 mm/d in the sand IWS. However, for the IWS system, a reduced RMSE was only obtainable by not considering a SMEF equation in the modification to Hargreaves equation. The higher efficiencies and higher R^2 values of the unmodified Hargreaves equation indicates that the potential equation is a good estimate for cumulative storm ET. If it is desirable to reduce the RMSE, this can be obtained through calculation of crop ET with SMEFs (except for the IWS where SMEF is not used).

Table 4.8: Performance of Hargreaves equation on storm basis

Observed	Hargreaves equation	RMSE (mm/d)	R^2	E	D (mm)	CRM	K_{int}	K_{mid}	K_{end}	SMEF
Sandy Loam UO	Unmodified	5.79	0.89	0.82	-951	-0.13	-	-	-	-
	Modified	3.25	0.95	0.94	0	0.00	0.45	1.02	0.35	Equation 3.6
Sand UO	Unmodified	10.6	0.79	0.39	-1872	-0.24	-	-	-	-
	Modified	6.61	0.85	0.76	1	0.00	0.52	1.32	0.79	Equation 3.5
Sand IWS	Unmodified	12.4	0.91	0.78	4040	0.27	-	-	-	-
	Modified*	4.62	0.91	0.87	0	0.00	1.40	1.43	0.95	-

*Sand IWS modification calculates crop ET with no soil moisture correction

Equation 3.6 is the most representative for the UO systems in the storm based calibration. In the UO systems, all crop coefficients are increased from that of the daily calibration. All are in an expected range, with the exception of the middle crop coefficient for sand UO. Initial crop coefficients are 0.45 and 0.52, middle crop coefficients are 1.02 and 1.32, and end crop coefficients are 0.35 and 0.79 for sandy loam and sand, respectively. The IWS system crop coefficients are smaller than that found in the daily calibration, but still higher than typical crop coefficients, due to the lack of a SMEF reduction factor. Initial, middle and end crop coefficient for the IWS are 1.40, 1.43, and 0.95, respectively. The higher efficiencies and higher R^2 values of the unmodified Hargreaves equation indicates that the potential equation is a good estimate for cumulative storm ET. If it is desirable to reduce the RMSE, this can be obtained through calculation of crop ET with SMEFs (expect for the IWS where SMEF is not used). The regression

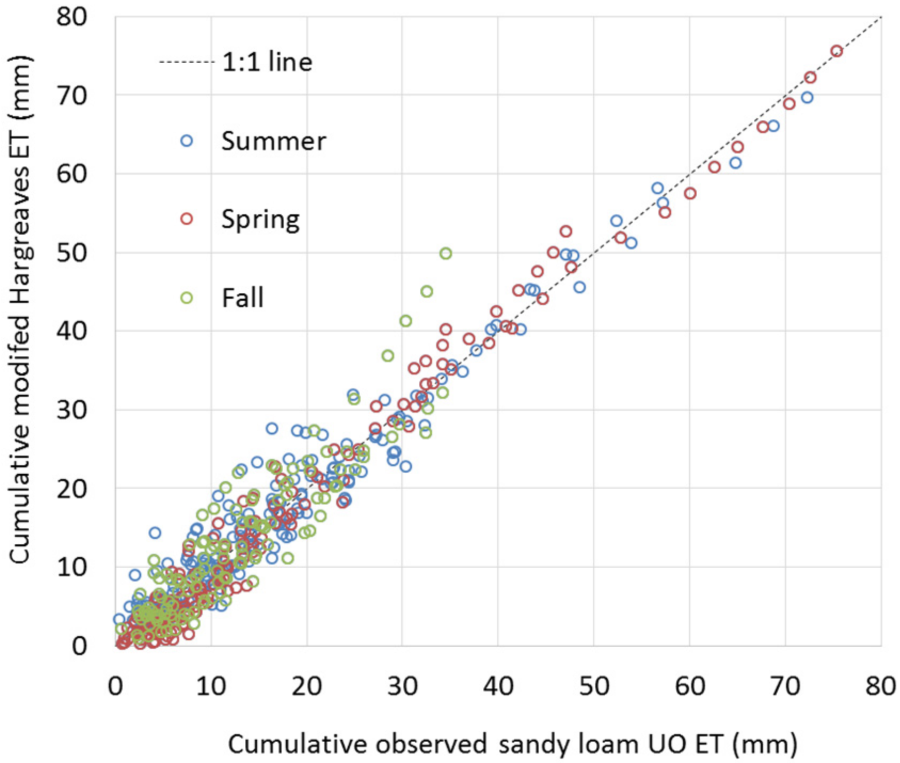

Figure 4.12: Regression of modified Hargreaves equation and observed sandy loam UO on storm basis

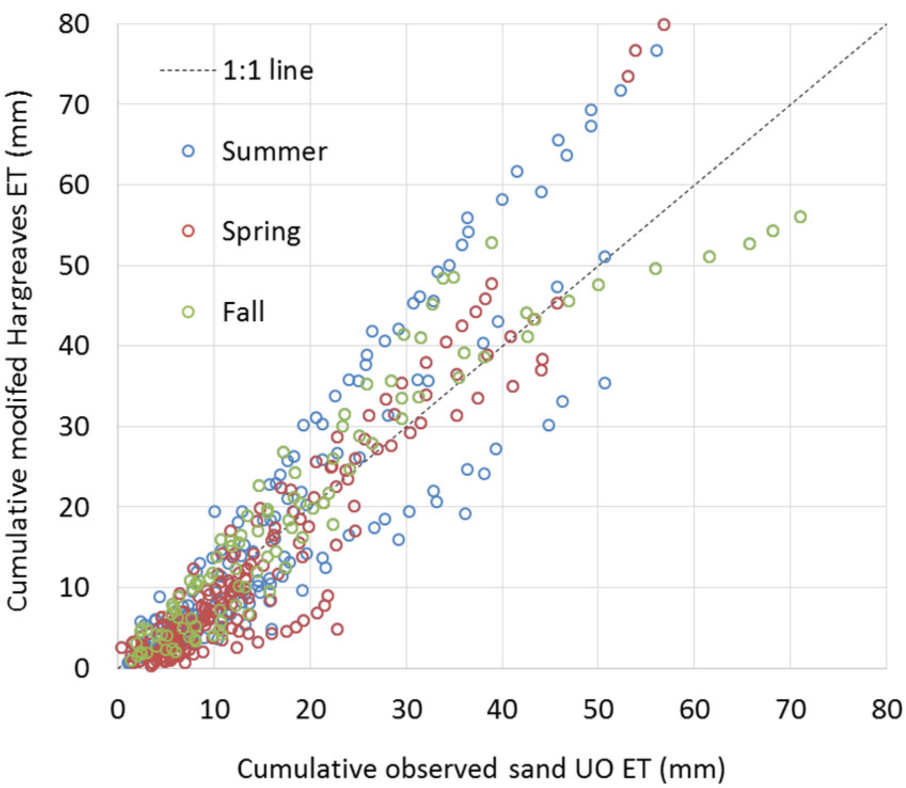

Figure 4.13: Regression of modified Hargreaves equation and observed sand UO on storm basis

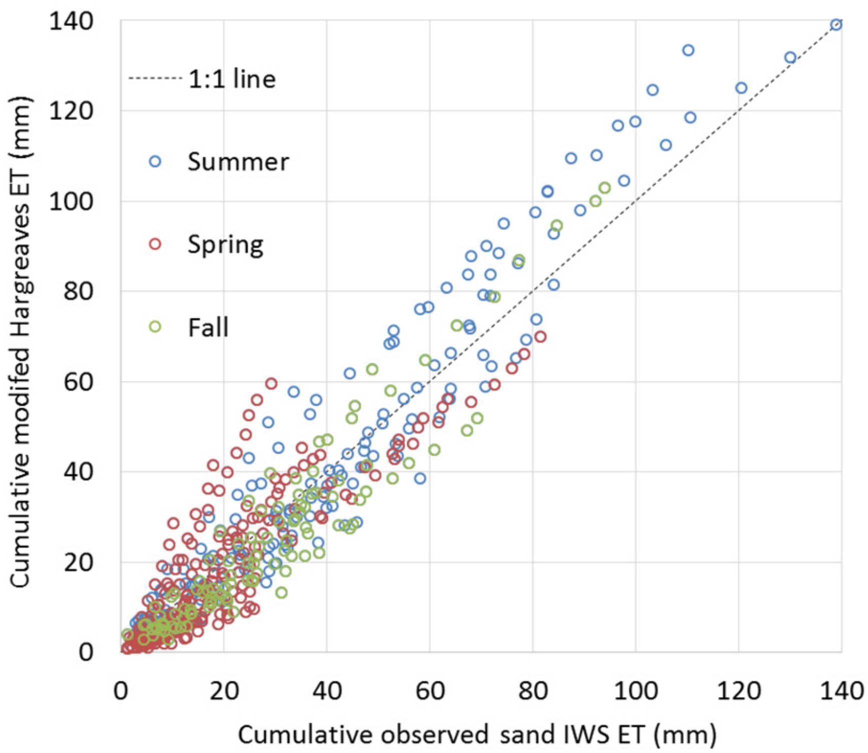

Figure 4.14: Regression of modified Hargreaves equation and observed sand IWS on storm basis

of modified Hargreaves equation on a storm based calibration with observed ET can be seen in Figure 4.12 for sandy loam UO, Figure 4.13 for sand UO, and Figure 4.14 for sand IWS. Seasonality is captured in the different colors: blue of summer, red for spring, and green for fall. For all seasons in all lysimeter configurations there is a similar spread, where this is no obvious variability in one season over the other two seasons.

4.4.2 ASCE PENMAN-MONTEITH EQUATION

Similar to the Hargreaves equation calibration, the performance criteria for both the ASCE Penman-Monteith equation in unmodified (Equation 2.2) and modified (Equation 2.4) form is presented for comparison (Table 4.9).

Table 4.9: Performance of Penman-Monteith equation on daily basis

Observed	Penman-Monteith equation	RMSE (mm/d)	R^2	E	D (mm)	CRM	K_{int}	K_{mid}	K_{end}	SMEF
Sandy Loam UO	Unmodified	1.98	0.16	0.09	-35	-0.02	-	-	-	-
	Modified	1.92	0.22	0.14	0	0.00	0.56	1.18	0.83	Equation 3.6
Sand UO	Unmodified	2.03	0.21	0.10	83	0.05	-	-	-	-
	Modified	1.88	0.31	0.29	0	0.00	0.45	1.30	0.92	Equation 3.2
Sand IWS	Unmodified	3.68	0.25	-0.14	1289	0.43	-	-	-	-
	Modified	2.77	0.47	0.69	0	0.00	1.73	1.84	1.62	Equation 3.2

The unmodified Penman-Monteith equation overestimates sandy loam UO very slightly (CRM of -0.02 and D of -35 mm), underestimates the sand UO system slightly (CRM of 0.05 and D of 85 mm), and underestimates the sand IWS (CRM of 0.43 and D of 1289 mm). Efficiencies for the UO systems are greater than or equal to 0, such that the unmodified Penman-Monteith equation would generally be an acceptable model for the observed data as it served as a better proxy to the observed data than the average of the observed data. However, for the IWS system the efficiency, E, is slightly negative indicating that it would not be an efficient model for this system without modification. With modification to the Penman-Monteith equation, improvements in model prediction are found as there is a slight decrease in RMSE, increase in R^2 and E, and an overall difference and CRM of 0. Both Hargreaves and Penman-Monteith equations perform similarly in both modified and unmodified forms for sandy loam UO. Both unmodified and modified versions of Penman-Monteith equation more closely estimate sand UO over modified and unmodified Hargreaves equations. For the IWS, the unmodified Hargreaves equation based on efficiency criteria, better estimates the unmodified Penman-Monteith equation, but the equations perform similarly in their modified forms.

For the UO systems, the R^2 values are very low, less than 0.5, for both unmodified and modified ASCE Penman-Monteith equation, indicating that there is not a strong correlation between daily the Penman-Monteith equation rates and daily observed rates. The unmodified Penman-Monteith equation predictions as compared to modified Penman-Monteith equation in the sand IWS system shows the largest increase in R^2 value from 0.25 to 0.47. The R^2 values for modified Penman-Monteith equation in the UO systems remain below 0.31. The same SMEF equations in the Hargreaves equation daily calibration are found to be most representative SMEFs for the Penman-Monteith equation on a daily calibration. The crop coefficients, used as variables for calibration are higher than Hargreaves equation daily calibrations. For the UO systems, the initial crop coefficients are 0.56 and 0.45, middle crop coefficients are 1.18 and 1.30, and end crop coefficients are 0.83 and 0.92 for sandy loam and sand, respectively. The middle crop coefficient of sand UO is slightly higher than the expected range. As for the IWS system, the crop coefficients are above the expected range, with 1.73 as the initial crop coefficient and 1.84 as the middle crop coefficient, and 1.62 as the end crop coefficient. Higher crop coefficients were expected for this lysimeter as it was the most underestimated by the model compared to the other two systems. These IWS crop coefficient values are slightly lower than we see in the Hargreaves equation daily calibration. The cumulative ET for daily based calibration calculated by modified Penman-Monteith equation is seen compared to the observed cumulative ET in Figure 4.15.

The resulting performance criterion on a storm basis for the unmodified Penman-Monteith equation shows stronger correlations (R^2 of 0.83, 0.78, 0.92 for sandy loam UO, sand UO, and

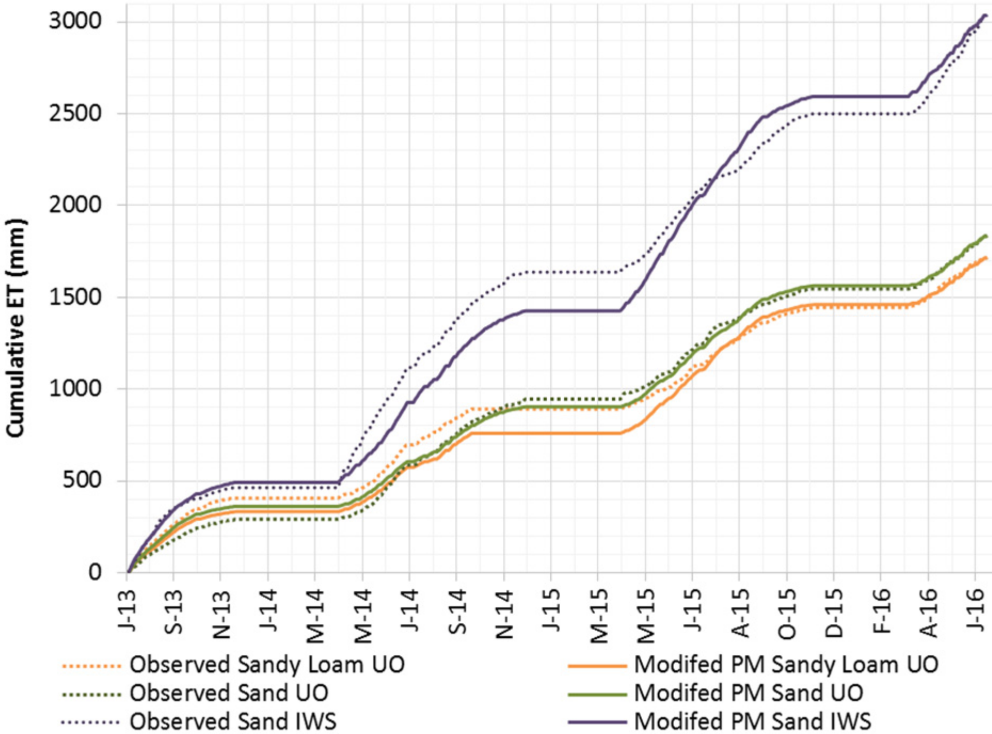

Figure 4.15: Cumulative ET of observed and modified Penman-Monteith equation

sand IWS), all of which are improved or stay the same by the use of modifications compared to the daily based calibration (Table 4.10). The RMSE is increased from the daily scale, which is similar to the results obtained when using the Hargreaves equation storm based calibration. With modification, the RMSE is able to decrease significantly from 5.71 mm/d to 3.37 mm/d for sandy loam UO, 8.32 mm/d to 5.41 mm/d in sand UO, and 16.7 mm/d to 4.43 mm/d in the sand IWS. However, for the IWS system, a reduced RMSE was only obtainable by not considering a SMEF equation in the modification to Penman-Monteith equation. The higher efficiencies and higher R^2 values of the unmodified Penman-Monteith equation indicates that the potential equation is a good estimate for cumulative storm ET. If it is desirable to reduce the RMSE, this can be obtained through the calculation of crop ET with SMEFs (except for the IWS where SMEF is not used).

Table 4.10: Performance of Penman-Monteith equation on storm basis

Observed	Penman-Monteith Equation	RMSE (mm/d)	R^2	E	D (mm)	CRM	K_{int}	K_{mid}	K_{end}	SMEF
Sandy Loam UO	Unmodified	5.71	0.83	0.83	58	0.01	-	-	-	-
	Modified	3.37	0.94	0.94	0	0.0	0.55	1.21	0.95	Equation 3.6
Sand UO	Unmodified	8.32	0.78	0.63	-336	0.0	-	-	-	-
	Modified	5.41	0.89	0.84	0	0.0	0.84	1.51	1.20	Equation 3.6
Sand IWS	Unmodified	16.7	0.92	0.61	6075	0.4	-	-	-	-
	Modified*	4.43	0.92	0.89	0	0.0	1.66	1.71	1.60	-

Similar to the Hargreaves equation, Equation 3.6 is the most representative for the UO systems in the storm based calibration. In the UO systems, most crop coefficients are increased from that of the daily calibration, with the exception of the initial crop coefficient for sandy loam UO. The sand UO middle and end crop coefficients are higher than the expected range. The initial crop coefficients are 0.55 and 0.84, middle crop coefficients are 1.21 and 1.51, and end crop coefficients are 0.95 and 1.20 for sandy loam and sand, respectively. The IWS system crop coefficients are smaller than that found in the daily calibration, but still higher than typical crop coefficients (Allen et al 1998; Section 3.7.2), due to the lack of a SMEF reduction factor. Initial, middle and end crop coefficient for the IWS are 1.66, 1.71, and 1.60, respectively.

The higher efficiencies and higher R^2 values of the unmodified Penman-Monteith equation indicates that the potential equation is a good estimate for cumulative storm ET. If it is desirable to reduce the RMSE, this can be obtained through calculation of crop ET with SMEFs (except for the IWS where SMEF is not used). The regression of the predicted values from the modified Penman-Monteith equation on a storm based calibration with observed ET are seen for sandy loam UO, for sand UO, and for sand IWS (Figure 4.16-Figure 4.18).

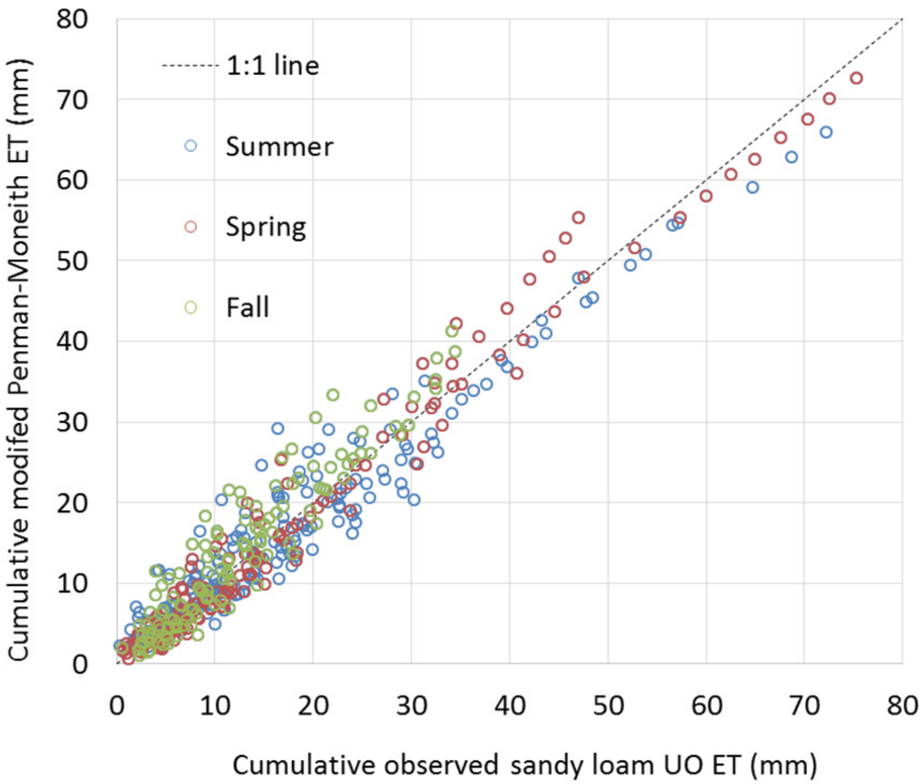

Figure 4.16: Regression of modified Penman-Monteith equation and observed sandy loam UO on storm basis

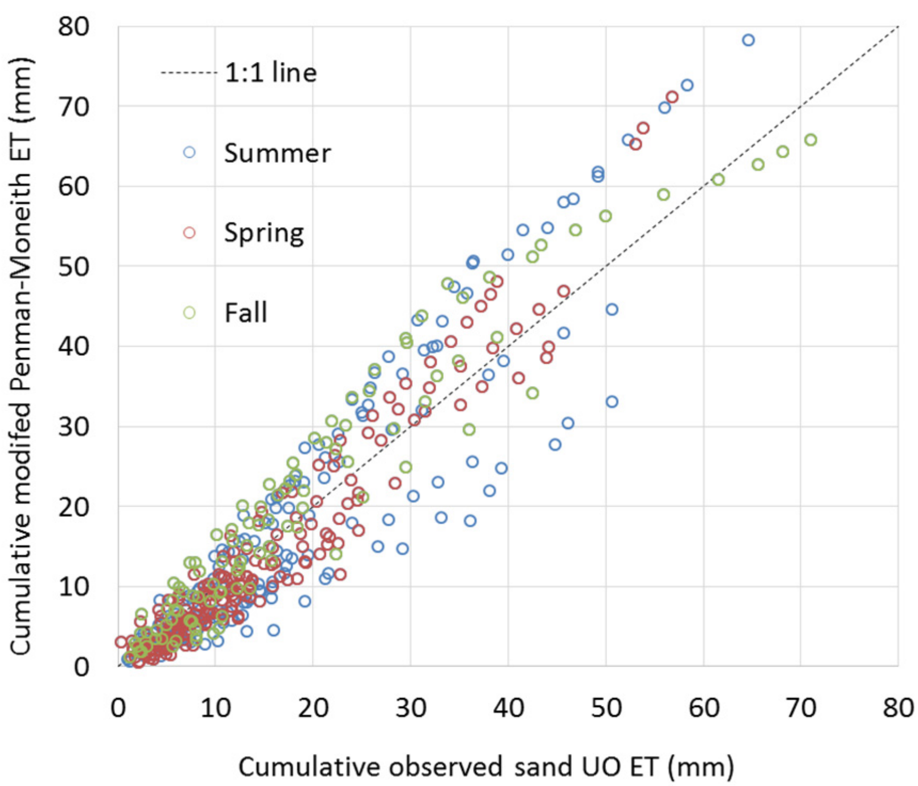

Figure 4.17: Regression of modified Penman-Monteith equation and observed sand UO on storm basis

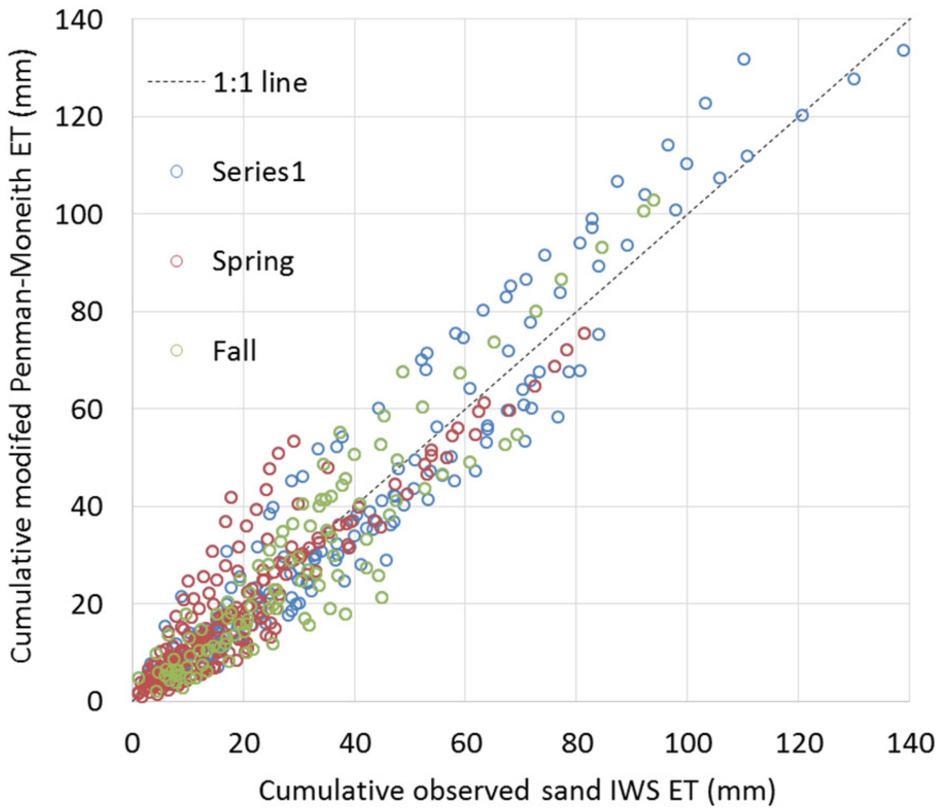

Figure 4.18: Regression of modified Penman-Monteith equation and observed sand IWS on storm basis

Overall, modifications to predictive equations will give a closer estimate to observed ET rates. Storm based calibration for a stormwater application results in good correlations with modified and unmodified versions of both the Hargreaves and the Penman-Monteith equations. Modifications to either equation are recommended as it will estimate observed ET better than that of the unmodified form. In the modified cases, both equations provide adequate estimates for all lysimeter configurations. If it is necessary to use an unmodified equation, either the unmodified Hargreaves or ASCE Penman-Monteith equation can provide an adequate estimate for sandy loam UO. For sand UO, the unmodified ASCE Penman-Monteith equation provides a better estimate compared to unmodified Hargreaves equation. The unmodified Hargreaves equation provides a better estimate for sand IWS compared to the unmodified Penman-Monteith equation (which is not recommended without crop based modifications). The modified version of Penman-Monteith equation on a storm basis is used for the continuous simulation to estimate crop ET.

4.5 RICHARDS EQUATION SOLVER

4.5.1 RAIN GARDEN WEIGHING LYSIMETERS

Richards equation solver, SWAP, simulated rain garden weighing lysimeters for July 13 2013-2016, producing ET and outflow output. The model simulation results are compared against the observed data for events greater than 25 mm for the large weighing lysimeters. The average outflow and ET after storm events greater than 25 mm and both observed and simulated data has a sample size of over 45 storms for the sand systems and 40 storms for the sandy loam. The results from the sandy loam UO lysimeter show a good agreement between the observed and simulated values for ET and outflow (Figure 4.19). The observed data from the sandy loam UO weighing lysimeter is similar to the simulated values, especially for ET. The observed ET data for sandy loam UO line up closer to the upper 95% confidence interval produced by the SWAP simulation. The observed outflow data falls close to the average simulated outflow during the first 4 days and days 11 and 12. The observed outflow for days between 4 and 10 are lower than that of the simulated values. The crop set used for sandy loam UO is the low set with a K_{dev} of 0.6, K_{mid} of 1.2, and K_{end} of 0.9. Figure 4.20 shows sand UO observed ET, observed outflow, simulated ET, and simulated outflow on days after events greater than 25 mm. The observed ET data for sand UO line up closer to the upper 95% confidence interval that SWAP simulates for ET and has very close values over all 12 days. Observed and simulated outflow data starts out at

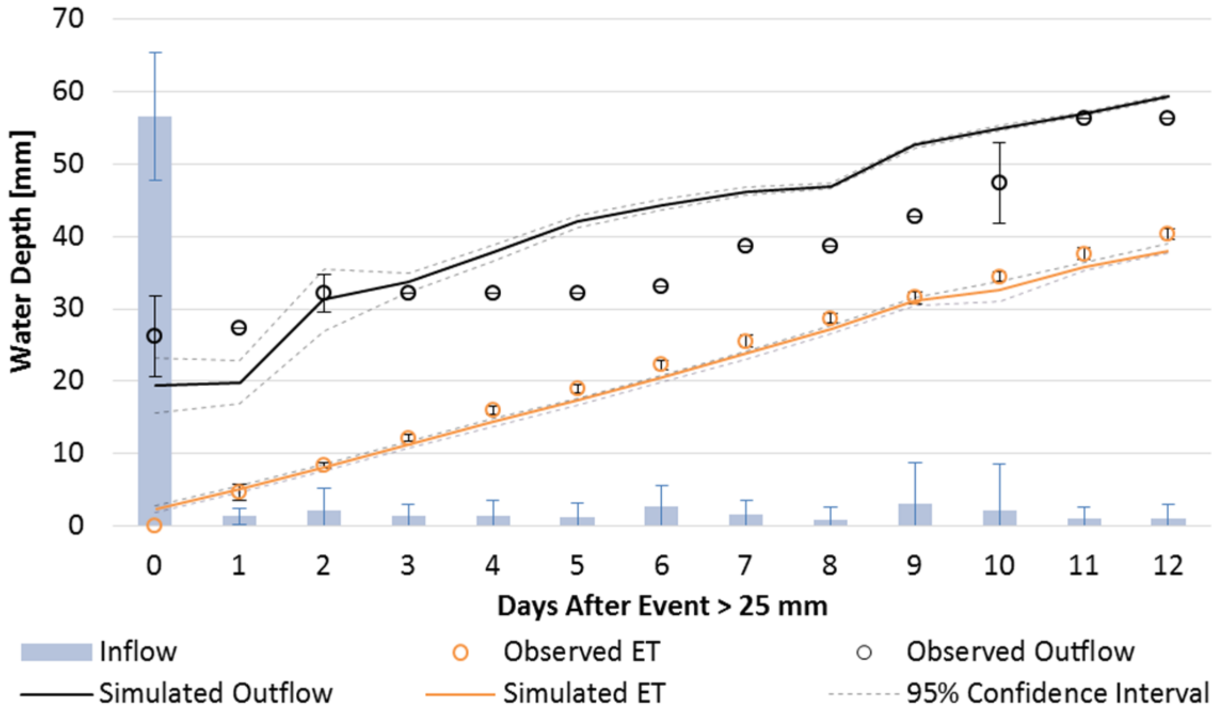

Figure 4.19: Sandy loam UO observed and simulated ET and outflow

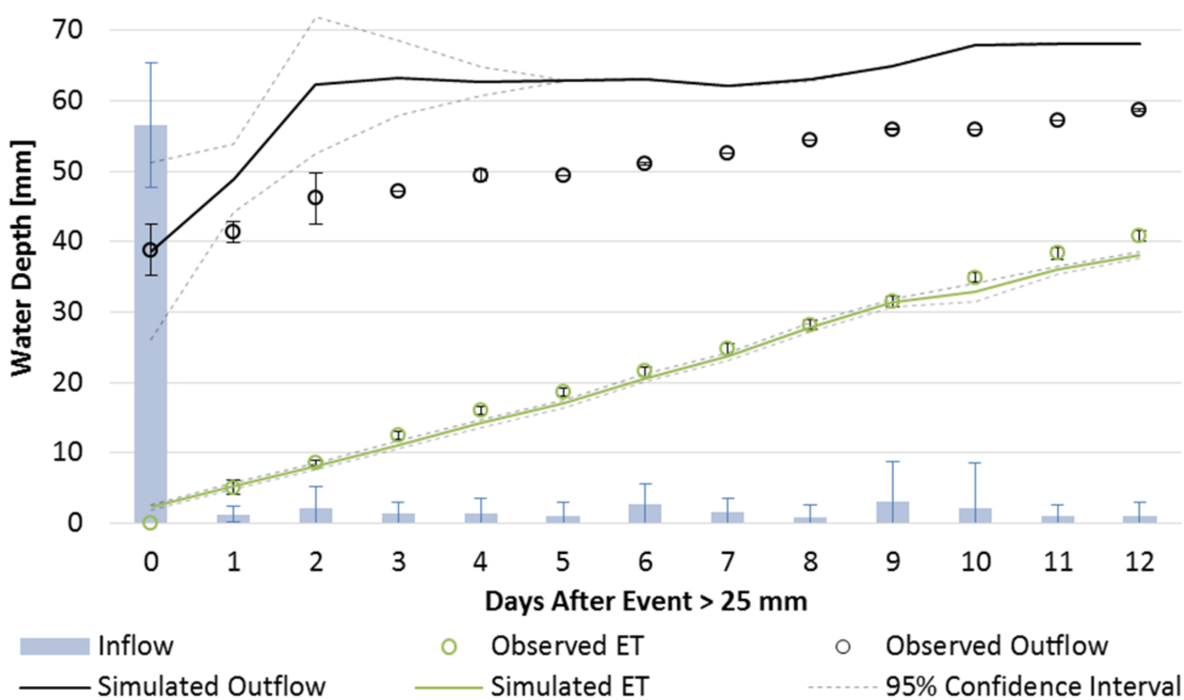

Figure 4.20: Sand UO observed and simulated ET and outflow

similar values at day 1, but then the simulated values remain about 15 mm higher than the observed values until the day 7 when it decreases to about a 10 mm difference. Although the outflow observed from the sand UO system is lower than that simulated, observed ET matches up very well with the simulated ET values. The crop set used for sand UO is the low set with a K_{dev} of 0.8, K_{mid} of 1.5, and K_{end} of 1.2.

The 95% confidence intervals are wider for the sand UO compared to the sandy loam UO for the first 4 days. The reason for a large variability of the sand UO outflow confidence intervals is that the saturated hydraulic conductivity of the soil is highest for sand (90 cm/d) and the amount of outflow is highly dependent on the amount of inflow. Since each storm has a different inflow amount, that variation in inflow amount is more apparent in the variation of outflow for soils with a high hydraulic conductivity (e.g. sand) than that of a soil with a lower saturated hydraulic conductivity (e.g. sandy loam).

The sand IWS simulated cumulative ET is less than the observed ET after the fourth day and underestimates by 5 mm and 10 mm on the sixth day and twelfth day, respectively (Figure 4.21). When the sand IWS was ponded, the actual ET was taken as potential ET. The simulated cumulative ET can be seen as conservative for this design. However, the outflow shows strong similarity between observed and simulated data with a dimensionless drainage resistance of 120. Drainage resistance was used as a calibration factor such that this drainage resistance may be only applicable to sand media and the IWS drainage system such that it is prudent to not extrapolate the IWS drainage regime over the other five soil types. The crop set used for sand UO is the maximum set with a K_{dev} of 1.8, K_{mid} of 2.0, and K_{end} of 1.8.

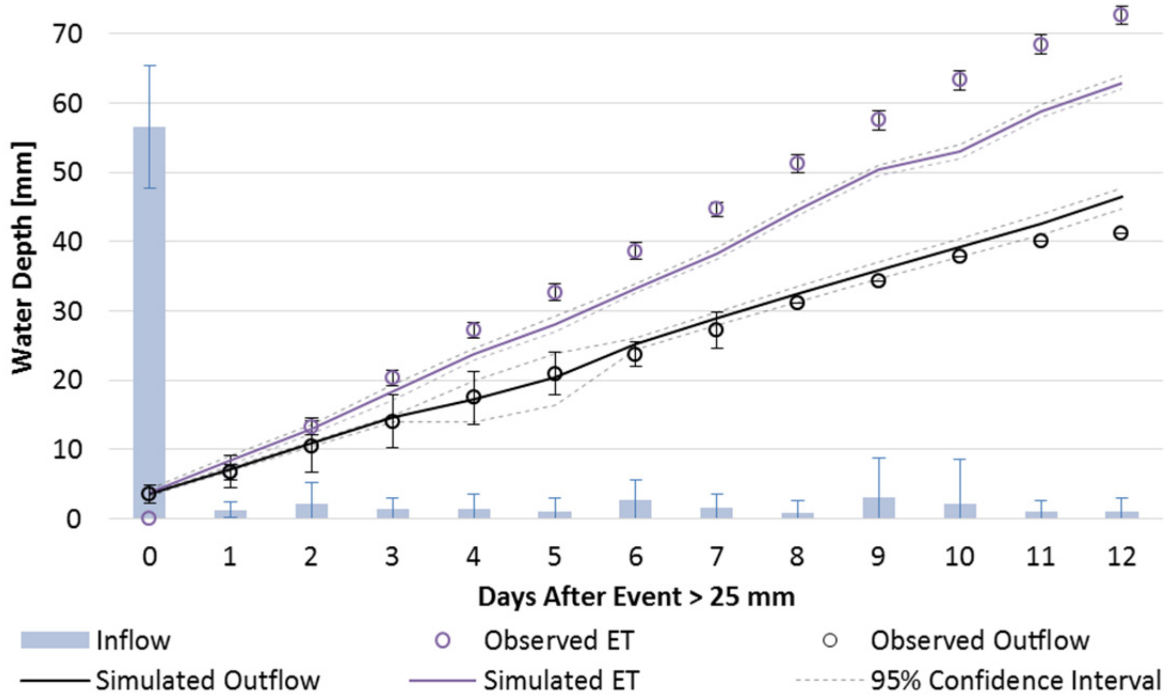

Figure 4.21: Sand IWS observed and simulated ET and outflow

Overall, the observed data from the weighing lysimeters confirms the SWAP simulation provides an adequate tool to model rain garden performance, especially in ET.

