EVALUATING SOIL TYPE AND FLOW PATH FOR THE OPTIMAL BALANCE OF INFILTRATION AND EVAPOTRANSPIRATION IN VEGETATED STORMWATER CONTROL MEASURES TO ACHIEVE MAXIMUM VOLUME AND POLLUTANT REMOVAL.

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NOMENCLATURE

α	van Genuchten air entry suction coefficient (kPa^{-1})
C_e	dissolved orthophosphate concentration at equilibrium (mg/L)
CEC	cation exchange capacity ($cmol^+$/kg)
D	drainage from the lysimeters (mm)
ΔS	change in storage in the lysimeters (mm)
ET	evapotranspiration from the lysimeters (mm)
FC	field capacity water content (%)
h	van Genuchten matric potential (kPa)
I	inflow from the lysimeters (mm)
K_{ad}	Langmuir adsorption constant (L/mg)
K_s	saturated hydraulic conductivity (cm/day)
M_0	initial mass of soil used to determine CEC (g)
n	van Genuchten pore size distribution coefficient (%)
N	nitrogen concentration used to determine CEC (mg/L)
Ψ	capillary suction (psi)
$PAWC$	plant available water content (%)
PWP	permanent wilting point water content (%)
q_e	sorbed orthophosphate concentration at equilibrium (mg/L)
Q_m	maximum orthophosphate adsorption capacity (mg/kg)
θ	volumetric water content (vol/vol) (%)
θ_r	van Genuchten residual water content (%)
θ_s	van Genuchten saturated water content (%)

ABSTRACT

Present rain garden design and research has focused on infiltration as the key volume reduction mechanism in vegetated stormwater control measures (SCMs), but the inclusion of evapotranspiration (ET) in the design of SCMs is a viable removal method. Design guidelines for soil types in rain gardens are often restrictive, but tailoring the soil media to site specific conditions, or using on-site soils, to promote either infiltration or ET can be beneficial to increase both volume and pollutant removal. A bench scale study was designed at Villanova University to assess the quantity and quality removal capabilities of five different USDA soil types. This study focused on investigating and quantifying two design parameters for vegetated SCMs, soil type and flow path, to maximize volume and pollutant reduction. It was hypothesized that the optimal balance between infiltration and ET for site-specific conditions will enable maximum volume and pollutant removal.

The results of this study indicate that the type of soil media used in vegetated SCMs plays a large role in the volume reduction mechanisms. As the saturated hydraulic conductivity of a soil decreases and the plant available water increases, more volume is removed through ET than infiltration, and vise versa. ET is a seasonally dependent process, and as such, the distribution of volume removal between deep infiltration and ET is also seasonally dependent. Dependent upon season, antecedent dry time, and soil type, the cumulative volume removal effects of ET between storm events have the ability to surpass the cumulative volume removal effects of infiltration. A longer hydraulic retention time in the root zone was also shown to increase volume removal through ET. Nitrogen and phosphorus removal was not significantly affected by media type, so volume removal goals of the SCM should be the main factor in media selection.

CHAPTER 1: INTRODUCTION

Water is a precious resource that we use every day for drinking, cleaning, energy and more, yet society tends to take the availability of water for granted. It is the duty of civil engineers and other environmental professionals to manage this natural resource, which is becoming even more of a challenge due to human activity. One of the most prevalent anthropogenic pollution sources in watersheds is stormwater runoff. In states across the country there has been a surge in flooding events due to an increase in stormwater runoff volume. This increase in runoff can be directly related to the development of impervious surfaces, especially in urban areas like the city of Philadelphia. This additional stormwater runoff contributes to higher pollutant levels in receiving waters, stream channel erosion, decreased groundwater discharge, and impairment to aquatic species (PA BMP Manual 2006). Urban stormwater runoff is the third leading cause of pollution, resulting in 32% of estuaries and 47% of lakes and reservoirs being identified as impaired by the EPA (The National Water Quality Inventory 2009).

The natural hydrological cycle continuously circulates water through the environment via the processes of precipitation, runoff, evapotranspiration, infiltration, groundwater recharge, and stream base flow. The hydrologic cycle is a mass balance that governs the movement of water in the environment, and if one aspect of the cycle is altered, it will alter other components as well. In a natural, undisturbed setting very little runoff is produced from a rainfall event; however, once development modifies the ground surface, the hydrologic cycle sees an increase in runoff (*Figure 1*). Impervious ground cover replaces natural soil and vegetation resulting in decreased infiltration into the soil and decreased evapotranspiration from plants; resulting in a net increase in runoff.

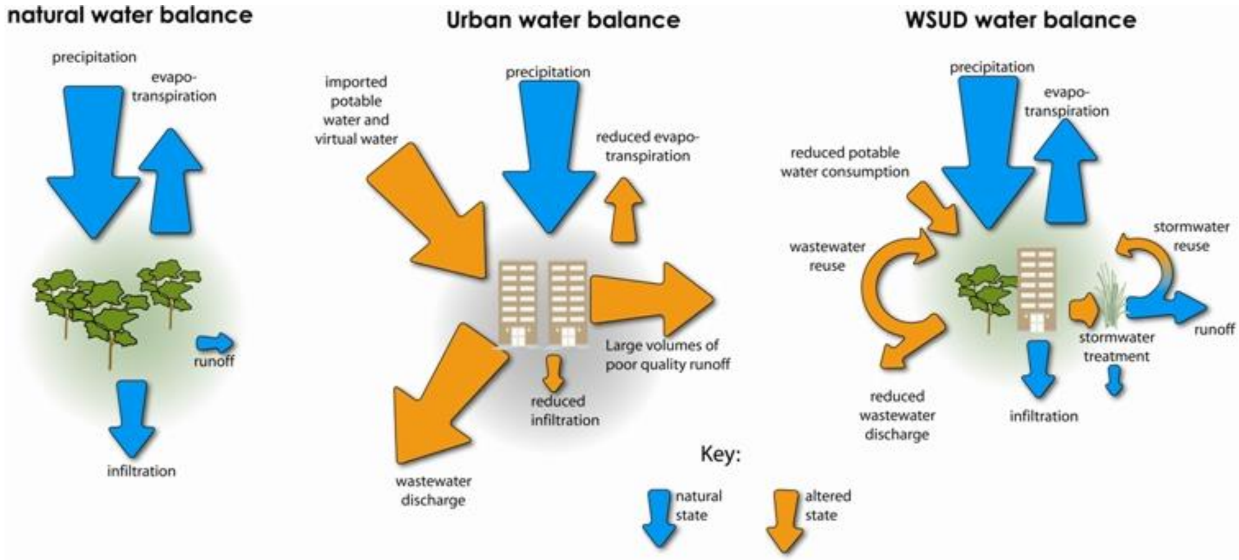

Figure 1: Altered Hydrological Cycle due to Urbanization and Water Sensitive Urban Design (WSUD) (Senn 2015)

This altered hydrologic cycle negatively affects receiving waters from both a water quantity and water quality perspective. Watersheds with 10% or more of impervious surfaces have been shown to negatively impact stream ecology, habitat and water quality, as well as increasing incision and bank erosion in streams (Winston et al. 2016). This phenomenon seen in receiving streams has be coined the "urban stream syndrome", which is indicative of flashy floods, channel erosion and changes in biota (Davis et al. 2012). According to the National Water Quality Inventory study published by the EPA in 2007, urban stormwater runoff was the number three source of impairment to water bodies. One of the most predominant examples of this impairment is the process of eutrophication. With an increased volume of runoff comes an increase in nutrient levels, specifically nitrogen and phosphorus, into surrounding water bodies. Fifteen percent of increased nitrogen and phosphorus loading into receiving bodies of water is due to urban runoff (Davis et al. 2006). These altered nutrient levels lead to the process of eutrophication resulting in harmful algal blooms, fish kills, degradation of habitat quality, and an overall alteration to local ecosystems (Li and Davis 2014; Song et al. 2011).

The National Pollutant Discharge Elimination System (NPDES) manages the quality of the nation's water bodies through controlling point and non-point source pollution. While point source pollution is more easily managed, non-point sources, such as stormwater runoff, have proven more difficult to manage (The National Water Quality Inventory 2009). Previous attempts to treat stormwater runoff involved the direct diversion of flow from urban areas through pipes directly into a nearby water body. This process has proven to be detrimental to receiving water bodies, especially in older cities, such as Philadelphia, that have combined sewer systems (CSS). During large flood events the combination of stormwater runoff and domestic sewage may exceed the capacity of the CSS leading to combined sewer overflow (CSO). Combined sewer overflow expels untreated waste and pathogens into nearby water bodies (Kim and Furumai 2016) making the management of urban stormwater runoff before it enters CSS another important consideration.

Civil and environmental engineers have come a long way in developing more innovative and sustainable methods to handle stormwater runoff. Stormwater control measures (SCMs) are sustainable engineering practices that help bring balance back to the hydrological cycle by mimicking natural conditions before urbanization (PA DEP 2006). Stormwater control measures, also referred to as Best Management Practices (BMPs), Water-Sensitive Urban Designs (WSUDs), or Stormwater Management Practices (SMPs), are used in primarily urban and suburban areas to mitigate the effects of increased runoff. These low impact development (LID) systems are designed to decrease stormwater runoff volume, rate, and duration as well as improve water quality, as stormwater quality is largely a function of stormwater quantity (Brown and Hunt 2011). Vegetated stormwater control measures are the most effective SCM as they reduce runoff through the combined processes of infiltration and evapotranspiration (ET). Vegetated SCMs also provide better volume removal for smaller storms that occur more frequently (Clary et al. 2011). Types of vegetated SCMs include constructed stormwater wetlands, bio-swales, tree trenches, green roofs, and rain gardens, among others.

Rain gardens, also called bioretention or bioinfiltration cells, are one of the most widely used SCMs as they serve to reduce the volume and pollutant levels in runoff as well as add to the aesthetics of an area (Brown et al. 2009; PA BMP Manual 2006). Rain gardens are excavated depressions that are graded to collect stormwater, backfilled with a soil media, and planted with tolerant species to store and treat both water quality and quantity (Figure 2). Stormwater runoff from the surrounding watershed is directed into the bowl of the rain garden where the majority is removed and treated through infiltration and ET as opposed to being directly diverted to nearby water bodies. The bowl of the rain garden allows for ponding, and the runoff volume that exceeds the bowl ponding depth will be removed by an overflow pipe. The performance of bioretention systems can be optimized through design features such as media depth, media type, vegetation type and cover, drainage configuration and the ponding depth (Brown and Hunt 2011; Davis et al. 2012)

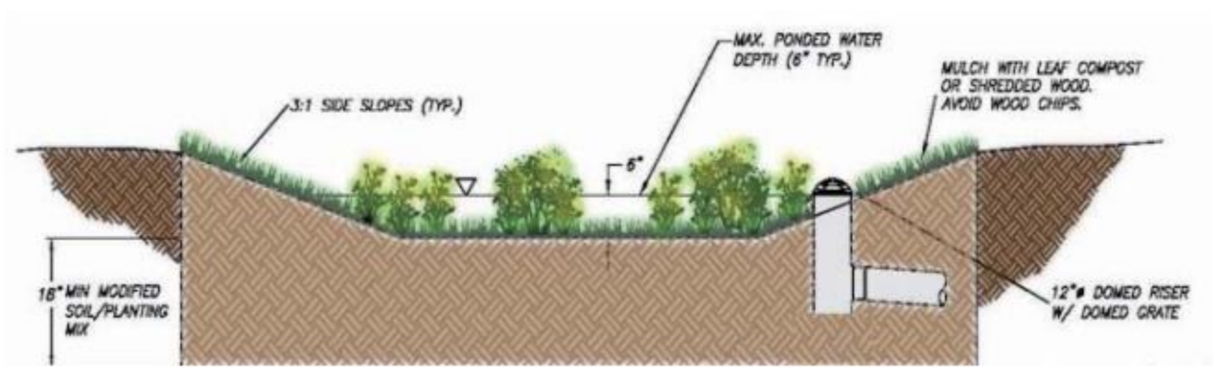

Figure 2: Typical Cross Section of a Rain Garden (PA BMP Manual 2006)

Present research to mitigate increased stormwater runoff through rain gardens has focused on infiltration as the key volume reduction mechanism (Davis et al. 2006). The inclusion of evapotranspiration (ET) in SCM design can also be a viable volume removal method (Wadzuk et al. 2014). Considering both infiltration and ET in SCM design may optimize volume reduction and pollutant reduction at specific sites. Soil media type and depth is one of the key characteristics that dictate the fate of water in a vegetated SCM, specifically a bioretention system or rain garden. This thesis will focus on investigating and quantifying the soil types and flow patterns that can be utilized in vegetated stormwater control measures to maximize volume and pollutant reduction.

CHAPTER 2: LITERATURE REVIEW

2.1 HYDROLOGIC PROCESSES IN SCMS

The two key natural hydrologic processes at work in a vegetated SCM are infiltration and evapotranspiration (ET). Water that is captured in an SCM is either infiltrated by gravity through the soil media until it reaches the native soil below or evapotranspired through the plant roots back into the atmosphere. Both infiltration and ET recover storage space within the SCM media to allow for more volume removal during the next rainfall event. Infiltration is beneficial as it is a large source of volume reduction and leads to shallow groundwater recharge (Brown and Hunt 2011). The rate of infiltration is largely a function of the type of soil media, which will be discussed in Section 2.2. The infiltration rate can be increased by the presence of macropores, which act as preferential pathways for the flow of water. Macropores can be formed by the decay of roots, burrows of invertebrates, and shrink-swell cracks in clayey soils (Lucas 2010). Compaction during construction, surface clogging of fine particles, viscosity effects due to temperature, and the intensity and duration of the storm event may also play a role in infiltration rate within a rain garden (Welker et al. 2013).

Evapotranspiration, a crucial part of the hydrologic cycle, has just recently begun to be considered in rain garden design. Evapotranspiration (ET) is the combined effects of evaporation of water from surfaces and transpiration from plant life. Evaporation includes any water that is returned to the atmosphere from the soil surface, depression storage, or intercepted storage, while transpiration includes water that is returned to the atmosphere via plant stomata or root uptake. The combined effects of evaporation and transpiration are commonly accounted for as ET. As the density of vegetation increases, transpiration will increase relative to evaporation. While potential evapotranspiration (PET) is fairly easily calculated based on the assumption of a saturated soil condition and known climatological parameters, actual ET is dependent on the varying moisture conditions in the soil. Transpiration is also dictated by the leaf structure, plant stomata shape, and pressure gradient, and therefore dependent on the type of vegetation and its growth stage (Feller 2010). In total, ET is energy driven and is dependent upon the amount of moisture available for the plants, the vegetation type and climactic conditions (Feng et al. 2012; Wadzuk et al. 2013). The rate of ET is limited by either precipitation (available water) or energy supply (climactic conditions), so it is enhanced when the two are in phase with one another (Feng et al. 2012).

Many current SCM designs focus on infiltration as the primary volume removal mechanism for stormwater runoff (Brown and Hunt 2011; Carpenter and Hallam 2010; Feng et al. 2013). The amount of water that a rain garden is typically designed to treat is based on the infiltrating volume available in the bowl and soil media. While infiltration does provide substantial reduction for both volume and pollutant levels in stormwater, it is not the only process at work in a these systems. Rain gardens are dynamic systems and solely considering infiltration will under credit the work the SCM is doing. The incorporation of ET in SCM design is limited, and there are large gaps in knowledge pertaining to the role of ET in rain gardens (Bradford and Denich 2008; Feng et al. 2013; Heasom and Traver 2007; Hickman et al. 2011; Li and Davis 2014; Wadzuk et al. 2013). Evapotranspiration plays a significant role in the hydrological cycle, accounting for up to 50% of the annual watershed budget in the Delaware River Basin Watershed (Hess et al. 2014) and between 40-70% in the Northeastern United States on an annual basis (Sanford and Selnick 2013). The inclusion of ET should be considered in SCM design to properly imitate natural hydrological conditions.

Although current rain garden designs do not include ET as a means of volume removal, ET is inadvertently contributing to a large percentage of volume reduction in SCMs. In one study by Lucas (2010) it was found that 47% of the precipitation was infiltrated in an infiltration trench and less than 6% was discharged, leaving an unquantified amount that was potentially removed through ET. Winston (2016) observed 20% of the inflow in a bioretention cell going to ET, and in a recent bioretention mesocosm study at Villanova University, up to 57% of the direct rainfall went to ET (Wadzuk et al. 2014). Evapotranspiration has been quantified in the agricultural field and other SCMs, such as green roofs and final landfill covers (Benson and Bareither 2012), indicating the potential to incorporate ET in rain garden design. From a green roof perspective, an average daily ET rate of 3 mm/day was quantified, equating to 66.1-87.8% of stormwater volume going to ET on an annual basis (Wadzuk et al. 2013). With slight design modifications, rain gardens can see similar removal through ET.

There is immense variability in volumetric reduction of stormwater because of varying designs and site conditions (Clary et al. 2011), but attributing the volume removal to the combined effects of infiltration and ET will offer a better understanding of rain garden design. Current rain garden design is highly empirical making it difficult to adapt designs to different landscapes, climates, etc. (Davis et al. 2012). As opposed to a rural setting, ET in urban settings is very dependent upon the surrounding land use and cover and the heterogeneity of urban surfaces, emphasizing the importance of site-specific design (Feng et al. 2013). It is hypothesized that bioretention SCM design for maximum volume and pollutant removal can be achieved by incorporating both infiltration and ET in design. These two mechanisms can be combined in different proportions to achieve maximum removal potential depending on the geographical and topographical aspects of a site. Most SCM designs are somewhere in between 100% infiltration and 100% ET (Wadzuk et al. 2013), and design modifications can be tailored to promote or inhibit one of the two components of the hydrological cycle as desired.

2.2 SOIL MIX DESIGN

The design component that is of primary importance in this research is the soil media type as it will dictate the primary volume removal mechanism. Current rain garden designs typically specify sandy soils due to their low hydraulic retention time to aid in the amount of infiltration that occurs (Brown and Hunt 2011; Heasom and Traver 2007). Likewise, many current and past research studies on bioinfiltration and bioretention systems have only tested soils consisting primarily of sand (Brown and Hunt 2011; Carpenter and Hallam 2010) due to its capacity to achieve a large volume reduction through infiltration. Davis (2006) performed a study with multiple bioretention columns constructed with the same soil mix of 50% sand, 30% topsoil, 10% organics and less than 5% clay. Dietz and Clausen (2005) investigated two full size rain gardens with identical soil compositions of 85% sand and a remainder of silt and clay. All of the soils tested in similar studies have been loamy sands or sandy loams, with little to no focus on the use of finer grained soils. While it is true sandier soils lend themselves well to infiltration, soils with lower hydraulic conductivities may lend themselves better to ET. More research is needed on soil media mixes used in rain gardens to promote both ET and infiltration.

2.2.1 Fine Grained versus Coarse Grained Soils

Soils in vegetated SCMs must balance the competing needs of draining a large volume of water quickly after a storm event and retaining water for plant health, ET and pollutant removal (Barrett et al. 2013; Brown and Hunt 2011; Hatt et al. 2007). While sandy soils have a low residence time creating more storage in the SCM, soils with a lower hydraulic conductivity, such as clays and silts, retain more water near the surface making more water available for ET (Figure 3). Sand can only retain about 14% of its weight in water while clays can retain much more (Carpenter and Hallam 2010). While sand is able to conduct water very well near saturation, it conducts very poorly at drier moisture contents where clays thrive. During dry periods clay particles will shrink, increasing the porosity of the media, and then swell during a storm event (Hatt et al. 2007). This phenomenon allows soils with clays to be more tolerant during drought periods. In one study by Shannak (2014) different soil media types were tested under different irrigation patterns, and it was found that the sandy soil required 58% more supplemental water on average than a silty clay soil.

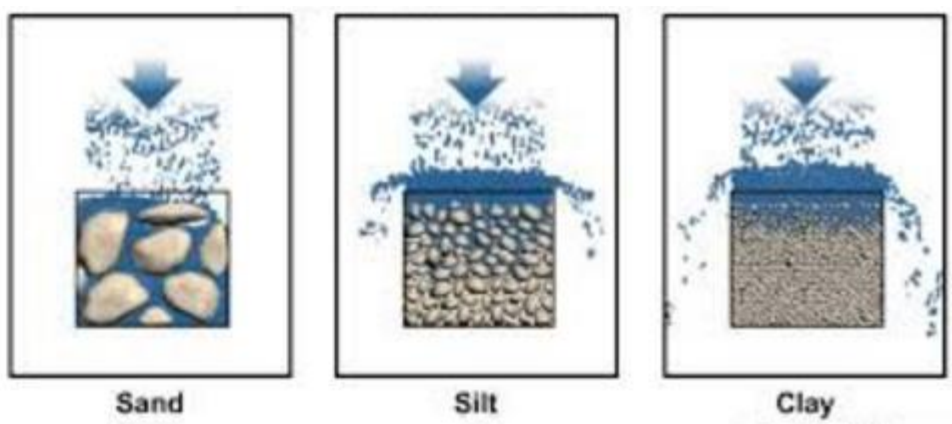

Figure 3: Infiltration Variations by Soil Type (COMET 2016)

When a soil is fully saturated, the water supply available for ET is unlimited. The total water available for ET can be taken as the difference between a soil's field capacity and wilting point, which is much greater for finer soils. The interaction between negative matric potential at varying moisture contents as illustrated by soil water characteristic curves (SWCCs) will be discussed in more detail in Section 3.1.4. Each soil is unique and quantitative properties such as saturated hydraulic conductivity, organic content, dry bulk density, porosity, grain size, and field capacity should be identified for each soil (Carpenter and Hallam 2010; Lucas 2010; Sileshi et al. 2012).

Evapotranspiration should not be taken as an entirely separate removal mechanism from infiltration as both processes can work together in runoff reduction. As ET removes soil moisture it is simultaneously reopening void space in the soil therefore increasing the storage capacity or the infiltration capacity (Wadzuk et al. 2013). The presence of vegetation maintains the infiltration rate in the soil over time by offsetting the effects of compaction and sedimentation. The microbial processes associated with vegetation also improve infiltration even when sediments begin to accumulate (Lucas 2010; Winston et al. 2016). When designing for ET in a bioretention system, it may not be desired that water move quickly through the soil media. Higher clay content, up to 20%, has been shown to produce healthier plants and more ET, in addition to increased pollutant concentration removal (Hatt et al. 2007; Lucas 2010; Sickles et al. 2007; Winston et al. 2016). In addition, fine filter media may lend to easier maintenance as clogging will occur in the surface layer which can be easily removed, as opposed to a coarse media in which the entire depth must be replaced (Hatt et al. 2007). The use of finer soil mixes has been generally avoided thus far in SCMs, but soils with quite high clay fractions have been shown to produce high saturated hydraulic conductivities, especially in the presence of vegetation (Sickles et al. 2007). The optimal balance of soil mixes in rain gardens can lead to the optimal balance of volume and pollutant reduction through ET and infiltration.

2.2.2 Current Soil Mix Specifications for Rain Gardens

Rain gardens are largely a function of soil mix design and more technical research is needed to determine the best soil mixes for optimal volume and pollutant removal from stormwater (Brown et al. 2009; Carpenter and Hallam 2010; Sickles et al. 2007). The variation and range in current 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 and Hallam 2010), with many more out there (Figure A1). Figure 4 shows some of the different rain garden designs recommended by various states. These soils are all limited to the lower left portion of the USDA triangle, and one aim of this research is to study finer grained soils for use in vegetated SCMs (as outlined in green).

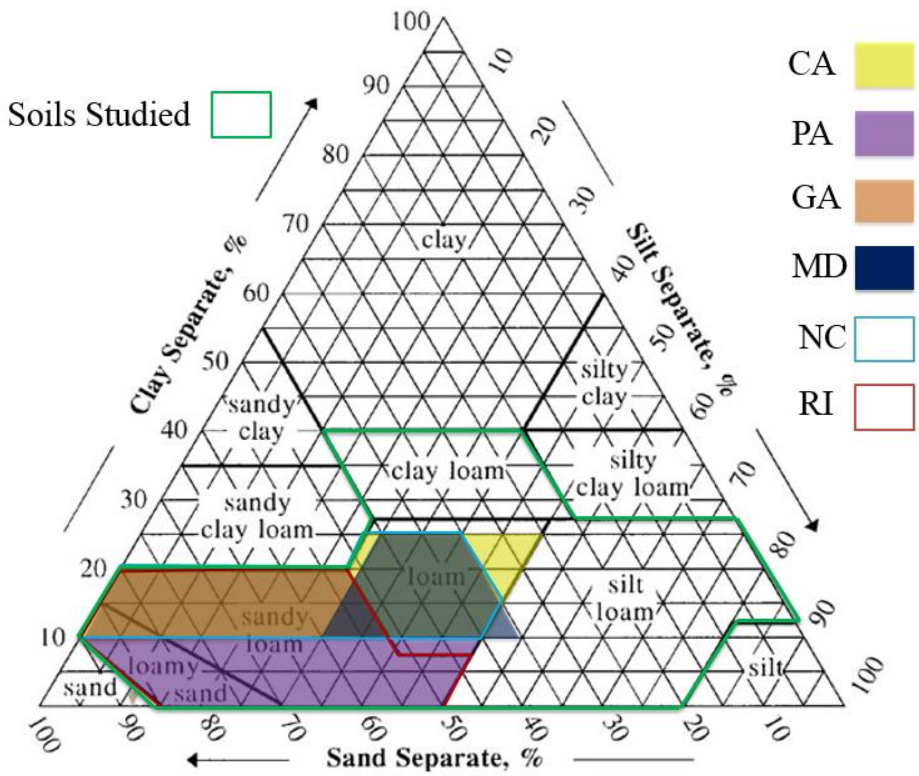

Figure 4: Varying Soil Mix Designs by State and the Soils Studied in this Research

The soil media composition specified by each state varies vastly from percentages of sand ranging from 35-80% and percentages of topsoil ranging from 20-30%. 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 soil mix compositions, yet this is a broad term lacking any technical classification. In one study by Sickles (2007), topsoil was used to refer to both native soil as well as commercial topsoil. Topsoil is sold on the market with 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. The most varied design recommendation across the board is the amount of clay content that should be used in rain garden mixes, ranging anywhere from less than 5% to greater than 25% (Carpenter and Hallam 2010). There is little published data on the effect of soil mixes on hydraulic performance and a more cohesive technical reference is needed.

There is also a dispute in the literature on the amount of organic content that provides the best volume and pollutant removal in vegetated SCMs (Barrett et al. 2013; Brown and Hunt 2011; Carpenter and Hallam 2010). Some bioretention designs utilize a top layer of organic material, such as grass or mulch, to act as an initial filter to the runoff. It has been shown that rain garden soils with a high organic content may actually increase the pollutant load leaving a bioretention system by acting as an additional nutrient source (Barrett et al. 2013; Brown and Hunt 2011; Culbertson and Hutchinson 2004). Naturally occurring soils that support plant growth typically only have between 2% and 10% organic matter (Bot and Benites 2005). The type of compost material is also a factor. For example, the amount of nitrogen released from woodchips or mulch would be much lower than the amount released from grass clippings or leaves because the carbon to nitrogen ratio (C/N) is so much lower in the former (Brown et al. 2013). Some of the mix designs currently specified may hinder pollutant removal because of the high organic content specified, which will be discussed further in the Section 2.3. In general, the use of compost and chemical fertilizers should be avoided in SCMs unless the initial phosphorus concentration is analyzed (Clary et al. 2011). There is a need for a broader range of hydrological soil properties to be specified with rain garden soil mixes (Carpenter and Hallam 2010), and researchers are continuing to modify SCM soil designs making the design parameters available to the public confusing and vague, yet very restrictive.

2.2.3 Site Specific Design: Soil Depth and Flow Path

Different geographical locations and topographical limitations may warrant a variation in soil mix design depending on the volume reduction mechanism that is desired. Site location will also dictate the desired flow pattern and media depth. In one study by Brown (2011), deeper media depths in bioretention cells had about 10% more total volume removal, but this was only considering infiltration as the main volume removal mechanism. Although deeper media depths perform better on a volume reduction standpoint when infiltration is considered as the volume reduction mechanism, some locations with limited vertical depth may require bioretention systems utilizing ET as the primary removal mechanism. In urban areas with underlying infrastructure, areas with karst topography, contaminated soils, or a seasonally high groundwater table flow is limited in the vertical direction. In these cases, water in the SCM can be directed in a combined horizontal and vertical flow path by using a finer soil media with a shallower depth to promote more ET. Considering shallower design depths and altered flow paths for rain gardens may be advantageous in areas where infiltration is not that effective or allowable and ET is the desired removal mechanism. Other sites may favor deeper rain garden designs that utilize infiltration as the primary removal mechanism.

Native soils are often seen as inadequate for being poorly infiltrating (Carpenter and Hallam 2010), but in many cases native soils may be perfectly suitable for rain garden design (Welker et al. 2013). Depending on the site-specific goals, native soils can be reused in the soil mix design saving time and money. For example, the use of native soils may enhance the natural ET process that occurs at a specific site (Benson and Bareither 2012) making it unnecessary to import costly engineered media. By altering soil media, media depth, and flow path, a shorter or longer hydraulic retention time will promote either infiltration or ET, respectively. Rain gardens are often ignored as a stormwater management option at sites where the underlying soils are considered bad, but the natural underlying conditions can be tailored to aid in the design of a rain garden (Clary et al. 2011). The underlying soil greatly impacts SCM performance, but there have been numerous studies showing the successful implementation of rain gardens in areas with fine underlying soils without the use of underdrains (Carpenter and Hallam 2010). In Ohio two bioretention cells were installed at a site with NRCS type D soil and the runoff volume was reduced by 60% (Winston et al. 2016). Underdrains were used in these rain gardens, but it is possible that the SCMs could have achieved even more volume removal without the underdrains. The presence of an internal water storage (IWS) zone in a rain garden through the use of an upturned outlet elbow may also add to the volume removal in a location where the underlying soils are poor. While underdrains and IWS zones may be beneficial at some sites, the use of a finer media soil mix within the rain garden can act somewhat as an IWS by creating a longer hydraulic retention time. Fine soil media in the rain garden will keep more water available to infiltrate between consecutive storm events. In general, the hydraulic conductivity of underlying soils at a site should not be considered a restriction for the installation of a vegetated SCM (Sileshi et al. 2012; Winston et al. 2016).

2.3 POLLUTANT REMOVAL

In addition to reducing the volume of stormwater runoff, vegetated SCMs also reduce the pollutant levels in runoff. As rain and snowmelt wash over impervious areas they collect pollutants from streets, agricultural areas, construction sites and other impervious surfaces. Some common pollutants picked up by stormwater runoff are animal waste, motor oil and grease, trash, fertilizers and pesticides, yard clippings, and eroded sediment. The high nutrient levels present in these pollutants leads to increased nutrient levels, specifically nitrogen (N) and phosphorus (P), in the runoff and eventually the surrounding water bodies. These nutrient spikes trigger eutrophication and algal blooms in receiving waters (Hatt et al. 2007). Urban stormwater runoff is a top ten cause of nutrient impairment in rivers, streams, lakes and estuaries, especially in nutrient sensitive watersheds (Brown and Hunt 2011).

Not only do rain gardens serve to reduce the peak flow in watersheds, but they are an effective means to reduce the total nitrogen and phosphorous content in runoff. The soil media within the bioretention zone acts as a filtration device and can play a large role in the nitrogen and phosphorous removal. Following a rainfall event, the main nutrient removal processes in bioretention systems are filtration, adsorption, sedimentation, ion exchange, chemical precipitation and biological decomposition (Brown et al. 2009; Yan et al. 2015). It should be noted that the majority of nitrogen and phosphorous removal, and pollutant removal in general, can be attributed to the physical volume reduction of the stormwater in the bioretention cell through infiltration and evapotranspiration (Brown et al. 2009; Li and Davis 2014). The presence of vegetation within the bioretention cell also greatly increases the nutrient removal capabilities. Barrett (2013) showed that the addition of plants in bioretention filter media significantly improved pollutant removal with up to 79% removal of total nitrogen (TN) and 94% of total phosphorus (TP), while media without plants exported significant concentrations of nitrate and nitrite. Although, it may be necessary to harvest the plant biomass at the end of the season, otherwise any nutrients captured by the vegetation can be transferred back into the soil media when the vegetation decays (Lucas and Greenway 2012).

There are numerous theories on which type of soil or layers of soil may be best for this nutrient removal (Davis et al. 2006; Hsieh et al. 2007; Kim et al. 2003), but a sandy soil is still typically used in current designs. Pollutant removal can be limited if the soils in the bioretention system are too sandy (Brown and Hunt 2011), as sandy systems have a short hydraulic retention time and do not allow for large concentration reductions of pollutants. Although a higher pollutant load removal is usually seen with sandier soils due to mass volume reduction through infiltration, soils with a longer hydraulic retention time may see better reductions in pollutant concentrations. Slower infiltration rates and longer hydraulic residence time are generally correlated with higher nutrient removal as the clay particles provide the majority of adsorption sites and additional removal through fine filtration, ionic adhesion and surface complexation (Drake et al. 2010; Hatt et al. 2007; Lucas and Greenway 2012).

The targeted nutrient for removal should also be considered in design. Stormwater runoff contains many forms of nitrogen and phosphorus, each with different removal processes. In general, phosphorus is more easily removed as the majority is sorbed to soil particles. Nitrogen undergoes many physical and chemical transformations within a bioretention cell so the different forms are much harder to remove. Davis (2006) observed a good removal of phosphorus (70-80%), ammonium (60-80%) and TKN (55-65%), but a poor removal of nitrate (less than 20%) while some cells even produced nitrate, exemplifying the complicated fate of nitrogen in rain gardens. The ratio of nitrogen to phosphorus (N:P ratio) in receiving water bodies dictates what the limiting nutrient is for eutrophication. The limiting nutrient, usually N or P but more commonly P in freshwater systems, limits the amount of production in an ecosystem as it is usually present in the smallest quantity in water bodies. The N:P ratio at which the limiting nutrient changes from nitrogen to phosphorus is about 15-30 meaning anything greater than that value will be phosphorus limiting and anything less than that value will be nitrogen limiting (Blecken et al. 2010). Determining the limiting nutrient in a watershed can dictate removal goals, and removal of phosphorus may be more important in many circumstances.

2.3.1 Phosphorus Removal

The majority of phosphorus in stormwater runoff is present as orthophosphate which includes the forms PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$, and H_sPO_4 (Passaro 2014). The most common orthophosphate found in runoff is PO_4^{3-} which will be the form that is of primary interest in this research. Orthophosphate is also referred to soluble reactive phosphorus (SRP), but the term orthophosphate will be used for the remainder of this thesis. Orthophosphate is readily available for consumption by bacteria, algae, and plants and plays a key role in biomass growth which is why its removal is important for the avoidance of eutrophication. SRP is usually bound to the total suspended solids (TSS) in stormwater, therefore the most effective process for removing P in SCMs is through adsorption, sedimentation, and chemical precipitation (Clary et al. 2011; Yan et al. 2015). Phosphorus removal can be considered short term (through plant uptake or exchangeable sorption) or long term (through sedimentation or burial). The long term fate of phosphorus is not as complex as nitrogen as there are typically no biological pathways that exist within SCMs that convert phosphorus into its gaseous form; therefore it will just accumulate in the soil media over time or be taken up by plants (May and Sivakumar 2009).

The amount of orthophosphate removed from the influent stormwater is dependent upon the adsorption capacity of the adsorbent, which in the case of rain gardens is the soil media. This thesis will measure and analyze the orthophosphate adsorption capacity of different soil types, which will be discussed in more detail in the Methods section. The chemical removal capacity of phosphorus may also be limited due to clogging, as all chemical constituents that depend on the removal of TSS will fail (Hatt et al. 2007). The ability for a soil to retain phosphorus will decrease slightly if the pH falls below acidic, but temperature effects have been shown to have a negligible effect on the removal of P (Barrett et al. 2013; Blecken et al. 2010). The presence of vegetation significantly decreases the concentration of all forms of P in the effluent (Barrett et al. 2013; Yan et al. 2015), and Henderson (2007) found the addition of plants increased phosphorus retention from 85% to 94%. The addition of a planting mix or soil with high organic content is not necessary to achieve total phosphorus removal and may cause the re-suspension of SRP leading to increased effluent phosphorus concentrations (Barrett et al. 2013; Clary et al. 2011). While deeper media depths have shown higher TP reduction due to a greater volume reduction (Brown and Hunt 2011), the presence of an IWS zone or the time between storm events has not been shown to affect overall removal of phosphorus, unlike nitrogen (Barrett et al. 2013; Hatt et al. 2007).

2.3.2 Nitrogen Removal

Nitrogen removal is complicated due to the multiple chemical forms nitrogen takes in stormwater runoff including particulate organic nitrogen (PON), nitrate (NO_3-N), nitrite (NO_2-N), ammonium (NH_4-N), and dissolved organic nitrogen (DON) (Li et al, 2014). Total nitrogen (TN) refers to all forms of nitrogen while total kjeldahl nitrogen (TKN) refers to all forms of nitrogen except nitrite and nitrate (NO_x) (Passaro 2014). Although the effluent concentration of TN usually sees a mean decrease of about 30-60% in a bioretention cell (Brown et al. 2013; Hsieh et al. 2007; Li and Davis 2014), the effluent NO_3-N and DON concentrations are usually higher in the effluent than in the influent. The chemical and biological activities occurring within the bioretention cell between rainfall events produce nitrate (Brown et al. 2013); therefore, the removal of nitrate in bioretention cells is the most difficult. During the time particulate organic nitrogen (PON) is in the bioretention cell, it is converted to nitrate through the processes of mineralization, ammonification, and nitrification (Li and Davis 2014; Lucas and Greenway 2012). Ammonium and nitrite are also converted to nitrate through nitrification under aerobic conditions. Therefore, the leaching DON and NO_3-N can account for the majority of the effluent nitrogen concentration that escapes the bioretention cell (Brown et al. 2013), whereas PON, TKN, and NO_2-N are effectively removed through bioretention.

Because of the multiple species of nitrogen present, removal can occur by sedimentation/filtration, adsorption, mineralization, or biological transformation. The majority of nitrogen removal can be attributed to the physical volume reduction of the stormwater in the bioretention cell through infiltration and evapotranspiration (*Figure 5*). PON is transformed to ammonium (NH_4) through ammonification and ammonium is transformed to nitrite (NO_2) and nitrate (NO_3) through nitrification (Kim et al. 2003)

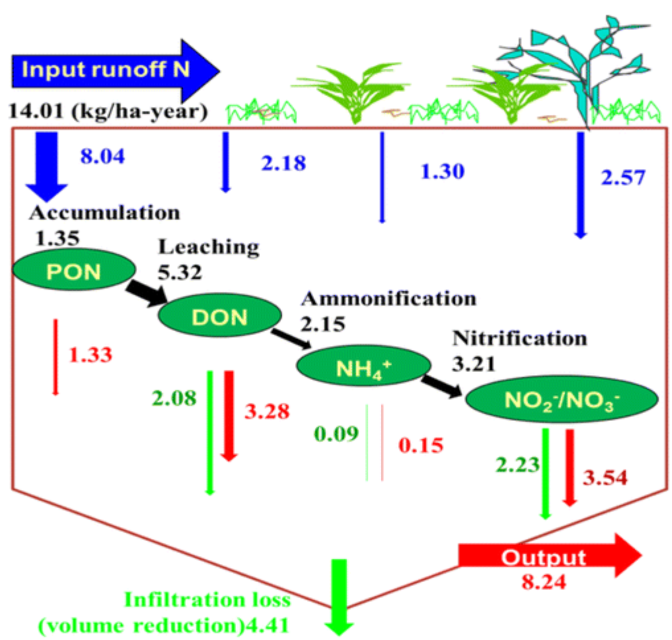

Figure 5: The Fate of Nitrogen in a Bioretention System (Li and Davis 2014)

As mentioned previously, three of the nitrogen species (PON, TKN, and NO_2-N) are fairly easily removed and their removal can be attributed to specific physical and chemical processes. The removal of PON is directly related to the TSS removal with a 0.91 correlation coefficient (Li and Davis 2014); therefore, PON is removed mostly by physical filtration. Also, since a large portion of PON is converted to NO_3-N through ammonification, the addition of filter media to adsorb PON initially might help to reduce some of the nitrate output (Davis et al. 2006; Li and Davis 2014). Ammonium removal is primarily through ion exchange adsorption to negatively charged clays and organic matter in the soil media (Hsieh et al. 2007), but some ammonium is transformed to nitrate through nitrification. Nitrite also undergoes nitrification and speciates to nitrate. Since nitrate does not sorb to soil, any removal of nitrate in an SCM is seen as a plus (Davis et al. 2006). Although bioretention systems are capable of removing organic nitrogen, the process of nitrification somewhat negates that since excess nitrate is leached through the system. Despite this, studies have shown an overall decrease in TKN and TN in systems (Barrett et al. 2013). This may be partly due to other mechanisms capable of transforming nitrate such as dissimilatory nitrate reduction (DNR) and denitrification.

The volume and rate of rainfall entering a bioretention system also affects the removal of nitrogen. An increased flow rate will hypothetically cause the water to move through the soil column faster limiting the contact time between the stormwater and the soil, therefore limiting the nitrogen uptake and removal. It was found that the removal of nitrogen was less efficient when the flow rate, intensity and duration were increased (Brown and Hunt 2011; Davis et al. 2006). A regulated outflow is capable of retaining almost 50% more total nitrogen than an unregulated outflow because there is a direct correlation between hydraulic retention time and mass retention of nitrogen (Lucas and Greenway 2012). Although there may be an initial spike in the effluent nitrate concentration due to the rapid wash-off of the influent nitrogen load, the outflow concentrations will be lowered over time since the runoff is technically becoming diluted. This phenomenon is known as the first flush. Even though there is always a net mass reduction of nitrate in a bioretention cell, the output concentrations are usually higher than the input concentrations (Davis et al. 2006). This may be due to the fact that other forms of nitrogen are being converted to nitrate in the bioretention cell in between rainfall events. While increased retention time and lower flow rates allow for more sorption of PON and ammonia, it also allows more time for nitrification and the production of nitrate, which is not easily retained in the system. Because of this, effluent concentrations of TN were up to seven times higher following extended dry periods between storm events compared to shorter dry times between events (Brown et al. 2013; Hatt et al. 2007).

There are numerous theories on which type of soil or layers of soil may be best for nitrogen removal (Davis et al. 2006; Hsieh et al. 2007; Kim et al. 2003), and it has been recommended that the role of different soils for this purpose should be explored in future studies. In one study (Davis et al. 2006), nitrogen removal was monitored at two rain garden sites: “Greenbelt” which had a greater media depth and contained less sand and “Largo” which was a shallower facility with engineered soil and more sand. It was hypothesized that the removal of nitrogen would be greater at Greenbelt, but it turned out the nutrient removal at both sites was fairly comparable. The bioretention performance for total nitrogen and nitrate can be seen in Figure 6. At both sites there is an overall decrease in TN concentration, but an increase in nitrate concentration which coincides with typical behavior. The Largo site (hollow circles) exhibited slightly more nitrate exportation than the Greenbelt site (shaded circles) indicating that the site with more sand and a shallower media depth added to the nitrification process. This makes sense since a higher hydraulic retention time in the media will lead to a higher retention of nitrogen (Brown and Hunt 2011), as well as the fact that soils with a higher clay content contain more binding sites for TKN. Low permeability cells with finer media may lead to the establishment of a denitrification zone within the SCM promoting the treatment of ammonia and nitrate (Hsieh et al. 2007; Winston et al. 2016).

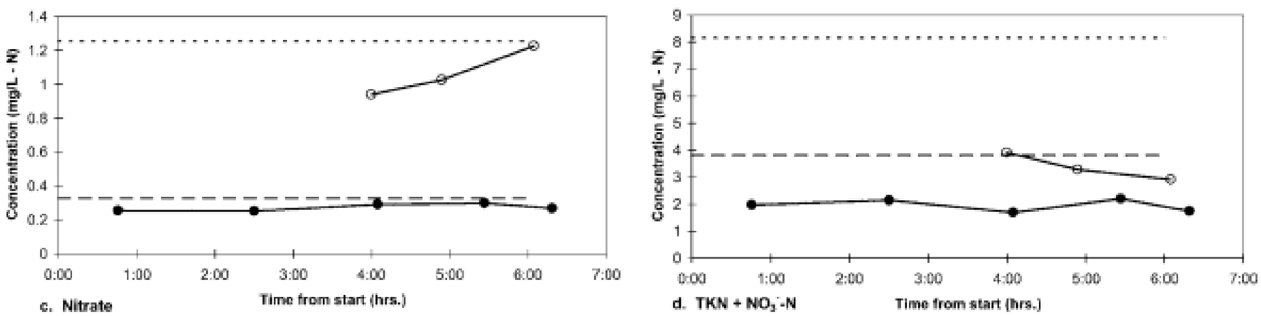

Figure 6: Bioretention Performance of Nitrate (left) and Total Nitrogen (right) at Two Different Rain Garden Sites (Davis et al. 2006)

Some bioretention cells utilize a top layer of organic matter such as grass or mulch to act as an initial filter to the runoff. As mentioned previously, these layers may actually add to the effluent nitrogen concentration in a bioretention cell due to the natural nitrogen present in the media.

The addition and type of vegetation in bioretention systems has also been studied to optimize nitrogen removal. Plants uptake nitrogen from soil in the form of nitrate (NO_3) and ammonium (NH_4) with nitrate being the most available form in aerobic environments. Although studies have shown that plant uptake of nitrogen can attribute to its removal, this is more of a temporary method as the nitrogen will most likely be released back into the soil when the vegetation decays. The only way to truly get nitrogen removal through vegetation would be to cut the plants and remove them from the system after the growing season is over (Clary et al. 2011; Davis et al. 2006; Li and Davis 2014). Many of these simulation experiments are performed over a short time period, but it is hypothesized that vegetation may have a long term effect on the uptake and attenuation of pollutants with the ability to remove up to 90% of the nitrogen captured in the soil through nitrogen assimilation (Davis et al. 2006). Since nitrate accumulates in bioretention cells between storm events, plants have the ability to take up some of this nitrogen leading to a lower effluent concentration during the next storm event (Barrett et al. 2013).

The pH and temperature of a bioretention system may also play a role in nitrogen removal. Davis et al. (2006) concluded that varying the pH between 6 and 8 had negligible effects on the nitrogen and nitrate concentrations of the effluent sample. The fluctuation of pH in this range has not proved to have any large effects on microbial denitrification rates. The temperature of the media was found to be negatively correlated to nitrate removal. Higher soil temperatures speeds up the nitrification process leading to significant increases of nitrate and nitrite in the effluent (Blecken et al. 2010; Brown et al. 2013).

As discussed previously, the removal of nitrate in these systems proves relatively tricky due to the lack of physiochemical interaction with the soil media. Nitrate retention is not necessarily expected in a bioretention system due to its mobile anionic state (Davis et al. 2006; Hsieh et al. 2007), but more studies are being performed to assess ways to increase denitrification in the soil layers which may effectively remove some nitrate. During the time between rainfall events, the bioretention cell will drain and become aerobic allowing for the nitrification of organic nitrogen to nitrate (Blecken et al. 2010; Hsieh et al. 2007), therefore a good way to decrease nitrate concentration is to limit nitrification and promote denitrification during this time. Denitrification is a microbial process that converts nitrate to nitrogen gas (N_2) which is much less harmful to the environment. The denitrification process can be seen in Equation 1.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO\uparrow \rightarrow N_2O\uparrow \rightarrow N_2\uparrow \qquad \text{(Equation 1)}$$

One method hypothesized to help increase denitrification and decrease the nitrate output is through creating an IWS zone (Brown et al. 2013; Brown and Hunt 2011). The creation of an IWS zone can create and maintain anaerobic conditions during the dry period between rainfall events. Anaerobic conditions are essential for denitrification so that both the incoming nitrate as well as the nitrate produced within the cell can be transformed to N_2. If the soil media is not allowed to drain between events, nitrate will be trapped in the pore spaces which will become anaerobic and allow for the biological denitrification process. A bioretention system with a low permeability layer may act as a way to retain the water in the column thus creating an anaerobic zone for denitrification. A moderate reduction of nitrate was seen with such a set up as long as there was a carbon source, such as mulch, provided to facilitate this process (Hsieh et al. 2007). Utilizing a fine filter media will create pore storage between events acting somewhat as an anaerobic IWS (Clary et al. 2011).

For optimal conditions to occur for denitrification there must be a sufficient electron donor and carbon source within the cell. In one experiment (Kim et al. 2003), numerous potential organic carbon sources were tested including alfalfa, leaves, compost, newspaper, sawdust, wheat straw, and wood chips. The ideal electron donor of this group would provide a decomposition rate that would be fast enough to allow denitrification during the time in which the water was retained in the cell, but not allow decomposition to occur too rapidly so that excess organic compounds would be added to the stormwater effluent. Alfalfa and wheat straw both had a high removal rate of nitrate, but their lower carbon to nitrogen ratio (more available N) caused over decomposition of the nitrate resulting in increased total nitrogen and turbidity in the effluent. The higher decomposition rates with these sources can be due to possible ammonification or dissimilatory nitrate reduction (DNR) which would cause the excess formation of total nitrogen in the cell. Based on the results of this experiment, it was determined that newspaper and wood chips would be the best electron donor for denitrification in the IWS zone in an engineered bioretention system which can be correlated to their C/N ratio (Kim et al. 2003). More research is needed to see if adding electron donors is worth the additional nitrate removal that is achieved because of the possibility of producing more effluent TKN. The coupling of the nitrification and denitrification processes rely on having aerobic and anaerobic zones in close proximity to one another which is tricky in these smaller systems in which conditions may not be conducive to significant denitrification (Clary et al. 2011; Hatt et al. 2007). Barret (2013) observed that a submerged IWS zone did not significantly increase nitrate removal as compared to a system with no IWS zone, but this may have also been limited to the depth of the media and time scale of the experiment not allowing for the soil to go anaerobic.

Bioretention cells are an effective stormwater control measure capable of reducing the total nitrogen content in runoff by means of physical and chemical adsorption of particulate organic nitrogen, nitrite, and ammonia. Although nitrate has proven much more difficult to remove and accounts for the majority of the effluent TN concentration, there are ways in which nitrate removal can be accomplished. The selection of a filter media with the right carbon to nitrogen ratio and the creation of a saturated anaerobic zone through an IWS zone or fine media may promote denitrification and add to the removal of nitrate and total nitrogen.

CHAPTER 3: METHODS

The goal of this research is to investigate and quantify the soil types and flow patterns that can be utilized in vegetated SCMs, specifically rain gardens, to maximize volume and pollutant reduction. It is hypothesized that the optimal balance between infiltration and ET for site-specific conditions will enable optimized volume and pollutant removal. The research methods and results discussed in this thesis is referred to as the Optimal Balance (OB) study. This study is separated into two main components: the study of volume removal (water quantity) and pollutant removal (water quality). The water quantity methods are discussed in Chapter 3.1 and the water quality methods are discussed in Chapter 3.2. Both components were studied at the bench-scale through the use of twelve discrete non-weighing lysimeters.

The Optimal Balance research site is located at the northern end of the Villanova University Campus (Figure 7). The site is near the Villanova University School of Law and adjacent to the Constructed Stormwater Wetland (CSW) site and the Evapotranspiration (ET) study site at Villanova University. The OB study site is geographically located at latitude 40° 2' N and longitude 75° 20' W at an elevation of approximately 120 m (290 ft) above sea level.

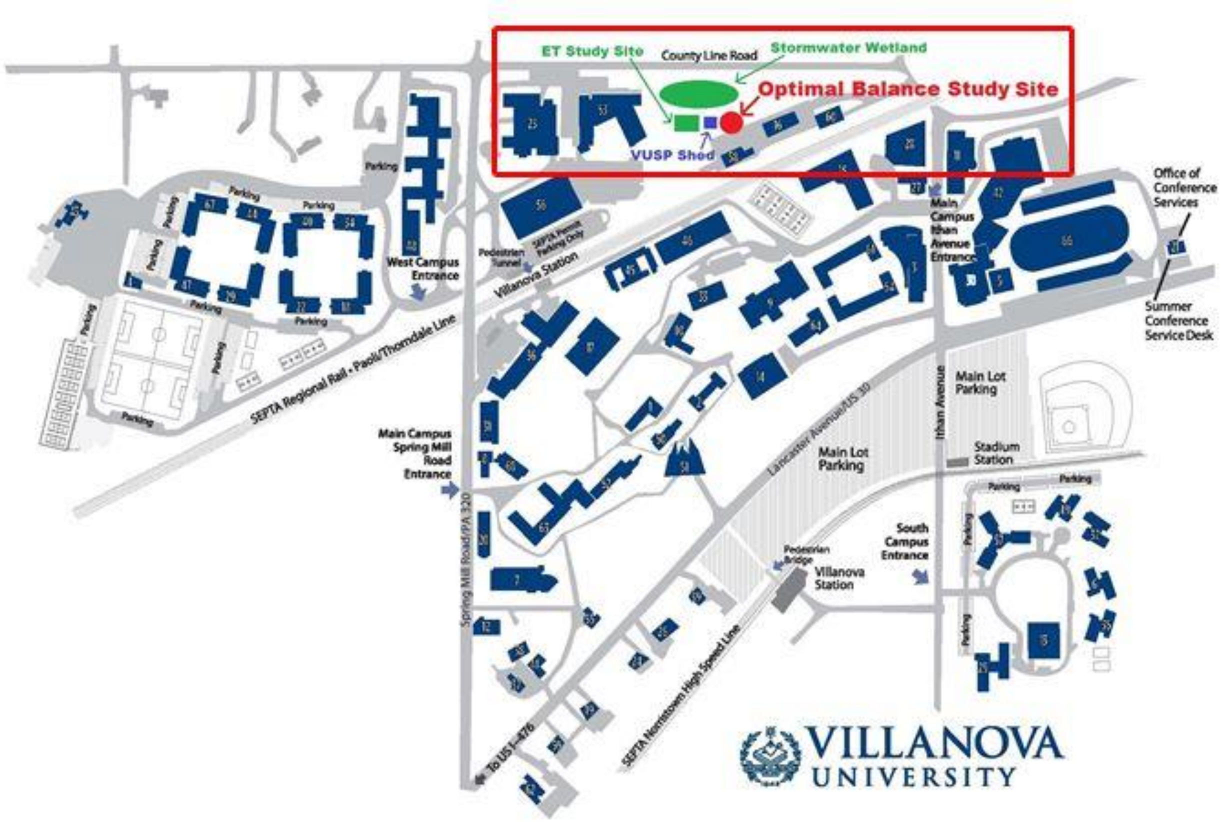

Figure 7: Location of the Optimal Balance Site on Villanova University's Campus

3.1 WATER QUANTITY TESTING METHODS

To quantify volume removal through infiltration and ET in bioretention SCMs, an experimental setup was designed to test different soil mixes, soil depths, and flow patterns. A series of twelve discrete weighing lysimeters were constructed that contain five different soil mixes and two different flow paths. Dosage pumps were used to simulate typical precipitation and stormwater runoff in the Pennsylvania area, and evapotranspiration was calculated on a daily basis using a mass balance for each lysimeter. This section will discuss the lysimeter design and instrumentation, the classification of the soil types, and the vegetation.

3.1.1 Lysimeter Design

There are twelve lysimeters, six vertical flow lysimeters and six horizontal flow lysimeters (Figure 8). The six lysimeters in each flow configuration contain a different soil media, with the exception of one control lysimeter. The five soil types that were studied in each flow configuration are a sandy loam, loamy sand, loam, clay loam, and silt loam, which are discussed further in section 3.1.2 and 3.1.3. For both vertical and horizontal configurations, the soil media within each lysimeter is representative of a vegetated SCM. Volume removal through infiltration and ET is calculated using a mass balance for each of the twelve lysimeters. This section will discuss the mass balance and instrumentation, the two flow configurations, and the storm events that were simulated over the course of the study.

Figure 8: Optimal Balance Lysimeters: Vertical and Horizontal Flow Configuration

3.1.1.1 Mass Balance and Instrumentation

To quantify the volume removal of stormwater runoff through ET, a mass balance was applied to each of the twelve lysimeters. Since ET cannot be directly measured, the evapotranspiration (ET) is equal to the Inflow (I) minus the drainage (D) and the change in storage (ΔS) (Equation 2).

$$ET = I - D - \Delta S \qquad \text{(Equation 2)}$$

Inflow is measured by a nearby rain gauge and a known pumping rate, the change in storage is measured by the change in weight of each lysimeter, and the drainage is measured by tipping bucket rain gauges. Each term in the mass balance is based on a period of one day, and ET is calculated on a daily basis.

3.1.1.1.1 Inflow

Rain gardens in Pennsylvania are designed to collect runoff from surrounding impervious areas based on a loading ratio, which is the ratio of directly connected impervious area to infiltrating SCM area (PA BMP 2006). The Pennsylvania BMP Manual limits rain garden design to a loading ratio of 5:1. To achieve this loading ratio, a water distribution system was used to simulate runoff from surrounding impervious areas based on the rainfall naturally falling on the lysimeters. Fauna Marin Balling Light Dosage pumps transmit water to each of the lysimeters representing runoff from a storm event. The automatic dosage pumps are programmable to release the desired volume of water into each of the twelve lysimeters over a 24 hour period. The peristaltic pumps draw water from a 150 liter storage tank located on site (Figure 9) and distribute the water into each lysimeters through an irrigation system (Figure 10). The storage tank contains tap water from the nearby Villanova University School of Law.

Figure 9: Influent Reservoir (left) and Automatic Dosage Pumps (right) used to Simulate Stormwater Runoff into the Lysimeters

Figure 10: Water Irrigation over the Vertical (left) and Horizontal (right) Lysimeters

In addition to the simulated runoff, a MetOne 375H heated rain gauge located 10 m (33 ft) from the lysimeters measures the natural rainfall entering the lysimeters (Figure 11). The inflow term in the mass balance represents a combination of the natural precipitation and the dosed runoff volume. The simulated runoff from the pumps and the natural rainfall from a storm event are summed over a 24 hour period from 12 AM to 12 AM to provide the daily inflow term (I) in Equation 2.

Figure 11: MetOne 375H Heated Rain Gauge that measures Natural Precipitation into the Lysimeters

3.1.1.1.2 Drainage

The drainage from each lysimeter is equivalent to the amount of deep infiltration occurring in a SCM. Deep infiltration refers to the water that infiltrates through the soil past the root zone and would be likely to reach the groundwater table in a natural system or the underdrain if present. Effluent water volume from each lysimeter is measured by two means. The first method provides a reading of water leaving the lysimeter every five minutes through a 16 cm (6 in) Texas Electronics TR-525I rain gauge tipping bucket placed directly beneath each lysimeter (Figure 12).

Figure 12: Texas Electronics TR-525I Tipping Bucket Rain Gauge beneath Each Lysimeter

After the water exits the rain gauge it is directed into a 1000 ml graduated cylinder which acts as a secondary drainage measurement (Figure 13). The cylinders are wrapped with pipe insulation to prevent any additional evaporation of water once it exits the lysimeters.

Figure 13: Insulated Graduated Cylinders below the Rain Gauge Tipping Buckets

The volume of water in the graduated cylinders is recorded each day and compared to the water volume measured through the rain gauge. Results indicate the volume measured by the rain gauges is equal to the volume measured by the graduated cylinders. Since the tipping buckets provide a more accurate reading as well as a time component, they are used to supply the drainage volume in the mass balance. The volume of water through the tipping bucket is summed each day from 12 AM to 12 AM to provide the daily drainage term (D) in Equation 2.

3.1.1.1.3 Change in Storage

The change in storage is equivalent to the change in weight of each lysimeter. An A&D GP-61K scale is used to manually measure the lysimeters daily (Figure 14). The lysimeters are weighed approximately the same time each day, and the weights are linearly interpolated to 12

AM to provide a daily change in storage (ΔS) in Equation 2. The lysimeters are removed from their resting locations atop the rain gauges and placed on the scale one by one while being careful not to disturb or pull out any vegetation in the process. During a storm simulation event, the lysimeters are weighed directly before the start of the simulation and directly after.

Figure 14: Horizontal Lysimeter in the Process of being weighed on the A&D GP-61K Scale

3.1.1.1.4 Evapotranspiration

The daily evapotranspiration (ET) volume is calculated from Equation 2. All terms in the mass balance are reported in mm. The inflow (I) and drainage (D) are measured in inches while the change in storage (ΔS) is measured in grams and converted to mm based on the surface area of the lysimeters.

The total expected error in this system is equal to ±0.54 mm in the vertical configuration and ±0.62 mm in the horizontal configuration if all components of the mass balance are required to calculate the ET. The error is different for the two configurations since they have different volumes of soils and surface areas. The expected error for all instrumentation as it relates to mm of water is seen in (Table 1). The scale has a standard deviation error of ±0.2 g, which equates to ±0.03 mm of water in the vertical lysimeters and ±0.03 mm of water in the horizontal lysimeters. The horizontal lysimeters are much heavier (~27,000 g) such that an error of ±0.2 g is much less of a factor compared to the lighter (~8,500 g) vertical lysimeters. The majority of ET values are calculated during days with no rainfall or outflow, such that the system error is reduced to that of the change in storage, ±0.03 mm in the vertical lysimeters and ±0.003 mm in the horizontal lysimeters.

Table 1: Instrumentation Error for each Component of the Mass Balance to Calculate ET

Parameter	**Change in Storage**	**Inflow**		**Outflow**	**Total**
Instrumentation	A&D Industrial Bench Scale (GP-61K)	Met-One heated tipping bucket rain gauge (Model 375)	Light Dosing Pump (Fauna Marin Balling)	Texas Electronics tipping bucket rain gauge (TR-525I)	All Instrumentation
Instrument Error	±0.2 g	±0.1%	±1 ml	±1%	NA
Vertical Error (mm water)	±0.03	±0.25	±0.01	±0.25	±0.54
Horizontal Error (mm water)	±0.003	±0.25	±0.12	±0.25	±0.62

3.1.1.2 Flow Path and Depth

The depth of soil within a vegetated SCM and the flow path of water through the soil are two design components that are considered in this study. To compare how these design components affect volume removal, two different lysimeter configurations were constructed. Since this is a bench scale study, the two configurations, vertical flow and horizontal flow, are not meant to directly represent soil depths and flow patterns that occur in rain gardens, but to serve as a comparison between one another.

The flow of water within a rain garden occurs primarily in the vertical direction, which is what the vertical lysimeter configuration is modeling. Each of the six vertical lysimeters, designated ‘A’ through ‘F’, are constructed from cylindrical PVC piping 61 cm (2 ft) in length and 10 cm (4 in) in nominal diameter (Figure 15). The soil media is placed to a depth of 46 cm (18 in) within the column which allows for 8 cm (3 in) of ponding depth. This is below the typical 6 inches (16 cm) of ponding depth recommended in the PA BMP manual (2006). This ponding depth was selected to be consistent with that of the horizontal lysimeters which were limited to this depth.