4.5.2 BENCH SCALE LYSIMETERS

The bench scale study runs from August 24 2015-2016 for comparison to data on events greater than 25 mm. Results from SWAP are compared with observed data for all soil types with 95% confidence intervals (Figure 4.22-Figure 4.26). Loamy sand, sandy loam, and loam use middle crop coefficient set where the silt loam and clay loam used the maximum crop coefficient set to provide the closest match in observed ET to simulated ET.

Observed loamy sand outflow shows good agreement with the simulated outflow (Figure 4.22). Observed loamy sand ET shows strong similarity with the simulated ET until day 8. From day 9 to day 12, the observed loamy sand ET is greater than the simulated ET by about 10 mm.

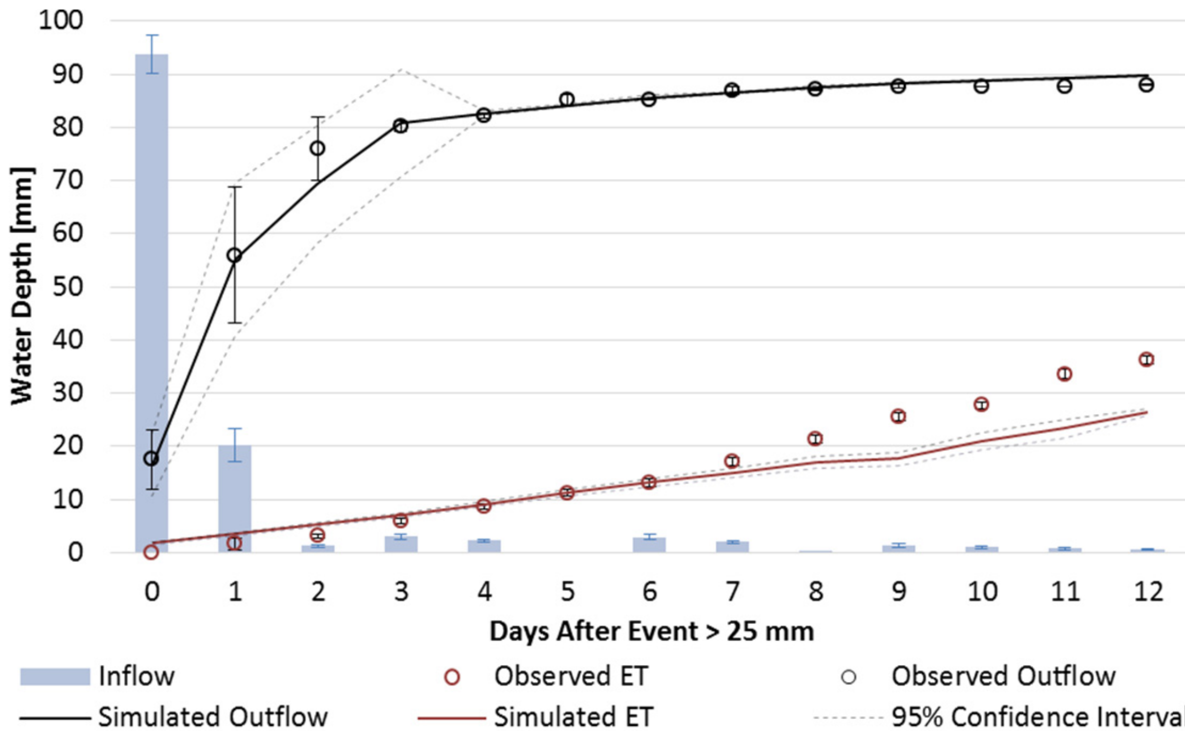

Figure 4.22: Loamy sand bench scale observed and simulated ET and outflow

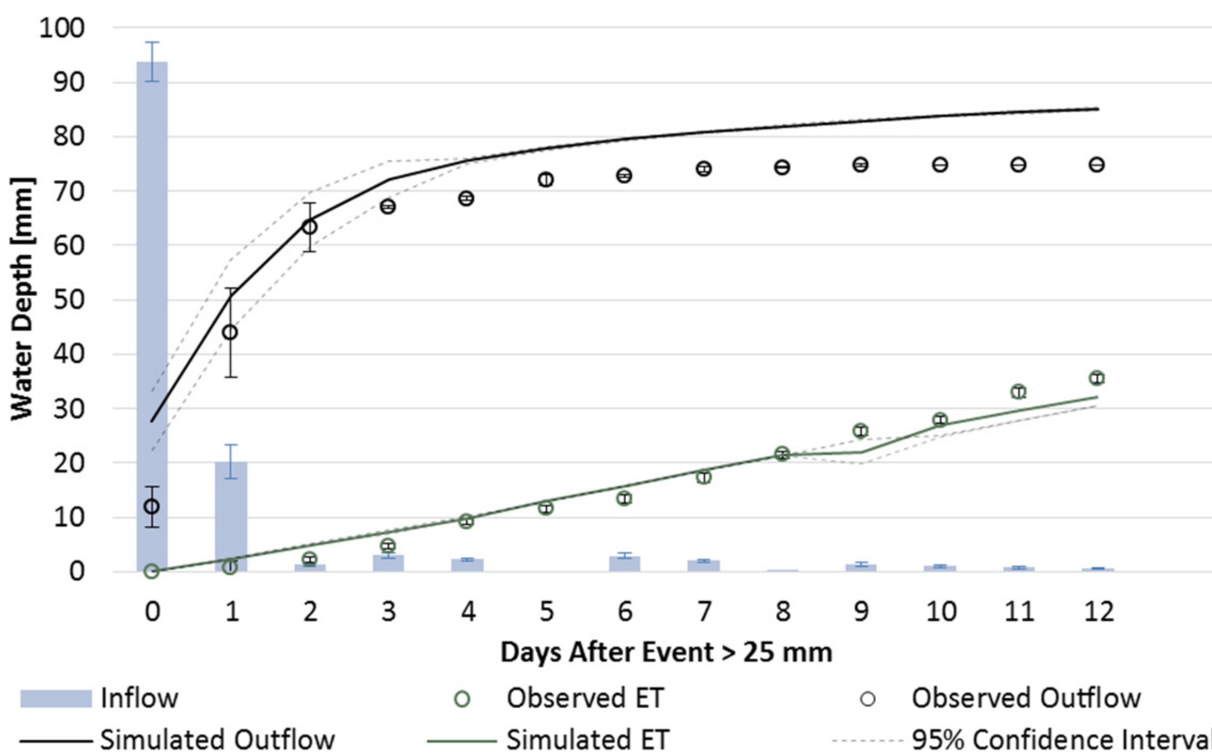

Figure 4.23: Sandy loam bench scale observed and simulated ET and outflow

The observed sandy loam outflow is consistently less than the simulated outflow by about 5 to 10 mm with the exception of the day 0 where the average observed outflow is greater than the simulated outflow by about 10 mm (Figure 4.23). Overall, simulated outflow for sandy loam is a similar trend and within 10 mm of observed outflow.

The sandy loam observed ET is less than that the simulated ET from day 0 to 3 by 5 mm, similar to the simulated ET from day 4 to 7, and slightly greater than simulated ET from day 8 to 12 by 5 mm. For 6 days of cumulative ET, SWAP results for sandy loam provide adequate estimates, and for 12 days of cumulative ET, SWAP results for sandy loam provide conservative estimates.

Observed loam outflow is typically less than simulated outflow, with day 0 having a difference of about 15 mm between observed and simulated values, on average (Figure 4.24). The

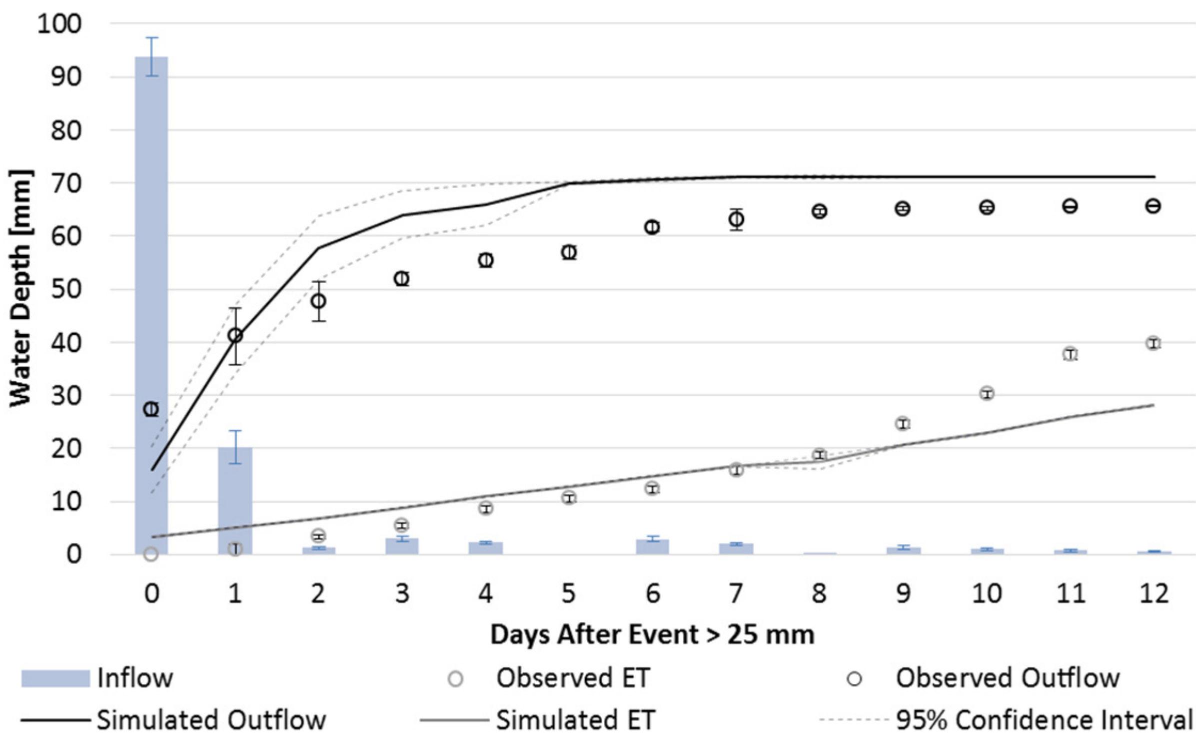

Figure 4.24: Loam bench scale observed and simulated ET and outflow

observed and simulated loam outflow values are most similar during day 1 to 3 and then the observed values become consistently lower by 5-10 mm for the following days. Observed and simulated ET matches well for the loam soil.

The observed silt loam outflow matches the simulated outflow by day 1 to 3 and then less than the simulated outflow for the following days by about 8 mm (Figure 4.25). The observed

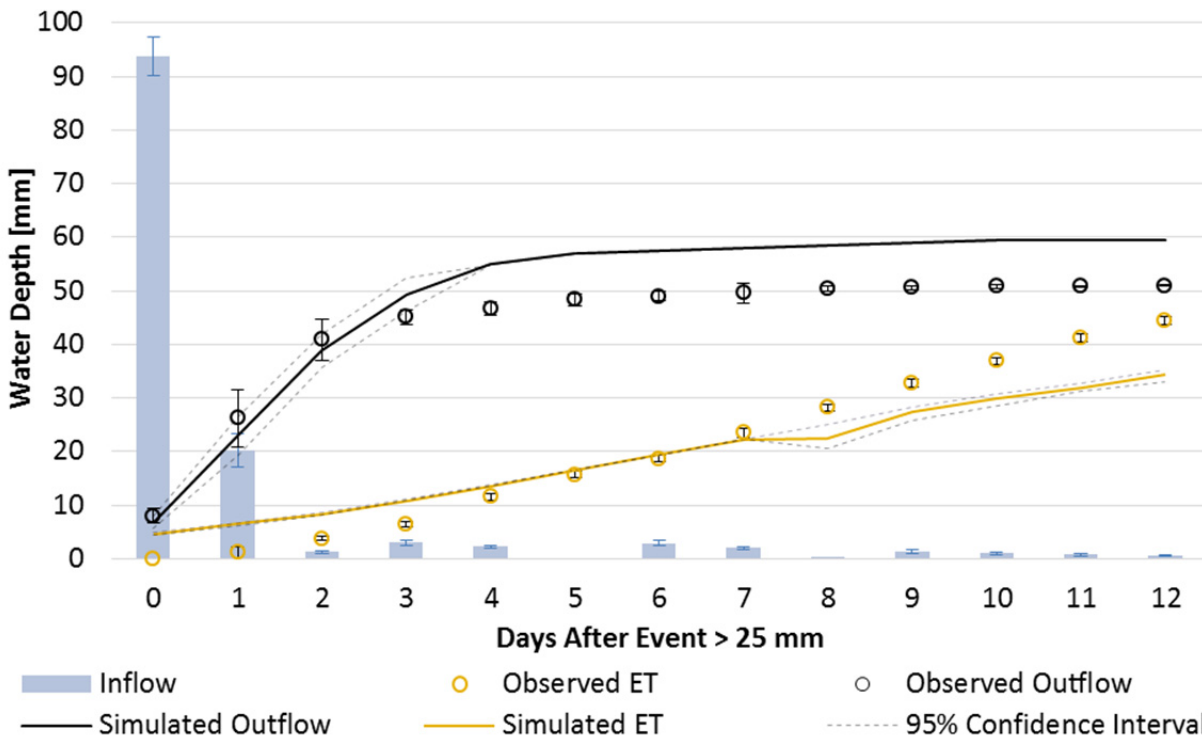

Figure 4.25: Silt loam bench scale observed and simulated ET and outflow

outflow higher than the simulated on day 1 and 2 for silt loam could be indicating observed macropore flow, which is not considered in the simulation and creating the difference in observed and simulated outflow trends. With macropore flow, the outflow is expected to be happening mostly on day 0 to 2 and exhibit cumulative outflow curve close to the shape of a cumulative outflow curve produced by a soil with high saturated hydraulic conductivity.

The observed outflow from clay loam falls on or within the 95% confidence intervals of the simulated on days 0 to 3, however observed values are closer to the upper limit of the 95% confidence intervals during days 0 to 2 (Figure 4.26). From days 4 to 12, the observed outflow

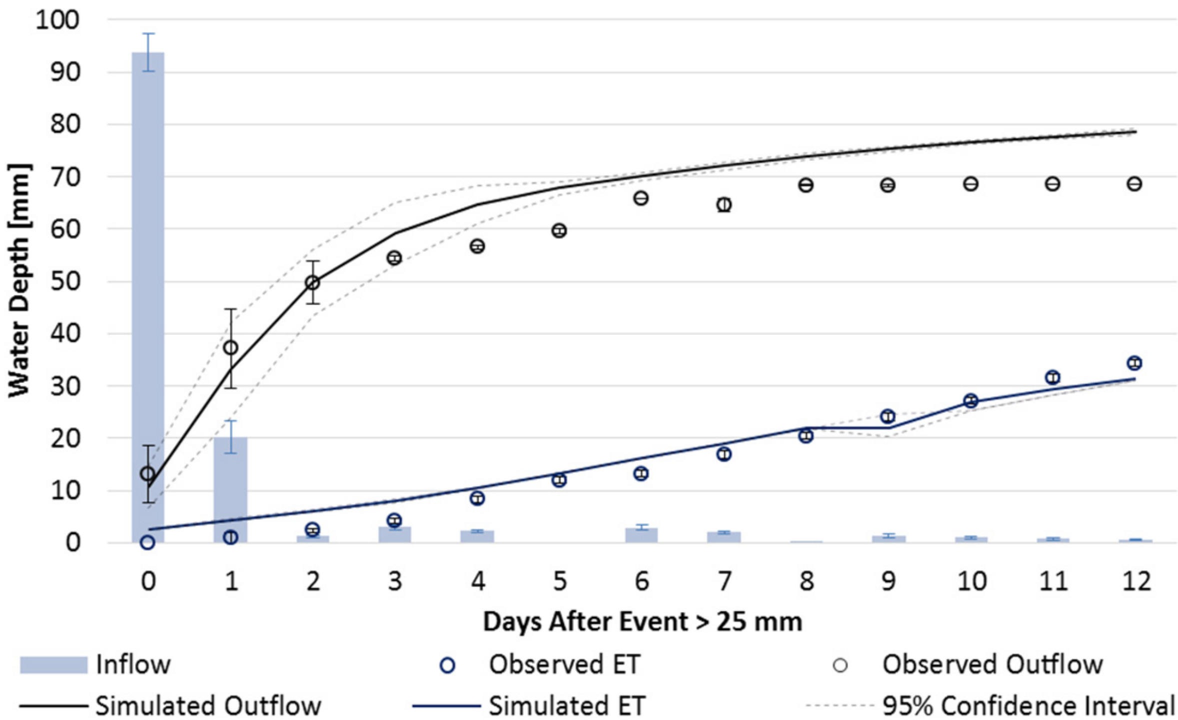

Figure 4.26: Clay loam bench scale observed and simulated ET and outflow

from clay loam remains between 5 to 10 mm less than the simulated values. The higher outflow behavior right after the storm event implies possible macropore flow within the clay loam. Observed clay loam ET shows strong similarity to the simulated ET values for all 12 days.

Overall simulated and observed results show good agreement for the bench scale study. The bench scale's cumulative observed outflow data is often a little less than the cumulative simulated outflow data but within 10 mm. The cumulative simulated ET data is a good estimate for the observed ET on day 6 after and event greater than 25 mm. The bench scale study verifies that the SWAP program is a reliable tool to model these devices.

4.5.3 RAIN GARDEN DESIGN EXTRAPOLATIONS

The SWAP simulated bioretention, bioretention with IWS, bioinfiltration underlined with hydrologic soil group A (sand from UO system), bioinfiltration underlined with hydrologic soil group B (sandy loam from UO system), and bioinfiltration underlined with hydrologic soil group C rain garden designs. For all rain garden designs, a low (K_{dev} of 0.6, K_{mid} of 1.2, and K_{end} of 0.9), middle (K_{dev} of 0.9, K_{mid} of 1.5, and K_{end} of 1.2), and maximum (K_{dev} of 1.8, K_{mid} of 2.0, and K_{end} of 1.8) crop coefficient set is modeled. Ponding depths of 7.5 cm, 15, and 30 cm are considered. Rooting and depth of media for 152 cm, 90 cm, 66 cm, 46 cm, and 20 cm are simulated. Five different soil types (sand from UO system, loamy sand from bench scale, sandy loam from UO system, loam from bench scale, silt loam from bench scale, clay loam from bench scale) are modeled.

The exception to these extrapolated scenarios is bioretention with IWS. For the IWS, depth of ponding, media, rooting, and IWS depth vary; the IWS depth remained about 50% of the soil column depth. Because the IWS lysimeter requires a drainage resistance for calibration and IWS systems are typically built with sandy soils, sand media is deemed the most appropriate soil to use for extrapolation. The maximum crop coefficient was the only one used for the IWS case as it creates a conservative estimate of IWS ET performance compared to the observed data. These combinations of simulations total 1095 (270 for bioretention cases, 15 for bioretention with IWS cases, and 810 for bioinfiltration cases). Cumulative ET 6 days (APPENDIX K) and 12 days (APPENDIX L) between events greater than 25 mm were determined for all scenarios.

4.6 EVAPOTRANSPIRATION ACCOUNTING

The sandy loam UO system has a rooting depth of 660 mm and produces, on average, 22 mm of ET during the 6 days between events. This 22 mm of ET divided by the rooting depth produces a soil moisture of 0.03 vol/vol that is removed through ET through the soil column. This soil moisture volume is less than 0.14 vol/vol, which is the maximum of ET available soil moisture for sandy loam. The soil moisture that will be removed via gravity is 0.23 vol/vol. Considering both ET and gravity removal, the sandy loam UO system will have a total removal equivalent to 26%. If 12 days between storm events is used, this would allow time for 40 mm of ET to occur, thusly increasing the total removal to 29%. Similarly, sand UO system provides 20 mm of ET during 6 days between events and would provide a void space credit of 33% considering both gravity (0.30 vol/vol) and ET removal and 36% after 12 days.

It is unusual for IWS to be built in PA as they are typically used in places with sandy soils (e.g NC; Brown et al. 2009). Due to the lack of implementation of IWS in PA, the static design standards for rain gardens do not include the IWS design such that the follow analysis is working on the assumption that the static design can be applied to IWS design. The IWS would provide reduction of water via gravity for only half of the soil column decreasing the gravity component to 0.15 vol/vol, as the bottom half is hypothetically saturated. The ET component is much larger in this column, namely 40 mm over 6 days providing a 0.06 soil moisture reduction, totaling 0.21 vol/vol (21%). If we are to consider ET over 12 days in the IWS system, 72 mm of ET, on average, is produced resulting in a soil moisture removal of 0.11 vol/vol and a total removal of 26%. A soil void space credit close to what is provided by the PWD guidance manual of 30% for sand can almost be obtained in the IWS case with sand (i.e. 26%) if ET for 12 days is included in the void space credit.

Gravity and ET available soil moisture are dependent on wilting point, field capacity and saturation of the soil types, and these values range even within soil type. Three literature sources along with the chosen values (based on data and literature) for gravity and ET available soil moisture are presented (Table 4.11). The values for gravity and ET available soil moisture

Table 4.11: Gravity and ET available soil moisture for different soil types

Available Soil Moisture [vol/vol]	(Rawls et al. 1982)		(Rawls et al. 1998)		(Saxton and Rawls 2006)		Chosen Values	
	Gravity	ET	Gravity	ET	Gravity	ET	Gravity	ET
Sand	0.33	0.06	0.34	0.05	0.36	0.05	0.30	0.11
Loamy Sand	0.27	0.07	0.28	0.07	0.34	0.07	0.24	0.09
Sandy Loam	0.20	0.11	0.20	0.10	0.27	0.10	0.23	0.14
Loam	0.16	0.15	0.13	0.14	0.18	0.14	0.17	0.16
Silt Loam	0.23	0.13	0.13	0.18	0.17	0.20	0.21	0.23
Clay Loam	0.07	0.12	0.08	0.10	0.12	0.14	0.14	0.24

can be expected to vary slightly, but the chosen values are those that will represent the full void space credit for the soils in this study. The chosen values for ET available void space provide the upper boundary for ET void space credit. Both ET and total void space credit will be presented such that users can define their own gravity available soil moisture and add it the ET void space credit to receive a more site specific total void space credit removal.

4.6.1 BIORETENTION SIMULATION

The SWAP 1-D Richards equation simulator bioretention results are presented via average ET 6 days after storm events greater than 25 mm divided by the rooting depth. Results from the 6 day cumulative bioretention ET are shown for six soil types with 15 cm of ponding depth (Figure 4.27). The three different crop coefficient sets are represented by a dotted line for low, a solid

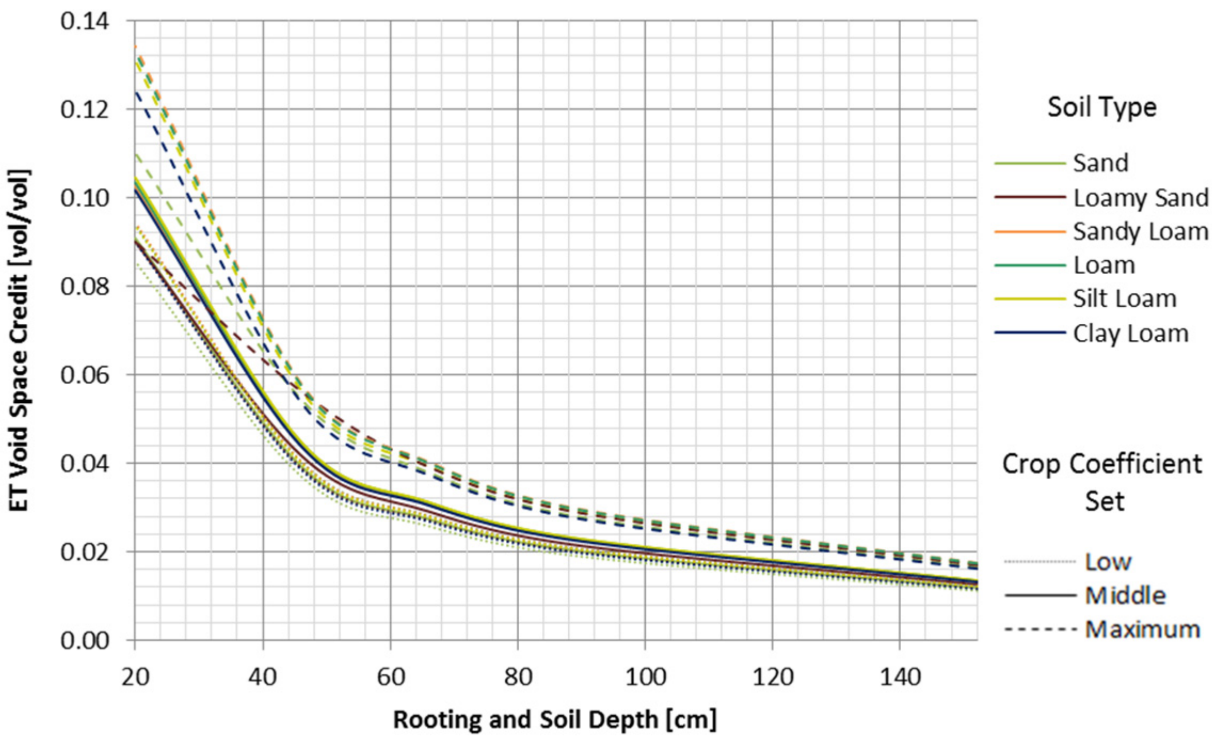

Figure 4.27: Bioretention ET void space credit for 6 days of cumulative ET

line for middle, and a dashed line for maximum. The maximum crop coefficient set has higher void space credits for all soil types, as higher cumulative ET rates are found via SWAP simulations (APPENDIX K). It was found that variations in ponding depth (7.5, 15, and 30 cm) had insignificant impacts on void space accounting method for bioretention such that the 15 cm ponding depth is representative of ponding depths between the ranges of 7.5 cm to 30 cm.

Soil type has an effect on the amount of ET that will be produced in bioretention design, though the differences are slight and limited to about 0.005 vol/vol difference between the lowest (sand) and highest (silt loam) ET void space credit at 40 cm depth for low crop coefficient set.

Similar ET void space credit difference based on soil type can be found for the middle crop coefficient set as the low crop coefficient set. The maximum crop set shows the largest difference in soil type ET void space accounting, especially around the 20 cm soil and rooting depth. A difference of about 0.3 vol/vol ET void space credit exists between sandy loam and loam or silt loam. The reason for these differences is that there is an upper limit to the ET void space credit based on soil type. The ET void space credit is limited to ET available water (difference between field capacity and wilting point) which changes based on soil type. Since WP and FC are difficult to determine and can change between soils that are within soil type, this value is a representation of an upper limit as the amount of ET that can be produced is a function of water availability.

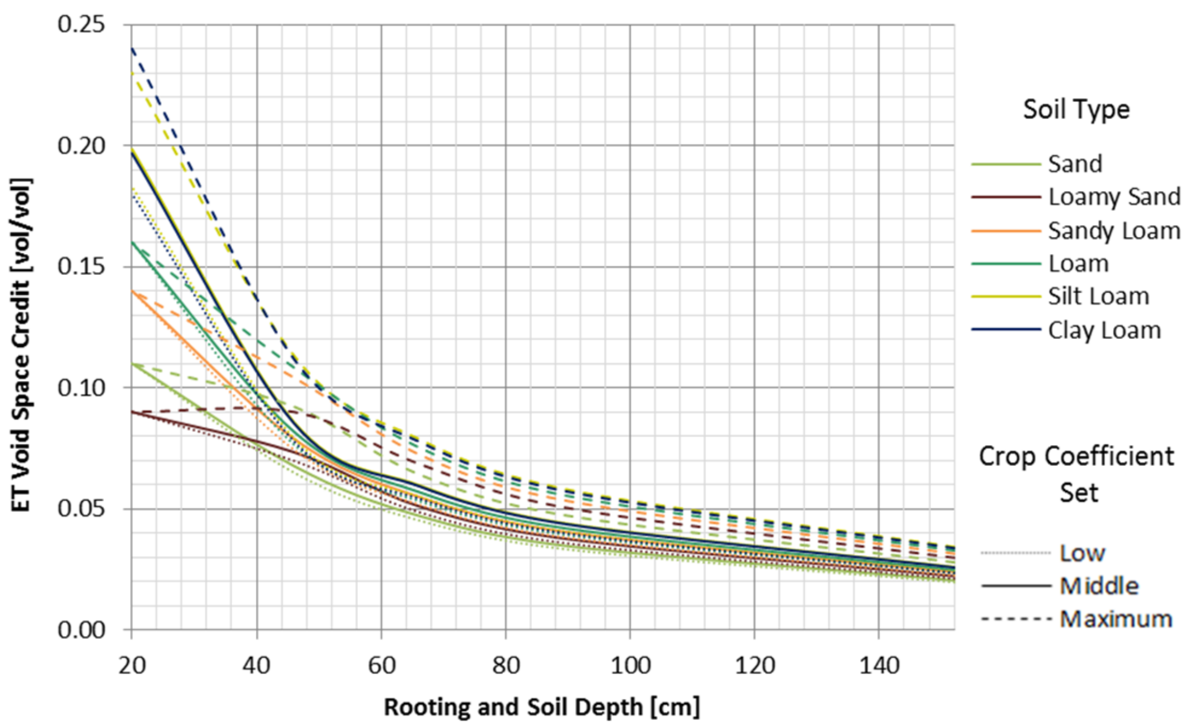

Figure 4.28: Bioretention ET void space credit for 12 days of cumulative ET

The maximum ET void space credit allowed is that of the difference between field capacity and wilting point, or the ET available void space. Typical values of FC and WP for each soil type are used. Similarly, ET void space accounting for 12 days between events in bioretention is determined (Figure 4.28). These values are overall higher ET void space credits, as there will be more ET over the longer duration. The effect of the upper limit of ET available soil moisture is more prevalent for 12 days of cumulative ET, specifically for rooting and soil depths between 20 and 50 cm.

The total void space credit for 6 days between events greater than 25 mm is the summation of the gravity available soil moisture and the ET available soil moisture (Figure 4.29). The total void space accounting is highly influenced by the amount of gravity available soil moisture, which is

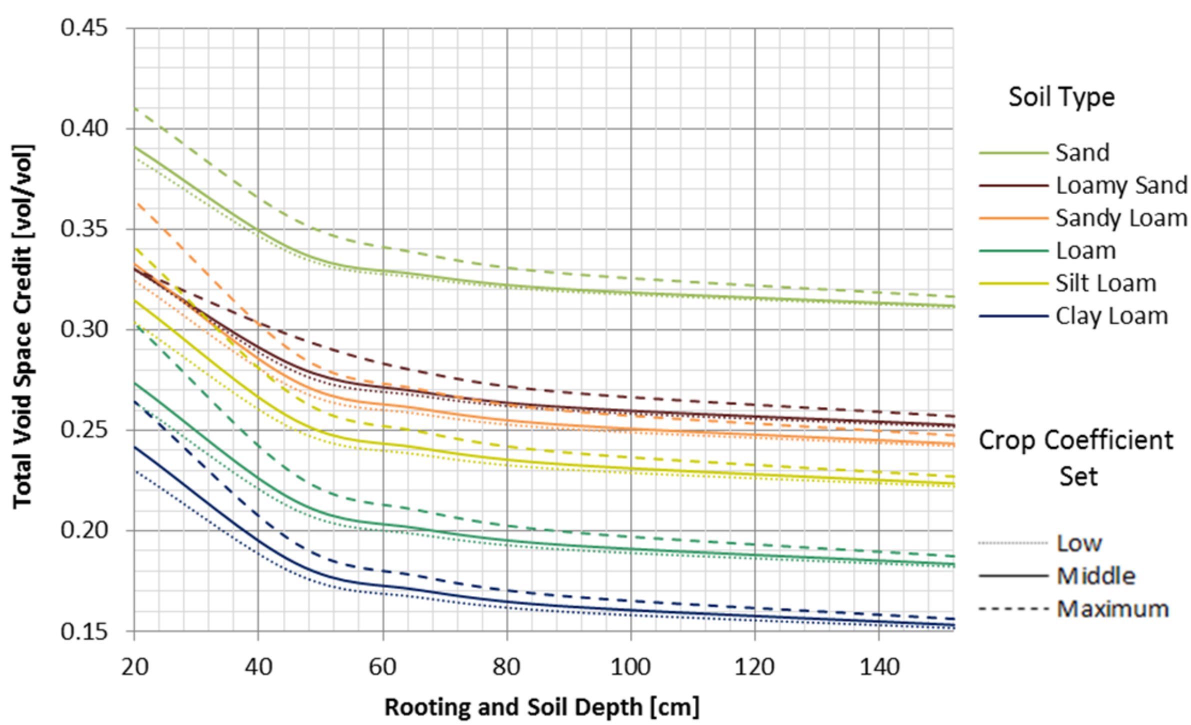

Figure 4.29: Bioretention total void space credit for 6 days of cumulative ET

very high for sand soil (0.41 vol/vol at 20 cm depth) and the lowest for clay loam soil (0.15 vol/vol at 152 cm depth).

The sand, loamy sand, and sandy loam that are typically used in rain garden media in PA are outperforming their current void space credits based on the PADEP BMP manual and PWD Guidance Manual. The sand soil outperforms the 30% void space credit by 1% to 2% in media and rooting depth of 152 cm (depending on crop factor set) and by 8% to 11% in media and rooting depth of 20 cm (depending on crop factor set). Similarly, loamy sand and sandy loam, on average, outperforms their attributed void space account of 20% by 5% (20 cm media and rooting depth) to 13% (152 cm media and rooting depth). Loam, silt loam and clay loam produce a minimum void space credit (at 152 cm soil and rooting depth) of about 18%, 23% and 16%, respectively. Considering 12 days between storm events produces higher values of total

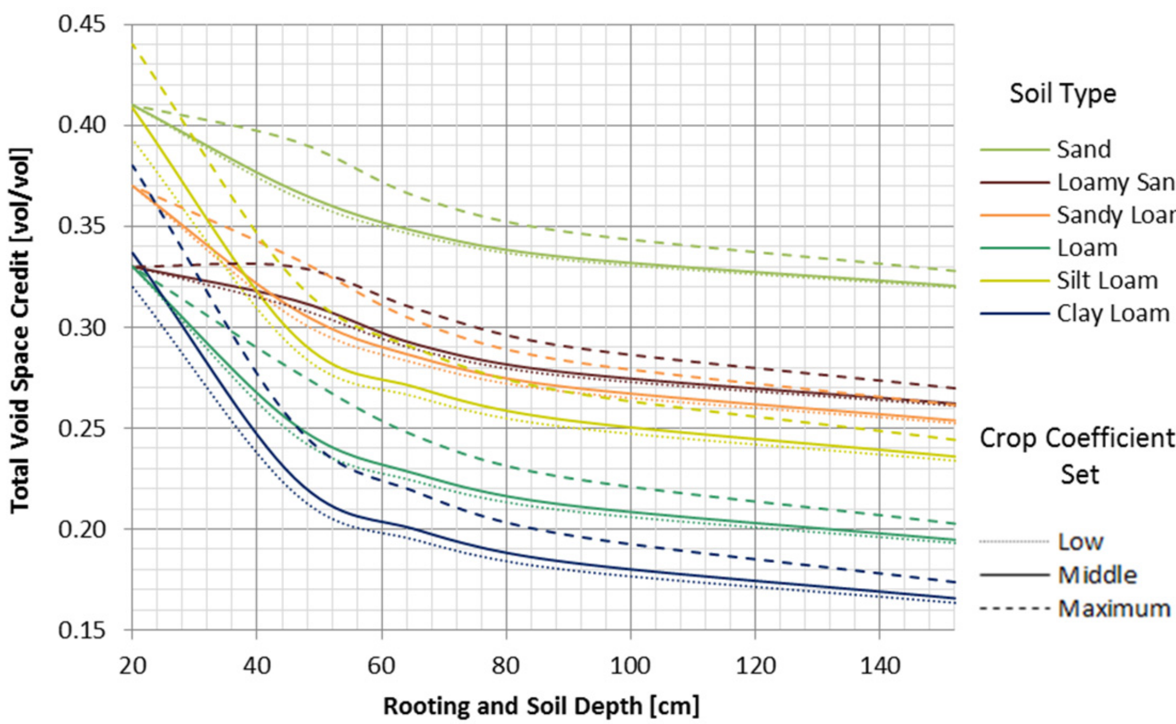

Figure 4.30: Bioretention total void space credit for 12 days of cumulative ET

void space credit (Figure 4.30), increasing minimum void space credit (at 152 cm media and rooting depth) by 1% for all soil types. With the exception of clay loam soil between 60 cm to 152 cm media and rooting depth, almost all values are greater than the 20% void space credit typically attributed to a typical rain garden soil in PA. The soil containing a higher content of fine grains (loam, silt loam, and clay loam) are able to achieve a higher total void space credit in media and rooting depths between 20 to 30 cm compared to the soils containing a higher content of coarse grains (sand, loamy sand, and sandy loam) as the finer grain soils have ET available soil moistures compared to coarser grain soils.

4.6.2 BIORETENTION WITH IWS SIMULATION

Bioretention with IWS simulation is focused on sand media with a maximum crop coefficient set and an IWS depth half of the total soil column depth. Results on a 6 day and 12 day cumulative ET basis reveal that ponding depth has an effect on void space accounting for rooting and soil depths between 20 and 40 cm (Figure 4.31). The total void space credit for bioretention with an IWS has a minimum (at 152 cm rooting and soil depth) of 16% for 6 days of cumulative ET and 18% for 12 days of cumulative ET.

The ponding depth is represented by a dotted line for 7.5 cm, solid line for 15 cm, and a dashed line for 30 cm. The calculation of ET and total void space credit is different for an IWS than a bioretention or bioinfiltration design. The top half of the column in treated the same way as a bioretention or bioinfiltration design where the ET void space credit is limited by ET available soil moisture and the gravity available soil moisture is 0.30 for sand soil. However, the bottom half (or IWS zone) is treated as conservatively saturated where water can only leave via ET and not gravity. The total void space credit for bioretention with IWS is seen in Figure 4.32.

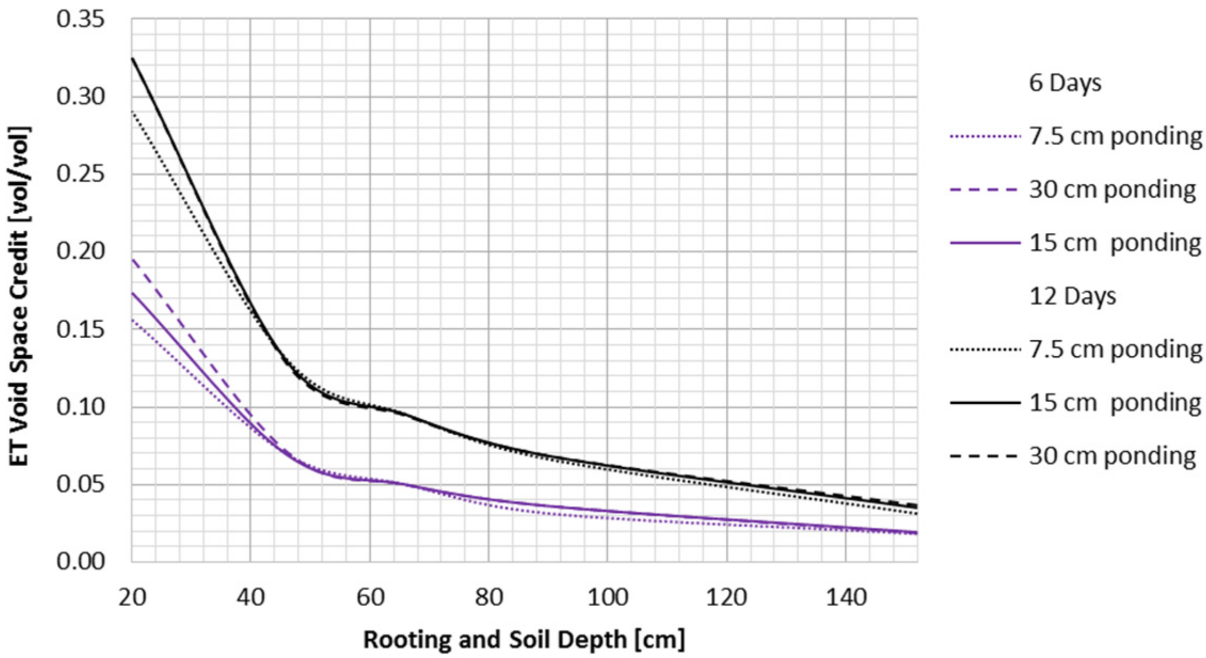

Figure 4.31: Bioretention with IWS ET void space credit

The total void space credit for bioretention with IWS 6 day and 12 day cumulative ET is compared to bioretention without an IWS for the same soil type of sand and ponding depth of 15 cm (Figure 4.33). There are noticeable differences between the crediting system for bioretention with and without IWS, where it would be more incentivized to build a bioretention rain garden without an IWS as there is more credit to the gravity driven processes. However, the IWS system simulation is conservative as the maximum crop coefficient underestimated observed values by 5 to 10 mm of ET for 6 and 12 day cumulative ET, respectively. The static storage crediting system does not include IWS design such that the calculations used to obtain a comparison to static storage design may not be the most descriptive of a bioretention with

IWS functionality. Due to underestimation of ET and limitations to the static storage design, ET void space crediting for bioretention with IWS is typically lower than of bioretention.

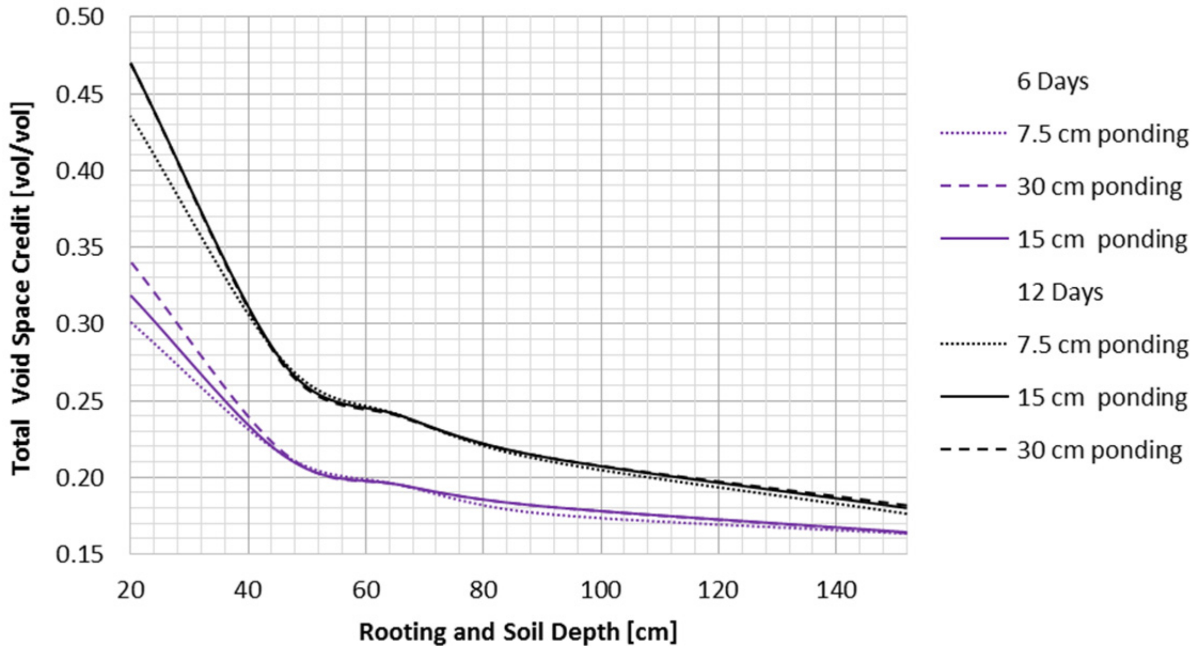

Figure 4.32: Bioretention with IWS total void space credit

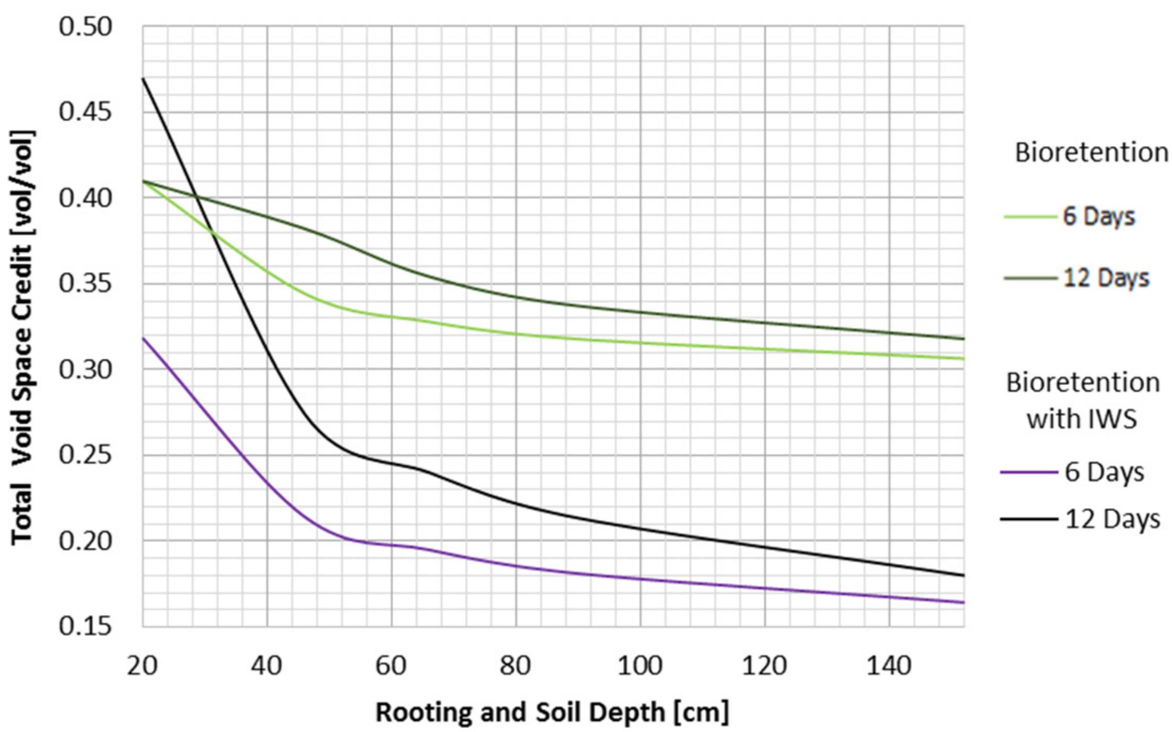

Figure 4.33: Comparison of bioretention with and without IWS total void space credit

4.6.3 BIOINFILTRATION IN GROUP A SOIL SIMULATION

Bioinfiltration design with hydrologic soil group A (K_{sat} of 90 cm/d, represented by sand soil) is simulated with a deep groundwater table. Results from the 6 day cumulative ET from bioinfiltration in hydrologic group A are shown for six soil types with 15 cm of ponding depth (Figure 4.34). The three different crop coefficient sets are represented by a dotted line for low,

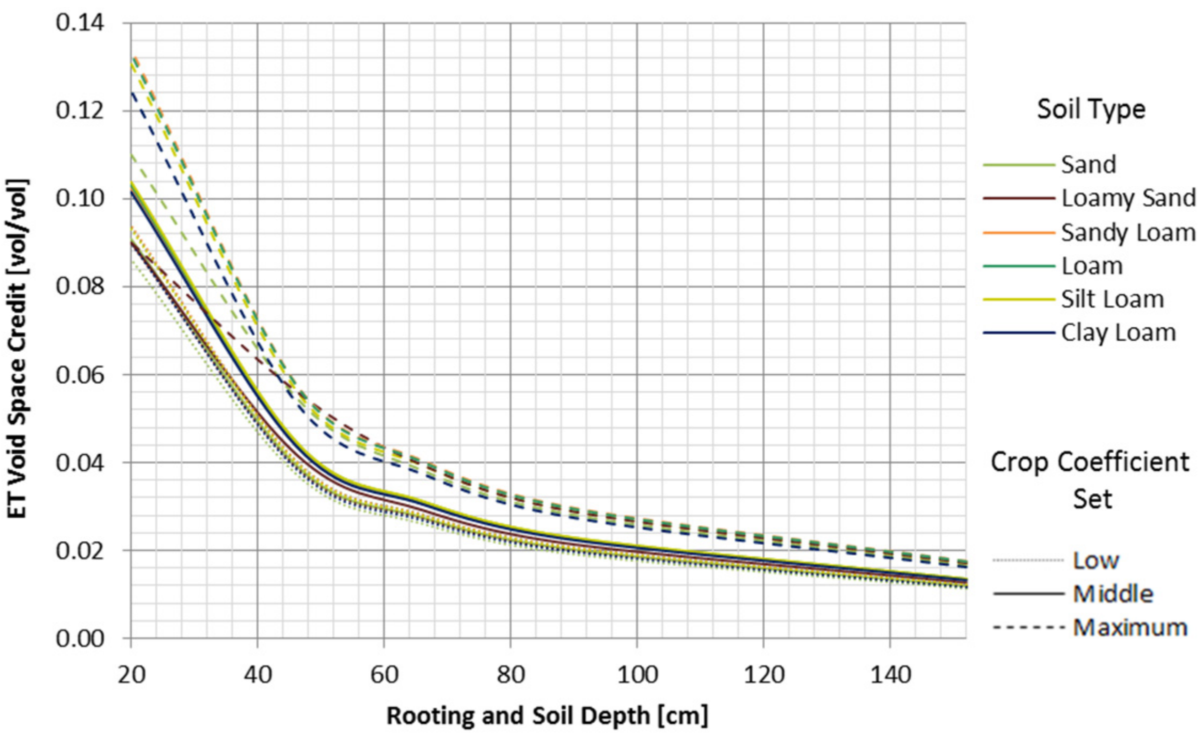

Figure 4.34: Bioinfiltration in hydrologic group A soil ET void space credit for 6 days of cumulative ET

a solid line for middle, and a dashed line for maximum. The maximum crop coefficient set has higher void space credits for all soil types, as higher cumulative ET rates are found via SWAP simulations (APPENDIX K). It was found that variations in ponding depth (7.5, 15, and 30 cm) had insignificant impacts on void space accounting method for bioinfiltration in hydrologic soil group A such that the 15 cm ponding depth is representative of ponding depths between the ranges of 7.5 cm to 30 cm. Loamy sand soil is the only soil that is notably influence by the ET available soil moisture upper limit at rooting and soil depth range of 20 cm to 40 cm. Similar to the 6 day of cumulative ET, 12 days of cumulative ET for bioinfiltration with an underlying soil of hydrologic group A is seen in Figure 4.35. Sand, loamy sand, sandy loam, and loam are soil types that are affected by the ET available soil moisture upper limit (most notably in the maximum crop coefficient set) at rooting and soil depth range of 20 cm to 50 cm. Results from bioinfiltration in hydrologic group A soil are very similar to bioretention design, but with less variability of ET void space credit among soil types for low and middle crop coefficient sets.

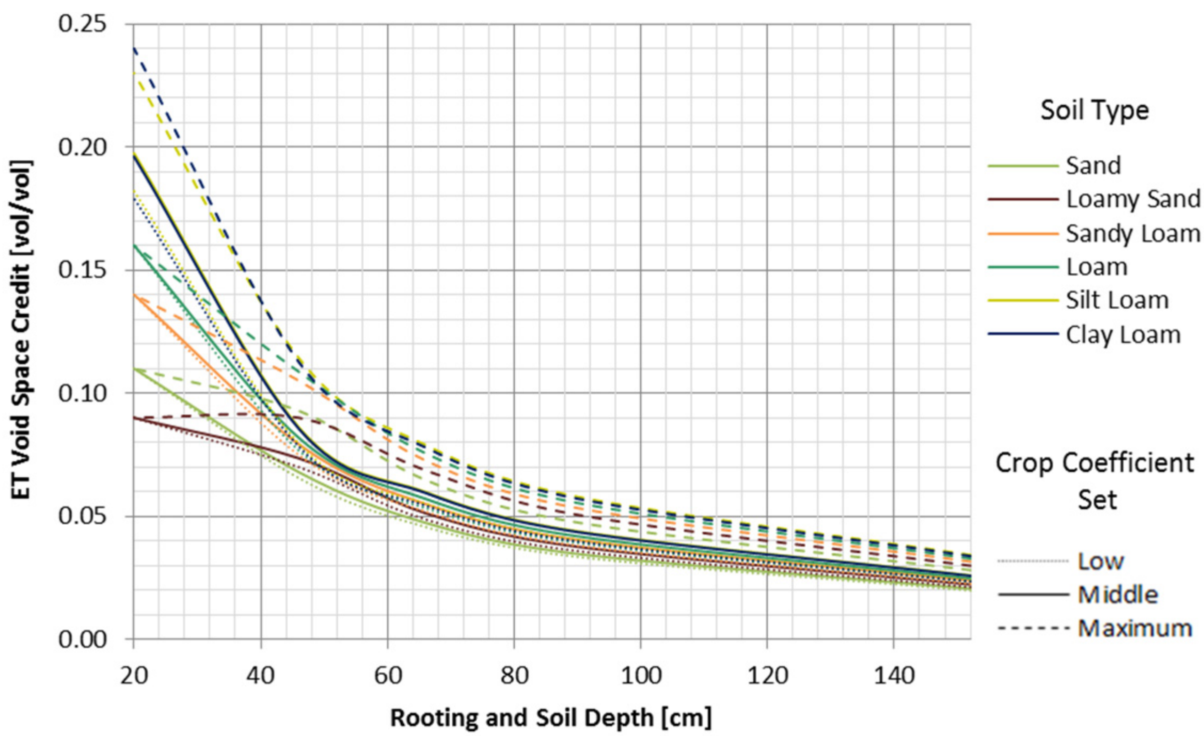

Figure 4.35: Bioinfiltration in hydrologic group A soil ET void space credit for 12 days of cumulative ET

Total void space credit for 6 days (Figure 4.36) and 12 day (Figure 4.37) of cumulative ET after events greater than 25 mm are also similar to that of bioretention design.

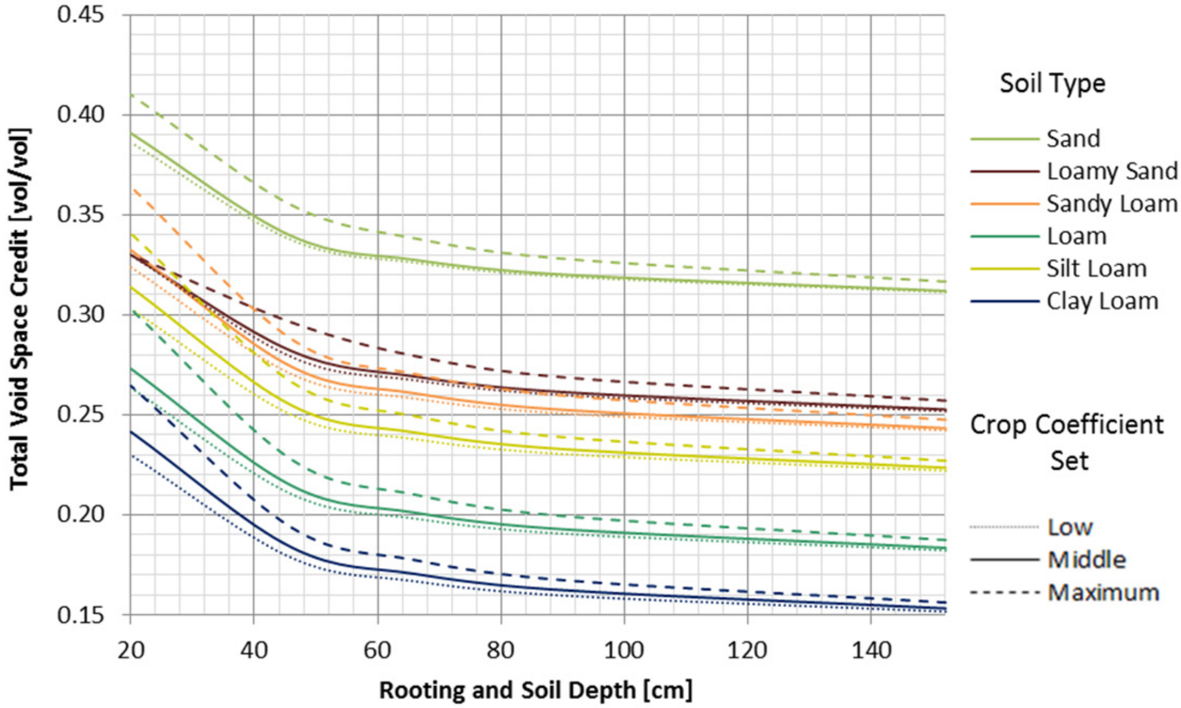

Figure 4.36: Bioinfiltration in hydrologic group A soil total void space credit for 6 days of cumulative ET

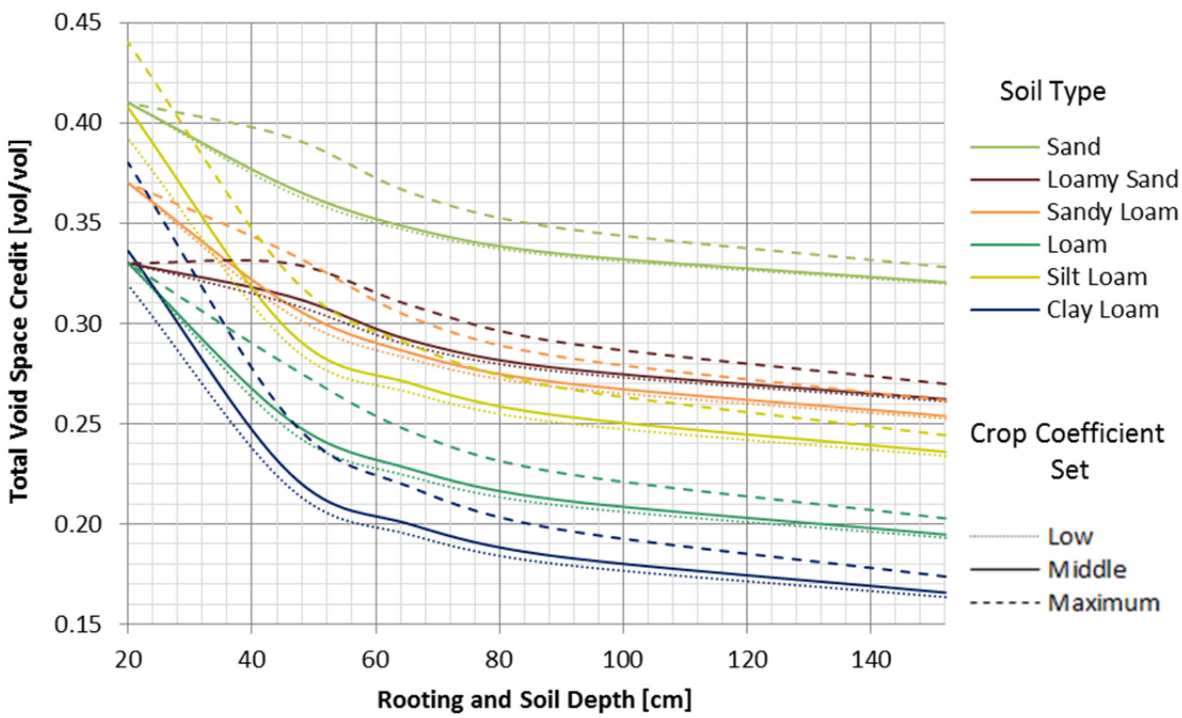

Figure 4.37: Bioinfiltration in hydrologic group A soil total void space credit for 12 days of cumulative ET

4.6.4 BIOINFILTRATION IN B TYPE SOIL SIMULATION

Bioinfiltration design with hydrologic soil group B (K_{sat} of 50 cm/d, represented by sandy loam soil) is simulated with a deep groundwater table. Results from the 6 day cumulative ET from bioinfiltration in hydrologic group B are shown for six soil types with 15 cm of ponding depth (Figure 4.38). The three different crop coefficient sets are represented by a dotted line for low,

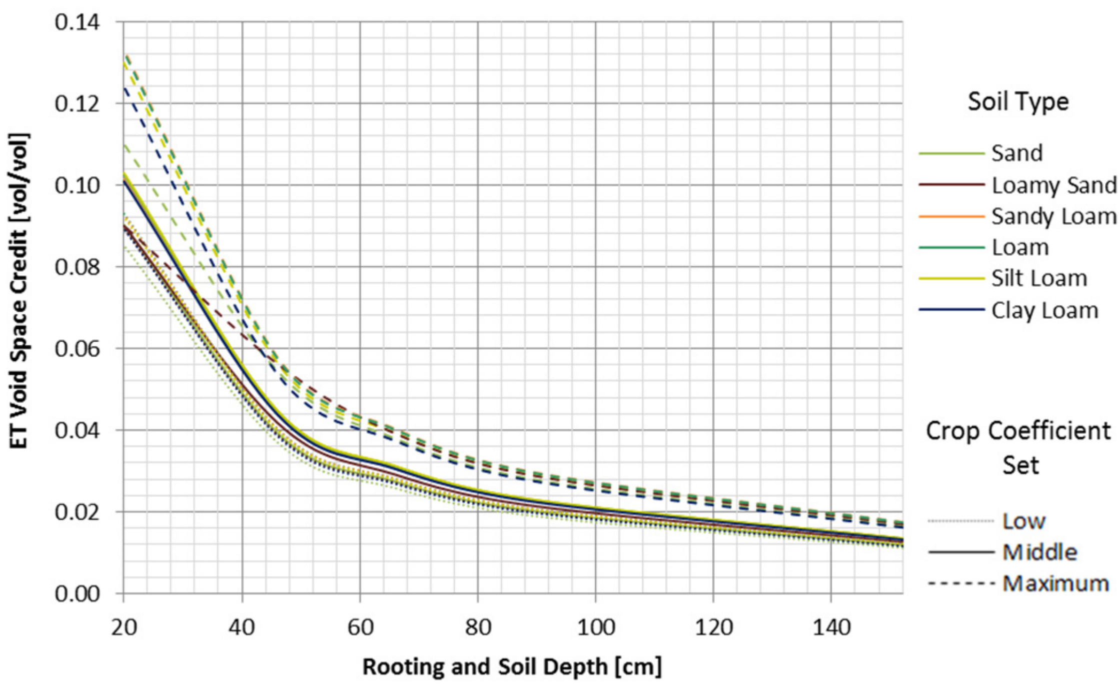

Figure 4.38: Bioinfiltration in hydrologic group B soil ET void space credit for 6 days of cumulative ET

a solid line for middle, and a dashed line for maximum. Similar to bioinfiltration and bioretention, ponding depth variations had insignificant impacts on void space accounting method for bioinfiltration underlined with hydrologic group B soil such that the 15 cm ponding depth is representative of ponding depths between the ranges of 7.5 cm to 30 cm. The 12 days of cumulative ET for bioinfiltration with an underlying soil of hydrologic group B is seen in Figure 4.39. Results from bioinfiltration with an underlying soil of hydrologic group B are very similar to that of bioretention and bioinfiltration with an underlying soil of hydrologic group C results. The total void space credit is found in APPENDIX M for 6 and 12 days of cumulative ET.

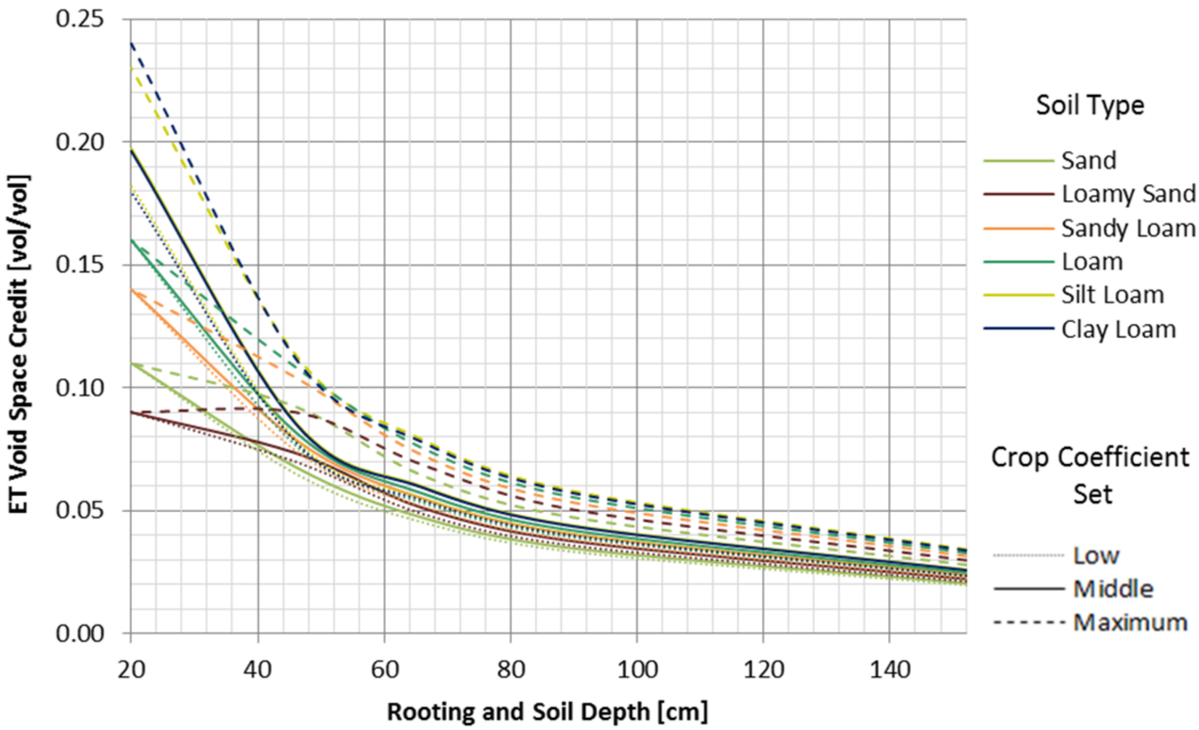

Figure 4.39: Bioinfiltration in hydrologic group B soil ET void space credit for 12 days of cumulative ET

4.6.5 BIOINFILTRATION IN C TYPE SOIL SIMULATION

Bioinfiltration design with hydrologic soil group C (K_{sat} of 12 cm/d, represented by silt loam soil) is simulated with a deep groundwater table. Results from the 6 day cumulative ET from bioinfiltration in hydrologic group C are shown for six soil types with 15 cm of ponding depth (Figure 4.40). The three different crop coefficient sets are represented by a dotted line for low, a solid line for middle, and a dashed line for maximum. All soil types are functioning very similarly as the underlying soil with a relatively low infiltration rate is controlling the movement of water. Some differences can be seen among loamy sand, sand, and the rest of the soil types (i.e. sandy loam, loam, silt loam and clay loam) between media and rooting depths of 20 cm to 50 cm, where loamy sand and sand are limited to their ET available soil moisture.

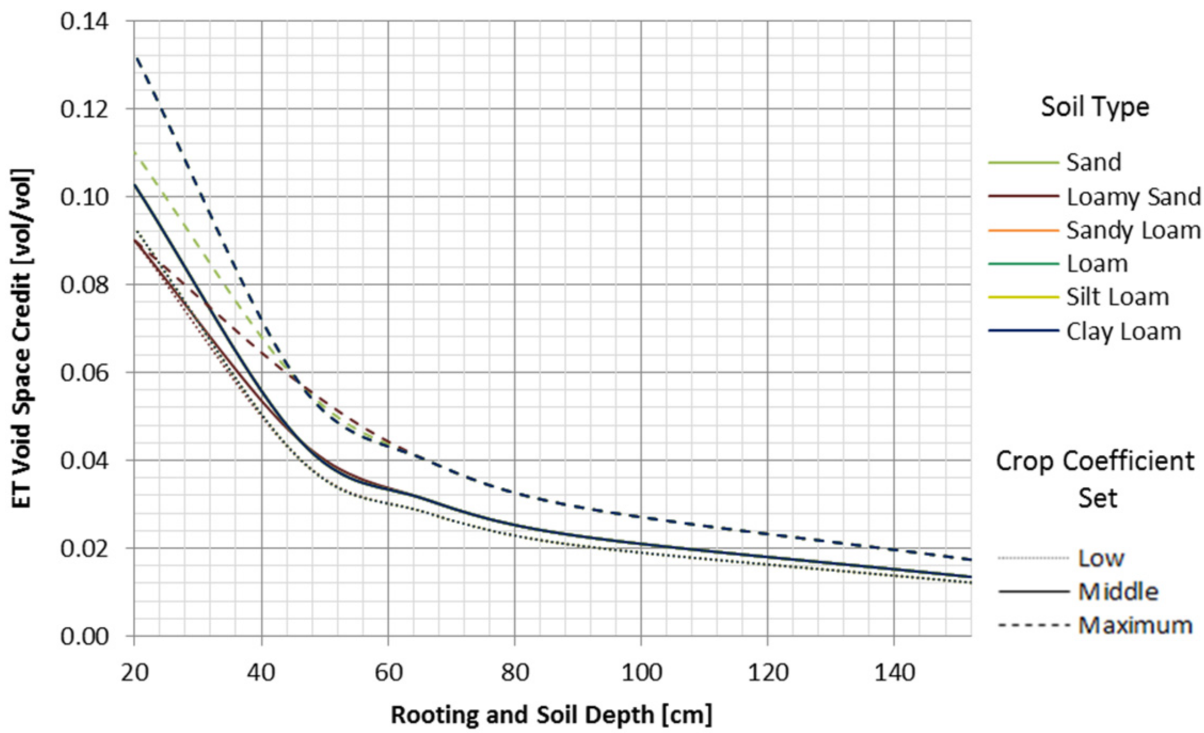

Figure 4.40: Bioinfiltration in hydrologic group C soil ET void space credit for 6 days of cumulative ET

The 12 days of cumulative ET for bioinfiltration with an underlying soil of hydrologic group B is seen in Figure 4.39. Void space credit for all soil types for 12 days of cumulative ET are the same for media and rooting depths between 60 cm to 152 cm. However, soil types have variations for media and rooting depths between 20 cm and 60 cm due to influence of the upper limit based on ET available soil moisture. Results from bioinfiltration with an underlying soil of hydrologic group C are different than that of bioretention and bioinfiltration with an underlying soil of hydrologic group A or B results. The total void space credit can be found in APPENDIX M for 6 and 12 days of cumulative ET.