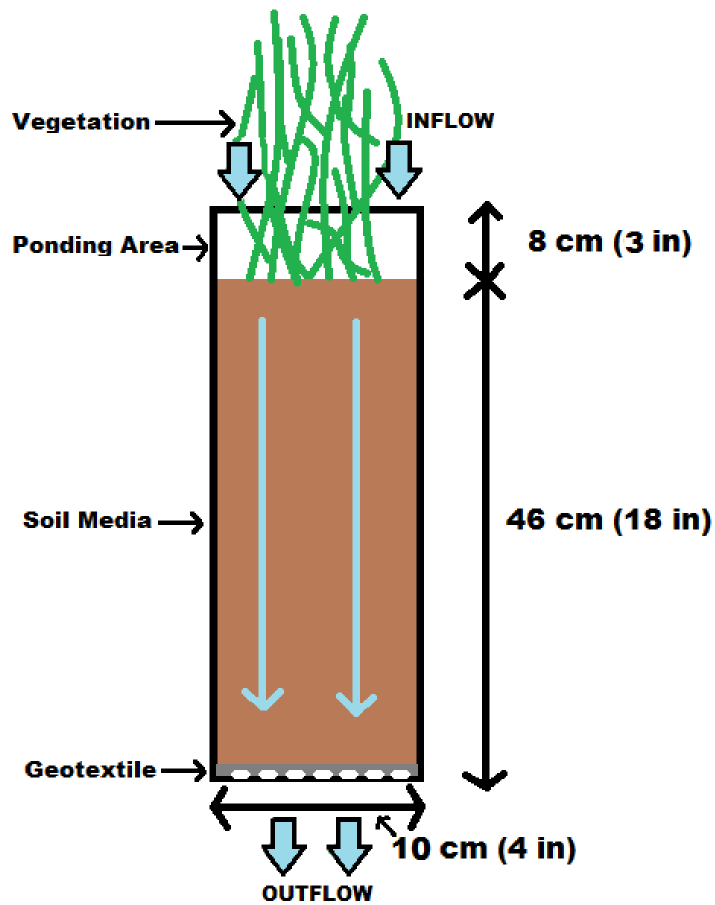

Figure 15: Vertical Lysimeter Schematic

At the bottom of each lysimeter three layers of geotextile fabric hold the soil media in place and ensure that fine particles do not leave the system with the outflow of water. The geotextile is a non-woven Terram product known as WeedGaurd with an opening size of 0.16 mm and a permittivity of 150 m^{-2} s^{-1} (Terram 2012). At the bottom of each PVC column a flat cap was glued to form the base. Each cap has eight 1 cm (0.4 in) outflow holes. These holes allow for the drainage of water that has percolated through the soil out of the bottom of the lysimeter and into the rain gauge beneath. Since the 4 inch (10 cm) diameter column will be placed atop the 6 inch diameter rain gauge, a rubber fitting was placed between the two devices to ensure that no excess water enters the rain gauge besides the volume leaving the lysimeter. After the effluent water exits the rain gauge, it flows through a funnel and a short length of vinyl tubing into the 1000 ml graduated cylinder below (Figure 16).

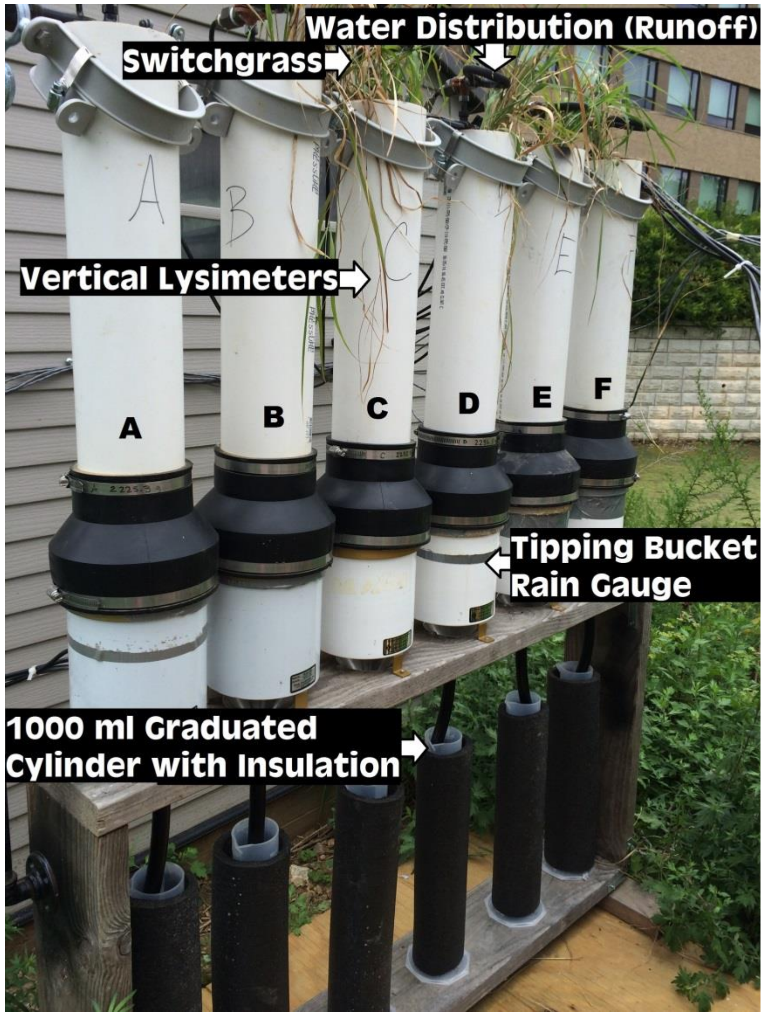

Figure 16: Vertical Lysimeter Configuration

Aside from the shape of the lysimeters, the horizontal lysimeter configuration is identical to that of vertical lysimeter configuration. The horizontal lysimeters, designated ‘G’ through ‘L,’ are in the shape of a long, rectangular box constructed from sheets of PVC. The horizontal lysimeters are representative of a shallow rain garden or a vegetated swale system in which water flows within the media in both the horizontal and vertical direction. The lysimeters sit on a wooden stand constructed so that the boxes are on a slope of 2.5%. This slope is the same as another rain garden and swale system at Villanova University and will allow water to flow in the desired fashion. Although the exact flow path within the horizontal lysimeters is unknown, it is hypothesized to be some combination of horizontal and vertical flow dependent on the type of soil media. The inner dimensions of the lysimeter boxes are 67 cm x 28.5 cm x 11 cm (26.50 in x 11.25 in x 4.13 in). The soil media is filled to a depth of 20 cm (7.87 in) allowing for 8.5 cm (3 in) of ponding depth (Figure 17).

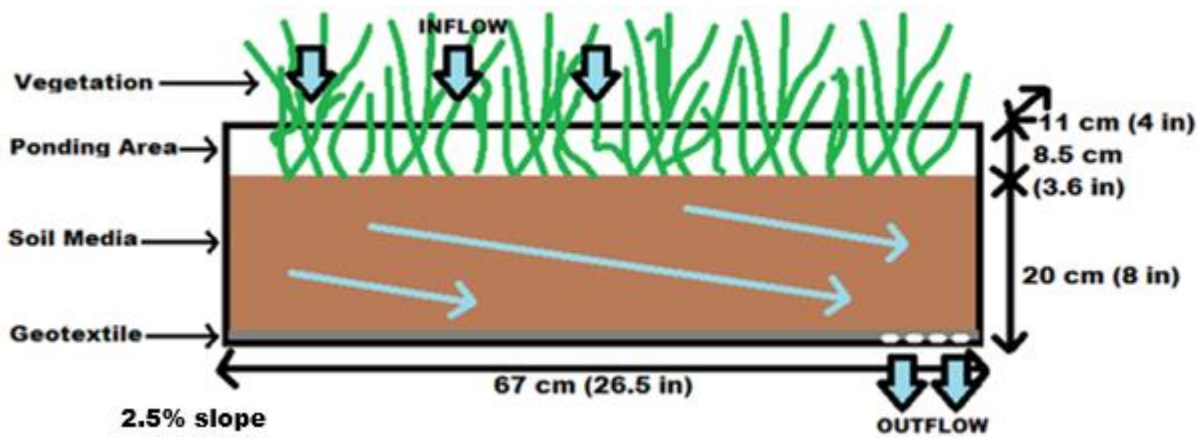

Figure 17: Horizontal Lysimeter Schematic

Pumped water enters the top half of the horizontal lysimeter through the irrigation system and travels through the soil media to the outlet located on the bottom downhill edge of each lysimeter; direct rainfall is over the entire surface. The bottom of all horizontal lysimeters was also lined with three layers of the geotextile fabric to hold the soil in place. The bottom corner of each lysimeter contains eight 1 cm (0.4 in) outflow holes, consistent with that of the vertical lysimeters. A PVC pipe shape converter is placed at the end of each horizontal lysimeter so that the lysimeter fits into the rain gauge that sits beneath it. To ensure no excess water is entering the rain gauge besides the volume leaving the lysimeter, durable plastic strips were fastened onto the lysimeters creating a shield above the rain gauges. From here on, the setup is identical to that of the vertical lysimeters (Figure 18).

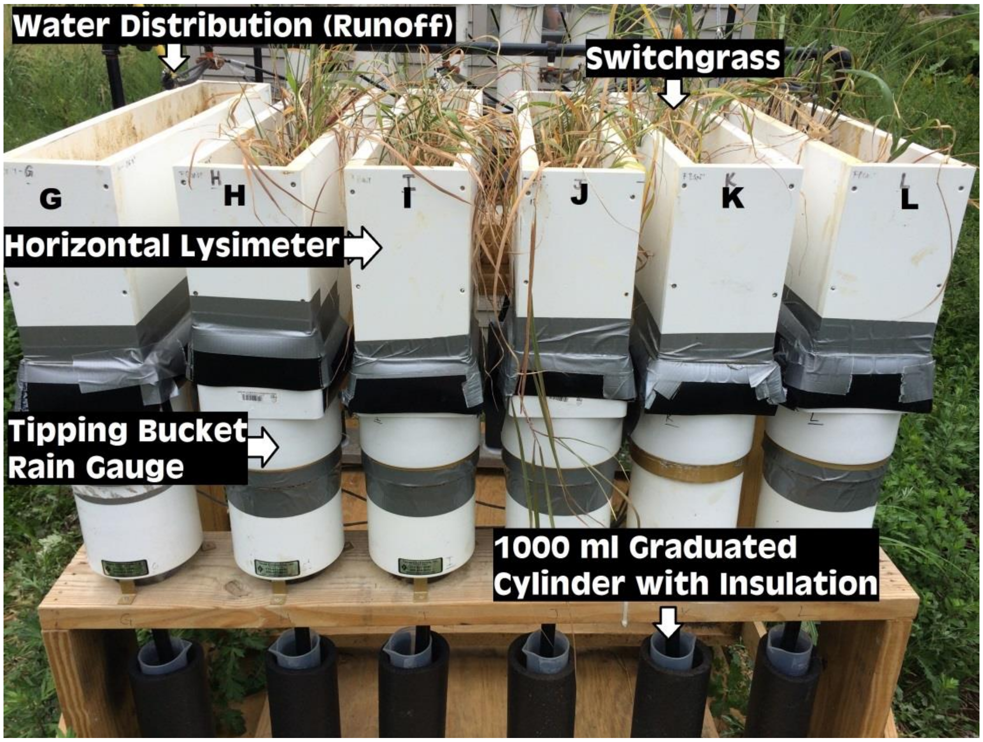

Figure 18: Horizontal Lysimeter Configuration

3.1.1.3 Storm Simulations

To measure the performance of each lysimeter, storm simulation events were periodically performed. Rain gardens are designed to collect runoff based on a 5:1 loading ratio from surrounding impervious areas (PA BMP Manual 2006), but these lysimeters only receive direct rainfall on a 1:1 ratio. To achieve the 5:1 loading ratio, Fauna Marin Balling Light Doser pumps supply water to each of the lysimeters to simulate runoff based on the rainfall naturally falling on the lysimeters. The distribution system can handle a range of storm volumes and is optimized to add anywhere from 6.4 mm to 38.1 mm (0.25 in to 1.5 in) of water at a 5:1 ratio over a 24 hour period. The 19 mm and 38 mm (0.75 in and 1.5 in) storms relate to typical design criteria for

SCMs. There are three Fauna Marin Balling Light Doser pumps in total. Each dosing pump contains four different peristaltic pumps, for a total of twelve pumps between the three dosers. The pumps are designed to irrigate the desired amount of water each hour over a 24 hour period.

Storm simulation events can either be a combination of natural rainfall and simulated runoff, or completely simulated rainfall and runoff. The storm simulations are referred to as either "natural" or "simulated," but the natural events still contain simulated runoff. For a natural rainfall event the desired volume to be released each hour over the 24 hour period is calculated based on the expected forecast of rain. The storm size is predicted to an accuracy of 6.4 mm (0.25 inches) and the expected rainfall volume is multiplied by five to achieve the 5:1 loading ratio of runoff. For a natural event the total inflow volume (I) is the sum of the rainfall and the simulated runoff. An example of an inflow hydrograph for a 1 inch natural event can be seen in Figure 19. The natural rainfall is representative of a typical hyetograph while the dosed volume of water is representative of an inflow hydrograph to each of the lysimeters.

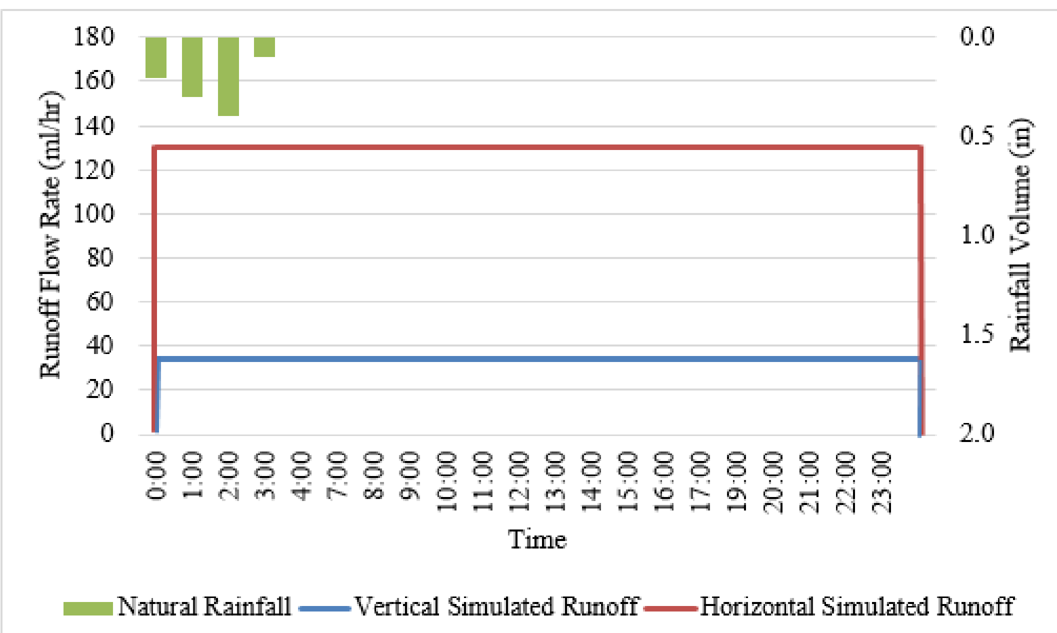

Figure 19: Example of a Hydrograph for a 1.0 inch Natural Storm Event

Storm events can also be purely simulated meaning that both the rainfall and runoff is supplied by the dosing pumps. A desired storm size between 6.4 mm to 38.1 mm (0.25 in to 1.5 in) is selected, and this volume was multiplied by six to achieve the 5:1 loading ratio. For a simulated event, the total inflow volume (I) is based purely on the irrigated volume. An example of the inflow hydrograph for a 1 inch simulated event is shown in Figure 20.

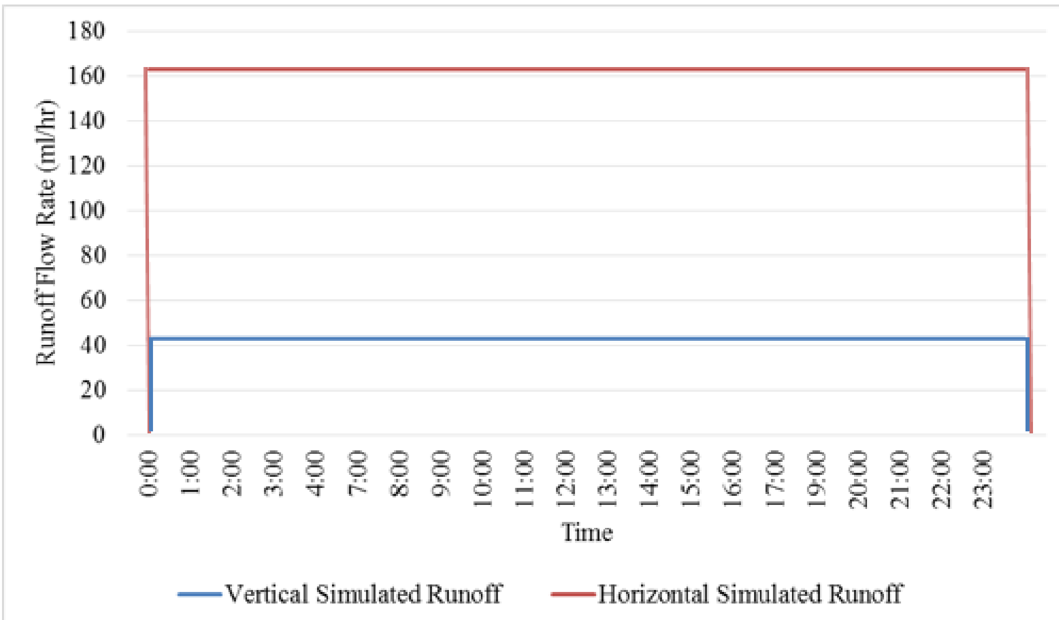

Figure 20: Example of a Hydrograph for a 1.00 inch Simulated Storm Event

In addition to the natural and simulated storm events, lysimeter performance is also monitored during pure rainfall events at a 1:1 ratio. This means that there was a natural rainfall event and the dosage pumps were not turned on to supply any additional runoff volume. While these events are not representative of typical SCM performance, they provide a comparison in terms of infiltration and ET to the simulated storm events.

The runoff volumes are calculated differently for the vertical and horizontal flow configuration. For the vertical lysimeters, the 5:1 loading ratio discussed previously is used. The flow rate (ml/hr) is calculated based on the expected rainfall amount and the surface area of the vertical lysimeter. The 5:1 loading ratio based on surface area was determined to be excessive for the horizontal lysimeters and not representative of the research goal since the surface area is much larger and the depth of the horizontal lysimeters is much shallower. Instead of using the 5:1 loading ratio, water was added to the horizontal lysimeters based on the equivalent soil volume ratio to the vertical lysimeters. The horizontal lysimeters contain 3.8 times the soil volume of vertical lysimeters. To calculate the dosing flow rate (ml/hr) for the horizontal lysimeters, the hourly dosing flow rate of the vertical lysimeters was multiplied by 3.8. This ratio can be applied to either a natural storm event or a simulated storm event. The hourly dosing rates and total runoff volumes corresponding to various storm sizes for both natural and simulated events can be seen in Table 2.

Table 2: Runoff Dosing for Storm Simulation Events

Storm Event	**Storm Size (in)**	**Hourly Dosing Rate (ml/hr)**		**Cumulative Volume over 24 Hours (ml)**	
		Vertical	**Horizontal**	**Vertical**	**Horizontal**
Simulated Event	0.25	11	41	264	984
	0.5	21	82	504	1968
	0.75	32	122	768	2928
	1	43	163	1032	3912
	1.25	54	204	1296	4896
	1.5	64	245	1536	5880
Natural Event	0.25	9	33	216	792
	0.5	17	66	408	1584
	0.75	26	98	624	2352
	1	34	130	816	3120
	1.25	43	163	1032	3912
	1.5	51	196	1224	4704

While all events will vary in terms of volume and timing, the primary input parameter into the mass balance for inflow (I) is the cumulative volume for each storm event. While this section describes how the runoff volumes for each storm event were selected, the cumulative inflow for each storm is the only value that will be used in the analysis of this research.

3.1.2 Vegetation

Plant type was kept consistent in all vegetated lysimeters, such that soil type is the main variable between lysimeters. *Panicum virgatum* (Switchgrass) was planted in all lysimeters, except the control lysimeters ‘A’ (vertical) and ‘G’ (horizontal) which contain no vegetation. The two control lysimeters are meant to serve as a comparison between a vegetated and a non-vegetated system. The Switchgrass was grown in Villanova University’s greenhouse and transplanted into each lysimeter prior to the start of the study. The initial plant mass ranged from 50 to 54 grams with an average height of 20 cm (7.8 in). A plant inspection is performed monthly to monitor the relationship between plant health and ET rate. The total leaf count and average leaf height are recorded every month, and photographs of the Switchgrass are taken from a consistent vantage point (Figure 21).

Figure 21: Average Leaf Height of Switchgrass being measured in the Horizontal Lysimeters

Switchgrass was chosen as it is native to the United States and very adaptable to most soils and environments (USDA NRCS 2011). Switchgrass is tolerant to a range of soil depths, has been shown to adapt in stressed drought conditions, requires low management, and is resistant to salt which is necessary for rock salt accumulation from de-icing of pavements in urban areas (Culbertson and Hutchinson 2004; Yimam et al. 2014). Switchgrass is a popular biofuel source since it has been shown to produce high ET rates, with an average of 3 to 4 mm/day during the growing season and an annual average of 676 mm (Wagle and Kakani 2014; Yimam et al. 2014). The ability of Switchgrass to produce high ET rates is due in part to its deep, productive root system. Switchgrass roots will continue to grow wherever water is available and are capable of reaching over 2 m in less than 32 weeks (Wang et al. 2015). In addition to producing high ET rates, Culbertson and Hutchinson (2004) documented that using Switchgrass in SCMs increased infiltration rates by over two orders of magnitude and reduced discharge by 70%. Switchgrass has also been shown in aid in nitrogen reduction due to its high nitrogen requirements (Culbertson and Hutchinson 2004).

3.1.3 Soil Classification

Five different soil types were analyzed in this research. All soils used were natural soils collected from various locations in the greater Philadelphia area. The soils were classified based on a sieve and hydrometer analysis (ASTM D422), plasticity index (ASTM D4318) and organic content (ASTM D2216). The soils were classified according to both the United States Department of Agriculture (USDA) and Unified Soil Classification System (USCS) (Table 3). The grain size distribution of each soil type can be seen in Figure 22. The five soil types will be referred to according to their USDA classification for the remainder of this thesis.

Table 3: USDA and USCS Classification of the Five Soil Types

USDA Classification	USCS Classification	Percent Sand (%)	Percent Silt (%)	Percent Clay (%)	Plasticity	Organic Content (%)
Sandy Loam	SM: Silty Sand	56	32	12	Non Plastic	4.91
Loamy Sand	SM: Silty Sand	80	14	6	Non Plastic	3.57
Loam	CL: Sandy Lean Clay	37	44	19	Medium Plasticity	5.95
Clay Loam	CL: Lean Clay with Sand	26	44	30	Medium Plasticity	3.97
Silt Loam	ML: Silt	29	55	16	Low Plasticity	4.87

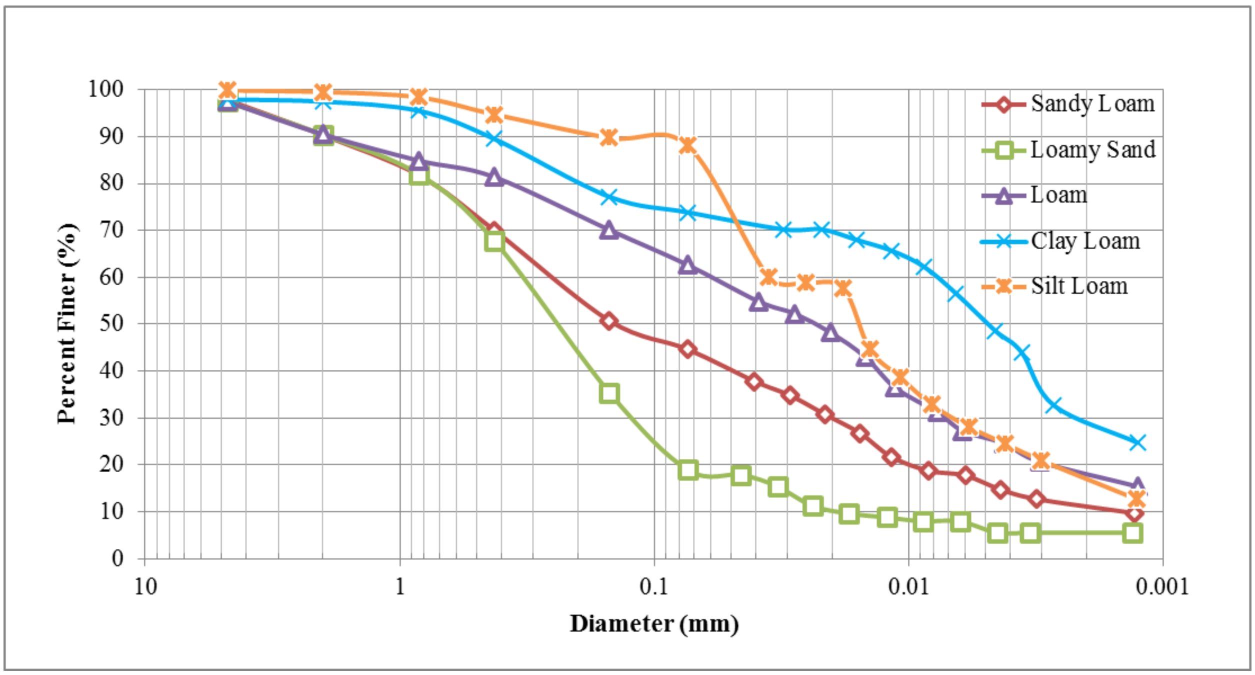

Figure 22: Grain Size Distribution of the Five Soil Types

The soil types were selected to span the lower portion of the USDA soil triangle outlined in blue (Figure 23). Current soils specifications for rain gardens are limited to the lower left corner of the triangle (sand, loamy sand, and sandy loam) due to their high infiltration rates. This thesis aims to study finer grained soils, such as loam, clay loam, and silt loam, which may lend themselves better to ET. The location of the five soil types used in this study are shown on the USDA triangle (Figure 23).

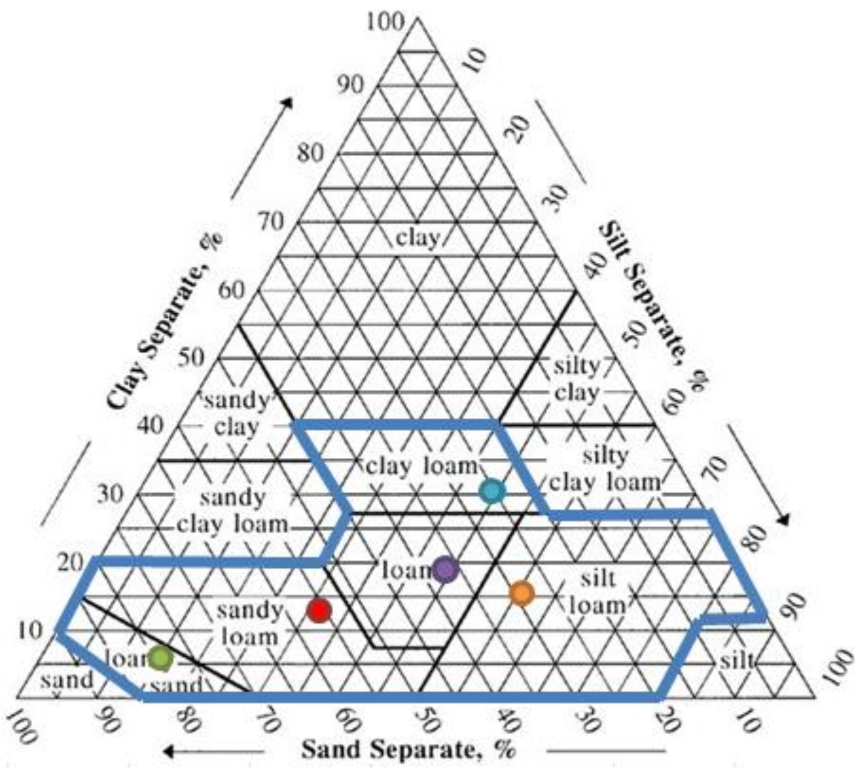

Figure 23: Location of the Five Soil Types on the USDA Classification Triangle

Each of the five soils occupy one vertical lysimeter and one horizontal lysimeter. The sandy loam soil occupies two lysimeters in each flow configuration since one lysimeter in each configuration acts as a control containing no vegetation. The sandy loam was chosen to occupy the control lysimeter since this is a typical soil type currently specified for rain garden design. The vertical lysimeters, designated 'A' through 'F,' and the horizontal lysimeters, designated 'G' through 'L,' along with the soil type they correspond to can be seen (Table 4). The soil was added to each lysimeters absent of any compaction to mimic typical conditions in a vegetated SCM. The initial bulk density of the soils in the lysimeters ranged from 1.2 to 1.4 g/cm^3.

Table 4: Lysimeter Designations According to Soil Type and Vegetative Condition

Lysimeter	Flow Configuration	Soil Type	Vegetation
A	Vertical	Sandy Loam	None
B	Vertical	Sandy Loam	Switchgrass
C	Vertical	Loamy Sand	Switchgrass
D	Vertical	Loam	Switchgrass
E	Vertical	Clay Loam	Switchgrass
F	Vertical	Silt Loam	Switchgrass
G	Horizontal	Sandy Loam	None
H	Horizontal	Sandy Loam	Switchgrass
I	Horizontal	Loamy Sand	Switchgrass
J	Horizontal	Loam	Switchgrass
K	Horizontal	Clay Loam	Switchgrass
L	Horizontal	Silt Loam	Switchgrass

3.1.4 Hydraulic Conductivity and Soil Water Characteristic Curves

To further characterize the performance of the soils for their use in vegetative SCMs, the saturated and unsaturated hydraulic conductivities were measured. The saturated hydraulic conductivity of the soils (K_s) was measured using a UMS KSAT device. The hydraulic performance of the soils during unsaturated conditions was modeled with soil water characteristic curves (SWCC). The SWCCs were created using Decagon Devices' HYPROP and WP4C Dew Point PotentiaMeter.

3.1.4.1 UMS KSAT

A UMS KSAT device was used to measure the hydraulic conductivity of the soils during saturated conditions. The measurements are based on the Darcy equation for saturated flow according to the German standards DIN 19683-9 and DIN 18130-1 for falling and constant head saturated hydraulic tests (Figure 24). The KSAT device is capable of measuring K_s down to 0.01 cm/day (0.004 in/day) and up to 5000 cm/day (2000 in/day) with a typical statistical accuracy between 2 and 10% (UMS KSAT Manual 2012).

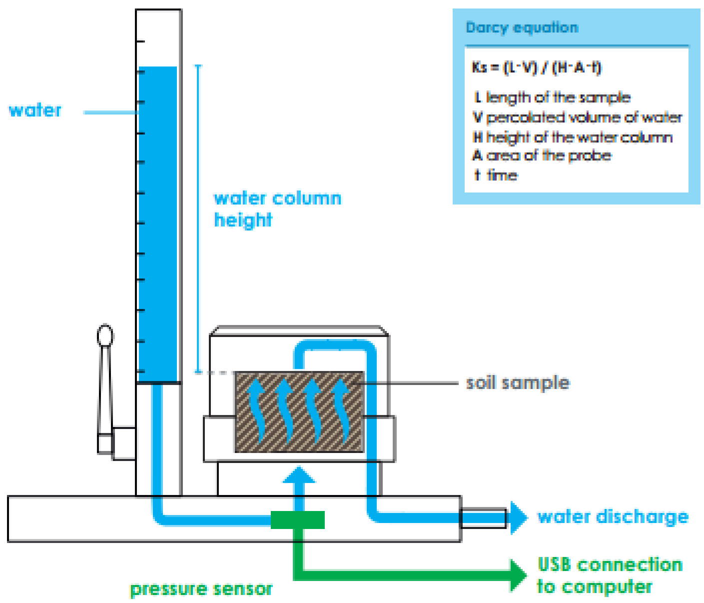

Figure 24: UMS KSAT Device used to Measure Saturated Hydraulic Conductivity (UMS KSAT Manual 2012)

Constant head tests, used for sandier soils, were performed for the loamy sand, sandy loam, and loam. Falling head tests, used for finer grained soils, were performed for the silt loam and clay loam. Soil samples we added to the KSAT measuring tin at the same density that they were added to the field lysimeters. The saturated hydraulic conductivity results represent an average of three tests performed for each soil type (Table 5). Since hydraulic conductivity is dependent on temperature, all results were standardized to 10 ^{o}C (50 ^{o}F). Typical K_s values for each soil type are also displayed (Saxton and Rawls 2006).

Table 5: Average Measured Saturated Hydraulic Conductivity Values from the UMS KSAT Device

Soil Type	Saturated Hydraulic Conductivity (K_s) (cm/d)	Saturated Hydraulic Conductivity (K_s) (m/s)	Saturated Hydraulic Conductivity (K_s) (in/hr)	Typical K_s for Soil Texture (Saxton and Rawls 2006) (in/hr)
Loamy Sand	124	1.45E-05	2.04	3.81
Sandy Loam	39	4.49E-06	0.63	1.98
Loam	20	2.33E-06	0.33	0.61
Silt Loam	5	5.62E-07	0.08	0.63
Clay Loam	2	2.09E-07	0.03	0.17

3.1.4.2 Soil Water Characteristic Curves: Hyprop and WP4C

While saturated hydraulic conductivity is indicative of soil hydraulic performance under saturated conditions, it can underestimate the infiltration capacity of soil in a SCM. The infiltration rates prior to saturation play a large role in SCM performance and should not be ignored (Lucas 2010). Soil water characteristic curves were created for the five soil types to monitor infiltration performance at varying saturation conditions. Soil water characteristic curves (SWCC), or soil water retention curves (SWRC), relate the water potential, or capillary suction (Ψ) to the volumetric water content (θ). SWCCs are a key soil property used in many fields of soil science and engineering (Too et al. 2014). Unsaturated hydraulic conductivity and capillary suction head can be used in the Green and Ampt equation used by many hydrologic models, so it is important that these properties are well understood as they dictate hydraulic performance in terms of infiltration and ET. While typical SWCCs exist for different soil types, these properties are highly variable and should be identified for specific soils for the best accuracy (Lucas 2010).

Capillary suction was measured at varying moisture contents using two devices. The UMS HYPROP device was used to measure tension at higher moisture contents. The water tension is measured through two tension shafts that are inserted into a soil sample. The water tension, also referred to as capillary suction and matrix potential, describes the energy that attracts water molecules within the pores of soil particles. The change in moisture content is based on the change in weight of the soil sample as water evaporates. This measurement method is based on Schindler's Evaporation Method and can measure the capillary suction between the ranges of saturation and the permanent wilting point (HYPROP Manual 2015).

The capillary suction at drier moisture contents is measured with a WP4C Dew Point PotentiaMeter manufactured by Decagon Devices, Inc. The WP4C is more accurate than the HYPROP at lower moisture contents and is able to measure tension in the range of 0 to -300 MPa with an accuracy of 1% (WP4C Manual 2013). The WP4C uses a chilled mirror dew point sensor to get the water potential and is compatible with ASTM D6836-07. The data from the HYPROP and WP4C were combined to create a SWCC for each of the five soil types (Figure 25).

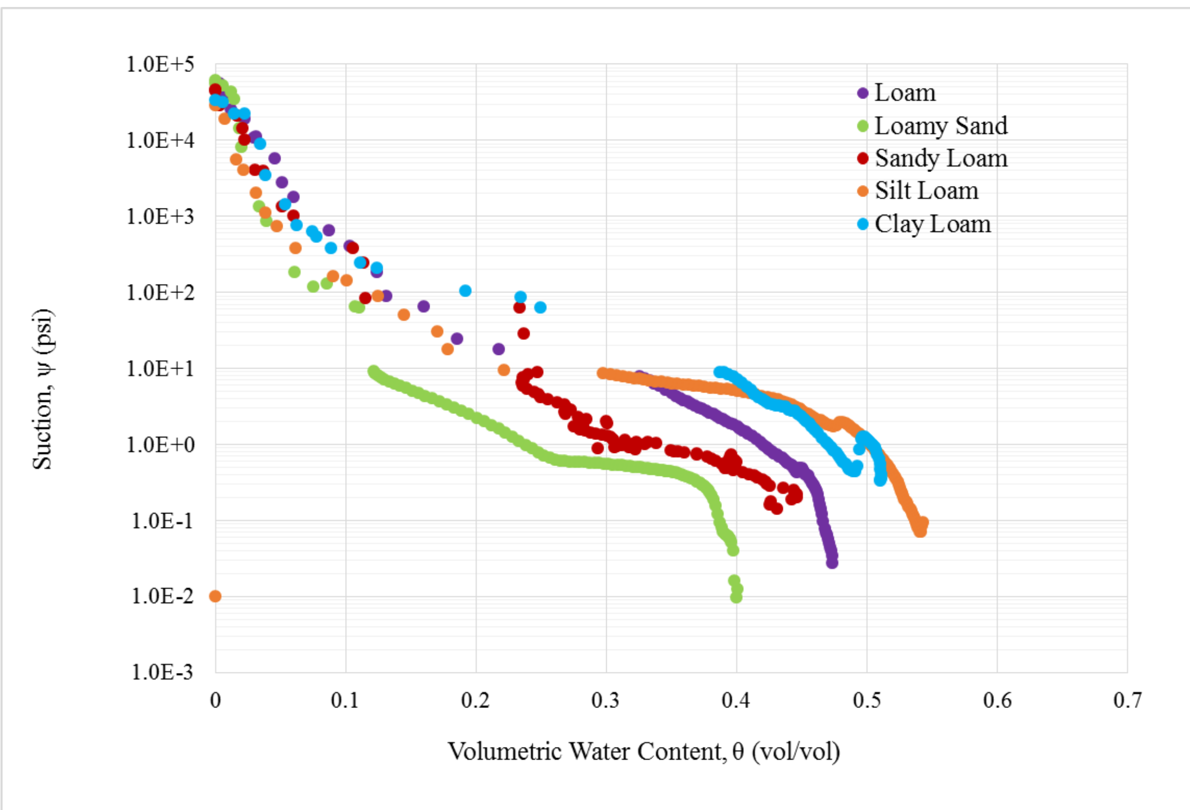

Figure 25: Measured SWCC for the Five Soil Types using the HYPROP and WP4C

To better interpret the data in terms of hydraulic performance, the raw data was fit to typical SWCC models using the program SWRC Fit (Seki 2007). SWRC Fit performs a non-linear fitting of SWCC data for three unimodal models: van Genuchten, Brooks and Corey, and Kosugi, and two bimodal models: Durner and Seki. The measured data plotted against these five models can be seen in the Appendix in Figures A2 through A11. Out of the five models, the R^2 values between the measured data were consistently highest for the van Genuchten model. Data analyzed outside this study in SWRC fit also indicate that the root mean square error (RMSE) is smallest for the Van Genuchten model and gives the best fit on average (Seki 2007).

The van Genuchten model is often used in conjunction with the Richards equation to describe the flow of water in the unsaturated zone. The moisture content at varying capillary suction heads is based on numerical parameters unique to each soil specimen (Equation 3). These dimensionless parameters were determined using SWRC Fit (Table 6).

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^{1-1/n}} \qquad \text{(Equation 3)}$$

Table 6: Van Genuchten SWCC Parameters and R^2 values determined using SWRC Fit

van Genuchten Parameters	Sandy Loam	Loamy Sand	Loam	Clay Loam	Silt Loam
Saturated Water Content (θ_s) (%)	0.438	0.385	0.451	0.499	0.517
Residual Water Content (θ_r) (%)	0	0	0	0	0
Air Entry Suction Coefficient (α) (kPa^{-1})	2.158	2.077	0.351	0.200	0.228
Pore Size Distribution Coefficient (n) (%)	1.241	1.343	1.330	1.353	1.573
R^2	0.946	0.811	0.895	0.989	0.884

The relationship between capillary suction and volumetric water content dictates how a specific soil performs in a vegetated SCM. When all voids in a soil sample are completely saturated with water (θ=θ_s) it theoretically has a suction value of 0 kPa (0 psi) which is deemed the saturated condition. The field capacity (FC) of a soil, the moisture content at which free drainage from a soil ceases, is often taken at a tension value of 33 kPa (5 psi). The permanent wilting point (PWP) of a soil, typically taken at a tension of 1500 kPa (218 psi), represents the moisture content at which plants will begin to wilt and not recover (Saxton and Rawls 2006). Theoretically, infiltration in an SCM will occur when the moisture content is between saturation and field capacity, and evapotranspiration will occur when the moisture content is between field capacity and permanent wilting point. At moisture contents lower than the PWP, the water is attached too strongly to the soil particles to be extracted by plants. The field capacity and permanent wilting point were determined from the van Genuchten model for each soil (Figure 26).

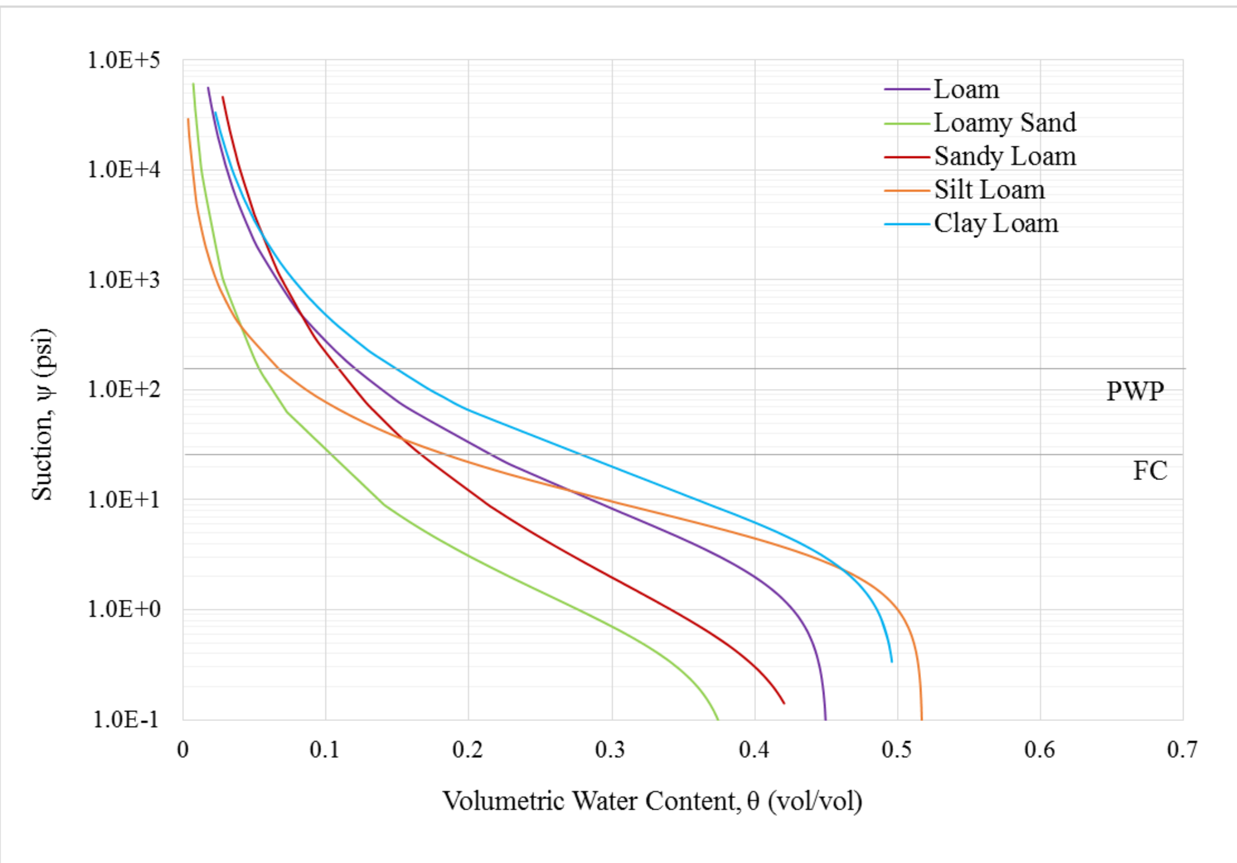

Figure 26: van Genuchten Model Fit to the Measured SWCC Data

The FC and PWP were compared to typical values for their soil texture according to Saxton and Rawls (2006) (Table 7). The total available water for both infiltration and evapotranspiration is equal to the saturated water content minus the PWP. The drainage available water, or the water available for infiltration, is equal to the saturated water content minus the FC. The moisture content between FC and PWP is defined as the plant available water capacity (PAWC), or the amount of water available for transpiration (Table 7). If the saturated water content (θ_s) is taken as 100%, the total available water, the drainage available water and the plant available water can also be expressed as a percentage as seen in Table 7. The values in parenthesis in the last three columns represent the portion of the saturated water content available to the different removal mechanisms.

Table 7: Field Capacity, Permanent Wilting Point, and Water Availability based on the Van Genuchten SWCC

Soil Type	**Saturated Water Content (θ_S) (% V)**	**Field Capacity (FC) (% V)**	***Typical FC (%V) (Saxton and Rawls 2006)***	**Permanent Wilting Point (PWP) (% V)**	***Typical PWP (%V) (Saxton and Rawls 2006)***	**Total Available Water (% V)**	**Drainage Available Water (% V)**	**Plant Available Water (% V)**
Loamy Sand	39	15	*12*	6	*5*	33 (85%)	24 (62%)	9 (23%)
Sandy Loam	44	25	*18*	11	*8*	33 (75%)	19 (43%)	14 (32%)
Loam	45	35	*28*	12	*14*	33 (73%)	10 (22%)	23 (51%)
Silt Loam	52	41	*31*	8	*11*	44 (85%)	11 (21%)	33 (63%)
Clay Loam	50	41	*36*	12	*22*	38 (76%)	9 (18%)	29 (58%)

Soils with higher plant available water, typically finer grained soils, can supply water to plants even when there has been no rainfall while sandier soils, with a lower PAWC, are more prone to drought (Saxton and Rawls 2006). While the soils in this study have relatively the same total available water, the loam, clay loam, and silt loam have a much higher percentage of plant available water. The silt loam has the highest plant available water at 33% (63% of the saturated water content) meaning it will theoretically have the highest ET rates and the most water removed through ET on a volume basis. The loamy sand and sandy loam only have 9% and 14, respectively, of water available for transpiration, and it is expected that they will exhibit less ET.

3.2 WATER QUALITY TESTING METHODS

Vegetated stormwater control measures serve to reduce the incoming pollutant load in stormwater runoff through the processes of filtration, adsorption, sedimentation, ion exchange, chemical precipitation and biological decomposition. The degree of pollutant removal through these processes is highly dependent on the type of soil media present. This research compares the pollutant removal capabilities of the five USDA soils previously discussed. Nutrient removal, specifically nitrogen and phosphorus, is the focus of this work. The ability of the different soil types to remove various forms of nitrogen and phosphorus was analyzed through three means: lysimeter field testing, cation exchange capacity, and batch isotherm experiments. The methods and experimental set up for each of these quality testing procedures is described in this section. The results of these studies will be discussed in Chapter 4.2 and will provide a comparison of the pollutant removal capabilities of the sandy loam, loamy sand, loam, clay loam, and silt loam soils.

3.2.1 Field Testing in the Lysimeters

The primary method used to compare nutrient removal capabilities of the soil types was through field testing in the lysimeters. The lysimeter set up and configuration used for quality testing is the same described in the previous section for quantity testing. Dosed tap water was irrigated to each of the twelve lysimeters over a 24 hour storm simulation period. The influent and effluent concentrations of TKN, TN, NO_2, NO_x, TP, and PO_4 were analyzed using a Simplicity Discrete Analyzer (Chinchilla Scientific). These field tests allow for a water quality comparison of the five different soil types under varying climatological and vegetative conditions in addition to the comparison of the vertical and horizontal flow configurations. Other than total suspended solids (TSS) initially present in the tap water, additional forms of TSS were not added to the simulated runoff, and TSS concentration was not analyzed as part of this study.

3.2.1.1 Storm Simulation Events

The storm simulations performed for water quality testing events were purely simulated events with no natural precipitation occurring. This was done so that the influent nutrient concentration would be known as opposed to having the influent sample being a composite of dosed water and actual precipitation. Similarly to water quantity testing events, the pumps were turned on for a 24 hour period to irrigate each lysimeter with the desired water volume. The storm sizes used for quality testing events were 25.4 and 38.1 mm (1.0 inch and 1.5 inch) events. All water quality storms were greater than or equal 1.0 inch to ensure sufficient effluent volumes of water. Two different size events were tested to see if storm size had any effect on pollutant removal. In total, 10 water quality testing events were run over an eight month period from March 2016 to October 2016. A list of all water quality testing events and the simulated storm size can be seen in Table 8.

Table 8: Water Quality Testing Events Performed in the Field

Event Designation	**Date of Event**	**Storm Simulation Size (in)**
1	3/8/2016	1.0
2	3/21/2016	1.0
3	4/19/2016	1.5
4	5/10/2016	1.5
5	5/31/2016	1.5
6	6/12/2016	1.5
7	7/5/2015	1.0
8	8/29/2016	1.5
9	9/5/2016	1.5
10	10/31/2016	1.5

After each storm simulation was complete the lysimeters were allowed to drain for a period of 12 to 24 hours before sample collection to ensure sufficient effluent volumes and accurate effluent concentrations. The effluent samples were collected from the 1000 ml graduated cylinders below each lysimeter (Figure 27). The water was then transferred from the graduated cylinders to sample collection bottles and taken back to the water resources laboratory at Villanova University for analysis. The nutrient analysis methods are described in Section 3.2.1.3. Prior to each quality testing event all graduated cylinders, sample collection bottles, and associated equipment were acid washed in a 10% HCl solution to ensure accuracy.

Figure 27: Graduated Cylinders that Collect Effluent Water Quality Samples

The influent nutrient concentration was the same for each of the twelve lysimeters since all of the dosing pumps draw water from the same source. Prior to each quality testing event the influent water was dosed according to the methods described in Section 3.2.1.2. The influent sample was then mixed using a drill bit mixer for a period of five minutes to ensure consistency. At the time of collection a grab sample was taken from the 150 liter influent reservoir which represents the initial nutrient concentrations entering the lysimeters (Figure 28).

Figure 28: Influent 150 L Water Reservoir containing Dosed Tap Water

3.2.1.2 Nutrient Analysis Methods

Nutrient analysis was performed at Villanova University in the Water Resources Laboratory as part of the research done by the Villanova Urban Stormwater Partnership (VUSP). For each field quality testing event thirteen grab samples, one influent and twelve effluent, were analyzed for various forms of nitrogen and phosphorus (Table 9).

Table 9: Water Quality Sample Names and Correspondence

Sample Name	Influent/Effluent	Soil Type	Flow Path
OB-P	Influent	All	All
OB-A	Effluent	Sandy Loam (Control)	Vertical
OB-B	Effluent	Sandy Loam	Vertical
OB-C	Effluent	Loamy Sand	Vertical
OB-D	Effluent	Loam	Vertical
OB-E	Effluent	Clay Loam	Vertical
OB-F	Effluent	Silt Loam	Vertical
OB-G	Effluent	Sandy Loam (Control)	Horizontal
OB-H	Effluent	Sandy Loam	Horizontal
OB-I	Effluent	Loamy Sand	Horizontal
OB-J	Effluent	Loam	Horizontal
OB-K	Effluent	Clay Loam	Horizontal
OB-L	Effluent	Silt Loam	Horizontal

Following each laboratory testing event the thirteen samples were analyzed for TKN, NO_x, NO_2, NH_3, TKP, and PO_4 using a Simplicity Discrete Analyzer (Chinchilla Scientific) which utilizes a photospectrometer to determine nutrient concentration through colorimetric analysis. All samples were also tested for Chloride (Cl^-) to serve as a conservative tracer. The specific testing methods for each of these constituents as well as the allowable concentration range can be seen in Table 10. While the lower concentration limit cannot be altered, the upper concentration limit can be altered following the dilution of samples. Samples that required dilution were either automatically diluted by the machine or diluted manually.

Table 10: Nutrient Analysis Methods used by the Simplicity Discrete Analyzer from Chinchilla Scientific

Nutrient	Concentration Range (mg/L)	Test Method
Nitrate (NO_3)	0.05-8	Discrete Analysis Systea Easy (1-Reagent) Nitrate Method
Nitrite (NO_2)	0.1-0.8	Discrete Analysis Method Easy Nitrite 353.2-01
Phosphate (PO_4)	0.01-0.5	Discrete Analysis Method Easy Phosphate 365.1-01
Chloride (Cl^-)	2-200	Discrete Analysis Method Easy Chloride 325.2-01
Total Kjeldahl Nitrogen (TKN)	0.1-8	Discrete Analysis Method Easy TKN 351.2-01
Total Kjeldahl Phosphorus (TKP)	0.05-5	Discrete Analysis Method Easy TKP 365.4-01

Tests for NO_x, PO_4, and Cl^- were run within 24 hours of a sampling event while preserved samples were run for TKP and TKN within 28 days of a sampling event. All samples were quality checked through control Blanks and a required Calibrant and Blank check after every 10 samples. A matrix spike and a matrix spike duplicate were also used as quality checks for each sample run as well as a bought independently-made source-check standard which was used to check the accuracy of in-house laboratory-made standards. Each storm event was analyzed and routinely checked for accuracy by the Quality Control Managers of the VUSP. Any data with unreliable results or insufficient quality controls was rejected and not used. Each of the thirteen field samples were also tested for pH, conductivity (µS/cm), and temperature (ºC) using a Hach HQ40d Portable pH and conductivity meter. These parameters were tested the day of sample collection in the Villanova University Water Resources Laboratory.

3.2.1.3 Nutrient Dosing Concentrations

All quality testing events utilized synthetic stormwater runoff dosed with typical nutrient concentrations. An extensive literature review was performed to determine the typical concentrations of TKN, TN, NO_x, TP, and PO_4 found in stormwater runoff. The influent nutrient dosing for this study will be based off these typical concentrations. Table 11 shows the results of four different studies conducted in the United States to quantify typical nutrient concentrations in stormwater runoff. These values represent concentrations found in urban areas subject to heavy development and significant impervious cover (Cole et al. 1984; May and Sivakumar 2009). The third and fourth column are from the same study (Cole et al. 1984), but the first represents median concentrations while the second represents the 90th percentile of nutrient concentrations found at an urban sites.

Table 11: Typical Nutrient Concentrations found in Urban Stormwater Runoff

Nutrient	Nationwide Geometric Means in Urban Runoff (May and Sivakumar 2009)	US EPA Seasonal Median for PA (Wadzuk and Traver 2008)	Nationwide Urban Runoff Program (NURP) Median Urban Site (Cole et al. 1984)	Nationwide Urban Runoff Program (NURP) 90th Percentile Urban Site (Cole et al. 1984)
TKN (mg/L)	1.65	NA	1.5	3.3
NO_X (mg/L)	0.43	NA	0.68	1.75
TN (mg/L)	2.17	4.91	NA	NA
PO_4 (mg/L)	0.09	NA	0.12	0.21
TP (mg/L)	0.27	0.14	0.33	0.7

To confirm these results, other scientific studies that utilized synthetic stormwater runoff were consulted (Table 12). There have been numerous studies where water is dosed to achieve typical nutrient concentrations in runoff, validating this research technique.

Table 12: Dosed Nutrient Concentrations used in Similar Scientific Studies

Nutrient	(Culbertson and Hutchinson 2004)	(Vacca 2013)	(Barrett et al. 2013)	(Blecken et al. 2010)	(Sickles et al. 2007)	(Hatt et al. 2007)
TKN (mg/L)	NA	NA		1.79	4	NA
NO_X (mg/L)	NA	NA	0.74	0.4	2	NA
TN (mg/L)	2	NA	NA	1.8	NA	2.1
PO_4 (mg/L)	0.6	0.6	0.35	NA	0.6	NA
TP (mg/L)	NA	NA	NA	0.31	NA	0.35

While the concentrations displayed in Table 11 and Table 12 vary slightly from one another, it was found all concentrations were generally well agreed upon for each constituent. The desired nutrient concentrations that will be used in the field portion of this study are shown in Table 13. These concentrations represent the average concentration of those presented previously, omitting the 90th percentile concentrations found by the EPA (1983). All concentrations were rounded up to the nearest 0.5 mg/L for simplicity.

The selected nutrient concentration for orthophosphate (PO_4) is based on the average of the typical concentrations found in runoff (Table 11) and does not include the concentrations used in similar studies (Table 12). This was done because this field portion of the quality testing was designed to mimic actual chemical and biological conditions that take place in bioretention systems. Because orthophosphate may undergo some physical and chemical changes within the bioretention cell, the higher PO_4 concentrations used in laboratory studies (Table 12) were not necessary for this field application. The desired value of PO_4 used in this research (Table 13) is based solely on actual runoff conditions. The higher PO_4 concentrations seen in similar studies will be used as a basis for the remainder of the quality testing work that will occur in the laboratory.

Table 13: Desired Nutrient Concentration of Synthetic Stormwater Runoff to be used in the Lysimeter Field Study at Villanova University

Nutrient	Desired Concentration (mg/L)
TKN	2.5
NO_X	1.0
TN	3.0
PO_4	0.15
TP	0.5

Due to the volume of water required for each storm event and the semi-isolated location of the lysimeters on Villanova University's campus, it was not feasible to create the synthetic stormwater runoff using deionized water. Instead, tap water sourced from the nearby Villanova University School of Law was used as the base for the synthetic runoff. Although the desired concentration of nutrients was determined, the initial concentration of these nutrients present in the tap water also needed to be determined. Three different grab samples were taken from the tap water source over the course of a one month period and analyzed for TKN, TN, NO_x, TP, PO_4, and Cl^- using the Simplicity Discrete Analyzer (Chinchilla Scientific). Table 14 shows the nutrient and chloride concentrations that were found in the tap water.

Table 14: Initial Nutrient Concentrations in the Tap Water Sourced from the Villanova University Law School

Nutrient	Tap Water Sample 1	Tap Water Sample 2	Tap Water Sample 3	Average Tap Water Sample
NO_X (mg/L)	2.517	1.452	1.421	*1.797*
TKN (mg/L)	0.254	0.333	0.187	*0.258*
TN (mg/L)	2.771	1.785	1.608	*2.055*
PO_4 (mg/L)	0.183	0.188	0.194	*0.188*
TKP (mg/L)	0.253	0.257	0.257	*0.256*
Cl^- (mg/L)	92.192	92.543	92.777	*92.504*

The nutrient concentrations in the tap water were higher than expected, and it was determined that only three nutrient concentrations in the tap water were below the desired nutrient concentration for this study (Table 13). The concentration of NO_x and PO_4 in the tap water was above the desired concentration, therefore no additional source of these constituents was needed. The concentration of total kjeldahl nitrogen (TKN) in the tap water was found to be 0.258 mg/L, requiring an additional source of TKN to meet the desired concentration. It was determined that an additional 2 mg/L of TKN would be sufficient to achieve the desired concentration (Table 15). While the total nitrogen (TN) concentration was also below the desired concentration of 3 mg/L, it was determined that an additional source of TN was not necessary as increasing the TKN concentration would increase the TN concentration. The source of TKN that will be used in this application is Ammonium Sulfate ($(NH_4)_2SO_4$) (Fisher Scientific CAS 7783-20-0). $(NH_4)_2SO_4$ was chosen as the additional source of TKN for consistency as it is the chemical used to make the TKN standards for the analysis using the Simplicity Discrete Analyzer (Chinchilla Scientific). An addition of 9.438 mg/L of $(NH_4)_2SO_4$ will be added to the tap water to create the appropriate synthetic runoff.

Total phosphorus (TP) and total kjeldahl phosphorus (TKP) measure the same constituents; therefore the terms will be used interchangeably. The concentration of TKP in the tap water was found to 0.256 mg/L which would require an additional 0.25 mg/L to achieve the desired concentration of 0.5 mg/L (Table 15). The additional source of TKP for the dosed runoff will be achieved through the addition of Potassium Dihydrogen Phosphate (KH_2PO_4) (Fisher Scientific CAS 7778-77-0). KH_2PO_4 was chosen as the source for TKP as this is the chemical used to make the standards in the analysis process of TKP using the Simplicity Discrete Analyzer. It was determined that 1.099 mg/L of KH_2PO_4 would be required to achieve the desired dosage of TKP in the synthetic runoff. A chloride concentration of 100 mg/L is considered sufficient to act as a conservative fluid tracer, and it was determined that the concentration of Cl^- present in the tap water was adequate for this purpose.

Table 15: Additional Nutrients Added to the Tap Water to Achieve the Desired Nutrient Concentrations for the Synthetic Stormwater Runoff

Nutrient	Desired Conc. (mg/L)	Average Tap Water Conc. (mg/L)	Additional Conc. Needed (mg/L)	Source of Nutrient Addition	Conc. of Nutrient Supplement (mg/L)
TKN	2.5	0.258	2	$(NH_4)_2SO_4$ (Ammonium Sulfate)	9.438 mg/L $(NH_4)_2SO_4$
NO_X	1.0	1.797	0	NA	NA
TN	3.0	2.055	0	NA	NA
PO_4	0.15	0.188	0	NA	NA
TP/TKP	0.5	0.256	0.25	KH_2PO_4 (Potassium Dihydrogen Phosphate)	NA 1.099 mg/L KH_2PO_4
Cl^-	100	92.504	0	NA	NA

Prior to each storm simulation event the appropriate concentrations of $(NH_4)_2SO_4$ and KH_2PO_4 were added to the appropriate volume of tap water in the 150 liter barrel. While they are in a sufficient range of the desired concentrations in Table 15, the influent nutrient concentrations determined for the synthetic stormwater were not expected to stay constant throughout the ten quality testing events. The initial concentrations in the tap water was expected to vary throughout the eight month period that quality testing events were occurring, and these concentrations (Table 15) are meant to serve as a basis for the nutrient concentrations. Each storm simulation event will analyze a unique grab sample from the influent reservoir in order to compare to the effluent concentrations for that event.

3.2.2 Cation Exchange Capacity

The cation exchange capacity will be measured for each of the five soil types to further quantify their pollutant removal capabilities. Although the cation exchange capacity (CEC) is not a direct measure of a soil's ability to remove pollutants, it can be a good indication of adsorption capabilities. The cation exchange capacity, measured in $cmol^{+}/kg$ (meq/100g), measures the amount of negatively charged sites on a soil's surface and indicates the ability of the soil to retain cations through electrostatic forces (Ross 1995). A soil with a high CEC can retain many cations in solution and indicates a highly fertile soil. The most common cations that are retained in a soil are calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+}) and sodium (Na^{+}). The negatively charged sites on the soil are also capable of retaining acid cations (H^{+}) which may be slightly misleading, but CEC is still a good overall indication of how productive a soil is at taking cations out solution (Dohrmann 2006; Ross 1995). Because of this, CEC can also be a good indication of nutrient availability for plant growth (Manrique et al. 1991).

Clay soils and organic matter (OM) usually have more cation exchange sites, so as a soil loses or gains OM the CEC will be altered (Ross 1995). Because clays have a higher CEC, determining the CEC can help quantify the amount of clay minerals that a soil contains (Dohrmann 2006). CEC typically increases with decreasing particle size due to changes in surface area and crystallinity with size. Even within the clay spectrum coarser clays like kaolinite have lower CEC values compared to finer clays (less than 2 microns) (Malcolm and Kennedy 1970). The CEC of kaolinite, a component of the clay loam soil used in this study, is linearly related to surface area as the time of exchange between cations increases as particle size increases (Malcolm and Kennedy 1970).

More emphasis is given to clays and silts in their contribution to cation exchange capacity, but studies have shown that coarser silts and sands also contribute to CEC. Malcolm and Kennedy (1970) show that the combination of silts and sands contributed up to 50% of the CEC for a soil. In contrast to clays and organic matter, the CEC of sands and gravel does not vary significantly and is highly related to the geology and weathering processes of the parent rock. Sands from parent material high in mica and feldspar will have a higher CEC than those high in quartz (Malcolm and Kennedy 1970), and sand and coarser material should not be overlooked in the determination of cation exchange capacity.

There are numerous methods to test for the cation exchange capacity of a soil, but this research will utilize the Standard Test Method for Measuring the Exchange Complex and Cation Exchange Capacity of Inorganic Fine-Grained Soils (ASTM D7503). This test method analyzes the CEC of a soil as well as the soluble and bound cations present in the soil. The soluble cations are the cations present in the pore water of a sample that are available to be exchanged with the bound cations on the soil surface. During the test method the soluble cations are washed from the soil sample using DI water and the extract is analyzed to find the soluble cations in solution. The bound cations (typically Ca^{2+}, Mg^{2+}, K^+ and Na^+), the cations naturally bound to the mineral surface, are "kicked" off the soil surface by mixing and filtering the soil with ammonium acetate. In this process the bound cations are replaced with nitrogen on the soil surface. The ammonium acetate extract is then tested to determine the quantity of bound cations. Finally, the excess nitrogen is washed off the soil with isopropanol and potassium chloride (KCl). The K^+ ions replace the N^+ ions on the soil which allows the extract to be tested for the nitrogen concentration to determine the CEC (ASTM D7503 2010).

Not only does the ammonium acetate solution remove the bound cations, it also acts as a buffer for the system to keep the pH near neutral. Soils will have a greater CEC near a pH of seven as opposed to acidic conditions, so for proper comparison between soil types the pH should be buffered near neutral (Ross 1995). It should be noted that if the pH of the soil in the field is not at neutral conditions, this method may slightly overestimate the CEC capacity, especially for soils in the Northeast which are typically more acidic in nature (Ross 1995).

The test was performed for each of the five soil samples (sandy loam, loamy sand, loam, silt loam, and clay loam) in addition to a duplicate sample for each soil type. The potassium chloride extract was analyzed for nitrogen using the Simplicity Discrete Analyzer (Chinchilla Scientific) for the analysis of total kjeldahl nitrogen (TKN) in mg/L according to the method in Table 10. In addition to the duplicate samples for each soil type, TKN was run and analyzed on three separate occasions to get an accurate nitrogen concentration for each of the soil samples. The nitrogen concentration used for each soil sample represents an average of the three test runs and an average of the original and duplicate samples. This nitrogen concentration can then be converted to CEC in $cmol^+/kg$ (meq/100g) through Equation 4 based on the nitrogen concentration (N) and the initial mass of soil used in the test (M_0).

$$CEC\left(\frac{cmol^+}{kg}\right) = N\left(\frac{mg}{L}\right) x \, \frac{1\,(cmol^+)}{140\,(mg)} \text{ x } \frac{0.25\,(L)}{M_0(g)} \, x\,1000\left(\frac{g}{kg}\right) \qquad \text{(Equation 4, ASTM D7503)}$$

3.2.3 Batch Isotherm Experiments

In addition to the determination of the cation exchange capacity and the field studies, an additional laboratory experiment will be performed to analyze the mass transfer of phosphorus in the five different soil types. The mass transfer of phosphorus in stormwater systems can be characterized through adsorption kinetics, adsorption isotherms and breakthrough behavior (Ma and Sansalone 2007), and this section will discuss the adsorption isotherms. This experiment will strictly analyze the mass transfer of orthophosphate (PO_4) since it is the most readily available form of phosphorus in stormwater runoff. The behavior of nitrogen will not be analyzed in this mass transfer study as the complex transformation processes of nitrogen in SCMs is not well represented by short term laboratory studies.

Batch sorption isotherm experiments were performed to determine the maximum adsorption capacity of the five different soil types used in this research. This is done by measuring the initial orthophosphate concentration sorbed to the soil and then measuring the additional orthophosphate concentration the soil is able to retain. The additional orthophosphate holding potential is determined by mixing a known aqueous orthophosphate solution with soil and measuring the aqueous orthophosphate concentration after a known period of time. It is assumed that the difference in orthophosphate concentration before and after mixing is due to the adsorption of orthophosphate to the soil. The equilibrium concentrations will allow for a quality removal comparison between soil types.

The mass of orthophosphate initially present in the soil was determined by mixing 0.3 grams of soil with 15 ml of 0.5 N HCl. This solution was then rotated in 50 ml containers in a reciprocal shaker at 100 rpm for 24 hours. After a period of 24 hours the solution was filtered through 0.45 μm filters and the extract was tested for orthophosphate (mg/L) according to the method described in Table 10 using the Simplicity Discrete Analyzer. This process was performed twice for each soil sample (1 duplicate), in addition to the typical quality control measures of two blank samples and two matrix spikes described previously.

The maximum amount of orthophosphate that each soil can retain was found by performing an adsorption isotherm study based on the method provided by Vacca et al. (2016). For each soil type, multiple 25 ml solutions with known orthophosphate concentrations were mixed with 0.2 grams of soil in 50 ml containers and rotated at 100 rpm for a period of 5 days. After the 5 day period the aqueous solutions were filtered through 0.45 μm filters and the extract was analyzed for PO_4 (mg/L) using the Simplicity Discrete Analyzer. The initial orthophosphate solutions contained concentrations of 0, 0.2, 1, and 2 mg/L of PO_4-P and were prepared using a molar ratio of 0.096 Na_2HPO_4 and 0.904 NaH_2PO_4 so that the solution was buffered at a pH of 7. The base of the orthophosphate solution was 0.01 M KCl to aid in the buffering process as well as provide a background concentration of electrolytes typically seen in stormwater runoff (Vacca et al. 2016; Yan et al. 2015). Buffering the solution is important for batch isotherm studies as adsorption capacity is directly related to pH (Özacar 2006; Song et al. 2011; Yan et al. 2015). Adsorption capacity increases as pH decreases, down to a pH around 4. At lower pH's the surface hydroxyl groups on the soil are protonized to OH_2^+ binding sites which are more easily replaceable, resulting in a higher adsorption capacity (Song et al. 2011). Additional factors that affect adsorption isotherm tests are the adsorbent material used, organic content, particle size, contact time, temp, and the range of initial concentrations (Fangqun et al. 2011).

Batch isotherm tests were done according to this method for the sandy loam, loamy sand, loam, silt loam, and clay loam, in addition to blank samples in which no soil mass was added to the orthophosphate solutions. This data can be used to plot the adsorbed orthophosphate concentration versus the aqueous orthophosphate concentration. This relationship can be modeled through the Langmuir isotherm which has been shown to accurately represent the adsorption capacity of orthophosphate in other batch studies (Özacar 2006; Song et al. 2011; Vacca et al.

2016). The Langmuir isotherm model can be used to predict the maximum concentration of orthophosphate that can be sorbed to the soil if the soil is at equilibrium with aqueous orthophosphate in a SCM. The maximum PO_4 concentration that can be adsorbed (Q_M) in mg/L is based on the sorbed orthophosphate concentration at equilibrium (q_e) in mg/L, dissolved orthophosphate concentration at equilibrium (C_e) in mg/L, and the Langmuir adsorption constant (K_{ad}) in L/mg as seen in Equation 5.

$$q_e = \frac{Q_M * K_{ad} * C_e}{1 + K_{ad} * C_e} \quad \text{(Equation 5)}$$

Each soil type has a unique Langmuir adsorption constant that was determined from the batch isotherm data using a non-linear curve fitting technique. The results of the batch isotherm study are presented in Section 4.2.1.2.

CHAPTER 4: RESULTS AND DISCUSSION

The results of the Optimal Balance study will be presented in two sections. Section 4.1 will discuss the water quantity results and section 4.2 will discuss the water quality results. The data that were analyzed were collected over a 15 month period from August of 2015 to October of 2016.

4.1 WATER QUANTITY RESULTS AND DISCUSSION

The water quantity data is based on 19 storm simulation events that were performed over the course of 15 months from August 2015 to October 2016. Storm simulations were not performed at the Optimal Balance site during the winter months from November to February. Following the fall 2015 season the site was winterized and all cold weather sensitive instrumentation was taken indoors. At the beginning of March all instrumentation was put back into place and storm simulations commenced for spring of 2016. During the winter months the twelve vegetated lysimeters remained outside so that the Switchgrass was exposed to typical weather conditions in the Pennsylvania area.

Since this study is analyzing ET, a seasonally dependent process, the storm simulations as well as the majority of the results are grouped by season. Storm simulations were performed over four seasons: fall 2015, spring 2016, summer 2016, and fall 2016 (Table 16). The five storm simulation events highlighted in red represent natural rainfall events with simulated runoff, and the remaining events are purely simulated events such that both rainfall and runoff were simulated. The storm simulations highlighted in blue represent storms where water quality data was collected. As discussed previously, different water volumes were applied to the vertical and horizontal lysimeters, and Table 16 displays those volumes in terms of the dosing rate per hour and total volume applied over the 24 hour storm simulation period.

Table 16: Storm Simulations Performed at the Optimal Balance Site from Fall 2015 to Fall 2016

Season	Date of Storm Simulation	Natural Rainfall (in)	Runoff Dosing Program Storm Size (in)	Vertical Dosing Rate (ml/hr)	Horizontal Dosing Rate (ml/hr)	Total Vertical Simulated Inflow (I_V) (in)	Total Horizontal Simulated Inflow (I_H) (in)
Fall 2015	8/24/2015	0	1.00	43	374	5.03	5.04
	9/10/2015	0.81	1.00	43	299	5.05	4.04
	9/29/2015	1.63	0.75	26	98	2.98	1.29
	10/12/2015	0	0.75	33	123	3.81	1.64
	10/20/2015	0	1.50	65	245	7.69	3.34
Spring 2016	3/8/2016	0	1.00	43	163	5.00	2.18
	3/21/2016	0	1.00	43	163	5.00	2.18
	4/6/2016	0.17	1.00	34	130	4.08	1.79
	4/19/2016	0	1.50	64	245	7.36	3.25
	5/10/2016	0	1.50	64	245	7.44	3.28
Summer 2016	5/31/2016	0	1.50	64	245	7.67	3.38
	6/12/2016	0	1.50	64	245	7.08	3.12
	6/22/2016	0	1.00	43	163	5.21	2.27
	7/5/2016	0	1.00	34	130	3.91	1.72
	7/25/2016	2.26	1.50	34	130	4.08	1.79
Fall 2016	8/29/2016	0	1.50	64	245	7.36	3.25
	9/5/2016	0	1.50	64	245	7.59	3.35
	9/18/2016	2.28	1.00	34	130	4.03	1.78
	10/31/2016	0.19	1.00	34	130	4.03	1.78

The results presented in this chapter are based on the data from these 19 storm simulations events, as well as the natural rainfall events that occurred between the simulated events. Table 17 displays all precipitation events that occurred throughout the study in terms of the duration of the rainfall event and the antecedent dry time before the next event. The average storm duration and antecedent dry time are presented for each season. The rainfall events with an (S) after them indicate a storm simulation event, referring to those in Table 16.

Table 17: Duration and Antecedent Dry Period of Each Storm Simulation and Natural Precipitation Event

Storm Simulation or Rainfall Event	**Duration of Rainfall Event (days)**				**Dry Time Before next Rainfall Event (days)**			
	Fall 2015	**Spring 2016**	**Summer 2016**	**Fall 2016**	**Fall 2015**	**Spring 2016**	**Summer 2016**	**Fall 2016**
1	2 (S)	2 (S)	2 (S)	2 (S)	12 (S)	3 (S)	1 (S)	1 (S)
2	4 (S)	4	1	3	15 (S)	5	1	1
3	4 (S)	2 (S)	1	2 (S)	5 (S)	2 (S)	1	11 (S)
4	3 (S)	1	1	2 (S)	5 (S)	3	3	8 (S)
5	2 (S)	2	2 (S)	3	5 (S)	3	2 (S)	8
6	2	6 (S)	1	1	9	6 (S)	5	9
7		2 (S)	2 (S)	3		2 (S)	3 (S)	7
8		1	2	2 (S)		2	7	3 (S)
9		1	2 (S)			1	6 (S)	
10		13 (S)	2			1 (S)	3	
11		2	1			4	4	
12			3 (S)				1 (S)	
13			2 (S)				4 (S)	
14			1				5	
15			1				3	
16			2				2	
17			1				6	
Average	3	3	2	2	9	3	3	6
Std. Dev.	1	3	1	1	4	2	2	4

It is difficult to separate volume removal through infiltration and ET for each individual event because of overlap in the water budget between events. In smaller systems like these lysimeters, water is stored in the media between events that may be available for infiltration and ET after the next event, making it hard to distinguish between each event. The point of Table 17 is not necessarily to analyze the duration and dry time between each event, but to compare these parameters on a seasonal basis. Looking at the differences in rainfall duration and dry time on a seasonal basis can help give insight to the balance of infiltration and ET over the different seasons.

Summer 2016 experienced the most rainfall events, but these rainfall events were shorter in duration than most other seasons, ranging from one to three days with an average event duration of 1.6 days. Because of the amount of precipitation events, the average dry time between events is on the lower side at about 3.4 days, but the antecedent dry time is pretty varied ranging from one to seven days. Spring 2016 had the longest duration events with one event that was a combination of a simulated storm event and natural precipitation lasting for 13 consecutive days. The spring season also had the shortest antecedent dry time between events at an average of about 3 days, making it the wettest season.

The average storm duration and dry time between events for each season is also presented in graphical form (Figure 29). Fall 2015 and fall 2016 were comparable in terms of both event duration and dry time between events. Fall 2015 experienced slightly longer duration events but less storm events than fall 2016. Both fall seasons were dominated by simulated storm events with few natural events in between. For both fall 2015 and 2016 the dry time between events was longest, with an average of 8.5 and 6 days, respectively. Both 2015 and 2016 had the longest inter-event times at 15 and 11 days, respectively, making both fall seasons the driest of the four seasons analyzed.

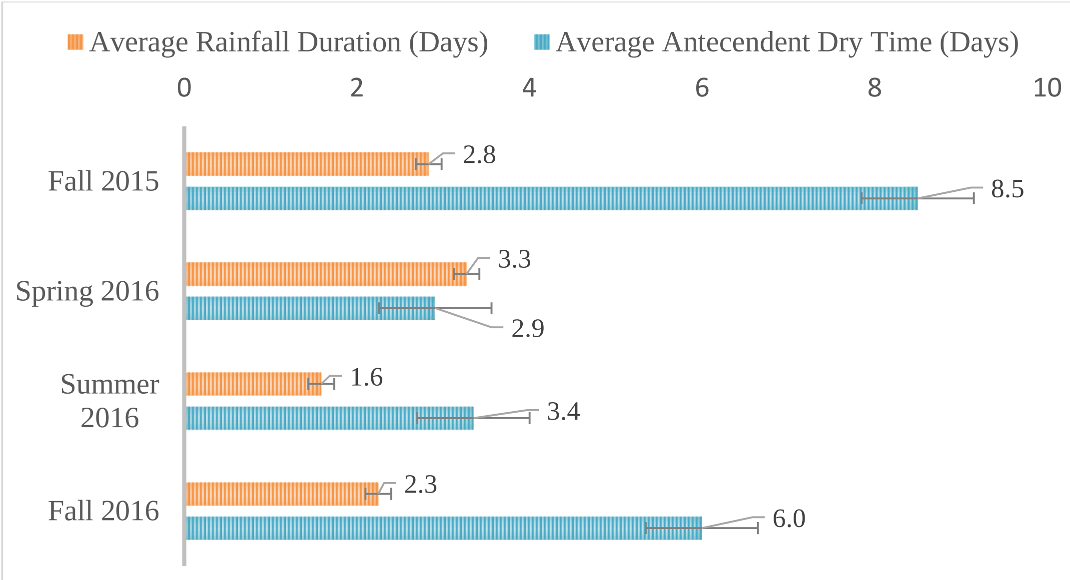

Figure 29: Average Rainfall Duration and Average Antecedent Dry Time for Seasons Studied (With Standard Error Bars)

The seasons were further analyzed on a statistical level by performing t-test comparisons of the average rainfall duration and antecedent dry time (Table 18). Paired t-tests were used to determine if the data sets for each season were statistically different from one another at a 90% confidence level. If two data sets have a calculated p-value less than 0.10, then the two data sets are deemed statistically different from one another. If two data sets have a calculated p-value greater than 0.10, then the two data sets are not statistically different from one another. In terms of rainfall duration, summer 2016 had statistically shorter duration events than the other three seasons. The antecedent dry time was statistically different for all seasons, except between the two fall seasons, which were similar, and between the spring and summer, also similar.

Table 18: Statistical T-test Comparison of Mean Rainfall Duration and Mean Antecedent Dry Time among Seasons

Seasonal Parameter	T-test Comparison (90% Confidence)	Season	Fall 2015	Spring 2016	Summer 2016	Fall 2016
Rainfall Duration	p-value	**Fall 2015**		0.774	0.002	0.219
	Statistically Different?			NO	YES	NO
	p-value	**Spring 2016**			0.065	0.436
	Statistically Different?				YES	NO
	p-value	**Summer 2016**				0.026
	Statistically Different?					YES
Antecedent Dry Time	p-value	**Fall 2015**		0.001	0.001	0.271
	Statistically Different?			YES	YES	NO
	p-value	**Spring 2016**			0.531	0.026
	Statistically Different?				NO	YES
	p-value	**Summer 2016**				0.029
	Statistically Different?					YES

The Optimal Balance site also contains a weather station that records temperature, solar radiation, relative humidity, and wind speed at five minute intervals. This weather data was not analyzed as it relates to ET as part of this study, but is available for future use. The average, maximum and minimum temperatures are displayed for each of the four seasons (Table 19). Since ET rates are affected by temperature, these values can serve as a general indication of ET potential for each season. The temperatures in the summer were the highest indicating the highest potential for ET, whereas the temperature discrepancy among the other three seasons is not as noticeable.

Table 19: Average, Maximum, and Minimum Temperatures for the Four Seasons

Temperature (^{0}F)	Fall 2015	Spring 2016	Summer 2016	Fall 2016
Average	62.9	57.8	80.7	68.4
Maximum	95.8	93.7	104.0	101.0
Minimum	29.2	26.6	54.8	35.5

The data analyzed in this section was calculated using the mass balance presented in Equation 2. Table 20 shows the difference between the expected error and the actual error based on the mass balance for each season. The expected error is based strictly on the error associated with each piece of instrumentation as displayed in Table 1 (Chapter 3). The instrumentation error found in Table 1 was multiplied by the number of days in each season to get the expected error (mm) since the mass balance is calculated on a daily basis. The actual error is determined based on the cumulative change in storage over each season. The total water storage displayed in Tables 21 through 25 in this section are taken as the inflow volume minus the deep infiltration and ET volumes, such that the total water balance is equal to 100%. In addition to this, the water storage was also calculated on a daily basis based on the weight of each lysimeter. The actual error represents the difference between the hypothetical water storage based on the mass balance and the measured water storage based on the daily lysimeter weights (Table 20). The actual error and the standard deviation are displayed for both flow configurations for each season.

Table 20: Expected and Actual Seasonal Error in Water Balance for Vertical and Horizontal Lysimeters

Season	Average Seasonal Error							
	Vertical Lysimeters				Horizontal Lysimeters			
	Actual (mm)	Expected (mm)	Actual (in)	Expected (in)	Actual (mm)	Expected (mm)	Actual (in)	Expected (in)
Fall 2015	104.0 ± 65.7	36.7	4.1 ± 2.6	1.4	133.3 ± 93.7	42.2	5.2 ± 3.7	1.7
Spring 2016	147.1 ± 70.8	39.4	5.8 ± 2.8	1.6	114.5 ± 43.1	45.3	4.5 ± 1.7	1.8
Summer 2016	123.7 ± 69.4	42.7	4.9 ± 2.7	1.7	78.7 ± 51.7	49.0	3.1 ± 2.0	1.9
Fall 2016	140.4 ± 111.0	30.2	5.5 ± 4.4	1.2	78.1 ± 61.3	34.7	3.1 ± 2.4	1.4
All Seasons	128.8 ± 79.2	149.0	5.1 ± 3.1	5.9	101.1 ± 62.4	171.1	4.0 ± 2.5	6.7

It is expected that the actual error is greater than the expected error because the expected error is solely based on instrumentation error, but in reality there were other possibilities for error in the system. Additional sources of error in the water balance can include:

- Dosing pumps supplying less water than programmed due to leaks in tubing and connections, pumps not being primed, error in programming, etc.
- Loss of water between irrigation system and lysimeters due to wind
- Mass of dry soil weight in each lysimeter not constant due to changes in mass throughout the study including loss of fine particles, addition of vegetation, etc.
- Error in water storage based on lysimeter weight due to unaccounted for debris such as insects, stones, etc.
- Residual water stored from season to season and stored water during the winter

Considering these additional sources of water loss, the actual error in the system is acceptable, amounting to an average of 3 to 5 inches of water per season. This error in the water balance is not expected to influence the results of this study since all data analysis was performed on a seasonal basis, not a storm basis.

4.1.1 Plant Health

The health of the Switchgrass in each lysimeter was analyzed on a monthly basis according to visual inspection, average leaf count, and average leaf height. In both vertical and horizontal flow configurations, the Switchgrass was transplanted to each lysimeter at the end of August 2015. Both vertical and horizontal flow configurations began with the same initial mass of Switchgrass. Following the winter season, the Switchgrass naturally grew back in each lysimeter during the spring season. The dead plant matter was left as leaf litter in each lysimeter following the growing season.

4.1.1.1 Vertical Lysimeters

Pictures of the Switchgrass were taken from a consistent vantage point for the duration of this study (Figure 30). In September, shortly after the Switchgrass was transplanted, a few of the leaves in each lysimeter began to brown. In October, about half of the leaves had browned, and by early November the Switchgrass in the vertical lysimeters was completely dead. The months not pictured are when storm simulations did not occur, or in the case of March, when the Switchgrass had not yet grown back.

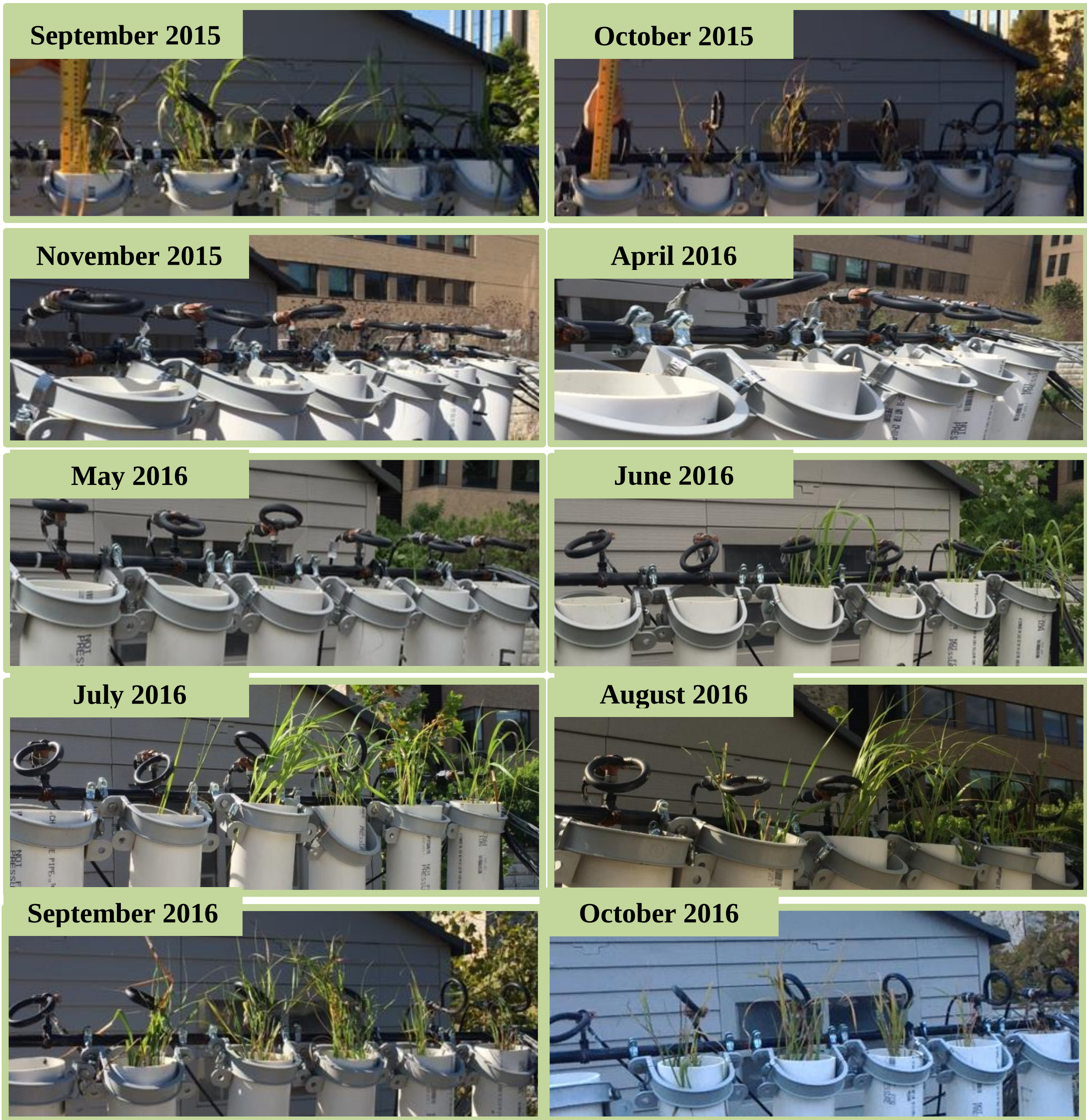

Figure 30: Pictures of Switchgrass in the Vertical Lysimeters on a Monthly Basis

In late May the Switchgrass began to slowly grow back, and during the months of July and August, the Switchgrass was at its healthiest. The growing pattern of the Switchgrass in this study is consistent with the typical growing season from May to September (Yimam 2014). As seen in the images from June and July, it was observed that the Switchgrass in Lysimeter B (Sandy Loam) was not growing back as dense compared to the other lysimeters, which is hypothesized to be because the planting did not take well initially in the fall. Additional Switchgrass was transplanted to Lysimeter B in the spring so that a proper comparison could be made between all vertical lysimeters. Besides Lysimeter B, no new Switchgrass was planted in the vertical lysimeters such that the vegetation naturally died and grew back between 2015 and 2016.

The average leaf count (Figure 31) and average leaf height (Figure 32) in the vertical lysimeters were plotted for the duration of the study. While this is not meant to be an in-depth plant study, these graphs provide a rough quantitative comparison of Switchgrass growth among soil types and over the course of the different seasons. Although the same plant mass was initially planted in all lysimeters, some vegetation took better than others so the initial leaf count shown in September 2015 should be kept in mind when looking at the leaf counts among soil types.

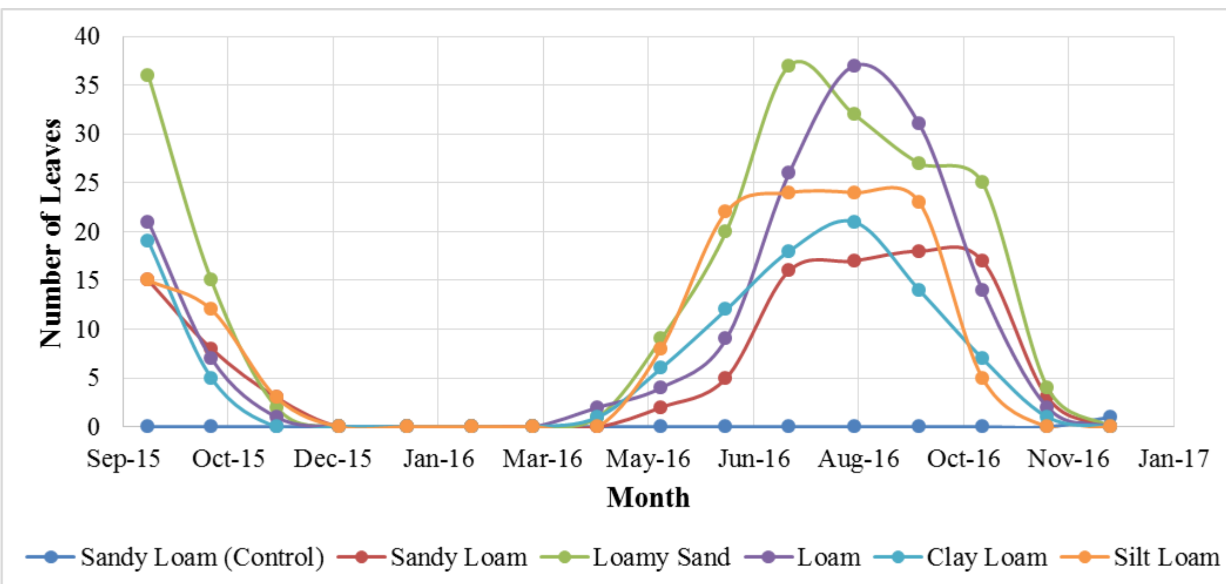

Figure 31: Switchgrass Leaf Count in the Vertical Lysimeters on a Monthly Basis

The dark blue line at the bottom of Figure 31 represents the control which contained no vegetation. For all other lysimeters, the number of leaves during the growing season ranged from 15 to 40 leaves of varying size. Surprisingly, the Switchgrass took well in the loamy sand regardless of it being the coarsest soil type. The Switchgrass in the loamy sand also peaked earlier in the spring season and began to die out faster than those in the other media. The loam and silt loam had the next highest number of leaves, both of which had leaf counts that increased from 2015 to 2016 after the dormant season. The loam had the densest Switchgrass with the leaf count reaching the highest peak of all soil types, but the silt loam soil retained a fairly constant leaf count over the entirety of the growing season. The clay loam and sandy loam had the lowest leaf count, but the clay loam grew back at the same density at which it was originally planted while the sandy loam required replanting.

The average leaf height shows much less variation among media (Figure 32). Leaf height can somewhat be correlated to leaf count as seen with the loamy sand having both the highest leaf count and average leaf height, but there is not as much discrepancy between the different media in the vertical lysimeters in terms of leaf height.

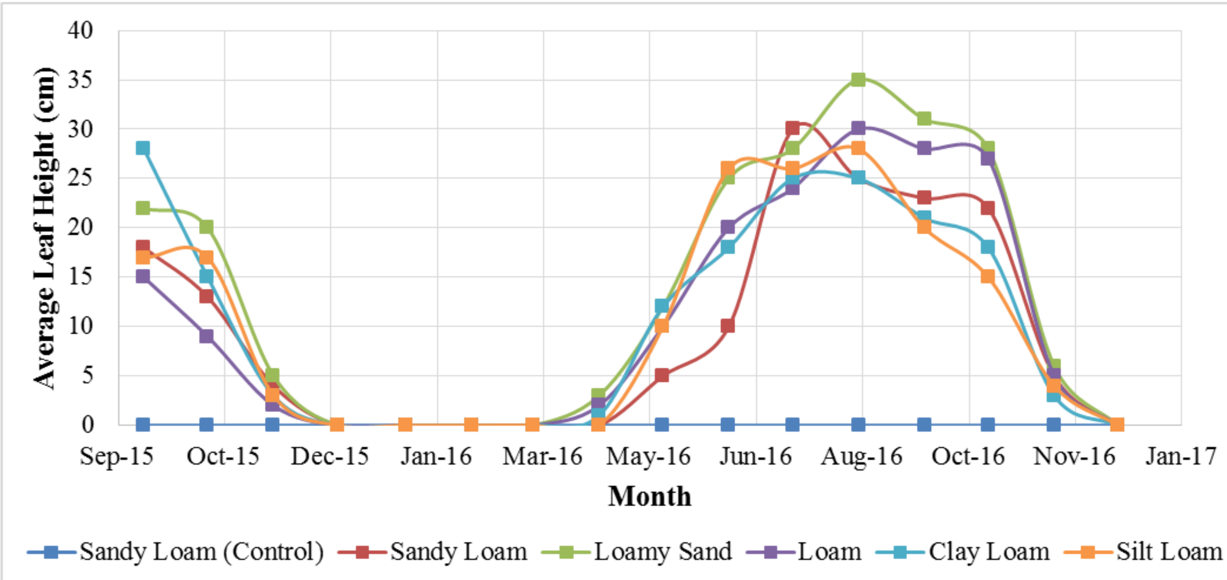

Figure 32: Average Leaf Height of Switchgrass in the Vertical Lysimeters on a Monthly Basis

While looking at this leaf data quantitatively can help compare the Switchgrass in the different soil types, the leaf count may exaggerate some differences between media. In reality, all vertical lysimeters (besides the control) had comparable amounts of Switchgrass that was not thought by the researchers to cause major differences in ET performance. To check this assumption, paired t-tests were performed comparing the number of leaves and leaf height each month among the different soil types (Table 21). At a 90% confidence level, the average leaf counts were found to be statistically different for the majority of vertical lysimeters, except for the silt loam which was shown to be similar to the sandy loam and loam. The clay loam was also shown to be statistically similar to the sandy loam. This indicates that in most cases the type of media played a role in the leaf count, but this may be due to other factors not considered. Average leaf height was shown to be less affected by media type than the average leaf count, with about half of the t-tests indicating significant differences among media.

Table 21: Statistical Paired T-Test Comparisons of Monthly Leaf Count and Leaf Height Among Different Soil Types in the Vertical Lysimeters (n= 13)

Leaf Count							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.004	0.003	0.003	0.008	0.004
Statistically different?			YES	YES	YES	YES	YES
p-value	**B**			0.004	0.064	1.000	0.213
Statistically different?				YES	YES	NO	NO
p-value	**C**				0.040	0.003	0.026
Statistically different?					YES	YES	YES
p-value	**D**					0.052	0.471
Statistically different?						YES	NO
p-value	**E**						0.067
Statistically different?							YES
Leaf Height							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.002	0.001	0.002	0.001	0.002
Statistically different?			YES	YES	YES	YES	YES
p-value	**H**			0.006	0.315	0.410	0.591
Statistically different?				YES	NO	NO	NO
p-value	**I**				0.004	0.022	0.009
Statistically different?					YES	YES	YES
p-value	**J**					0.883	0.751
Statistically different?						NO	NO
p-value	**K**						0.845
Statistically different?							NO

4.1.1.2 Horizontal Lysimeters

The Switchgrass in the horizontal lysimeters exhibited similar trends to the vertical lysimeters such that they began to brown in October and were fully dead by November. Although, the Switchgrass in the horizontal lysimeters began to grow back in early April, noticeably sooner than the vertical lysimeters. By late May the Switchgrass began to fully grow back, more densely than the previous fall season in most lysimeters.

Upon the spring season, it was observed that the Switchgrass in the clay loam was not growing back. This may be due in part to the soil type, but also because it did not transplant well the previous fall season as seen in the images from September and October 2015 (Figure 33). Since there is only one horizontal lysimeter per media type, it is not clear if this is due to the media or other conditions with the original Switchgrass that was planted. Regardless, in order to compare the ET performance among the horizontal lysimeters properly, additional Switchgrass seeds were planted in the clay loam. Because of this, the number of leaves and height of Switchgrass in the clay loam is much lower than to the other media. Even after replanting the clay loam, growth was very slow and plant density was low, indicating that the fine media may have prohibited sufficient growth of the Switchgrass.

Figure 33: Pictures of Switchgrass in the Horizontal Lysimeters on a Monthly Basis

The average leaf count was also plotted over the course of the study for the horizontal lysimeters (Figure 34). While the leaf counts show how each lysimeter matured over the course of the season, it should be noted that the Switchgrass in the silt loam was visually the healthiest. The Switchgrass in the horizontal silt loam had the thicket roots and stems, grew to the highest height at 65 cm and also flowered in the summer, which none of the other lysimeters did.

The horizontal lysimeters contained significantly more Switchgrass than the vertical lysimeters, between 60 to 180 leaves during the growing season, due to the larger surface area. The horizontal configuration had about four times as much Switchgrass as the vertical configuration, despite the fact that both configurations were planted with the same initial mass in August 2015. The loamy sand had the highest leaf count in 2016 followed by the silt loam and the sandy loam.

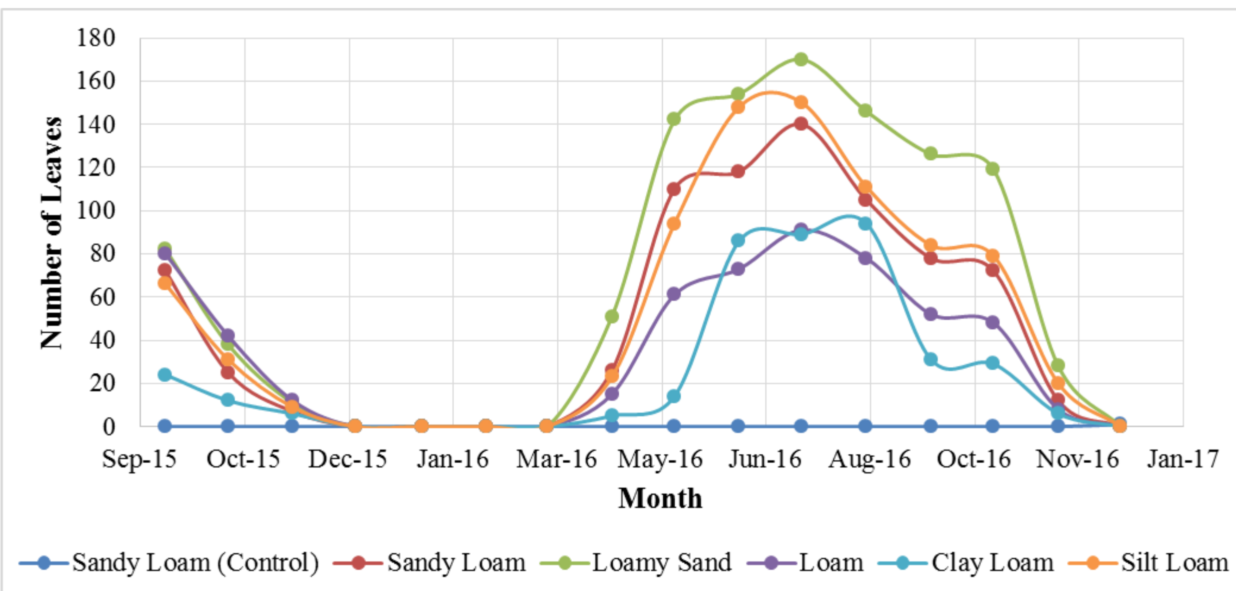

Figure 34: Switchgrass Leaf Count in the Horizontal Lysimeters on a Monthly Basis

The average leaf height in the horizontal lysimeters were comparable among the different media, except for the silt loam and clay loam (Figure 35). As mentioned, the Switchgrass in the silt loam grew to a noticeably higher height, and the Switchgrass in the clay loam was shorter since it was replanted in 2016.

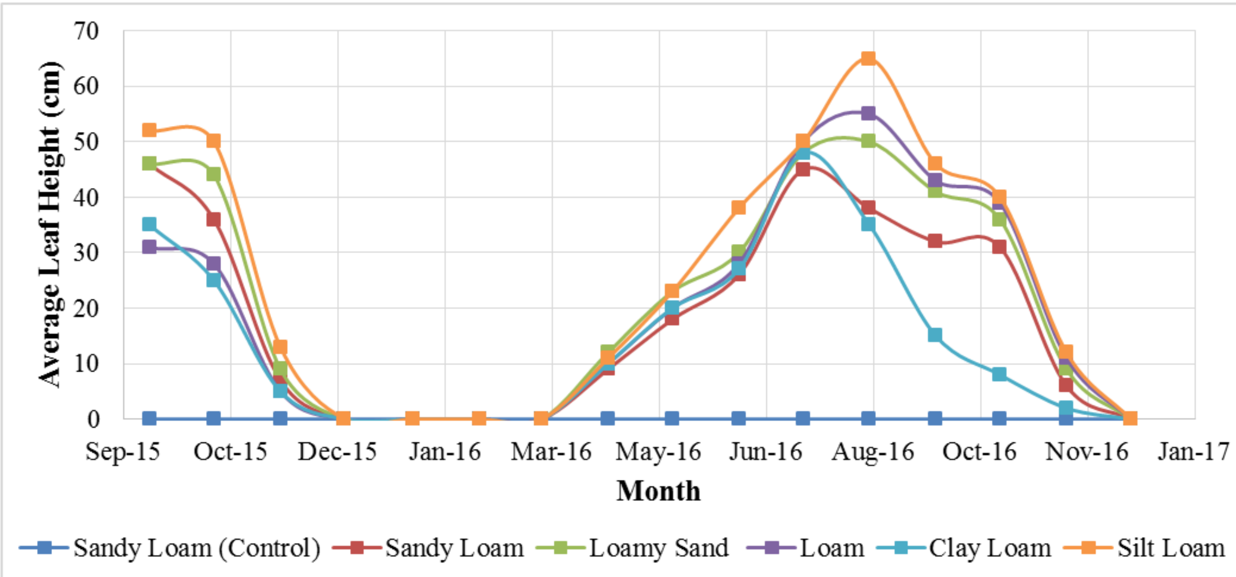

Figure 35: Average Leaf Height of Switchgrass in the Horizontal Lysimeters on a Monthly Basis

Figures 31 through 35 are meant to serve as a rough quantitative comparison among media that can be related to the ET data that is presented in the next section. There are many factors besides the type of media not assessed in this study that can play a role in the health of the Switchgrass, and this data is not meant to indicate which soil type aids the best in Switchgrass growth. Although other factors besides media type may be affecting leaf count and leaf height, paired t-tests were also performed on the plant data in the horizontal lysimeters at a 90% confidence level (Table 22). The Switchgrass in the horizontal lysimeters was significantly more affected by the media type than the vertical lysimeters in terms of leaf count and leaf height. All horizontal lysimeters, besides the silt loam and sandy loam, had significantly different leaf counts at a p-level of 0.10. All horizontal lysimeters, besides the loam and sandy loam and loam and loamy sand, had significantly different leaf heights at a p-level of 0.10.

Table 22: Statistical Paired T-Test Comparisons of Monthly Leaf Count and Leaf Height among Different Soil Types in the Horizontal Lysimeters (n= 13)

Leaf Count							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.002	0.001	0.001	0.011	0.002
Statistically different?			YES	YES	YES	YES	YES
p-value	**B**			0.001	0.028	0.005	0.211
Statistically different?				YES	YES	YES	NO
p-value	**C**				0.004	0.001	0.002
Statistically different?					YES	YES	YES
p-value	**D**					0.057	0.024
Statistically different?						YES	YES
p-value	**E**						0.002
Statistically different?							YES
Leaf Height							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.001	0.001	0.001	0.002	0.001
Statistically different?			YES	YES	YES	YES	YES
p-value	**H**			0.002	0.383	0.050	0.003
Statistically different?				YES	NO	YES	YES
p-value	**I**				0.249	0.008	0.007
Statistically different?					NO	YES	YES
p-value	**J**					0.055	0.016
Statistically different?						YES	YES
p-value	**K**						0.004
Statistically different?							YES

It is interesting that in both flow configurations, the loamy sand had the highest leaf counts and the clay loam had the lowest leaf counts. This is somewhat counterintuitive, as you would expect the soil with the lower hydraulic conductivity to produce healthier plats. This may be somewhat biased based on the type of vegetation used in this study, since Switchgrass is very tolerant and able to survive in all types of media and moisture conditions. It is also possible that the larger void space in the loamy sandy provided more oxygen to the vegetation. On the contrary, the silt loam also produced very healthy Switchgrass, so it is interesting that the vegetation grew best in the loamy sand and the silt loam, soils that are fundamentally different from one another in terms of water storage.

4.1.1.3 Deconstructed Root Mass: Horizontal Lysimeters

Following the end of the fall 2016 growing season, the six horizontal lysimeters were deconstructed to observe the growth of the Switchgrass roots in the different media. The vertical lysimeters were not deconstructed since they will continue to be studied. In all soil types besides the clay loam, the root growth was extensive and dense, and acted as a glue holding the mass of the soil together (Figure 36). The Switchgrass roots also grew into and through the different layers of the geotextile fabric at the bottom of the lysimeters (Figure 36).

Figure 36: Switchgrass Root Mass in the Loamy Sand Soil (left) and throughout the Loamy Sand Geotextile (right)

The mass of the Switchgrass roots were visually different among the types of media. To quantify this difference, the root mass within each horizontal lysimeter was carefully separated from the media, washed, dried and weighed (Table 23). This root mass includes the weight of the geotextile fabric, which included significant root growth.

Table 23: Root Mass of Switchgrass in the Horizontal Lysimeters Compared to the Average and Peak Leaf Counts

Soil Type	Root Mass (g)	Average Leaf Count	Peak Leaf Count (July)
Sandy Loam	235.1	48	140
Loamy Sand	430.3	67	170
Loam	256.6	35	91
Clay Loam	101.2	25	89
Silt Loam	303.1	51	150

The root mass in the horizontal lysimeters can be related to both the average leaf count and the peak leaf count during the growing season. The loamy sand soil, with the highest root mass of 430.3 grams, also had the highest average and peak leaf count. The silt loam soil, with the second highest root mass, also had the second highest leaf counts. The root growth in the clay loam soil was much less dense than the other media, which is also reflected in the lower leaf counts. The deconstruction of the horizontal lysimeters shows that leaf counts can be quantitatively related to root mass and can be a good indication of the overall plant heath, and therefore the ET potential, as will be discussed in Section 4.1.2.

4.1.2 Daily Evapotranspiration Rates

The daily evapotranspiration rates for the different media and flow configurations were compared. This section compares the average ET rates over each of the four seasons. The average daily ET rates for all twelve lysimeters are presented through box and whisker plots which display the range, median, and first and third quartiles of the data. The box and whisker plots do not include the inner and outer outliers in the data that were calculated as part of a statistical analysis. Two sample t-tests were also used to compare the average daily ET rates in all lysimeters for each season. T-tests were performed at a 90% confidence interval (p-level= 0.10) for all ET data. In addition to the box and whisker plots and t-tests, Section 4.1.3 provides the average ET rates in table form for each season. Days that lysimeter weights were not measured, seen in Table A1 in the Appendix, are not included in the ET data.

4.1.2.1 Fall 2015

For the fall of 2015, daily ET rates for all soil types and flow configurations ranged from 0 to 10 mm per day. The days that experience 0 mm of ET were the days that storm simulations or other precipitation events were occurring. Since lysimeter weights were not recorded during rainfall events, ET was assumed to be negligible while it was raining.

As a whole, the vertical configuration saw slightly more ET on a daily basis, an average of about 3 mm/day, than the horizontal configuration, an average of about 2 mm/day. This is because the vertical lysimeters were supplied roughly 2.3 times more water on a surface area basis. Although the horizontal lysimeters received 3.8 times the volume that the vertical lysimeters did, they are actually supplied less water in terms of surface area since they have a much shallower depth. Since all components of the mass balance are calculated in terms of surface area, the daily ET rates are lower in the horizontal configuration. Because of this, the ET rates in the vertical and horizontal flow configurations should not be directly compared. It is difficult to normalize the infiltration and ET data between the two flow configurations since the vertical lysimeters are more of a 1D system where the horizontal lysimeters are a 2D system. This concept will be expanded upon later in this section.

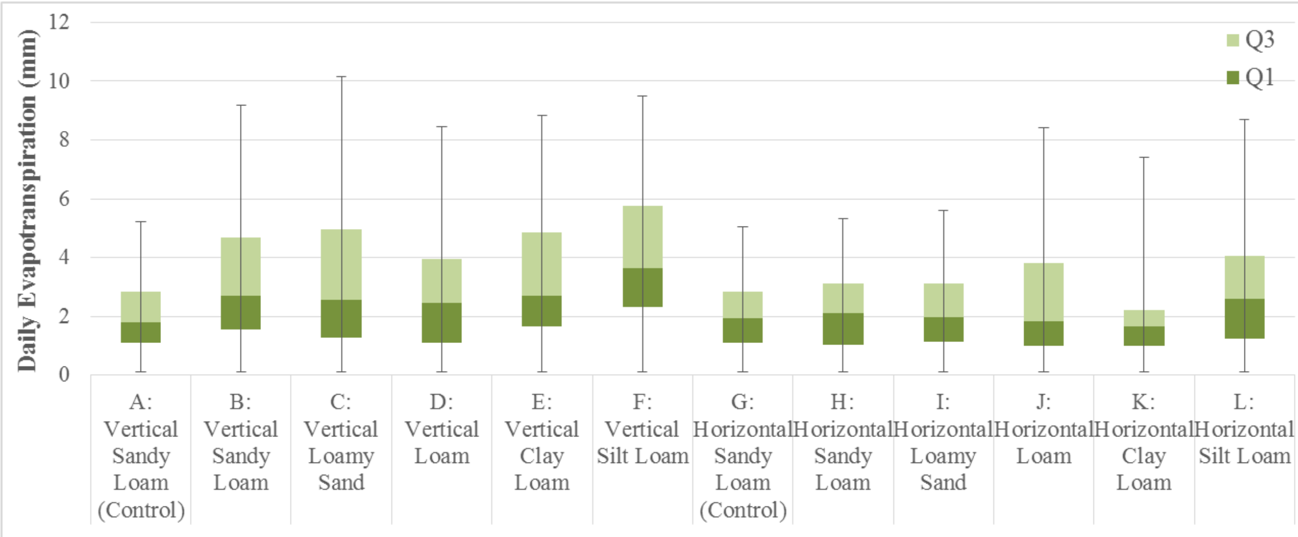

Figure 37: Fall 2015 Daily Evapotranspiration Rates

In control lysimeters ‘A’ and ‘G’ the daily ET rates were lowest, less than 2 mm/day, because the ET is strictly evaporation and no transpiration. In both flow configurations the silt loam had the highest daily ET rates. This is not surprising since the silt loam produced the healthiest plants and was indicated to have the highest plant available water through the SWCC presented in Section 3.4.1.2. Aside from the controls and the silt loam, all other soil media were comparable in terms of daily ET rates within their respective flow configuration.

The vertical configuration seems to have slightly more variation in ET among media type, possibly due the deeper root zone, and variation in moisture availability to the roots. Despite all soil types exhibiting similar median ET rates in the horizontal configuration, the three finer soils (loam, clay loam, and silt loam) saw a higher range of daily ET values compared to the coarser grained loamy sand and sandy loam.

T-tests were performed between the daily ET rates in the vertical and horizontal lysimeters for each soil type, and it was found that ET rates were significantly different between the two configurations. Because of this, t-test comparisons are only shown between media within their respective flow configuration for all seasons (Tables 24 through 28), not between the two configurations. For the fall 2015 season, daily ET rates in the vertical lysimeters were not different among media, except for the control and the silt loam. As seen in Figure 37, the vertical control had significantly lower ET rates than all other media, and the vertical silt loam had significantly higher ET rates than all other soil types except for the loamy sand (Table 24).

Table 24: Statistical T-Test Comparison of Mean Daily ET Values among Different Soil Types for Fall 2015 (n= 50)

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.002	0.005	0.033	0.005	0.000
Statistically different?			YES	YES	YES	YES	YES
p-value	**B**			0.811	0.403	0.804	0.075
Statistically different?				NO	NO	NO	YES
p-value	**C**				0.336	0.649	0.180
Statistically different?					NO	NO	NO
p-value	**D**					0.556	0.011
Statistically different?						NO	YES
p-value	**E**						0.044
Statistically different?							YES
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.603	0.715	0.302	0.194	0.017
Statistically different?			NO	NO	NO	NO	YES
p-value	**H**			0.886	0.580	0.092	0.059
Statistically different?				NO	NO	YES	YES
p-value	**I**				0.497	0.124	0.045
Statistically different?					NO	NO	YES
p-value	**J**					0.044	0.208
Statistically different?						YES	NO
p-value	**K**						0.001
Statistically different?							YES

In the horizontal configuration, daily ET rates were not affected by media type, with exceptions of the silt loam and clay loam. The horizontal silt loam had significantly higher ET rates than all soil types besides the loam. The horizontal clay loam had significantly lower daily ET rates than the sandy loam, loam, and silt loam.

4.1.2.2 Spring 2016

In spring of 2016 the change in daily ET rates can be related to the state of the vegetation (Figures 31 and 34). During the spring the Switchgrass was still in the growing phase and was not fully developed until the very end of the season. Since the Switchgrass did not even begin to grow until the end of May, the spring ET data can almost strictly be looked at in terms of evaporation. For most of the spring season, which ranged from March to May, transpiration is assumed to be negligible since very little Switchgrass was present. Because of this, all media saw very similar daily ET rates, except for the controls (Figure 38).

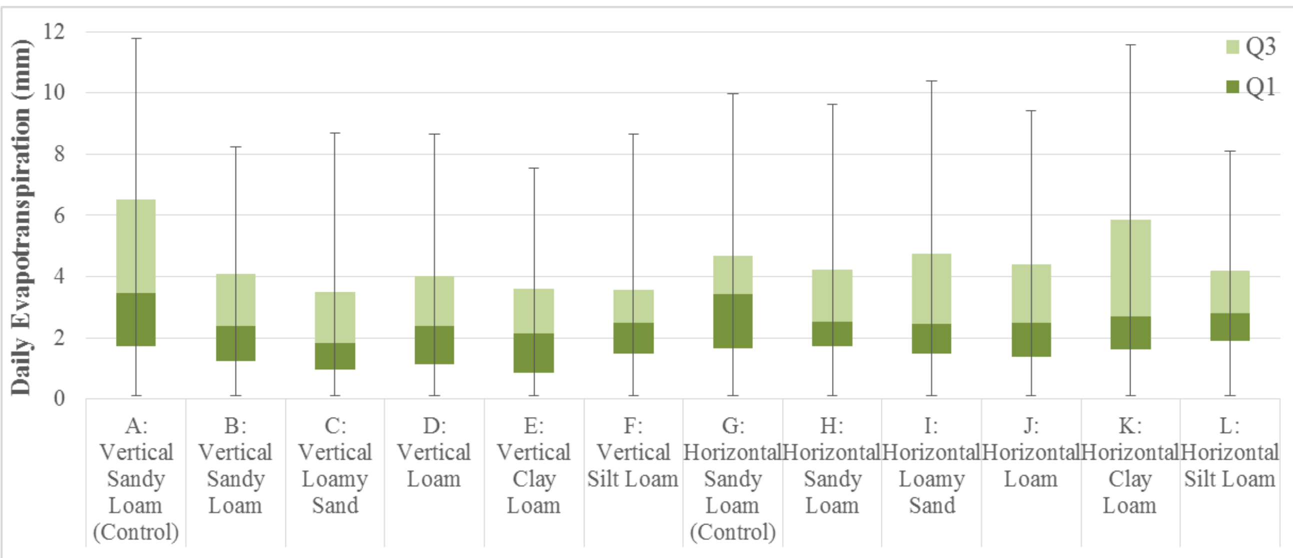

Figure 38: Spring 2016 Daily Evapotranspiration Rates

In contrast to the fall season, the controls saw noticeable higher daily ET rates than the other lysimeters because of the mass amount of ponding that occurred in them. Over the course of this study no ponding occurred in any lysimeters after about 12-24 hours after a storm event, except for the controls. The horizontal control would have ponded water for about 2 to 3 days after a storm simulation event while the vertical control would be ponded for up to a week after a storm simulation. Since the vertical control experienced ponded water for a longer period of time, daily evaporation rates were much higher than the horizontal control. The ponded water in the non-vegetated lysimeters shows the role vegetation plays in opening up void space for infiltration and potentially ET. Even though the Switchgrass is not yet visible in the spring, the roots were increasing the infiltration capacity in all of the vegetated lysimeters.

Other than the control lysimeters, ET rates were all significantly similar among the different soil types and flow configurations, meaning evaporation rate was not much affected by soil type or flow configuration in the spring. The only soil to experience higher ET in the spring would be the horizontal clay loam which possibly retained more ponded water during a simulation event. In general, median ET rates for spring ranged between 1 and 3 mm/day, noticeably less than that of the fall. Because of the lack of vegetation, daily ET rates were not significantly different between any media in either configuration, besides from the vertical control (Table 25).

Table 25: Statistical T-Test Comparison of Mean Daily ET Values among Different Soil Types for Spring 2016 (n=48)

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.014	0.005	0.017	0.001	0.006
Statistically different?			YES	YES	YES	YES	YES
p-value	**B**			0.526	0.944	0.189	0.729
Statistically different?				NO	NO	NO	NO
p-value	**C**				0.492	0.609	0.731
Statistically different?					NO	NO	NO
p-value	**D**					0.174	0.680
Statistically different?						NO	NO
p-value	**E**						0.316
Statistically different?							NO
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.703	0.703	0.445	0.796	0.569
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.998	0.721	0.544	0.879
Statistically different?				NO	NO	NO	NO
p-value	**I**				0.726	0.545	0.883
Statistically different?					NO	NO	NO
p-value	**J**					0.291	0.819
Statistically different?						NO	NO
p-value	**K**						0.428
Statistically different?							NO

4.1.2.3 Summer 2016

During the summer months from June to August, the lysimeters exhibited noticeably higher ET rates in all soil types and all flow configurations. This is expected due to the plant data presented in Section 4.1.1.2 as well as the average temperature data. Average median ET rates ranged from 4 to 6 mm/day in the vertical configuration and from 3 to 4 mm/day in the horizontal configuration (Figure 39). The range of ET rates was also much higher, reaching a maximum of 11 mm/day in the vertical configuration and 9 mm/day in the horizontal configuration.

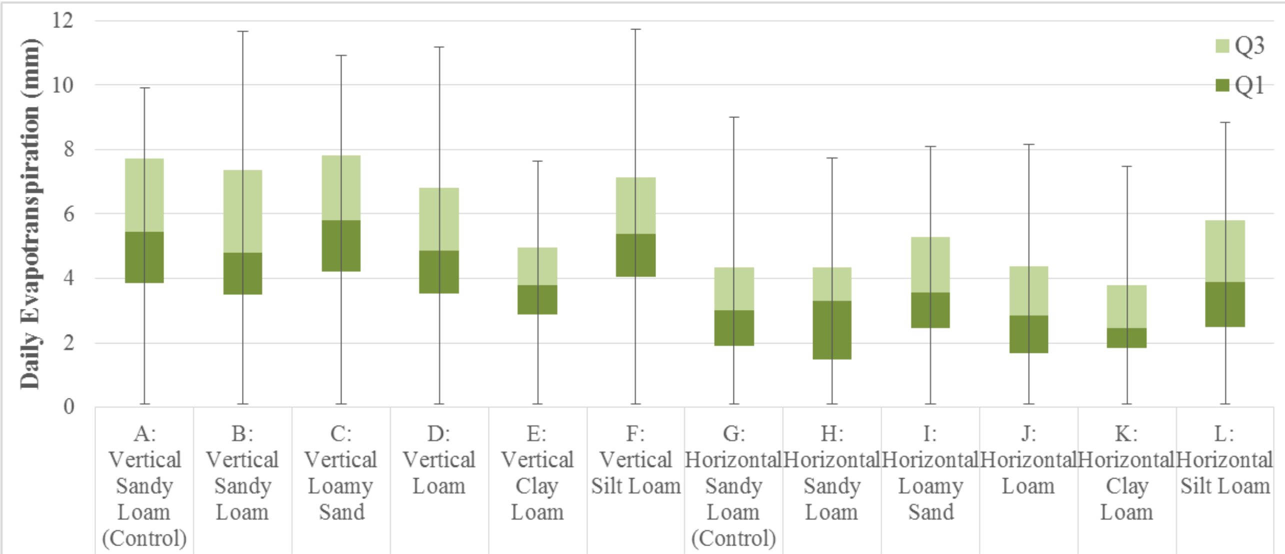

Figure 39: Summer 2016 Daily Evapotranspiration Rates

In the vertical flow configuration, daily ET rates were statistically similar among all soil types except for the clay loam (Table 26). Although it was expected the clay loam would have one of the higher ET rates based on the plant available water, in both configurations the clay loam had the lowest ET rates. This could be due to the presence of macropores in the clay soil resulting in a large volume of water to infiltrate leaving less stored water for ET. In the horizontal configuration, this is mostly likely because the Switchgrass had to be re-planted and was much less matured. As exhibited by the deconstruction of the horizontal lysimeters, it is also possible the clay loam was too fine to support vegetation.

In both flow configurations, the control lysimeters once again experienced what seems like high ET, but is really just a lot of evaporation due to the presence of ponded water. In both configurations the loamy sand and the silt loam displayed the highest daily ET rates. This makes sense for the silt loam which has the highest plant available water (33%), but is somewhat surprising for the loamy sand which has a very low plant available water (9%). The higher ET rates in these two soil types can be related back to the leaf count, which was the highest in the loamy sand and silt loam. From a statistical perspective, the horizontal loamy sand had higher ET rates than the loam and clay loam, and the silt loam had higher daily ET rates in the summer than all other media besides the loamy sand (Table 26). Despite all media seeing an increase in daily ET rates in the summer, the silt loam still saw the highest or second highest in both flow configurations.

Table 26: Statistical T-Test Comparison of Mean Daily ET Values among Different Soil Types for Summer 2016 (n= 60)

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.788	0.441	0.172	0.000	0.705
Statistically different?	**A**		NO	NO	NO	YES	NO
p-value	**B**			0.334	0.319	0.000	0.931
Statistically different?	**B**			NO	NO	YES	NO
p-value	**C**				0.039	0.000	0.267
Statistically different?	**C**				YES	YES	NO
p-value	**D**					0.011	0.339
Statistically different?	**D**					YES	NO
p-value	**E**						0.000
Statistically different?	**E**						YES
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.999	0.155	0.656	0.250	0.017
Statistically different?	**G**		NO	NO	NO	NO	YES
p-value	**H**			0.149	0.653	0.244	0.016
Statistically different?	**H**			NO	NO	NO	YES
p-value	**I**				0.062	0.009	0.281
Statistically different?	**I**				YES	YES	NO
p-value	**J**					0.495	0.005
Statistically different?	**J**					NO	YES
p-value	**K**						0.000
Statistically different?	**K**						YES

4.1.2.4 Fall 2016

Collecting data over two fall seasons was beneficial to see how the lysimeters behaved from one year to the next. As expected, the daily ET rates in the fall of 2016 decreased from the summer time as the Switchgrass began to die; but daily ET rates in the vertical configuration were higher than the previous fall season. Since the Switchgrass was transplanted in 2015, it is expected than the plants experienced more stress in 2015 and were not able to transpire as much water. Since the plants were able to grow back naturally in 2016 after the winter, they were healthier resulting in slightly higher ET rates (Figure 40).