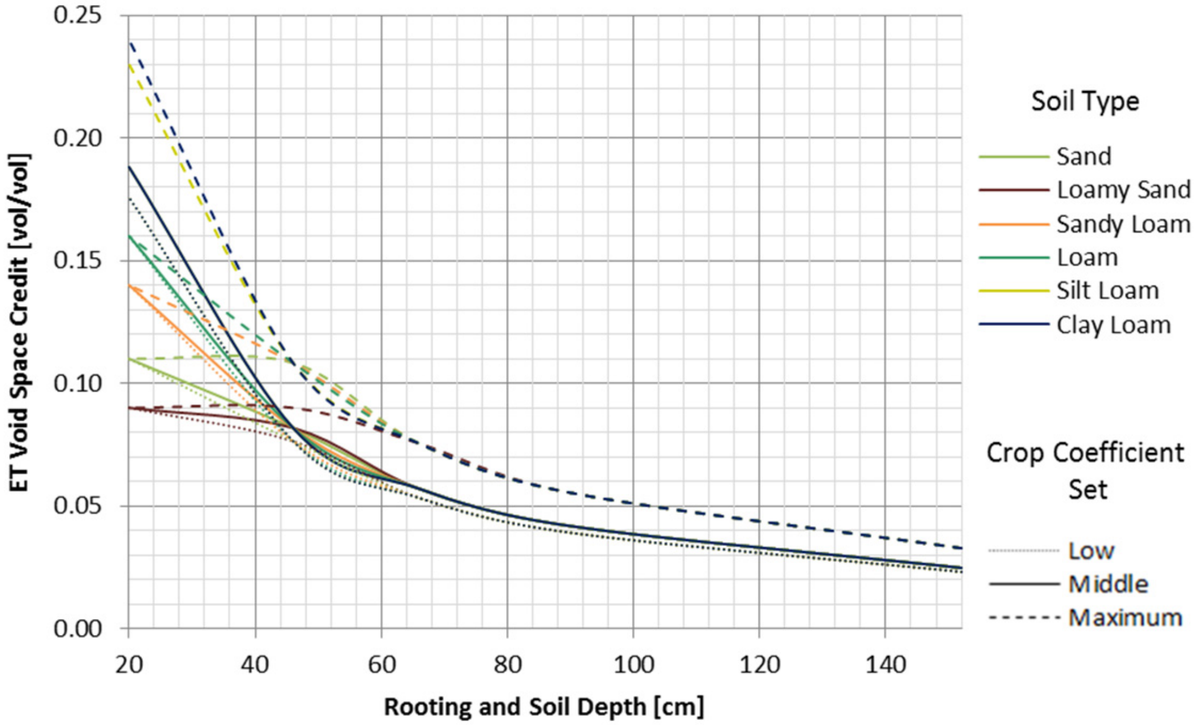

Figure 4.41: Bioinfiltration in hydrologic group C soil ET void space credit for 12 days of cumulative ET

CHAPTER 5. CONCLUSIONS

The purpose of this research is to find methods to incorporate ET in rain garden design. To do this, weighing lysimeter data along with predictive ET models and a 1-D Richards equation simulator were used to develop a method for void space accounting that considers ET into the current static storage volume design.

The rain garden lysimeters are sensitive enough to deliver reliable daily ET measurements. Daily evapotranspiration rates from three rain garden designs (sandy loam UO, sand UO, and sand IWS) using weighing lysimeters were obtained for a three year study from July 13 2013 to July 13 2016. Inflow was added on top of the systems to mimic runoff volumes. Annual (including winter) average evapotranspiration rates reveal that the IWS has statistically higher ET rates on average (4.4 ± 3.4 mm/d) compared to the UO systems (2.8 ± 2.2 mm/d for sandy loam and 2.7 ± 2.2 mm/d for sand). Annual average evapotranspiration rates over the growing season (excluding winter) are higher compared to the total annual average with 3.0 ± 2.0 mm/d for sandy loam UO, 3.0 ± 2.1 mm/d for sand UO, and 5.0 ± 3.1 mm/d for sand IWS. Evapotranspiration comprises 30%, 31%, and 53% of the total water budget for sandy UO, sand UO and sand IWS systems, respectively. Comparisons of the UO systems indicate that the additional fines in the sandy loam media do not inhibit ET rates and are not statistically different from sand media. Statistics on cumulative ET between storm event sizes greater than 6 mm revealed that the UO systems can evapotranspire an equivalent storm volume of 15 mm or less but the IWS can evapotranspire an equivalent storm volume of 40 mm, on average. An internal water storage drainage design can influence the amount of ET produced from the lysimeters on a daily and storm basis, providing about double the amount of ET in the system compared to the unconstricted outflow bioretention design. The IWS outflow produces on average, less volume of outflow compared to the UO systems and will stay ponded typically 3 days after a large event (> 25 mm) compared to the UO systems that will typically draw down on ponding about a day after an event.

Soil moisture is compared to weight readings and was found that it can be a suitable proxy to determine cumulative storm ET for all lysimeter types (R^2 of 0.88, 0.87, 0.77 for sandy loam UO, sand UO, and sand IWS, respectively, if all soil moisture readings at 10, 35, and 65 cm depths are used). Soil moisture tracking at the bottom of the lysimeter is most correlated to weight on a storm basis to determine if it is a suitable proxy to calculate ET. Tracking soil moisture at the top and bottom of a rain garden soil column is recommended to determine cumulative storm ET (R^2 of 0.88, 0.86, 0.76 for sandy loam UO, sand UO, and sand IWS, respectively), however tracking soil moisture at the bottom of the soil column is most critical (R^2 of 0.79, 0.86, 0.58 for sandy loam UO, sand UO, and sand IWS, respectively). From this analysis, it can be seen that there is a relationship between ET and the decrease in soil moisture such that soil moisture readings have the possibility of predicting ET on a storm volume basis.

The Hargreaves and ASCE Penman-Monteith reference equations with and without modifications for water availability and crop presence are calibrated on a daily and storm basis. Hargreaves equation provides an adequate estimate for rain garden ET for all systems without modification (efficiencies are approximately 0 or greater for all cases). Generally, Hargreaves equation on a daily basis overestimates the UO systems and underestimates the IWS.

Modifications to Hargreaves equation through crop factors and a soil moisture extraction function are able to reduce RMSE, increase R^2 and efficiency for all weighing lysimeter types. On a storm basis, Hargreaves equation estimates perform similarly to observed values on a daily basis but with higher R^2 and efficiency without modification (R^2 of 0.89, 0.79, 0.91 for sandy loam UO, sand UO, and sand IWS, respectively) and with modification, even higher R^2 and efficiency values can be obtained (R^2 of 0.95, 0.85, 0.91 for sandy loam UO, sand UO, and sand IWS, respectively).

The ASCE Penman-Monteith equation provides an adequate estimate for rain garden ET for the UO systems but not the IWS without modification (efficiencies of 0.14, 0.29, -0.14 for sandy loam UO, sand UO and sand IWS, respectively). Generally, ASCE Penman-Monteith equation estimates the UO systems well but underestimates the IWS system. Modifications to the Hargreaves equation through crop factors and a soil moisture extraction function are able to reduce RMSE, increase R^2 and efficiency for all weighing lysimeter types. On a storm basis, ASCE Penman-Monteith equation proves an adequate estimation (all efficiencies greater than 0) for all lysimeters types without modification (R^2 of 0.83, 0.78, 0.92 for sandy loam UO, sand UO, and sand IWS, respectively) and with modification, even higher R^2 and efficiency values can be obtained (R^2 of 0.94, 0.89, 0.92 for sandy loam UO, sand UO, and sand IWS, respectively). For both equations, crop coefficients were found in an expected range for the UO systems (0.5 to 1.5) but were high in the IWS system (1.6-2.0); soil moisture extraction functions not needed in calibration of IWS on a storm basis.

Both the Hargreaves and Penman-Monteith equations are capable of providing adequate estimates of ET in rain gardens for a UO system especially on a storm basis. A combination of crop coefficients and soil moisture extraction functions applied to reference Hargreaves and Penman-Monteith ET provided the best estimates for the UO systems. To predict ET using these equations for an IWS system, crop factors are recommended.

A 1-D Richards equation simulator, Soil Water Atmosphere and Plant (SWAP), uses the calibrated Penman-Monteith equation and its results are verified using the weighing lysimeter and bench scale study cumulative ET and outflow data on days after events greater than 25 mm. SWAP was then used as a tool for rain garden design void space credit. Soil media, depth of rooting and media, crop coefficients, ponding depth, and lower boundary condition (bioretention, bioretention with IWS, and bioinfiltration with hydraulic soil types A, B, and C) are varied to provide a wide range of rain garden design and the ET rates to be expected within 6 days and 12 days after a storm event.

Evapotranspiration void space credit is most sensitive to variation of soil type, media and rooting depth, and crop coefficient set. Differences in soil type are most prevalent when considering total void space credit (the summation of ET and gravity void space) where void space received by gravitational forces will play a large role in total void space credit, especially in soil and rooting depths between 60 cm to 152 cm. Soil media and rooting depth impact total void space credit, where the shallower depth (20 cm to 60 cm) typically have much higher void space credits compared to those of deeper depths (60 cm to 152 cm). This finding plays an important role in incentivizing the use of rain gardens or other vegetated storage systems to be used in shallower depths where primary volume loss mechanism is ET. The utilization of different crop coefficient sets will provide the user with different ET void space credits, with the low crop coefficient providing the lowest ET void space credit and the maximum providing the lowest ET void space credit for all soil types, soil depths, and rooting depths.

Lower boundary condition and ponding depth also have an effect on the ET void space credit in certain scenarios. Lower boundary conditions had a notable effect on ET void space credit in bioretention with IWS and bioinfiltration in hydrologic soil type C, where underlying soil controlled the movement of water. Ponding only had a notable effect in bioretention with IWS in shallow depth (between 20 and 60 cm) where an increase in ponding depth could provide an increase in ET void space credit. Bioretention and bioinfiltration in hydrologic soil type A and B produced similar ET void space credit results.

There are limitations to applicability of the ET and total void space credit as it is using site specific climate, plant, and soil data. Climate data may be applicable to areas around Villanova PA, such as Philadelphia, with similar climate type where the exact values of ET void space credit are probably applicable to credit the rain garden system. However, to expand on a widespread scale, the method should be mimicked rather than exact results used. A 1-D Richards equation such as SWAP can be used in conjunction with observed data to determine the void space accounting in that area. Only three plants were considered in this analysis, where a variety of plants are often used in rain gardens. However, three different crop coefficient sets were considered in this method such that the user can define which one represents their site specific scenario. Also, different soils will have different ET and gravity available soil moisture based on field capacity and wilting point, values that are typically hard to determine. If the user has a good understanding of these values, then it is recommended that the method is tailored to incorporate the site specific field capacity and wilting point. If not, the field capacity and wilting points utilized in this method are similar to that found in average literature values and are acceptable for general use.

Inclusion of more soil depths should focus on shallower depths and more depths analyzed between 10 cm to 70 cm, perhaps in increments of 10 cm such that there is a clearer understanding of the void space credit in the area where the slope is more rapidly changing. Future work into this void space accounting method can include more soil depths and media types such that other vegetated SCMs such as green roofs, tree trenches, and swales can include this ET and gravity void space accounting method.

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APPENDIX

APPENDIX A PLANT INSPECTION PHOTOS: WEIGHING LYSIMETERS

Sandy loam (left), sand (middle), and sand IWS (right) in July of 2013.

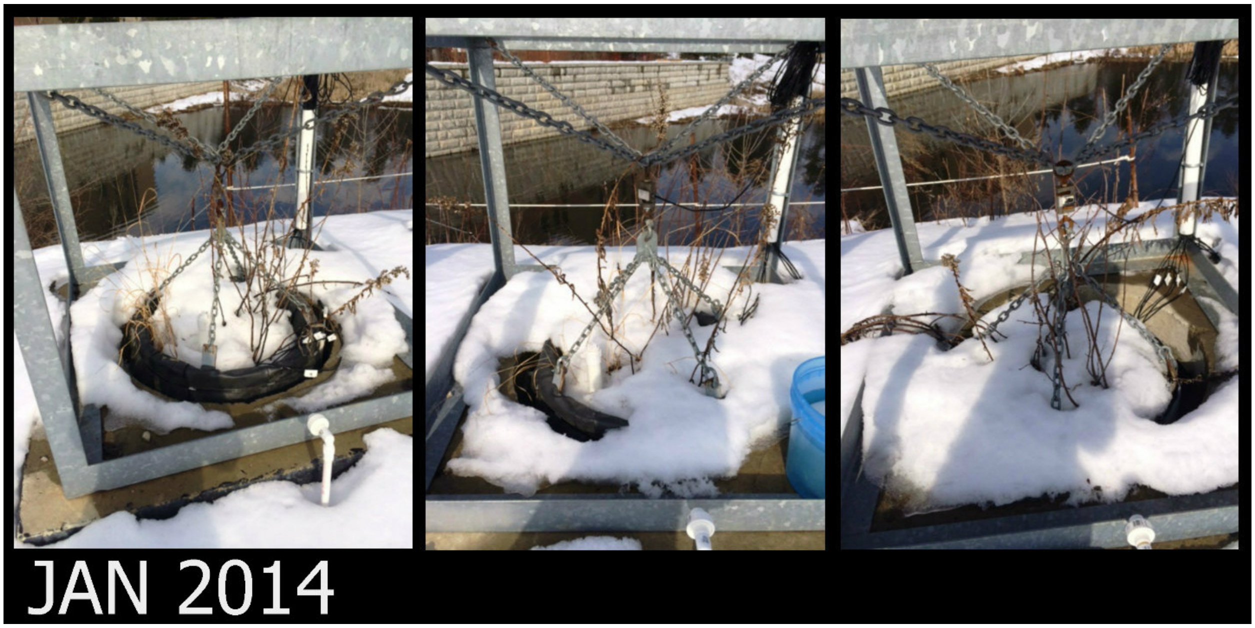
Sandy loam (left), sand (middle), and sand IWS (right) in August of 2013.

Sandy loam (left), sand (middle), and sand IWS (right) in September of 2013.

Sandy loam (left), sand (middle), and sand IWS (right) in October of 2013.

Sandy loam (left), sand (middle), and sand IWS (right) in November of 2013.

Sandy loam (left), sand (middle), and sand IWS (right) in December of 2013.



Sandy loam (left), sand (middle), and sand IWS (right) in January of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in February of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in March of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in April of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in May of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in June of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in July of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in August of 2014.

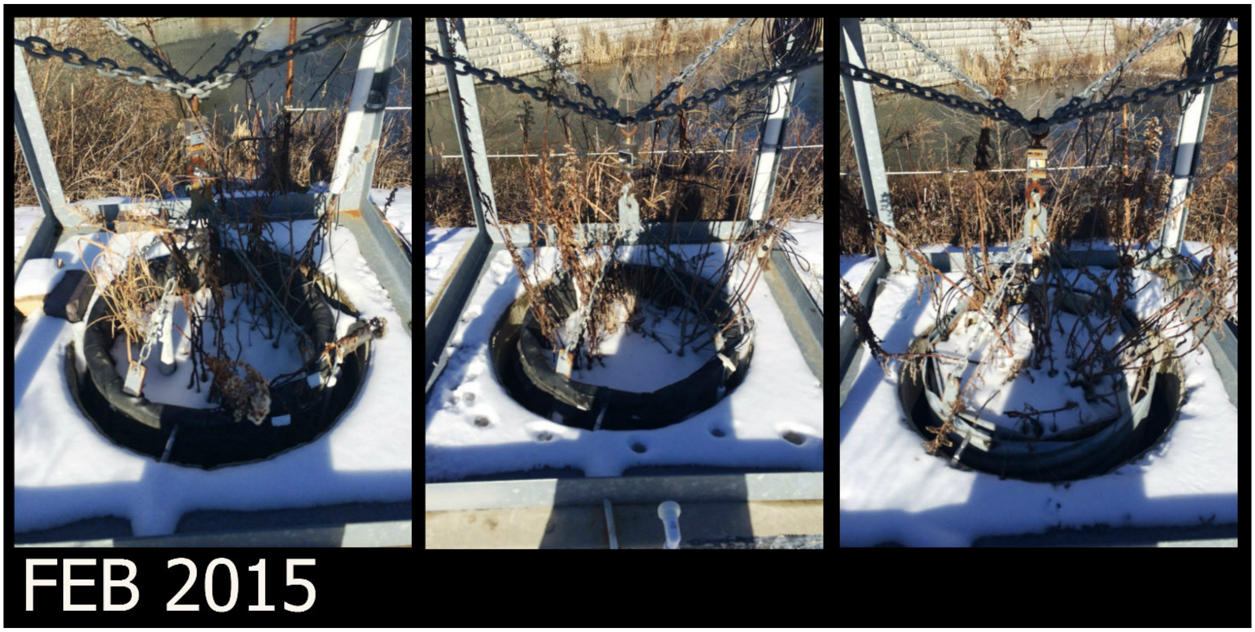
Sandy loam (left), sand (middle), and sand IWS (right) in September of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in October of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in November of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in December of 2014.

Sandy loam (left), sand (middle), and sand IWS (right) in January of 2015.



Sandy loam (left), sand (middle), and sand IWS (right) in February of 2015.

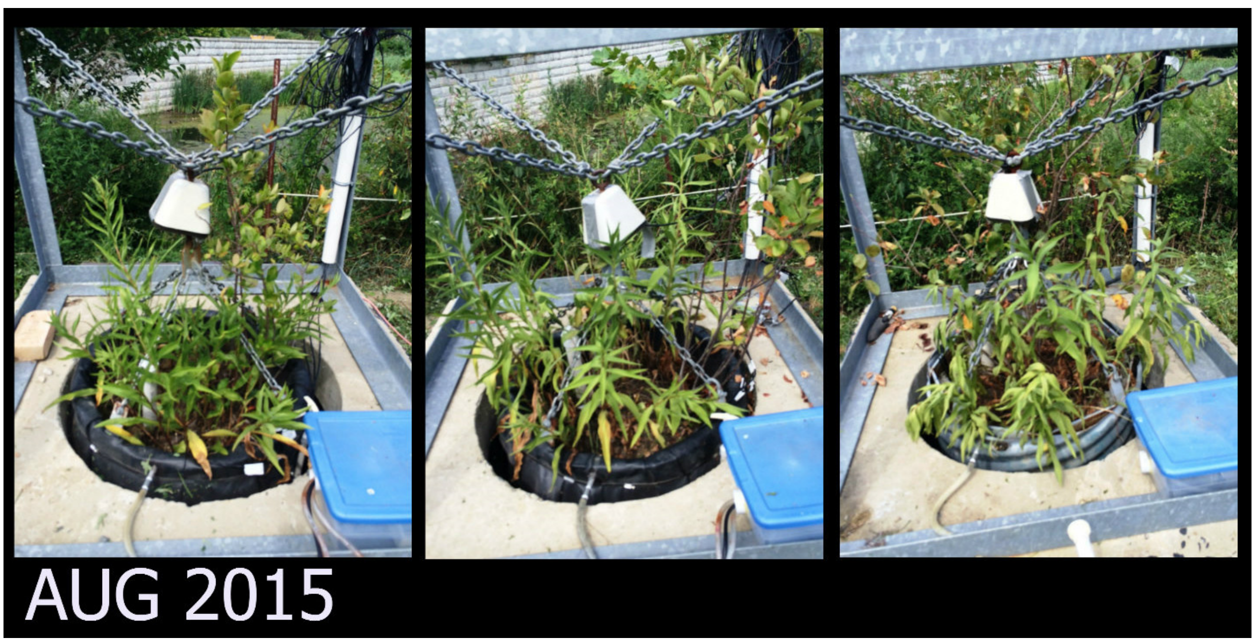
Sandy loam (left), sand (middle), and sand IWS (right) in March of 2015.

Sandy loam (left), sand (middle), and sand IWS (right) in April of 2015.

Sandy loam (left), sand (middle), and sand IWS (right) in May of 2015.

Sandy loam (left), sand (middle), and sand IWS (right) in June of 2015.

Sandy loam (left), sand (middle), and sand IWS (right) in July of 2015.

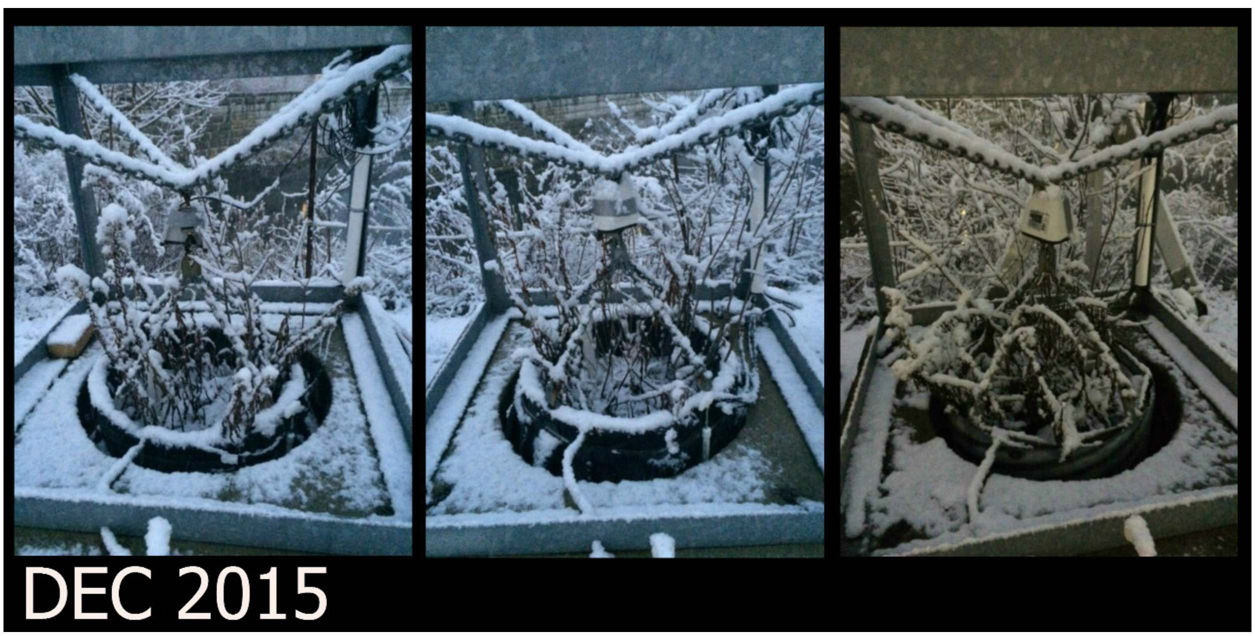


Sandy loam (left), sand (middle), and sand IWS (right) in August of 2015.

Sandy loam (left), sand (middle), and sand IWS (right) in September of 2015.

Sandy loam (left), sand (middle), and sand IWS (right) in October of 2015.

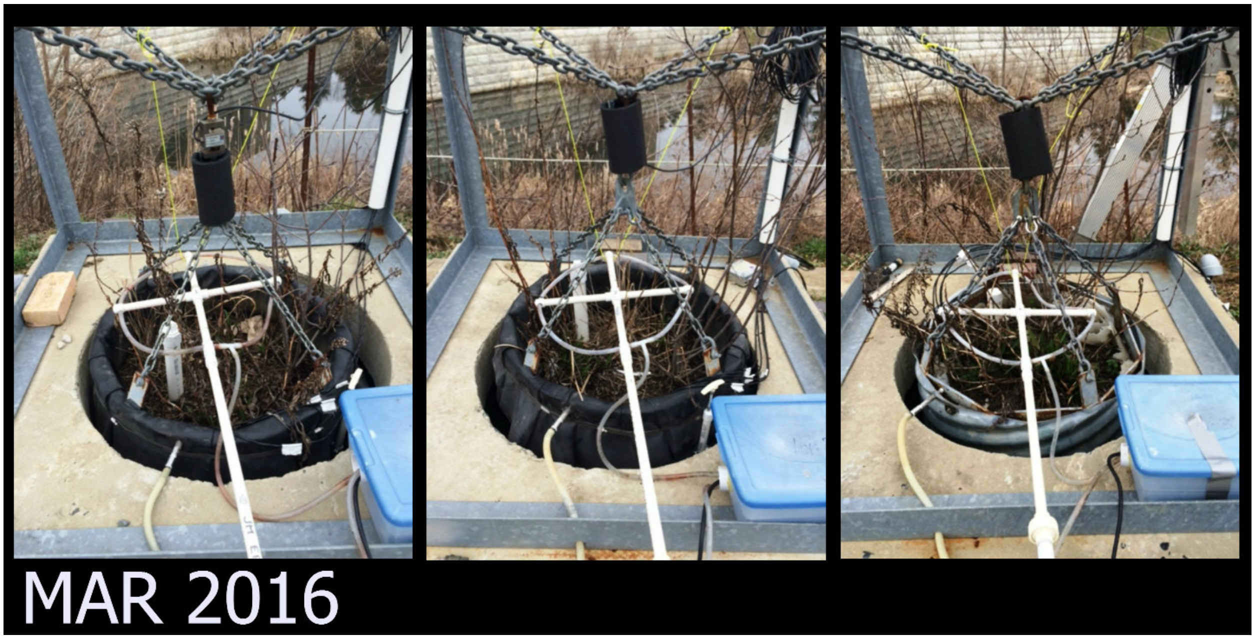
Sandy loam (left), sand (middle), and sand IWS (right) in November of 2015.



Sandy loam (left), sand (middle), and sand IWS (right) in December of 2015.

Sandy loam (left), sand (middle), and sand IWS (right) in January of 2016.

Sandy loam (left), sand (middle), and sand IWS (right) in February of 2016.



Sandy loam (left), sand (middle), and sand IWS (right) in March of 2016.

Sandy loam (left), sand (middle), and sand IWS (right) in April of 2016.

Sandy loam (left), sand (middle), and sand IWS (right) in May of 2016.

Sandy loam (left), sand (middle), and sand IWS (right) in June of 2016.

Sandy loam (left), sand (middle), and sand IWS (right) in July of 2016.

APPENDIX B PLANT INSPECTION PHOTOS: BENCH SCALE LYSIMETERS

Sandy loam, loamy sand, loam, silt loam, clay loam (left to right) in September of 2015.

Sandy loam, loamy sand, loam, silt loam, clay loam (left to right) in October of 2015.

Sandy loam, loamy sand, loam, silt loam, clay loam (left to right) in April of 2016.

Sandy loam, loamy sand, loam, silt loam, clay loam (left to right) in May of 2016.

Sandy loam, loamy sand, loam, silt loam, clay loam (left to right) in June of 2016.

Sandy loam, loamy sand, loam, silt loam, clay loam (left to right) in July of 2016.

Sandy loam, loamy sand, loam, silt loam, clay loam (left to right) in August of 2016.

APPENDIX C DATA SET POINTS REMOVED

Rain Garden Weighing Lysimeters

Year	Date(s) Excluded	Reason
2013	8/13	Rain intensity
	10/8-10/12	Maintenance
	11/26-11/28	Rain
	11/5	Maintenance
	11/22	Maintenance
	11/26-11/28	Rain intensity
	12/6-12/7	Rain intensity
	12/9-12/10	Rain intensity
	12/14-12/15	Cold
	12/19	Cold
	12/23-12/24	Cold
	1/2-1/4	Cold
	1/7-1/12	Cold
	1/14-1/15	Cold
	1/19	Cold
	1/22-1/24	Cold
2014	1/30	Cold
	2/5-2/6	Cold
	2/11-2/12	Cold
	2/18	Cold
	2/21-2/25	Cold
	2/27-2/28	Cold
	3/3	Cold
	3/6-3/9	Cold
	3/12-3/13	Cold
	3/19-3/24	Cold
	3/27-4/5	Simulated event caused overflow
	4/15-4/18	Simulated event
	4/30-5/2	Simulated event
	5/16-5/17	Simulated event
	7/3-7/10	Offline
	7/25-7/28	Simulated event and rain intensity
	8/6-8/9	Simulated event and rain intensity
	8/21-8/24	Simulated event and rain intensity
	9/1-9/2	Rain intensity
	9/7	Simulated event
	9/23/2016-2/7/2015	Sandy Loam UO Offline

	9/24-9/26	Simulated event and rain intensity
	10/16	Rain intensity
	10/22-10/23	Simulated event
	10/29-11/1	Simulated event and rain intensity
	11/17-11/18	Rain intensity
	12/9-12/10	Rain intensity
	12/24-12/25	Rain intensity
2015	1/1-1/5	Cold
	1/8-1/29	Cold
	1/31-2/7	Cold
	2/9	Cold
	2/13-3/3	Cold
	3/5	Cold
	3/9-3/15	Cold
	4/20-4/21	Simulated event
	7/10-7/13	Offline
	7/15	Rain intensity
	8/20	Rain intensity
	8/24-8/25	Simulated event
	9/10-9/11	Simulated event
	9/29-9/30	Simulated event
	10/2-10/3	Rain intensity
	10/12-10/13	Simulated event
	10/20-10/22	Simulated event
	10/29	Rain intensity
	11/10	Rain intensity
	11/16	Maintenance
	11/19-11/20	Rain intensity
	12/1-12/3	Rain intensity
	12/12-12/18	Cold
	12/22-12/31	Cold
	1/1-1/2	Cold
	1/8-1/17	Cold
	1/20	Cold
	1/22-1/24	Cold
2016	1/26-2/8	Cold
	2/9-2/11	Cold
	2/13-2/22	Cold
	2/24-2/28	Cold
	3/8-3/9	Simulated event
	3/14	Rain intensity

3/21-3/22	Simulated event
4/6-4/8	Simulated event
4/10	Rain intensity
4/19-4/20	Simulated event
5/10-5/11	Simulated event
5/24-5/26	Rain intensity
5/31-6/2	Simulated event
6/6	Maintenance
6/12-6/13	Simulated event
6/18-6/20	Maintenance
6/22-6/23	Simulated event
6/25-6/26	Rain intensity
7/6-7/8	Simulated event

Rain Garden Bench Scale Study

Year	Date(s) Excluded	Reason
2015	8/24-8/26	Simulated event
	9/7-9/8	Weights not taken
	9/10-9/11	Simulated event
	9/25-9/27	Weights not taken
	9/29-9/30	Simulated event
	9/31-10/1	Weights not taken
	10/2-10/3	Simulated event
	10/10	Weights not taken
	10/11-10/13	Simulated event
	10/20-10/21	Simulated event
	10/28-10/29	Simulated event
	11/31-3/1	Weights not taken (Winter)
2016	3/8-3/9	Simulated event
	3/13-3/15	Simulated event
	3/21-3/22	Simulated event
	3/23-3/28	Weights not taken
	4/6-4/8	Simulated event
	4/11	Simulated event
	4/17	Weights not taken
	4/19-4/20	Simulated event
	4/27-4/30	Simulated event
	5/5-5/7	Simulated event
	5/20-5/22	Simulated event
	5/29-6/2	Simulated event

6/5	Weights not taken
6/12-6/13	Simulated event
6/18	Weights not taken
6/22-6/23	Simulated event
7/4	Weights not taken
7/5-7/6	Simulated event
7/9	Weights not taken
7/23	Weights not taken
7/25-7/26	Simulated event
7/29-8/1	Simulated event
8/11	Weights not taken
8/13	Simulated event
8/17	Weights not taken
8/21-8/22	Simulated event

APPENDIX D SWAP: MAIN FILE EXAMPLE

Example: Sandy loam UO

```
**********************************************************************************
* Filename: Lys1.swp
* Contents: Main input data
**********************************************************************************
* Comment area: simulate bioretention rain garden: Sandy Loam UO for 3 yrs
*
**********************************************************************************

*   The main input file .swp contains the following sections:
*          - General section
*          - Meteorology section
*          - Crop section
*          - Soil water section
*          - Lateral drainage section
*          - Bottom boundary section
*          - Heat flow section
*          - Solute transport section


*** GENERAL SECTION ***

**********************************************************************************
* Part 1: Environment

  PROJECT   = 'Lys1'           ! Project description, [A80]
  PATHWORK  = '.\SWAP_Files\'    ! Path to work folder, [A80]
  PATHATM   = '.\SWAP_Files\'    ! Path to folder with weather files, [A80]
  PATHCROP  = '.\SWAP_Files\'    ! Path to directory with crop files, [A80]
  PATHDRAIN = '.\SWAP_Files\'    ! Path to folder with drainage files, [A80]
  SWSCRE    = 0                ! Switch, display progression of simulation run:
                        !  SWSCRE = 0:  no display to screen
                        !  SWSCRE = 1:  display water balance to screen
                        !  SWSCRE = 2:  display daynumber to screen
  SWERROR   = 1                ! Switch for printing errors to screen [Y=1, N=0]
**********************************************************************************


**********************************************************************************
* Part 2: Simulation period
*
  TSTART  = 13-jul-2013 ! Start date of simulation run, give day-month-year, [dd-mmm-yyyy]
  TEND    = 13-jul-2016 ! End   date of simulation run, give day-month-year, [dd-mmm-yyyy]
**********************************************************************************


**********************************************************************************
* Part 3: Output dates

* Number of output times during a day
  NPRINTDAY = 1      ! Number of output times during a day, [1..1000, I]

* If NPRINTDAY = 1, specify dates for output of state variables and fluxes
  SWMONTH = 0        ! Switch, output each month, [Y=1, N=0]
```

* If SWMONTH = 0, choose output interval and/or specific dates
PERIOD = 1 ! Fixed output interval, ignore = 0, [0..366, I]
SWRES = 0 ! Switch, reset output interval counter each year, [Y=1, N=0]
SWODAT = 0 ! Switch, extra output dates are given in table, [Y=1, N=0]

* If SWODAT = 1, list specific dates [dd-mmm-yyyy], maximum MAOUT dates:
OUTDATINT =
13-jul-2013
13-jul-2016
* End of table

* Output times for overall water and solute balances in *.BAL and *.BLC file
* Output can be provided at a fixed date in a year or at different dates:
SWYRVAR = 1 ! SWYRVAR = 0: each year output of balances at the same date
! SWYRVAR = 1: output of balances at different dates

* If SWYRVAR = 0 specify fixed date:
DATEFIX = 13 07 ! Specify day and month for output of yearly balances, [dd mm]