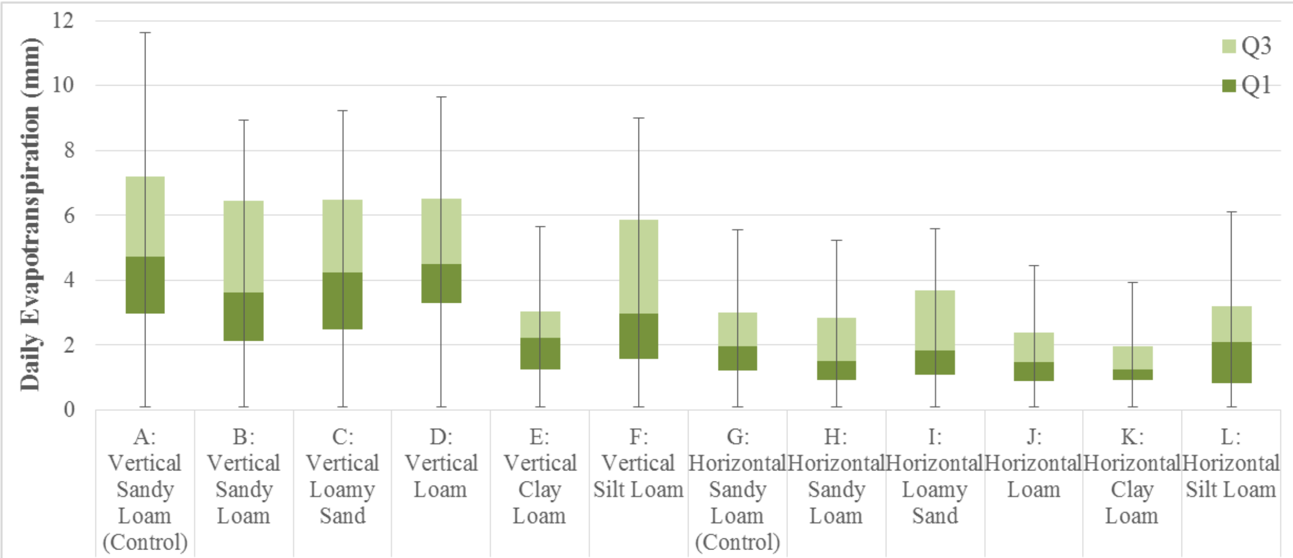

Figure 40: Fall 2016 Daily Evapotranspiration Rates

In the vertical configuration, the clay loam ET was significantly lower than the other media which can be related to the number of leaves (Figure 31, Table 27). It was expected that the clay loam would produce healthier vegetation, but the Switchgrass did not grow as well in the clay loam in both configurations. This could be due to one of three things. One could be the type of clay, kaolinite, used in this study. Another explanation could be that the soil was too fine so that too much water was retained, causing the media to drown the Switchgrass. The final and most likely explanation was that the clay loam soil contained macropores causing the water to infiltrate very quickly, leaving less water available for the plants.

Clay soils are prone to the formation of macropores due to desiccation cracking, and the ET and outflow data is suggestive of this phenomenon. Cracks form in clay soils when the soils are restrained while undergoing volume changes due to soil suction generated in the drying soil matrix (Kodikara et al. 2000). Desiccation cracking of clay soils and inter-clod macropore structure have a significant impact on hydraulic performance of soils in the field (Benson and Daniel 1990; Kodikara et al. 2000). In situ hydraulic conductivity of clays can be significantly up to six orders of magnitude higher in the field than laboratory hydraulic conductivity values. The fate of clods and inter-clod pores in clays are also very much affected by initial dry unit weight, with lower dry unit weights associated with large voids between particles in which water will flow, as opposed to between the clay particles themselves (Benson and Daniel 1990). Because the clay loam soil was added to the lysimeters dry, it makes sense that the soil formed large macropores. While breaking up clods in clay samples can eliminate this phenomenon, this is not feasible in these systems, and it is hypothesized that soils with too high of a clay content will form macropores and therefore are not a good media choice for bioretention SCMs.

Compared to the other three seasons, the vertical silt loam did not have the highest daily ET rates during fall 2016, and actually had significantly lower ET rates than the loam (Table 27). Over the course of the growing season, the Switchgrass in the silt loam matured faster than those in the other media and also died a little sooner, leading to a little less ET in the fall. In the horizontal configuration for fall 2016, daily ET rates were much lower across all media, but significantly lower in the loam and clay loam (Table 27).

Table 27: Statistical T-Test Comparison of Mean Daily ET Values among Different Soil Types for Fall 2016 (n= 42)

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.147	0.175	0.544	0.000	0.021
Statistically different?			NO	NO	NO	YES	YES
p-value	**B**			0.895	0.345	0.000	0.317
Statistically different?				NO	NO	YES	NO
p-value	**C**				0.405	0.000	0.251
Statistically different?					NO	YES	NO
p-value	**D**					0.000	0.056
Statistically different?						YES	YES
p-value	**E**						0.003
Statistically different?							YES
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.153	0.979	0.018	0.001	0.440
Statistically different?			NO	NO	YES	YES	NO
p-value	**H**			0.194	0.324	0.034	0.564
Statistically different?				NO	NO	YES	NO
p-value	**I**				0.032	0.002	0.484
Statistically different?					YES	YES	NO
p-value	**J**					0.227	0.143
Statistically different?						NO	NO
p-value	**K**						0.015
Statistically different?							YES

4.1.2.5 All Seasons

The average ET rates were compiled for all seasons besides fall 2016 (Figure 41). Fall 2016 was not included because the plot is meant to represent a typical year averaging data from the fall, summer, and spring seasons. 2015 data was used over 2016 data for the fall season since more storm simulations were performed in 2015, but using either fall season did not change the results substantially.

The range of ET rates over the course of one year is much more spread out. The vertical lysimeters have an average daily ET rate of 3 mm/day and the horizontal lysimeters have an average of 2 mm/day. These measured ET rates are consistent with typical ET rates observed by Switchgrass during the active growing season of 3-4 mm/day (Wagle 2014).

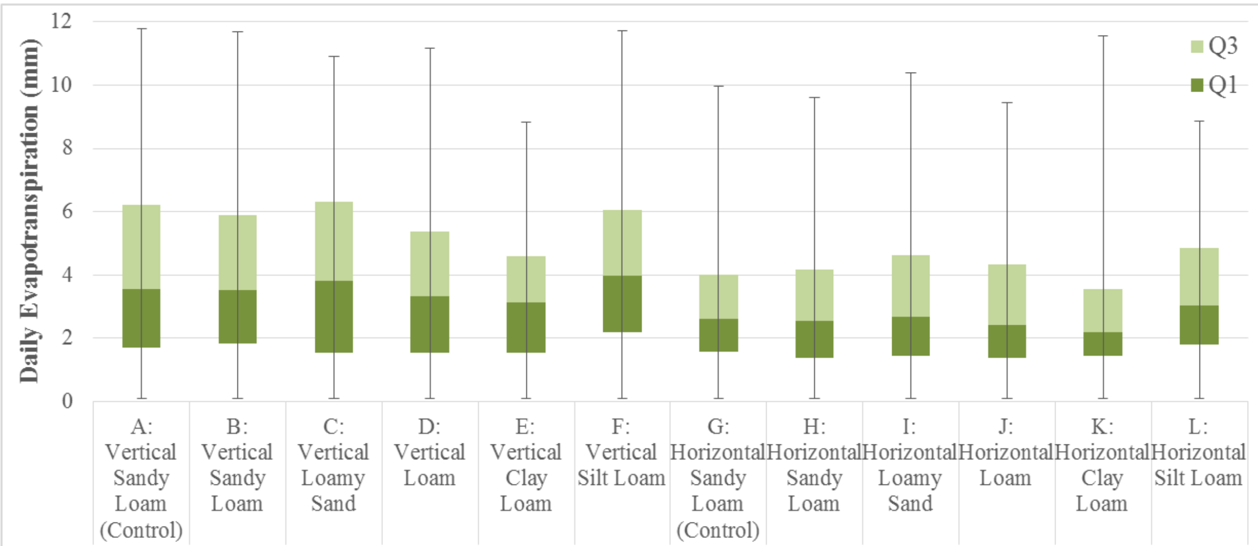

Figure 41: Daily Evapotranspiration Rates for All Seasons

Over the course of the year the silt loam had the highest daily ET rates in both flow configurations which supports the SWCC data that the silt loam would have the most plant available water. Regardless of the amount of water supplied to the system and the flow configuration, the silt loam still was able to produce the highest ET rates.

While the controls look to produce the same amount of ET as the other lysimeters over the course of the year, this is really all evaporation since lysimeters ‘A’ and ‘G’ contain no vegetation. The observed ponding in the control lysimeters supports the case for vegetated stormwater control measures. Not only does the vegetation remove a lot of water volume through ET, but the presence of vegetation also increases the infiltration capacity in the media by opening up more void space.

Based on this study, daily ET rates in the vertical lysimeters were not affected by media type over the course of one typical year, except for the clay loam which experienced significantly lower ET rates due to macropores (Table 28). In the horizontal configuration daily ET rates were much more varied among media over the course of the three seasons. The horizontal silt loam had significantly higher ET rates than all other horizontal media, except for the loamy sand; and the clay loam had significantly lower ET rates than the control, loamy sand, and silt loam (Table 28).

Table 28: Statistical T-Test Comparison of Mean Daily ET Values among Different Soil Types for All Seasons (n= 158)

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.278	0.677	0.162	0.000	0.402
Statistically different?			NO	NO	NO	YES	NO
p-value	**B**			0.520	0.758	0.000	0.402
Statistically different?				NO	NO	YES	NO
p-value	**C**				0.344	0.000	0.690
Statistically different?					NO	YES	NO
p-value	**D**					0.000	0.570
Statistically different?						YES	NO
p-value	**E**						0.000
Statistically different?							YES
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.485	0.453	0.305	0.085	0.063
Statistically different?						YES	YES
p-value	**H**			0.157	0.743	0.294	0.012
Statistically different?				NO	NO	NO	YES
p-value	**I**				0.085	0.018	0.284
Statistically different?					YES	YES	NO
p-value	**J**					0.466	0.005
Statistically different?							YES
p-value	**K**						0.001
Statistically different?							YES

4.1.3 Volume Removal: Infiltration and ET Balance on a Seasonal Basis

To better understand the distribution between infiltration and ET in vegetated stormwater control measures, the total volume removal through the two mechanisms was calculated on a seasonal basis. Tables 29 through 33 display the water balance (Equation 2) for each season that was analyzed in terms of the total inflow, total infiltration, total ET, and total water storage. Based on these volumes the total volume removal, volume removal through ET, and volume removal through infiltration was calculated.

For each season, the inflow for all vertical lysimeters should be equal, and the inflow for all horizontal lysimeters should be equal. The inflow is the combination of natural precipitation and simulated runoff over the course of the entire season. If inflow totals in one lysimeter differ slightly from the others, observed water losses in the system were manually subtracted from the seasonal totals. For example, if one of the pumps was observed to be leaking for a certain time period, this lost volume was subtracted from the total inflow over the season. Any differences in inflow among lysimeters are minor, and for the most part inflow is equal within each configuration.

The total volume removal represents the volume of water that left the lysimeters through ET and deep infiltration over the entire season. The volume not removed is equal to the volume that is cumulatively stored in the soil media over the course of each season. With the exception of the controls, none of the lysimeters experienced any overflow during the study, meaning all lysimeters were able to handle the amount of water supplied to them. The total volume removal should not be mistaken as the percentage of water the lysimeters were able to treat, because all lysimeters, besides the controls, were able to treat 100% of the water that was applied to them such that there was no overflow. The volume removal percentage indicates how much water left each lysimeter over the season versus how much was stored in the media.

4.1.3.1 Fall 2015

The fall 2015 volume removal data includes events that occurred between 8/24/2015 and 11/6/2015 including five storm simulations (Table 29). Over the season the vertical lysimeters received about 800 mm of water and the horizontal lysimeters received about 600 mm of water. The total volume removal through both flow configurations ranged from 31% to 86%. The vertical configuration experienced higher total volume removal, i.e. less water storage, ranging from 61% in the silt loam to 86% in the loamy sand. The volume removal in the horizontal flow configuration ranged from 31% in the clay loam to 85% in the control. Since the volume of media is greater in the horizontal configuration, less water was leaving the system between events, and more was being stored within the media because of the longer hydraulic retention time and greater available pore volume.

Table 29: Water Balance in the Vertical and Horizontal Lysimeters for Fall 2015

Soil Media	Sandy Loam (Control)	Sandy Loam	Loamy Sand	Loam	Clay Loam	Silt Loam
Vertical Lysimeters						
Lysimeter	**A**	**B**	**C**	**D**	**E**	**F**
Average Daily ET (mm)	2.10	3.41	3.63	3.03	3.10	4.26
Total Inflow (mm)	614.00	814.53	814.53	814.53	814.53	814.53
Total ET (mm)	111.16	182.02	176.15	162.19	160.80	220.41
Total Infiltration (mm)	338.13	469.30	525.85	418.58	359.70	275.75
Total Volume Removal (mm)	449.29	651.33	702.00	580.78	520.50	496.16
Total Water Storage (mm)	164.70	163.20	112.52	233.75	294.02	318.36
Total Volume Removal (%)	73	80	86	71	64	61
ET Removal (%)	25	28	25	28	31	44
Infiltration Removal (%)	75	72	75	72	69	56
Total Water Storage (%)	27	20	14	29	36	39
Horizontal Lysimeters						
Lysimeter	**G**	**H**	**I**	**J**	**K**	**L**
Average Daily ET (mm)	2.63	2.52	2.43	2.63	1.96	3.40
Total Inflow (mm)	593.66	593.66	593.66	593.66	593.66	593.66
Total ET (mm)	143.09	132.32	128.20	143.11	101.30	176.16
Total Infiltration (mm)	360.93	319.56	117.07	134.21	81.73	270.70
Total Volume Removal (mm)	504.02	451.88	245.28	277.32	183.03	446.85
Total Water Storage (mm)	89.64	141.78	348.38	316.34	410.63	146.81
Total Volume Removal (%)	85	76	41	47	31	75
ET Removal (%)	28	29	52	52	55	39
Infiltration Removal (%)	72	71	48	48	45	61
Total Water Storage (%)	15	24	59	53	69	25

Within both flow configurations, the silt loam soil produced the highest ET rates of 4.26 mm/d and 3.40 mm/d in the vertical and horizontal lysimeters, respectively. In the vertical configuration the sandy loam, a typical rain garden soil, saw 19% more total volume removal than the silt loam. Only 28% of the total volume removal in the sandy loam was through ET, whereas 44% can be attributed to ET in the silt loam. In the horizontal configuration, the silt loam and sandy loam saw the same total volume removal (75% and 76%), but the silt loam removed 10% more of that volume through ET.

It is interesting that the silt loam, despite having the highest ET rates in both configurations, had the lowest percent volume removal in the vertical configuration (61%) but one of the highest in the horizontal configuration (75%). In the vertical configuration, 56% of the volume removal was due to infiltration, but in the horizontal configuration 61% was due to infiltration, resulting in a much higher total volume removal. This comparison shows how altering the flow depth and volume of soil can aid or hinder the two removal mechanisms.

In the horizontal lysimeters, the loam, clay loam, and loamy sand experienced the lowest total volume removal, under 50%. It makes sense that the loam and clay loam, which contain finer grained soils, stored more water within the media. This amount of storage did not occur in the vertical configuration because flow was limited to the vertical direction, whereas in the horizontal configuration gravity did not play as large of a role in the infiltration removal. The loamy sand, the coarsest soil, saw a lot of water storage (59%) in the horizontal configuration, therefore the flow path dictated the storage more than the soil properties.

Another way to look at the distribution between infiltration and ET as it relates to total volume removal is in graphical form (Figure 42). This graph shows the percentage of volume removal in all lysimeters. The vertical configuration is represented by the lighter bars on the left and the horizontal configuration is represented by the darker bars on the right. The bottom, purple half of the bars shows the distribution of total water removal through infiltration, and the top, green half represents the total removal through ET

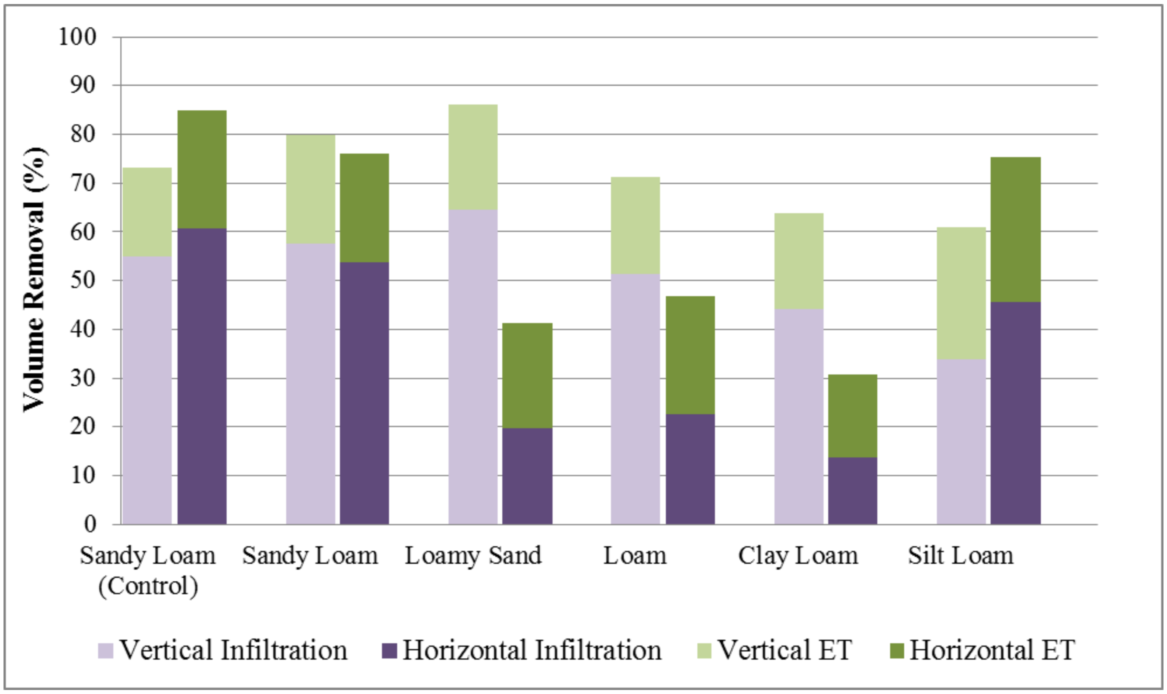

Figure 42: Volume Removal Balance through Infiltration and ET for Fall 2015

For most of the lysimeters, the distribution percentages (Figure 42) between infiltration and ET is roughly 75/25, respectively, but the distribution tends to move more towards 70/30 for the soils with more fine particles (loam and clay loam), and even closer to a 50/50 distribution for the silt loam. This trend is even more pronounced within the horizontal configuration. For the finer grained soils, the percentage of ET removal is equal to, if not greater, than the removal through infiltration. Although the soils with more fines exhibit slightly less volume removal in total, these soils may be desirable for a site where vertical infiltration is limited and enhancement of ET is the design goal.

4.1.3.2 Spring 2016

The data for the spring season were collected between 3/8/2016 and 5/31/2016 and included five storm simulations. It should be noted that the vegetation did not grow back until the very end of the spring season explaining why the daily ET rates are much lower than the fall. The total inflow was about 950 mm in the vertical configuration, and about 550 mm in the horizontal configuration, slightly more than the fall season. Unlike the fall season, daily ET rates were higher in the horizontal configuration than in the vertical configuration (Table 30). Since the Switchgrass grew back sooner in the horizontal lysimeters, they saw higher ET rates on a seasonal scale. Within each configuration, the daily ET rates did not vary much among soil type. This is because the majority of ET was in the form of evaporation, showing that the type of soil does not play a large role in the evaporation process. As seen with the graphs in the previous section, the highest ET rate was exhibited by the vertical control, producing an average of 1.68 mm more ET per day than its vegetated counterpart, due to the large volume of ponded water.

Table 30: Water Balance in the Vertical and Horizontal Lysimeters for Spring 2016

Soil Media	Sandy Loam (Control)	Sandy Loam	Loamy Sand	Loam	Clay Loam	Silt Loam
Vertical Lysimeters						
Lysimeter	**A**	**B**	**C**	**D**	**E**	**F**
Average Daily ET (mm)	4.55	2.87	2.36	2.97	2.44	3.05
Total Inflow (mm)	954.56	578.62	954.56	954.56	954.56	954.56
Total ET (mm)	228.01	123.80	86.73	131.92	105.35	140.05
Total Infiltration (mm)	328.80	418.00	848.83	544.51	529.35	540.43
Total Volume Removal (mm)	556.81	541.80	935.56	676.43	634.70	680.48
Total Water Storage (mm)	397.75	36.82	19.01	278.13	319.86	274.08
Total Volume Removal (%)	58	94	98	71	66	71
ET Removal (%)	41	23	9	20	17	21
Infiltration Removal (%)	59	77	91	80	83	79
Total Water Storage (%)	42	6	2	29	34	29
Horizontal Lysimeters						
Lysimeter	**G**	**H**	**I**	**J**	**K**	**L**
Average Daily ET (mm)	3.74	3.44	3.49	3.23	3.76	3.76
Total Inflow (mm)	578.36	445.12	527.56	361.81	527.56	527.56
Total ET (mm)	176.69	164.41	182.50	149.17	201.52	176.96
Total Infiltration (mm)	287.90	263.40	250.35	202.76	73.90	218.28
Total Volume Removal (mm)	464.59	427.81	432.85	351.93	275.42	395.24
Total Water Storage (mm)	113.78	17.31	94.71	9.88	252.14	132.32
Total Volume Removal (%)	80	96	82	97	52	75
ET Removal (%)	38	38	42	42	73	45
Infiltration Removal (%)	62	62	58	58	27	55
Total Water Storage (%)	20	4	18	3	48	25

Total volume removal in the vertical lysimeters ranged between 66% in the clay loam and 98% in the loamy sand, not including the controls. In the horizontal configuration, volume removal ranged between 52% in the clay loam and 97% in the loam. With the exception of the loamy sand and loam, the percent removal in each soil type was very similar between the two flow configurations. The vertical loamy sand experienced more volume removal and much less cumulative storage than the horizontal counterpart, which was expected due to the nature of the flow. On the contrary, the loam soil actually experienced more volume removal (less storage) in the horizontal configuration. The sandy loam, loam and silt loam removed more water in the horizontal configuration while the loamy sand and clay loam removed more in the vertical configuration.

For the spring season, especially in the vertical configuration, volume removal was dominated by infiltration (Figure 43). In the vertical loamy sand about 90% of the volume was removed through infiltration. In all other vertical soils about 75-85% of the volume was removed through infiltration, even for the finer grained soils that showed much more removal through ET in the fall.

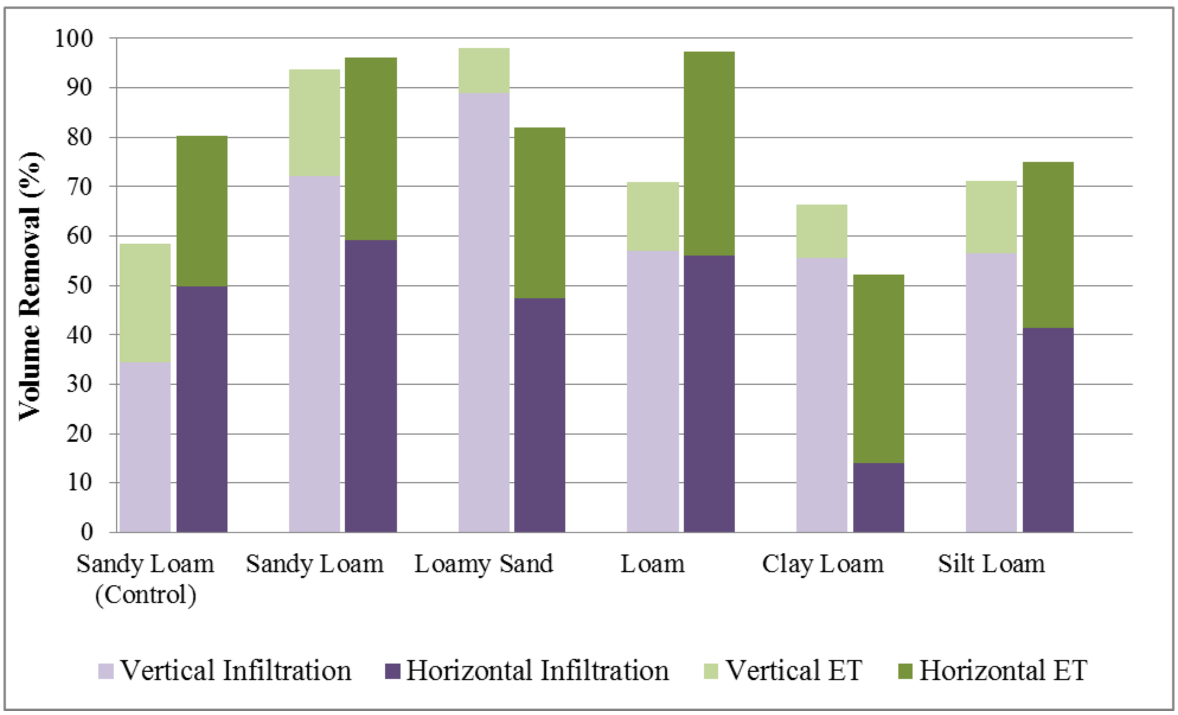

Figure 43: Volume Removal Balance through Infiltration and ET for Spring 2016

In the horizontal configuration distribution between infiltration and ET was much closer, with ET playing a larger role than in the vertical systems. This may be because the vegetation grew back sooner resulting in more ET at the end of the season. Also, the longer hydraulic retention time in the horizontal configuration resulted in more water stored within the media, making more available through ET. As discussed previously, spring was the wettest season containing the longest duration events and shortest antecedent dry time between events. Although the vegetation may have been in its early stages, the weather patterns still provided a lot of water availability to the Switchgrass. Even the coarser grained soils (sandy loam, loamy sand, and loam) saw about a 60/40 distribution between infiltration and ET. The silt loam saw a 50/50 distribution between the two volume removal mechanisms, showing that even with less developed vegetation, silt loam still provides the most water for transpiration. Surprisingly, the clay loam in the horizontal configuration removed 73% of the total volume through ET. Since the Switchgrass did not grow back well in this lysimeter, it is hypothesized that the clay loam acted as a non-vegetated system, retaining a lot of water at the surface for evaporation.

4.1.3.3 Summer 2016

The data from the summer were collected between 6/1/2016 and 8/26/2016 and included five storm simulations. The total inflow to the vertical and horizontal lysimeters was about 1000 mm and 600 mm, respectively, more than the fall and spring seasons. The quantity data from summer 2016 exhibits the maximum volume removal potential through evapotranspiration. The combination of the healthy Switchgrass and the summer temperatures allowed for ET rates to be maximized. Average daily ET rates ranged from 4.02 to 5.93 mm/day in the vertical lysimeters and 3.30 to 4.25 mm/day in the horizontal lysimeters, with much higher maximum values.

The total volume removal is comparable between the two flow configurations, unlike the other seasons where one configuration was consistently higher, or it varied from soil type to soil type. If anything, the horizontal configuration sees slightly more volume removal than the vertical configuration. Since the vertical lysimeters favor infiltration and the horizontal lysimeters favor ET, it is evident that ET plays a large role in the summer time, exhibited by more volume removal in the horizontal configuration (Table 31).

Table 31: Water Balance in the Vertical and Horizontal Lysimeters for Summer 2016

Soil Media	Sandy Loam (Control)	Sandy Loam	Loamy Sand	Loam	Clay Loam	Silt Loam
Vertical Lysimeters						
Lysimeter	**A**	**B**	**C**	**D**	**E**	**F**
Average Daily ET (mm)	5.64	5.56	5.93	5.21	4.02	5.52
Total Inflow (mm)	1041.34	1041.34	1041.34	1041.34	1041.34	1041.34
Total ET (mm)	315.89	283.31	331.25	332.35	256.88	354.35
Total Infiltration (mm)	232.03	320.06	487.38	449.48	432.58	311.90
Total Volume Removal (mm)	547.91	603.37	818.63	781.83	689.46	666.25
Total Water Storage (mm)	493.43	437.97	222.71	259.51	351.88	375.10
Total Volume Removal (%)	53	58	79	75	66	64
ET Removal (%)	58	47	40	43	37	53
Infiltration Removal (%)	42	53	60	57	63	47
Total Water Storage (%)	47	42	21	25	34	36
Horizontal Lysimeters						
Lysimeter	**G**	**H**	**I**	**J**	**K**	**L**
Average Daily ET (mm)	3.48	3.33	3.86	3.30	3.23	4.25
Total Inflow (mm)	629.30	568.34	608.98	608.98	608.98	608.98
Total ET (mm)	247.82	219.70	259.22	252.27	223.76	265.19
Total Infiltration (mm)	275.85	216.28	173.24	246.47	224.91	187.02
Total Volume Removal (mm)	523.67	435.98	432.46	498.74	448.67	452.22
Total Water Storage (mm)	105.63	132.36	176.53	110.24	160.32	156.77
Total Volume Removal (%)	83	77	71	82	74	74
ET Removal (%)	47	50	60	51	50	59
Infiltration Removal (%)	53	50	40	49	50	41
Total Water Storage (%)	17	23	29	18	26	26

The total volume removal in the vertical lysimeters ranged between 53% (control) and 79% (loamy sand). The total volume removal in the sandy loam was less than expected, at only 58%.

The remainder of the volume was cumulatively stored in the media, but it is unclear why the vertical sandy loam stored so much compared to the other seasons. The loamy sand and loam had comparable volume removal at about 75%, both having a 60/40 distribution between infiltration and ET. While the silt loam only removed 64% of total volume, this is only about 6 inches less removed over course of the season compared to the loamy sand. The silt loam removed over half of the water through ET showing the capability of ET to remove more volume in the summer, even in a configuration that favors infiltration.

In the horizontal lysimeters volume removal ranged between 71% and 83% for the different soil types. In all lysimeters besides the control, the distribution between infiltration and ET was at least 50/50, meaning all of the soil types removed at least half of the water through ET (Figure 44). Both the loamy sand and silt loam had a distribution of about 40/60 of infiltration to ET. This distribution is not surprising for the silt loam, but is a little surprising for the loamy sand which is the coarsest mix. But, this does make sense according to the monthly leaf counts which show the loamy sand and silt loam having the most dense and tallest Switchgrass plants.

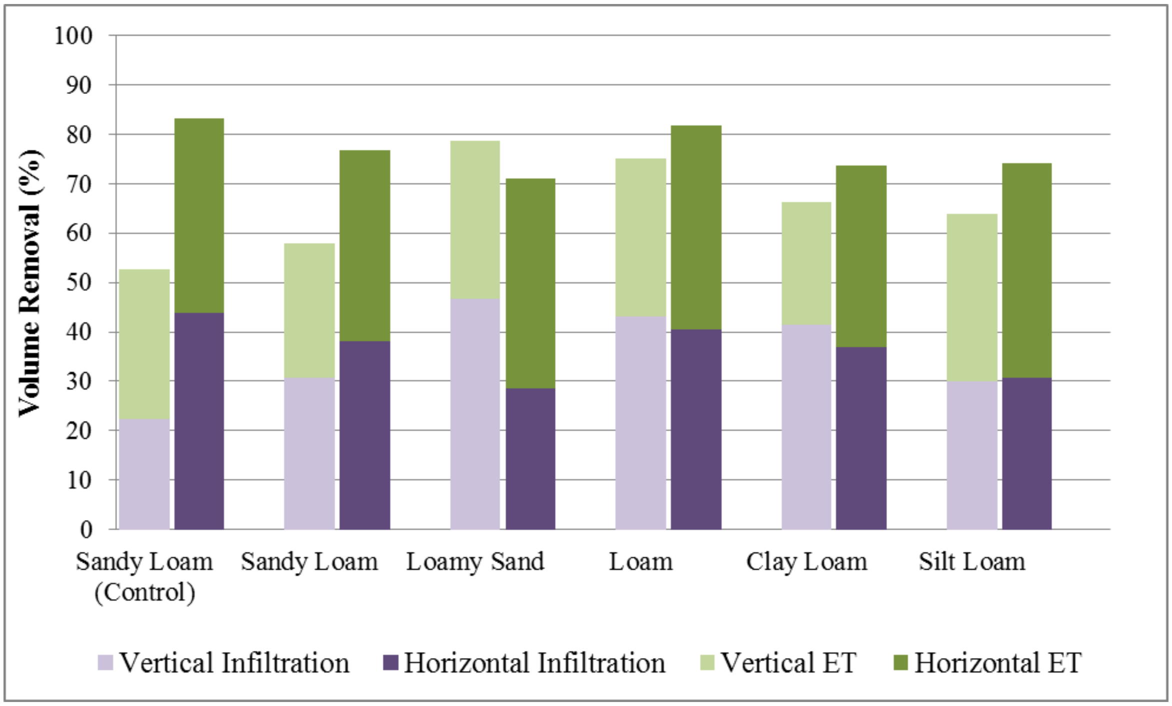

Figure 44: Volume Removal Balance through Infiltration and ET for Summer 2016

In the vertical lysimeters, which favor infiltration, the distribution between infiltration and ET ranged from 60/40 to 50/50. This distribution in the horizontal lysimeters, with the shallower media depth, ranged from 50/50 to 40/60. Despite the horizontal lysimeters providing more storage volume in general, the shallower media depth allows the Switchgrass roots to have access to more of the water between storm events leading to more ET removal between events. At sites where vertical infiltration is limited, creating a longer hydraulic retention time in the media and using a soil like a silt loam can enhance the effects of ET.

4.1.3.4 Fall 2016

The last season tested in this study was the fall of 2016. The data from this season was collected from 8/27/2016 to 11/4/2016 and contained five storm simulations. Inflow was about 900 mm in the vertical lysimeters and about 500 mm in the horizontal lysimeters, which is comparable with the previous fall season as well as the spring season (Table 32).

Table 32: Water Balance in the Vertical and Horizontal Lysimeters for Fall 2016

Soil Media	**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Vertical Lysimeters						
Lysimeter	**A**	**B**	**C**	**D**	**E**	**F**
Average Daily ET (mm)	4.92	4.18	4.25	4.96	2.86	3.61
Total Inflow (mm)	882.61	882.61	882.61	882.61	882.61	882.61
Total ET (mm)	206.25	170.99	165.12	150.97	96.34	132.05
Total Infiltration (mm)	235.53	253.60	315.98	216.87	300.24	295.57
Total Volume Removal (mm)	441.78	424.59	481.10	367.84	396.58	427.62
Total Water Storage (mm)	440.83	458.02	401.52	514.77	486.04	454.99
Total Volume Removal (%)	50	48	55	42	45	48
ET Removal (%)	47	40	34	41	24	31
Infiltration Removal (%)	53	60	66	59	76	69
Total Water Storage (%)	50	52	45	58	55	52
Horizontal Lysimeters						
Lysimeter	**G**	**H**	**I**	**J**	**K**	**L**
Average Daily ET (mm)	2.24	2.11	2.68	1.98	1.85	2.21
Total Inflow (mm)	469.70	469.70	469.70	469.70	469.70	469.70
Total ET (mm)	95.71	81.04	126.26	87.04	68.69	83.78
Total Infiltration (mm)	151.95	178.93	200.41	175.31	122.76	163.86
Total Volume Removal (mm)	247.66	259.97	326.67	262.35	191.46	247.65
Total Water Storage (mm)	222.04	209.73	143.03	207.34	278.24	222.05
Total Volume Removal (%)	53	55	70	56	41	53
ET Removal (%)	39	31	39	33	36	34
Infiltration Removal (%)	61	69	61	67	64	66
Total Water Storage (%)	47	45	30	44	59	47

For both flow configurations and all soil types, total volume removal was much less than other seasons, between 41% and 76%, meaning there was more water storage in the media between events. Fall 2016 had a greater number of rainfall events than fall 2015 and a shorter average antecedent dry time at 6 days compared to an average 8.5 days in 2015, which could explain the increase in water storage (Table 32). Water storage during this season could also be greater due to a buildup of water in the media over the course of the study. In fall 2015, all media began completely dry, but by fall 2016 the average residual water content was slightly higher.

In the vertical lysimeters volume removal ranged from 42% to 55%, 20% less on average than the previous fall. The coarser soils have about a 60/40 distribution between infiltration and ET, and the finer soils (silt loam and clay loam) have a 70/30 distribution (Figure 45). This is interesting because as the soils become finer the distribution should shift more towards ET, not infiltration, as it does during the other seasons. It is unclear why the finer vertical soils are experiencing so much more infiltration, but it is possibly due to the increase in macropores, those of which were visible in the clay loam.

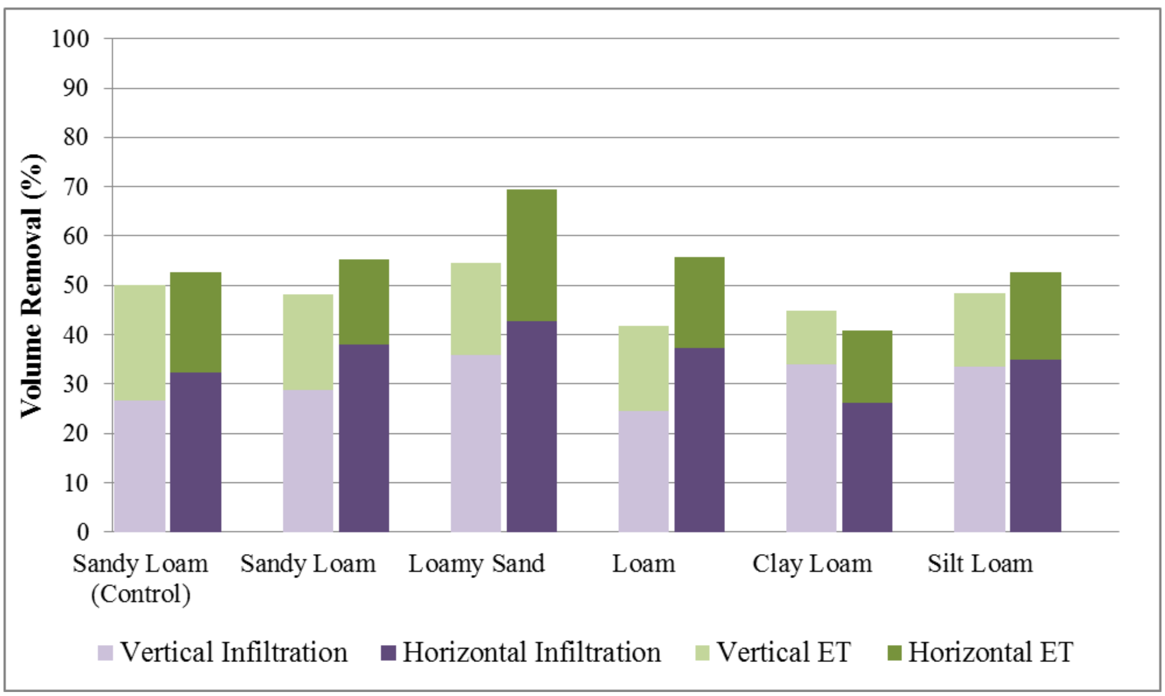

Figure 45: Volume Removal Balance through Infiltration and ET for Fall 2016

In the horizontal lysimeters, volume removal is slightly higher, ranging from 41% to 70%. Despite the increase in seasonal storage, the loamy sand had the highest volume removal and the clay loam had the lowest volume removal, the same trend as fall 2015. In the horizontal configuration all of the soils see a similar distribution of infiltration to ET of 60/40. Compared to fall 2015, there is very little variation between the infiltration/ET distributions among the different soil types.

4.1.3.5 All Seasons

The same table and chart was compiled for all seasons including fall 2015, spring 2016, and summer 2016 to gain a comprehensive view of infiltration and ET over the course of one year. Once again, fall 2016 was not included in this data so that the data would not be skewed towards multiple fall seasons. Also, as discussed previously, the fall 2015 data was more reliable than the fall 2016 data and included more storm simulation events.

Table 33: Water Balance in the Vertical and Horizontal Lysimeters for All Seasons

Soil Media	Sandy Loam (Control)	Sandy Loam	Loamy Sand	Loam	Clay Loam	Silt Loam
Vertical Lysimeters						
Lysimeter	**A**	**B**	**C**	**D**	**E**	**F**
Average Daily ET (mm)	4.10	3.94	3.97	3.74	3.18	4.27
Total Inflow (mm)	2609.90	2434.49	2810.43	2810.43	2810.43	2810.43
Total ET (mm)	655.05	589.14	594.13	626.46	523.03	714.81
Total Infiltration (mm)	898.97	1207.37	1862.06	1412.58	1321.63	1128.08
Total Volume Removal (mm)	1554.02	1796.50	2456.19	2039.04	1844.66	1842.89
Total Water Storage (mm)	1055.88	637.99	354.24	771.39	965.77	967.54
Total Volume Removal (%)	60	74	87	73	66	66
ET Removal (%)	42	33	24	31	28	39
Infiltration Removal (%)	58	67	76	69	72	61
Total Water Storage (%)	40	26	13	27	34	34
Horizontal Lysimeters						
Lysimeter	**G**	**H**	**I**	**J**	**K**	**L**
Average Daily ET (mm)	3.28	3.10	3.26	3.05	2.98	3.80
Total Inflow (mm)	1801.32	1607.12	1730.20	1564.45	1730.20	1730.20
Total ET (mm)	567.60	516.43	569.93	544.56	526.58	618.31
Total Infiltration (mm)	924.68	799.24	540.66	583.43	380.54	676.01
Total Volume Removal (mm)	1492.28	1315.67	1110.58	1127.99	907.12	1294.31
Total Water Storage (mm)	309.05	291.46	619.62	436.47	823.08	435.89
Total Volume Removal (%)	83	82	64	72	52	75
ET Removal (%)	38	39	51	48	58	48
Infiltration Removal (%)	62	61	49	52	42	52
Total Water Storage (%)	17	18	36	28	48	25

Within each flow configuration, the daily ET rates are similar among the different soil types, with major exceptions being the clay loam and the silt loam (Table 33). In both flow configurations the silt loam had the highest average daily ET rates. This makes sense since the silt loam was shown to have the highest plant available water and significantly higher ET rates in all seasons. In both configurations the clay loam had the lowest daily ET rates. It is hypothesized that the presence of macropores in the clay loam caused the water to infiltrate faster than it should have, leaving less water available for ET.

All lysimeters saw total volume removal between 52% and 87%. For the majority of the vertical lysimeters the distribution between infiltration and ET was around 70/30, except for the control and the silt loam where it leaned more towards 60/40. In the horizontal configuration, except for the control and sandy loam, the distribution of most soils was about 50/50 (Figure 46). Despite the individual seasons having varying performance between the two removal mechanisms, ET accounts for a good portion of the total volume removal over this given year. In the vertical configuration ET accounts for up to 42% of the total volume removed, and in the horizontal configuration ET accounts for up to 58% of the total volume removed, consistent with regional ET studies in Northeastern Unites States (Sanford and Selnick 2013).

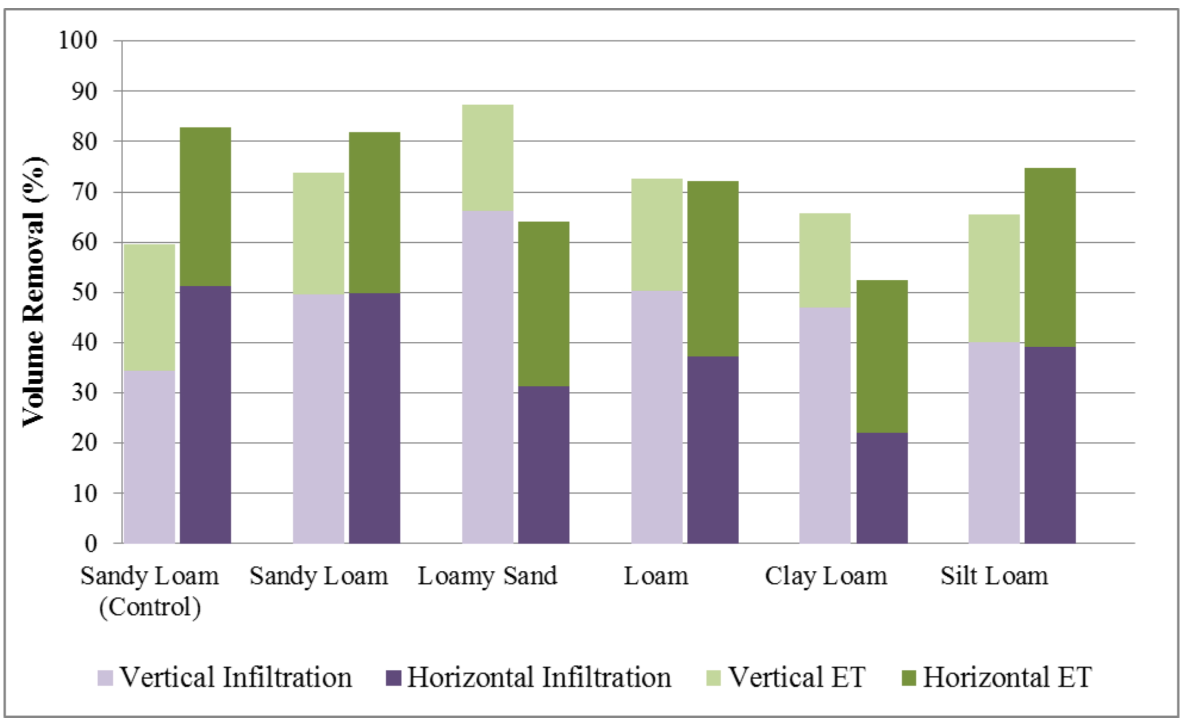

Figure 46: Volume Removal Balance through Infiltration and ET for All Seasons

Although media differs in how much they store, all media and configurations were successfully able to handle the 1.0 or 1.5 inch storm at the 5:1 loading ratio. This study indicates that the 5:1 loading ratio according to surface area underestimates the volume removal potential of these systems as has been shown with many other studies at Villanova University (Brown et al. 2009). Although it was not done in this study, it would be helpful to use the lysimeters to classify the maximum amount of water each soil type could handle before overflow occurs; which may also indicate if it is better to design these systems based on total soil volume rather than surface area.

Despite minor differences in total volume removal, the main difference in data between both configurations can be seen through the distribution between infiltration and ET. The horizontal configuration clearly favors ET, especially for soils with lower hydraulic conductivities. The vertical (1D) vs. horizontal (2D) configurations are really showing how a longer hydraulic retention favors more ET. In this study, the longer hydraulic retention time is achieved through the horizontal flow configuration, but this could be achieved through other means in an SCM. Making design modifications to vegetated SCMs to achieve a longer hydraulic retention time, therefore more ET, can be done by adding an underdrain with an upturned elbow, creating an internal water storage zone, or using a lower hydraulic conductivity soil. Such design modifications would be helpful for the implementation of rain gardens in areas where infiltration depth is limited or the underlying soils are poorly infiltrating.

4.1.4 Average Cumulative Infiltration and ET on an Event Basis

4.1.4.1 Fall 2015

Other than a seasonal mass balance, another beneficial way to look at the data is through the performance of infiltration and ET during the dry periods following a storm event. In this section two graphs are presented for each season, one for the vertical lysimeters, and one for the horizontal lysimeters. Each graph contains the daily cumulative volume of water infiltrated (mm) and daily cumulative volume of water evapotranspired (mm) following a storm simulation event. All data represents an average of all storm events over that particular season. It should also be noted that the scale for infiltration and ET is the same on each plot, but may differ between plots to show discrepancies between soil types, flow configurations, and seasons.

In all plots, the dashed lines with diamond markers represent the average cumulative infiltration following a storm simulation, and the solid lines with "X" markers represent the average cumulative ET following a storm simulation. Infiltration and ET data were only averaged for events with simulated runoff, not for natural rainfall events.

Figure 47 shows the average cumulative infiltration and ET volumes following all storm simulations in fall 2015. While the majority of infiltration occurred during the first two to three days following a storm simulation, the infiltration capacity reached a maximum about three days after the start of a rainfall event. While ET was negligible during the storm simulation and was slow to accumulate during the first few days, the cumulative volume removal through ET steadily increased until the next storm simulation.

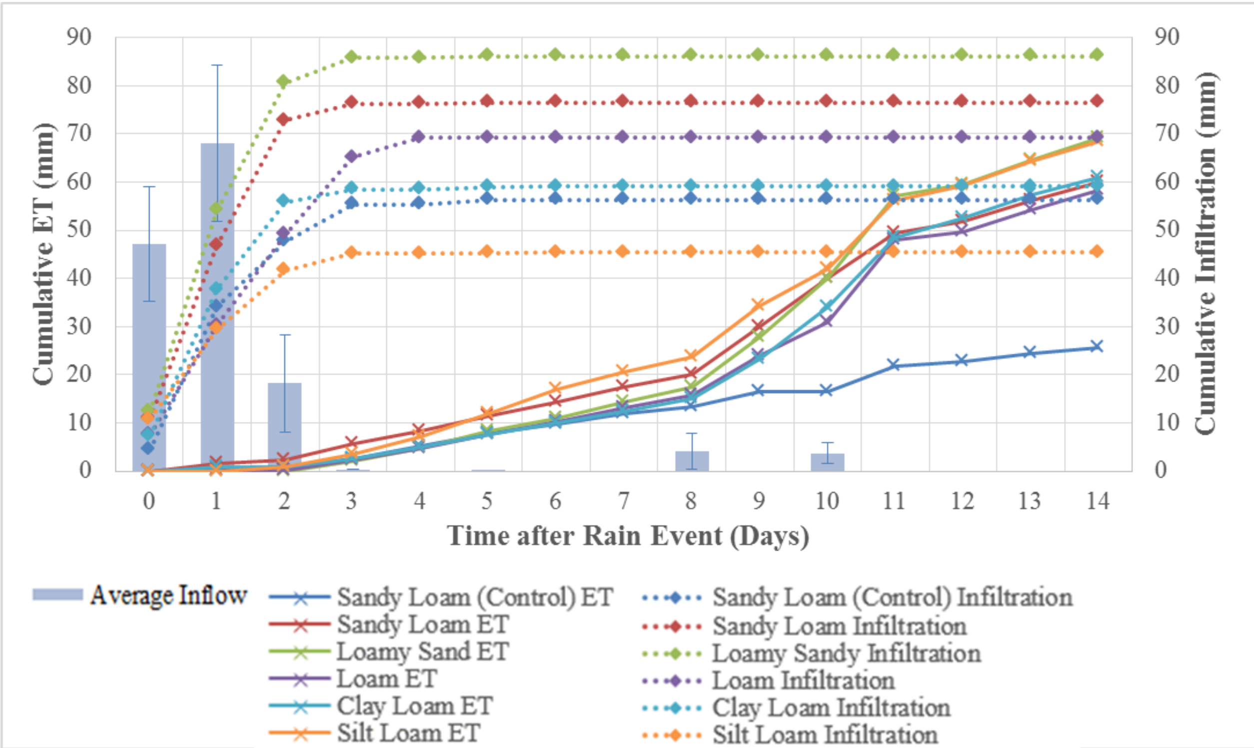

Figure 47: Fall 2015 Average Cumulative Infiltration and ET following Storm Simulations in the Vertical Lysimeters (n=6)

Differences in infiltration capacity can be seen among the different soil types. As expected, the loamy sand, the coarsest soil, had the highest infiltration capacity, followed by the sandy loam soil. The sandy loamy control had a much lower total infiltration capacity compared to its vegetated counterpart illustrating how vegetation also increases infiltration capacity. The loam had the next highest infiltration capacity followed by the clay loam and then the silt loam. The clay loam should have a lower infiltration capacity than the silt loam based on the saturated hydraulic conductivity, but as discussed, it is expected that the clay loam had some macropores increasing the total infiltration capacity. Aside from the clay loam, the cumulative infiltration capacity after a storm event can be directly related to the saturated hydraulic conductivity and SWCC data.

Cumulative ET is fairly comparable among soils for the first week or so and then there seems to be some separation based on soils with higher daily ET rates. The vertical control experienced much less ET due to the lack of vegetation. The silt loam experienced the most ET, closely followed by the loamy sand. It is a little surprising that the loamy sand produced as much cumulative ET as the silt loam, but silt loam ET surpassed the silt loam infiltration while the loamy sand ET did not come close to reaching the loamy sand infiltration capacity. The clay loam and silt loam, the two fine grained soils, had cumulative ET totals that surpass the cumulative infiltration totals. It should be noted that the cumulative effects of ET only surpassed those of infiltration providing sufficient dry time after a storm event. In the case of the silt loam, it took about 10 days for the ET volume to reach the infiltration volume, but took up to 14 days for the clay loam.

In the horizontal configuration, the same general trends in infiltration and ET can be seen for fall of 2015; but ET plays a larger role in volume removal, and cumulative removal through infiltration is much lower in many of the soils (Figure 48).

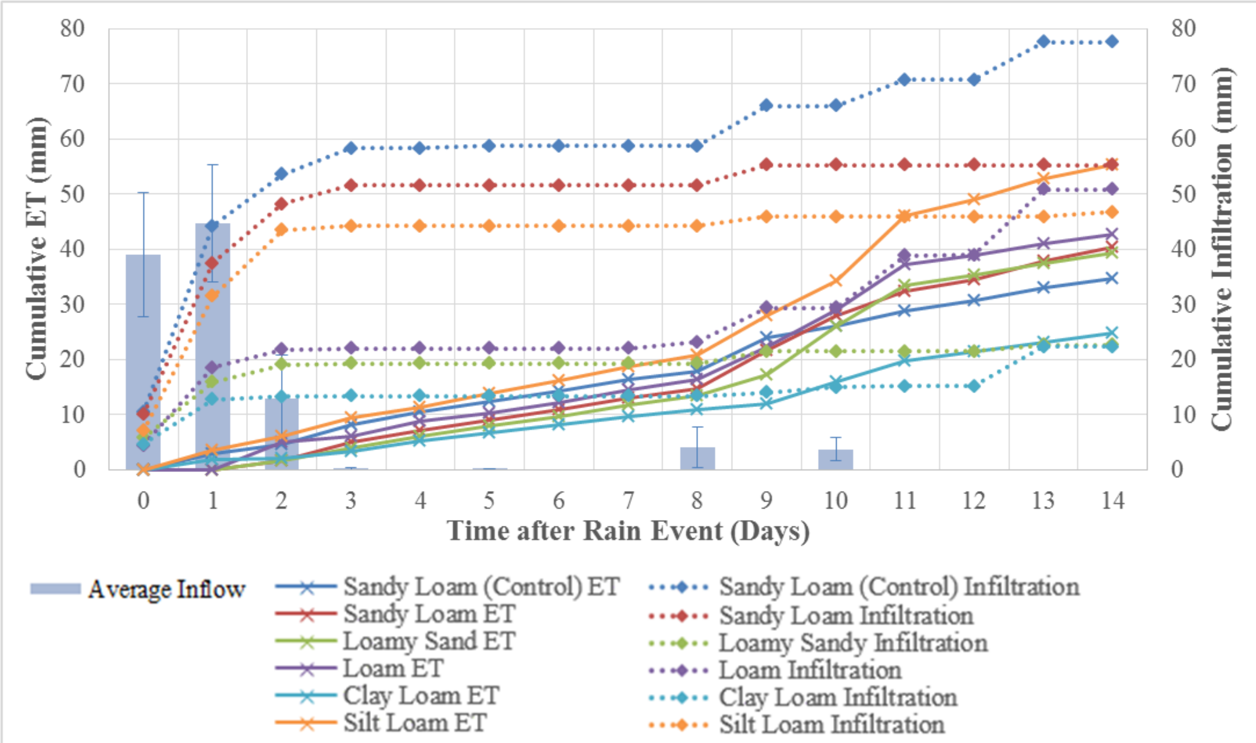

Figure 48: Fall 2015 Average Cumulative Infiltration and ET following Storm Simulations in the Horizontal Lysimeters (n=6)

Unlike the other lysimeters, cumulative infiltration in the horizontal control did not max-out but continued to increase during the dry time. This makes sense because after it rained, lysimeter 'G' had water ponded for a couple of days such that the media continued to infiltrate even during the dry time. The sandy loam and silt loam had the next highest infiltration capacities. This is surprising for the silt loam but may be due to the media recovering more room for infiltration through more ET. Surprisingly, the loamy sand and loam had lower cumulative infiltration volumes in the horizontal configuration.

The cumulative ET volume in the horizontal lysimeters reached or surpassed the cumulative capacity of infiltration for more soil types than in the vertical configuration. This once again shows that the horizontal configuration, with a longer hydraulic retention time, favors more ET.

4.1.4.2 Spring 2016

Following storms in the spring, vertical cumulative ET was very low since the vegetation did not grow back until the end of the season. Any ET was in the form of evaporation, and there was little variation among media. Most soils reached between only 10 and 20 mm of cumulative ET two weeks after a storm simulation event (Figure 49). Even though the Switchgrass was not visible during most of the spring, the roots may have opened up some void space in the media, which is why the control saw the lowest cumulative infiltration. In general, infiltration capacity decreased with decreasing hydraulic conductivity, with the exception of the sandy loam.

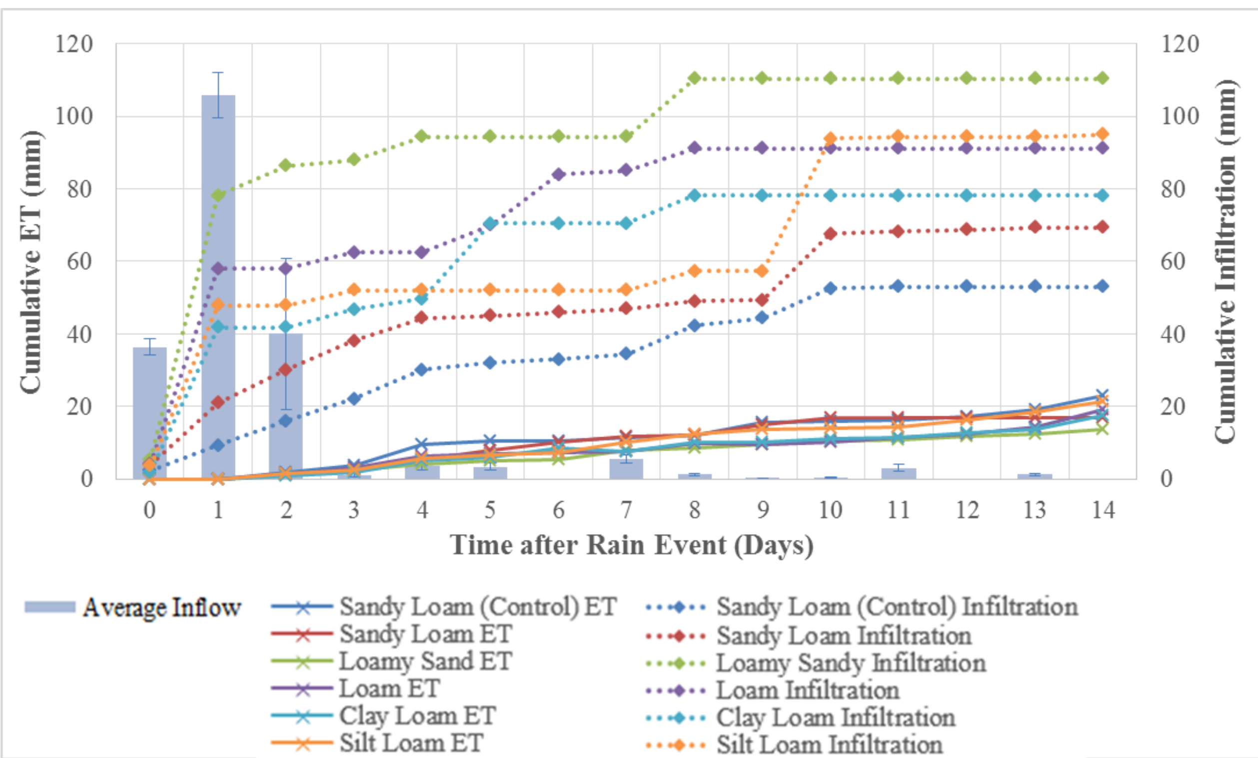

Figure 49: Spring 2016 Average Cumulative Infiltration and ET following Storm Simulations in the Vertical Lysimeters (n=10)

In the spring the horizontal configuration saw slightly more infiltration than the vertical because the Switchgrass began to grow back a little earlier in the season (Figure 50). The difference in cumulative ET volumes was not as varied as in the fall, as expected. While the horizontal control did not see more infiltration initially, it did reach the highest infiltration capacity, and this can again be attributed to the ponded volume during the dry time.

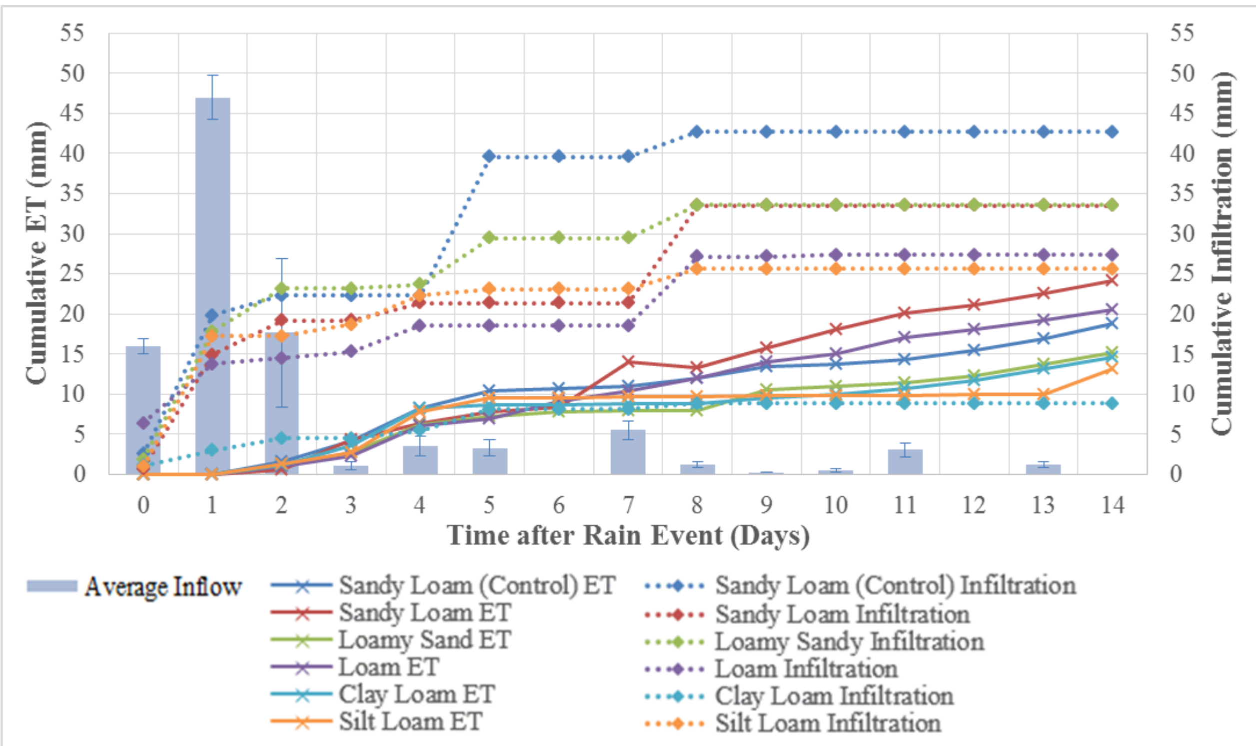

Figure 50: Spring 2016 Average Cumulative Infiltration and ET following Storm Simulations in the Horizontal Lysimeters (n=10)

None of the soils cumulative ET volumes surpassed the cumulative infiltration volume except for the clay loam. In general infiltration dominated volume removal in the spring.

4.1.4.3 Summer 2016

The cumulative volume data from the summer displays the full effects of ET. In the vertical configuration, for all soil types besides the loamy sand, the cumulative ET capacity surpassed the cumulative infiltration capacity given sufficient dry time following a storm simulation event (Figure 51).

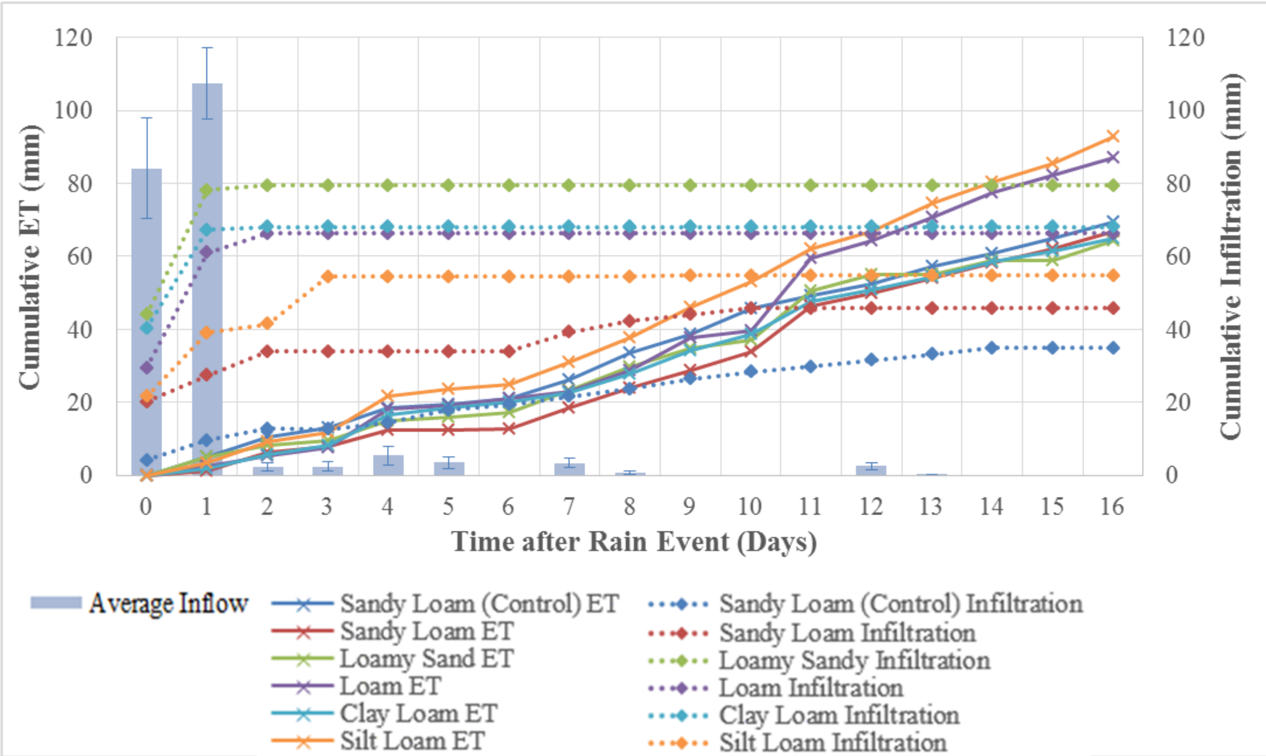

Figure 51: Summer 2016 Average Cumulative Infiltration and ET following Storm Simulations in the Vertical Lysimeters (n=8)

It should be noted that the plot spans up to 16 days after a storm event until the next storm occurs. As seen in Table 17, there was not always 16 days of dry time following a storm event. If there is a shorter dry time between events, you can expect different behavior in terms of whether infiltration or ET is dominant. If there were only 2 to 5 days before the next rain event, the volume removal through ET would account for much less water. If there were 10 days of dry time, finer grained soils such as the silt loam would achieve as much cumulative ET as infiltration volume; and if there was over two weeks of dry time, volume removal through ET could surpass the volume that was infiltrated for multiple soil types. Although more dry days allow for more ET, it is also important that there are not so many dry days such that the moisture content goes below the permanent wilting point causing the plants in the lysimeters to die. The permanent wilting point was not observed to be reached in this study.

Regardless of the number of dry days after a simulation event, cumulative ET was able to "beat out" cumulative infiltration at a faster rate in the summer. For the silt loam soil this point occurred after an average of 10 days, but for the loam soil this occurred after an average of 12 days. Regardless if this point was reached, the ET still cumulatively removed a large portion of the inflow volume. Despite the summer season experiencing more inflow than the other seasons, less cumulative infiltration occurred, most likely due to the increase in ET. All soils once again max out in terms of infiltration after about the first 2 or 3 days.

In the horizontal flow configuration, the cumulative ET grows at an even faster rate (Figure 52). It is visually evident that the ET capacity is higher than the vertical configuration, even more so than other seasons.

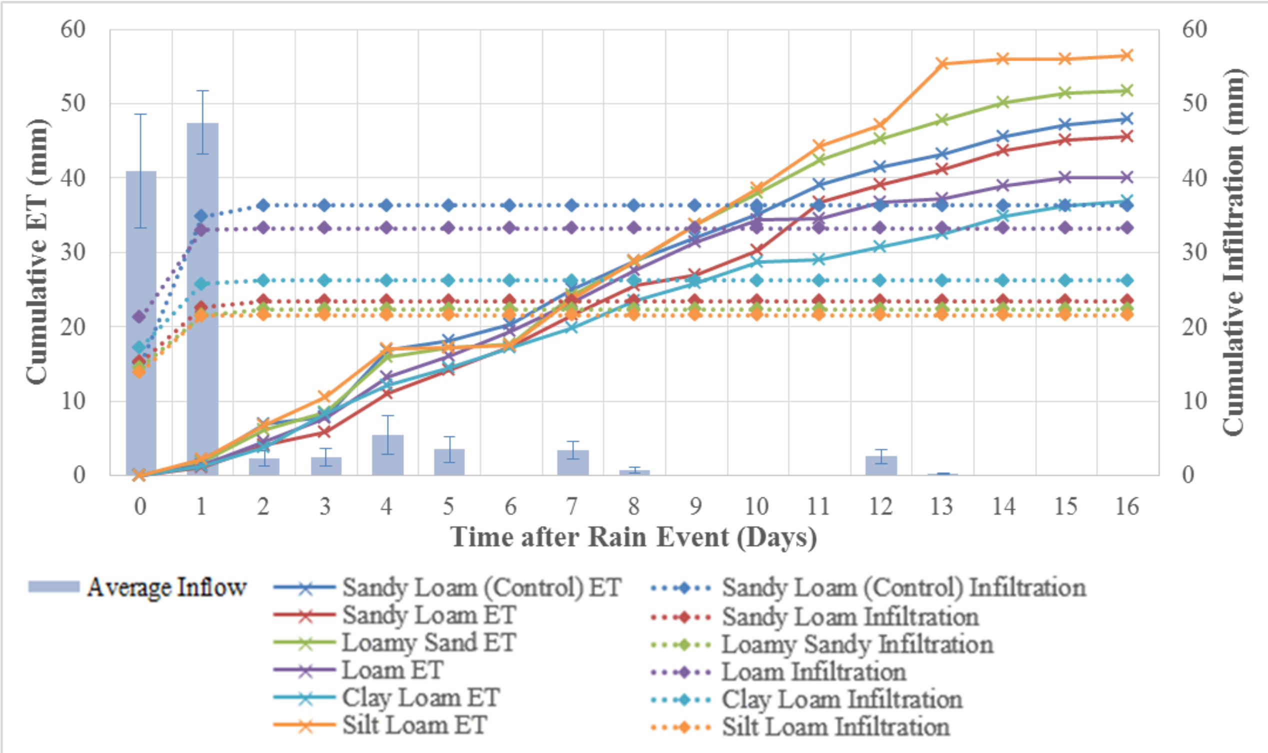

Figure 52: Summer 2016 Average Cumulative Infiltration and ET following Storm Simulations in the Horizontal Lysimeters (n=8)

Among all soil types, there was not much variation in cumulative infiltration volume (between 20 and 35 mm). Also for all soil types, the cumulative ET capacity easily reached and surpassed the cumulative infiltration capacity given sufficient dry time following an event (between 1 to 2 weeks). For the silt loam, loamy sand, and sandy loam, the ET capacity reached the infiltration capacity after about one week. For the clay loam and silt loam, this occurred about 9 days after a simulation event. Even if there were only 4 days after a rainfall event, the cumulative ET volume already reached about half of the total infiltration volume for the majority of media.

4.1.4.4 Fall 2016

Similar to the mass balance data, the cumulative volume removal data for fall of 2016 was small in comparison to the total inflow data (Figure 53 and 54), indicating the large amount of water stored within the media. Because of this, it is difficult to differentiate performance between the different media. The clay loam actually had the highest infiltration capacity in the vertical flow configuration, followed by the loamy sand and the silt loam. The cumulative ET volumes were similar between media, with the exception of the clay loam which exhibited noticeably lower ET.

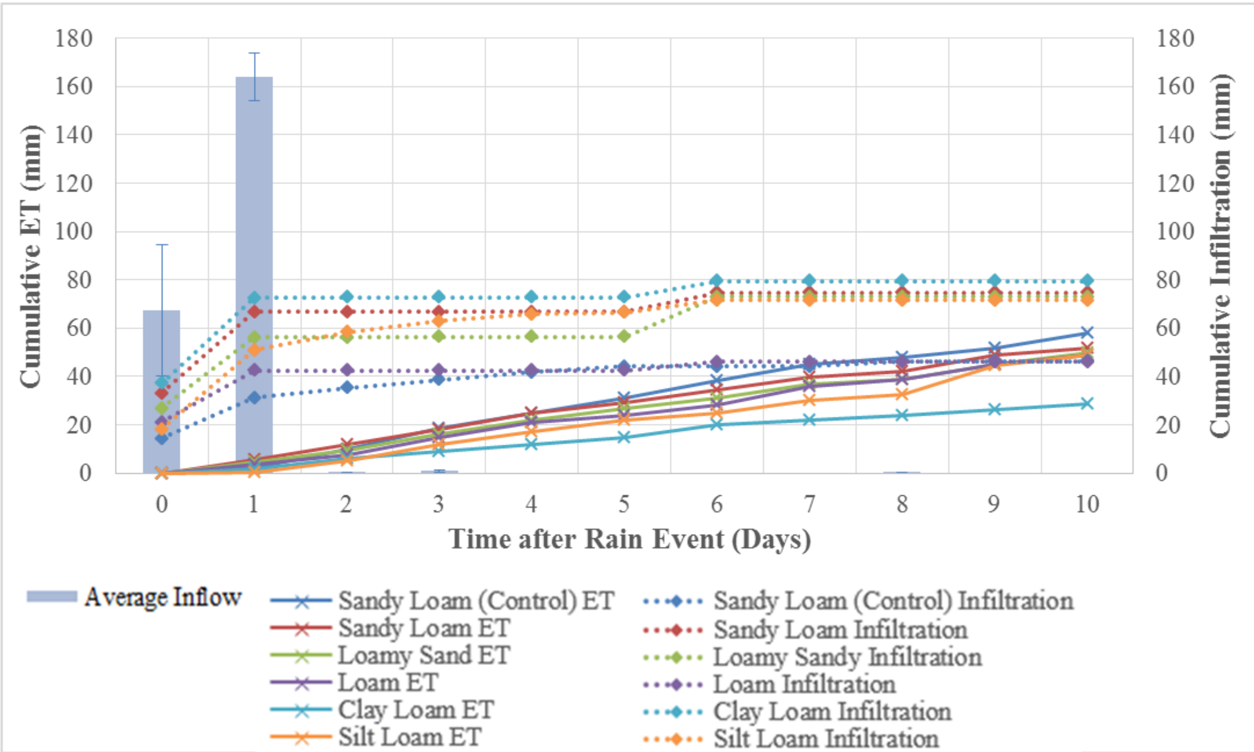

Figure 53: Fall 2016 Average Cumulative Infiltration and ET following Storm Simulations in the Vertical Lysimeters (n=4)

Within the horizontal configuration, the cumulative infiltration volume increased with increasing hydraulic conductivity. As opposed to the other seasons, there are no exceptions to this trend, with the loamy sand infiltrating the highest volume and the clay loam infiltrating the smallest volume (Figure 54). In all soil types, the cumulative ET volume never surpassed the cumulative infiltration volume. It should be noted that the plots for fall 2016 only go up to 10 days because there were no storm simulations with greater than 10 antecedent dry days. This may be visually misleading in terms of total cumulative volume removal, but it's still clear that fall 2016 saw the lowest volume removal through both removal mechanisms.

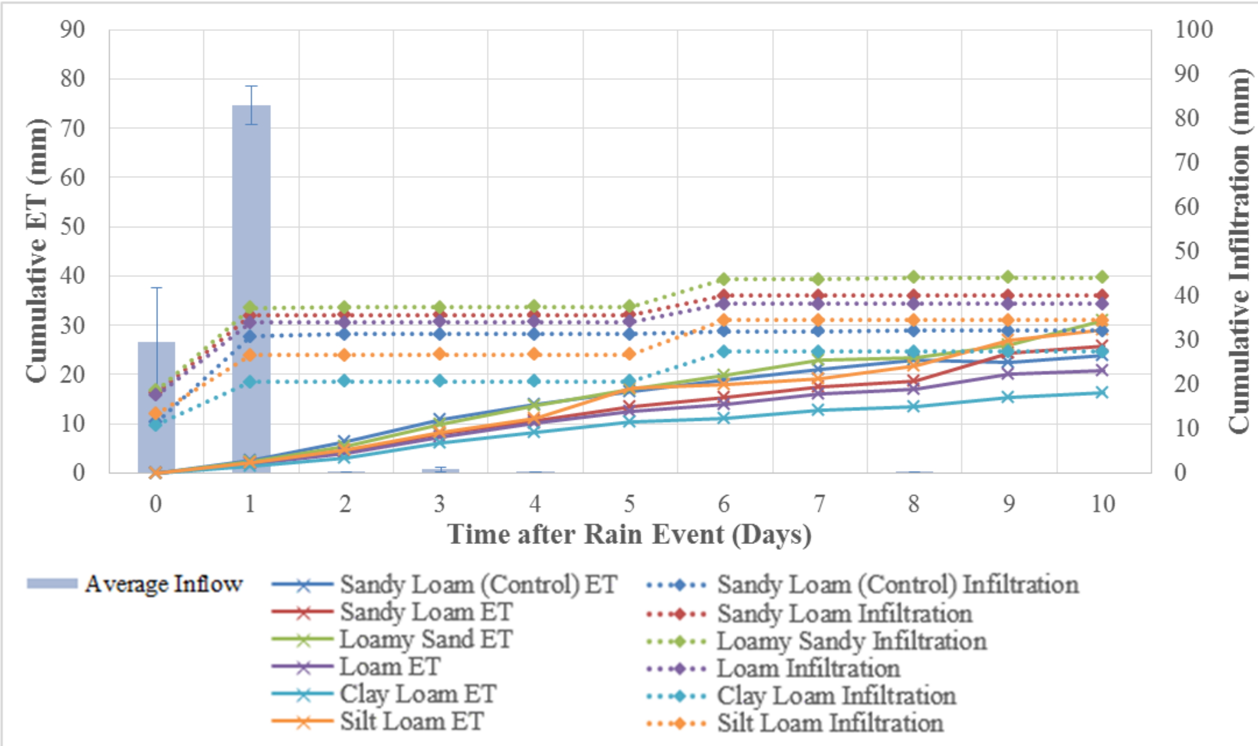

Figure 54: Fall 2016 Average Cumulative Infiltration and ET following Storm Simulations in the Horizontal Lysimeters (n=4)

4.1.4.5 All Seasons

To create cumulative infiltration and ET graphs representative of data throughout the entire year, the cumulative infiltration and ET data was averaged for fall 2015, spring 2016, and summer 2016. These graphs are meant to portray to cumulative contributions of the two removal mechanisms over the course of the one year the data was collected.

Over the course of one year, it is clear that infiltration is the dominant removal mechanism in the vertical lysimeters (Figure 55). Infiltration volume varied among soil type with the loamy sand, the coarsest soil, seeing the most infiltration, and the control, lacking vegetation to open up flow paths, seeing the lowest infiltration capacity. The clay loam saw a fairly high infiltration capacity most likely due to the presence of macropores, while the sandy loam saw a lower infiltration capacity than expected, as seen with the other seasons.

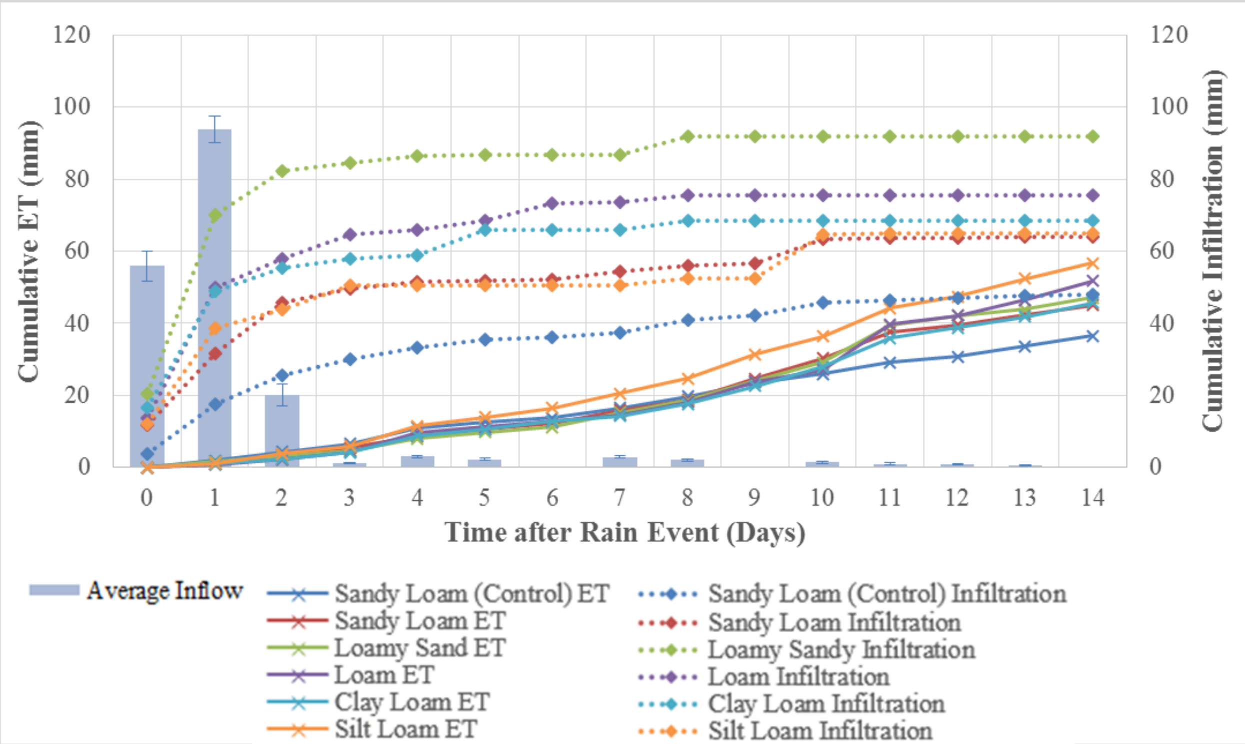

Figure 55: All Seasons Average Cumulative Infiltration and ET following Storm Simulations in the Vertical Lysimeters (n=24)

The difference in cumulative ET among soil types is not evident in the vertical configuration, except for the silt loam and the control. The silt loam soil, with the highest daily ET rates over the year, separated itself from the other soil types in terms of increased ET capacity. The control, which contained no vegetation, saw less removal through ET on a yearly basis, but still a comparable amount due to the mass amount of evaporation from the ponded water. Even after two weeks of dry time between events, the cumulative ET volume did not surpass the cumulative infiltration volume for any of the soil types, showing that over the course of one year infiltration is the dominant volume removal mechanism in the vertical lysimeters.

In the horizontal configuration, the cumulative contribution of ET over the course of one year was more evident (Figure 56). Once again, cumulative infiltration capacity was more varied among soil type, whereas cumulative ET capacity was more constant among soil type. Although, over the course of one year the silt loam was able to cumulatively remove more volume through ET due to higher daily ET rates than the other soil types.

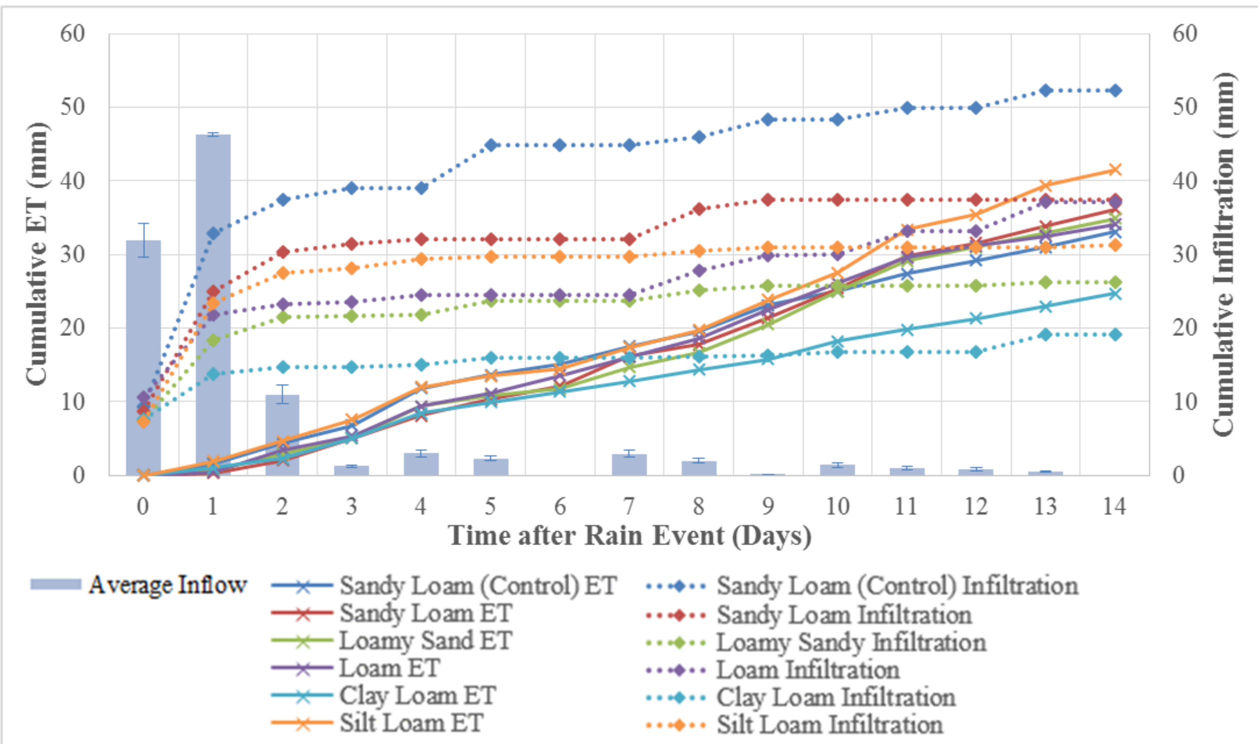

Figure 56: All Seasons Average Cumulative Infiltration and ET following Storm Simulations in the Horizontal Lysimeters (n=24)

In summary, the cumulative effects of infiltration and evapotranspiration are seasonally dependent. In the spring, infiltration was clearly the dominant volume removal mechanism because of the lack of vegetation. In the summer, given sufficient dry time between events, the cumulative effects of ET were able to surpass the cumulative effects of infiltration. The point at which cumulative ET capacity surpasses cumulative infiltration capacity varied by soil type; with this phenomenon occurring soonest in the silt loam soil. By creating a longer hydraulic retention time in the unsaturated zone, the cumulative effects of ET were maximized in the horizontal lysimeters, regardless of media.

These cumulative infiltration and ET charts show how much precipitation patterns, especially the number of antecedent dry days before an event, play a role in the removal mechanism. Antecedent dry time is often considered in terms of water quality removal, but it should also be considered in volume removal if a specific removal mechanism is desired. In an area where rainfall events occur more frequently, designing stormwater control measures to favor ET may not be as beneficial as an area with longer dry times between events. If a rain garden is designed to promote ET with a longer hydraulic retention time and finer media, it is also imperative that there is enough dry time between events to allow the volume removal through ET to accumulate.

4.1.5 Moisture Content Analysis

The daily moisture content in the lysimeters was calculated on a volume basis by subtracting the known dry soil weight from the measured lysimeter weight each day. The initial dry weights of each lysimeters are based on weights that were taken at the beginning of the study in fall 2015 after the dry soil and initial vegetation was placed in each lysimeter. The initial dry weights in each lysimeter are based on the initial plant mass and initial soil volume, and it is possible that there was a loss of fine particles in the effluent over the course of the study, which would alter the dry weight of each lysimeter. Other changes in weight are also expected throughout the study such as additional mass of vegetation, and dirt and debris that collected on the lysimeters over time (Table 20).

Since the dry soil weight in each lysimeters is merely an estimate over the entire study, the moisture contents in the lysimeters are also an estimate. With that being said, the daily change in moisture content is accurate since many of these factors do not change or accumulate from day to day. The moisture content trends among the different soil types can be helpful when looking at the data collected throughout the study.

4.1.5.1 Continuous Moisture Content Data

The estimated daily moisture contents were plotted for both the vertical lysimeters (Figure 57) and the horizontal lysimeters (Figure 58). The inflow was also plotted with the moisture content data to present the relationship between inflow and the change in moisture content. In the vertical configuration, the pattern in moisture content was very similar among soil types, with peaks and drops in moisture content occurring around the same time and at similar magnitudes (Figure 57). After an inflow event, the moisture content spiked up due to the addition of water, and then slowly decreased, somewhat steadily, until the next inflow event occurred.

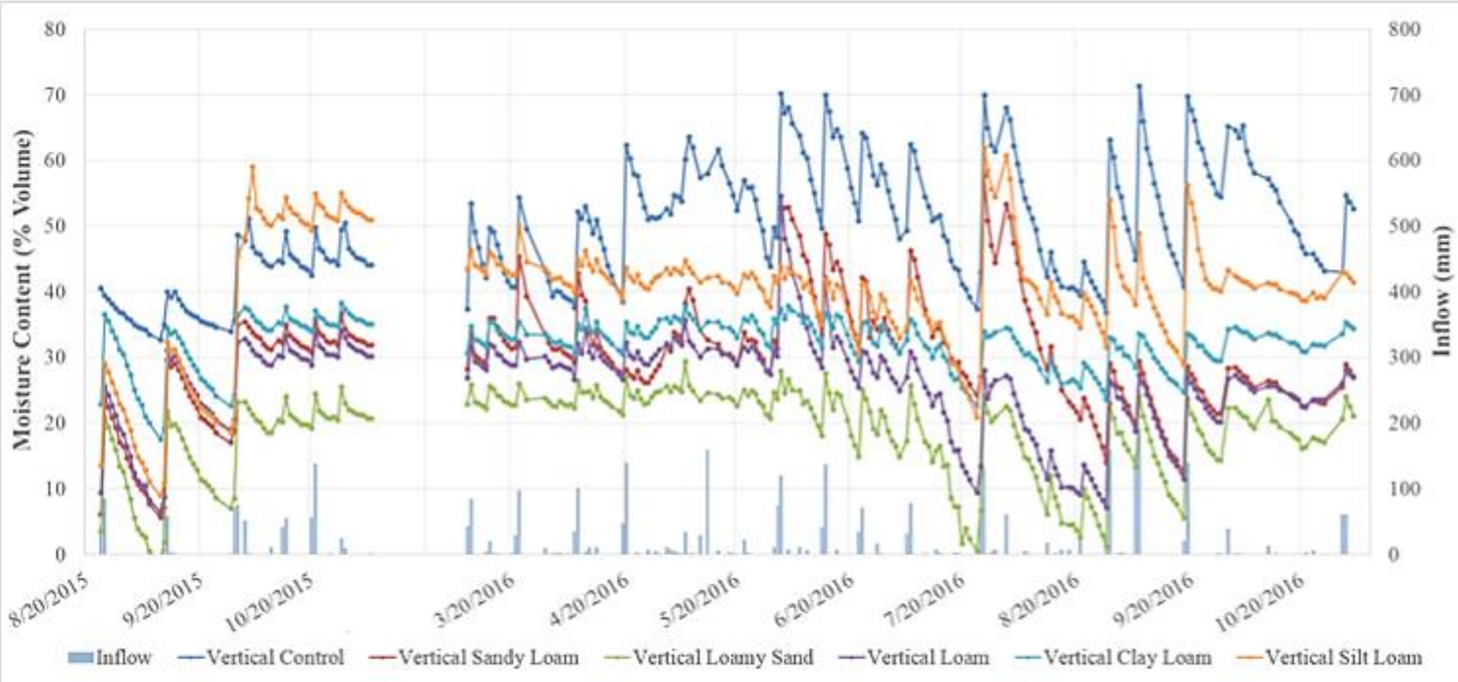

Figure 57: Daily Moisture Contents and Inflow in the Vertical Lysimeters

During the fall of 2015, the moisture content in all lysimeters was lower than the other seasons because the soil was in a dry state when the study began. Over the course of the fall season and into the next year, the media retained some of the water, such that the moisture content never dropped back down past the initial dry water content, except for the loamy sand soil.

The different soil types in the vertical flow configuration exhibit similar changes in moisture content, but the range in these moisture contents varies (Figure 57). Throughout the study, the non-vegetated control lysimeter experienced the highest moisture contents. This makes sense because the vertical control was ponded throughout the entire study, so this moisture content also accounts for the ponded water. Because of this ponded water, the control lysimeter saw much higher peaks in the moisture content curve.

Although all vertical lysimeters were supplied with the same inflow volume, the varying moisture content data is indicative of how each soil handles the water differently. Aside from the control, the silt loam had the highest moisture contents in the vertical configuration. This makes sense since it has the highest plant available water, meaning it holds the most water in its pores. The clay loam had one of the next highest moisture contents, but the moisture content curve was more dampened out with less peaks and valleys. This may be due to the presence of macropores causing a lot of the inflow water to directly infiltrate. The sandy loam and loam experienced moisture contents on a similar level as one another, with the sandy loam seeing a little more storage. The loamy sand, the coarsest soil with the lowest plant available water, saw the lowest range of moisture contents.

In the horizontal configuration the range in moisture contents was not as varied among the different soil types (Figure 58). Despite being provided the same volume of water on a soil volume basis as the vertical lysimeters, the moisture contents in the horizontal lysimeters were noticeably lower. This means that the horizontal lysimeters stored less water on a volume basis over the course of the study. The non-vegetated horizontal control lysimeter exhibited higher peaks in moisture content when water was applied which represents the ponded water in the lysimeter. These peaks dissipate faster than in the vertical control because the water does not pond for as long in the horizontal flow configuration.

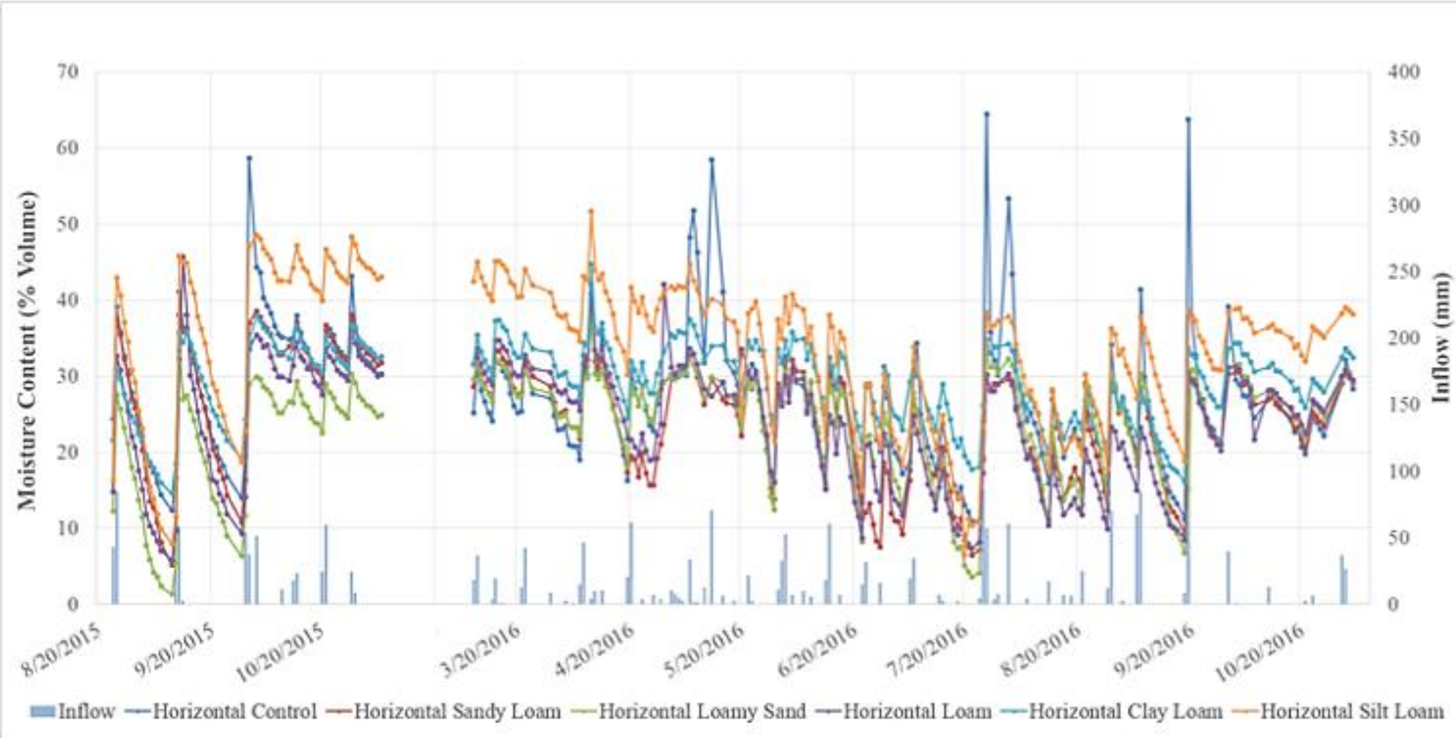

Figure 58: Daily Moisture Contents and Inflow in the Horizontal Lysimeters

While the moisture contents do not vary as much among media in the horizontal lysimeters, the silt loam consistently holds the most water in the media. This again confirms the measured plant available water from the SWCC and reflects the higher ET rates in this media, regardless of the flow configuration. Although the difference between soil types is not as visually evident, the range in moisture contents still decreases in the same order as the vertical configuration. The silt loam has the highest moisture contents, followed by the clay loam, the loam, the sandy loam, and the loamy sand. This is also the order of the soil types from highest plant available water content to lowest plant available water content, showing a direct correlation between the moisture content measured in the field and the plant available water measured by the soil water characteristic curves.

4.1.5.2 Moisture Content Related to Known Soil Parameters

The moisture content data presented thus far provides some interesting relationships in terms of soil type and season, but it would be beneficial if the moisture content could also be predictive of behavior in media. As seen in Section 3.1.4.2, the saturated moisture content, field capacity, and permanent wilting point moisture contents were determined for each of the soil types. A relationship may exist between the FC, PWP and the measured moisture contents such that the moisture content can be used to predict when infiltration and ET will occur. The continuous moisture contents were plotted alongside the measured inflow, infiltration, and evapotranspiration. The location of the saturated moisture content, the field capacity, and the permanent wilting point were also plotted to see if there was any clear relationships between these parameters. This plot is shown for the vertical sandy loam (Figure 59), but the other soil types are displayed in the Appendix in Figures A12 through A21.

In a fully saturated condition following an inflow event, infiltration would hypothetically occur when the moisture content in the media was between the saturated water content and the field capacity, and ET would occur when the moisture content was in between the field capacity and the permanent wilting point. As seen with the sandy loam soil in the vertical configuration (Figure 59), and all other lysimeters, this relationship cannot be seen. This is because after a rainfall event, the moisture content in the media does not always reach the saturated condition. Regardless of where the moisture content falls within the "zones" of drainage available water or plant available water, both infiltration and ET are occurring. After a storm event there are usually about two days of infiltration and then the remaining reduction in moisture content before the next event is due to ET. This phenomenon is evident in all soil types regardless of the observed moisture content.

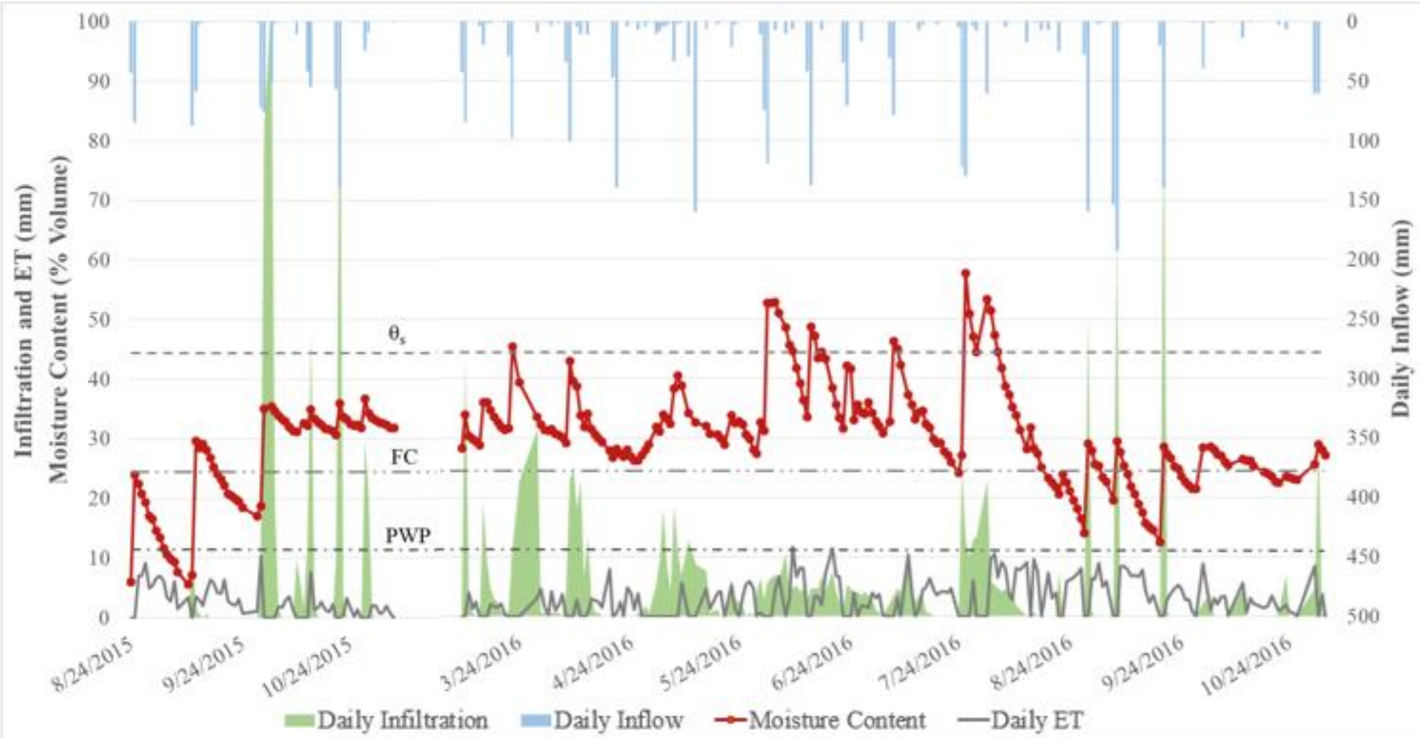

Figure 59: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Vertical Sandy Loam

It is possible that this relationship between the moisture content curve and when volume removal switches from infiltration to ET is not visible because the measured field capacity is off from the actual field capacity. To see if there is there is a consistent field capacity being observed in the data, the moisture content at which volume removal switched from infiltration to ET was determined for all storms. This was done for both the vertical and horizontal configuration, but is shown for only the vertical configuration (Table 34). These moisture contents were averaged for each soil type, and was deemed the estimated field capacity from the data (Figure 59). It was found that the estimated field capacity from the data was fairly close to the measured field capacity from the SWCC. Some values were higher than the measured values, and some were lower, but generally correspond to the trend of the measured values among the different soil types.

Table 34: Measured Field Capacity from the SWCC compared to the Estimated Field Capacity from the Data

Soil Type	Measured Field Capacity from SWCC (% Volume)	Estimated Field Capacity from Data (% Volume)	Standard Deviation of the Estimated FC (% Volume)
Sandy Loam	25	31.5	4.2
Loamy Sand	15	22.6	1.7
Loam	35	30.9	5.3
Clay Loam	41	33.9	2.1
Silt Loam	41	45.2	5.1

While it is possible that these values could represent the actual field capacity, the standard deviation of these moisture contents is high. The moisture content at which volume removal switches from infiltration to ET is variable as seen by the above moisture content curve for the sandy loam (Figure 59). This moisture content where the removal mechanism changes is not constant, and may show that the field capacity is not something that can be directly represented in the field. Rather than looking at the field capacity as a static point, the moisture content at which removal switches from infiltration to ET may be dynamic and dependent on multiple conditions in the system.

4.1.5.3 Slope of the Moisture Content Curve

Although the FC and PWP cannot be directly related to the measured moisture content in terms of when infiltration and ET are occurring, the slope of the moisture content curve after a rainfall event may be more telling. As mentioned, the moisture content spikes upward following a storm event, and then slowly decreases until the next storm event occurs. On a larger scale, this decreasing slope looks constant (Figure 59), but on an individual storm scale there is a different slope in the moisture content curve depending on whether infiltration or ET is occurring (Figure 60).

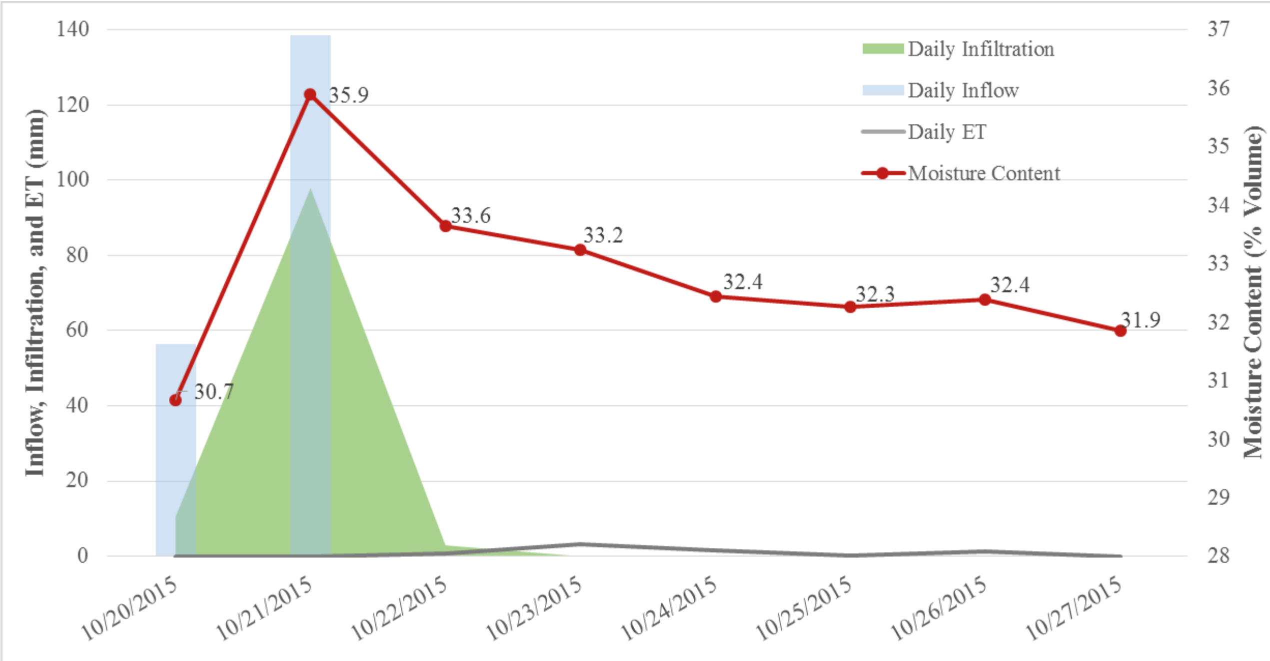

Figure 60: October 20th Storm Simulation Moisture Content Curve for the Vertical Sandy Loam compared to Inflow, Infiltration, and ET

For an event that occurred on 10/20/2015, the slope of the moisture content curve is steeper when infiltration is occurring, and then becomes more gradual during the time ET is occurring. This is a zoomed-in version of the above figure (Figure 59) to one specific storm, but for all storm events this change in slope in the moisture content curve is evident. For each soil type within each flow configuration, the average slope of the moisture content curve was calculated for when infiltration was occurring and for when ET was occurring. These slopes will be referred to as the "infiltration slope" and the "ET slope," referencing the slope of the moisture content curve when the respective volume removal mechanism was occurring.

The average slopes were calculated for the entire study and not separated by season (Table 35). While infiltration and ET are seasonally dependent, the moisture content data is meant to serve as a general representation of the entire year. Also, the slope of the moisture curves was only calculated for single-peaking storm events, such as the one seen in Figure 60. Single-peaking, well defined events that did not contain subsequent inflow events between storm simulations were used for this calculation. There were many storm events that happened right after one another and were not single-peaking, especially during the spring season, which were not used since the slope of the moisture content curves would be affected by subsequent events.

Table 35: Average Slope of the Moisture Content Curve during Infiltration and Evapotranspiration (n=8)

Soil Type	Flow Configuration	Infiltration Slope (% Volume)				ET Slope (% Volume)			
		Average	Std. Dev.	Lower 95% C.I.	Upper 95% C.I.	Average	Std. Dev.	Lower 95% C.I.	Upper 95% C.I.
Sandy Loam	Vertical	-2.4	1.7	-1.3	-3.5	-0.8	0.5	-0.5	-1.1
	Horizontal	-1.6	0.5	-1.3	-2.0	-1.2	0.4	-0.9	-1.5
Loamy Sand	Vertical	-2.4	0.2	-2.3	-2.5	-0.7	0.5	-0.3	-1.0
	Horizontal	-1.9	1.9	-0.6	-3.2	-1.3	0.6	-0.9	-1.6
Loam	Vertical	-1.6	0.8	-1.0	-2.1	-0.7	0.4	-0.4	-1.0
	Horizontal	-2.2	2.3	-0.6	-3.8	-1.1	0.4	-0.8	-1.4
Clay Loam	Vertical	-1.0	0.7	-0.5	-1.4	-0.5	0.3	-0.3	-0.7
	Horizontal	-1.2	0.5	-0.9	-1.6	-0.8	0.2	-0.7	-1.0
Silt Loam	Vertical	-3.3	2.2	-1.8	-4.8	-0.8	0.4	-0.5	-1.0
	Horizontal	-1.2	0.4	-1.0	-1.5	-1.1	0.4	-0.8	-1.4

The infiltration portion of the moisture content curve has a steeper slope than the ET portion of the curve, which is true for all soil types and for both flow configurations. As seen with the cumulative data, water lost through infiltration occurred at a faster rate than the water lost through ET. In reality, the slope of the infiltration portion of the moisture content curve should be significantly steeper than those shown in Table 35. The moisture contents are based on the weights taken manually after the storm simulation was ended. The peak in moisture content is most likely occurring during the storm simulation, so it would be interesting to install soil moisture meters that take more frequent readings. Regardless, the soil moisture estimates still allow for a comparison between the different soil types.

In all soil types besides the clay loam and loam, the infiltration slope is greater in the vertical configuration than the horizontal configuration. This makes sense since the vertical lysimeters see more removal through infiltration. In all soil types, the ET slope is steeper in the horizontal configuration than the vertical configuration. The slope for each soil type can generally be related to the volume removal seen in each soil type. Although the slope in the moisture content curve is telling for this study, the slopes cannot necessarily be applied to predict volume removal in other studies. It would be beneficial if a soil's known soil parameters, such as the saturated water content, field capacity and permanent wilting point, could be used as a predictor in terms of infiltration performance.

4.1.5.4 Moisture Content as a Predictor to Infiltration

Theoretically, if the volumetric moisture content after a storm simulation event reached the saturated moisture content, then you would expect the volume of water lost through infiltration to equal the drainage available water. If the moisture content did not begin at the saturated water content, then you would expect the loss in volume during infiltration to be equal to the actual moisture content minus the field capacity. The higher the initial moisture content following a storm simulation, the higher you would expect the drop in moisture content to be while infiltration was occurring. Because in most cases the water content never reaches this saturated value, the drop in moisture content in the lysimeters due to infiltration was less than the drainage available water. As seen with the estimation of the actual field capacity (Table 26), this point may not be static, but some relationship can still be made between the drop in moisture content during infiltration and the initial moisture content following a storm.

The drop in moisture content when infiltration was occurring was compared to the initial moisture content following a storm event (Figure 61 and 62). This was done for both single-peaking, well-define events (n=8) (Figure 61), and for all events over the study (n=25) (Figure 62). The plots are presented for the vertical configuration as the 1D system is more homogeneous in terms of moisture content. The drainage available water versus the saturated moisture content was also plotted for each soil type, represented by the hollow data points. These data points represent the maximum drop in water content during infiltration if the soil were fully saturated following a storm event.

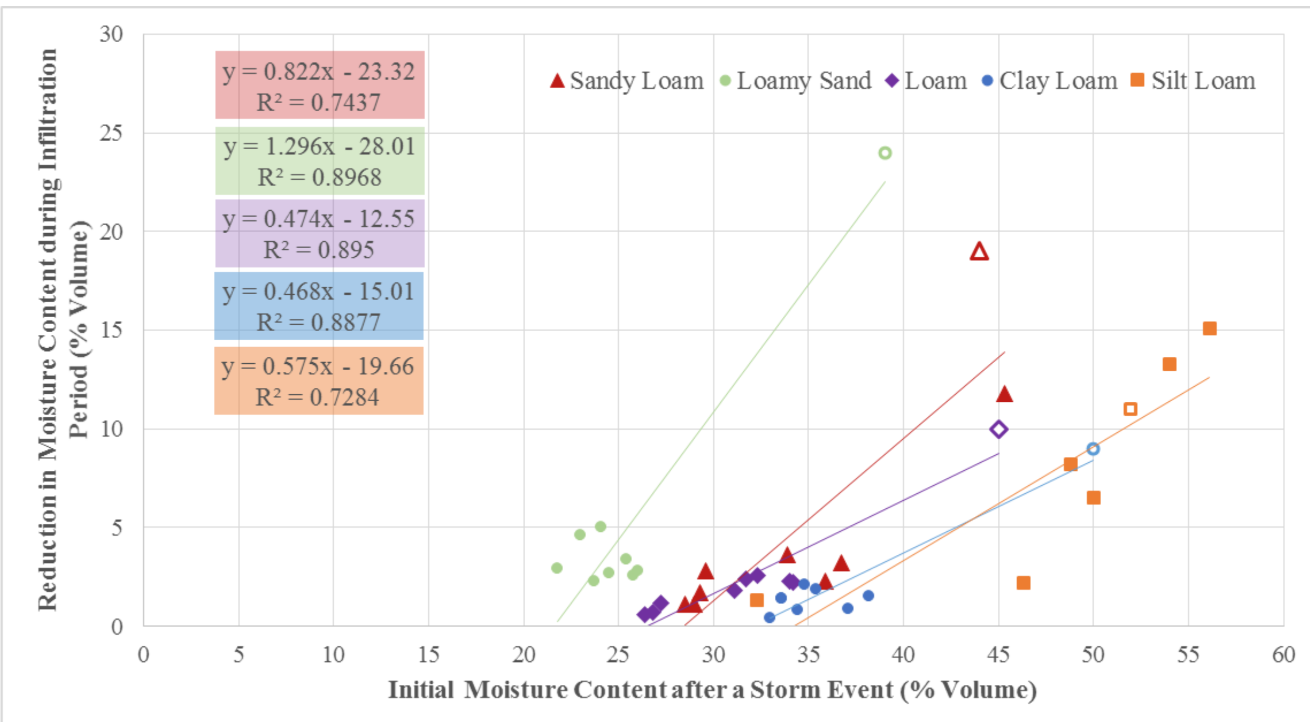

Figure 61: Drop in Moisture Content during Volume Removal through Infiltration based on Initial Moisture Content for Single-Peaking Storm Events (n=8)

A linear relationship was found between the initial moisture content and the drop in moisture content during infiltration. The R^2 value ranged from 0.72 to 0.90 for all five soil types, representing a good fit between the measured data and the linear regression. For all soil types besides the silt loam, the moisture content never reached the saturated moisture content.

This data suggests that if the moisture content after a storm event is known and you have an estimate of the soil properties, specifically the soil's saturated water content and field capacity, then you can predict the drop in moisture content in the system during infiltration. This drop in moisture content during infiltration may not be able to directly predict the volume loss through infiltration since this is also dependent on the intensity and duration of the rainfall event.

Regardless if the linear regression has the ability to directly predict volume removal through infiltration, it provides a comparison of the moisture loss during infiltration among the different soil types, similar to what was seen in Table 35. The rate of infiltration (the slope of the line) and the range of moisture contents (the location of the lines along the x-axis) can be directly related to the type of soil and that soil's measured saturated and unsaturated hydraulic conductivity. Moving left to right on the x-axis, the soils trend from coarsest to finest. The loamy sand has the lowest moisture contents, and infiltration occurs at the fastest rate, as shown by the drop in moisture content during infiltration. The silt loam and the clay loam, the finest soils, have the highest moisture contents and most gradual slope (Figure 61).

A similar relationship can be seen when these data are plotted for all storm simulations, not just the single-peaking, well-defined storm events. For all events, the slope of the linear regressions is more gradual for all soil types (Figure 62). This is because these storm events are not well-defined, and may contain multiple precipitation events one after another. Because of this, the media does not have the full ability to infiltrate water before the next event occurs, such that the drop in moisture content due to infiltration is stopped short. Because of this, the drop in moisture content during infiltration is also more varied for all events, as seen by the worsened relationship between the measured data and the linear regression. Regardless, a linear relationship can still be seen for this data, and is telling of the infiltration performance among the different soil types.

Once again, the loamy sand and the sandy loam, the two coarser grained soils, have a steeper slope, indicating a faster infiltration rate. The loam, silt loam, and clay loam have more gradual slopes representing the slower loss in water volume during infiltration. This data was analyzed for the entire study to include more data points, but it is expected that this drop in moisture content during infiltration will vary among the different seasons because of changes in infiltration rates due to viscosity and changes in the vegetative condition.

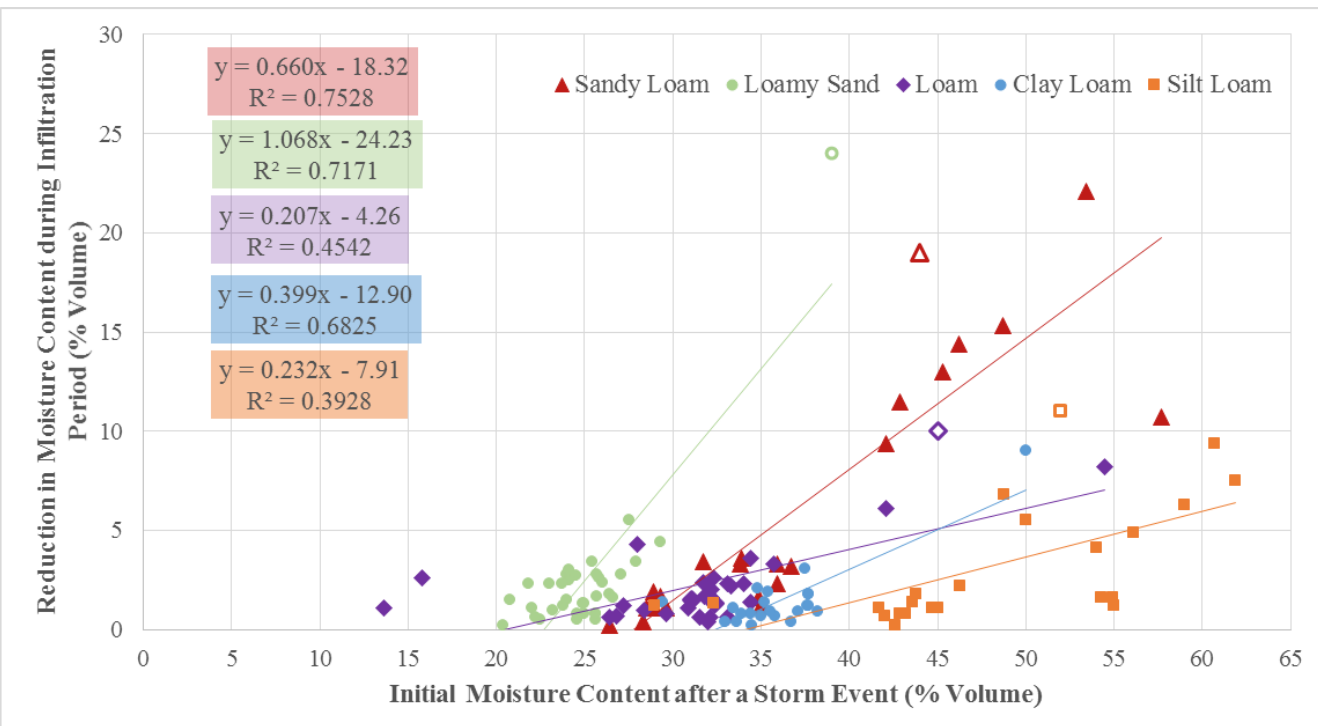

Figure 62: Drop in Moisture Content during Volume Removal through Infiltration based on Initial Moisture Content for All Storm Events (n=25)

A similar relationship was not developed for the measured moisture content during ET and the PWP because depending on the amount of dry time between events, the moisture content may never reach the permanent wilting point. Also, since the measured ET is calculated based on the daily change in moisture content, the relationship between moisture content and ET is obvious. The daily ET rate as it relates to moisture content is much more predictable, such that a fairly constant ET rate is occurring from when infiltration ceases to when the next storm event occurs.

The moisture content data were primarily analyzed for the vertical configuration and not the horizontal configuration. As mentioned previously, volume removal is much more complicated in the horizontal configuration because the exact flow path of the water is unknown and the moisture content is expected to be varied in different locations of the horizontal lysimeters. For this reason, volume removal results were not able to be normalized in terms of surface area between the vertical and horizontal flow configurations. The vertical system can be represented in one dimension, whereas the horizontal system can only be represented in two dimensions. It is difficult to compare the performance of a 1D system and a 2D system, such that the results cannot be directly compared or normalized.

The comparison of the two flow configurations can be somewhat misleading since volume removal is presented in terms of mm, which is calculated on a surface area basis. It is better to compare the two configurations in terms of the distribution between infiltration and ET. Calculating volume removal on a surface area basis, and therefore designing these systems on a surface area basis, may not be the best option. The vertical and horizontal lysimeters were supplied the same amount of runoff on a soil volume basis, but the distribution in removal between infiltration and ET is very different between the two configurations. The data suggest that converting all volume removal to a surface area basis may be misleading and may not give the system as much credit as it deserves, as shown by the horizontal configuration.

4.2 WATER QUALITY RESULTS AND DISCUSSION

This section will discuss the results of the water quality portion of the Optimal Balance study according to the methods presented in Section 3.2. Section 4.2.1 will discuss the results of the laboratory quality testing and Section 4.2.2 will discuss the results of the field quality testing in the lysimeters.

4.2.1 Laboratory Testing

Performing testing on a laboratory scale provides a more controlled environment in which water quality removal can be analyzed. Laboratory testing analyzed the nutrient removal capabilities of the five soil types by measuring their cation exchange capacity (CEC) and maximum orthophosphate adsorption capacity through batch isotherm tests. These laboratory results can be compared to the field testing results presented in Section 4.2.2.

4.2.1.1 Cation Exchange Capacity

In accordance with ASTM D7503, the potassium chloride extract filtered through each soil was analyzed for total kjeldahl nitrogen (TKN), which is required for the determination of CEC. Quality controls including duplicate samples for each soil type, blank samples, and matrix spikes were utilized. The cation exchange capacity of each soil type, representing an average of the two duplicate samples, can be seen in Table 36. The standard deviation of the two duplicate samples is shown in parenthesis beside the average.

Table 36: Cation Exchange Capacity of the Five Soil Types Measured using ASTM D7503

Soil Type	Cation Exchange Capacity ($cmol^+/kg$)	USDA Grain Size Distribution
Loamy Sand	6.97 (± 3.44)	80% Sand 14% Silt 6% Clay
Sandy Loam	9.39 (± 0.57)	56% Sand 32% Silt 12% Clay
Loam	17.81 (± 2.12)	37% Sand 44% Silt 19% Clay
Silt Loam	12.09 (± 0.38)	29% Sand 55% Silt 16% Clay
Clay Loam	17.80 (± 2.62)	26% Sand 44% Silt 30% Clay

The loam and clay loam have the highest CEC values at 17.81 and 17.80 $cmol^+/kg$, respectively, indicating the most fertile soils. The loamy sand and sandy loam have the lowest CEC values at 9.39 and 6.97 $cmol^+/kg$, respectively. The values measured in this study are consistent with typical values and other CEC tests performed on soils with similar textures (Barrett et al. 2013; Mengal 1914; Ross 1995; T. L. Culbertson and S.L. Hutchinson 2004). Hypothetically, CEC is highest in clay soils and then decreases towards sandier soils (Figure 63), which was exhibited in this study. For the most part, the measured CEC can be related to the clay content in the soil (Table 36). The loam and clay loam have the highest clay content, at 19% and 30%, respectively, while the sandy loam and loamy sand have the lowest clay content at 12% and 6%, respectively. The silt loam has the third highest clay content, and also has the third highest CEC.