* If SWYRVAR = 1 specify all output dates [dd-mmm-yyyy], maximum MAOUT dates:
OUTDAT =
22-jul-2013
27-jul-2013
31-jul-2013
12-aug-2013
27-aug-2013
20-sep-2013
11-oct-2013
26-nov-2013
28-mar-2014
14-apr-2014
29-apr-2014
15-may-2014
26-may-2014
08-jun-2014
24-jun-2014
01-jul-2014
13-jul-2014
26-jul-2014
11-aug-2014
20-aug-2014
30-aug-2014
04-sep-2014
23-sep-2014
14-oct-2014
21-oct-2014
28-oct-2014
16-nov-2014
02-mar-2015
19-apr-2015
31-may-2015
17-jun-2015
25-jun-2015
08-jul-2015
14-jul-2015
19-aug-2015
23-aug-2015

```
  09-sep-2015
  28-sep-2015
  11-oct-2015
  19-oct-2015
  27-oct-2015
  09-nov-2015
  18-nov-2015
  05-apr-2016
  09-apr-2016
  18-apr-2016
  30-apr-2016
  05-may-2016
  09-may-2016
  20-may-2016
  28-may-2016
  11-jun-2016
  21-jun-2016
  03-jul-2016
* End of table
********************************************************************************


********************************************************************************
* Part 4: Output files

* General information
  OUTFIL   = 'Result1' ! Generic file name of output files, [A16]
  SWHEADER = 1        ! Print header at the start of each balance period, [Y=1, N=0]

* Optional files
  SWVAP  = 1       ! Switch, output profiles of moisture, solute and temperature, [Y=1, N=0]
  SWBLC  = 1       ! Switch, output file with detailed yearly water balance, [Y=1, N=0]
  SWATE  = 0       ! Switch, output file with soil temperature profiles, [Y=1, N=0]
  SWBMA  = 0       ! Switch, output file with water fluxes, only for macropore flow, [Y=1, N=0]
  SWDRF  = 0       ! Switch, output of drainage fluxes, only for extended drainage, [Y=1, N=0]
  SWSWB  = 0       ! Switch, output surface water reservoir, only for extended drainage, [Y=1, N=0]

* Output for water quality models (PEARL, ANIMO) or other specific use (SWAFO to DZNEW)

* Optional output files
  SWAFO  = 1       ! Switch, output file with formatted hydrological d0ata
              ! SWAFO = 0: no output
              ! SWAFO = 1: output to a file named *.AFO
              ! SWAFO = 2: output to a file named *.BFO

  SWAUN  = 1       ! Switch, output file with unformatted hydrological data
              ! SWAUN = 0: no output
              ! SWAUN = 1: output to a file named *.AUN
              ! SWAUN = 2: output to a file named *.BUN

* Critical deviation of water balance; in case of larger deviation, an error file is created (*.DWB.CSV)
  CRITDEVMASBAL = 0.00001  ! Critical Deviation in water balance during PERIOD [0.0..1.0 cm, R]

* If SWAFO = 1 or 2, or SWAUN = 1 or 2: fine vertical discretization can be lumped
  SWDISCRVERT = 0   ! SWDISCRVERT = 0: no conversion
              ! SWDISCRVERT = 1: convert vertical discretization,

* If SWDISCRVERT = 1 then specify:
```

```
 NUMNODNEW = 3    ! New number of nodes [1..macp, I, -]
* List thickness of each compartment, total thickness should correspond to Soil Water Section, part 4
 DZNEW     = 10.0 25.0 31.0 ! thickness of compartments [1.0d-6...5.0d2, cm, R]
**********************************************************************************


*** METEOROLOGY SECTION ***

**********************************************************************************
* General data

* File name
 METFIL = 'LysdailyET'  ! File name of meteorological data without extension .YYY, [A200]
                        ! Extension is equal to last 3 digits of year, e.g. 003 denotes year 2003

* Use of reference evapotranspiration data from meteorological file instead of basic data
 SWETR  =  1           ! Switch, use reference ET values of meteo file [Y=1, N=0]

* If SWETR = 0, specify:
 LAT    =    40.038     ! Latitude of meteo station, [-60..60 degrees, R, North = +]
 ALT    =   124.887     ! Altitude of meteo station, [-400..3000 m, R]
 ALTW   =     2.0       ! Altitude of wind speed measurement (10 m is default) [0..99 m, R]

* Use of detailed meteorological records for both ET and rainfall (< 1 day) instead of daily values
 SWMETDETAIL = 0       ! Switch, use detailed meteorological records of both ET and rainfall [Y=1, N=0]

* In case of detailed meteorological weather records (SWMETDETAIL = 1), specify:
 NMETDETAIL = 1        ! Number of weather data records per day, [1..96 -, I]

* In case of daily meteorological weather records (SWMETDETAIL = 0):
 SWETSINE = 0          ! Switch, distribute daily Tp and Ep according to sinus wave [Y=1, N=0]

 SWRAIN = 3            ! Switch for use of actual rainfall intensity (only if SWMETDETAIL = 0):
                       ! SWRAIN = 0: Use daily rainfall amounts
                       ! SWRAIN = 1: Use daily rainfall amounts + mean intensity
                       ! SWRAIN = 2: Use daily rainfall amounts + duration
                       ! SWRAIN = 3: Use short time rainfall intensities, as supplied in separate file

* If SWRAIN = 1, then specify mean rainfall intensity RAINFLUX [0.d0..1000.d0 mm/d, R]
* as function of time TIME [0..366 d, R], maximum 30 records
  TIME    RAINFLUX
   1.0       20.0
 360.0       20.0
* End of table

* If SWRAIN = 3, then specify file name of file with detailed rainfall data
  RAINFIL = 'LysRain'    ! File name of detailed rainfall data without extension .YYY, [A200]
                         ! Extension is equal to last 3 digits of year, e.g. 003 denotes year 2003
**********************************************************************************


*** CROP SECTION ***

**********************************************************************************
* Part 1: Crop rotation scheme during simulation period

* Specify information for each crop (maximum MACROP):
* CROPSTART  = date of crop emergence, [dd-mmm-yyyy]
```

```
* CROPEND    = date of crop harvest, [dd-mmm-yyyy]
* CROPNAME   = crop name, [A40]
* CROPFIL    = name of file with crop input parameters without extension .CRP, [A40]
* CROPTYPE   = type of crop model: simple = 1, detailed general = 2, detailed grass = 3

  CROPSTART     CROPEND      CROPNAME   CROPFIL    CROPTYPE
  13-jul-2013   30-nov-2013  '13Grass1'  '13Grass1'    1
  01-apr-2014   30-nov-2014  '14Grass1'  '14Grass1'    1
  01-apr-2015   30-nov-2015  '15Grass1'  '15Grass1'    1
  01-apr-2016   13-jul-2016  '16Grass1'  '16Grass1'    1
* End of table
**********************************************************************************


**********************************************************************************
* Part 2: Fixed irrigation applications

* Switch for fixed irrigation applications
  SWIRFIX = 0    ! SWIRFIX = 0: no irrigation applications are prescribed
                 ! SWIRFIX = 1: irrigation applications are prescribed

* If SWIRFIX = 1, specify:

* Switch for separate file with fixed irrigation applications
* SWIRGFIL  = 0  ! SWIRGFIL = 0: data are specified in the .swp file
                 ! SWIRGFIL = 1: data are specified in a separate file

* If SWIRGFIL  = 0 specify information for each fixed irrigation event (max. MAIRG):
* IRDATE   = date of irrigation, [dd-mmm-yyyy]
* IRDEPTH  = amount of water, [0.0..100.0 cm, R]
* IRCONC   = concentration of irrigation water, [0.0..1000.0 mg/cm3, R]
* IRTYPE   = type of irrigation: sprinkling = 0, surface = 1

      IRDATE   IRDEPTH    IRCONC   IRTYPE
  05-jan-1980      0.5    1000.0       1
* end of table

* If SWIRGFIL  = 1, specify name of file with data of fixed irrigation applications:
* IRGFIL = 'testirri'      ! File name without extension .IRG [A16]
**********************************************************************************


*** SOIL WATER SECTION ***

**********************************************************************************
* Part 1: Initial soil moisture condition

 SWINCO = 1 ! Switch, type of initial soil moisture condition:
          ! 1 = pressure head as function of depth is input
          ! 2 = pressure head of each compartment is in hydrostatic equilibrium
          !    with initial groundwater level
          ! 3 = read final pressure heads from output of previous Swap simulation

* If SWINCO = 1, specify (maximum MACP):
* ZI = soil depth, [-10000..0 cm, R]
* H  = initial soil water pressure head, [-1.d10..1.d4 cm, R]

    ZI       H
```

```
  -10.0     -7.1
  -35.0    155.5
  -66.0    -22.8
* End of table

* If SWINCO = 2, specify:
  GWLI   = -500.0  ! Initial groundwater level, [-10000..100 cm, R]

* If SWINCO = 3, specify:
  INIFIL = '.\SWAP_Files\result.end'   ! name of final with extension .END [a200]
**********************************************************************************


**********************************************************************************
* Part 2: Ponding, runoff and runon

* Ponding
  PONDMX  = 15.0  ! In case of ponding, minimum thickness for runoff, [0..1000 cm, R]

* Runoff
  RSRO    = 0.001 ! Drainage resistance for surface runoff [0.001..1.0 d, R]
  RSROEXP = 2.5   ! Exponent in drainage equation of surface runoff [0.1..10.0 -, R]

* Runon
* Specify whether runon data are provided in extra input file
  SWRUNON = 0     ! 0 = No input of runon data
                  ! 1 = Runon data are provided in extra input file

* If SWRUNON = 1, specify name of file with runon input data
* This file may be an output *.inc file (with only 1 header) of a previous Swap-simulation
  RUFIL = 'runon.inc' ! File name with extension [A80]
**********************************************************************************


**********************************************************************************
* Part 3: Soil evaporation
*
  SWCFBS = 0   ! Switch for use of soil factor CFBS to calculate Epot from ETref
           ! 0 = CFBS is not used
           ! 1 = CFBS is used

* If SWCFBS = 1, specify soil factor CFBS:
  CFBS   = 1.0 ! Coefficient to derive Epot from ETref [0.1..1.5 -, R]
*
*
  SWREDU = 0   ! Switch, method for reduction of potential soil evaporation:
           ! 0 = reduction to maximum Darcy flux
           ! 1 = reduction to maximum Darcy flux and to maximum Black (1969)
           ! 2 = reduction to maximum Darcy flux and to maximum Bo/Str. (1986)

 COFRED = 0.35 ! Soil evaporation coefficient of Black, [0..1 cm/d1/2, R],
           ! or Boesten/Stroosnijder, [0..1 cm1/2, R]

 RSIGNI =  0.5 ! Minimum rainfall to reset method of Black [0..1 cm/d, R]
**********************************************************************************


**********************************************************************************
```

```
* Part 4: Vertical discretization of soil profile

* Specify the following data (maximum MACP lines):
* ISOILLAY = number of soil layer, start with 1 at soil surface, [1..MAHO, I]
* ISUBLAY  = number of sub layer, start with 1 at soil surface, [1..MACP, I]
* HSUBLAY  = height of sub layer, [0.0..1000.0 cm, R]
* HCOMP    = height of compartments in this layer, [0.0..1000.0 cm, R]
* NCOMP    = number of compartments in this layer (= HSUBLAY/HCOMP), [1..MACP, I]

 ISOILLAY ISUBLAY  HSUBLAY    HCOMP    NCOMP
    1       1       10.0      0.5       20
    1       2       56.0      1.0       56
* end of table
**********************************************************************************


**********************************************************************************
* Part 5: Soil hydraulic functions

* Switch for Mualem - van Genuchten parameters or detailed tabels:
  SWSOPHY = 0   ! 0 = Mualem - van Genuchten parameters
                ! 1 = Detailed tables

* If SWSOPHY = 0, specify for each soil layer (maximum MAHO):
* ISOILLAY1 = number of soil layer, as defined in part 4 [1..MAHO, I]
* ORES   = Residual water content, [0..0.4 cm3/cm3, R]
* OSAT   = Saturated water content, [0..0.95 cm3/cm3, R]
* ALFA   = Shape parameter alfa of main drying curve, [0.0001..1 /cm, R]
* NPAR   = Shape parameter n, [1..4 -, R]
* KSAT   = Saturated vertical hydraulic conductivity, [1.d-5..1000 cm/d, R]
* LEXP   = Exponent in hydraulic conductivity function, [-25..25 -, R]
* ALFAW  = Alfa parameter of main wetting curve in case of hysteresis, [0.0001..1 /cm, R]
* H_ENPR = Air entry pressure head [-40.0..0.0 cm, R]

  ISOILLAY1  ORES    OSAT     ALFA    NPAR     KSAT      LEXP    ALFAW H_ENPR  KSATEXM
      1    0.000   0.436     0.539   1.306  050.00     0.500    0.539 -0.1 050.00
* --- end of table

* If SWSOPHY = 1, specify names of input files [A80] with soil hydraulic tables for each soil layer:
  FILENAMESOPHY = 'topsoil_sand_B2.csv', 'subsoil_sand_O2.csv'
**********************************************************************************


**********************************************************************************
* Part 6: Hysteresis of soil water retention function

* Switch for hysteresis:
  SWHYST = 0   ! 0 = no hysteresis
               ! 1 = hysteresis, initial condition wetting
               ! 2 = hysteresis, initial condition drying

* If SWHYST = 1 or 2, specify:
 TAU = 0.2     ! Minimum pressure head difference to change wetting-drying, [0..1 cm, R]
**********************************************************************************


**********************************************************************************
* Part 7: Maximum rooting depth
```

```
 RDS  = 66.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]
**********************************************************************************


**********************************************************************************
* Part 8: Similar media scaling of soil hydraulic functions

 SWSCAL = 0 ! Switch for similar media scaling [Y=1, N=0]; no hysteresis is allowed
         ! in case of similar media scaling (SWHYST = 0)

* If SWSCAL = 1, specify:
 NSCALE = 3 ! Number of simulation runs, [1..MASCALE, I]

* Supply the scaling factors for each simulation run and each soil layer:

 RUN    SOIL1     SOIL2
  1      0.5       2.0
  2      1.0       1.0
  3      2.0       0.5
  4      1.0       1.0
  5      3.0       3.0
* End of table


* Part 9: Preferential flow due to macropores

 SWMACRO = 0    ! Switch for macropore flow, [0..2, I]:
            ! 0 = no macropore flow
            ! 1 = macropore flow


* Part 10: Snow and frost

* Snow
 SWSNOW = 0   ! Switch, calculate snow accumulation and melt, [Y=1, N=0]

* If SWSNOW = 1, specify:
 SNOWINCO = 22.0     ! Initial snow water equivalent, [0.0...1000.0 cm, R]
 TEPRRAIN = 2.0      ! Temperature above which all precipitation is rain,[ 0.0...5.0 ºC, R]
 TEPRSNOW = -2.0     ! Temperature below which all precipitation is snow,[-5.0...0.0 ºC, R]
 SNOWCOEF = 0.3      ! Snowmelt calibration factor, [0.0...10.0 -, R]

* Frost
 SWFROST = 0  ! Switch, in case of frost: reduce soil water flow, [Y=1, N=0]

* If SWFROST = 1, then specify soil temperature to start end end flux-reduction
 tfroststa = 0.0     ! Soil temperature (ºC) where reduction of water fluxes starts [-10.0,5.0, oC, R]
 tfrostend = -1.0    ! Soil temperature (ºC) where reduction of water fluxes ends [-10.0,5.0, oC, R]


* Part 11 Numerical solution of Richards' equation

 DTMIN       = 1.0d-7 ! Minimum timestep, [1.d-7..0.01 d, R]
 DTMAX       = 0.01   ! Maximum timestep, [ 0.01..0.5 d, R]
 GWLCONV     = 100.0  ! Maximum dif. Groundwater level between iterations, [1.d-5..1000 cm, R]
 CritDevh1Cp  = 2.0d-2 ! Maximum relative difference in pressure heads per compartment, [1.0d-10..0.1 -, R]
 CritDevh2Cp  = 1.0d-1 ! Maximum difference in pressure heads per compartment, [1.0d-10..1.0 cm, R]
```

```
 CritDevPondDt = 1.0d-4 ! Maximum water balance error of ponding layer, [1.0d-6..0.1 cm, R]
 MaxIt        = 100    ! Maximum number of iteration cycles, [5..100 -, I]
 MaxBackTr     = 10     ! Maximum number of back track cycles within an iteration cycle, [1..10 -,I]

* Switch for mean of hydraulic conductivity, [1..4 -, I]:
* 1 = unweighted  arithmic mean; 2 = weighted  arithmic mean
* 3 = unweighted geometric mean; 4 = weighted geometric mean
 Swkmean = 1

* Switch for explicit/implicit solution Richards equation with hydraulic conductivity, [1..2 -, I]:
 SwkImpl = 0   ! 0 = explicit solution
           ! 1 = implicit solution
**********************************************************************************


*** LATERAL DRAINAGE SECTION ***

**********************************************************************************
* Specify whether lateral drainage to surface water should be included

 SWDRA = 0  ! Switch, simulation of lateral drainage:
        ! 0 = No simulation of drainage
        ! 1 = Simulation with basic drainage routine
        ! 2 = Simulation of drainage with surface water management

* If SWDRA = 1 or SWDRA = 2 specify name of file with drainage input data:
 DRFIL = 'Hupsel' ! File name with drainage input data without extension .DRA, [A16]
**********************************************************************************


*** BOTTOM BOUNDARY SECTION ***

**********************************************************************************
* Bottom boundary condition

 SWBBCFILE  = 0    ! Switch for file with bottom boundary conditions:
             ! SWBBCFILE = 0: data are specified in the .swp file
             ! SWBBCFILE = 1: data are specified in a separate file

* If SWBBCFILE = 1 specify name of file with bottom boundary conditions:
* BBCFIL = ‘ ‘      ! File name without extension .BBC [A16]

* If SWBBCFILE = 0, select one of the following options:
        ! 1  Prescribe groundwater level
        ! 2  Prescribe bottom flux
        ! 3  Calculate bottom flux from hydraulic head of deep aquifer
        ! 4  Calculate bottom flux as function of groundwater level
        ! 5  Prescribe soil water pressure head of bottom compartment
        ! 6  Bottom flux equals zero
        ! 7  Free drainage of soil profile
        ! 8  Free outflow at soil-air interface

SWBOTB = 8  ! Switch for bottom boundary [1..8,-,I]

* Options 6,7 and 8 require no additional bottom input data
**********************************************************************************
```

```
**********************************************************************************
* SWBOTB = 1  Prescribe groundwater level

* specify DATE [dd-mmm-yyyy] and groundwater level [cm, -10000..1000, R]
*
     DATE1    GWLEVEL        ! (max. MABBC records)
 01-jan-2001   -197.5
 31-jan-2001   -197.5
* End of table
**********************************************************************************


**********************************************************************************
* SWBOTB = 2   Prescribe bottom flux

* Specify whether a sine or a table are used to prescribe the bottom flux:
  SW2    = 2      ! 1 = sine function; 2 = table

* In case of sine function (SW2 = 1), specify:
  SINAVE =  0.1   ! Average value of bottom flux, [-10..10 cm/d, R, + = upwards]
  SINAMP =  0.05  ! Amplitude of bottom flux sine function, [-10..10 cm/d, R]
  SINMAX =  91.0  ! Time of the year with maximum bottom flux, [1..366 d, R]

* In case of table (SW2 = 2), specify date [dd-mmm-yyyy] and bottom flux QBOT2
* [-100..100 cm/d, R, positive = upwards]:

      DATE2     QBOT2          ! (maximum MABBC records)
  01-jan-1980      0.1
  30-jun-1980      0.2
  23-dec-1980     0.15
* End of table
**********************************************************************************


**********************************************************************************
* SWBOTB = 3    Calculate bottom flux from hydraulic head in deep aquifer

* Switch to suppress vertical hydraulic resistance between model bottom and groundwater level
  SWBOTB3RESVERT = 0 ! 0 = Include vertical hydraulic resistance
                 ! 1 = Suppress vertical hydraulic resistance

* Switch for numerical solution of bottom flux: 0 = explicit, 1 = implicit
  SWBOTB3IMPL = 0    ! 0 = explicit solution (choose always when SHAPE < 1.0)
                 ! 1 = implicit solution

* Specify:
  SHAPE  =   0.79  ! Shape factor to derive average groundwater level, [0.0..1.0 -, R]
  HDRAIN =  -110.0 ! Mean drain base to correct for average groundwater level, [-10000..0 cm, R]
  RIMLAY =   500.0 ! Vertical resistance of aquitard, [0..10000 d, R]

* Specify whether a sine function or a table are used to prescribe hydraulic head of deep aquifer:
  SW3    = 1       ! 1 = sine function;  2 = table

* In case of sine function (SW3  = 1), specify:
  AQAVE  =  -140.0 ! Average hydraulic head in underlaying aquifer, [-10000..1000 cm, R]
  AQAMP  =    20.0 ! Amplitude hydraulic head sinus wave, [0..1000 cm, R]
  AQTMAX =  120.0  ! First time of the year with maximum hydraulic head, [1..366 d, R]
  AQPER  =  365.0  ! Period hydraulic head sinus wave, [1..366 d, I]
```

```
* In case of table (SW3  = 2), specify date [dd-mmm-yyyy] and average hydraulic head
* HAQUIF in underlaying aquifer [-10000..1000 cm, R]:

      DATE3    HAQUIF          ! (maximum MABBC records)
 01-jan-1980     -95.0
 30-jun-1980    -110.0
 23-dec-1980     -70.0
* End of table

* An extra groundwater flux can be specified which is added to above specified flux
 SW4   = 1       ! 0 = no extra flux; 1 = include extra flux

* If SW4 = 1, specify date [dd-mmm-yyyy] and bottom flux QBOT4 [-100..100 cm/d, R,
* positive = upwards]:

      DATE4     QBOT4          ! (maximum MABBC records)
 01-jan-1980       1.0
 30-jun-1980     -0.15
 23-dec-1980       1.2
* End of table
**********************************************************************************


**********************************************************************************
* SWBOTB = 4     Calculate bottom flux as function of groundwater level

* Specify whether an exponential relation or a table is used to calculate the bottom flux
* from the groundwater level:
 SWQHBOT = 2       ! 1 = exponential relation;  2 = table

* In case of an exponential relation (SWQHBOT  = 1),
* specify coefficients of relation qbot = A exp (B*abs(groundwater level))
 COFQHA =  0.1  ! Coefficient A, [-100..100 cm/d, R]
 COFQHB =  0.5  ! Coefficient B  [-1..1 /cm, R]

* In case of a table (SWQHBOT  = 2),
* specify groundwaterlevel Htab [-10000..1000, cm, R]  and bottom flux QTAB [-100..100 cm/d, R]
* Htab is negative below the soil surface, Qtab is negative when flux is downward.
 HTAB   QTAB
 -0.1   -0.35
 -70.0  -0.05
-125.0  -0.01
* End of table
**********************************************************************************


**********************************************************************************
* SWBOTB = 5     Prescribe soil water pressure head of bottom compartment

* Specify DATE [dd-mmm-yyyy] and bottom compartment pressure head HBOT5 [-1.d10..1000 cm, R]:

      DATE5     HBOT5          ! (maximum MABBC records)
 01-jan-2001       0.0
 31-dec-2001       0.0
* End of table
**********************************************************************************
```

```
*** HEAT FLOW SECTION ***

**********************************************************************************
* Part 1: Specify whether simulation includes heat flow

  SWHEA  = 0 ! Switch for simulation of heat transport, [Y=1, N=0]
**********************************************************************************

**********************************************************************************
* Part 2: Heat flow calculation method

  SWCALT = 2     ! Switch for method: 1 = analytical method, 2 = numerical method
**********************************************************************************

**********************************************************************************
* Part 3: Analytical method

* If SWCALT = 1 specify the following heat parameters:
  TAMPLI = 10.0 ! Amplitude of annual temperature wave at soil surface, [0..50 C, R]
  TMEAN  = 15.0 ! Mean annual temperature at soil surface, [5..30 C, R]
  TIMREF = 90.0 ! Time in the year with top of sine temperature wave [1..366 d, R]
  DDAMP  = 50.0 ! Damping depth of temperature wave in soil, [0..500 cm, R]
**********************************************************************************

**********************************************************************************
* Part 4: Numerical method

* If SWCALT = 2 specify the following heat parameters:

* Specify for each soil type the soil texture (g/g mineral parts)
* and the organic matter content (g/g dry soil):

  ISOILLAY5  PSAND    PSILT    PCLAY    ORGMAT         ! (maximum MAHO records)
    1       0.80    0.15    0.05    0.100
    2       0.80    0.15    0.05    0.100
* End of table

* If SWINCO = 1 or 2, list initial temperature TSOIL [-20..40 C, R] as function of
* soil depth ZH [-1.0d5..0 cm, R]:

     ZH    TSOIL   ! (maximum MACP records)
   -10.0    15.0
   -40.0    12.0
   -70.0    10.0
   -95.0     9.0
* End of table

* Define top boundary condition:
  SwTopbHea = 1     ! 1 = use air temperature of meteo input file as top boundary
                    ! 2 = use measured top soil temperature as top boundary

* If SwTopbHea = 2, specify name of input file with soil surface temperatures
  TSOILFILE = 'Haarweg' ! File name without extension .TSS, [A16]

* Define bottom boundary condition:
  SwBotbHea = 1     ! 1 = no heat flux; 2 = prescribe bottom temperature
```

```
* If SwBotbHea = 2, specify a tabel with dates and temperatures at bottom boundary

  DATET         TBOT   ! (maximum MABBC records)
  01-jan-1980   -15.0
  30-jun-1980   -20.0
  23-dec-1980   -10.0
* End of table
**********************************************************************************


*** SOLUTE SECTION ***

**********************************************************************************
* Part 1: Specify whether simulation includes solute transport

  SWSOLU = 0 ! Switch for simulation of solute transport, [Y=1, N=0]
**********************************************************************************


**********************************************************************************
* Part 2: Top boundary and initial condition

  CPRE = 0.0    ! Solute concentration in precipitation, [1..100 mg/cm3, R]

* If SWINCO = 1 or 2, list initial solute concentration CML [1..1000 mg/cm3, R]
* as function of soil depth ZC [-10000..0 cm, R], max. MACP records:
     ZC      CML
   -10.0      0.0
   -95.0      0.0
* End of table
**********************************************************************************


**********************************************************************************
* Part 3: Miscellaneous parameters as function of soil depth

* Specify for each soil layer (maximum MAHO)
* ISOILLAY6 = number of soil layer, as defined in soil water section (part 4) [1..MAHO, I]
* LDIS      = dispersion length, [0..100 cm, R]
* KF        = Freundlich adsorption coefficient, [0..100 cm3/mg, R]
* BDENS     = dry soil bulk density, [500..3000 mg/cm3, R]
* DECPOT    = potential decomposition rate, [0..10 /d, R]

 ISOILLAY6    LDIS        KF     BDENS  DECPOT
    1       5.00  0.0001389   1315.00    0.0
    2       5.00  0.0001378   1318.00    0.0
* --- end of Table
**********************************************************************************


**********************************************************************************
* Part 4: Diffusion constant and solute uptake by roots

  DDIF = 0.0    ! Molecular diffusion coefficient, [0..10 cm2/day, R]
  TSCF = 0.0    ! Relative uptake of solutes by roots, [0..10 -, R]
**********************************************************************************
```

```
**********************************************************************************
* Part 5: Adsorption

 SWSP = 0      ! Switch, consider solute adsorption, [Y=1, N=0]

* In case of adsorption (SWSP = 1), specify:
 FREXP = 0.9   ! Freundlich exponent, [0..10 -, R]
 CREF  = 1.0   ! Reference solute concentration for adsorption, [0..1000 mg/cm3, R]
**********************************************************************************


**********************************************************************************
* Part 6: Decomposition

 SWDC = 0      ! Switch, consideration of solute decomposition, [Y=1, N=0]

* In case of solute decomposition (SWDC = 1), specify:
 GAMPAR = 0.0  ! Factor reduction decomposition due to temperature, [0..0.5 /ºC, R]
 RTHETA = 0.3  ! Minimum water content for potential decomposition, [0..0.4 cm3/cm3, R]
 BEXP   = 0.7  ! Exponent in reduction decomposition due to dryness, [0..2 -, R]

* List the reduction of pot. decomposition for each soil type, [0..1 -, R]:

 ISOILLAY7  FDEPTH         ! (maximum MAHO records)
     1      1.00
     2      0.65
* End of table
**********************************************************************************


**********************************************************************************
* Part 7: Solute residence in the saturated zone

 SWBR = 0       ! Switch, consider mixed reservoir of saturated zone [Y=1, N=0]

* Without mixed reservoir (SWBR = 0), specify:
 CDRAIN = 0.1   ! solute concentration in groundwater, [0..100 mg/cm3, R]

* In case of mixed reservoir (SWBR = 1), specify:
 DAQUIF = 110.0 ! Thickness saturated part of aquifer, [0..10000 cm, R]
 POROS  = 0.4   ! Porosity of aquifer, [0..0.6 -, R]
 KFSAT  = 0.2   ! Linear adsorption coefficient in aquifer, [0..100 cm3/mg, R]
 DECSAT = 1.0   ! Decomposition rate in aquifer, [0..10 /d, R]
 CDRAINI = 0.2  ! Initial solute concentration in groundwater, [0..100 mg/cm3, R]
**********************************************************************************
```

APPENDIX E SWAP: CROP FILE EXAMPLE

Example: Sand UO for 2014

```
**********************************************************************************
* Filename: 14Grass2.crp
* Contents: SWAP 3.2 - Crop data of simple model
**********************************************************************************
* Comment area: Modified from original example "NatureGrass" or NatureGrassMod.CRP for RG Simulations
*
**********************************************************************************

*** PLANT GROWTH SECTION ***

**********************************************************************************************
* Part 1: Crop development

  IDEV = 1 ! length of growth period: 1 = fixed, 2 = variable

* If fixed growth period (IDEV = 1), specify:
  LCC  =   244 ! Length of the crop cycle [1..366 days, I]

* If variable growth period (IDEV = 2), specify:
  TSUMEA = -      ! Temperature sum from emergence to anthesis [0..10000 C, R]
  TSUMAM = -      ! Temperature sum from anthesis to maturity  [0..10000 C, R]
  TBASE  = -      ! Start value of temperature sum [-10..30 C, R]
**********************************************************************************************

**********************************************************************************************
* Part 2: Light extinction

  KDIF   =    0.80 ! Extinction coefficient for diffuse visible light [0..2 -, R]
  KDIR   =    0.73 ! Extinction coefficient for direct visible light  [0..2 -, R]
**********************************************************************************************

**********************************************************************************************
* Part 3: Leaf area index or soil cover fraction

  SWGC = 1 ! choice between LAI [=1] or soil cover fraction [=2]

* If SWGC = 1, list leaf area index [0..12 ha/ha, R],    as function of dev. stage [0..2 -,R]:
* If SWGC = 2, list soil cover fraction [0..1 m2/m2, R], as function of dev. stage [0..2 -,R]:

*       DVS   LAI or SCF  ( maximum 36 records)
  GCTB =
      0.00   0.0
      0.10   0.8
      0.30   2.4
      0.50   3.7
      0.60   4.1
      0.80   4.6
      1.00   3.8
      1.10   2.9
      1.20   4.0
      1.30   4.1
      1.70   3.3
      1.90   2.2
```

```
      2.00   1.0
* End of table
**********************************************************************************************

**********************************************************************************************
* Part 4: crop factor or crop height

  SWCF = 1 ! choice between crop factor [=1] or crop height [=2]
* Choose crop factor if ETref is used, either from meteo input file (SWETR = 1) or with Penman-Monteith
* Choose crop height if Penman-Monteith should be used with actual crop height, albedo and resistance

* If SWCF = 1, list crop factor CF [0.5..1.5, R],   as function of dev. stage DVS [0..2 -,R]:
* If SWCF = 2, list crop height CH [0..1000 cm, R], as function of dev. stage DVS [0..2 -,R]:
* (maximum 36 records)

    DVS      CH     CF
    0.0    000.0    0.84
    0.1    490.0    1.01
    0.3    577.0    1.39
    0.5    600.0    1.51
    0.6   1017.0    1.51
    0.8    986.0    1.51
    1.0   1055.0    1.51
    1.1   1024.0    1.51
    1.2    973.0    1.51
    1.3   1220.0    1.51
    1.7   1143.0    1.48
    1.9   1125.0    1.31
    2.0   1107.0    1.23
* End of table

* If SWCF = 2, in addition to crop height list crop specific values for:
  ALBEDO =   0.23 ! crop reflection coefficient [0..1.0 -, R]
  RSC    =   70.0 ! Minimum canopy resistance [0..10^6 s/m, R]
  RSW    =    0.0 ! Canopy resistance of intercepted water [0..10^6 s/m, R]
**********************************************************************************************

**********************************************************************************************
* Part 5: rooting depth

* List rooting depth [0..1000 cm, R], as a function of development stage [0..2 -,R]:

*       DVS   RD    (maximum 36 records)
  RDTB =
      0.0   66.00
      0.1   66.00
      0.3   66.00
      0.5   66.00
      0.6   66.00
      0.8   66.00
      1.0   66.00
      1.1   66.00
      1.2   66.00
      1.3   66.00
      1.7   66.00
      1.9   66.00
      2.0   66.00
* End of table
```

```
**********************************************************************************************

**********************************************************************************************
* Part 6: yield response

* List yield response factor [0..5 -,R], as function of development stage [0..2 -,R]:

*       DVS   KY   (maximum 36 records)
  KYTB =
      0.00   1.00
      0.10   1.00
      0.30   1.00
      0.50   1.00
      0.60   1.00
      0.80   1.00
      1.00   1.00
      1.10   1.00
      1.20   1.00
      1.30   1.00
      1.70   1.00
      1.90   1.00
      2.00   1.00
* End of table
**********************************************************************************************

**********************************************************************************************
* Part 7: soil water extraction by plant roots

  HLIM1  =       0.0 ! No water extraction at higher pressure heads, [-100..100 cm, R]
  HLIM2U =      -1.0 ! h below which optimum water uptake starts for top layer, [-1000..100 cm, R]
  HLIM2L =      -1.0 ! h below which optimum water uptake starts for sub layer, [-1000..100 cm, R]
  HLIM3H =    -200.0 ! h below which water uptake reduction starts at high Tpot, [-10000..100 cm, R]
  HLIM3L =    -800.0 ! h below which water uptake reduction starts at low Tpot, [-10000..100 cm, R]
  HLIM4  =   -8000.0 ! Wilting point, no water extraction at lower pressure heads, [-16000..100 cm, R]
  ADCRH  =       1.0 ! Level of high atmospheric demand, [0..5 cm/d, R]
  ADCRL  =       0.1 ! Level of low atmospheric demand,  [0..5 cm/d, R]
**********************************************************************************************

**********************************************************************************************
* Part 8: salt stress

* only when solutes are simulated (SWSOLU=1 in SWP-file)

* relation between ECsat and crop reduction
  ECMAX  =       5.6 ! ECsat level at which salt stress starts, [0..20 dS/m, R]
  ECSLOP =       7.6 ! Decline of rootwater uptake above ECMAX [0..40 %/dS/m, R]

* relation between concentration and ECsat
  C2ECa  =     1.492 ! coefficient a to convert concentration to EC [0.0..1000.0 -, R]
  C2ECb  =     1.0   ! exponent b to convert concentration to EC [0.0..10.0 -, R]
* Switch to enter factor f (SWC2ECF ) per profile or per soil layer/horizon [1,2 -, I]
*    if SWC2ECF = 1 then enter one C2ECf-value for model profile
*    if SWC2ECF = 2 then enter one C2ECf-value for each soil layer/horizon
  SWC2ECF = 1
* factor f to convert concentration to EC [0.0..10.0 -, R];
*    dependent on SWC2ECF one value for model profile or a value for each soil horizon
  C2ECf  = 1.0
**********************************************************************************************
```

```
*******************************************************************************************
* Part 9: interception

 SWINTER =  0  ! Switch for rainfall interception method:
           ! 0 = No interception calculated
           ! 1 = Agricultural crops (Von Hoyningen-Hune and Braden)
           ! 2 = Trees and forests (Gash)

* In case of interception method for agricultural crops (SWINTER = 1) specify:
 COFAB  =      0.35 ! Interception coefficient Von Hoyningen-Hune and Braden, [0..1 cm, R]

* In case of interception method for trees and forests (SWINTER = 2) specify as function
* of time of the year T [0..366 d, R]:
* PFREE = free throughfall coefficient, [0.d0..1.d0 -, R]
* PSTEM = stem flow coefficient, [0.d0..1.d0 -, R]
* SCANOPY = storage capacity of canopy, [0.d0..10.d0 cm, R]
* AVPREC = average rainfall intensity, [0.d0..100.d0 cm, R]
* AVEVAP = average evaporation intensity during rainfall from a wet canopy, [0.d0..10.d0 cm, R]

     T     PFREE    PSTEM    SCANOPY     AVPREC     AVEVAP  ! (maximum 36 records)
    0.0       0.9     0.05       0.4       6.0       1.5
  365.0       0.9     0.05       0.4       6.0       1.5
* End of table
*******************************************************************************************

*******************************************************************************************
* Part 10: Root density distribution and root growth

* List relative root density [0..1 -, R], as function of relative rooting depth [0..1 -, R]:

*    Rdepth Rdensity  (maximum 11 records)
 RDCTB =
0.083 0.05
0.167 0.55
0.333 0.20
0.500 0.10
0.667 0.05
0.833 0.04
1.000 0.01
* End of table
*******************************************************************************


*** IRRIGATION SCHEDULING SECTION ***

*******************************************************************************
* Part 1: General

 SCHEDULE = 0  ! Switch for application irrigation scheduling [Y=1, N=0]

* If SCHEDULE = 0, no more information is required in this input file!
* If SCHEDULE = 1, continue ....

 STARTIRR = 30 3 ! Specify day and month after which irrigation scheduling is allowed [dd mm]
 ENDIRR = 31 12  ! Specify day and month after which irrigation scheduling is NOT allowed [dd mm]
 CIRRS = 0.0     ! solute concentration of scheduled irrig. water, [0..100 mg/cm3, R]
 ISUAS = 1       ! Switch for type of irrigation method:
```

```
             ! 0 = sprinkling irrigation
             ! 1 = surface irrigation

* Specify pressure head at field capacity
* required for timing options  TCS = 2, 3, or 4 and depth option DCS = 1, else dummy
  phFieldCapacity = -100.0   ! soil hydraulic pressure head [-1000.0 .. 0.0,cm, R]

**********************************************************************************


**********************************************************************************
* Part 2: Irrigation time criteria

*** Choose one of the following 5 timing options:
  TCS = 1  ! Switch, timing criterion  [1..6, I]]
!         TCS = 1   :  Daily Stress
!         TCS = 2   :  Depletion of Readily Available Water
!         TCS = 3   :  Depletion of Totally Available Water
!         TCS = 4   :  Depletion Water Amount
!         TCS = 5   :  Pressure head or moisture content
!         TCS = 6   :  Fixed weekly irrigation, rootzone to field capacity


*** Daily stress criterion (TCS = 1)
* If TCS = 1, specify mimimum of ratio actual/potential transpiration Trel [0..1, R],
* as function of development stage DVS_tc1 [0..2, R], maximum 7 records:
  DVS_tc1  Trel
     0.0  0.95
     2.0  0.95
* End of table


*** Depletion of Readily Available Water (TCS = 2)
* If TCS = 2, specify minimal fraction of readily available water RAW [0..1, R],
* as function of development stage DVS_tc2 [0..2, R], maximum 7 records:
  DVS_tc2   RAW
     0.0  0.95
     2.0  0.95
* End of table


*** Depletion of Totally Available Water (TCS = 3)
* If TCS = 3, specify minimal fraction of totally available water TAW [0..1, R],
* as function of development stage DVS_tc3 [0..2, R], maximum 7 records:
  DVS_tc3   TAW
     0.0  0.50
     2.0  0.50
* End of table


*** Depletion Water Amount (TCS = 4)
* If TCS = 4, specify maximum amount of water depleted below field cap. DWA [0..500 mm, R],
* as function of development stage DVS_tc4 [0..2, R], maximum 7 records:
  DVS_tc4   DWA
     0.0  40.0
     2.0  40.0
* End of table
```

```
*** Pressure head or Moisture content (TCS = 5)
* If TCS = 5, specify:
  PHORMC = 0   ! Switch, use pressure head (PHORMC=0) or water content (PHORMC=1)
  DCRIT = -30.0! Depth of the sensor [-100..0 cm, R]
* Also specify critical pressure head [-1.d6..-100 cm, R] or moisture content
* [0..1.0 cm3/cm3, R], as function of development stage DVS_tc5 [0..2, R]:
  DVS_tc5  Value_tc5
     0.0    -1000.0
     2.0    -1000.0
* End of table


*** Fixed weekly irrigation, rootzone to field capacity (TCS = 6)
* If TCS = 6, specify:
* Threshold for weekly irrigation; only irrigate when deficit is higher than threshold
  irgthreshold = 1.0       ! threshold value  [0.0..20.0 mm, R]


*** Select (optional) fixed time interval:
  tcsfix = 0  ! Switch, fixed timing criterion  [0 or 1, I]]
* If tcsfix = 1, specify:
  irgdayfix = 7    !   length of interval (number of days) [1..365, I]

**********************************************************************************


**********************************************************************************
* Part 3: Irrigation depth criteria

*** Choose one of the following 2 options for irrigation depth:
* Next line is required for Swap303 - swap3177
  DCS = 1      ! Switch, depth criterion  [1..2, I]]
!            DCS = 1 :  Back to Field Capacity
!            DCS = 2 :  Fixed Irrigation Depth


*** Back to Field Capacity (DCS = 1)
* If DCS = 1, specify amount of under (-) or over (+) irrigation dI [-100..100 mm, R],
* as function of development stage DVS_dc1 [0..2, R], maximum 7 records:
  DVS_dc1   dI
    0.0  10.0
    2.0  10.0
* End of table


*** Fixed Irrigation Depth (DCS = 2)
* If DCS = 2, specify fixed irrigation depth FID [0..400 mm, R],
* as function of development stage DVS_dc2 [0..2, R], maximum 7 records:
  DVS_dc2   FID
     0.0  60.0
     2.0  60.0
* End of table


*** Select (optional) limitations of irrigation depth:
  dcslim = 0  ! Switch, limited irrigation depth  [0=No, 1=Yes]   [0..1, I]
* If dcslim = 1, specify:
```

irgdepmin = 0.0 ! minimum irrigation depth [0.0d0 .. 100.0d0, mm, I]
irgdepmax = 0.0 ! maximum irrigation depth [irgdepmin .. 1.0d7, mm, I]

* End of .crp file !