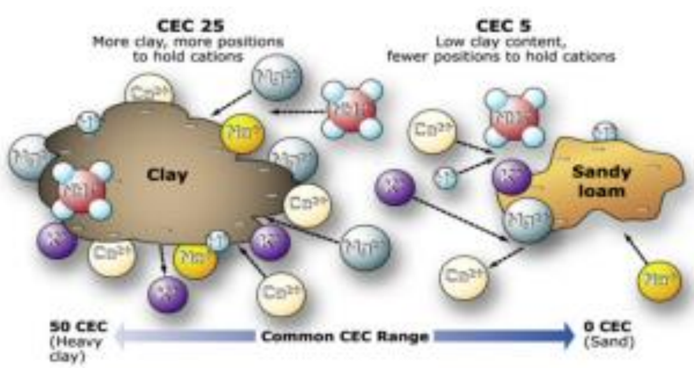

Figure 63: Typical Range of CEC According to Soil Texture (Granco Minerals 2013)

The type of clay can also play a large role in the CEC. Kaolinite, the type of clay present in the clay loam, typically has a lower CEC value around 10 $cmol^+/kg$, compared to other clays that have a higher CEC value ranging from 25-100 $cmol^+/kg$ (Mengal 1914). Although the clay loam has the highest clay percentage, it has a very similar CEC value to the loam. The loam has a lower clay content, but it may contain another type of clay with a higher cation exchange capacity.

A soil with a high CEC can retain many cations in solution on its surface and indicates a highly fertile soil. Cation exchange capacity cannot be directly related to the removal of nitrogen and phosphorus, which exist as anions in solution. Nutrient adsorption, specifically orthophosphate adsorption, can be attributed to basic adsorption to the soil itself, or to bound cations on the clay minerals. Surface groups on a soil's exchange complex, such as aluminate, have the ability to protonate in water, resulting in a positive charge on a soil's surface which provides an adsorption site for anions such as orthophosphate (Edzwald et al. 1976). Orthophosphate adsorption is also related to the free metal content of clays. Although the relationship between nutrient removal and CEC is complicated depending on the pH of a solution and the type of clays present, a higher CEC can generally be correlated with better nutrient removal due to ionic adsorption and general soil fertility. Based on the CEC measured in the laboratory, the loam and clay loam should have the highest adsorption capacity and the sandy loam and loamy sand should have the lowest adsorption capacity; but this can be dependent on many other factors such as the pH and type of ions present in solution.

4.2.1.2 Batch Isotherm Adsorption Tests

Batch adsorption isotherms tests were performed for orthophosphate in all soils according to the methods discussed in Section 3.2.3. The batch isotherm data can be used to plot the adsorbed orthophosphate concentration versus the aqueous orthophosphate concentration at equilibrium.

This relationship can be modeled through the Langmuir isotherm which has been shown to accurately represent the adsorption capacity of orthophosphate in other batch studies (Özacar 2006; Song et al. 2011; Vacca et al. 2016). The Langmuir isotherm model can be used to predict the maximum concentration of orthophosphate that can be adsorbed to the soil if the soil is at equilibrium with aqueous orthophosphate in a SCM. The maximum PO_4 concentration that can be adsorbed (Q_M) in mg/L is based on the sorbed orthophosphate concentration at equilibrium (q_e) in mg/L, dissolved orthophosphate concentration at equilibrium (C_e) in mg/L, and the Langmuir adsorption constant (K_{ad}) in L/mg as seen in Equation 6.

$$q_e = \frac{Q_M * K_{ad} * C_e}{1 + K_{ad} * C_e} \qquad \text{(Equation 6)}$$

Each soil type has a unique Langmuir adsorption constant that was determined from the batch isotherm data using a non-linear curve fitting technique. The results of the batch isotherm study are presented in Figure 64 and Table 37.

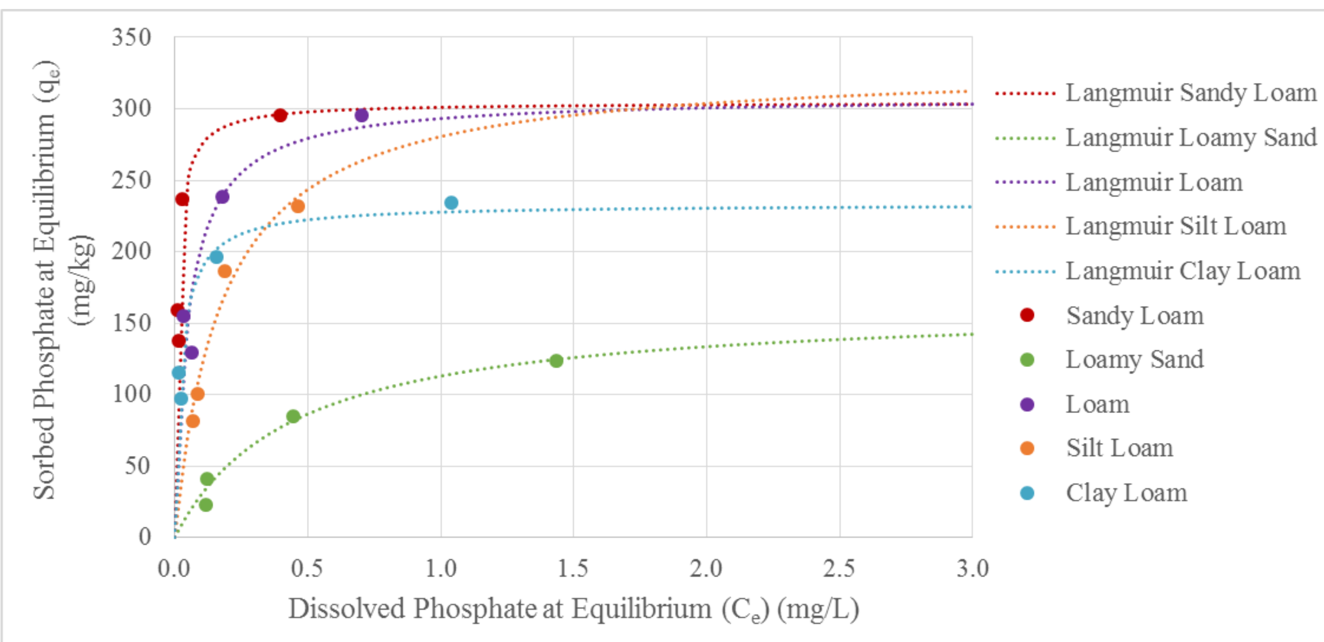

Figure 64: Orthophosphate Batch Isotherm Sorption Results for the Five Soil Types

To determine the maximum orthophosphate adsorption capacity of each soil type, the concentration of orthophosphate initially sorbed to each soil type was determined. As they existed in nature, the sandy loam and loam soils had the highest initial orthophosphate concentration, and the loamy sandy contained the lowest initial orthophosphate concentration (Table 37). The maximum adsorption capacity represents the total number of binding sites available for orthophosphate sorption. Based on the batch study and Langmuir isotherm model, the loamy sand has the lowest orthophosphate holding capacity at 164 mg/kg, as expected due to the coarseness of the material and the measured CEC value. The sandy loam and loam have similar maximum adsorption capacities of 305 and 309 mg/kg, respectively, and the silt loam has the highest maximum adsorption capacity of 331 mg/kg. Despite having one of the higher CEC values, the clay loam has the second lowest orthophosphate holding capacity of 234 mg/kg. No direct relationship can be made between the CEC and the maximum orthophosphate adsorption capacity.

Table 37: Langmuir Constants, Maximum Adsorption Capacity, and CEC Comparison

	Sandy Loam	**Loamy Sand**	**Loam**	**Silt Loam**	**Clay Loam**
Initial Sorbed Phosphate (mg/kg)	137.2	30.7	132.7	87.2	97.8
Additional Phosphate Holding Capacity (mg/kg)	167.6	133.1	176.2	244.0	135.6
Langmuir Constant (K_{ad}) (L/mg)	90.55	2.24	19.10	5.55	40.53
Maximum Adsorption Capacity (Q_M) (mg/kg)	304.8	163.8	308.9	331.2	233.5
CEC ($cmol^+/kg$)	9.39	10.41	17.81	12.09	17.08

Although the maximum adsorption capacity is telling in some circumstances, the additional orthophosphate holding capacity indicates how much orthophosphate the soil can actually hold, and was calculated by subtracting the orthophosphate concentration initially present on the soil from the maximum adsorption capacity. The additional orthophosphate holding capacity exhibits the same trend as the maximum orthophosphate holding capacity such that the silt loam, sandy loam and loam will be able to retain the most orthophosphate, and the clay loam and loamy sand will retain the least. Although, based on the lower initial concentration of orthophosphate on the silt loam, the silt loam is expected to have the highest additional orthophosphate holding capacity at 244 mg/kg, much higher than the other soil types.

The Langmuir constant (K_{ad}), which is related to the initial slope of the sorption curve (Figure 64), physically represents the Gibbs free energy exchange, specifically how easily a molecule is brought from the liquid phase to the bound state at the soil interface (Volesky 2004). In other words, K_{ad} is related to the adsorption binding energy, and a higher K_{ad} value represents a higher affinity of the orthophosphate (adsorbate) to the soil (adsorbent). The Langmuir constants of the sandy loam and clay loam are much higher than that of the other soil types, indicating a better binding between these two soils and orthophosphate. The Langmuir constant, i.e. the slope of the isotherm, comes into play when looking at the range of the aqueous orthophosphate concentration. Although the silt loam has the highest maximum adsorption capacity, it does not reach this capacity unless the concentration of orthophosphate in solution is about 2 mg/L because of the lower K_{ad} value (Figure 64). The typical concentration of orthophosphate in stormwater runoff is about 0.15 mg/L, and the best way to compare the orthophosphate removal among the soil types for pollutant removal in SCMs would be by drawing a vertical line upwards from the x-axis at a concentration of 0.15 mg/L (Figure 64). Comparing the soil types' sorption curves along this line is more telling for which of these soils will perform best in stormwater systems (Volesky 2004). At an aqueous orthophosphate concentration around 0.15 mg/L the loamy sand will still have the worst adsorption potential, but the silt loam will have the second worst at around 100 mg/kg. The sandy loam will have the best orthophosphate removal potential around 275 mg/kg, followed by the loam and clay loam, around 225 mg/kg and 200 mg/kg, respectively. The sorption potential at this concentration can be directly related to the modeled Langmuir constant (K_{ad}). While the maximum orthophosphate adsorption capacity is important, considering the Langmuir constant is also telling if the concentration of adsorbate in solution is known. Based on the batch isotherm study and the influent orthophosphate concentration of 0.15 mg/L that was used in this field study, it is expected that the sandy loam and loam soil will see the most phosphorous removal in the field.

4.2.2 Quality Testing in the Lysimeters

This section will discuss the results of the water quality testing performed at the Optimal Balance site as described in Section 3.2.1. Influent and effluent samples from all twelve lysimeters were analyzed for Cl^-, TKN, NO_2, NO_x, TKP, and PO_4 using a Simplicity Discrete Analyzer (Table 10). Ten different quality events were performed between March and October of 2016 (Table 8), and the results presented in this section represent an average of those events. Because the influent concentration of each nutrient was kept relatively constant among events, the results of each individual event are not presented in this section. The full water quality results of each testing event can be seen in the Appendix in Tables A2 through A9.

The pH, conductivity (μS/cm), and temperature (°C) of each sample was also measured for each event. No relationships were found between either of these parameters and the effluent nutrient concentrations. Varying pH within the neutral range, between about 6 and 8, has been shown to have negligible effects on effluent nutrient concentrations (Davis et al. 2006). The pH of samples tested in this study ranged from 6.87 to 8.41 with an average pH of 7.69, so it is not surprising that a relationship between pH and effluent concentration was not found. Varying temperatures have shown to have no influence on phosphorus removal (Barrett et al. 2013; Blecken et al. 2010), but increased temperatures have been related to higher effluent concentrations of nitrate and nitrite due to increased nitrification (Davis et al. 2006). Such a relationship between temperature and NO_x concentration was not observed in this study, possibly due to fairly consistent temperatures averaging around 23.42 °C (74.16 °F). Finally, although electrical conductivity can indicate the concentration of an ion in solution, such as PO_4^{3-}, effluent nutrient concentrations did not vary drastically among soil type, leading to little discrepancy between effluent concentration and conductivity.

4.2.2.2 Chloride

As discussed in Chapter 3, chloride concentrations were measured since it is a conservative tracer. The effluent chloride concentrations were used to confirm the volume of water that was stored during each storm simulation event. Chloride is non-reactive and should not sorb to the soil media; therefore any chloride that is removed in the lysimeter should indicate water than was stored in the media. Hypothetically, if no water was stored in the media during the simulation, the influent and effluent concentrations of chloride should be equal. Based on the quantity data discussed in Chapter 4.1, water is stored in the media during storm simulations, and the chloride concentration stored in the media should reflect that volume.

To confirm this, the effluent chloride concentrations in each lysimeter were subtracted from the influent concentration to get the concentration of chloride stored in the media during each storm simulation. The distribution of chloride between what was stored in the media and what left with the effluent at the time of sample collection is shown in orange (Figure 65). The volume of water stored in each lysimeter during this same time frame was calculated based on the known inflow and lysimeter weights and is shown in blue (Figure 65). The average percentage of chloride stored in the media and average percentage of water stored in the media, indicated by the lighter portions of the chart, are equal, confirming the accuracy of the water quantity measurements.

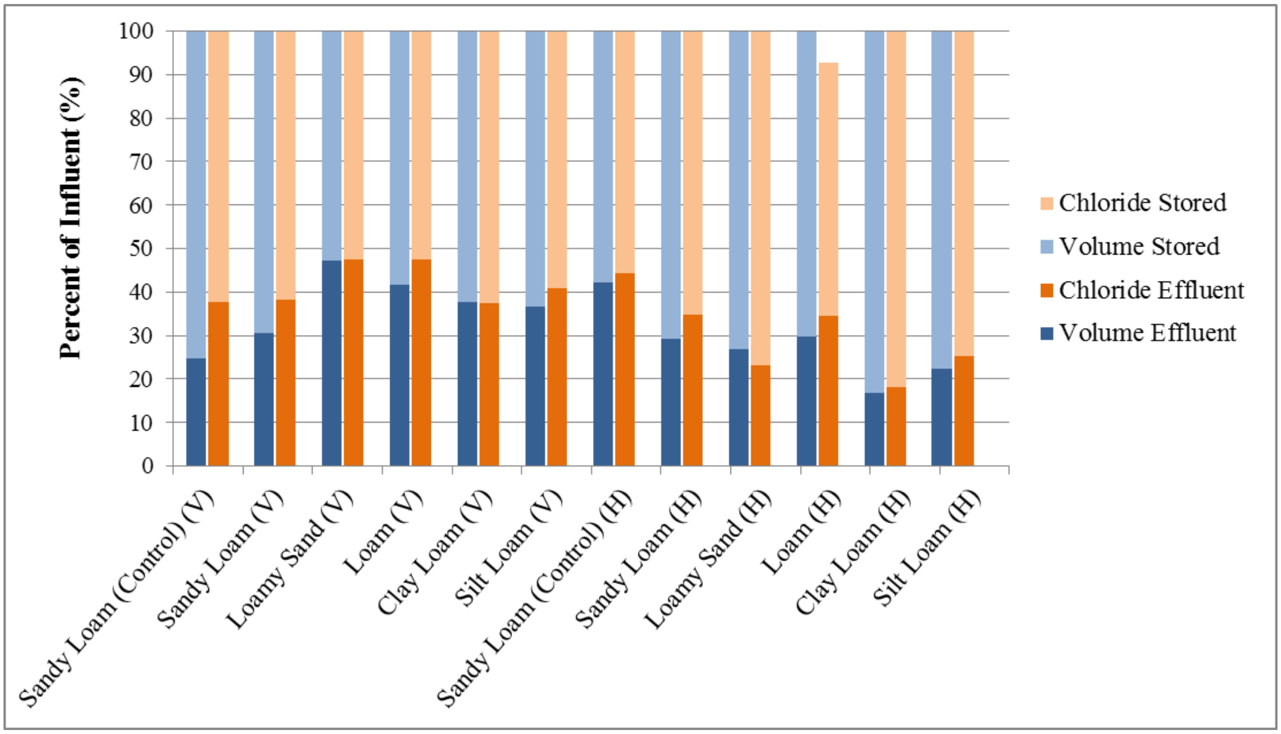

Figure 65: Percent of Chloride Mass Stored versus Percent of Water Volume Stored following a Storm Simulation

For all twelve lysimeters, a clear relationship between chloride storage and volume storage can be seen. The average error between chloride storage and water storage in the lysimeters is small at 3.6%, which can be attributed to the error in instrumentation alone. The variation in chloride storage between flow configurations and among soil types confirms the data discussed in Chapter 4.1. The horizontal lysimeters store more water than the vertical lysimeters, and coarser soils such as the loamy sand store less water in the media than finer grained soils. In all lysimeters, the amount of water and chloride stored ranges between 55% and 85%, noticeably greater than the mass leaving the lysimeters. Although this may seem like a lot of water being stored in the media, these values represent the time right after the storm simulation was turned off, before any water had a chance to be removed through ET.

4.2.2.3 Phosphorus

Phosphorus removal was very good in all soil types and flow configurations, removing up to 98.3% of the total influent phosphorus mass. For all events, the average influent TKP concentration was 0.627 mg/L, and the average influent PO_4 concentration was 0.604 mg/L, with PO_4 accounting for the majority of influent phosphorus (Tables 38 and 39). Figure 66 shows the average effluent total phosphorus concentration in each lysimeter, broken down into PO_4 (dark green) and all remaining forms of P (light green). The entire green bar represents the average total phosphorus concentration, or TKP, in the effluent samples. Effluent orthophosphate concentrations ranged from 0.024 mg/L to 0.052 mg/L in all lysimeters, far below the median orthophosphate concentration of 0.257 mg/L observed in bioretention SCMs as part of the International Stormwater BMP Database (Leisenring et al. 2014). Effluent TKP concentrations ranged from 0.052 mg/L to 0.141 mg/L, also below the median 0.240 mg/L observed in bioretention SCMs (Leisenring et al. 2014).

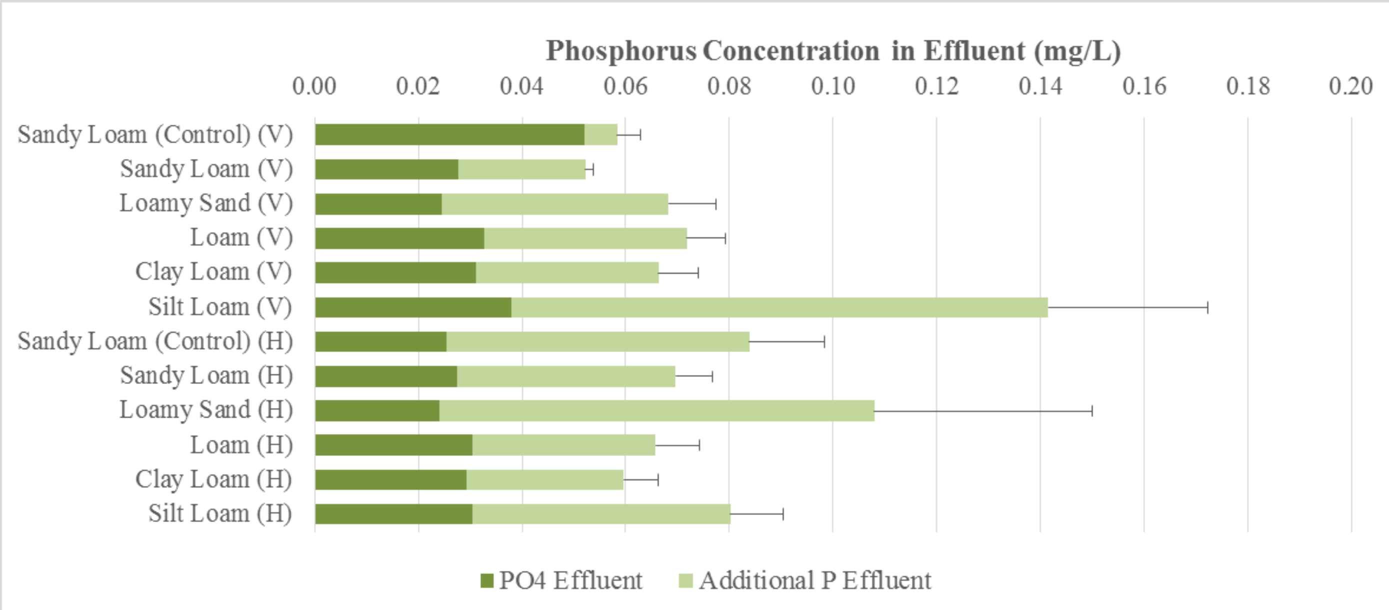

Figure 66: Average and Standard Error of the Effluent Phosphorus Concentrations in the Vertical and Horizontal Lysimeters Following a Storm Simulation (n=7)

As seen in Figure 66, effluent phosphorus concentrations showed little variation between the vertical and horizontal configurations. Paired statistical t-tests were performed between the vertical and horizontal lysimeters in terms of effluent PO_4 and TKP concentrations which can be seen in the Appendix (Table A10). The results of these tests indicate at a 95% confidence level there is no difference in effluent PO_4 concentration between the two flow configurations for any of the soil types. The tests also indicate that there is no difference in effluent TKP concentrations between the vertical and horizontal configurations, besides for the silt loam, in which the average effluent concentration is significantly higher in the vertical configuration.

Tables 38 and 39 display the PO_4 and TKP results, respectively, in terms of effluent concentration, percent removal, mass retained, and percent removal on a mass basis in the vertical and horizontal lysimeters. Percent removal of PO_4 on a concentration basis ranges from 91.3% to 96.0% in the vertical lysimeters and from 94.8% to 96.0% in the horizontal lysimeters (Table 38).

Percent removal of TKP on a concentration basis ranges from 77.0% to 91.2% in the vertical lysimeters and 81.9% to 90.1% in the horizontal lysimeters (Table 39). In general, orthophosphate sees slightly better removal than TKP as expected due to its affinity to soil particles.

There seems to be no variation in phosphorus removal among the different soil types in either configuration. To test this hypothesis, paired statistical t-tests were performed at the 95% confidence level (Table A16 and A17). It was found that there was no difference in effluent PO_4 concentrations among any of the soil types in the vertical configuration (Table A16). It was also found that there was no difference in TKP concentrations in any of the soil types in the vertical configuration, except for the silt loam which saw slightly higher effluent TKP concentrations than the other soil types (Table A17). The tests also indicate no significant difference in effluent PO_4 or TKP concentrations in the horizontal configuration between any of the soil types (Tables A16 and A17).

Table 38: Effluent Concentration, Mass Removal, and Percent Removal for Orthophosphate (PO_4) in the Vertical and Horizontal Lysimeters (n=8)

Flow Path	PO_4 Influent Conditions	PO_4 Effluent Conditions	A/G: Sandy Loam (Control)	B/H: Sandy Loam	C/I: Loamy Sand	D/J: Loam	E/K: Clay Loam	G/L: Silt Loam
Vertical Flow Configuration	Influent Concentration = 0.604 ± 0.1 mg/L	Effluent Concentration (mg/L)	0.052 ± 0.028	0.027 ± 0.013	0.024 ± 0.013	0.032 ± 0.016	0.031 ± 0.011	0.037 ± 0.017
		Percent Removal (Concentration Basis) (%)	91.3 ± 5.4	95.5 ± 1.7	96.0 ± 1.7	94.8 ± 1.9	95.0 ± 1.3	93.6 ± 3.2
	Influent Mass= 0.788 ± 0.2 mg	Mass Retained (mg)	0.773 ± 0.059	0.729 ± 0.144	0.772 ± 0.170	0.770 ± 0.170	0.763 ± 0.180	0.768 ± 0.170
		Percent Removal (Mass Basis) (%)	97.9 ± 0.4	98.3 ± 0.7	98.1 ± 1.2	97.9 ± 1.2	98.1 ± 0.7	97.6 ± 1.0
Horizontal Flow Configuration	Influent Concentration = 0.604 ± 0.1 mg/L	Effluent Concentration (mg/L)	0.025 ± 0.012	0.027 ± 0.011	0.024 ± 0.012	0.030 ± 0.013	0.029 ± 0.012	0.030 ± 0.011
		Percent Removal (Concentration Basis) (%)	95.8 ± 1.7	95.4 ± 1.5	96.0 ± 1.7	94.8 ± 1.9	95.2 ± 1.5	94.8 ± 2.1
	Influent Mass= 3.014 ± 0.7 mg	Mass Retained (mg)	2.964 ± 0.667	2.788 ± 0.497	2.978 ± 0.664	2.785 ± 0.495	2.992 ± 0.667	2.975 ± 0.664
		Percent Removal (Mass Basis) (%)	98.3 ± 0.9	98.3 ± 1.0	98.8 ± 0.8	98.2 ± 1.1	99.3 ± 0.4	98.7 ± 0.8

Table 39: Effluent Concentration, Mass Removal, and Percent Removal for Total Kjeldahl Phosphorus (TKP) in the Vertical and Horizontal Lysimeters (n=7)

Flow Path	TKP Influent Conditions	TKP Effluent Conditions	A/G: Sandy Loam (Control)	B/H: Sandy Loam	C/I: Loamy Sand	D/J: Loam	E/K: Clay Loam	G/L: Silt Loam
Vertical Flow Configuration	Influent Concentration = 0.627 ± 0.1 mg/L	Effluent Concentration (mg/L)	0.058 ± 0.011	0.052 ± 0.004	0.068 ± 0.024	0.071 ± 0.020	0.066 ± 0.020	0.141 ± 0.081
		Percent Removal (Concentration Basis) (%)	90.5 ± 3.5	91.2 ± 1.9	88.5 ± 5.2	88.2 ± 3.9	88.9 ± 4.1	77.0 ± 12.3
	Influent Mass= 0.737 ± 0.2 mg	Mass Retained (mg)	0.737 ± 0.053	0.653 ± 0.154	0.703 ± 0.214	0.704 ± 0.218	0.711 ± 0.224	0.690 ± 0.200
		Percent Removal (Mass Basis) (%)	96.9 ± 0.7	96.6 ± 0.4	95.6 ± 1.5	95.5 ± 1.4	96.4 ± 1.6	94.2 ± 2.0
Horizontal Flow Configuration	Influent Concentration = 0.627 ± 0.1 mg/L	Effluent Concentration (mg/L)	0.083 ± 0.039	0.069 ± 0.019	0.107 ± 0.111	0.065 ± 0.022	0.059 ± 0.017	0.080 ± 0.026
		Percent Removal (Concentration Basis) (%)	86.8 ± 4.7	88.2 ± 3.6	81.9 ± 19.2	88.7 ± 4.6	90.1 ± 3.7	87.1 ± 4.6
	Influent Mass= 2.819 ± 0.9 mg	Mass Retained (mg)	2.684 ± 0.840	2.606 ± 0.551	2.751 ± 0.858	2.467 ± 0.589	2.774 ± 0.869	2.907 ± 0.796
		Percent Removal (Mass Basis) (%)	95.2 ± 1.9	96.6 ± 1.5	97.6 ± 1.1	96.8 ± 1.9	98.3 ± 1.6	97.5 ± 1.2

Phosphorus removal was also converted to a mass basis based on the known volume of runoff entering the lysimeters. In the vertical lysimeters, the mass of PO_4 retained in the media ranged from 0.729 mg to 0.773 mg, and the mass of TKP retained in the media was slightly less, ranging from 0.653 mg to 0.737 mg. The horizontal lysimeters retain more phosphorus on a mass basis than the vertical lysimeters due to the increased mass of P entering the system. Since the horizontal lysimeters receive roughly 3.8 times the volume of water as the vertical lysimeters, the incoming nutrient load is also 3.8 times higher on a mass basis. The horizontal lysimeters retain an average between 2.788 mg and 2.978 mg of PO_4 out of the influent 3.014 mg. This mass retained translates to a removal rate of PO_4 on a mass basis between 97.6% and 98.3% in the vertical lysimeters and between 98.3% and 99.3% in the horizontal lysimeters. On a mass basis, between

94.2% and 96.9% of TKP is removed in the vertical lysimeters and between 95.2% and 98.3% in the horizontal lysimeters. Percent removal of phosphorus on a concentration and mass basis can be seen in the Appendix in graphical form in Figures A22 and A23. While there is a slight increase in removal rate when moving from a concentration to a mass basis, this increase is very small since the removal rates of PO_4 and TKP are already so high on a concentration basis. This is expected due to the predictable removal of phosphorus, especially PO_4, through soil sorption.

Based on the known mass of phosphorus applied to the lysimeters, Figure 67 displays the distribution of phosphorus between what was retained and what left with the effluent water. The orange portion of the bars represents the phosphorus that was sorbed to the soil media, and the green portion represents the mass that left with the effluent water. As discussed previously, phosphorus removal was very good, with 95% to 99% of total phosphorus being removed in the different media and flow configurations. Orthophosphate (PO_4) was the dominating species of phosphorus removed in the system, with other forms of P being the main exports from the lysimeters. The difference in effluent phosphorus concentrations among the soil types seen in Figure 66 is muddled in Figure 67 due to the overall high removal rates of P. As shown by the t-tests, there is no variation in PO_4 or TKP removal among the different media, despite one exception in the vertical lysimeters.

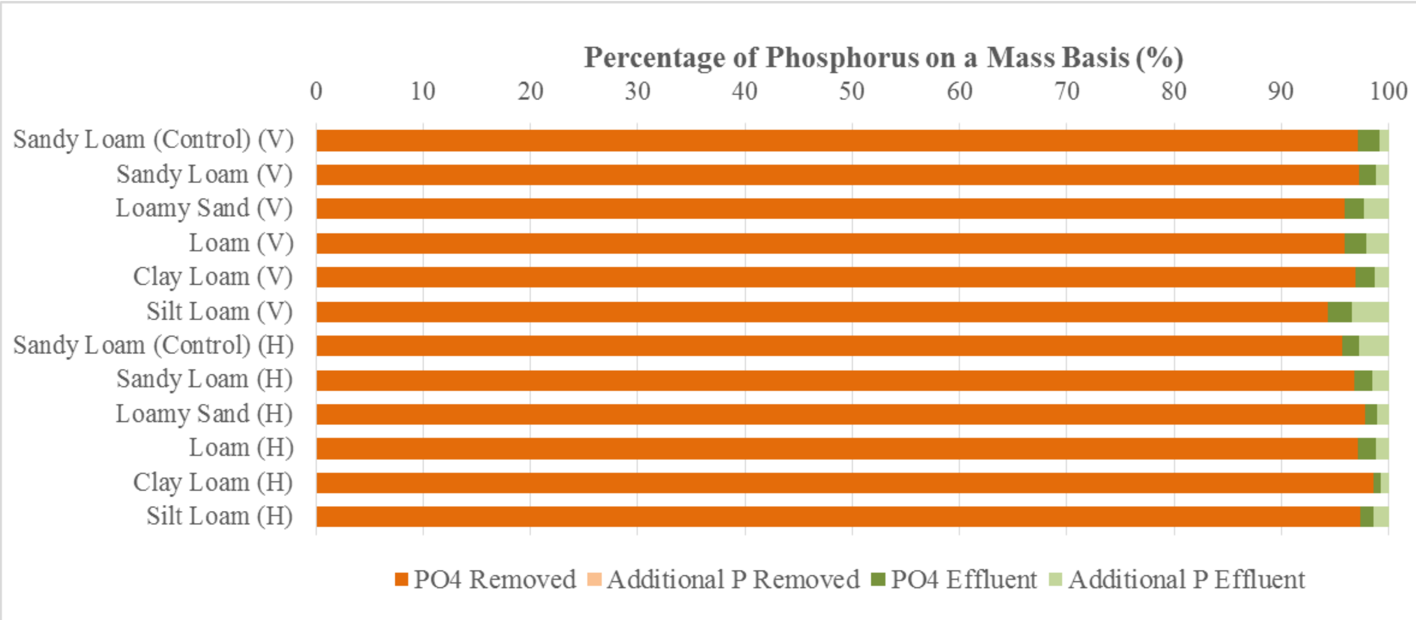

Figure 67: Average Distribution between the Mass of Phosphorus Stored in the Media and the Mass of Phosphorus in the Effluent Water for each Lysimeter following a Storm Simulation

The differences in orthophosphate adsorption potential among the media shown at the laboratory scale (through the batch isotherm tests) are not visible in the field results. Despite some of the media having different maximum adsorption capacities of orthophosphate on the laboratory scale, this does not come into play on the field scale due to the mass of soil used in these systems. The maximum adsorption capacity of PO_4 determined from the isotherm tests, around 300 mg/kg, is much greater than the mass of PO_4 these systems will see in the field. The vertical lysimeters, which contain around 1 kg of soil, retain about 0.7 mg of soil during each inflow event. This means that the vertical lysimeters could potentially adsorb orthophosphate from about 430 different loading events before reaching their maximum capacity. A typical rain garden, which contains about 75,000 times the amount of soil the vertical lysimeters do, would be capable of removing orthophosphate from over 32 million runoff events at a 5:1 loading ratio before it reached its maximum orthophosphate adsorption capacity. The maximum adsorption discrepancy among different types of media on the laboratory scale does not come into play in larger scale systems such as bioretention SCMs because of the mass amount of media used. From a phosphorus removal basis, the type of soil media used in a rain garden does not make a difference. Regardless of the type of media used, total phosphorus removal averaged around 87% on a concentration basis and 97% on a mass basis.

4.2.2.4 Nitrogen

Nitrogen removal was more varied than phosphorus removal among testing events and soil types, as expected, due to the many different species of nitrogen found in stormwater runoff and their complex removal mechanisms. As stated, the results presented for nitrogen in this section represent an average of the quality testing events performed at the Optimal Balance site, and detailed results for the individual testing events can be found in the Appendix in Tables A2 through A7. Concentrations of NO_2, NO_x, NH_3, and TKN were measured directly. NO_3 concentrations were calculated by subtracting NO_2 from NO_x, and total nitrogen (TN) concentrations were calculated by adding the NO_x and TKN concentrations. The average influent TN concentration for all events was 4.248 mg/L, and average effluent TN concentrations ranged from 0.742 mg/L to 2.970 mg/L in the different lysimeters. Figure 68 compares the average effluent nitrogen concentrations broken down into the different species of nitrogen.

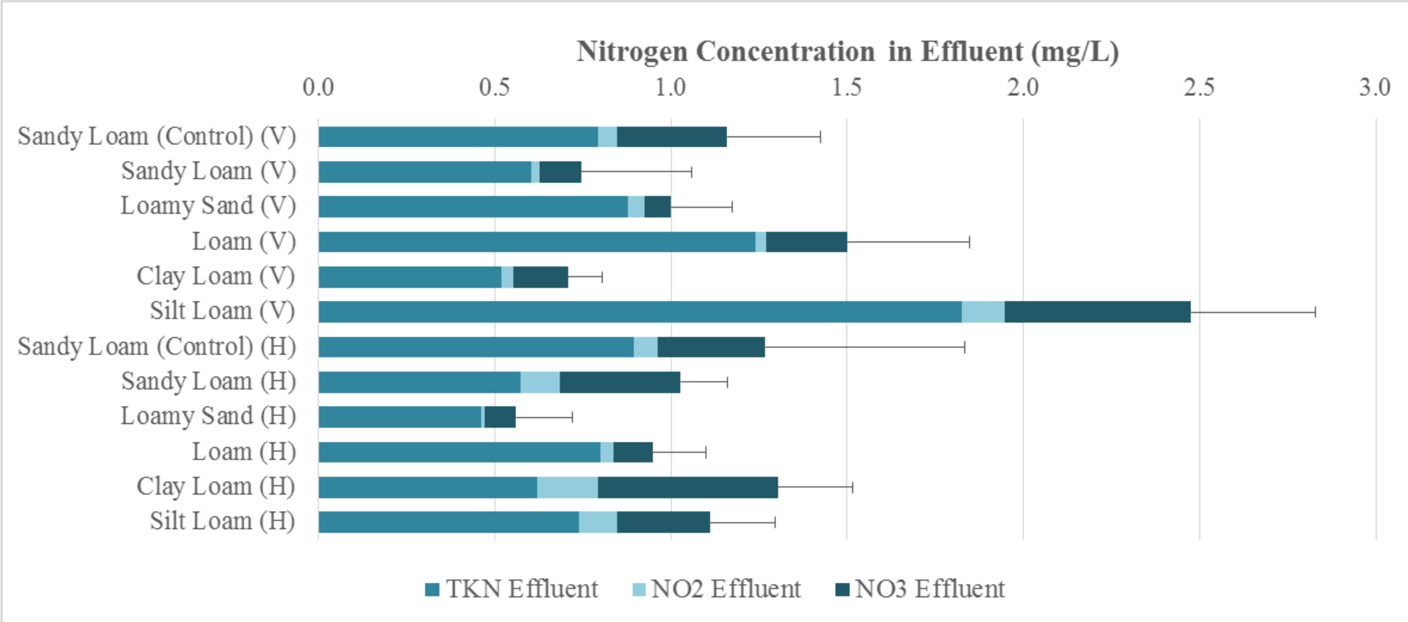

Figure 68: Average and Standard Error of the Effluent Nitrogen Concentrations in the Vertical and Horizontal Lysimeters Following a Storm Simulation

TKN accounts for the largest percentage of the effluent nitrogen concentration because it has the highest influent concentration of all species at 2.753 mg/L. Although NO_3 concentrations are noticeably higher than NO_2 in the effluent, the lysimeters saw a better reduction in NO_3 concentration than NO_2 concentration. (Table 40 and 41). Based on the effluent nitrogen concentrations, it is not clear if one flow configurations performed better than the other. Paired statistical t-tests were performed at the 95% confidence level to see if there was any difference in effluent nitrogen concentrations between the vertical and horizontal configurations for each soil type (Table A10). For nitrate and total nitrogen, there was no significant difference between the two configurations in any of the soil types. The loamy sand performed significantly better in the horizontal configuration for NO_2 removal, but NO_2 removal was comparable between configurations in all other soil types. Effluent NO_x concentrations were significantly higher in the vertical silt loam than the horizontal silt loam, but the same in all other media (Table A10). Finally, effluent TKN concentrations did not differ significantly between the two flow configurations, except for the loamy sand and loam which had higher effluent TKN concentrations in the vertical configuration. Any significant differences in effluent nitrogen concentrations between the two configurations consist of the horizontal configuration performing better than the vertical configuration. It was expected that the horizontal configuration would perform better in terms of nitrogen removal because of the longer hydraulic retention time, but it cannot be said for all soil types that the longer hydraulic retention time increased nitrogen removal. It was hypothesized that the horizontal configuration would act similar to an internal water storage zone such that a denitrification zone would be formed, increasing NO_3 removal. Since the NO_3 concentrations were shown not to be affected by flow configuration in any soil type, it can be concluded that no such denitrification zone was formed. This may be because there was not a substantial carbon source available for denitrification and because the lysimeters were too small for a denitrification zone to be formed. Also, although some species of nitrogen were removed better in the horizontal configuration, effluent total nitrogen concentrations were not different between the different flow configurations, concluding that the longer hydraulic retention time in the horizontal configuration did not improve overall nitrogen retention (Table A10).

Tables 40 through 45 show the performance of nitrogen in terms of effluent concentration, percent removal, mass retained, and percent removal on a mass basis in the vertical and horizontal lysimeters. Nitrite (NO_2) saw the most variation in effluent concentration among the different storm testing events and in turn the lowest removal rates of all nitrogen species (Table 40). Influent nitrite concentrations were the lowest of all species of nitrogen, averaging 0.593 mg/L. Although the average effluent NO_2 concentrations ranged between 0.011 mg/L and 0.193 mg/L in the different soil types and flow configurations, some individual events actually saw production of nitrite within the lysimeters. The production of nitrite is reflected by the negative removal rates in some of the soil media in both flow configurations (Table 40). Removal rates of NO_2 on a concentration basis ranged from -75.2% to 37.2% in the vertical lysimeters and from -40.4% to 52.5% in the vertical lysimeters. These low removal rates can be attributed to a few events where effluent concentrations of NO_2 were up to 500 times higher than the influent concentration. Table A2 in the Appendix shows the change in effluent NO_2 concentrations during the different events. Although there were some events with very bad removal of NO_2, others had removal rates of over 99%. This variation in effluent NO_2 among events is reflected by the very high standard deviations in nitrite reduction (Table 40). Removal efficiency of NO_2 could not be correlated to any other factors such as antecedent dry time, and the removal efficiency of NO_2 between events and among different soil types was somewhat random.

To see if there was any correlation between NO_2 removal and the different soil types, paired statistical t-tests were performed (Table A11). At a 95% confidence level the effluent concentrations of NO_2 in the vertical silt loam were significantly higher than all other soil types in the vertical configuration. Also, effluent NO_2 concentrations were significantly lower in the vertical sandy loam compared to the control and the loamy sand. In the horizontal configuration, there were no differences in effluent NO_2 concentrations in any of the soil types. It is hypothesized that there may have been some macropores or preferential flow paths in the vertical silt loam since the horizontal silt loam performed as well as all other soil types in the horizontal flow configuration.

Table 40: Effluent Concentration, Mass Removal, and Percent Removal for Nitrite (NO_2) in the Vertical and Horizontal Lysimeters (n=8)

Flow Path	NO_2 Influent Conditions	NO_2 Effluent Conditions	A/G: Sandy Loam (Control)	B/H: Sandy Loam	C/I: Loamy Sand	D/J: Loam	E/K: Clay Loam	G/L: Silt Loam
Vertical Flow Configuration	Influent Concentration = 0.593 ± 1.2 mg/L	Effluent Concentration (mg/L)	0.054 ± 0.024	0.024 ± 0.016	0.049 ± 0.028	0.034 ± 0.018	0.039 ± 0.032	0.136 ± 0.096
		Percent Removal (Concentration Basis) (%)	-13.9 ± 122.8	37.2 ± 37.8	3.7 ± 68.5	29.5 ± 50.8	6.4 ± 100.2	-75.2 ± 228.3
	Influent Mass= 1.019 ± 1.8 mg	Mass Retained (mg)	1.101 ± 2.080	0.794 ± 1.822	0.982 ± 1.716	0.996 ± 1.714	1.130 ± 1.782	1.264 ± 1.725
		Percent Removal (Mass Basis) (%)	65.0 ± 41.5	78.8 ± 13.7	62.7 ± 28.9	76.4 ± 17.7	70.2 ± 25.4	23.1 ± 128.8
Horizontal Flow Configuration	Influent Concentration = 0.593 ± 1.2 mg/L	Effluent Concentration (mg/L)	0.076 ± 0.113	0.112 ± 0.132	0.011 ± 0.004	0.045 ± 0.039	0.193 ±0.371	0.106 ± 0.147
		Percent Removal (Concentration Basis) (%)	-10.4 ± 103.5	6.9 ± 79.4	52.5 ± 46.1	-40.4 ± 137.4	2.8 ± 72.9	-36.3 ± 179.0
	Influent Mass= 3.907 ± 6.9 mg	Mass Retained (mg)	4.199 ± 6.538	4.119 ± 6.766	4.417 ± 6.922	4.988 ± 7.283	4.157 ± 6.426	4.308 ± 7.226
		Percent Removal (Mass Basis) (%)	59.0 ± 38.2	70.4 ± 31.3	89.4 ±13.0	72.0 ± 25.5	81.6 ± 21.9	57.5 ± 78.5

Nitrite concentrations were also converted to a mass basis based on the known influent volume of water. On a mass basis, removal of NO_2 ranged from 23.1% to 78.8% in the vertical lysimeters and between 57.5% and 89.4% in the horizontal lysimeters. Although there was nitrite production during some events, mass reduction of nitrite was positive on average for all soil types in both flow configurations. Also, because the influent concentration of nitrite was so small in comparison to the total nitrogen concentration, as is the case in typical stormwater runoff, the poor NO_2 removal does not play a large role in overall nitrogen removal.

Table 41 shows the average performance of nitrate (NO_3) in the different lysimeters. In both configurations, the average effluent NO_3 concentration ranged from 0.088 mg/L to 0.549 mg/L, translating to a removal rate between 47.1% and 86.5% on a concentration basis. Data from the International Stormwater BMP database indicates a median effluent NO_3 concentration of 0.39 mg/L in bioretention systems, consistent with the values measured in this study (Leisenring et al. 2014). Except for one storm event (Table A3), nitrate was not produced in any of the lysimeters. Removal rates of nitrate increase when converted from a concentration to a mass basis, with up to 96.7% of NO_3 removed on a mass basis. It is somewhat surprising that nitrate retention was decent since similar studies saw very low nitrate retention and some nitrate production (Davis et al. 2006; Hsieh et al. 2007). Because nitrite removal was poor and nitrate removal was decent in this study, the process of nitrification, which converts NO_2 to NO_3, may have been limited in the lysimeters. Paired statistical t-tests indicate at the 95% confidence level that the type of soil, in either the vertical or horizontal configuration, did not play a role in nitrate removal (Table A12).

Table 41: Effluent Concentration, Mass Removal, and Percent Removal for Nitrate (NO_3) in the Vertical and Horizontal Lysimeters (n=5)

Flow Path	NO_3 Influent Conditions	NO_3 Effluent Conditions	A/G: Sandy Loam (Control)	B/H: Sandy Loam	C/I: Loamy Sand	D/J: Loam	E/K: Clay Loam	G/L: Silt Loam
Vertical Flow Configuration	Influent Concentration = 0.898 ± 0.6 mg/L	Effluent Concentration (mg/L)	0.313 ± 0.150	0.118 ± 0.085	0.076 ± 0.044	0.231 ± 0.155	0.154 ± 0.082	0.445 ± 0.463
		Percent Removal (Concentration Basis) (%)	68.9 ± 24.3	86.5 ± 7.9	84.3 ± 14.1	74.4 ± 8.0	69.4 ± 23.6	58.7 ± 28.3
	Influent Mass= 1.111 ± 0.7 mg	Mass Retained (mg)	1.521 ± 0.661	1.233 ± 0.684	1.078 ± 0.737	0.973 ± 0.619	0.905 ± 0.695	1.002 ± 0.697
		Percent Removal (Mass Basis) (%)	90.7 ± 8.1	95.8 ± 3.0	93.9 ± 5.9	88.3 ± 4.9	90.0 ± 6.4	83.9 ± 9.3
Horizontal Flow Configuration	Influent Concentration = 0.898 ± 0.6 mg/L	Effluent Concentration (mg/L)	0.306 ± 0.370	0.340 ± 0.272	0.088 ± 0.004	0.109 ± 0.098	0.509 ± 0.549	0.263 ± 0.241
		Percent Removal (Concentration Basis) (%)	57.3 ± 47.4	64.6 ± 20.3	81.4 ± 13.1	81.2 ± 11.1	47.1 ± 39.9	68.6 ± 15.5
	Influent Mass= 4.244 ± 2.8 mg	Mass Retained (mg)	3.775 ± 2.817	3.616 ± 2.021	3.596 ± 2.689	2.394 ± 1.268	3.418 ± 2.360	3.278 ± 2.306
		Percent Removal (Mass Basis) (%)	88.0 ± 16.3	87.0 ± 10.7	96.1 ± 2.3	96.7 ± 1.0	94.1 ± 4.2	91.1 ± 8.8

Concentration reduction of NO_x (Table 42) was similar to that of NO_3, ranging from 50.8% to 89.1% in the vertical configuration and from 48.7% to 84.9% in the horizontal configuration. Effluent NO_x concentrations ranged from 0.108 mg/L to 0.727 mg/L, consistent with NO_x data from other bioretention studies (Leisenring et al. 2014) and far below the water quality standard of 10 mg/L NO_x-N set by the PA DEP (PA DEP 2008). On a mass basis, removal of NO_x ranged from 83.4% to 95.8% in the vertical configuration, and from 82.8% to 96.5% in the horizontal configuration. In the vertical configuration, paired t-tests indicated no difference in effluent NO_x concentration among soil types, except for the vertical silt loam which saw higher effluent concentrations than all other soil types besides the control. In the horizontal configuration the silt loam saw higher effluent concentrations than the loamy sand, but no other significant differences were seen regarding effluent NO_x concentration and media type (Table A13).

Table 42: Effluent Concentration, Mass Removal, and Percent Removal for NO_x in the Vertical and Horizontal Lysimeters (n=9)

Flow Path	NO_x Influent Conditions	NO_x Effluent Conditions	A/G: Sandy Loam (Control)	B/H: Sandy Loam	C/I: Loamy Sand	D/J: Loam	E/K: Clay Loam	G/L: Silt Loam
Vertical Flow Configuration	Influent Concentration = 1.360 ± 0.7 mg/L	Effluent Concentration (mg/L)	0.337 ± 0.137	0.155 ± 0.130	0.108 ± 0.043	0.297 ± 0.272	0.200 ± 0.105	0.727 ± 0.579
		Percent Removal (Concentration Basis) (%)	72.6 ± 22.9	86.7 ± 8.3	89.1 ± 9.8	77.0 ± 16.5	79.4 ± 22.1	50.8 ± 31.9
	Influent Mass= 1.900 ± 1.1 mg	Mass Retained (mg)	2.201 ± 1.210	1.596 ± 1.133	1.832 ± 1.109	1.708 ± 1.076	1.937 ± 1.128	1.577 ± 1.084
		Percent Removal (Mass Basis) (%)	92.2 ± 7.8	95.8 ± 3.0	95.5 ± 3.4	89.6 ± 8.1	93.5 ± 87.6	83.4 ± 13.1
Horizontal Flow Configuration	Influent Concentration = 1.360 ± 0.7 mg/L	Effluent Concentration (mg/L)	0.663 ± 0.750	0.379 ± 0.417	0.194 ± 0.227	0.314 ± 0.456	0.723 ± 0.669	0.518 ± 0.461
		Percent Removal (Concentration Basis) (%)	53.0 ± 50.7	70.3 ± 26.6	84.9 ± 12.4	74.6 ± 25.2	48.7 ± 41.2	63.2 ± 27.1
	Influent Mass= 7.276 ± 4.4 mg	Mass Retained (mg)	6.855 ± 4.137	6.129 ± 4.406	5.988 ± 3.287	6.006 ± 4.655	6.859 ± 4.127	6.536 ± 4.258
		Percent Removal (Mass Basis) (%)	82.8 ± 17.8	88.3 ± 12.5	96.5 ± 2.5	91.7 ± 12.0	94.7 ± 3.7	89.2 ± 11.1

Because of complications with laboratory equipment, NH_3 concentrations were only measured for two storm simulations events. Based on those two events, removal of NH_3 in the lysimeters was good, with the concentration in the effluent decreasing by up to 96.3% (Table 43). On a mass basis, removal of ammonia was up to 99.4%. Removal of ammonia in SCMs is expected to be high based on the transformation of NH_3 to NO_2 and NO_3 through ammonification. Effluent concentrations of NH_3 were very low, ranging from 0.020 mg/L to 0.157 mg/L despite an average influent concentration of 1.525 mg/L.

Table 43: Effluent Concentration, Mass Removal, and Percent Removal for Ammonia (NH_3) in the Vertical and Horizontal Lysimeters (n=2)

Flow Path	**NH_3 Influent Conditions**	**NH_3 Effluent Conditions**	**A/G: Sandy Loam (Control)**	**B/H: Sandy Loam**	**C/I: Loamy Sand**	**D/J: Loam**	**E/K: Clay Loam**	**G/L: Silt Loam**
Vertical Flow Configuration	Influent Concentration = 1.525 ± 1.1 mg/L	Effluent Concentration (mg/L)	NA	NA	0.157 ± 0.097	0.029 ± 0.001	0.042 ± 0.013	0.025 ± 0.013
		Percent Removal (Concentration Basis) (%)	NA	NA	88.2 ± 2.1	96.0 ± 2.9	95.5 ± 2.3	95.3 ± 4.1
	Influent Mass= 2.299 ± 1.7 mg	Mass Retained (mg)	NA	NA	2.151 ± 1.550	2.279 ± 1.657	2.279 ± 1.656	2.292 ± 1.659
		Percent Removal (Mass Basis) (%)	NA	NA	93.7 ± 0.2	98.2 ± 1.3	98.3 ± 1.1	99.3 ± 0.5
Horizontal Flow Configuration	Influent Concentration = 1.525 ± 1.1 mg/L	Effluent Concentration (mg/L)	0.020 ± 0.010	0.030 ± 0.001	0.020 ± 0.014	0.030 ± 0.078	0.027 ± 0.003	0.020 ± 0.010
		Percent Removal (Concentration Basis) (%)	96.3 ± 3.2	93.1 ± 0.0	96.3 ± 3.2	93.1 ± 0.0	96.1 ± 3.0	96.3 ± 3.2
	Influent Mass= 8.816 ± 6.4 mg	Mass Retained (mg)	8.782 ± 6.372	2.413 ± 0.001	8.795 ± 6.368	2.403 ± 0.040	8.786 ± 6.380	8.79 ± 6.366
		Percent Removal (Mass Basis) (%)	98.8 ± 1.0	98.1 ± 0.0	99.3 ± 0.6	97.7 ± 0.0	98.9 ± 1.0	99.4 ± 0.5

Despite some variation in NO_x removal rates, removal of TKN was fairly consistent among events. In both configurations effluent TKN concentrations were decreased by up to 82.1% in the different media (Table 44). Average effluent TKN concentrations in all lysimeters ranged between 0.460 mg/L and 1.826 mg/L, comparable to median concentrations ranging from 1.10 mg/L to 1.40 mg/L in other bioretention studies (Leisenring et al. 2014). Besides for the vertical silt loam, which saw higher effluent concentrations than the control, sandy loam, and clay loam (Table A14), effluent concentrations of TKN were not affected by media type. The paired t-tests also indicate no significant difference in effluent TKN concentrations in any of the horizontal lysimeters. Once again, because the horizontal silt loam performed as well as the other media in the horizontal configuration, it is expected that the vertical silt loam had preferential pathways allowing the nutrients to bypass the media. On a mass basis percent removal of TKN was higher in both configurations, ranging from 70.3% to 98.0%.

Table 44: Effluent Concentration, Mass Removal, and Percent Removal for Total Kjeldahl Nitrogen (TKN) in the Vertical and Horizontal Lysimeters (n=4)

Flow Path	TKN Influent Conditions	TKN Effluent Conditions	A/G: Sandy Loam (Control)	B/H: Sandy Loam	C/I: Loamy Sand	D/J: Loam	E/K: Clay Loam	G/L: Silt Loam
Vertical Flow Configuration	Influent Concentration = 2.753 ± 0.7 mg/L	Effluent Concentration (mg/L)	0.793 ± 0.561	0.602 ± 0.507	0.879 ± 0.351	1.239 ± 0.793	0.518 ± 0.187	1.826 ± 0.324
		Percent Removal (Concentration Basis) (%)	73.6 ± 16.0	81.5 ± 11.8	67.5 ± 12.3	50.2 ± 37.0	79.8 ± 8.1	31.8 ± 12.4
	Influent Mass= 3.589 ± 1.4 mg	Mass Retained (mg)	3.338 ± 1.532	3.373 ± 1.571	2.868 ± 1.220	3.018 ± 1.424	3.292 ± 1.437	2.875 ± 1.574
		Percent Removal (Mass Basis) (%)	92.01 ± 5.8	94.6 ± 2.4	80.5 ± 4.1	76.5 ± 16.0	92.8 ± 2.1	70.3 ± 20.5
Horizontal Flow Configuration	Influent Concentration = 2.753 ± 0.7 mg/L	Effluent Concentration (mg/L)	0.894 ± 0.418	0.574 ± 0.460	0.460 ± 0.112	0.799 ± 0.188	0.622 ± 0.194	0.739 ± 0.362
		Percent Removal (Concentration Basis) (%)	62.9 ± 21.4	79.4 ± 16.9	82.1 ± 5.8	68.0 ± 3.9	74.8 ± 10.9	71.5 ± 15.7
	Influent Mass= 13.718 ± 5.3 mg	Mass Retained (mg)	11.535 ± 6.230	11.774 ± 7.145	12.653 ± 5.488	7.438 ± 3.042	13.048 ± 5.770	11.846 ± 6.026
		Percent Removal (Mass Basis) (%)	86.0 ± 7.9	91.6 ± 6.0	94.3 ± 1.2	91.8 ± 5.7	98.0 ±1.1	91.0 ± 5.0

Total nitrogen removal was calculated based on the combined concentrations of NO_x and TKN. TN removal was good, with the effluent concentration decreasing by between 30.1% and 84.2% in the vertical configuration and between 46.6% and 80.8% in the horizontal configuration (Table 45). All lysimeters decreased the effluent TN concentration below 4.91 mg/L, which is the maximum water quality standard target set by the Pennsylvania DEP (PA DEP 2008). As stated previously, no correlation was found between flow configuration and TN removal. The effluent TN concentrations were significantly higher (95% confidence) in the vertical silt loam than the vertical control, sandy loam and clay loam, which was the same case for TKN. In the horizontal configuration, media type did not significantly affect the effluent total nitrogen concentration. This means that besides for in the vertical silt loam, which is hypothesized to have had preferential flow paths, effluent total nitrogen concentrations were not affected by media type or flow configuration. From a mass basis, the average total nitrogen removal in all lysimeters was between 75.5% and 97.2%.

Table 45: Effluent Concentration, Mass Removal, and Percent Removal for Total Nitrogen (TN) in the Vertical and Horizontal Lysimeters (n=4)

Flow Path	**TN Influent Conditions**	**TN Effluent Conditions**	**A/G: Sandy Loam (Control)**	**B/H: Sandy Loam**	**C/I: Loamy Sand**	**D/J: Loam**	**E/K: Clay Loam**	**G/L: Silt Loam**
Vertical Flow Configuration	Influent Concentration = 4.248 ± 0.7 mg/L	Effluent Concentration (mg/L)	1.146 ± 0.528	0.764 ± 0.628	0.981 ± 0.344	1.781 ± 0.691	0.742 ± 0.192	2.970 ± 0.704
		Percent Removal (Concentration Basis) (%)	74.7 ± 6.9	84.2 ± 10.3	75.8 ± 11.3	55.3 ± 20.3	81.6 ± 6.5	30.1 ± 12.5
	Influent Mass= 4.807 ± 1.9 mg	Mass Retained (mg)	4.894 ± 1.929	5.034 ± 1.921	4.103 ± 1.815	3.946 ± 1.883	4.540 ± 1.884	3.869 ± 2.121
		Percent Removal (Mass Basis) (%)	91.2 ± 1.6	95.0 ± 0.1	86.9 ± 4.7	79.4 ± 11.0	94.8 ± 0.7	75.5 ± 11.3
Horizontal Flow Configuration	Influent Concentration = 4.248 ± 0.7 mg/L	Effluent Concentration (mg/L)	2.101 ± 1.129	1.440 ± 0.265	0.771 ± 0.320	1.676 ± 0.306	2.030 ± 0.425	1.700 ± 0.374
		Percent Removal (Concentration Basis) (%)	46.6 ± 29.3	64.4 ± 12.0	80.8 ± 8.8	55.7 ± 5.5	51.1 ± 12.1	58.1 ± 12.5
	Influent Mass= 18.366 ± 7.5 mg	Mass Retained (mg)	16.317 ± 7.571	18.155 ± 7.293	17.534 ± 7.193	13.783 ± 0.399	17.805 ± 6.952	16.707 ± 7.096
		Percent Removal (Mass Basis) (%)	88.0 ± 3.7	95.2 ± 3.4	95.9 ± 0.2	92.3 ± 0.0	97.2 ±1.2	94.2 ± 3.0

Figures A24 through A29 in the Appendix compare the percent removal of the different nitrogen species on a concentration basis and on a mass basis. For all species of nitrogen, percent removal on a mass basis is much greater than percent removal on a concentration basis. For phosphorus there was not much increase in removal going from a concentration to a mass basis, but for nitrogen, whose removal rates were much lower and varied in terms of concentration, the mass removal was much higher. This trend shows the important role of volume reduction in pollutant reduction, especially for nitrogen, in stormwater control measures. As seen with other studies (Brown et al. 2009; Li and Davis 2014), the majority of nitrogen reduction through SCMs can be attributed to the physical volume removal of water.

Figure 69 displays the mass distribution of nitrogen in all twelve lysimeters between what was retained in the media and what left with the effluent water. The purple portion of the bars represents the nitrogen that was sorbed to the soil media, and the blue portion represents the mass that left with the effluent water. The different shades of purple and blue depict the different species of nitrogen (Figure 69).

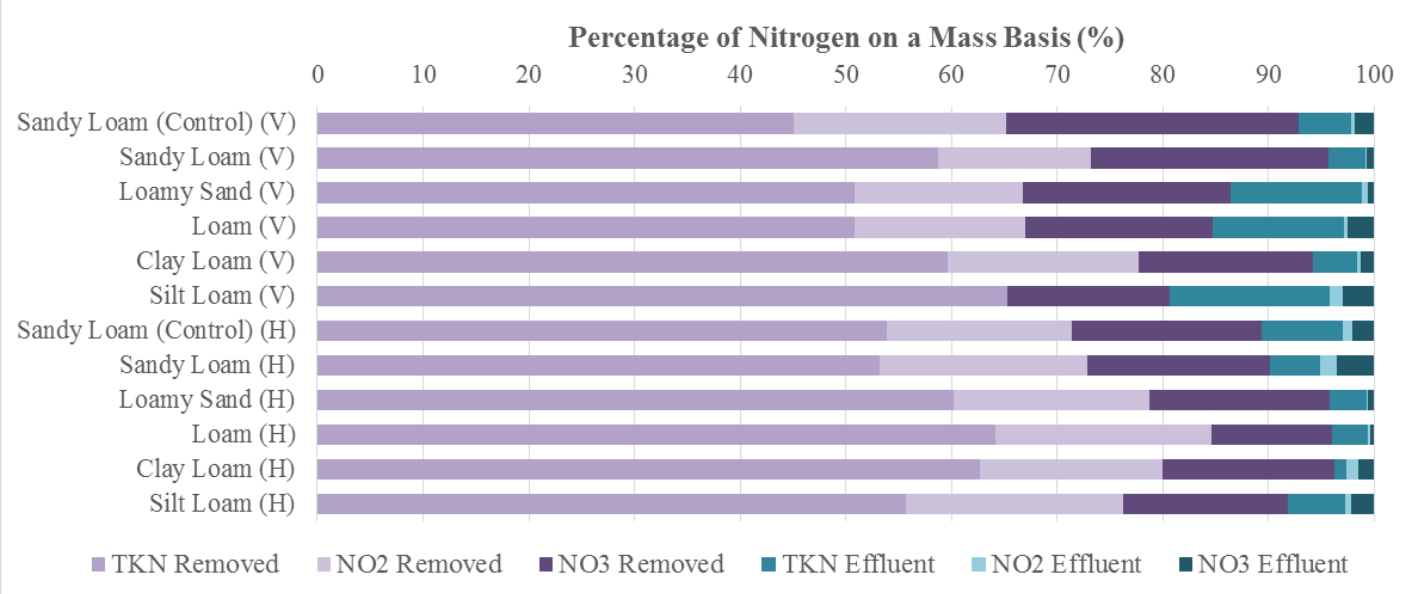

Figure 69: Average Distribution between the Mass of Nitrogen Stored in the Media and the Mass of Nitrogen in the Effluent Water for each Lysimeter following a Storm Simulation

All paired t-tests referenced previously in this section compare the effluent nutrient concentrations between the different soil types. Although there was a couple instances when effluent concentrations were different among media, noticeably the vertical silt loam, for the most part soil type did not play a significant role in the effluent nutrient concentrations. Additional paired t-tests were performed at the 95% confidence level comparing the percent removal on a mass basis in all of the lysimeters. These tests show that percent removal on a mass basis, for all species of phosphorus and nitrogen in this study, was not at all affected by the type of soil media. Although Figure 69 shows some variation in nitrogen removal among media, these differences were not shown to be significant enough to claim any soil type was better at reducing the mass of nitrogen in stormwater runoff. The quality testing at the Optimal Balance site indicates that from a nutrient removal perspective, all types of soil media perform equally. Since nitrogen and phosphorus removal is not affected by media type, volume removal goals of the SCM site should be the main factor in media selection. Nutrient removal in actual rain gardens is also expected to be better than what has been shown by this study, because short-term bioretention studies tend to underestimate the performance of pollutant retention since the root zone is not fully established (Lucas and Greenway 2012).

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 CONCLUSIONS

The goal of this research was to investigate and quantify the soil types and flow patterns that can be utilized in vegetated stormwater control measures (SCMs), specifically rain gardens, to maximize volume and pollutant reduction. This section will summarize the research results from the Optimal Balance study in terms of both water quantity and water quality.

5.1.1 Water Quantity Conclusions

The results of this study indicate that the type of soil media used in vegetated SCMs plays a large role in the volume reduction mechanisms. Throughout all of the seasons tested in this study, the silt loam soil produced significantly higher evapotranspiration (ET) rates than all other soil types. During the fall season the silt loam exhibited an average ET rate of 4.26 mm/day while average ET rates in all other soils ranged between 3.03 mm/day and 3.63 mm/day. In the summer the silt loam exhibited an average daily ET rate of 5.52 mm/day, leading to the highest volume removal through ET in the summer. The higher ET rates exhibited by the silt loam soil reflect the high plant available water capacity (PAWC) of 33% determined by using the van Genuchten soil water characteristic curves. The clay loam soil exhibited the lowest daily ET rates with an average of 2.44 mm/day in the fall and 4.02 mm/day in the summer. Soils with too high of a clay content, such as the clay loam, are prone to the formation of clods and macropores and therefore may not be a good media choice for vegetated SCMs. The control lysimeters, those planted without vegetation, showed the important role vegetation plays in stormwater control measures. Both control lysimeters experienced significant ponding and overflow and decreased total volume removal by an average of 16%, showing the role of vegetation not only increases ET but also increases void space for deep infiltration. Besides for silt loam, clay loam, and controls, no significant difference in ET rates were measured among the remaining types of soil. In the summer, average ET rates in the loamy sand, sandy loam, and loam ranged between 4.02 mm/day and 5.93 mm/day. In the fall and spring the average ET rates in these soils ranged between 3.03 mm/day and 3.63 mm/day, and between 2.36 mm/day and 2.97 mm/day, respectively.

Although the field capacity and permanent wilting point moisture contents measured for each soil did not predict the timing of infiltration and ET in the lysimeters, the measured drainage available water and plant available water was indicative of the volume removal proportions through deep infiltration and ET. Additionally, the measured saturated hydraulic conductivity (K_{sat}) can be indicative of the dominant volume removal mechanism in the different soils. As the saturated hydraulic conductivity of a soil decreases and the plant available water increases, more volume is removed through ET. As the saturated hydraulic conductivity of a soil increases and the plant available water decreases, more volume is removed through infiltration. The loamy sand, with a K_{sat} of 24 cm/day and PAWC of 9%, saw a distribution between deep infiltration and ET of 75% to 25% in the fall, 60% to 40% in the summer, and 91% to 9% in the spring. The silt loam, with a K_{sat} of 5 cm/day and PAWC of 33%, saw a distribution between infiltration and ET of 56% to 44% in the fall, 47% to 53% in the summer and 79% to 21% in the spring. Overall, as the soils range from coarse to fine, the volume removal distribution shifts from more infiltration to more ET. This trend is true for all soils tested in this study, besides the clay loam soil which can be explained by the presence of macropores and poor vegetative health.

The results of this study reiterate that ET is a seasonally dependent process, and as such, the distribution of volume removal between deep infiltration and ET is also seasonally dependent.

During the spring season before the vegetation grew back, low daily ET rates resulted in ET accounting for between only 9% and 23% of volume removal in the different soil types. In the summer, when ET rates were at their maximum, volume removal through ET in the lysimeters ranged between 37% and 60% of the total volume removed in the system. During the fall season, removal through ET in the different media ranged between 25% and 55%. Regardless of the type of media, deep infiltration dominated volume removal in the spring and ET dominated volume removal in the summer because of the temperatures and the vegetative condition. Despite the different soil types seeing variation in ET performance among the different seasons, ET accounts for a large portion of volume removal in these systems, especially in the summer time, showing the need for ET to be incorporated into rain garden design.

Dependent upon season, antecedent dry time, and soil type, the cumulative volume removal effects of ET between storm events have the ability to surpass the cumulative volume removal effects of infiltration. On a storm basis, the contribution of ET to the total volume removed is highly dependent on the amount of dry time before the next event. Due to the lack of vegetation in the spring, the cumulative effects of ET are not expected to match that of infiltration. In the fall, the cumulative effects of ET may surpass those of infiltration for the silt loam soil given sufficient dry time. During the summer, when ET is at its peak, the cumulative volume removal through ET may surpass that of infiltration for multiple soil types if there are one to two weeks of dry time before the next storm event. Finer grained soils, such as the silt loam, will see this effect happen sooner than the coarser grained soils such as the loamy sand, loam, and sandy loam.

The horizontal flow configuration tested in the study shows the ability of a longer hydraulic retention time in the root zone to increase volume removal through ET. Despite being provided the same inflow volume on a soil mass basis, the horizontal flow configuration consistently removed more volume through ET than the vertical flow configuration. Volume removal through ET in the horizontal configuration increased by an average of 12% in the fall, 10% in the summer, and 30% in the spring compared to the vertical configuration. In the finer media, such as the silt loam, performance through ET was even greater in the horizontal flow configuration. Making design modifications to vegetated SCMs to create a longer hydraulic retention time, and therefore more ET, can be achieved by adding an underdrain with an upturned elbow, creating an internal water storage zone, or using a soil with a lower hydraulic conductivity. The comparison between the vertical and horizontal configuration also indicates that calculating volume removal on a surface area basis, and therefore designing these systems on a surface area basis, may not be the best option.

The performance of the Optimal Balance lysimeters in terms of removal through deep infiltration and ET is very much dependent on the season, dry time between events, hydraulic retention time in the root zone, and of course the type of soil media used. This study shows that volume removal through ET accounts for a large portion of the water balance in SCMS, and has the potential to account for more if certain design modifications are made. It is clear that rain gardens should be designed to account for the large amount of volume removal through ET. A soil's hydraulic properties can be generally indicative of the performance in an SCM, but each soil is different and should be treated as so. Vegetated bioretention SCMs are very dynamic systems, and design components should be considered as parts contributing to a whole. There is no perfect design, or more specifically no perfect soil type, to be used for rain gardens. Each bioretention SCM should be designed on a site-specific basis and utilize the natural components of the site to achieve the desired volume removal. There is no universal "optimal balance" between infiltration and ET, but rather an optimal balance for each site's needs.

5.1.2 Water Quality Conclusions

All of the soil types and flow configurations analyzed in this study successfully removed nutrients, providing results similar to those found in other bioretention studies. Effluent phosphorus concentrations were shown to be unaffected by the type of media used or the flow configuration. Although differences in the maximum orthophosphate adsorption capacity among the different soil types were shown on the laboratory scale, no such differences in orthophosphate, or total phosphorus, removal were shown from the field testing in the lysimeters. In all lysimeters the average reduction in orthophosphate concentration ranged between 93.6% and 96.0%, and the average mass reduction of PO_4 ranged from 97.6% to 99.3%. The average reduction in TKP, or total phosphorus, concentration was between 77.0% and 90.1%, and the average reduction in TKP mass ranged from 94.2% to 98.3%. Overall, phosphorus removal was good, and was not significantly affected by the type of media.

As seen with other bioretention studies, nitrogen retention was not as good as phosphorus retention, but all lysimeters saw an average reduction in effluent total nitrogen concentration between 30.1% and 84.2%. During some events, the lysimeters saw production of nitrite in the media, with the average reduction in NO_2 concentration ranging between -75.2% and 52.5%. Despite this, average NO_2 removal on a mass basis was between 23.1% and 89.4%. Average NO_3 removal was between 47.1% and 86.5% on a concentration basis and between 83.9% and 96.7% on a mass basis. Similarly, average NO_x removal ranged between 48.7% and 89.1% on a concentration basis and between 82.8% and 96.5% on a mass basis. The average reduction in TKN concentration in all types of media ranged from 31.8% to 82.1%. On a mass basis percent removal of TKN was higher in both configurations, ranging from 70.3% to 98.0%. Total nitrogen concentration also increased when converted to a mass basis, with removal rates between 75.5%

and 97.2% in all lysimeters. For all nitrogen species, removal rates were significantly increased when converted from a concentration to a mass basis, reiterating the large role that physical volume reduction plays in pollutant reduction, especially for nitrogen.

Based on the ten storm simulation events performed at the site, statistical paired t-tests indicate that soil type does not play a large role in effluent nitrogen concentration. The vertical silt loam was the only lysimeter shown to have significantly higher effluent nitrogen concentrations than the other lysimeters, but it is hypothesized that the vertical silt loam contained preferential pathways allowing the influent water to bypass the media. Effluent nitrogen concentrations in the horizontal silt loam are not statistically different than the other media in the horizontal configuration, confirming the comparable performance among all soil types. Although some differences were shown between soil types on a concentration removal basis, statistical tests indicate no significant differences in the mass removal of nitrogen in any of the soil types, which is true for all species of nitrogen. The quality testing at the Optimal Balance site indicates that from a nutrient removal perspective, all types of soil media perform equally. Since nitrogen and phosphorus removal is not affected by media type, volume removal goals of the SCM should be the main factor in media selection.

5.2 FUTURE WORK

Additional work will be performed at the Optimal Balance site to further characterize volume removal performance through infiltration and ET. Storm simulations will continue at the site for an additional year, absent of any quality testing. The additional year of data will allow for a comparison of infiltration and ET performance between multiple seasons and varying climatologic conditions. Based on the data from the initial phase of the study, some soil types will no longer be tested. The clay loam and control lysimeters will no longer be studied as their performance was shown to be undesirable for bioretention SCMs. The four soils that will continue to be tested as part of the Optimal Balance study are the loamy sand, sandy loam, loam, and silt loam.

In addition to the changes in media, additional types of vegetation will be tested in the lysimeters. Two additional types of vegetation will be planted in each of the four soil types for a total of twelve lysimeters. All horizontal lysimeters will be converted to vertical lysimeters for a proper comparison between the different types of vegetation, therefore all twelve lysimeters will be in the vertical configuration. Additional metrics to quantify ET such as the leaf area index (LAI) and leaf water potential (Ψ_{lf}) will be measured for each type of vegetation. These direct measurements of ET will allow for a comparison between the ET measured through the mass balance.

Breakthrough testing of phosphorus in the different soil types will be performed as an additional form of water quality testing at the laboratory scale. The mass transfer of phosphorus in stormwater systems can be characterized through adsorption kinetics, adsorption isotherms and breakthrough behavior, but the Optimal Balance study only tested the maximum orthophosphate holding capacity through adsorption isotherms. Characterizing the kinetics of orthophosphate removal in the different media through breakthrough curve testing will be helpful to see how long it takes orthophosphate to emerge in the different types of media.

Other research being performed at Villanova University to quantify ET can be tied into the results of the Optimal Balance study. Amanda Hess, a PhD candidate at Villanova University, has been doing research on evapotranspiration and has used the water quantity data from the Optimal

Balance site to model ET in different types of media using SWAP. The ET data from the Optimal Balance study has been used to calibrate predictive ET equations such as Penman-Monteith and Hargreaves in SWAP, and formulate a way to account for ET volume removal in rain gardens. Amanda's dissertation should be read in conjunction with this thesis to see the full results of the data from this study. Additionally, a model of the bioinfiltration traffic island (BTI) on Villanova's campus is being modeled with HYDRUS to quantify the water balance through deep infiltration and evapotranspiration. The results of this 2D HYDRUS model will be compared to water balance in the lysimeters to confirm the water quantity data measured in the Optimal Balance study in an actual rain garden.

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APPENDIX

State	Recommended design technique	Ponding depth	Drawdown time	Infiltration of in situ soil	Permeability of soil medium	Planting medium composition	Planting medium depth (ft)	Clay content (%)
LID	—	3–6 in.	4–6 h	—	>1.5 in./h	50% construction sand, 20–30% compost soil, 20–30% leaf compost	>2.5	—
Prince George's County	TR-55 methodology	6 in.	<48 h	1 in./h	—	—	—	<5
California	—	6 in. max	72 h	—	>0.5 in./h	Sandy loam, loamy sand, or loam texture. 1–3% organic material	<4	10–25
Delaware	DURMM	6 in. min	24–48 h	0.5 or 1.02 in./h measured in field without underdrain recommended. With underdrain no minimum recommended	Must percolate design flows within 48 h	Sand, sphagnum peat moss, and mulch	3–4	—
Georgia	RFS Darcy law method	6 in. max	48 h	0.5 in./h. pH between 5.5 and 6.5	0.25 in./h	Sandy loam or loamy sand. 1.5–3% organic material	<4	10–25
Indiana	—	7.6 in. ave.	15–48 h	0.5 in./h min	—	—	—	—
Maryland	RFS Darcy law method	12 in.	48 h	≥0.52 in./h	—	35–60% sand, 30–55% silt, and 10–25% clay	2.5–4	10–25
Massachusetts	—	—	72 h	—	—	—	—	—
Michigan	Darcy law method	6–18 in.	48 h	>0.25 in./h	—	20–40% organic compost, 30–50% sand, 20–30% topsoil	1.5–4	<10
Minnesota	Impervious area method	6–9 in.	—	—	0.25 in./h	—	4	—
New York	RFS Darcy law method	6 in.	—	—	0.25 in./h	—	4	—
North Carolina	Rational method	6 in. max	<96 h	—	—	Sandy loam, loamy sand, or loam with a minimum of 35% sand	<4	10–25
Pennsylvania	Rational method	6 in.	<72 h	—	—	An organic amended soil consisting of 20–30% compost and 70–80% topsoil	4	<10
Rhode Island	RFS Darcy law method	6–9 in.	<72 h	>1 in./h	—	—	4	—
Vermont	RFS Darcy law method	6 in.	—	—	0.25 in./h	—	2.5–4	—
Virginia	Impervious area method	6 in.	24 h	—	—	50% sand, 30% leaf compost, and 20% topsoil. Topsoil shall be loamy sand or sandy loam. Or 50% sand and 50% fibric peat be used	>2.5	<5
Washington	WWHM3 model	<12 in.	—	—	—	—	—	—
Wisconsin	RECARGA	6–12 in.	Required not to exceed 24 h	—	—	Mixture of 40% sand, 20% topsoil and 40% compost	>3	—

Figure A1: Published Design Guidelines for Bioretention Cells as of February 2010 (Carpenter and Hallam 2010)

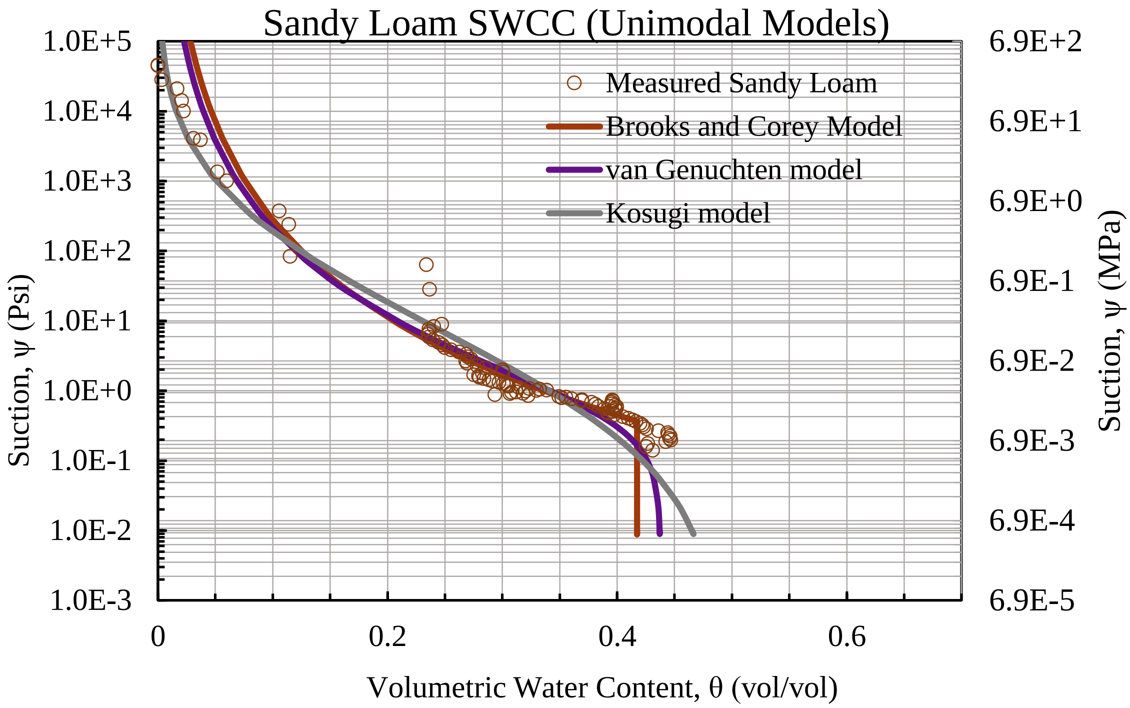

Figure A2: Unimodal SWCC Models fit to the Sandy Loam SWCC Data

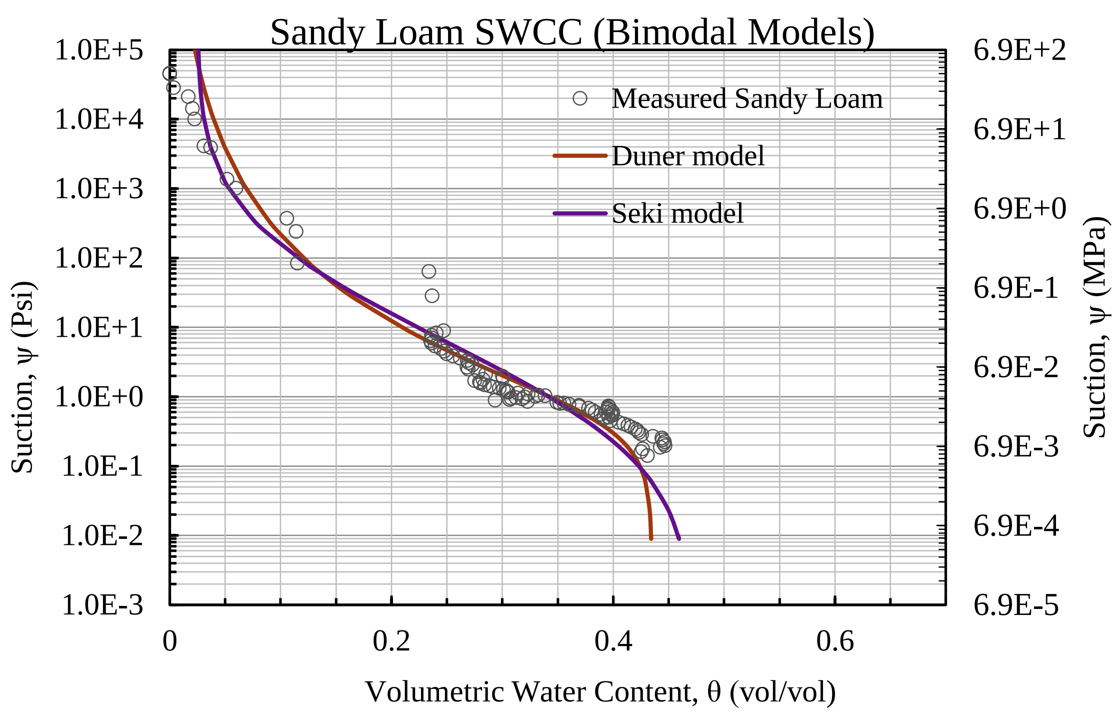

Figure A3: Bimodal SWCC Models fit to the Sandy Loam SWCC Data

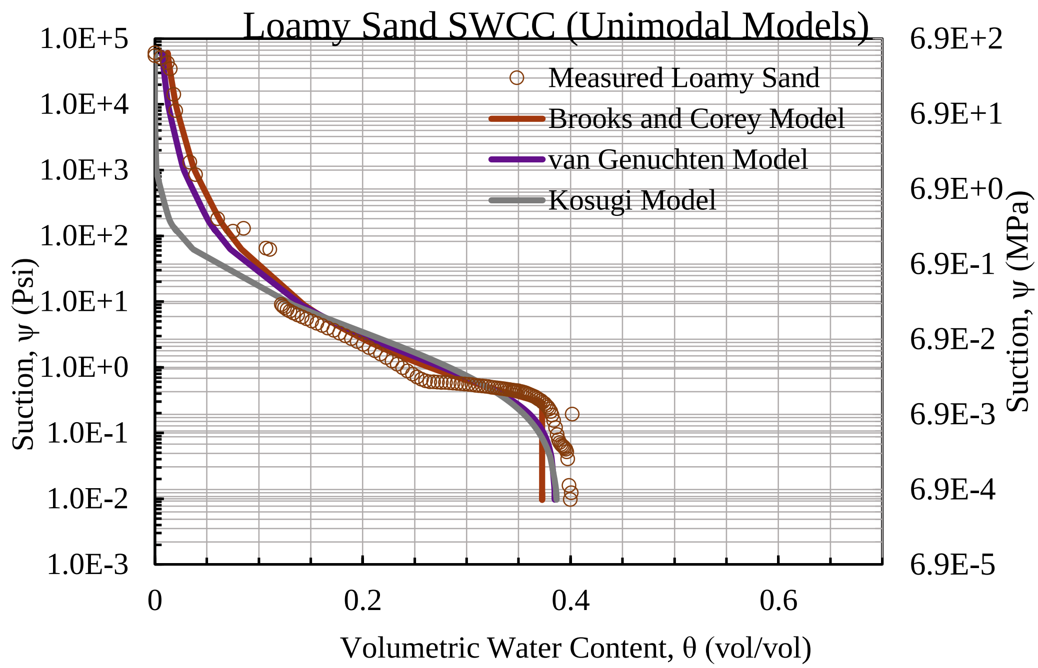

Figure A4: Unimodal SWCC Models fit to the Loamy Sand SWCC Data

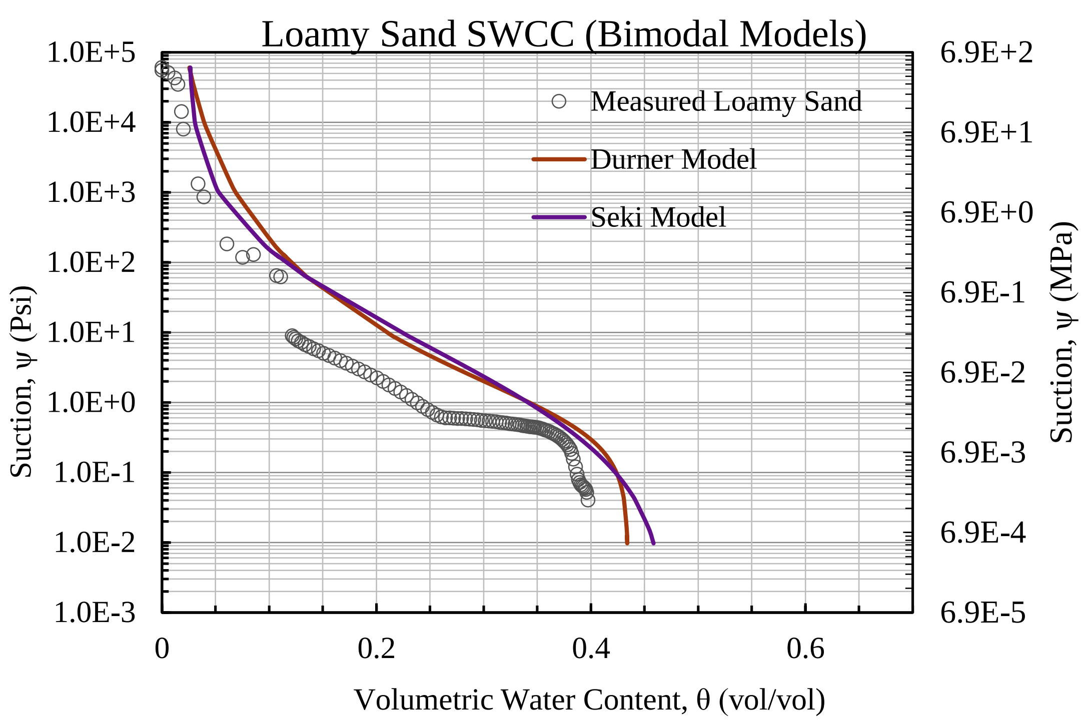

Figure A5: Bimodal SWCC Models fit to the Loamy Sand SWCC Data

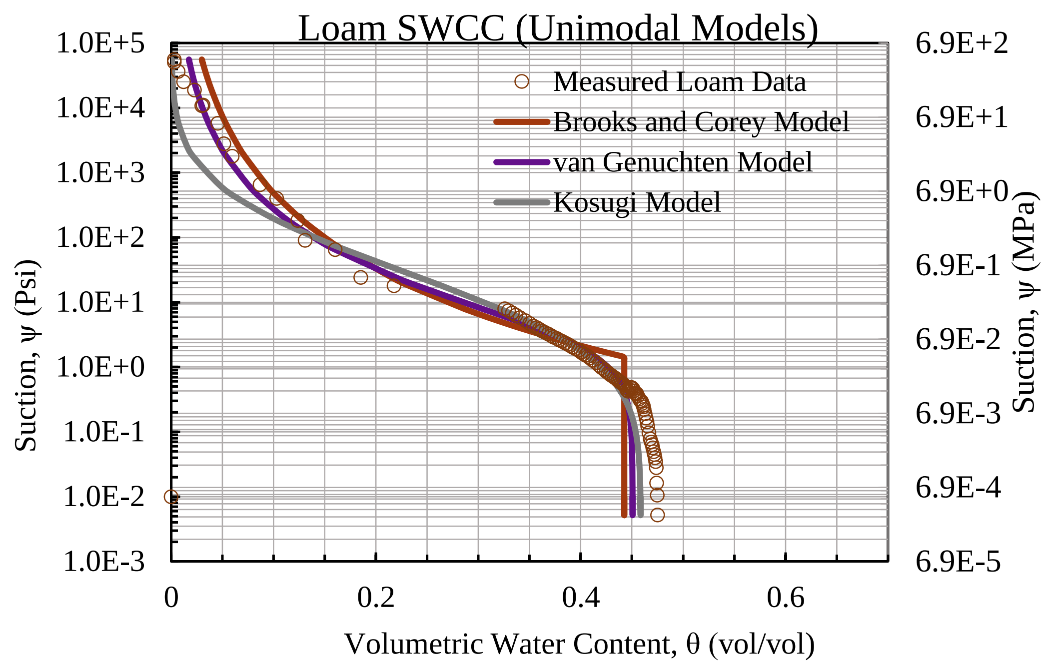

Figure A6: Unimodal SWCC Models fit to the Loam SWCC Data

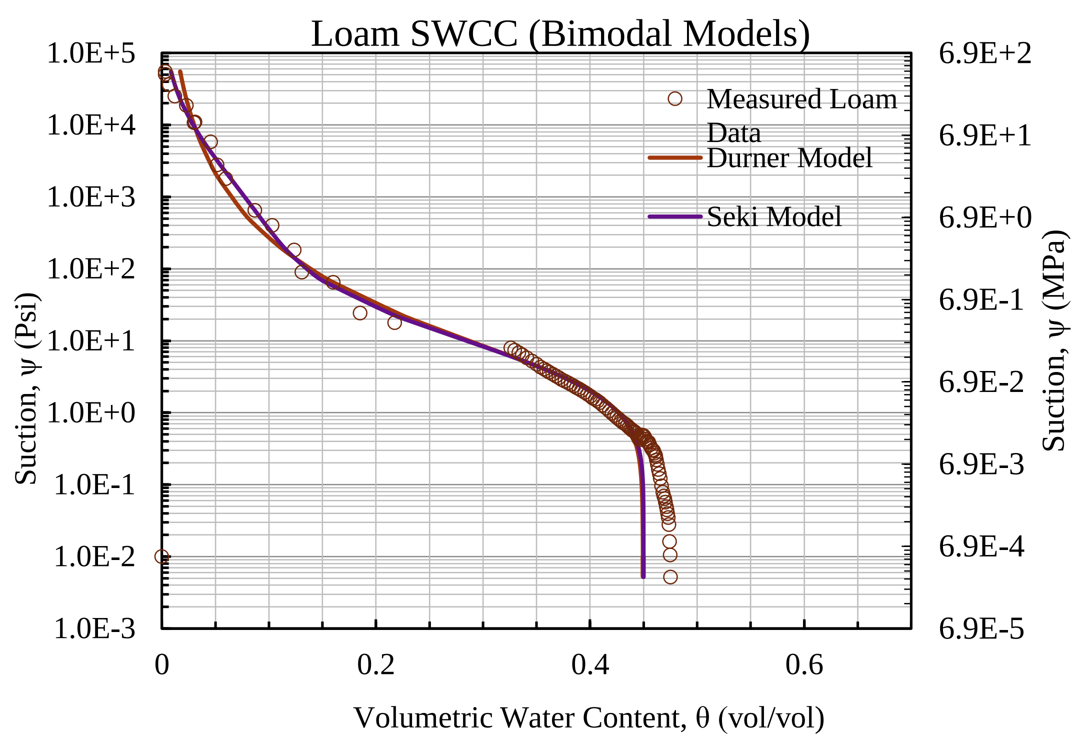

Figure A7: Bimodal SWCC Models fit to the Loam SWCC Data

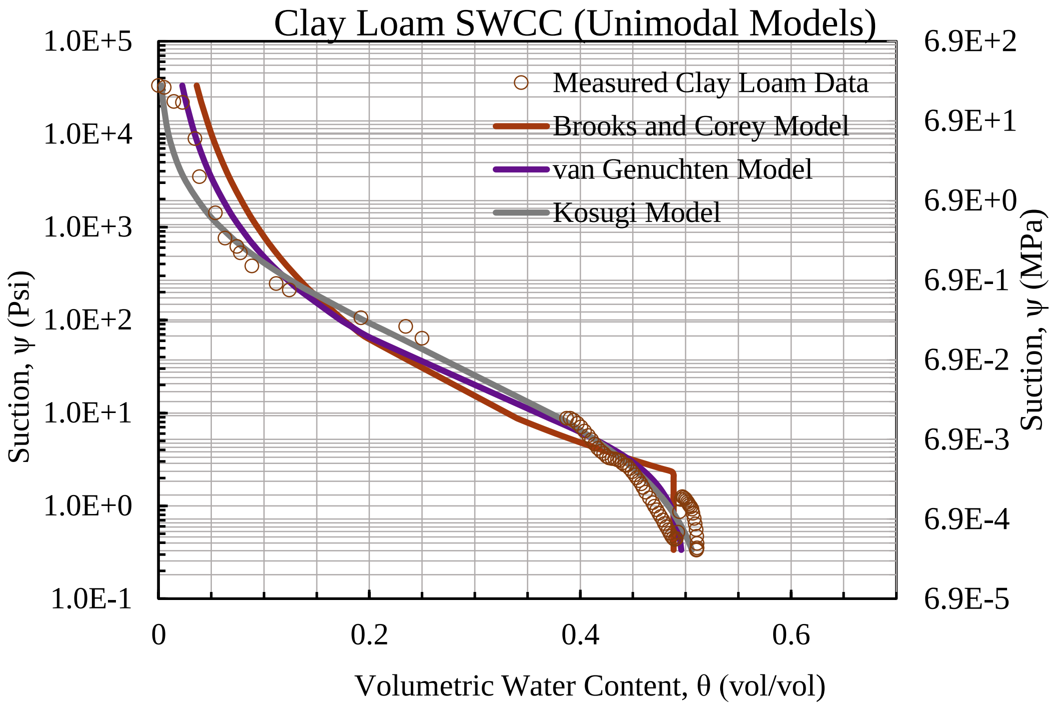

Figure A8: Unimodal SWCC Models fit to the Clay Loam SWCC Data

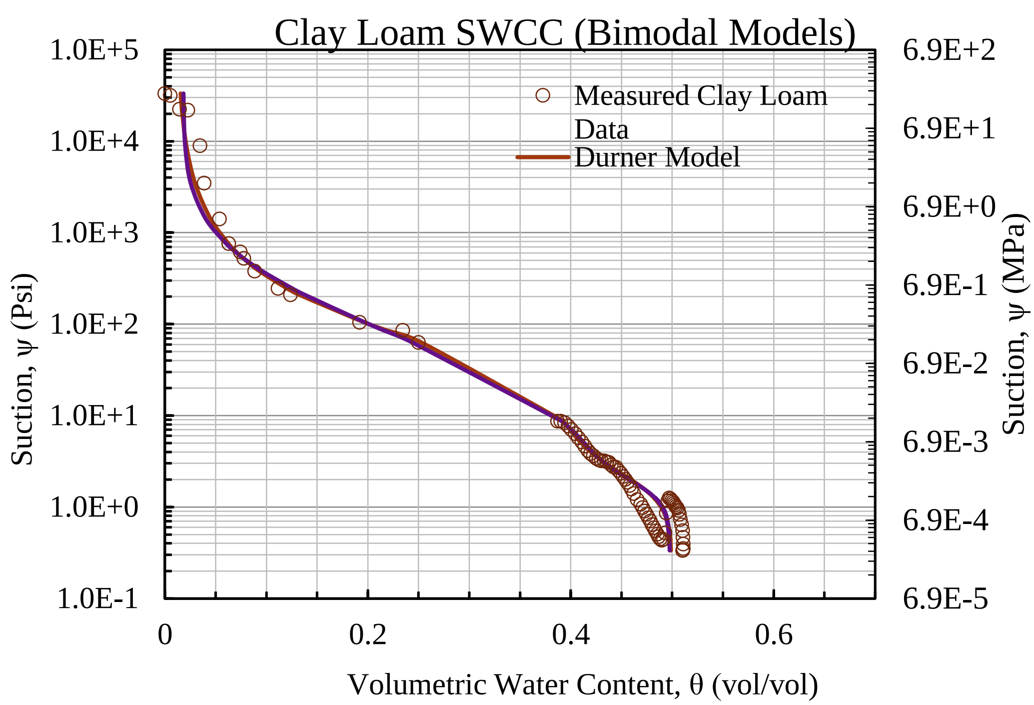

Figure A9: Bimodal SWCC Models fit to the Clay Loam SWCC Data

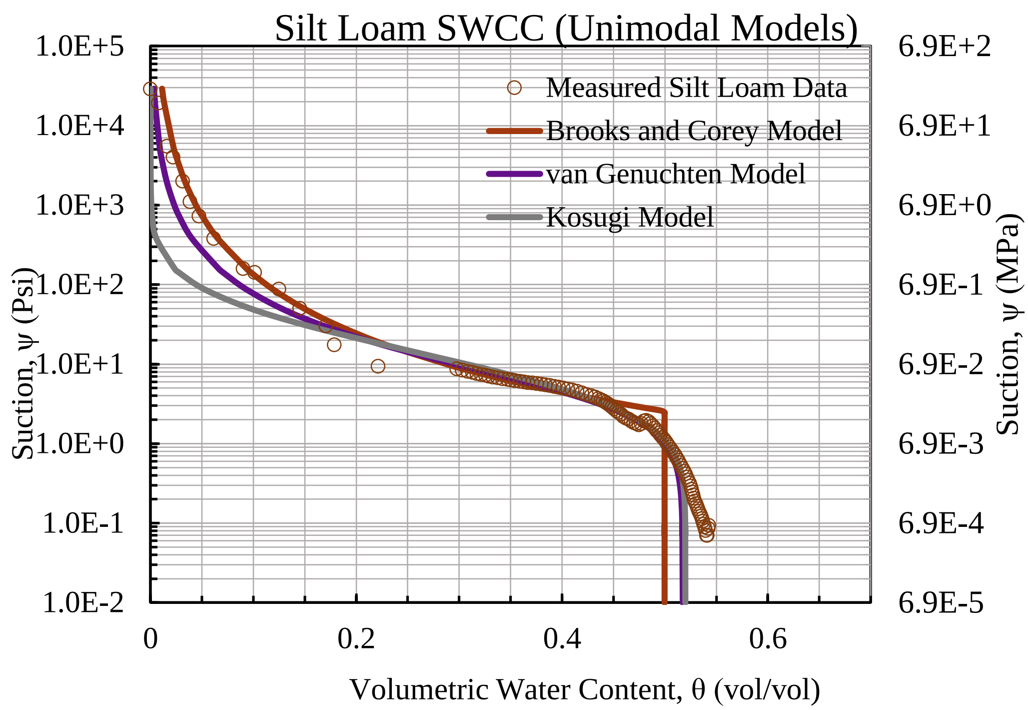

Figure A10: Unimodal SWCC Models fit to the Silt Loam SWCC Data

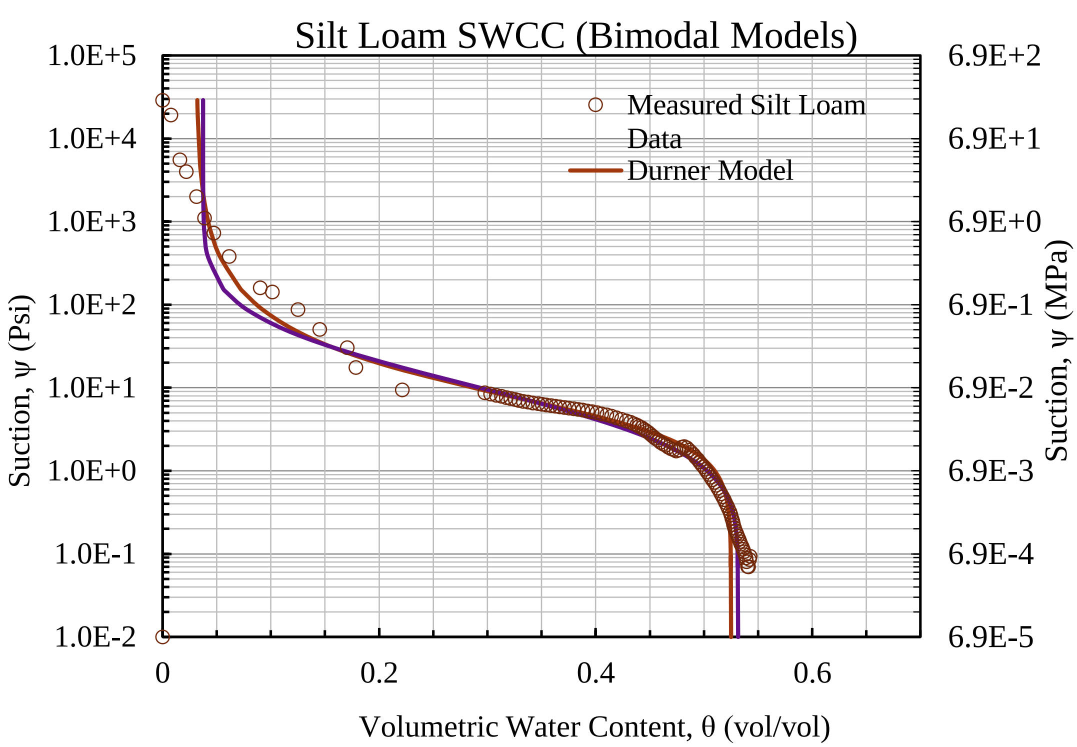

Figure A11: Bimodal SWCC Models fit to the Silt Loam SWCC Data

Table A1: Days during the Optimal Balance Study when ET Rates were not included

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

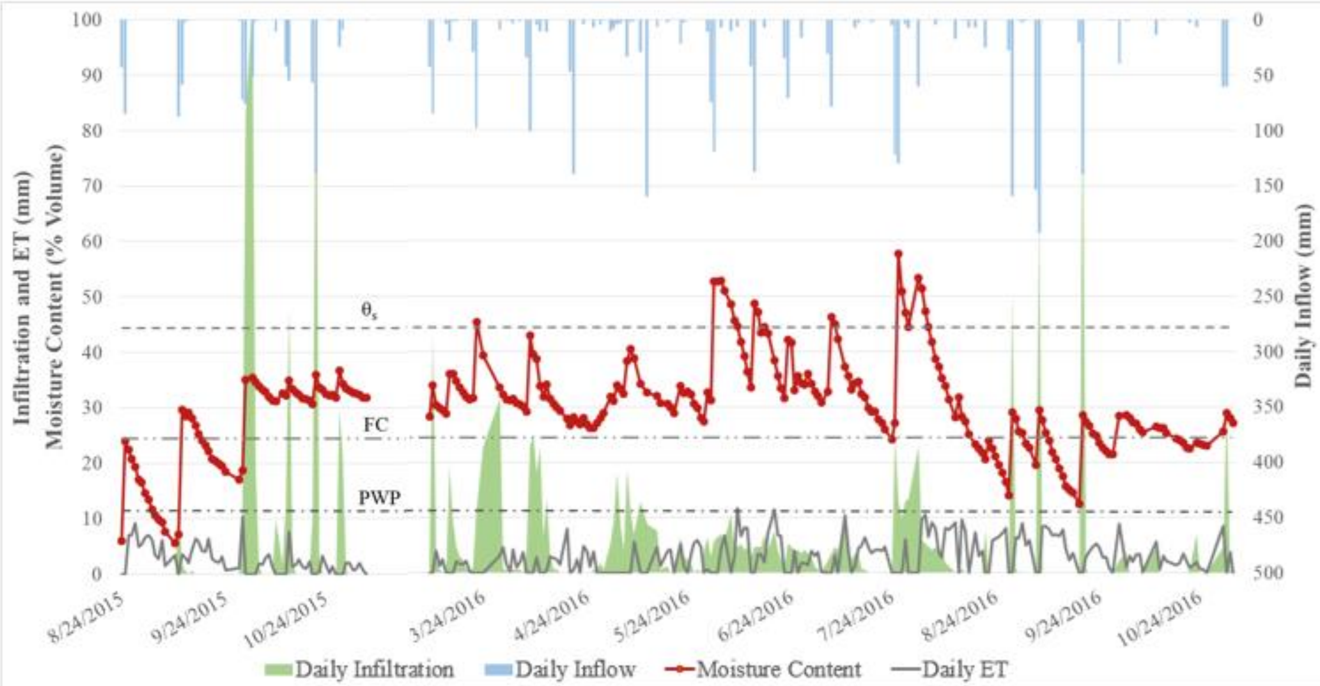

Figure A12: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Vertical Sandy Loam

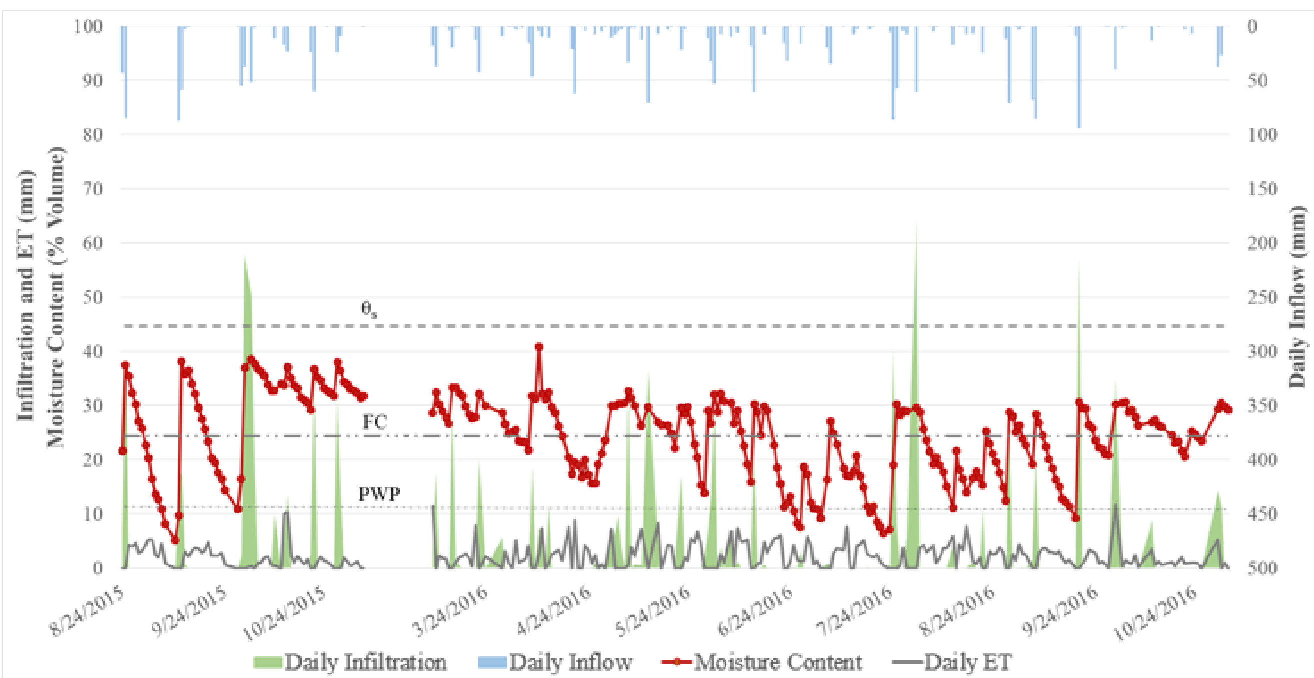

Figure A13: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Horizontal Sandy Loam

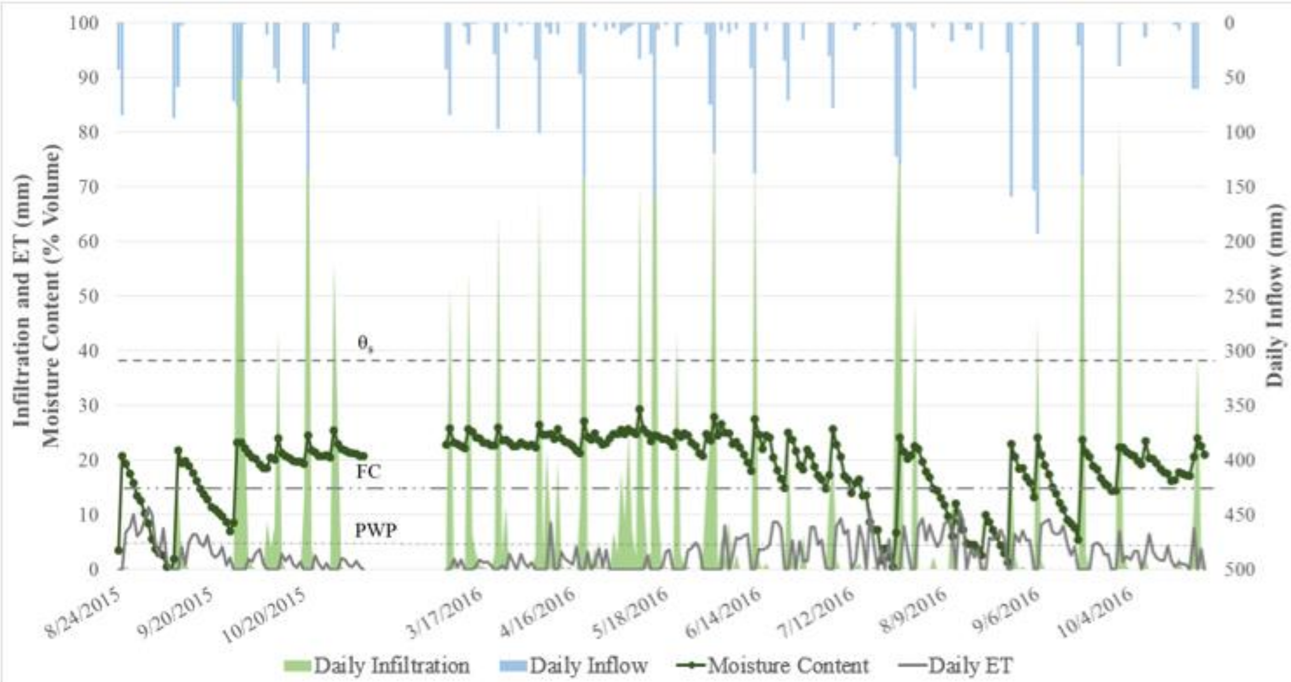

Figure A14: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Vertical Loamy Sand

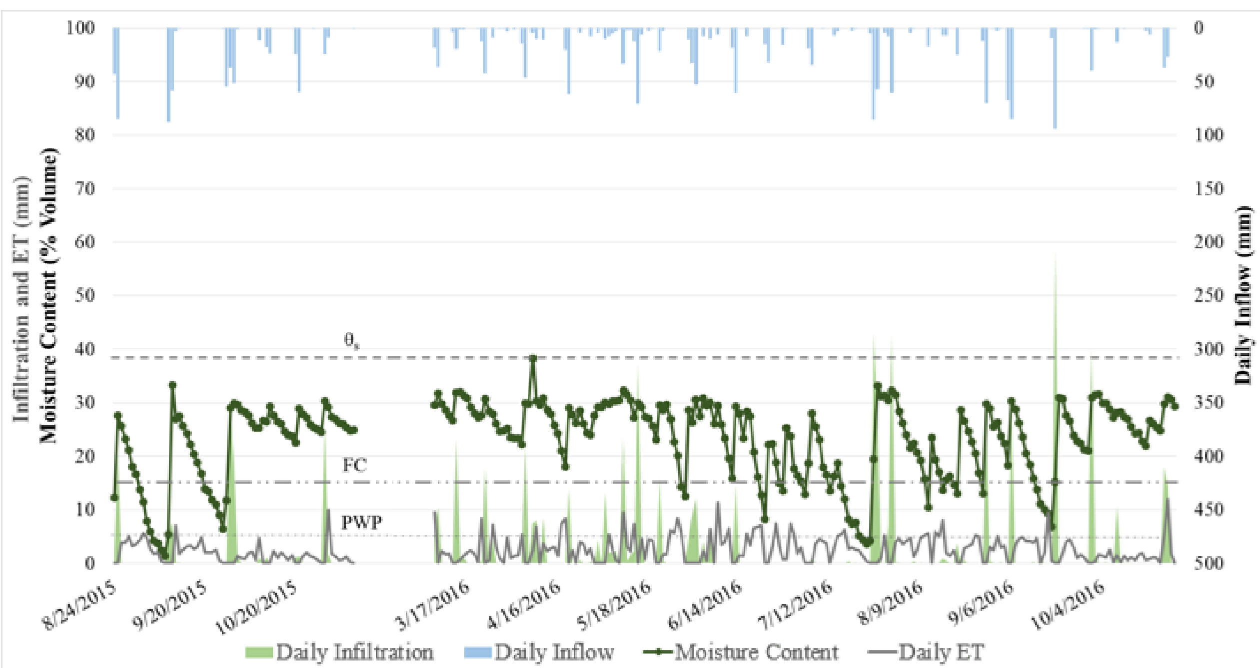

Figure A15: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Horizontal Loamy Sand

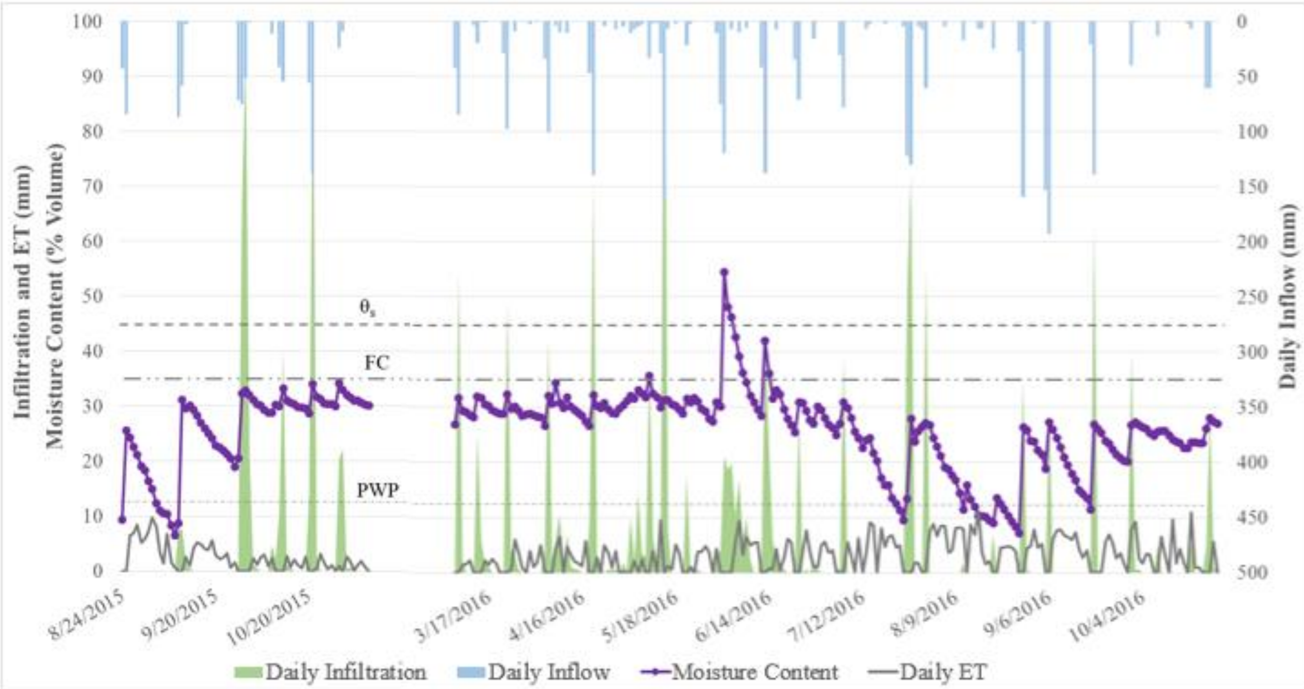

Figure A16: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Vertical Loam

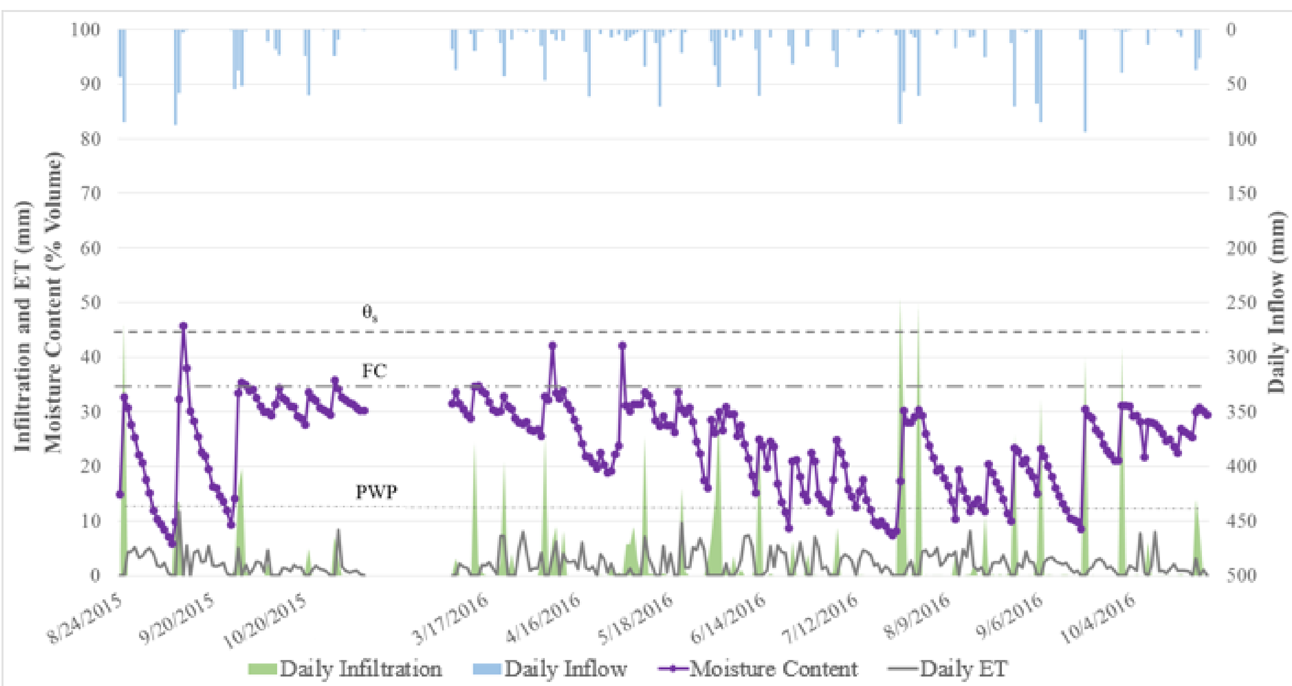

Figure A17: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Horizontal Loam

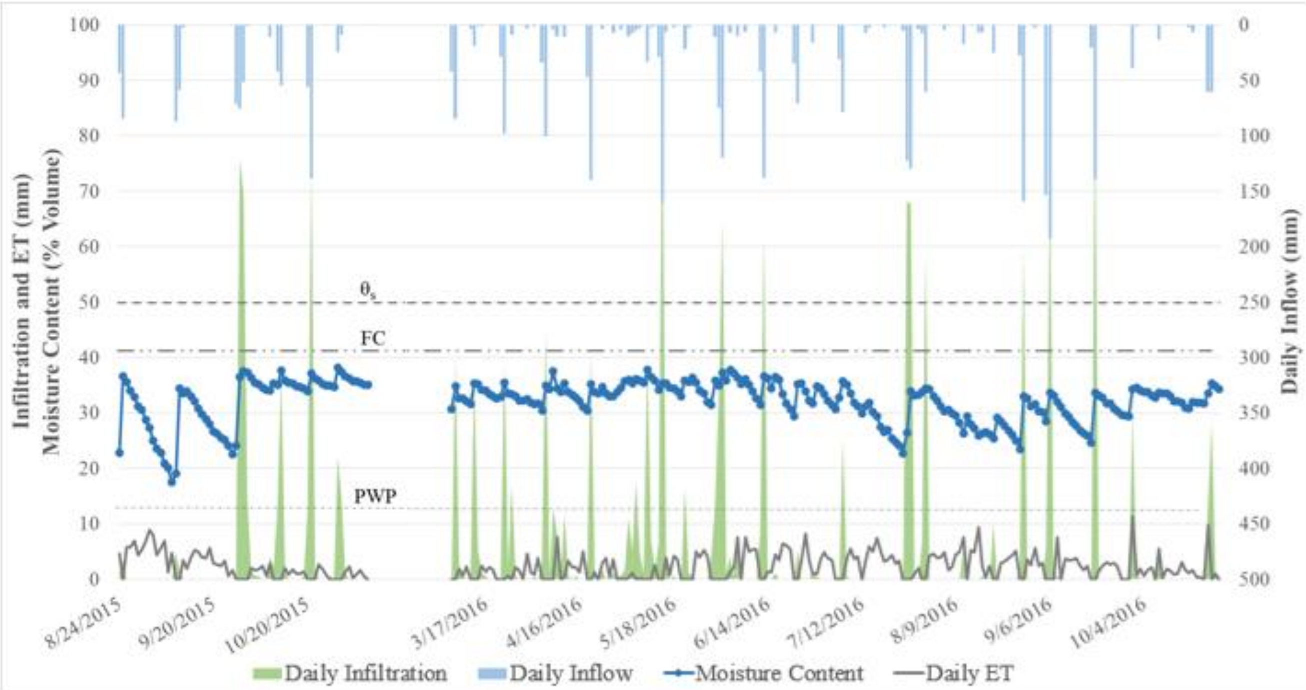

Figure A18: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Vertical Clay Loam

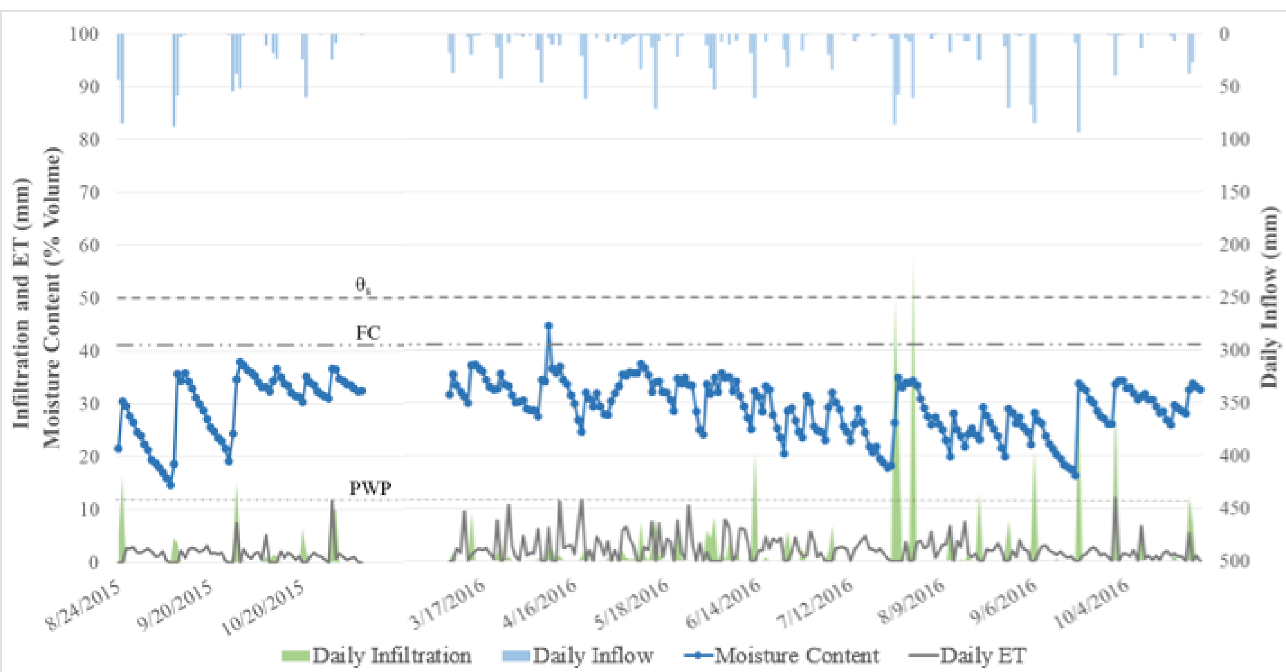

Figure A19: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Horizontal Clay Loam