APPENDIX F SWAP: RAIN FILE EXCERPT

Excerpt: Weighing lysimeters August 13 2013

```
**************************************************************************
* File name: LysRain.013
* Contents:  Detailed rainfall input data
**************************************************************************
* Comments:
* 1. Input similar to tipping-bucket rain measurements:
*     t1   rainamount_1
*     t2   rainamount_2 (rain amount (mm) between t1 and t2)
* 2. In order to calculate the correct rainfall intensity, the first rainfall
*    record should be at or before the start of the simulation
**************************************************************************

 Station      Day   Month   Year      Time       Amount
*            nr     nr     nr         d          mm
'BioretenET'  13     08   2013  0.18024347       00.00
'BioretenET'  13     08   2013  0.18030404       00.00
'BioretenET'  13     08   2013  0.18036461       00.00
'BioretenET'  13     08   2013  0.18042517       00.00
'BioretenET'  13     08   2013  0.18048574       00.00
'BioretenET'  13     08   2013  0.18054630       00.00
'BioretenET'  13     08   2013  0.18060687       00.00
'BioretenET'  13     08   2013  0.18066743       00.00
'BioretenET'  13     08   2013  0.18072800       00.00
'BioretenET'  13     08   2013  0.18078857       00.00
'BioretenET'  13     08   2013  0.18084913       00.00
'BioretenET'  13     08   2013  0.18090970       00.00
'BioretenET'  13     08   2013  0.18097026       00.00
'BioretenET'  13     08   2013  0.18103083       00.00
'BioretenET'  13     08   2013  0.18109139       00.00
'BioretenET'  13     08   2013  0.18115196       00.51
'BioretenET'  13     08   2013  0.18121252       00.76
'BioretenET'  13     08   2013  0.18127309       01.78
'BioretenET'  13     08   2013  0.18133366       02.03
'BioretenET'  13     08   2013  0.18139422       01.52
'BioretenET'  13     08   2013  0.18145479       01.02
'BioretenET'  13     08   2013  0.18151535       00.76
'BioretenET'  13     08   2013  0.18157592       05.84
'BioretenET'  13     08   2013  0.18163648       13.46
'BioretenET'  13     08   2013  0.18169705       04.06
'BioretenET'  13     08   2013  0.18175762       11.18
'BioretenET'  13     08   2013  0.18181818       09.91
```

'BioretenET'	13	08	2013	0.18187875	08.38
'BioretenET'	13	08	2013	0.18193931	10.41
'BioretenET'	13	08	2013	0.18199988	02.54
'BioretenET'	13	08	2013	0.18206044	03.30
'BioretenET'	13	08	2013	0.18212101	02.03
'BioretenET'	13	08	2013	0.18218158	02.54
'BioretenET'	13	08	2013	0.18224214	00.25
'BioretenET'	13	08	2013	0.18230271	00.25
'BioretenET'	13	08	2013	0.18236327	00.00
'BioretenET'	13	08	2013	0.18242384	00.00
'BioretenET'	13	08	2013	0.18248440	00.00
'BioretenET'	13	08	2013	0.18254497	00.00
'BioretenET'	13	08	2013	0.18260554	00.00
'BioretenET'	13	08	2013	0.18266610	00.00
'BioretenET'	13	08	2013	0.18272667	00.00
'BioretenET'	13	08	2013	0.18278723	00.00
'BioretenET'	13	08	2013	0.18284780	00.00
'BioretenET'	13	08	2013	0.18290836	00.00
'BioretenET'	13	08	2013	0.18296893	00.00
'BioretenET'	13	08	2013	0.18302950	00.00
'BioretenET'	13	08	2013	0.18309006	00.00
'BioretenET'	13	08	2013	0.18315063	00.00
'BioretenET'	13	08	2013	0.18321119	00.00
'BioretenET'	13	08	2013	0.18327176	00.00
'BioretenET'	13	08	2013	0.18333232	00.00
'BioretenET'	13	08	2013	0.18339289	00.00
'BioretenET'	13	08	2013	0.18345346	00.00
'BioretenET'	13	08	2013	0.18351402	00.00
'BioretenET'	13	08	2013	0.18357459	00.00
'BioretenET'	13	08	2013	0.18363515	00.00
'BioretenET'	13	08	2013	0.18369572	00.00
'BioretenET'	13	08	2013	0.18375628	00.00
'BioretenET'	13	08	2013	0.18381685	00.00
'BioretenET'	13	08	2013	0.18387742	00.00
'BioretenET'	13	08	2013	0.18393798	00.00
'BioretenET'	13	08	2013	0.18399855	00.00
'BioretenET'	13	08	2013	0.18405911	00.00
'BioretenET'	13	08	2013	0.18411968	00.00
'BioretenET'	13	08	2013	0.18418024	00.00
'BioretenET'	13	08	2013	0.18424081	00.00
'BioretenET'	13	08	2013	0.18430137	00.00
'BioretenET'	13	08	2013	0.18436194	00.00
'BioretenET'	13	08	2013	0.18442251	00.00
'BioretenET'	13	08	2013	0.18448307	00.00
'BioretenET'	13	08	2013	0.18454364	00.00
'BioretenET'	13	08	2013	0.18460420	00.00

'BioretenET'	13	08	2013	0.18466477	00.00
'BioretenET'	13	08	2013	0.18472533	00.00
'BioretenET'	13	08	2013	0.18478590	00.00
'BioretenET'	13	08	2013	0.18484647	00.00
'BioretenET'	13	08	2013	0.18490703	00.00
'BioretenET'	13	08	2013	0.18496760	00.00
'BioretenET'	13	08	2013	0.18502816	00.00
'BioretenET'	13	08	2013	0.18508873	00.00
'BioretenET'	13	08	2013	0.18514929	00.00
'BioretenET'	13	08	2013	0.18520986	00.00
'BioretenET'	13	08	2013	0.18527043	00.00
'BioretenET'	13	08	2013	0.18533099	00.00
'BioretenET'	13	08	2013	0.18539156	00.00
'BioretenET'	13	08	2013	0.18545212	00.00
'BioretenET'	13	08	2013	0.18551269	00.00
'BioretenET'	13	08	2013	0.18557325	00.00
'BioretenET'	13	08	2013	0.18563382	00.00
'BioretenET'	13	08	2013	0.18569439	00.00
'BioretenET'	13	08	2013	0.18575495	00.00
'BioretenET'	13	08	2013	0.18581552	00.00
'BioretenET'	13	08	2013	0.18587608	00.00
'BioretenET'	13	08	2013	0.18593665	00.00
'BioretenET'	13	08	2013	0.18599721	00.00

APPENDIX G SWAP: METEOROLOGICAL FILE EXCERPT

Excerpt: Weighing lysimeters August 2013

```
***********************************************************************
* Filename: LysdailyET.013
* Contents: SWAP - Meteorological data
***********************************************************************
* Comment area:
*
*
***********************************************************************
  Station   DD MM YYYY    RAD   Tmin   Tmax    HUM   WIND   RAIN   ETref
*           nr nr   nr  kJ/m2     C      C   kPa    m/s     mm     mm
***********************************************************************
 'BioretenET'  1  8 2013  1000.   20.   20.  0.70   1.0  032.0   1.04
 'BioretenET'  2  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.98
 'BioretenET'  3  8 2013  1000.   20.   20.  0.70   1.0  000.5   2.14
 'BioretenET'  4  8 2013  1000.   20.   20.  0.70   1.0  000.0   4.36
 'BioretenET'  5  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.82
 'BioretenET'  6  8 2013  1000.   20.   20.  0.70   1.0  000.3   2.59
 'BioretenET'  7  8 2013  1000.   20.   20.  0.70   1.0  000.5   1.59
 'BioretenET'  8  8 2013  1000.   20.   20.  0.70   1.0  008.6   3.02
 'BioretenET'  9  8 2013  1000.   20.   20.  0.70   1.0  000.5   2.64
 'BioretenET' 10  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.43
 'BioretenET' 11  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.68
 'BioretenET' 12  8 2013  1000.   20.   20.  0.70   1.0  000.0   2.85
 'BioretenET' 13  8 2013  1000.   20.   20.  0.70   1.0  082.6   2.93
 'BioretenET' 14  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.86
 'BioretenET' 15  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.65
 'BioretenET' 16  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.33
 'BioretenET' 17  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.53
 'BioretenET' 18  8 2013  1000.   20.   20.  0.70   1.0  001.8   1.85
 'BioretenET' 19  8 2013  1000.   20.   20.  0.70   1.0  000.0   2.24
 'BioretenET' 20  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.52
 'BioretenET' 21  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.66
 'BioretenET' 22  8 2013  1000.   20.   20.  0.70   1.0  000.0   2.94
 'BioretenET' 23  8 2013  1000.   20.   20.  0.70   1.0  000.0   1.82
 'BioretenET' 24  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.41
 'BioretenET' 25  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.22
 'BioretenET' 26  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.84
 'BioretenET' 27  8 2013  1000.   20.   20.  0.70   1.0  000.0   4.34
 'BioretenET' 28  8 2013  1000.   20.   20.  0.70   1.0  033.5   0.92
 'BioretenET' 29  8 2013  1000.   20.   20.  0.70   1.0  000.0   2.38
 'BioretenET' 30  8 2013  1000.   20.   20.  0.70   1.0  000.5   2.77
 'BioretenET' 31  8 2013  1000.   20.   20.  0.70   1.0  000.0   3.05
```

APPENDIX H SWAP: DRAINAGE FILE EXAMPLE

Example: Sand IWS

```
**********************************************************************************
* Filename: Lys3IWS.dra
* Contents: drainage data
**********************************************************************************
* Comment area: simulate internal water storage in sand lysimeter
*
**********************************************************************************

*   The file with drainage data .dra contains the following sections:
*         - Basic drainage section (3 methods)
*         - Extended drainage section
*         - Lateral drainage section

**********************************************************************************

* Option for interflow in highest drainage level (shallow system with short residence time)
 SWINTFL = 0       ! Switch for interflow [0,1, I]

* If SWINTFL = 1, specify:
 COFINTFLB = 0.5   ! Coefficient for interflow relation [0.01..10.0 d, R]
 EXPINTFLB = 1.0   ! Exponent for interflow relation [0.1..1.0 -, R]
**********************************************************************************


*** BASIC DRAINAGE SECTION ***

**********************************************************************************
* Part 0: General

  DRAMET = 3 ! Switch, method of lateral drainage calculation:
*            METHOD 1 = Use table of drainage flux - groundwater level relation
*            METHOD 2 = Use drainage formula of Hooghoudt or Ernst
*            METHOD 3 = Use drainage/infiltration resistance, multi-level if needed

*********************************************************************************

* METHOD 1 - Part 1: Table of drainage flux - groundwater level relation (DRAMET = 1)

* If SWDIVD = 1, specify the drain spacing:
 LM1 = 30.  ! Drain spacing, [1..1000 m, R]

* Specify drainage flux Qdrain [-100..1000 cm/d, R] as function of groundwater level
* GWL [-1000.0..10.0 cm, R, negative below soil surface]; maximum of 25 records
* start with highest groundwater level:

   GWL    Qdrain
```

```
  -20.0       0.5
  -100.       0.1
* End of table
**********************************************************************************

* METHOD 2 - Part 2: Drainage formula of Hooghoudt or Ernst (DRAMET = 2)

* Drain characteristics:
  LM2    =  1.      ! Drain spacing, [1..1000 m, R]
  SHAPE = 1.0       ! Shape factor to account for actual location between drain and water divide [0.0..1.0 -, R]
  WETPER =  30.0    ! Wet perimeter of the drain, [0..1000 cm, R]
  ZBOTDR = -31.0    ! Level of drain bottom, [-1000..0 cm, R, neg. below soil surface]
  ENTRES =   0.0    ! Drain entry resistance, [0..1000 d, R]

* Soil profile characteristics:

  IPOS = 2   ! Switch for position of drain:
*           1 = On top of an impervious layer in a homogeneous profile
*           2 = Above an impervious layer in a homogeneous profile
*           3 = At the interface of a fine upper and a coarse lower soil layer
*           4 = In the lower, more coarse soil layer
*           5 = In the upper, more fine soil layer

* For all positions specify:
  BASEGW =  -66.    ! Level of impervious layer, [-1d4..0 cm, R]
  KHTOP  =  240.    ! Horizontal hydraulic conductivity top layer, [0..1000 cm/d, R]

* In addition, in case IPOS = 3,4,5
  KHBOT  =  10.0    ! horizontal hydraulic conductivity bottom layer, [0..1000 cm/d, R]
  ZINTF  = -150.    ! Level of interface of fine and coarse soil layer, [-1d4..0 cm, R]
* In addition, in case IPOS = 4,5
  KVTOP  =   5.0    ! Vertical hydraulic conductivity top layer, [0..1000 cm/d, R]
  KVBOT  =  10.0    ! Vertical hydraulic conductivity bottom layer, [0..1000 cm/d, R]

* In addition, in case IPOS = 5
  GEOFAC =  4.8     ! Geometry factor of Ernst, [0..100 -, R]
**********************************************************************************

* METHOD 3 - Part 3: Drainage and infiltration resistance (DRAMET = 3)

  NRLEVS = 1        ! Number of drainage levels, [1..5, I]

**********************************************************************************
* Part 3a: Drainage to level 1

  DRARES1 =  150.  ! Drainage resistance, [10..1d5 d, R]
  INFRES1 =  150.  ! Infiltration resistance, [0..1d5 d, R]
  SWALLO1 =   3   ! Switch, for allowance drainage/infiltration:
            ! 1 = Drainage and infiltration are both allowed
            ! 2 = Drainage is not allowed
            ! 3 = Infiltration is not allowed
```

```
 ZBOTDR1 = -31.0 ! Level of drainage medium bottom, [-1000..0 cm, R]
 SWDTYP1 = 1     ! Type of drainage medium: 1 = drain tube, 2 = open channel

* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
 L1 =  10.       ! Drain spacing, [1..1000 m, R]

* In case of open channel (SWDTYP1 = 2), specify date DATOWL1 [dd-mmm-yyyy] and channel
* water level LEVEL1 [cm, negative if below soil surface], maximum MAOWL records:
    DATOWL1   LEVEL1
  12-jan-1981    -90.0
  14-dec-1981    -90.0
* End of table

**********************************************************************************

*** EXTENDED DRAINAGE SECTION ***

**********************************************************************************
* Part 0: Reference level

 ALTCU = 0.0 ! ALTitude of the Control Unit relative to reference level
*             AltCu = 0.0 means reference level coincides with
*             surface level [-300000..300000 cm, R]
**********************************************************************************
* Part 1a: drainage characteristics
*
 NRSRF = 0 ! number of subsurface drainage levels [1..5, I]
*
*** Table with physical characteristics of each subsurface drainage level:
*
* LEVEL   ! drainage level number [1..NRSRF, I]
* SWDTYP  ! type of drainage medium [open=0, closed=1]
* L       ! spacing between channels/drains [1..1000 m, R]
* ZBOTDRE ! altitude of bottom of channel or drain [ALTCU-1000..ALTCU-0.01 cm,R]
* GWLINF  ! groundw. level for max. infiltr. [-1000..0 cm rel. to soil surf., R]
* RDRAIN  ! drainage resistance [1..100000 d, R]
* RINFI   ! infiltration resistance [1..100000 d, R]
* Variables RENTRY, REXIT, WIDTHR and TALUDR must have realistic values when the
*        type of drainage medium is open (second column of this table:SWDTYP=0)
*        For closed pipe drains (SWDTYP=1) dummy values may be entered
* RENTRY  ! entry resistance [1..100 d, R]
* REXIT   ! exit resistance [1..100 d, R]
* WIDTHR  ! bottom width of channel [0..100 cm, R]
* TALUDR  ! side-slope (dh/dw) of channel [0.01..5, R]
*
LEV  SWDTYP    L   ZBOTDRE GWLINF RDRAIN RINFI RENTRY REXIT  WIDTHR TALUDR
 1    0      250.0  1093.0 -350.0 150.0  4000.0  0.8    0.8  100.0  0.66
 2    0      200.0  1150.0 -300.0 150.0  1500.0  0.8    0.8  100.0  0.66
* End_of_table
*
*
```

* Part 1b: Separate criteria for highest (shallow) drainage system
*
 SWNRSRF = 0   ! Switch to introduce rapid subsurface drainage [0..2, I]
*   0 = no rapid drainage
*   1 = rapid drainage in the highest drainage system (=NRSRF)
*   (implies adjustment of RDRAIN of highest drainage system)
*   2 = rapid drainage as interflow according to a power relation
*   (implies adjustment of RDRAIN of highest drainage system)
* When SWRNSRF = 1, then enter realistic values for rapid drainage
 RSURFDEEP   = 30.0   ! maximum resistance of rapid subsurface Drainage [0.001..1000.0 d, R]
 RSURFSHALLOW = 10.0   ! minimum resistance of Rapid subsurface Drainage [0.001..1000.0 d, R]
*
* When SWRNSRF = 2, then enter coefficients of power function
 COFINTFL = 0.1   ! coefficient of interflow relation [0.01..10.0 d-1, R]
 EXPINTFL = 0.5   ! exponent of interflow relation [0.1...1.0 -, R]
*
*
* Switch to adjust the bottom of the model discharge layer in case of lateral (swdivdra=1)
* interflow or rapid drainage (Swnrsrf=1 or Swnrsrf=2).
* When the switch is on (SwTopnrsrf=1) then the bottom of the highest order drainage
* system (Zbotdr(NumDrain)) represents the max depth of the interflow.
SwTopnrsrf = 0 ! Switch to enable adjustment of model discharge layer [0,1, I]

****
* Part 0: General

 SWDIVD = 0 ! Calculate vertical distribution of drainage flux in groundwater [Y=1, N=0]

* If SWDIVD = 1, specify anisotropy factor COFANI (horizontal/vertical saturated hydraulic
* conductivity) for each soil layer (maximum MAHO), [0..1000 -, R] :
 COFANI =   1.0   1.0

****
* Switch to adjust upper boundary of model discharge layer
 SWDISLAY = 0 ! switch to adjust discharge layer [0,1,2, -, I]
*
* If SWDISLAY = 1, specify for the drainage systems 1 - NRLEVS or NRSRF:
* - swtopdislay(madr)   ! Switch, for each drainage level, to distribute drainage
*   flux vertically with a given position of the top of the
*   model discharge layers: [0,1 - , I] 0 = no; 1 = yes
* - ztopdislay(madr)   ! Array with depth of top of model discharge layer for
*   each drain level, see also swtopdislay (L);
* If SWDISLAY = 2, then specify ftopdislay instead of ztopdislay:
* - ftopdislay(madr)   ! Array with factor of top of model discharge layer for
*   each drain level, see also swtopdislay ();

* (level is a dummy array, just as either ztopdislay or ftopdislay)
 level swtopdislay ztopdislay ftopdislay
   1   1   -200.0   0.5
   2   0   -0.01   0.0
   3   0   -0.01   0.0

4	0	-0.01	0.0
5	0	-0.01	0.0

* end of SWDISLAY-table

****

APPENDIX I SWAP: OUTPUT WBA FILE EXCERPT

Excerpt: Sandy Loam July-August 2013

```
* Project:      Lys1
* File content:  cumulative water balance components (cm)
* File name:     .\Files\Result1.wba
* Model version: Swap 3.2.36
* Generated at:  12-Feb-2017 20:44:46
*
     Date,Day,  Dcum,Rain_g,Rain_n,Irr_g,Irr_n,  RunOn, RunOff,  Tpot,  Tact,  Epot,  Eact,   Drain,     Bot,   DStor,      Gwl,  Pond,
Wbal,     Date2
13-Jul-2013,194,    1,  0.02,  0.02,  0.0,  0.0,   0.00,   0.00,  0.24,  0.24,  0.15,  0.15,   0.000,   0.000,  -0.368,         ,  0.00, 0.00,13-
Jul-2013
14-Jul-2013,195,    2,  0.02,  0.02,  0.0,  0.0,   0.00,   0.00,  0.55,  0.54,  0.34,  0.34,   0.000,   0.000,  -0.863,         ,  0.00, 0.00,14-
Jul-2013
15-Jul-2013,196,    3,  0.02,  0.02,  0.0,  0.0,   0.00,   0.00,  0.93,  0.92,  0.58,  0.44,   0.000,   0.000,  -1.338,         ,  0.00, 0.00,15-
Jul-2013
16-Jul-2013,197,    4,  0.02,  0.02,  0.0,  0.0,   0.00,   0.00,  1.31,  1.30,  0.81,  0.49,   0.000,   0.000,  -1.767,         ,  0.00, 0.00,16-
Jul-2013
17-Jul-2013,198,    5,  0.02,  0.02,  0.0,  0.0,   0.00,   0.00,  1.68,  1.67,  1.03,  0.52,   0.000,   0.000,  -2.174,         ,  0.00, 0.00,17-
Jul-2013
18-Jul-2013,199,    6,  0.02,  0.02,  0.0,  0.0,   0.00,   0.00,  2.10,  2.09,  1.29,  0.55,   0.000,   0.000,  -2.621,         ,  0.00, 0.00,18-
Jul-2013
19-Jul-2013,200,    7,  0.02,  0.02,  0.0,  0.0,   0.00,   0.00,  2.48,  2.47,  1.51,  0.57,   0.000,   0.000,  -3.022,         ,  0.00, 0.00,19-
Jul-2013
20-Jul-2013,201,    8,  0.18,  0.18,  0.0,  0.0,   0.00,   0.00,  2.83,  2.82,  1.72,  0.71,   0.000,   0.000,  -3.358,         ,  0.00, 0.00,20-
Jul-2013
21-Jul-2013,202,    9,  0.18,  0.18,  0.0,  0.0,   0.00,   0.00,  3.17,  3.16,  1.91,  0.74,   0.000,   0.000,  -3.725,         ,  0.00, 0.00,21-
Jul-2013
22-Jul-2013,203,   10,  0.30,  0.30,  0.0,  0.0,   0.00,   0.00,  3.43,  3.43,  2.07,  0.86,   0.000,   0.000,  -3.984,         ,  0.00, 0.00,22-
Jul-2013
*
     Date,Day,  Dcum,Rain_g,Rain_n,Irr_g,Irr_n,  RunOn, RunOff,  Tpot,  Tact,  Epot,  Eact,   Drain,     Bot,   DStor,      Gwl,  Pond,
Wbal,     Date2
23-Jul-2013,204,   11,  3.33,  3.33,  0.0,  0.0,   0.00,   0.00,  0.28,  0.28,  0.16,  0.15,   0.000,  -0.239,   2.660,         ,  0.00, 0.00,23-
Jul-2013
24-Jul-2013,205,   12,  3.33,  3.33,  0.0,  0.0,   0.00,   0.00,  0.52,  0.52,  0.30,  0.29,   0.000,  -0.584,   1.936,         ,  0.00, 0.00,24-
Jul-2013
25-Jul-2013,206,   13,  3.33,  3.33,  0.0,  0.0,   0.00,   0.00,  0.72,  0.72,  0.41,  0.40,   0.000,  -0.899,   1.313,         ,  0.00, 0.00,25-
Jul-2013
26-Jul-2013,207,   14,  3.33,  3.33,  0.0,  0.0,   0.00,   0.00,  1.05,  1.04,  0.59,  0.53,   0.000,  -1.187,   0.567,         ,  0.00, 0.00,26-
Jul-2013
27-Jul-2013,208,   15,  3.33,  3.33,  0.0,  0.0,   0.00,   0.00,  1.35,  1.35,  0.75,  0.58,   0.000,  -1.452,  -0.054,         ,  0.00, 0.00,27-
Jul-2013
*
     Date,Day,  Dcum,Rain_g,Rain_n,Irr_g,Irr_n,  RunOn, RunOff,  Tpot,  Tact,  Epot,  Eact,   Drain,     Bot,   DStor,      Gwl,  Pond,
Wbal,     Date2
28-Jul-2013,209,   16,  2.16,  2.16,  0.0,  0.0,   0.00,   0.00,  0.21,  0.21,  0.11,  0.11,   0.000,  -0.245,   1.599,         ,  0.00, 0.00,28-
Jul-2013
29-Jul-2013,210,   17,  2.21,  2.21,  0.0,  0.0,   0.00,   0.00,  0.59,  0.59,  0.32,  0.31,   0.000,  -0.473,   0.837,         ,  0.00, 0.00,29-
Jul-2013
30-Jul-2013,211,   18,  2.21,  2.21,  0.0,  0.0,   0.00,   0.00,  0.94,  0.94,  0.50,  0.49,   0.000,  -0.685,   0.096,         ,  0.00, 0.00,30-
Jul-2013
31-Jul-2013,212,   19,  2.21,  2.21,  0.0,  0.0,   0.00,   0.00,  1.21,  1.21,  0.64,  0.56,   0.000,  -0.884,  -0.446,         ,  0.00, 0.00,31-
Jul-2013
*
```

Date,Day, Dcum,Rain_g,Rain_n,Irr_g,Irr_n, RunOn, RunOff, Tpot, Tact, Epot, Eact, Drain, Bot, DStor, Gwl, Pond,
Wbal, Date2
01-Aug-2013,213, 20, 3.20, 3.20, 0.0, 0.0, 0.00, 0.00, 0.08, 0.08, 0.04, 0.04, 0.000, -0.186, 2.893, , 0.00, 0.00,01-
Aug-2013
02-Aug-2013,214, 21, 3.20, 3.20, 0.0, 0.0, 0.00, 0.00, 0.40, 0.40, 0.21, 0.21, 0.000, -0.362, 2.236, , 0.00, 0.00,02-
Aug-2013
03-Aug-2013,215, 22, 3.25, 3.25, 0.0, 0.0, 0.00, 0.00, 0.57, 0.57, 0.29, 0.29, 0.000, -0.528, 1.861, , 0.00, 0.00,03-
Aug-2013
04-Aug-2013,216, 23, 3.25, 3.25, 0.0, 0.0, 0.00, 0.00, 0.92, 0.92, 0.47, 0.47, 0.000, -0.685, 1.180, , 0.00, 0.00,04-
Aug-2013
05-Aug-2013,217, 24, 3.25, 3.25, 0.0, 0.0, 0.00, 0.00, 1.23, 1.23, 0.63, 0.54, 0.000, -0.834, 0.655, , 0.00, 0.00,05-
Aug-2013
06-Aug-2013,218, 25, 3.28, 3.28, 0.0, 0.0, 0.00, 0.00, 1.44, 1.44, 0.73, 0.60, 0.000, -0.975, 0.264, , 0.00, 0.00,06-
Aug-2013
07-Aug-2013,219, 26, 3.99, 3.99, 0.0, 0.0, 0.00, 0.00, 1.57, 1.56, 0.79, 0.66, 0.000, -1.110, 0.659, , 0.00, 0.00,07-
Aug-2013
08-Aug-2013,220, 27, 4.19, 4.19, 0.0, 0.0, 0.00, 0.00, 1.81, 1.81, 0.91, 0.78, 0.000, -1.238, 0.360, , 0.00, 0.00,08-
Aug-2013
09-Aug-2013,221, 28, 4.24, 4.24, 0.0, 0.0, 0.00, 0.00, 2.03, 2.03, 1.02, 0.88, 0.000, -1.361, -0.033, , 0.00, 0.00,09-
Aug-2013
10-Aug-2013,222, 29, 4.24, 4.24, 0.0, 0.0, 0.00, 0.00, 2.31, 2.31, 1.15, 1.02, 0.000, -1.479, -0.565, , 0.00, 0.00,10-
Aug-2013
11-Aug-2013,223, 30, 4.24, 4.24, 0.0, 0.0, 0.00, 0.00, 2.61, 2.61, 1.29, 1.14, 0.000, -1.591, -1.095, , 0.00, 0.00,11-
Aug-2013
12-Aug-2013,224, 31, 4.24, 4.24, 0.0, 0.0, 0.00, 0.00, 2.85, 2.84, 1.41, 1.18, 0.000, -1.699, -1.483, , 0.00, 0.00,12-
Aug-2013
*
Date,Day, Dcum,Rain_g,Rain_n,Irr_g,Irr_n, RunOn, RunOff, Tpot, Tact, Epot, Eact, Drain, Bot, DStor, Gwl, Pond,
Wbal, Date2
13-Aug-2013,225, 32, 8.25, 8.25, 0.0, 0.0, 0.00, 0.00, 0.24, 0.19, 0.11, 0.10, 0.000, -0.104, 7.864, , 0.00, 0.00,13-
Aug-2013
14-Aug-2013,226, 33, 8.25, 8.25, 0.0, 0.0, 0.00, 0.00, 0.56, 0.50, 0.27, 0.25, 0.000, -0.204, 7.297, , 0.00, 0.00,14-
Aug-2013
15-Aug-2013,227, 34, 8.25, 8.25, 0.0, 0.0, 0.00, 0.00, 0.86, 0.80, 0.41, 0.39, 0.000, -0.300, 6.759, , 0.00, 0.00,15-
Aug-2013
16-Aug-2013,228, 35, 8.25, 8.25, 0.0, 0.0, 0.00, 0.00, 1.13, 1.07, 0.54, 0.52, 0.000, -0.393, 6.268, , 0.00, 0.00,16-
Aug-2013
17-Aug-2013,229, 36, 8.25, 8.25, 0.0, 0.0, 0.00, 0.00, 1.42, 1.36, 0.67, 0.58, 0.000, -0.482, 5.830, , 0.00, 0.00,17-
Aug-2013
18-Aug-2013,230, 37, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 1.57, 1.52, 0.75, 0.64, 0.000, -0.568, 5.702, , 0.00, 0.00,18-
Aug-2013
19-Aug-2013,231, 38, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 1.76, 1.70, 0.83, 0.73, 0.000, -0.652, 5.347, , 0.00, 0.00,19-
Aug-2013
20-Aug-2013,232, 39, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 2.05, 1.99, 0.97, 0.80, 0.000, -0.739, 4.898, , 0.00, 0.00,20-
Aug-2013
21-Aug-2013,233, 40, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 2.35, 2.29, 1.11, 0.83, 0.000, -0.961, 4.345, , 0.00, 0.00,21-
Aug-2013
22-Aug-2013,234, 41, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 2.59, 2.53, 1.22, 0.85, 0.000, -1.382, 3.659, , 0.00, 0.00,22-
Aug-2013
23-Aug-2013,235, 42, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 2.74, 2.68, 1.29, 0.87, 0.000, -1.799, 3.074, , 0.00, 0.00,23-
Aug-2013
24-Aug-2013,236, 43, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 3.02, 2.97, 1.42, 0.89, 0.000, -2.178, 2.399, , 0.00, 0.00,24-
Aug-2013
25-Aug-2013,237, 44, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 3.29, 3.23, 1.55, 0.90, 0.000, -2.522, 1.777, , 0.00, 0.00,25-
Aug-2013
26-Aug-2013,238, 45, 8.43, 8.43, 0.0, 0.0, 0.00, 0.00, 3.60, 3.55, 1.70, 0.91, 0.000, -2.836, 1.134, , 0.00, 0.00,26-
Aug-2013

27-Aug-2013,239,   46, 8.43, 8.43, 0.0, 0.0,   0.00,   0.00, 3.96, 3.91, 1.86, 0.92,   0.000, -3.125,   0.478,   , 0.00, 0.00,27-Aug-2013

APPENDIX J MATLAB CODE EXAMPLE

Example: Low Crop Coefficient Set

```
%************************************************************************
% SWAP ET MATLAB Code
% Amanda Hess Dissertation 2017
%************************************************************************
clear all;
path(path,'X:\0-Databases\Common_MATLAB_Files\Functions');
path(path,'C:\SWAPr\Files');

%************************************************************************
% Read in Simulation Data
%************************************************************************
SIM_DATA = xlsread('SWAPSims.xlsx','SWAPSims', 'A271:E361');
bottom = SIM_DATA(:,1);
pond   = SIM_DATA(:,2);
depth  = SIM_DATA(:,3);
soil1  = SIM_DATA(:,4);
soil2  = SIM_DATA(:,5);
Nsims = length(bottom);
writeET=zeros(Nsims, 1);
writeET1=zeros(Nsims, 1);

for S=1:Nsims,   %************************************************************************
  % Read Main Input File (MIF)
%************************************************************************
  numrows=796;
  fid = fopen('l.swp','r');
    MIF = cell(1, numrows);
  for k = 1:numrows,
      MIF{k} = fgetl(fid);
  end
    fclose(fid);

%************************************************************************
  % Modify Main Input File (MIF)
%************************************************************************
    %bottom boundry condition
    if bottom(S) == 1,
      MIF{514} = strcat(' SWBOTB = 7  ! Switch for bottom boundary [1..8,-,I]'); %Soil-soil
      %Rooting and soil depth profile
      if depth(S) == 1,
        MIF{405} = strcat('  RDS  =152.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
        MIF{354} = strcat('    1     1     10.0     0.5     20');
        MIF{355} = strcat('    1     2     142.0     1.0     142');
        MIF{356} = strcat('    2     3     48.0     1.0     48');
      elseif depth(S) == 2,
        MIF{405} = strcat('  RDS  = 90.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
        MIF{354} = strcat('    1     1     10.0     0.5     20');
```

```
      MIF{355} = strcat('    1      2      80.0      1.0      80');
      MIF{356} = strcat('    2      3     110.0      1.0     110');
    elseif depth(S) == 3,
      MIF{405} = strcat('  RDS  = 66.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2      56.0      1.0      56');
      MIF{356} = strcat('    2      3     134.0      1.0     134');
    elseif depth(S) == 4,
      MIF{405} = strcat('  RDS  = 46.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2      36.0      1.0      36');
      MIF{356} = strcat('    2      3     154.0      1.0     154');
    elseif depth(S) == 5,
      MIF{405} = strcat('  RDS  = 20.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2      10.0      1.0      10');
      MIF{356} = strcat('    2      3     180.0      1.0     180');
   end
elseif  bottom(S) == 2,
   MIF{514} = strcat(' SWBOTB = 8  ! Switch for bottom boundary [1..8,-,I]'); %Soil-air
   %Rooting and soil depth profile
    if depth(S) == 1,
      MIF{405} = strcat('  RDS  =152.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2     142.0      1.0     142');
      MIF{356} = strcat('');
    elseif depth(S) == 2,
      MIF{405} = strcat('  RDS  = 90.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2      80.0      1.0      80');
      MIF{356} = strcat('');
    elseif depth(S) == 3,
      MIF{405} = strcat('  RDS  = 66.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2      56.0      1.0      56');
      MIF{356} = strcat('');
    elseif depth(S) == 4,
      MIF{405} = strcat('  RDS  = 46.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2      36.0      1.0      36');
      MIF{356} = strcat('');
    elseif depth(S) == 5,
      MIF{405} = strcat('  RDS  = 20.0   ! Maximum rooting depth allowed by the soil profile, [1..5000 cm, R]');
      MIF{354} = strcat('    1      1      10.0      0.5      20');
      MIF{355} = strcat('    1      2      10.0      1.0      10');
      MIF{356} = strcat('');
   end
 end

%Rain garden media
if soil1(S)==1,
   MIF{380} = strcat('      1    0.000   0.470     5.687   1.303  090.00     0.500    5.687 -0.1 090.00');
```

```
    elseif soil1(S)==2,
      MIF{380} = strcat('     1    0.000   0.438     2.158   1.241  090.00     0.500    2.158 -0.1 090.00');
    elseif soil1(S)==3,
      MIF{380} = strcat('     1    0.000   0.436     0.539   1.306  050.00     0.500    0.539 -0.1 050.00');
    elseif soil1(S)==4,
      MIF{380} = strcat('     1    0.000   0.451     0.352   1.330  012.00     0.500    0.352 -0.1 012.00');
    elseif soil1(S)==5,
      MIF{380} = strcat('     1    0.000   0.517     0.228   1.573  006.00     0.500    0.228 -0.1 006.00');
    elseif soil1(S)==6,
      MIF{380} = strcat('     1    0.000   0.499     0.200   1.353  004.00     0.500    0.200 -0.1 004.00');
    end

    %Underlying Soil
    if soil2(S)==1,
      MIF{381} = strcat('     1    0.000   0.470     5.687   1.303  090.00     0.500    5.687 -0.1 090.00');
    elseif soil2(S)==3,
      MIF{381} = strcat('     1    0.000   0.436     0.539   1.306  050.00     0.500    0.539 -0.1 050.00');
    elseif soil2(S)==4,
      MIF{380} = strcat('     1    0.000   0.451     0.352   1.330  012.00     0.500    0.352 -0.1 012.00');
    else
      MIF{381} = strcat('');
    end

    %Ponding depth
    if pond(S)==1,
      MIF{303} = strcat('  PONDMX  =  7.5  ! In case of ponding, minimum thickness for runoff, [0..1000 cm, R]');
    elseif pond(S)==2,
      MIF{303} = strcat('  PONDMX  = 15.0  ! In case of ponding, minimum thickness for runoff, [0..1000 cm, R]');
    elseif pond(S)==3,
      MIF{303} = strcat('  PONDMX  = 30.0  ! In case of ponding, minimum thickness for runoff, [0..1000 cm, R]');
    end

%*************************************************************************
  % Write New Main Input File (MIF)
%*************************************************************************
  fid = fopen('h.swp','w');
  fprintf(fid,'%s\r\n',MIF{:});
  fclose(fid);
  dos('"C:\SWAP\swap.exe" h.swp');

%*************************************************************************
  % Record Results
%*************************************************************************
  %Read WBA file
  numrows=1212;
  fid = fopen('l.wba','r');
  WBA = cell(1, numrows);
  for k = 1:numrows,
    WBA{k} = fgetl(fid);
  end
  fclose(fid);
```

```
  %Get average ET after 6 days
  V = [39; 53; 70; 96; 119; 310; 327; 345; 358; 373; 391; 400; 414; 429; 447; 458; 477; 498; 521; 530; 539; 560; 718; 762; 781; 791; 814; 858; 877; 898; 913; 923; 933; 948; 959; 1106; 1117; 1144; 1157; 1167; 1183; 1195; 1209];
  ET = zeros(size(V));
  for j = 1:43,
      if WBA{V(j,:)}(132:137)==' 0.00', %If ponded, take potential ET
        ET(j,:) = str2double(WBA{V(j,:)}(73:78))+str2double(WBA{V(j,:)}(87:92));
      else
        ET(j,:) = str2double(WBA{V(j,:)}(66:71))+str2double(WBA{V(j,:)}(80:85));
      end
  end
  ET = mean(ET);
  ET = ET*10;

  %Get average ET after 12 days
  V1 = [59; 76; 102; 125; 316; 333; 364; 379; 420; 435; 483; 504; 545; 566; 724; 768; 797; 820; 864; 883; 904; 939; 1173];
  ET1 = zeros(size(V1));
  for j = 1:23,
     if WBA{V1(j,:)}(132:137)==' 0.00', %If ponded, take potential ET
       ET1(j,:) = str2double(WBA{V1(j,:)}(73:78))+str2double(WBA{V1(j,:)}(87:92));
     else
      ET1(j,:) = str2double(WBA{V1(j,:)}(66:71))+str2double(WBA{V1(j,:)}(80:85));
      end
  end
  ET1 = mean(ET1);
  ET1 = ET1*10;

  %Write Results
  writeET(S)=ET;
  writeET1(S)=ET1;

end

%*****************************************************************************
% All Done!
%*****************************************************************************
```

APPENDIX K 6 DAY SWAP BATCH MODE OUTPUT

Bioretention								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	17.06	17.92	18.57	18.61	18.49	17.90
		90	17.07	17.92	18.57	18.61	18.49	17.90
		66	17.09	17.93	18.57	18.62	18.49	17.90
		46	17.09	17.94	18.60	18.63	18.50	17.90
		20	17.11	18.10	18.88	18.81	18.80	18.12
	15	152	17.03	17.91	18.54	18.55	18.39	17.70
		90	17.03	17.91	18.54	18.56	18.40	17.70
		66	17.04	17.91	18.55	18.56	18.40	17.71
		46	17.05	17.92	18.57	18.57	18.40	17.72
		20	17.10	18.09	18.86	18.78	18.72	17.98
	30	152	17.03	17.91	18.54	18.55	18.39	17.69
		90	17.03	17.91	18.54	18.56	18.40	17.70
		66	17.04	17.91	18.55	18.56	18.40	17.71
		46	17.05	17.92	18.57	18.57	18.40	17.72
		20	17.10	18.09	18.86	18.78	18.72	17.98
Middle	7.5	152	18.08	19.23	20.29	20.54	20.65	20.28
		90	18.07	19.23	20.28	20.54	20.65	20.28
		66	18.08	19.23	20.28	20.54	20.65	20.28
		46	18.08	19.23	20.32	20.55	20.65	20.29
		20	18.17	19.35	20.51	20.68	20.92	20.42
	15	152	18.08	19.22	20.29	20.52	20.60	20.13
		90	18.08	19.22	20.29	20.53	20.60	20.13
		66	18.08	19.22	20.29	20.53	20.60	20.14
		46	18.07	19.21	20.31	20.54	20.60	20.15
		20	18.16	19.34	20.51	20.67	20.89	20.31
	30	152	18.08	19.22	20.29	20.52	20.60	20.13
		90	18.08	19.22	20.29	20.53	20.60	20.13
		66	18.08	19.22	20.29	20.53	20.60	20.14
		46	18.07	19.21	20.31	20.54	20.60	20.15
		20	18.16	19.34	20.51	20.67	20.89	20.31
Maximum	7.5	152	25.11	25.93	26.64	26.56	26.19	25.03
		90	25.10	25.93	26.63	26.56	26.19	25.04
		66	25.11	25.92	26.65	26.56	26.19	25.04
		46	25.11	25.92	26.71	26.58	26.19	25.06
		20	25.25	26.08	26.86	26.66	26.37	25.10
	15	152	25.03	25.85	26.59	26.46	25.95	24.64

		90	25.03	25.85	26.60	26.46	25.96	24.66
		66	25.03	25.86	26.61	26.46	25.96	24.67
		46	25.04	25.86	26.67	26.49	25.96	24.71
		20	25.21	26.04	26.83	26.57	26.18	24.83
	30	152	25.03	25.85	26.59	26.46	25.95	24.64
		90	25.03	25.85	26.60	26.46	25.95	24.65
		66	25.03	25.86	26.61	26.46	25.96	24.67
		46	25.04	25.86	26.67	26.49	25.96	24.70
		20	25.21	26.04	26.83	26.57	26.18	24.83

Bioretention with IWS				
Crop Set	Ponding Depth [cm]	Soil/Rooting Depth [cm]	IWS Depth [cm]	Sand Cumulative ET [mm]
Maximum	7.5	152	76	27.83
		90	45	28.25
		66	33	33.04
		46	23	32.07
		20	10	31.25
	15	152	76	29.34
		90	45	32.58
		66	33	33.01
		46	23	31.91
		20	10	34.72
	30	152	76	28.51
		90	45	32.59
		66	33	32.91
		46	23	32.73
		20	10	39.14

Bioinfiltration Underline with Hydrologic Soil Type A								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	17.20	18.11	18.67	18.68	18.53	17.93
		90	17.20	18.03	18.64	18.64	18.50	17.91
		66	17.20	17.99	18.59	18.64	18.51	17.93
		46	17.20	17.94	18.62	18.64	18.50	17.92
		20	17.20	18.06	18.79	18.77	18.69	18.12
	15	152	17.23	18.05	18.62	18.61	18.43	17.73

		90	17.23	17.96	18.63	18.59	18.41	17.73
		66	17.23	18.02	18.59	18.61	18.41	17.73
		46	17.23	17.95	18.60	18.59	18.42	17.76
		20	17.23	17.97	18.77	18.71	18.61	17.99
		152	17.23	18.09	18.63	18.62	18.42	17.73
		90	17.23	17.98	18.64	18.60	18.41	17.72
	30	66	17.23	17.98	18.61	18.60	18.41	17.72
		46	17.23	17.96	18.60	18.60	18.41	17.76
		20	17.23	18.02	18.76	18.72	18.61	17.98
Middle	7.5	152	18.33	19.32	20.36	20.57	20.67	20.33
		90	18.33	19.24	20.31	20.57	20.65	20.29
		66	18.33	19.25	20.31	20.57	20.65	20.29
		46	18.33	19.28	20.30	20.56	20.65	20.30
		20	18.33	19.36	20.42	20.61	20.80	20.41
	15	152	18.16	19.29	20.33	20.57	20.62	20.17
		90	18.16	19.26	20.28	20.55	20.62	20.15
		66	18.16	19.27	20.34	20.56	20.61	20.16
		46	18.16	19.29	20.30	20.56	20.62	20.16
		20	18.16	19.31	20.47	20.62	20.76	20.30
	30	152	18.16	19.30	20.32	20.57	20.64	20.16
		90	18.16	19.24	20.36	20.56	20.61	20.15
		66	18.16	19.24	20.29	20.55	20.61	20.15
		46	18.16	19.27	20.29	20.55	20.61	20.16
		20	18.16	19.30	20.46	20.61	20.76	20.30
Maximum	7.5	152	25.34	26.17	26.83	26.63	26.24	25.09
		90	25.34	26.01	26.74	26.61	26.23	25.07
		66	25.34	26.02	26.79	26.61	26.20	25.05
		46	25.34	25.97	26.78	26.58	26.23	25.09
		20	25.34	26.12	26.94	26.65	26.34	25.17
	15	152	25.25	26.09	26.73	26.58	26.02	24.69
		90	25.25	25.94	26.70	26.50	25.98	24.69
		66	25.25	26.04	26.72	26.51	26.01	24.71
		46	25.25	25.88	26.65	26.55	25.99	24.72
		20	25.25	26.00	26.81	26.58	26.14	24.90
	30	152	25.24	26.06	26.75	26.59	26.00	24.69
		90	25.24	26.07	26.71	26.56	25.97	24.70
		66	25.24	26.01	26.79	26.53	25.98	24.71
		46	25.24	25.89	26.69	26.56	25.98	24.72
		20	25.24	25.99	26.91	26.57	26.15	24.89

Bioinfiltration Underline with Hydrologic Soil Type B								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	17.08	17.94	18.58	18.61	18.49	17.90
		90	17.08	17.93	18.58	18.62	18.50	17.91
		66	17.07	17.93	18.58	18.62	18.49	17.91
		46	17.06	17.93	18.58	18.63	18.50	17.91
		20	17.05	17.90	18.58	18.63	18.49	17.96
	15	152	17.04	17.91	18.54	18.56	18.40	17.70
		90	17.04	17.92	18.54	18.56	18.39	17.70
		66	17.04	17.91	18.54	18.56	18.40	17.71
		46	17.04	17.92	18.54	18.57	18.40	17.74
		20	17.02	17.87	18.54	18.59	18.42	17.84
	30	152	17.04	17.91	18.54	18.55	18.40	17.70
		90	17.04	17.92	18.54	18.56	18.39	17.70
		66	17.04	17.91	18.54	18.56	18.40	17.71
		46	17.04	17.92	18.54	18.57	18.40	17.73
		20	17.02	17.87	18.54	18.59	18.41	17.83
Middle	7.5	152	18.08	19.24	20.29	20.55	20.65	20.28
		90	18.09	19.24	20.29	20.55	20.65	20.29
		66	18.08	19.23	20.29	20.54	20.65	20.29
		46	18.08	19.23	20.29	20.55	20.65	20.29
		20	18.04	19.19	20.29	20.52	20.60	20.28
	15	152	18.08	19.23	20.29	20.53	20.60	20.13
		90	18.08	19.23	20.29	20.53	20.60	20.13
		66	18.08	19.23	20.29	20.53	20.60	20.14
		46	18.08	19.23	20.29	20.53	20.60	20.15
		20	18.03	19.19	20.29	20.51	20.57	20.17
	30	152	18.08	19.23	20.29	20.53	20.60	20.13
		90	18.08	19.23	20.29	20.53	20.60	20.13
		66	18.08	19.23	20.29	20.53	20.60	20.14
		46	18.08	19.23	20.29	20.53	20.60	20.15
		20	18.03	19.20	20.29	20.52	20.57	20.17
Maximum	7.5	152	25.10	25.92	26.64	26.56	26.19	25.04
		90	25.12	25.93	26.64	26.57	26.19	25.04
		66	25.11	25.92	26.64	26.57	26.19	25.04
		46	25.13	25.92	26.64	26.57	26.19	25.05
		20	25.09	25.89	26.64	26.55	26.16	25.06
	15	152	25.03	25.85	26.61	26.46	25.95	24.65
		90	25.03	25.87	26.61	26.47	25.96	24.67
		66	25.04	25.86	26.61	26.47	25.96	24.68

		46	25.06	25.85	26.61	26.48	25.97	24.71
		20	25.02	25.83	26.61	26.49	25.96	24.79
	30	152	25.03	25.85	26.61	26.46	25.95	24.64
		90	25.03	25.87	26.61	26.47	25.95	24.66
		66	25.05	25.85	26.61	26.48	25.96	24.68
		46	25.06	25.85	26.61	26.48	25.97	24.71
		20	25.01	25.83	26.61	26.49	25.96	24.80

Bioinfiltration Underline with Hydrologic Soil Type C								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	18.63	18.63	18.63	18.63	18.63	18.63
		90	18.63	18.63	18.63	18.63	18.63	18.63
		66	18.63	18.63	18.63	18.63	18.63	18.63
		46	18.63	18.63	18.63	18.63	18.63	18.63
		20	18.63	18.63	18.63	18.63	18.63	18.63
	15	152	18.57	18.57	18.57	18.57	18.57	18.57
		90	18.57	18.57	18.57	18.57	18.57	18.57
		66	18.57	18.57	18.57	18.57	18.57	18.57
		46	18.57	18.57	18.57	18.57	18.57	18.57
		20	18.57	18.57	18.57	18.57	18.57	18.57
	30	152	18.57	18.57	18.57	18.57	18.57	18.57
		90	18.57	18.57	18.57	18.57	18.57	18.57
		66	18.57	18.57	18.57	18.57	18.57	18.57
		46	18.57	18.57	18.57	18.57	18.57	18.57
		20	18.57	18.57	18.57	18.57	18.57	18.57
Middle	7.5	152	20.55	20.55	20.55	20.55	20.55	20.55
		90	20.55	20.55	20.55	20.55	20.55	20.55
		66	20.54	20.54	20.54	20.54	20.54	20.54
		46	20.55	20.55	20.55	20.55	20.55	20.55
		20	20.52	20.52	20.52	20.52	20.52	20.52
	15	152	20.53	20.53	20.53	20.53	20.53	20.53
		90	20.53	20.53	20.53	20.53	20.53	20.53
		66	20.53	20.53	20.53	20.53	20.53	20.53
		46	20.53	20.53	20.53	20.53	20.53	20.53
		20	20.51	20.51	20.51	20.51	20.51	20.51
	30	152	20.53	20.53	20.53	20.53	20.53	20.53
		90	20.53	20.53	20.53	20.53	20.53	20.53
		66	20.53	20.53	20.53	20.53	20.53	20.53
		46	20.53	20.53	20.53	20.53	20.53	20.53

		20	20.52	20.52	20.52	20.52	20.52	20.52
Maximum	7.5	152	26.56	26.56	26.56	26.56	26.56	26.56
		90	26.57	26.57	26.57	26.57	26.57	26.57
		66	26.57	26.57	26.57	26.57	26.57	26.57
		46	26.57	26.57	26.57	26.57	26.57	26.57
		20	26.55	26.55	26.55	26.55	26.55	26.55
	15	152	26.46	26.46	26.46	26.46	26.46	26.46
		90	26.47	26.47	26.47	26.47	26.47	26.47
		66	26.47	26.47	26.47	26.47	26.47	26.47
		46	26.48	26.48	26.48	26.48	26.48	26.48
		20	26.49	26.49	26.49	26.49	26.49	26.49
	30	152	26.46	26.46	26.46	26.46	26.46	26.46
		90	26.47	26.47	26.47	26.47	26.47	26.47
		66	26.48	26.48	26.48	26.48	26.48	26.48
		46	26.48	26.48	26.48	26.48	26.48	26.48
		20	26.49	26.49	26.49	26.49	26.49	26.49

APPENDIX L 12 DAY SWAP BATCH MODE OUTPUT

Bioretention								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	29.90	32.12	34.22	35.18	36.43	35.93
		90	29.89	32.12	34.22	35.18	36.43	35.93
		66	29.93	32.12	34.22	35.20	36.43	35.93
		46	29.93	32.14	34.25	35.20	36.44	35.93
		20	29.89	32.23	34.65	35.37	36.63	36.09
	15	152	29.87	32.12	34.19	35.15	36.38	35.77
		90	29.87	32.12	34.19	35.15	36.38	35.79
		66	29.87	32.12	34.20	35.16	36.38	35.80
		46	29.87	32.12	34.22	35.17	36.39	35.80
		20	29.88	32.22	34.63	35.34	36.58	35.99
	30	152	29.87	32.12	34.19	35.15	36.38	35.78
		90	29.87	32.12	34.19	35.15	36.38	35.79
		66	29.87	32.12	34.20	35.16	36.38	35.80
		46	29.87	32.12	34.22	35.17	36.39	35.80
		20	29.88	32.22	34.63	35.34	36.58	35.99
Middle	7.5	152	31.13	33.77	36.28	37.65	39.50	39.36
		90	31.13	33.77	36.26	37.65	39.50	39.36
		66	31.14	33.76	36.27	37.64	39.50	39.36
		46	31.13	33.75	36.30	37.66	39.52	39.37
		20	31.09	33.73	36.54	37.70	39.72	39.43
	15	152	31.12	33.74	36.27	37.62	39.47	39.18
		90	31.12	33.74	36.27	37.62	39.47	39.19
		66	31.12	33.74	36.27	37.61	39.47	39.20
		46	31.13	33.75	36.30	37.63	39.48	39.22
		20	31.09	33.71	36.55	37.67	39.70	39.34
	30	152	31.12	33.74	36.27	37.62	39.47	39.18
		90	31.12	33.74	36.27	37.62	39.47	39.19
		66	31.12	33.74	36.27	37.61	39.47	39.20
		46	31.13	33.75	36.30	37.63	39.48	39.21
		20	31.09	33.71	36.55	37.67	39.70	39.34
Maximum	7.5	152	42.48	45.36	47.91	49.86	52.19	51.60
		90	42.47	45.37	47.89	49.87	52.19	51.60
		66	42.47	45.36	47.91	49.87	52.19	51.60
		46	42.47	45.31	47.97	49.90	52.20	51.63
		20	42.70	45.63	48.55	50.17	52.97	51.98
	15	152	42.41	45.27	47.87	49.77	52.07	51.34

		90	42.41	45.27	47.87	49.78	52.07	51.36
		66	42.41	45.28	47.87	49.78	52.07	51.37
		46	42.41	45.25	47.93	49.82	52.08	51.43
		20	42.67	45.60	48.53	50.10	52.90	51.84
	30	152	42.41	45.27	47.87	49.77	52.07	51.33
		90	42.41	45.27	47.87	49.78	52.07	51.35
		66	42.41	45.28	47.87	49.78	52.07	51.37
		46	42.41	45.25	47.93	49.82	52.08	51.42
		20	42.67	45.60	48.53	50.10	52.90	51.84

Bioretention with IWS				
Crop Set	Ponding Depth [cm]	Soil/Rooting Depth [cm]	IWS Depth [cm]	Sand Cumulative ET [mm]
Maximum	7.5	152	76	47.60
		90	45	59.74
		66	33	62.85
		46	23	60.08
		20	10	58.12
	15	152	76	53.24
		90	45	61.63
		66	33	62.77
		46	23	59.51
		20	10	66.51
	30	152	76	55.80
		90	45	61.63
		66	33	62.36
		46	23	58.80
		20	10	68.47

Bioinfiltration Underline with Hydrologic Soil Type A								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	30.10	32.35	34.32	35.29	36.45	35.98
		90	30.10	32.27	34.30	35.21	36.45	35.96
		66	30.10	32.22	34.19	35.22	36.44	35.96
		46	30.10	32.16	34.25	35.22	36.45	35.96
		20	30.10	32.28	34.45	35.36	36.58	36.10
	15	152	30.13	32.32	34.24	35.23	36.42	35.81

		90	30.13	32.17	34.27	35.19	36.41	35.80
		66	30.13	32.27	34.24	35.22	36.39	35.81
		46	30.13	32.14	34.27	35.19	36.42	35.84
		20	30.13	32.18	34.43	35.28	36.54	36.03
	30	152	30.14	32.40	34.25	35.24	36.40	35.81
		90	30.14	32.21	34.28	35.19	36.39	35.80
		66	30.14	32.21	34.27	35.20	36.40	35.80
		46	30.14	32.14	34.24	35.20	36.40	35.84
		20	30.14	32.19	34.45	35.29	36.55	36.02
Middle	7.5	152	31.47	33.87	36.37	37.70	39.52	39.41
		90	31.47	33.81	36.28	37.70	39.50	39.37
		66	31.47	33.77	36.33	37.69	39.51	39.37
		46	31.47	33.85	36.27	37.66	39.50	39.39
		20	31.47	33.93	36.40	37.66	39.63	39.43
	15	152	31.23	33.90	36.34	37.67	39.47	39.22
		90	31.23	33.83	36.27	37.64	39.47	39.20
		66	31.23	33.84	36.37	37.66	39.49	39.21
		46	31.23	33.83	36.28	37.67	39.49	39.24
		20	31.23	33.83	36.45	37.65	39.61	39.34
	30	152	31.23	33.90	36.30	37.68	39.49	39.21
		90	31.23	33.77	36.33	37.66	39.48	39.20
		66	31.23	33.80	36.27	37.64	39.50	39.22
		46	31.23	33.81	36.26	37.66	39.50	39.22
		20	31.23	33.86	36.43	37.65	39.62	39.33
Maximum	7.5	152	42.89	45.70	48.09	49.94	52.21	51.65
		90	42.89	45.50	48.02	49.93	52.23	51.63
		66	42.89	45.53	48.05	49.93	52.20	51.62
		46	42.89	45.43	48.04	49.90	52.26	51.67
		20	42.89	45.67	48.44	50.05	52.66	51.90
	15	152	42.70	45.59	47.95	49.90	52.11	51.38
		90	42.70	45.42	47.98	49.85	52.10	51.38
		66	42.70	45.50	47.98	49.84	52.12	51.42
		46	42.70	45.30	47.94	49.88	52.10	51.44
		20	42.70	45.48	48.33	50.00	52.57	51.79
	30	152	42.71	45.57	48.03	49.93	52.10	51.40
		90	42.71	45.58	47.93	49.92	52.09	51.40
		66	42.71	45.50	48.04	49.87	52.09	51.41
		46	42.71	45.30	47.95	49.90	52.11	51.44
		20	42.71	45.47	48.33	49.96	52.57	51.79

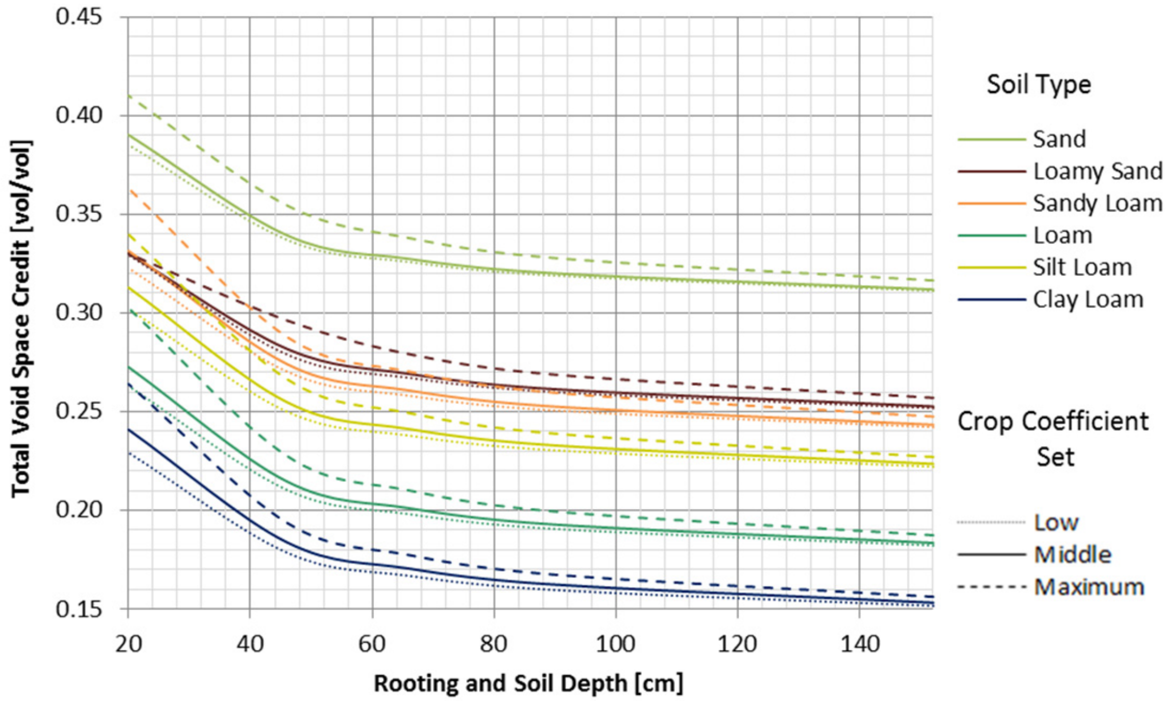
Bioinfiltration Underline with Hydrologic Soil Type B								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	29.92	32.16	34.23	35.18	36.43	35.93
		90	29.91	32.14	34.23	35.19	36.43	35.93
		66	29.92	32.14	34.23	35.20	36.43	35.94
		46	29.89	32.15	34.23	35.20	36.43	35.95
		20	29.88	32.13	34.23	35.20	36.43	35.99
	15	152	29.88	32.13	34.20	35.15	36.38	35.78
		90	29.88	32.13	34.20	35.15	36.38	35.78
		66	29.88	32.13	34.20	35.16	36.38	35.79
		46	29.88	32.14	34.20	35.16	36.39	35.83
		20	29.85	32.10	34.20	35.17	36.40	35.91
	30	152	29.88	32.13	34.20	35.14	36.38	35.78
		90	29.88	32.14	34.20	35.16	36.38	35.78
		66	29.88	32.14	34.20	35.16	36.39	35.79
		46	29.88	32.14	34.20	35.17	36.39	35.82
		20	29.85	32.10	34.20	35.17	36.40	35.90
Middle	7.5	152	31.13	33.79	36.28	37.65	39.51	39.36
		90	31.13	33.78	36.28	37.65	39.50	39.36
		66	31.13	33.76	36.28	37.64	39.50	39.36
		46	31.15	33.77	36.28	37.66	39.50	39.37
		20	31.15	33.78	36.28	37.64	39.47	39.33
	15	152	31.12	33.74	36.27	37.63	39.47	39.18
		90	31.12	33.75	36.27	37.62	39.47	39.19
		66	31.13	33.75	36.27	37.63	39.47	39.20
		46	31.13	33.77	36.27	37.63	39.48	39.22
		20	31.13	33.77	36.27	37.63	39.45	39.25
	30	152	31.13	33.74	36.27	37.63	39.47	39.18
		90	31.12	33.75	36.27	37.63	39.47	39.19
		66	31.12	33.76	36.27	37.62	39.47	39.20
		46	31.13	33.76	36.27	37.63	39.48	39.22
		20	31.13	33.78	36.27	37.63	39.46	39.24
Maximum	7.5	152	42.56	45.36	47.91	49.88	52.20	51.60
		90	42.51	45.37	47.91	49.89	52.19	51.60
		66	42.48	45.38	47.91	49.89	52.19	51.60
		46	42.51	45.39	47.91	49.87	52.20	51.62
		20	42.53	45.29	47.91	49.81	52.11	51.56
	15	152	42.43	45.28	47.89	49.80	52.07	51.35
		90	42.44	45.28	47.89	49.81	52.08	51.36

		66	42.43	45.30	47.89	49.80	52.08	51.38
		46	42.44	45.30	47.89	49.82	52.09	51.43
		20	42.43	45.24	47.89	49.76	52.02	51.44
	30	152	42.43	45.29	47.89	49.79	52.07	51.34
		90	42.44	45.28	47.89	49.81	52.08	51.37
		66	42.45	45.29	47.89	49.81	52.07	51.38
		46	42.44	45.29	47.89	49.83	52.09	51.42
		20	42.43	45.23	47.89	49.77	52.01	51.45

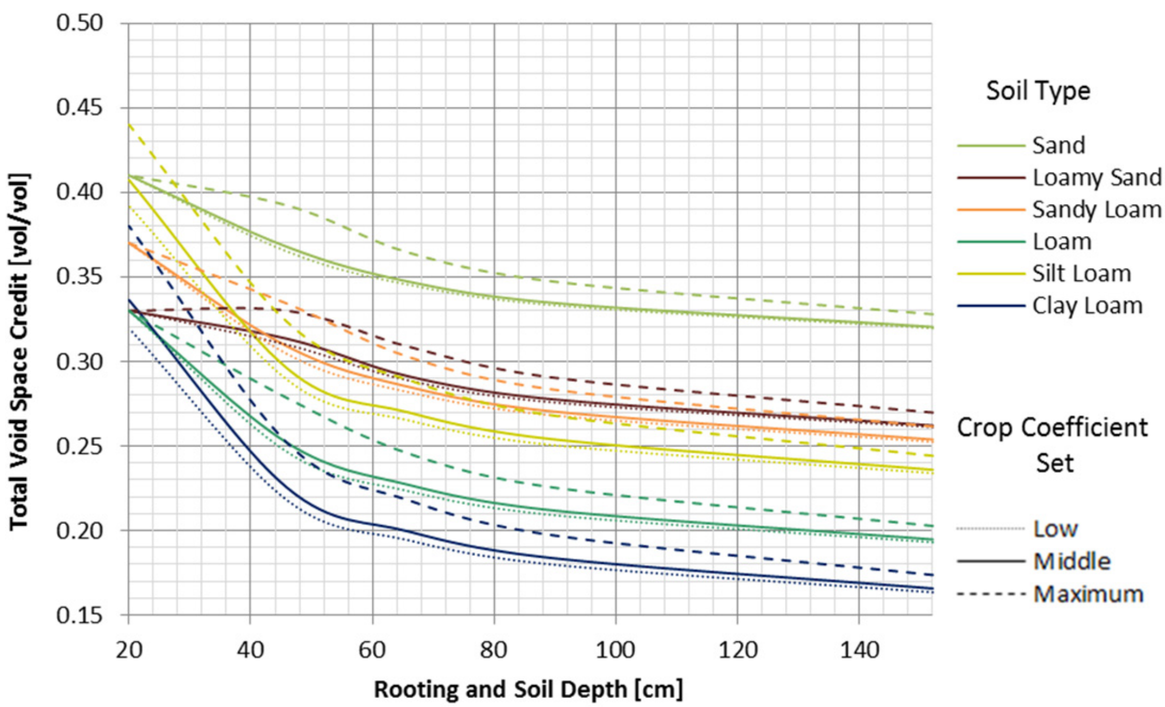
Bioinfiltration Underline with Hydrologic Soil Type C								
Crop Set	Pond Depth [cm]	Soil/Rooting Depth [cm]	Soil Type Cumulative ET [mm]					
			Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Clay Loam
Low	7.5	152	35.20	35.20	35.20	35.20	35.20	35.20
		90	35.20	35.20	35.20	35.20	35.20	35.20
		66	35.20	35.20	35.20	35.20	35.20	35.20
		46	35.20	35.20	35.20	35.20	35.20	35.20
		20	35.20	35.20	35.20	35.20	35.20	35.20
	15	152	35.16	35.16	35.16	35.16	35.16	35.16
		90	35.16	35.16	35.16	35.16	35.16	35.16
		66	35.16	35.16	35.16	35.16	35.16	35.16
		46	35.16	35.16	35.16	35.16	35.16	35.16
		20	35.16	35.16	35.16	35.16	35.16	35.16
	30	152	35.16	35.16	35.16	35.16	35.16	35.16
		90	35.16	35.16	35.16	35.16	35.16	35.16
		66	35.16	35.16	35.16	35.16	35.16	35.16
		46	35.16	35.16	35.16	35.16	35.16	35.16
		20	35.16	35.16	35.16	35.16	35.16	35.16
Middle	7.5	152	37.65	37.65	37.65	37.65	37.65	37.65
		90	37.65	37.65	37.65	37.65	37.65	37.65
		66	37.64	37.64	37.64	37.64	37.64	37.64
		46	37.66	37.66	37.66	37.66	37.66	37.66
		20	37.64	37.64	37.64	37.64	37.64	37.64
	15	152	37.63	37.63	37.63	37.63	37.63	37.63
		90	37.62	37.62	37.62	37.62	37.62	37.62
		66	37.63	37.63	37.63	37.63	37.63	37.63
		46	37.63	37.63	37.63	37.63	37.63	37.63
		20	37.63	37.63	37.63	37.63	37.63	37.63
	30	152	37.63	37.63	37.63	37.63	37.63	37.63
		90	37.63	37.63	37.63	37.63	37.63	37.63
		66	37.62	37.62	37.62	37.62	37.62	37.62

		46	37.63	37.63	37.63	37.63	37.63	37.63
		20	37.63	37.63	37.63	37.63	37.63	37.63
Maximum	7.5	152	49.88	49.88	49.88	49.88	49.88	49.88
		90	49.89	49.89	49.89	49.89	49.89	49.89
		66	49.89	49.89	49.89	49.89	49.89	49.89
		46	49.87	49.87	49.87	49.87	49.87	49.87
		20	49.81	49.81	49.81	49.81	49.81	49.81
	15	152	49.80	49.80	49.80	49.80	49.80	49.80
		90	49.81	49.81	49.81	49.81	49.81	49.81
		66	49.80	49.80	49.80	49.80	49.80	49.80
		46	49.82	49.82	49.82	49.82	49.82	49.82
		20	49.76	49.76	49.76	49.76	49.76	49.76
	30	152	49.79	49.79	49.79	49.79	49.79	49.79
		90	49.81	49.81	49.81	49.81	49.81	49.81
		66	49.81	49.81	49.81	49.81	49.81	49.81
		46	49.83	49.83	49.83	49.83	49.83	49.83
		20	49.77	49.77	49.77	49.77	49.77	49.77

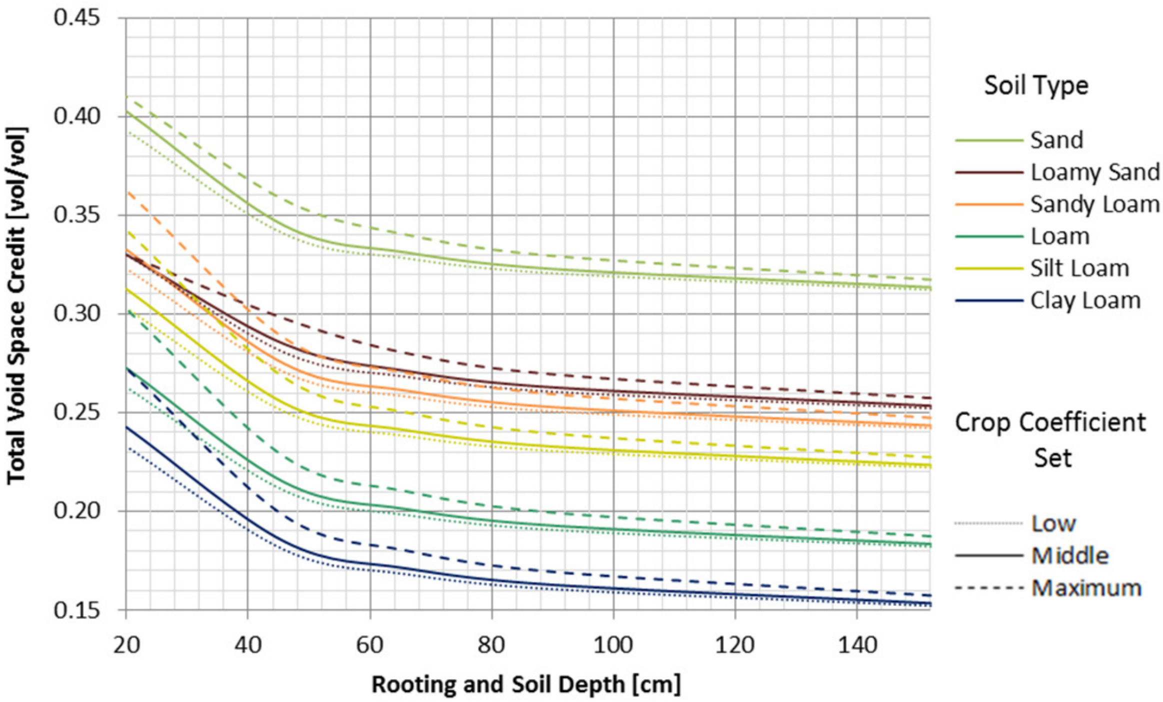
APPENDIX M VOID SPACE GRAPHS



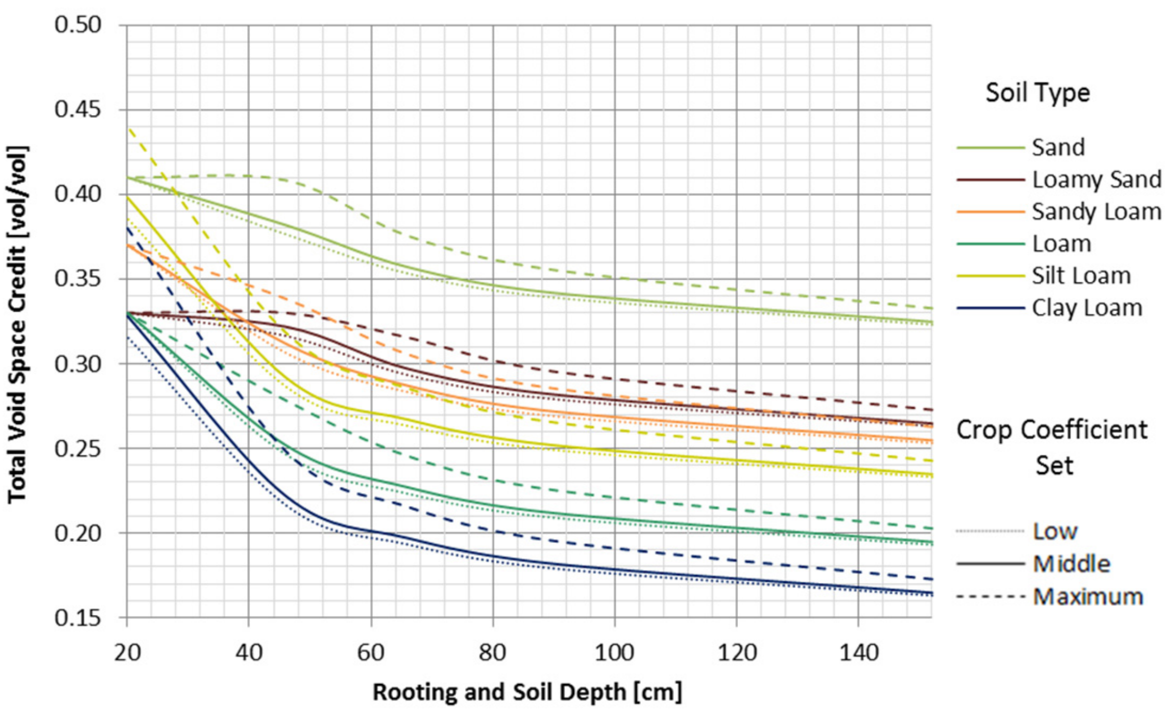
Bioinfiltration in hydrologic group B soil total void space credit for 6 days of cumulative ET



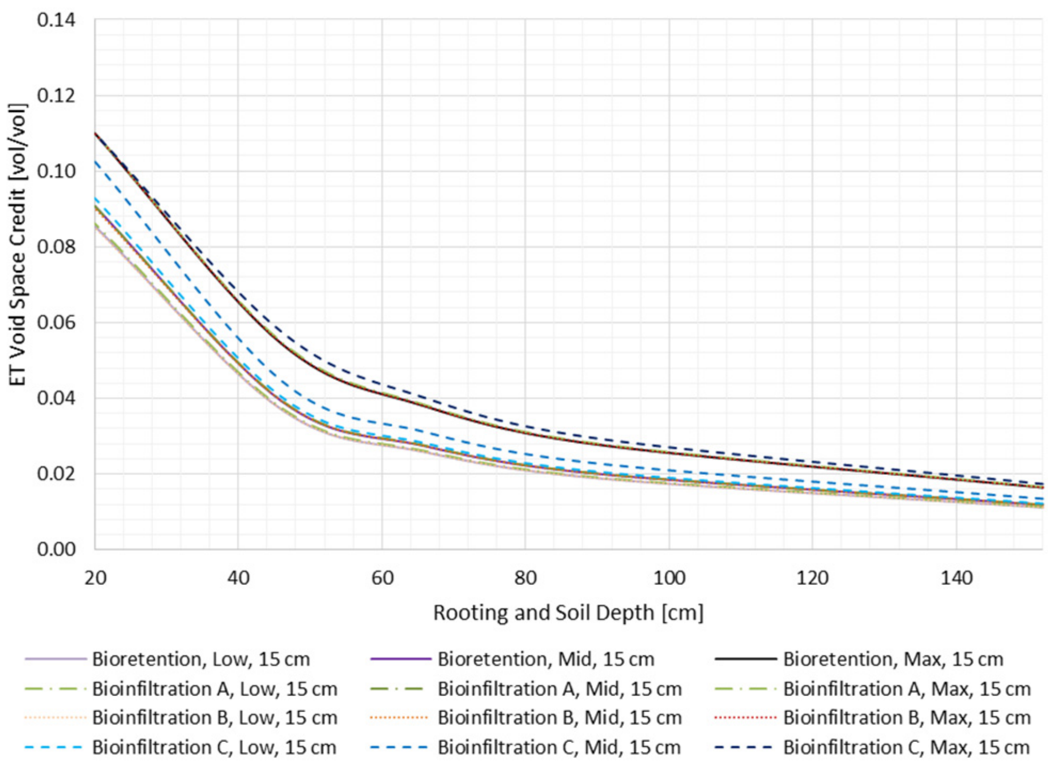
Bioinfiltration in hydrologic group B soil total void space credit for 12 days of cumulative ET



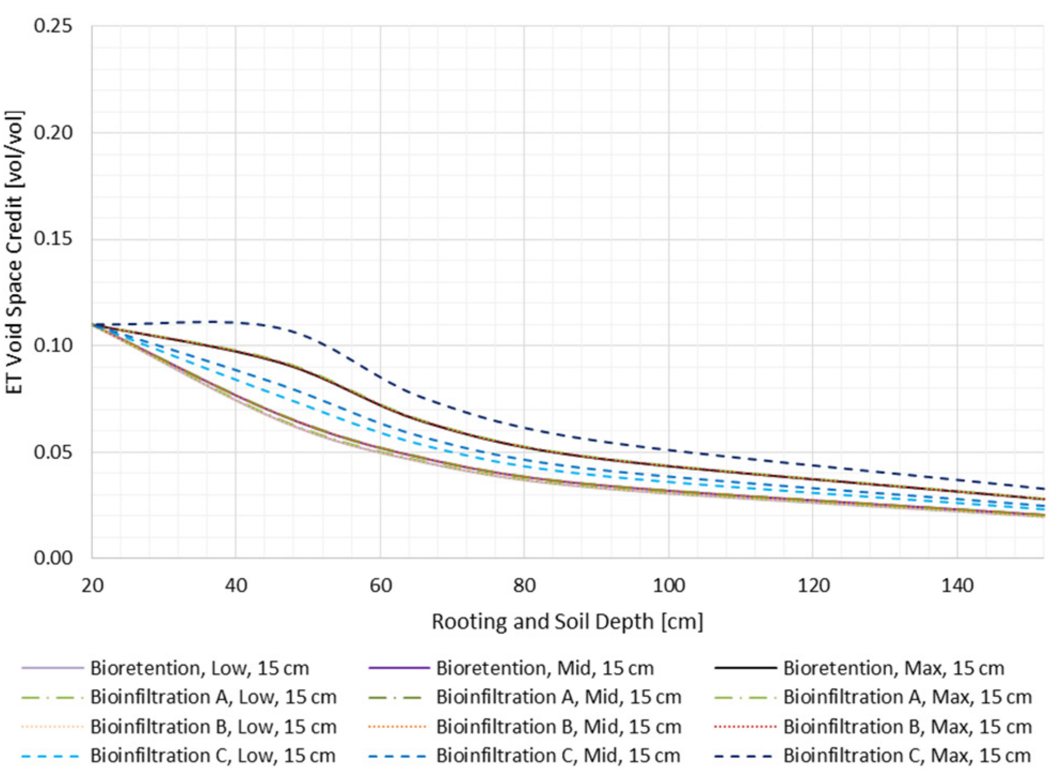
Bioinfiltration in hydrologic group C soil total void space credit for 6 days of cumulative ET



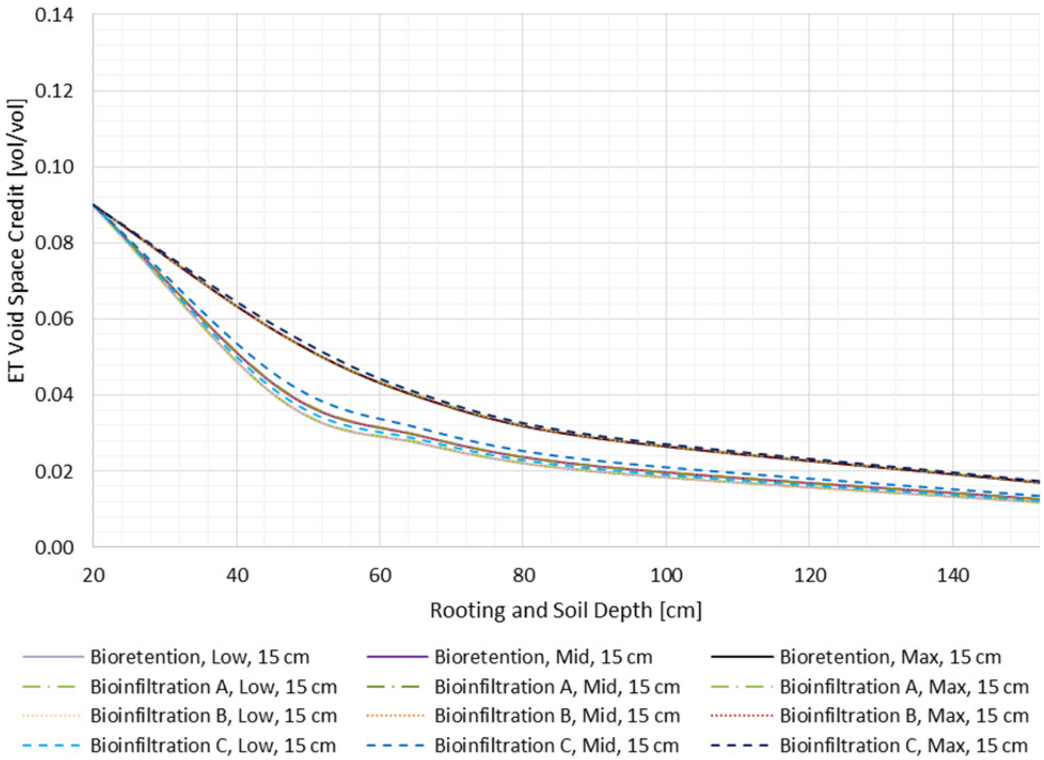
Bioinfiltration in hydrologic group soil total void space credit for 12 days of cumulative ET



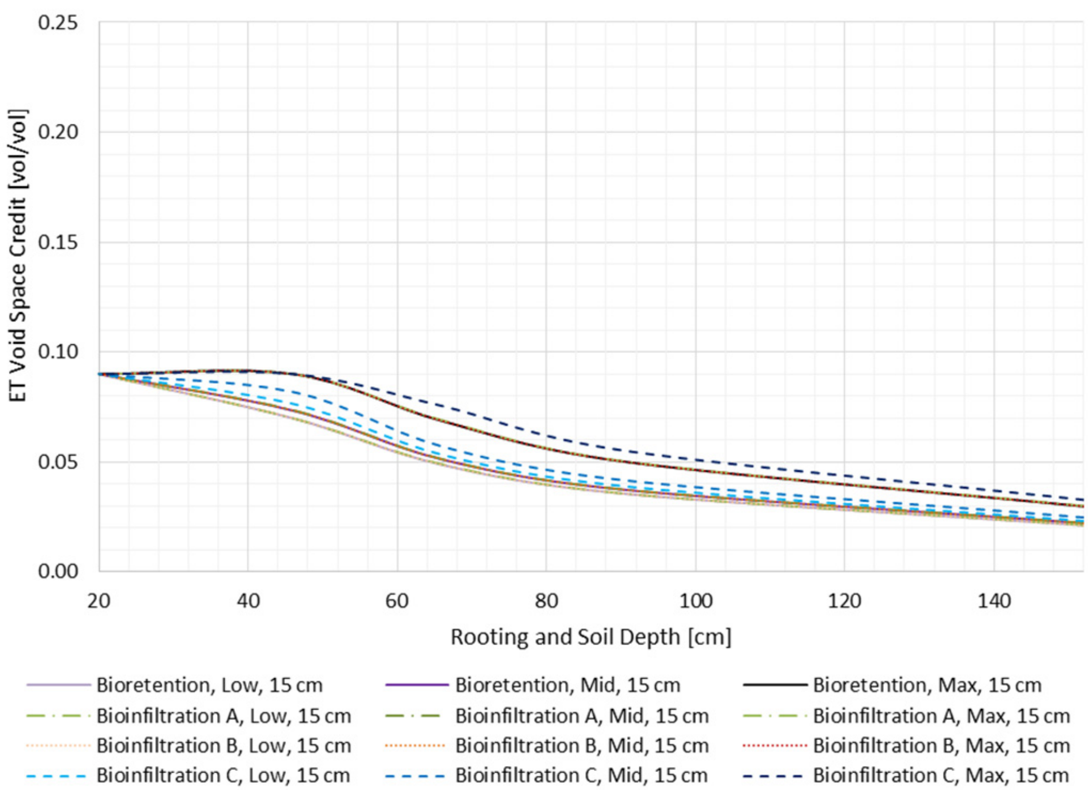
Sand media ET void space credit for 6 days of cumulative ET



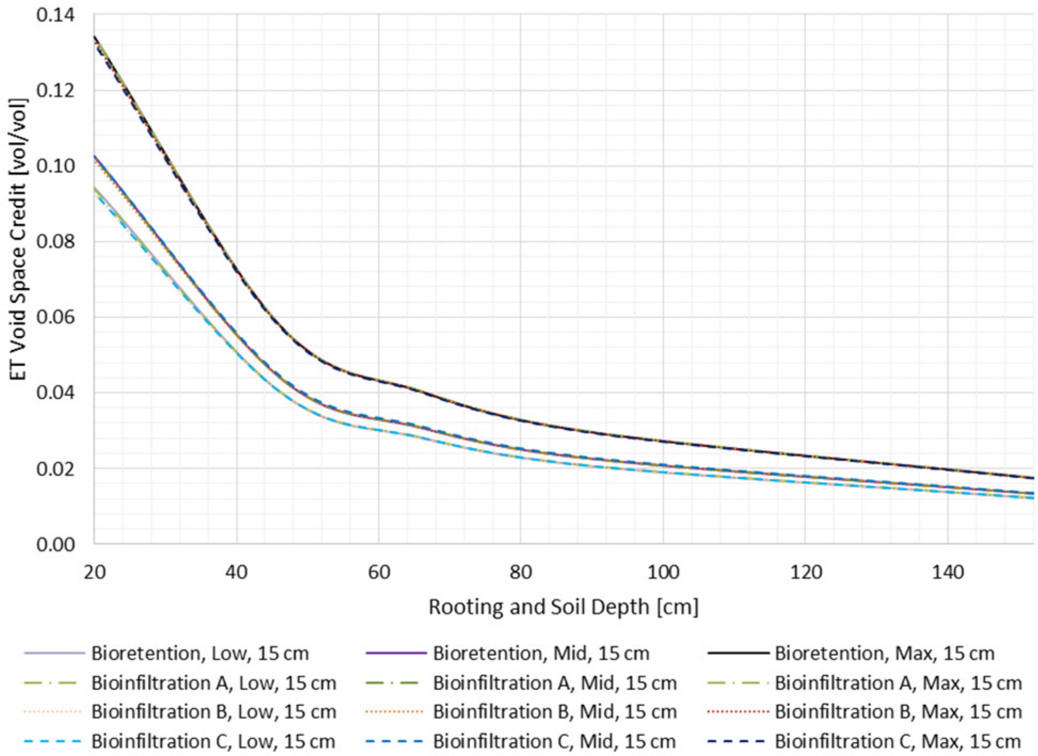
Sand media ET void space credit for 12 days of cumulative ET



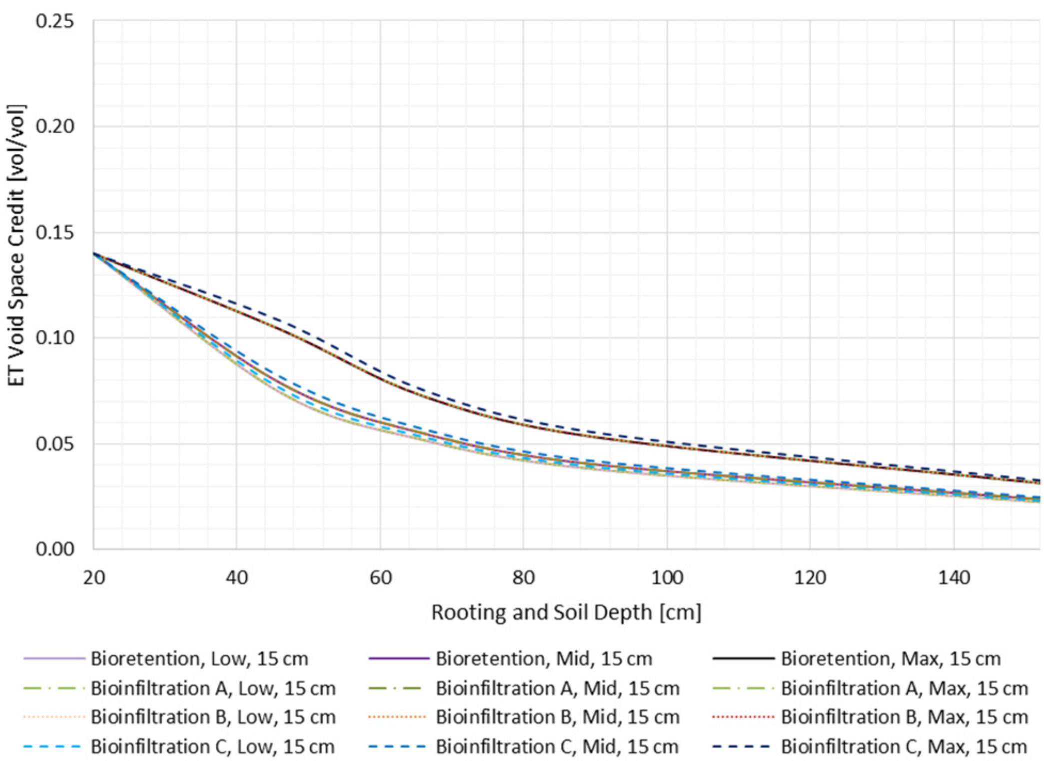
Loamy sand media ET void space credit for 6 days of cumulative ET



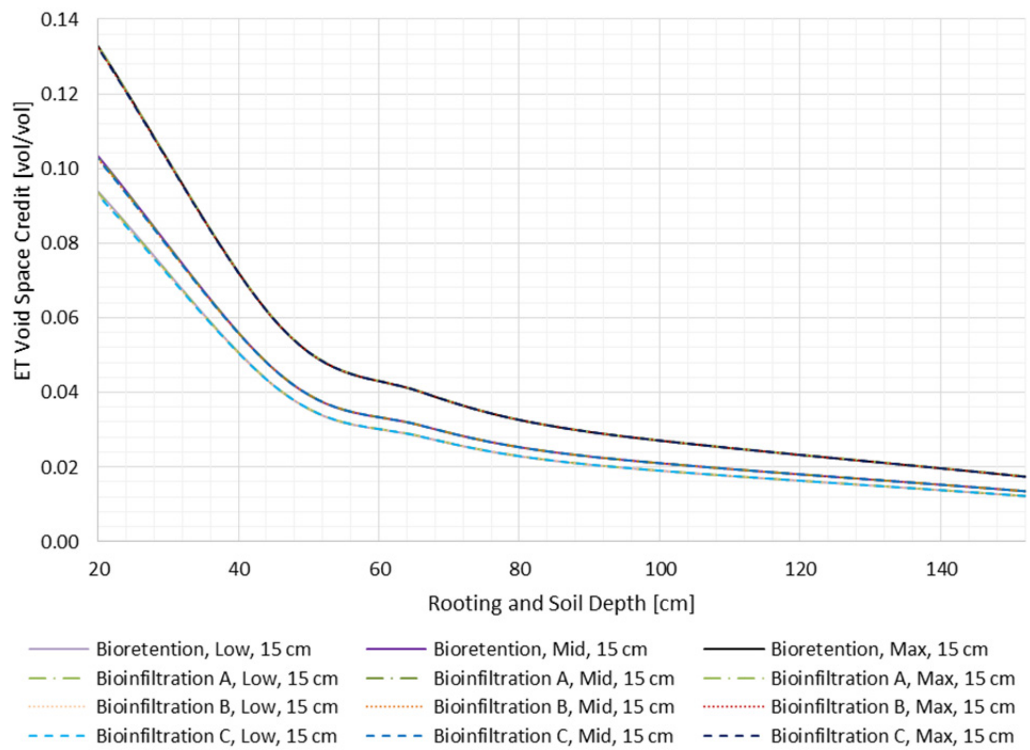
Loamy sand media ET void space credit for 12 days of cumulative ET



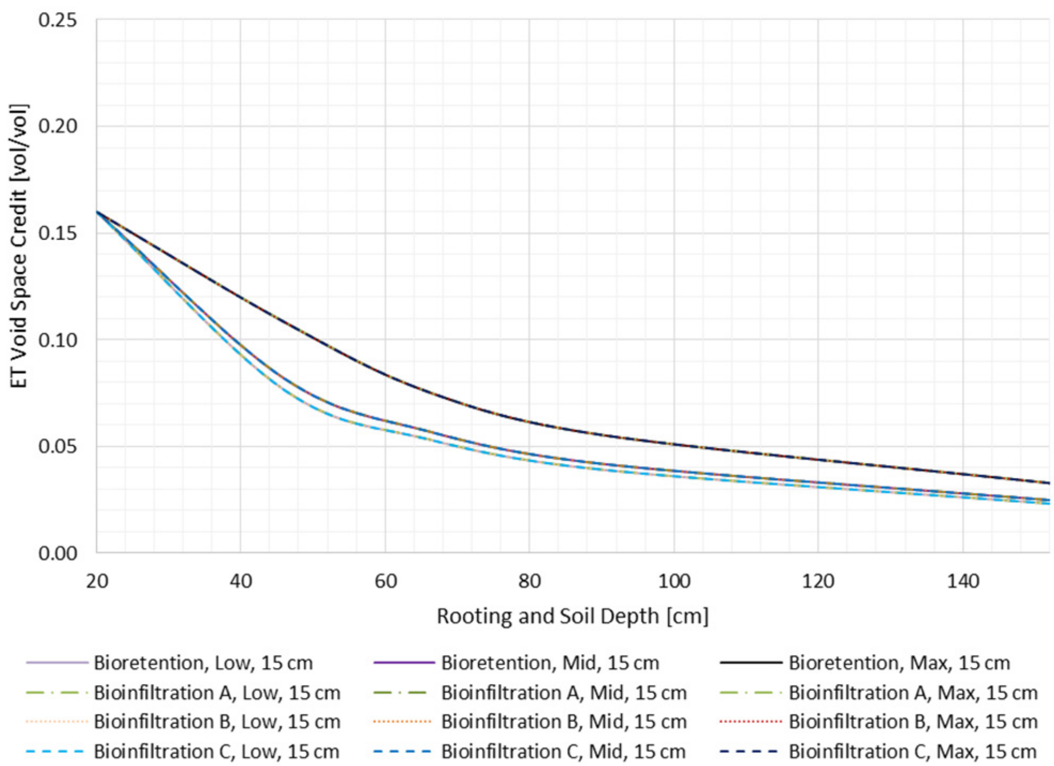
Sandy loam media ET void space credit for 6 days of cumulative ET



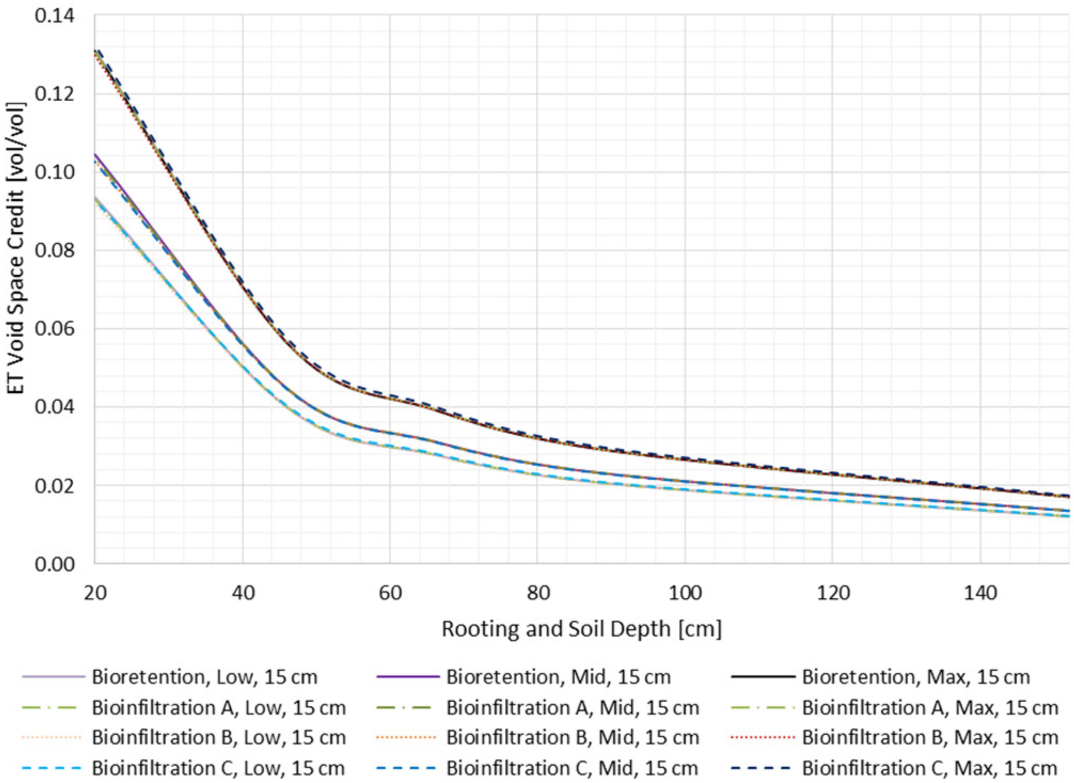
Sandy loam media ET void space credit for 12 days of cumulative ET



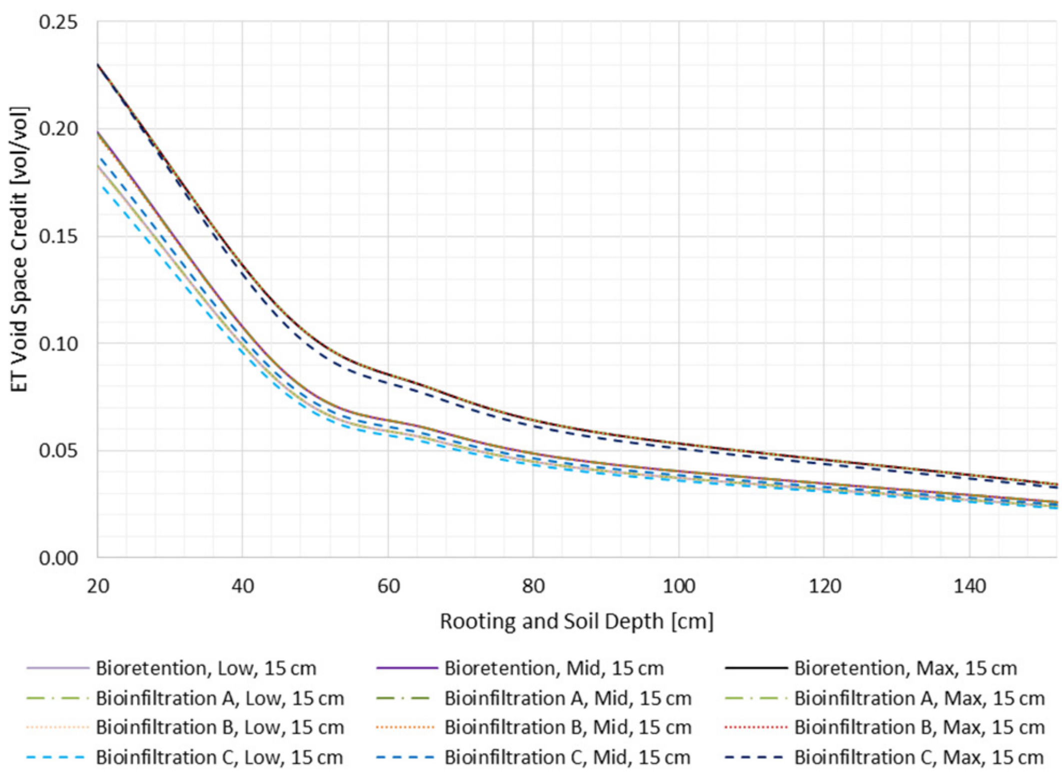
Loam media ET void space credit for 6 days of cumulative ET



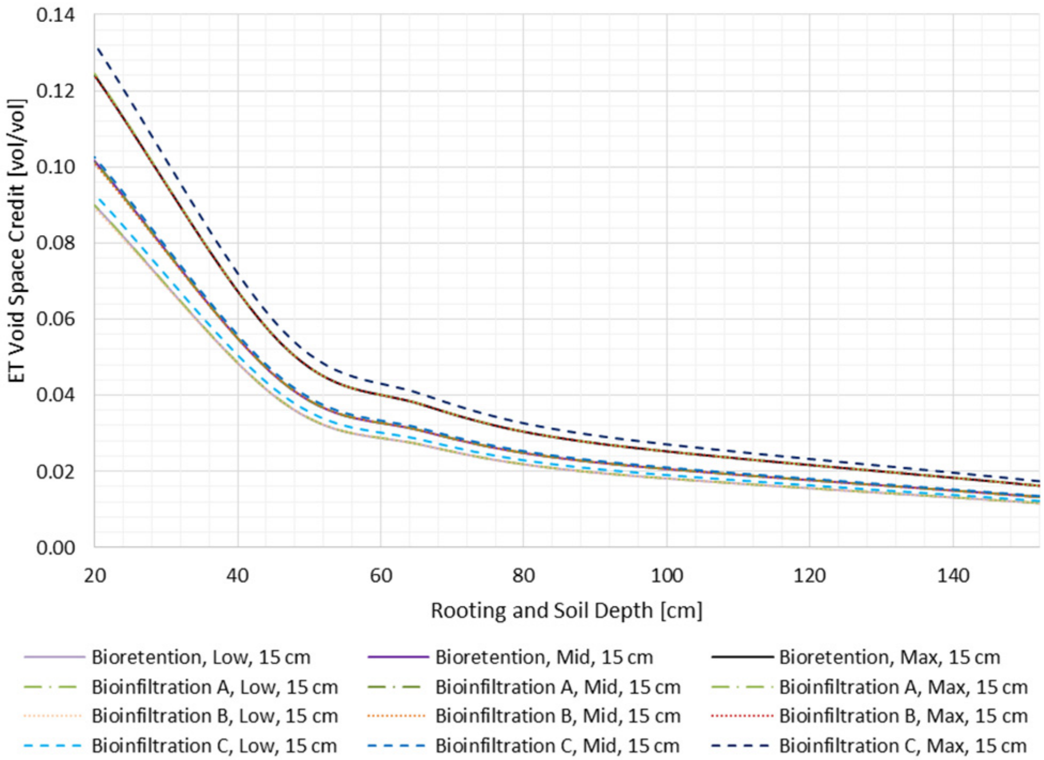
Loam media ET void space credit for 12 days of cumulative ET



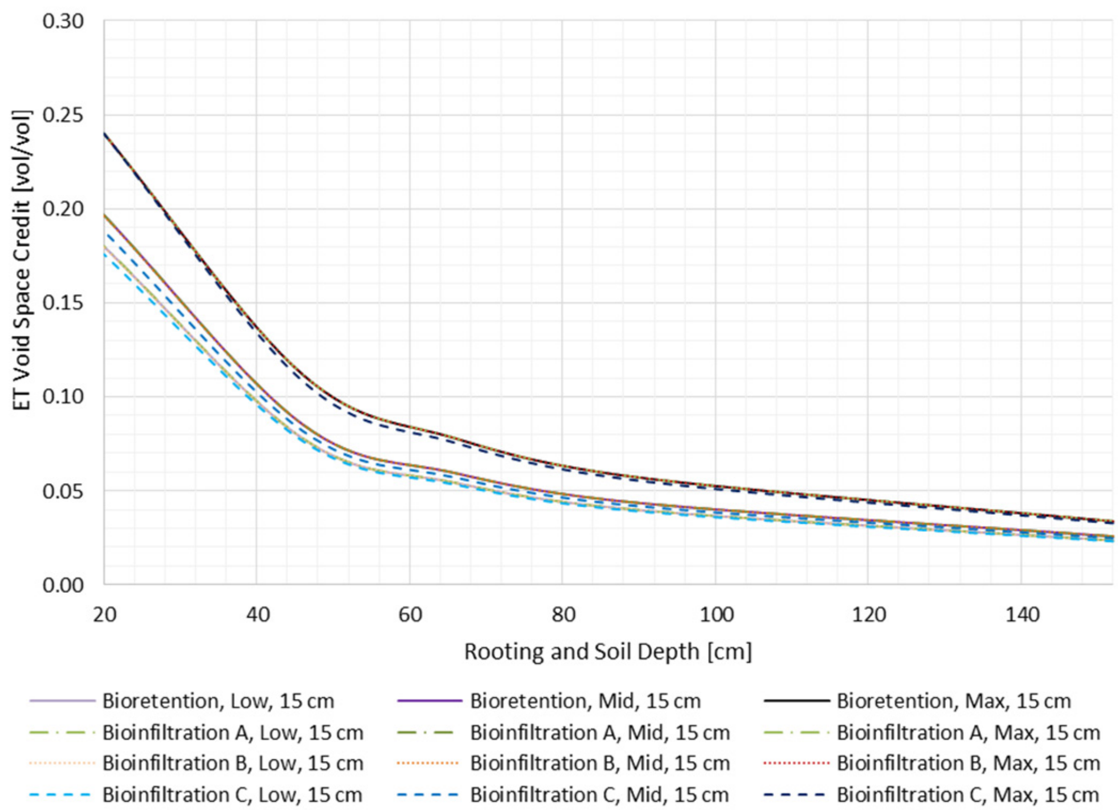
Silt loam media ET void space credit for 6 days of cumulative ET



Silt loam media ET void space credit for 12 days of cumulative ET



Clay loam media ET void space credit for 6 days of cumulative ET



Clay loam media ET void space credit for 12 days of cumulative ET