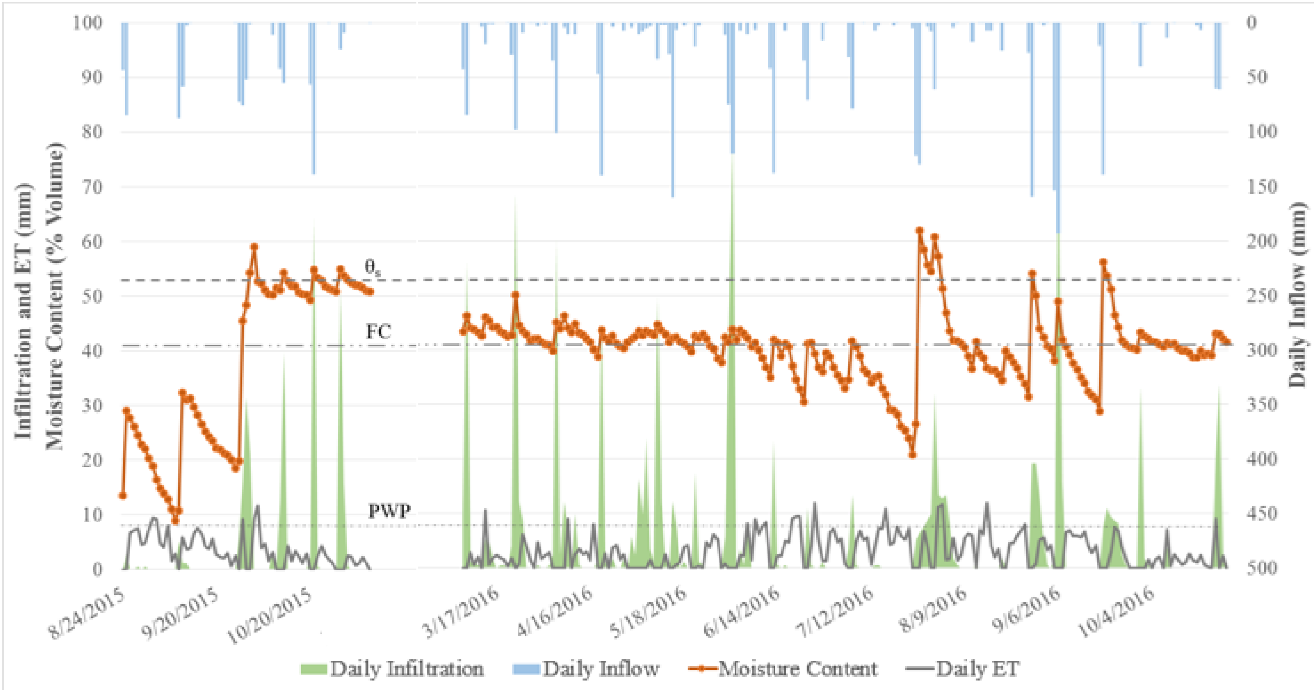

Figure A20: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Vertical Silt Loam

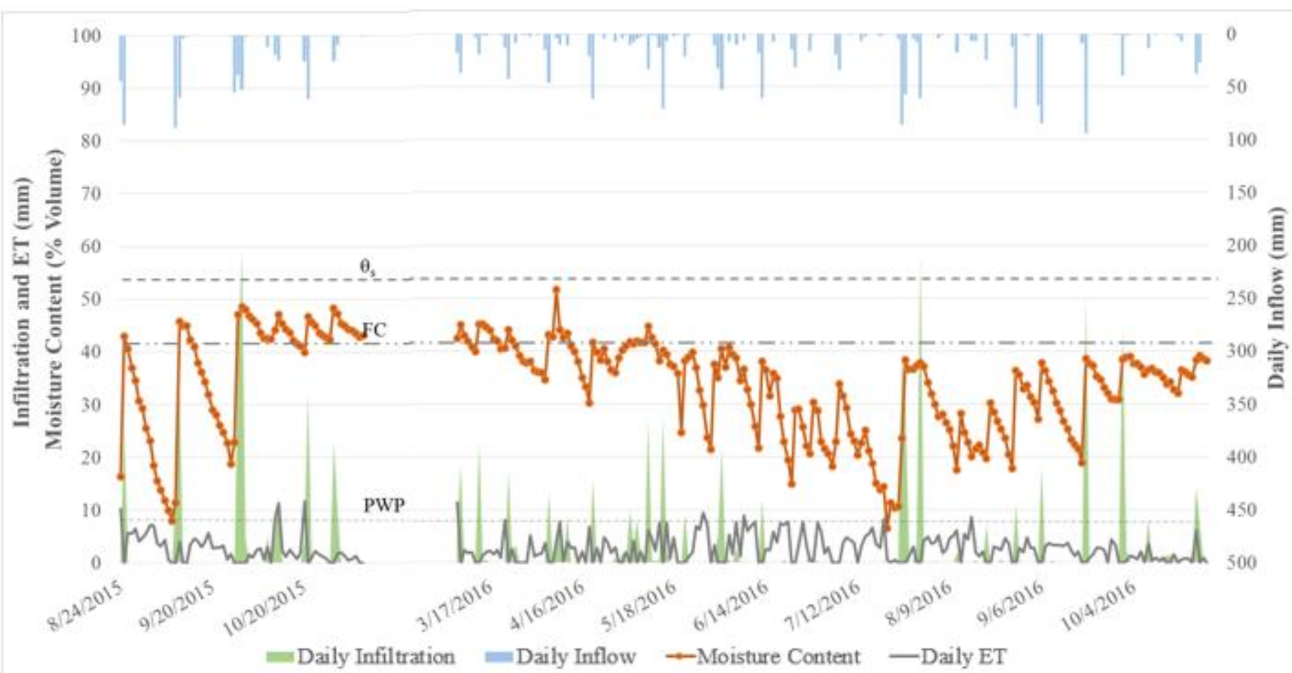

Figure A21: Moisture Content, Infiltration, ET, and Inflow compared to the Saturated Water Content, Field Capacity, and Permanent Wilting Point for the Horizontal Silt Loam

Table A2: NO_2 Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P	0.029	0.052		0.135	3.340	1.735		0.020	0.010	0.010	0.666	1.153
	OB-A	0.028	0.022		0.072	0.070			0.081			0.054	0.024
	OB-B	0.022	0.012		0.053	0.041			0.020	0.010	0.010	0.024	0.016
	OB-C	0.053	0.054		0.098	0.059	0.067		0.041	0.010	0.010	0.049	0.027
	OB-D	0.036	0.027		0.050	0.062	0.052		0.020	0.014	0.011	0.034	0.018
	OB-E	0.023			0.070	0.107	0.010		0.020	0.010	0.032	0.039	0.034
	OB-F	0.194			0.118	0.292	0.138		0.182	0.010	0.018	0.136	0.093
	OB-G	0.055			0.010	0.350	0.051		0.020	0.014	0.033	0.076	0.113
	OB-H	0.077			0.086	0.405	0.177		0.020	0.010	0.010	0.112	0.132
	OB-I	0.007			0.010	0.010	0.010		0.020	0.010	0.010	0.011	0.004
	OB-J	0.111				0.010	0.076		0.051	0.010	0.010	0.045	0.039
	OB-K	0.036			0.096	1.100	0.068		0.020	0.025	0.010	0.193	0.371
	OB-L	0.164			0.085	0.013	0.442		0.020	0.010	0.010	0.106	0.147
Percent Removal (%)	OB-A	3.4	57.7		46.7	97.9			-303.0	0.0	0.0	-13.9	122.8
	OB-B	24.1	76.9		60.8	98.8			0.0	0.0	0.0	37.2	38.3
	OB-C	-82.8	-3.8		27.4	98.2	96.1		-105.3	0.0	0.0	3.7	68.5
	OB-D	-24.1	48.1		63.3	98.1	97.0		0.0	-40.9	-5.4	29.5	50.8
	OB-E	20.7			48.0	96.8	99.4		0.0	0.0	-220.3	6.4	100.2
	OB-F	-569.0			12.6	91.3	92.0			0.0	-78.0	-75.2	228.3
	OB-G	-89.7			92.6	89.5	97.1		0.0	-36.9	-225.7	-10.4	110.6
	OB-H	-165.5			36.3	87.9	89.8		0.0	0.0	0.0	6.9	79.4
	OB-I	75.9			92.6	99.7	99.4		0.0	0.0	0.0	52.5	46.1
	OB-J	-282.8				99.7	95.6		-155.2	0.0	0.0	-40.4	137.4
	OB-K	-24.1			28.9	67.1	96.1		0.0	-148.6	0.0	2.8	72.9
	OB-L	-465.5			37.0	99.6	74.5		0.0	0.0	0.0	-36.3	179.0
Mass (mg)	OB-P (V)	0.030	0.054		0.207	5.276	2.528		0.030	0.016	0.008	1.019	1.8
	OB-P (H)	0.113	0.203		0.793	20.237	9.697		0.116	0.060	0.032	3.907	6.9
	OB-A	0.009	0.009		0.021	0.017			0.035			0.018	0.0
	OB-B	0.009	0.007		0.013	0.021			0.008	0.005	0.003	0.009	0.0
	OB-C	0.026	0.036		0.110	0.060	0.043		0.008	0.004	0.003	0.036	0.0
	OB-D	0.017	0.013		0.050	0.055	0.033		0.006	0.003	0.003	0.023	0.0
	OB-E	0.008			0.055	0.095	0.006		0.010	0.006	0.007	0.027	0.0
	OB-F	0.108			0.020	0.315	0.028			0.008	0.003	0.080	0.1
	OB-G	0.076			0.045	1.336	0.088		0.042	0.029	0.040	0.236	0.4
	OB-H	0.114			0.251	1.530	0.262		0.038	0.016	0.002	0.316	0.5
	OB-I	0.008			0.031	0.021	0.010		0.036	0.021	0.001	0.018	0.0
	OB-J	0.030				0.035	0.137		0.094	0.025	0.007	0.055	0.0
	OB-K	0.005			0.080	1.688	0.115		0.011	0.044	0.006	0.278	0.6
	OB-L	0.265			0.183	0.028	0.388		0.016	0.013	0.000	0.128	0.1
Mass Retained (mg)	OB-A	0.021	0.044		0.186	5.259			-0.005			1.101	2.1
	OB-B	0.021	0.047		0.194	5.256			0.022	0.010	0.005	0.794	1.8
	OB-C	0.004	0.017		0.097	5.216	2.485		0.023	0.012	0.005	0.982	1.8
	OB-D	0.013	0.041		0.156	5.222	2.495		0.025	0.012	0.005	0.996	1.8
	OB-E	0.022			0.151	5.182	2.523		0.021	0.009	0.001	1.130	1.9
	OB-F	-0.078			0.187	4.962	2.500			0.008	0.006	1.264	1.9
	OB-G	0.038			0.749	18.901	9.609		0.074	0.031	-0.008	4.199	6.8
	OB-H	0.000			0.542	18.707	9.435		0.078	0.044	0.030	4.119	6.8
	OB-I	0.105			0.762	20.216	9.687		0.080	0.039	0.031	4.417	7.2
	OB-J	0.083				20.202	9.560		0.022	0.035	0.025	4.988	7.6
	OB-K	0.109			0.713	18.549	9.582		0.105	0.016	0.026	4.157	6.7
	OB-L	-0.151			0.611	20.208	9.309		0.100	0.047	0.032	4.308	7.2
Mass Removal (%)	OB-A	69.0	82.3		89.8	99.7			-15.6			65.0	41.5
	OB-B	71.4	87.4		93.6	99.6			72.6	66.8	60.2	78.8	13.7
	OB-C	11.9	31.8		46.9	98.9	98.3		75.0	75.5	63.0	62.7	28.9
	OB-D	42.4	76.6		75.6	99.0	98.7		81.0	79.1	58.6	76.4	17.7
	OB-E	74.1			73.2	98.2	99.8		68.2	59.8	18.0	70.2	25.4
	OB-F	-262.5			90.3	94.0	98.9			50.4	67.6	23.1	128.8
	OB-G	33.3			94.4	93.4	99.1		63.5	52.1	-24.2	58.8	40.9
	OB-H	-0.4			68.4	92.4	97.3		67.0	73.7	95.0	70.5	31.3
	OB-I	92.5			96.0	99.9	99.9		69.2	65.5	96.3	88.5	13.6
	OB-J	73.7				99.8	98.6		19.2	57.8	77.9	71.2	27.4
	OB-K	96.0			89.9	91.7	98.8		90.4	26.2	80.4	81.9	23.3
	OB-L	-133.6			77.0	99.9	96.0		86.1	78.0	99.3	57.5	78.5

Table A3: NO_3 Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P	0.762	1.75		1.493		0.210		0.744		0.431	0.898	0.550
	OB-A	0.491	0.124		0.324							0.313	0.150
	OB-B	0.078	0.038		0.284				0.080		0.109	0.118	0.086
	OB-C	0.047	0.086		0.002		0.076		0.099		0.146	0.076	0.044
	OB-D	0.276	0.473		0.369		0.048		0.080		0.138	0.231	0.155
	OB-E	0.077			0.166		0.090		0.131		0.308	0.154	0.083
	OB-F	0.411			1.211				0.064		0.092	0.445	0.463
	OB-G	0.946			0.117		0.049		0.112			0.306	0.370
	OB-H	0.465			0.729				0.080		0.090	0.341	0.272
	OB-I	0.093			0.090		0.090		0.080		0.090	0.089	0.004
	OB-J	0.273					0.024		0.049		0.090	0.109	0.098
	OB-K	0.8			1.461		0.032		0.140		0.116	0.510	0.549
	OB-L	0.412			0.670		0.051		0.095		0.090	0.264	0.241
Percent Removal (%)	OB-A	35.6	92.9		78.3							68.9	24.3
	OB-B	89.8	97.8		81.0				89.3		74.7	86.5	7.9
	OB-C	93.8	95.1		99.9		63.9		86.7		66.2	84.3	14.1
	OB-D	63.8	73.0		75.3		77.1		89.3		68.0	74.4	8.0
	OB-E	89.9			88.9		57.1		82.4		28.7	69.4	23.6
	OB-F	46.1			18.9				91.5		78.6	58.7	28.3
	OB-G	-24.1			92.1		76.5		84.9			57.4	47.4
	OB-H	39.0			51.2				89.3		79.1	64.6	20.3
	OB-I	87.8			94.0		57.1		89.3		79.1	81.4	13.1
	OB-J	64.2					88.4		93.4		79.1	81.3	11.1
	OB-K	-5.0			2.2		84.6		81.1		73.0	47.2	39.9
	OB-L	45.9			55.1		75.7		87.2		79.1	68.6	15.5
Mass (mg)	OB-P (V)	0.784	1.801		2.287		0.306		1.128		0.358	1.111	0.7
	OB-P (H)	2.979	6.841		8.772		1.173		4.327		1.372	4.244	2.8
	OB-A	0.162	0.053		0.095							0.104	0.0
	OB-B	0.030	0.021		0.071				0.033		0.036	0.038	0.0
	OB-C	0.023	0.058		0.002		0.049		0.018		0.045	0.033	0.0
	OB-D	0.132	0.219		0.375		0.031		0.023		0.045	0.137	0.1
	OB-E	0.026			0.131		0.052		0.063		0.065	0.067	0.0
	OB-F	0.229			0.206				0.114			0.183	0.0
	OB-G	1.300			0.523		0.086		0.238		-0.040	0.421	0.5
	OB-H	0.687			2.127				0.154		0.014	0.745	0.8
	OB-I	0.112			0.282		0.093		0.143		0.011	0.128	0.1
	OB-J	0.073					0.044		0.090		0.063	0.068	0.0
	OB-K	0.102			1.221		0.055		0.078		0.073	0.306	0.5
	OB-L	0.665			1.440		0.045		0.077		0.002	0.446	0.6
Mass Retained (mg)	OB-A	0.622	1.748		2.192							1.521	0.7
	OB-B	0.754	1.780		2.216				1.095		0.322	1.233	0.7
	OB-C	0.761	1.743		2.285		0.257		1.110		0.313	1.078	0.7
	OB-D	0.653	1.582		1.912		0.275		1.105		0.313	0.973	0.6
	OB-E	0.758			2.156		0.253		1.065		0.293	0.905	0.7
	OB-F	0.555			2.081				1.015		0.358	1.002	0.7
	OB-G	1.679			8.249		1.086		4.089			3.776	2.8
	OB-H	2.291			6.646				4.173		1.357	3.617	2.0
	OB-I	2.866			8.490		1.080		4.184		1.361	3.596	2.7
	OB-J	2.905					1.129		4.237		1.308	2.395	1.3
	OB-K	2.877			7.552		1.118		4.249		1.299	3.419	2.4
	OB-L	2.313			7.333		1.128		4.250		1.370	3.279	2.3
Mass Removal (%)	OB-A	79.3	97.0		95.9							90.7	8.1
	OB-B	96.1	98.8		96.9				97.1		89.9	95.8	3.0
	OB-C	97.0	96.8		99.9		84.1		98.4		87.5	93.9	5.9
	OB-D	83.2	87.8		83.6		89.9		98.0		87.4	88.3	4.9
	OB-E	96.7			94.3		82.9		94.4		81.7	90.0	6.4
	OB-F	70.8			91.0				89.9			83.9	9.3
	OB-G	56.4			94.0		92.6		94.5		102.9	88.1	16.3
	OB-H	76.9			75.8				96.4		98.9	87.0	10.7
	OB-I	96.2			96.8		92.1		96.7		99.2	96.2	2.3
	OB-J	97.5					96.3		97.9		95.4	96.8	1.0
	OB-K	96.6			86.1		95.3		98.2		94.7	94.2	4.2
	OB-L	77.7			83.6		96.2		98.2		99.8	91.1	8.8

Table A4: NO_x Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P	0.791	1.802	1.759	1.628	2.570	1.945		0.764	0.544	0.441	1.360	0.701
	OB-A	0.519	0.146		0.396	0.288						0.337	0.137
	OB-B	0.1	0.05		0.336	0.370			0.100	0.011	0.119	0.155	0.130
	OB-C	0.1	0.14	0.067	0.100	0.116	0.143		0.140	0.012	0.156	0.108	0.043
	OB-D	0.312	0.5	0.939	0.419	0.143	0.100		0.100	0.018	0.148	0.298	0.273
	OB-E	0.1	0.166	0.393	0.236	0.115	0.100		0.151		0.340	0.200	0.105
	OB-F	0.605	0.721	1.919	1.329	0.588	1.010		0.245	0.017	0.110	0.727	0.579
	OB-G	1.001	2.044	1.656	0.127	0.233	0.100		0.132	0.011		0.663	0.750
	OB-H	0.542	1.242		0.815	0.100	0.109		0.100	0.026	0.100	0.379	0.417
	OB-I	0.1	0.276	0.768	0.100		0.100		0.100	0.011	0.100	0.194	0.227
	OB-J	0.384	1.371			0.100	0.100		0.100	0.045	0.100	0.314	0.444
	OB-K	0.836	1.39	1.85	1.557	0.472	0.100		0.160	0.024	0.126	0.724	0.670
	OB-L	0.576	1.296	1.215	0.755	0.100	0.493		0.115	0.019	0.100	0.519	0.461
Percent Removal (%)	OB-A	34.4	91.9		75.7	88.8						72.7	22.9
	OB-B	87.4	97.2		79.3	85.6			86.9	97.9	73.0	86.8	8.3
	OB-C	87.4	92.2	96.2	93.9	95.5	92.7		81.6	97.8	64.7	89.1	9.8
	OB-D	60.6	72.3	46.6	74.3	94.4	94.9		86.9	96.8	66.3	77.0	16.5
	OB-E	87.4	90.8	77.7	85.5	95.5	94.9		80.3		23.0	79.4	22.1
	OB-F	23.5	60.0	-9.1	18.3	77.1	48.0		67.9	96.9	75.0	50.9	31.9
	OB-G	-26.5	-13.4	5.9	92.2	90.9	94.9		82.7	97.9		53.1	50.7
	OB-H	31.5	31.1		49.9	96.1	94.4		86.9	95.2	77.3	70.3	26.6
	OB-I	87.4	84.7	56.3	93.9		94.9		86.9	97.9	77.3	84.9	12.4
	OB-J	51.5	23.9			96.1	94.9		86.9	91.7	77.3	74.6	25.2
	OB-K	-5.7	22.9	-5.2	4.4	81.6	94.9		79.0	95.6	71.3	48.8	41.3
	OB-L	27.2	28.1	30.9	53.6	96.1	74.6		84.9	96.4	77.3	63.2	27.2
Mass (mg)	OB-P (V)	0.814	1.855	2.667	2.494	4.061	2.834		1.158	0.851	0.366	1.900	1.1
	OB-P (H)	3.092	7.044	10.227	9.565	15.574	10.870		4.443	3.263	1.404	7.276	4.4
	OB-A	0.172	0.063		0.116	0.071						0.105	0.0
	OB-B	0.039	0.028		0.084	0.186			0.042	0.006	0.039	0.061	0.1
	OB-C	0.050	0.095	0.067	0.112	0.118	0.092		0.026	0.005	0.048	0.068	0.0
	OB-D	0.149	0.232	0.644	0.426	0.127	0.064		0.029	0.004	0.048	0.191	0.2
	OB-E	0.034	0.080	0.147	0.186	0.102	0.058		0.073		0.072	0.094	0.0
	OB-F	0.337	0.555	0.798	0.226	0.634	0.205		0.114	0.013	0.017	0.322	0.3
	OB-G	1.375	3.204	2.721	0.568	0.889	0.175		0.280	0.024		1.154	1.1
	OB-H	0.801	2.251		2.378	0.378	0.161		0.192	0.041	0.016	0.777	0.9
	OB-I	0.121	0.443	0.805	0.313		0.103		0.179	0.023	0.012	0.250	0.3
	OB-J	0.103	2.647			0.346	0.181		0.184	0.114	0.070	0.521	0.9
	OB-K	0.107	0.584	0.646	1.301	0.725	0.170		0.089	0.043	0.079	0.416	0.4
	OB-L	0.930	1.903	1.428	1.622	0.217	0.433		0.093	0.026	0.002	0.739	0.7
Mass Retained (mg)	OB-A	0.642	1.792		2.378	3.990						2.201	1.2
	OB-B	0.775	1.827		2.410	3.875			1.117	0.845	0.327	1.596	1.1
	OB-C	0.765	1.760	2.599	2.382	3.942	2.743		1.133	0.846	0.319	1.832	1.1
	OB-D	0.665	1.623	2.023	2.068	3.934	2.770		1.130	0.847	0.318	1.709	1.1
	OB-E	0.781	1.775	2.520	2.308	3.958	2.776		1.086		0.294	1.937	1.1
	OB-F	0.477	1.299	1.868	2.268	3.427	2.629		1.045	0.838	0.350	1.578	1.0
	OB-G	1.717	3.840	7.506	8.998	14.685	10.695		4.163	3.239		6.855	4.1
	OB-H	2.291	4.792		7.188	15.196	10.709		4.251	3.221	1.387	6.130	4.4
	OB-I	2.971	6.601	9.422	9.252		10.767		4.264	3.240	1.392	5.989	3.3
	OB-J	2.989	4.397			15.229	10.689		4.259	3.149	1.333	6.006	4.7
	OB-K	2.985	6.460	9.581	8.265	14.850	10.700		4.354	3.220	1.325	6.860	4.1
	OB-L	2.162	5.141	8.799	7.943	15.357	10.437		4.350	3.237	1.401	6.536	4.3
Mass Removal (%)	OB-A	78.9	96.6		95.4	98.3						92.3	7.8
	OB-B	95.2	98.5		96.6	95.4			96.4	99.3	89.3	95.8	3.0
	OB-C	93.9	94.9	97.5	95.5	97.1	96.8		97.8	99.5	86.9	95.5	3.4
	OB-D	81.7	87.5	75.9	82.9	96.9	97.7		97.5	99.5	86.8	89.6	8.1
	OB-E	95.9	95.7	94.5	92.5	97.5	97.9		93.7		80.3	93.5	5.3
	OB-F	58.6	70.1	70.1	90.9	84.4	92.8		90.2	98.5	95.5	83.4	13.1
	OB-G	55.5	54.5	73.4	94.1	94.3	98.4		93.7	99.3		82.9	17.8
	OB-H	74.1	68.0		75.1	97.6	98.5		95.7		98.9	86.8	12.7
	OB-I	96.1	93.7	92.1	96.7		99.0		96.0	99.3	99.2	96.5	2.5
	OB-J	96.7	62.4			97.8	98.3		95.9	96.5	95.0	91.8	12.0
	OB-K	96.6	91.7	93.7	86.4	95.3	98.4		98.0	98.7	94.4	94.8	3.7
	OB-L	69.9	73.0	86.0	83.0	98.6	96.0		97.9	99.2	99.8	89.3	11.1

Table A5: NH_3 Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P			2.61			0.440					1.525	1.085
	OB-A												
	OB-B												
	OB-C			0.254			0.061					0.157	0.097
	OB-D			0.028			0.030					0.029	0.001
	OB-E			0.055			0.030					0.043	0.013
	OB-F			0.013			0.039					0.026	0.013
	OB-G			0.01			0.030					0.020	0.010
	OB-H						0.030					0.030	0.000
	OB-I			0.01			0.030					0.020	0.010
	OB-J						0.030					0.030	0.000
	OB-K			0.024			0.030					0.027	0.003
	OB-L			0.01			0.030					0.020	0.010
Percent Removal (%)	OB-A												
	OB-B												
	OB-C			90.3			86.1					88.2	2.1
	OB-D			98.9			93.2					96.1	2.9
	OB-E			97.9			93.2					95.5	2.4
	OB-F			99.5			91.2					95.4	4.1
	OB-G			99.6			93.2					96.4	3.2
	OB-H						93.2					93.2	0.0
	OB-I			99.6			93.2					96.4	3.2
	OB-J						93.2					93.2	0.0
	OB-K			99.1			93.2					96.1	3.0
	OB-L			99.6			93.2					96.4	3.2
Mass (mg)	OB-P (V)			4.0			0.641					2.299	1.7
	OB-P (H)			15.2			2.458					8.816	6.4
	OB-A												
	OB-B												
	OB-C			0.255			0.039					0.147	0.1
	OB-D			0.019			0.019					0.019	0.0
	OB-E			0.021			0.017					0.019	0.0
	OB-F			0.005			0.008					0.007	0.0
	OB-G			0.016			0.052					0.034	0.0
	OB-H						0.044					0.044	0.0
	OB-I			0.010			0.031					0.021	0.0
	OB-J						0.054					0.054	0.0
	OB-K			0.008			0.051					0.030	0.0
	OB-L			0.012			0.026					0.019	0.0
Mass Retained (mg)	OB-A												
	OB-B												
	OB-C			3.702			0.602					2.2	1.6
	OB-D			3.937			0.622					2.3	1.7
	OB-E			3.936			0.623					2.3	1.7
	OB-F			3.951			0.633					2.3	1.7
	OB-G			15.158			2.406					8.8	6.4
	OB-H						2.414					2.4	0.0
	OB-I			15.164			2.427					8.8	6.4
	OB-J						2.404					2.4	0.0
	OB-K			15.166			2.407					8.8	6.4
	OB-L			15.163			2.432					8.8	6.4
Mass Removal (%)	OB-A												
	OB-B												
	OB-C			93.6			93.9					93.7	0.2
	OB-D			99.5			97.0					98.3	1.3
	OB-E			99.5			97.3					98.4	1.1
	OB-F			99.9			98.8					99.3	0.5
	OB-G			99.9			97.9					98.9	1.0
	OB-H						98.2					98.2	0.0
	OB-I			99.9			98.7					99.3	0.6
	OB-J						97.8					97.8	0.0
	OB-K			99.9			97.9					98.9	1.0
	OB-L			99.9			98.9					99.4	0.5

Table A6: TKN Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P	2.749	2.18	2.26	3.824							2.753	0.655
	OB-A	0.1	0.804		1.474							0.793	0.561
	OB-B	0.169	0.324		1.314							0.602	0.507
	OB-C	1.445	0.496	0.722	0.854							0.879	0.351
	OB-D	1.733	2.279	0.377	0.569							1.239	0.793
	OB-E	0.794	0.403	0.577	0.300							0.519	0.187
	OB-F	1.432	1.821	1.723	2.330							1.826	0.324
	OB-G	0.874	1.481	0.922	0.300							0.894	0.418
	OB-H	1.223	0.2		0.300							0.574	0.460
	OB-I	0.609	0.369	0.529	0.334							0.460	0.113
	OB-J	0.987	0.611									0.799	0.188
	OB-K	0.656	0.723	0.809	0.300							0.622	0.194
	OB-L	1.127	0.286	1.062	0.485							0.740	0.362
Percent Removal (%)	OB-A	96.4	63.1		61.5							73.6	16.1
	OB-B	93.9	85.1		65.6							81.5	11.8
	OB-C	47.4	77.2	68.1	77.7							67.6	12.3
	OB-D	37.0	-4.5	83.3	85.1							50.2	37.0
	OB-E	71.1	81.5	74.5	92.2							79.8	8.1
	OB-F	47.9	16.5	23.8	39.1							31.8	12.4
	OB-G	68.2	32.1	59.2	92.2							62.9	21.5
	OB-H	55.5	90.8		92.2							79.5	17.0
	OB-I	77.8	83.1	76.6	91.3							82.2	5.8
	OB-J	64.1	72.0									68.0	3.9
	OB-K	76.1	66.8	64.2	92.2							74.8	10.9
	OB-L	59.0	86.9	53.0	87.3							71.6	15.7
Mass (mg)	OB-P (V)	2.829	2.244	3.426	5.858							3.589	1.4
	OB-P (H)	10.745	8.521	13.140	22.467							13.718	5.3
	OB-A	0.033	0.346		0.432							0.270	0.2
	OB-B	0.065	0.182		0.329							0.192	0.1
	OB-C	0.717	0.335	0.723	0.957							0.683	0.2
	OB-D	0.827	1.056	0.258	0.578							0.680	0.3
	OB-E	0.266	0.194	0.215	0.237							0.228	0.0
	OB-F	0.799	1.403	0.717	0.396							0.829	0.4
	OB-G	1.201	2.321	1.515	1.337							1.593	0.4
	OB-H	1.807	0.363		0.875							1.015	0.6
	OB-I	0.736	0.592	0.554	1.048							0.733	0.2
	OB-J	0.266	1.180									0.723	0.5
	OB-K	0.084	0.304	0.283	0.251							0.230	0.1
	OB-L	1.820	0.420	1.248	1.041							1.132	0.5
Mass Retained (mg)	OB-A	2.796	1.792		5.426							3.338	1.5
	OB-B	2.764	1.827		5.529							3.373	1.6
	OB-C	2.112	1.760	2.703	4.901							2.869	1.2
	OB-D	2.002	1.623	3.168	5.280							3.018	1.4
	OB-E	2.563	1.775	3.211	5.621							3.292	1.4
	OB-F	2.031	1.299	2.709	5.461							2.875	1.6
	OB-G	9.545	3.840	11.625	21.130							11.535	6.2
	OB-H	8.938	4.792		21.591							11.774	7.1
	OB-I	10.010	6.601	12.585	21.419							12.654	5.5
	OB-J	10.480	4.397									7.438	3.0
	OB-K	10.662	6.460	12.857	22.216							13.049	5.8
	OB-L	8.926	5.141	11.892	21.426							11.846	6.0
Mass Removal (%)	OB-A	98.8	84.6		92.6							92.0	5.8
	OB-B	97.7	91.9		94.4							94.6	2.4
	OB-C	74.7	85.1	78.9	83.7							80.6	4.1
	OB-D	70.8	53.0	92.5	90.1							76.6	16.0
	OB-E	90.6	91.3	93.7	96.0							92.9	2.1
	OB-F	71.8	37.5	79.1	93.2							70.4	20.5
	OB-G	88.8	72.8	88.5	94.0							86.0	8.0
	OB-H	83.2	95.7		96.1							91.7	6.0
	OB-I	93.2	93.0	95.8	95.3							94.3	1.2
	OB-J	97.5	86.2									91.8	5.7
	OB-K	99.2	96.4	97.8	98.9							98.1	1.1
	OB-L	83.1	95.1	90.5	95.4							91.0	5.0

Table A7: Total Nitrogen Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P	3.54	3.982	4.019	5.452							4.248	0.720
	OB-A	0.619	0.95		1.869							1.146	0.529
	OB-B	0.269	0.374		1.651							0.765	0.628
	OB-C	1.545	0.636	0.789	0.954							0.981	0.344
	OB-D	2.045	2.779	1.316	0.987							1.782	0.691
	OB-E	0.894	0.569	0.97	0.536							0.742	0.192
	OB-F	2.037	2.542	3.642	3.659							2.970	0.704
	OB-G	1.875	3.525	2.578	0.427							2.101	1.130
	OB-H	1.765	1.442		1.115							1.441	0.265
	OB-I	0.709	0.645	1.297	0.434							0.771	0.320
	OB-J	1.371	1.982									1.677	0.306
	OB-K	1.492	2.113	2.659	1.857							2.030	0.425
	OB-L	1.703	1.582	2.277	1.240							1.700	0.374
Percent Removal (%)	OB-A	82.5	76.1		65.7							74.8	6.9
	OB-B	92.4	90.6		69.7							84.2	10.3
	OB-C	56.4	84.0	80.4	82.5							75.8	11.3
	OB-D	42.2	30.2	67.3	81.9							55.4	20.3
	OB-E	74.7	85.7	75.9	90.2							81.6	6.5
	OB-F	42.5	36.2	9.4	32.9							30.2	12.5
	OB-G	47.0	11.5	35.9	92.2							46.6	29.3
	OB-H	50.1	63.8		79.5							64.5	12.0
	OB-I	80.0	83.8	67.7	92.0							80.9	8.8
	OB-J	61.3	50.2									55.7	5.5
	OB-K	57.9	46.9	33.8	65.9							51.1	12.1
	OB-L	51.9	60.3	43.3	77.3							58.2	12.5
Mass (mg)	OB-P (V)	3.614	4.045	3.426	8.145							4.807	1.9
	OB-P (H)	13.724	15.362	13.140	31.239							18.366	7.5
	OB-A	0.196	0.399		0.527							0.374	0.1
	OB-B	0.096	0.204		0.400							0.233	0.1
	OB-C	0.740	0.393	0.723	0.959							0.704	0.2
	OB-D	0.959	1.275	0.258	0.953							0.861	0.4
	OB-E	0.292	0.194	0.215	0.368							0.267	0.1
	OB-F	1.028	1.403	0.717	0.603							0.937	0.3
	OB-G	2.500	2.321	1.515	1.860							2.049	0.4
	OB-H	2.494	0.363		3.002							1.953	1.1
	OB-I	0.848	0.592	0.554	1.330							0.831	0.3
	OB-J	0.339	1.180									0.759	0.4
	OB-K	0.186	0.304	0.283	1.471							0.561	0.5
	OB-L	2.485	0.420	1.248	2.480							1.658	0.9
Mass Retained (mg)	OB-A	3.418	3.646		7.618							4.894	1.9
	OB-B	3.518	3.841		7.745							5.035	1.9
	OB-C	2.873	3.652	2.703	7.186							4.103	1.8
	OB-D	2.655	2.770	3.168	7.192							3.946	1.9
	OB-E	3.321	3.851	3.211	7.777							4.540	1.9
	OB-F	2.586	2.642	2.709	7.543							3.870	2.1
	OB-G	11.224	13.041	11.625	29.379							16.317	7.6
	OB-H	11.230	14.999		28.237							18.155	7.3
	OB-I	12.876	14.770	12.585	29.909							17.535	7.2
	OB-J	13.385	14.182									13.784	0.4
	OB-K	13.538	15.058	12.857	29.768							17.805	7.0
	OB-L	11.239	14.942	11.892	28.759							16.708	7.1
Mass Removal (%)	OB-A	90.1	90.1		93.5							91.3	1.6
	OB-B	95.0	95.0		95.1							95.0	0.1
	OB-C	90.3	90.3	78.9	88.2							86.9	4.7
	OB-D	68.5	68.5	92.5	88.3							79.4	11.0
	OB-E	95.2	95.2	93.7	95.5							94.9	0.7
	OB-F	65.3	65.3	79.1	92.6							75.6	11.3
	OB-G	84.9	84.9	88.5	94.0							88.1	3.7
	OB-H	97.6	97.6		90.4							95.2	3.4
	OB-I	96.1	96.1	95.8	95.7							96.0	0.2
	OB-J	92.3	92.3									92.3	0.0
	OB-K	98.0	98.0	97.8	95.3							97.3	1.2
	OB-L	97.3	97.3	90.5	92.1							94.3	3.0

Table A8: PO_4 Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P	0.748	0.684	0.728		0.554	0.511		0.536	0.544	0.529	0.604	0.092
	OB-A	0.05	0.030			0.099			0.030			0.052	0.028
	OB-B	0.05	0.030			0.031			0.030	0.011	0.014	0.028	0.013
	OB-C	0.05	0.030	0.022		0.030	0.010		0.030	0.012	0.013	0.025	0.013
	OB-D	0.057	0.054	0.042		0.030	0.010		0.030	0.018	0.022	0.033	0.016
	OB-E	0.05	0.030	0.044		0.030	0.018		0.030		0.015	0.031	0.012
	OB-F	0.05	0.030	0.05		0.030	0.072		0.030	0.017	0.024	0.038	0.017
	OB-G	0.05	0.030	0.016		0.030	0.010		0.030	0.011	0.025	0.025	0.012
	OB-H	0.05	0.030			0.030	0.010		0.030	0.026	0.016	0.027	0.012
	OB-I	0.05	0.030	0.018		0.030	0.010		0.030	0.011	0.014	0.024	0.013
	OB-J	0.05	0.030			0.030	0.012		0.030	0.045	0.017	0.031	0.013
	OB-K	0.05	0.043	0.031		0.030	0.010		0.030	0.024	0.017	0.029	0.012
	OB-L	0.05	0.030	0.021		0.030	0.048		0.030	0.019	0.016	0.031	0.012
Percent Removal (%)	OB-A	93.3	95.6			82.2			94.4			91.4	5.4
	OB-B	93.3	95.6			94.4			94.4	97.9	97.4	95.5	1.7
	OB-C	93.3	95.6	97.0		94.6	98.0		94.4	97.8	97.6	96.0	1.7
	OB-D	92.4	92.1	94.2		94.6	98.0		94.4	96.8	95.9	94.8	1.9
	OB-E	93.3	95.6	94.0		94.6	96.4		94.4		97.1	95.1	1.3
	OB-F	93.3	95.6	93.1		94.6	85.8		94.4	96.9	95.4	93.7	3.2
	OB-G	93.3	95.6	97.8		94.6	98.0		94.4	97.9	95.2	95.9	1.7
	OB-H	93.3	95.6			94.6	98.1		94.4	95.2	97.0	95.5	1.5
	OB-I	93.3	95.6	97.5		94.6	98.0		94.4	97.9	97.3	96.1	1.7
	OB-J	93.3	95.6			94.6	97.7		94.4	91.7	96.8	94.9	1.9
	OB-K	93.3	93.7	95.7		94.6	98.1		94.4	95.6	96.7	95.3	1.5
	OB-L	93.3	95.6	97.1		94.6	90.6		94.4	96.4	97.0	94.9	2.1
Mass (mg)	OB-P (V)	0.770	0.704	1.104		0.876	0.745		0.813	0.851	0.440	0.788	0.2
	OB-P (H)	2.924	2.674	4.233		3.358	2.856		3.118	3.263	1.685	3.014	0.7
	OB-A	0.017	0.013			0.024			0.013			0.017	0.0
	OB-B	0.019	0.017			0.015			0.012	0.006	0.005	0.012	0.0
	OB-C	0.025	0.020	0.022		0.030	0.006		0.006	0.005	0.004	0.015	0.0
	OB-D	0.027	0.025	0.029		0.027	0.006		0.009	0.004	0.007	0.017	0.0
	OB-E	0.017	0.014	0.016		0.027	0.011		0.014		0.003	0.015	0.0
	OB-F	0.028	0.023	0.021		0.032	0.015		0.014	0.013	0.004	0.019	0.0
	OB-G	0.069	0.047	0.026		0.114	0.017		0.064	0.024	0.031	0.049	0.0
	OB-H	0.074	0.054			0.113	0.014		0.058	0.041	0.003	0.051	0.0
	OB-I	0.060	0.048	0.019		0.062	0.010		0.054	0.023	0.002	0.035	0.0
	OB-J	0.013	0.058			0.104	0.021		0.055	0.114	0.012	0.054	0.0
	OB-K	0.006	0.018	0.011		0.046	0.017		0.017	0.043	0.011	0.021	0.0
	OB-L	0.081	0.044	0.025		0.065	0.042		0.024	0.026	0.000	0.038	0.0
Mass Retained (mg)	OB-A	0.753	0.691			0.851			0.800			0.774	0.1
	OB-B	0.750	0.687			0.860			0.800	0.845	0.435	0.730	0.1
	OB-C	0.745	0.684	1.1		0.845	0.738		0.807	0.846	0.436	0.773	0.2
	OB-D	0.743	0.679	1.1		0.849	0.738		0.804	0.847	0.433	0.771	0.2
	OB-E	0.753	0.690	1.1		0.849	0.734		0.798		0.436	0.764	0.2
	OB-F	0.742	0.681	1.1		0.843	0.730		0.799	0.838	0.436	0.769	0.2
	OB-G	2.855	2.627	4.2		3.244	2.839		3.054	3.239	1.654	2.965	0.7
	OB-H	2.850	2.619			3.245	2.842		3.060	3.221	1.682	2.789	0.5
	OB-I	2.863	2.626	4.2		3.296	2.846		3.064	3.240	1.683	2.979	0.7
	OB-J	2.910	2.616			3.255	2.835		3.063	3.149	1.673	2.786	0.5
	OB-K	2.917	2.656	4.2		3.312	2.840		3.101	3.220	1.674	2.993	0.7
	OB-L	2.843	2.630	4.2		3.293	2.814		3.094	3.237	1.684	2.975	0.7
Mass Removal (%)	OB-A	97.9	98.2			97.2			98.4			97.9	0.4
	OB-B	97.5	97.6			98.2			98.5	99.3	99.0	98.3	0.7
	OB-C	96.8	97.1	98.0		96.5	99.1		99.3	99.5	99.1	98.2	1.2
	OB-D	96.5	96.4	97.4		97.0	99.1		98.9	99.5	98.4	97.9	1.2
	OB-E	97.8	97.9	98.5		97.0	98.6		98.2		99.3	98.2	0.7
	OB-F	96.4	96.7	98.1		96.3	98.0		98.3	98.5	99.2	97.7	1.0
	OB-G	97.7	98.2	99.4		96.6	99.4		98.0	99.3	98.2	98.3	0.9
	OB-H	97.5	98.0			96.6	99.5		98.2	98.7	99.8	98.3	1.0
	OB-I	97.9	98.2	99.6		98.1	99.6		98.3	99.3	99.9	98.9	0.7
	OB-J	99.5	97.8			96.9	99.3		98.2	96.5	99.3	98.2	1.1
	OB-K	99.8	99.3	99.7		98.6	99.4		99.5	98.7	99.4	99.3	0.4
	OB-L	97.2	98.4	99.4		98.1	98.5		99.2	99.2	100.0	98.8	0.8

Table A9: TKP Data for all Quality Testing Events

		3.10.16	3.23.16	4.21.16	5.10.16	5.31.16	6.12.16	7.5.16	8.29.16	9.5.16	10.31.16	AVERAGE	STD. DEV
Concentration (mg/L)	OB-P	0.661	0.784	0.756			0.578	0.586	0.526		0.501	0.627	0.102
	OB-A	0.05	0.05						0.075			0.058	0.012
	OB-B	0.05	0.05						0.059		0.050	0.052	0.004
	OB-C	0.058	0.05	0.057			0.100	0.050	0.112		0.050	0.068	0.024
	OB-D	0.059	0.088	0.056			0.100	0.050	0.094		0.055	0.072	0.020
	OB-E	0.05	0.05	0.05			0.100	0.095	0.061		0.058	0.066	0.020
	OB-F	0.05	0.057	0.272			0.232	0.182	0.112		0.085	0.141	0.081
	OB-G	0.052	0.169	0.078			0.100	0.050	0.082		0.055	0.084	0.039
	OB-H	0.078	0.051				0.100		0.069		0.050	0.070	0.019
	OB-I	0.067	0.058	0.05			0.100	0.377	0.054		0.050	0.108	0.111
	OB-J	0.05	0.05				0.100	0.050	0.094		0.050	0.066	0.022
	OB-K	0.05	0.05	0.05			0.100	0.050	0.066		0.051	0.060	0.017
	OB-L	0.05	0.072	0.106			0.122		0.081		0.050	0.080	0.027
Percent Removal (%)	OB-A	92.4	93.6						85.7			90.6	3.5
	OB-B	92.4	93.6						88.8		90.0	91.2	1.9
	OB-C	91.2	93.6	92.5			82.7	91.4	78.7		90.0	88.6	5.2
	OB-D	91.1	88.8	92.6			82.7	91.4	82.1		89.0	88.2	3.9
	OB-E	92.4	93.6	93.4			82.7	83.8	88.4		88.4	89.0	4.1
	OB-F	92.4	92.7	64.0			59.9	68.9	78.7		83.0	77.1	12.3
	OB-G	92.1	78.4	89.7			82.7	91.4	84.4		89.0	86.8	4.7
	OB-H	88.2	93.5				82.7		86.9		90.0	88.3	3.6
	OB-I	89.9	92.6	93.4			82.7	35.7	89.7		90.0	82.0	19.2
	OB-J	92.4	93.6				82.7	91.4	82.1		90.0	88.7	4.6
	OB-K	92.4	93.6	93.4			82.7	91.4	87.5		89.8	90.1	3.6
	OB-L	92.4	90.8	86.0			78.9		84.6		90.0	87.1	4.6
Mass (mg)	OB-P (V)	0.680	0.807	1.146			0.842	0.472	0.797		0.416	0.737	0.2
	OB-P (H)	2.584	3.065	4.395			3.231	1.808	3.058		1.594	2.819	0.9
	OB-A	0.017	0.022						0.033			0.024	0.0
	OB-B	0.019	0.028						0.025		0.017	0.022	0.0
	OB-C	0.029	0.034	0.057			0.064	0.015	0.021		0.015	0.034	0.0
	OB-D	0.028	0.041	0.038			0.064	0.016	0.027		0.018	0.033	0.0
	OB-E	0.017	0.024	0.019			0.058	0.020	0.029		0.012	0.026	0.0
	OB-F	0.028	0.044	0.113			0.047	0.028	0.052		0.013	0.046	0.0
	OB-G	0.071	0.265	0.128			0.175	0.061	0.174		0.067	0.134	0.1
	OB-H	0.115	0.092				0.148		0.133		0.008	0.099	0.0
	OB-I	0.081	0.093	0.052			0.103	0.044	0.097		0.006	0.068	0.0
	OB-J	0.013	0.097				0.181	0.035	0.173		0.035	0.089	0.1
	OB-K	0.006	0.021	0.017			0.170	0.031	0.037		0.032	0.045	0.1
	OB-L	0.081	0.106	0.125			0.107		0.065		0.001	0.081	0.0
Mass Retained (mg)	OB-A	0.664	0.785						0.765			0.738	0.1
	OB-B	0.661	0.779						0.773		0.400	0.653	0.2
	OB-C	0.652	0.773	1.089			0.778	0.456	0.777		0.401	0.704	0.2
	OB-D	0.652	0.766	1.108			0.778	0.455	0.770		0.398	0.704	0.2
	OB-E	0.664	0.783	1.127			0.784	0.452	0.768		0.404	0.712	0.2
	OB-F	0.652	0.763	1.033			0.795	0.444	0.746		0.403	0.691	0.2
	OB-G	2.512	2.800	4.267			3.056	1.746	2.884		1.528	2.685	0.8
	OB-H	2.469	2.972				3.082		2.926		1.586	2.607	0.6
	OB-I	2.503	2.971	4.343			3.127	1.763	2.962		1.589	2.751	0.9
	OB-J	2.570	2.968				3.049	1.772	2.885		1.559	2.467	0.6
	OB-K	2.577	3.044	4.378			3.060	1.776	3.021		1.563	2.774	0.9
	OB-L	2.503	2.959	4.271			3.123		2.993		1.593	2.907	0.8
Mass Removal (%)	OB-A	97.6	97.3						95.9			96.9	0.7
	OB-B	97.2	96.5						96.9		96.0	96.7	0.4
	OB-C	95.8	95.8	95.0			92.4	96.7	97.4		96.3	95.6	1.5
	OB-D	95.9	94.9	96.7			92.4	96.5	96.6		95.7	95.5	1.4
	OB-E	97.5	97.0	98.4			93.1	95.7	96.3		97.0	96.4	1.6
	OB-F	95.9	94.6	90.1			94.4	94.2	93.5		96.9	94.2	2.0
	OB-G	97.2	91.4	97.1			94.6	96.6	94.3		95.8	95.3	1.9
	OB-H	95.5	97.0				95.4		95.7		99.5	96.6	1.5
	OB-I	96.9	97.0	98.8			96.8	97.5	96.8		99.6	97.6	1.1
	OB-J	99.5	96.8				94.4	98.0	94.3		97.8	96.8	1.9
	OB-K	99.8	99.3	99.6			94.7	98.3	98.8		98.0	98.4	1.6
	OB-L	96.9	96.6	97.2			96.7		97.9		99.9	97.5	1.2

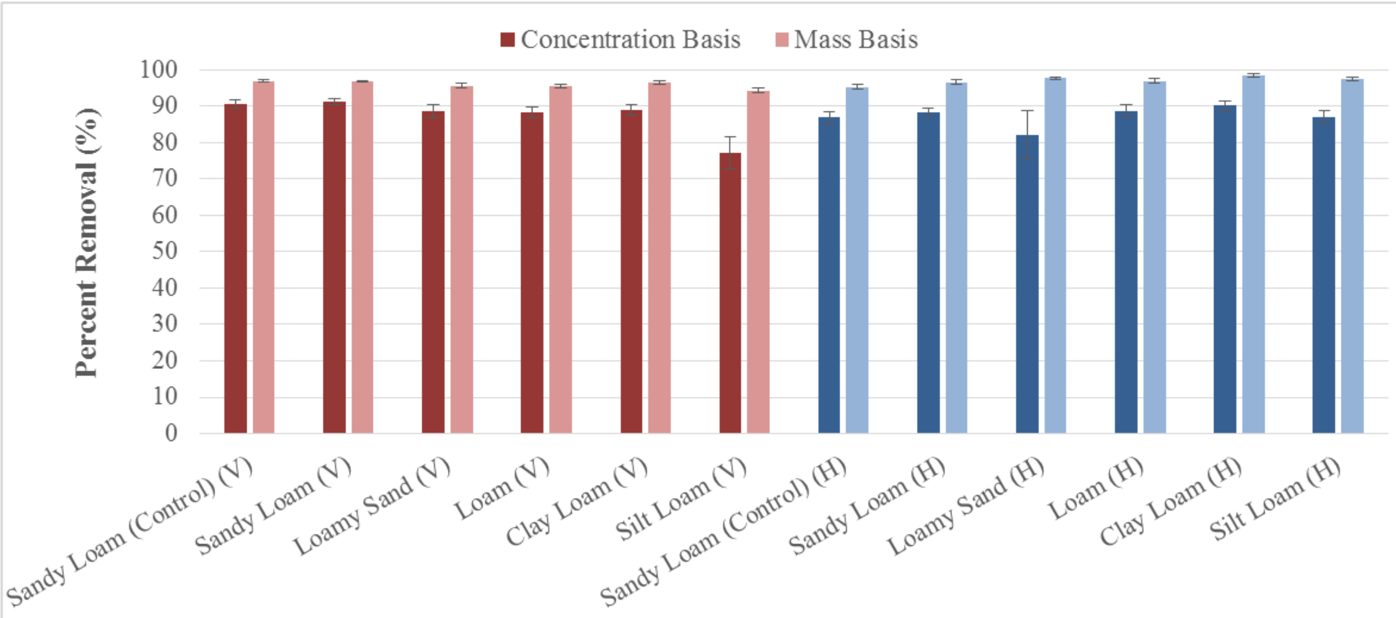

Figure A22: PO_4 Percent Removal on a Concentration and Mass Basis for All Lysimeters

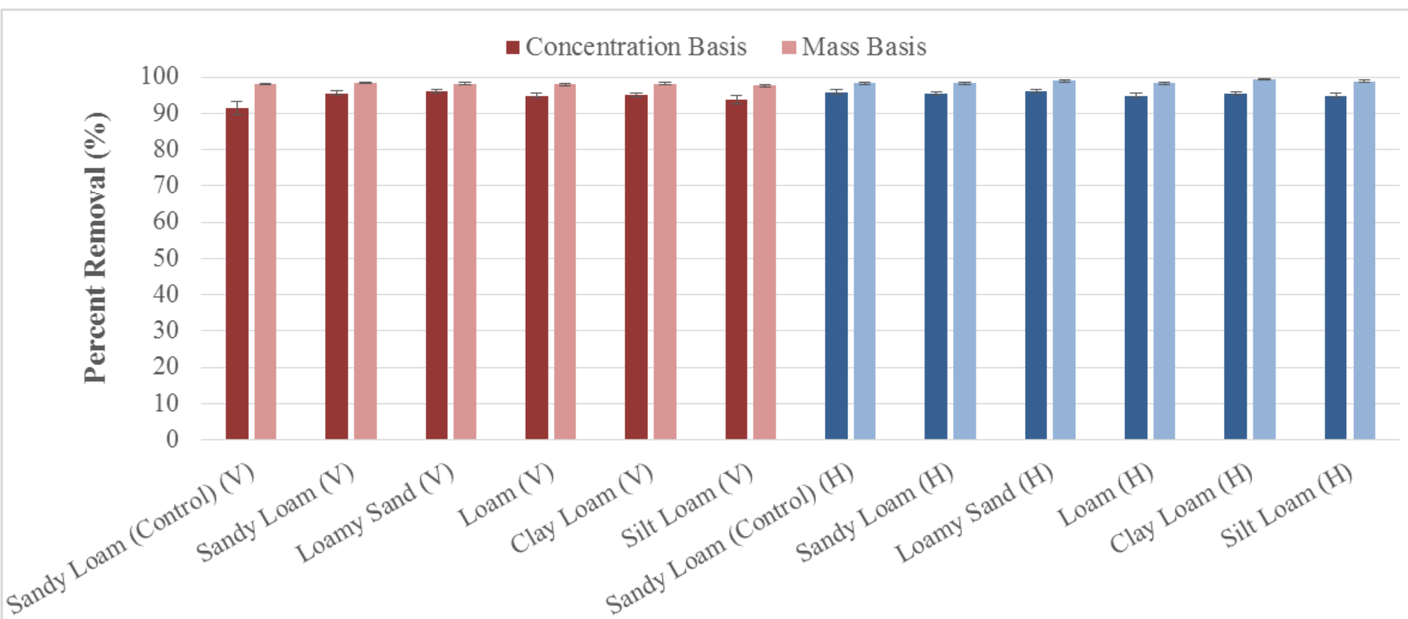

Figure A23: TKP Percent Removal on a Concentration and Mass Basis for All Lysimeters

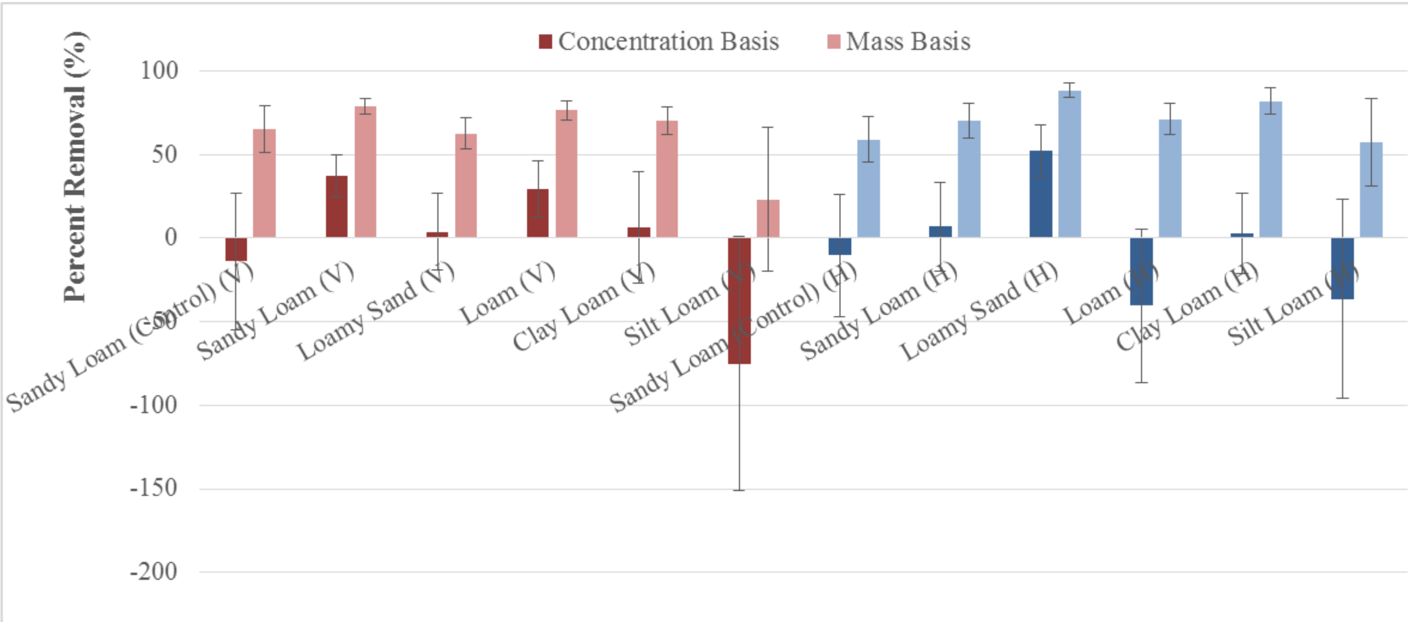

Figure A24: NO_2 Percent Removal on a Concentration and Mass Basis for All Lysimeters

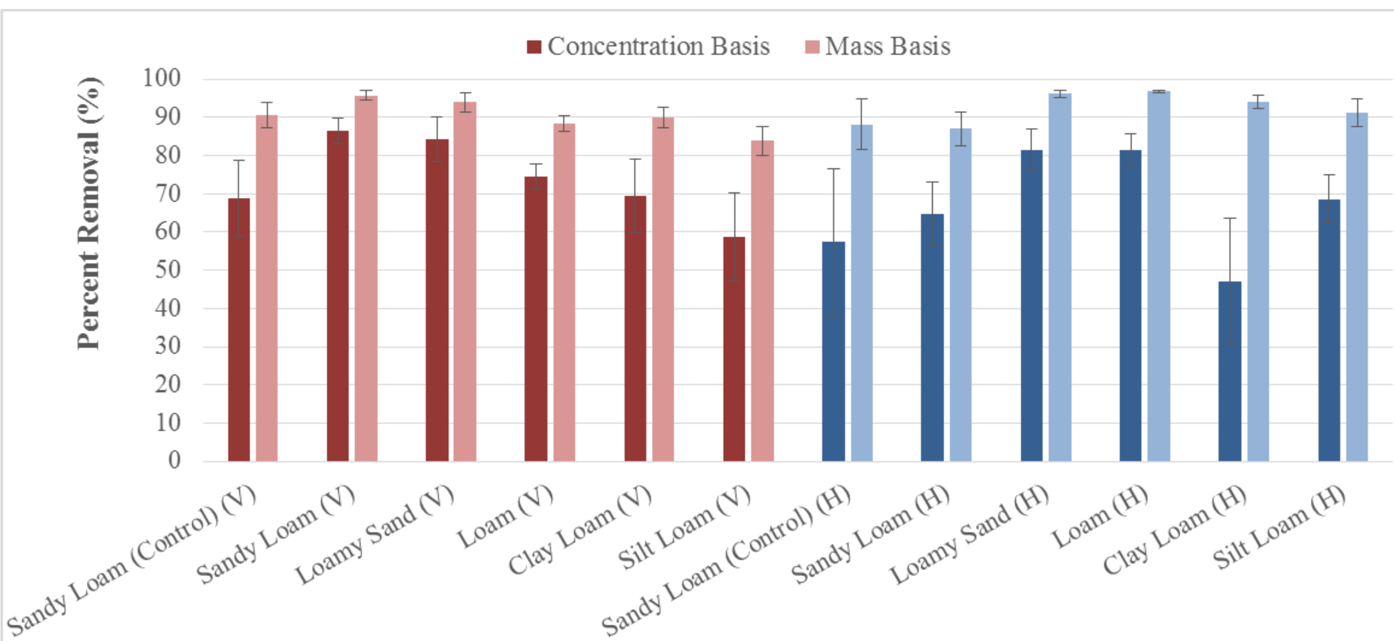

Figure A25: NO_3 Percent Removal on a Concentration and Mass Basis for All Lysimeters

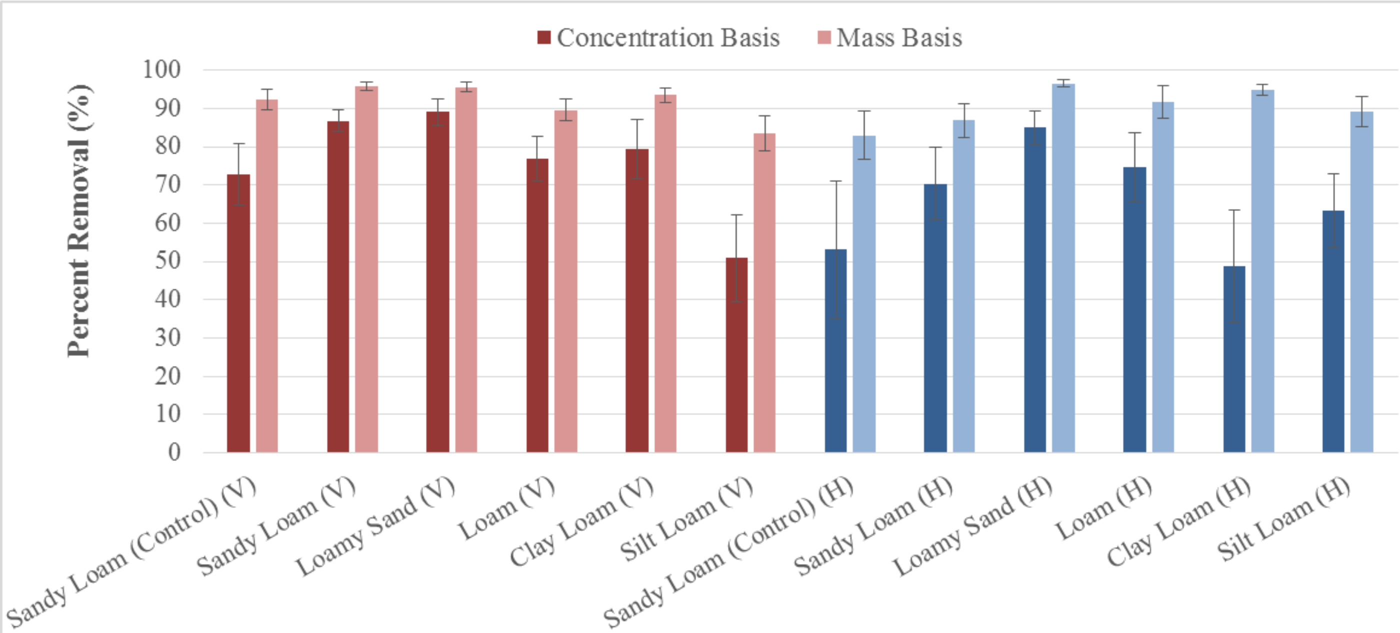

Figure A26: NO_x Percent Removal on a Concentration and Mass Basis for All Lysimeters

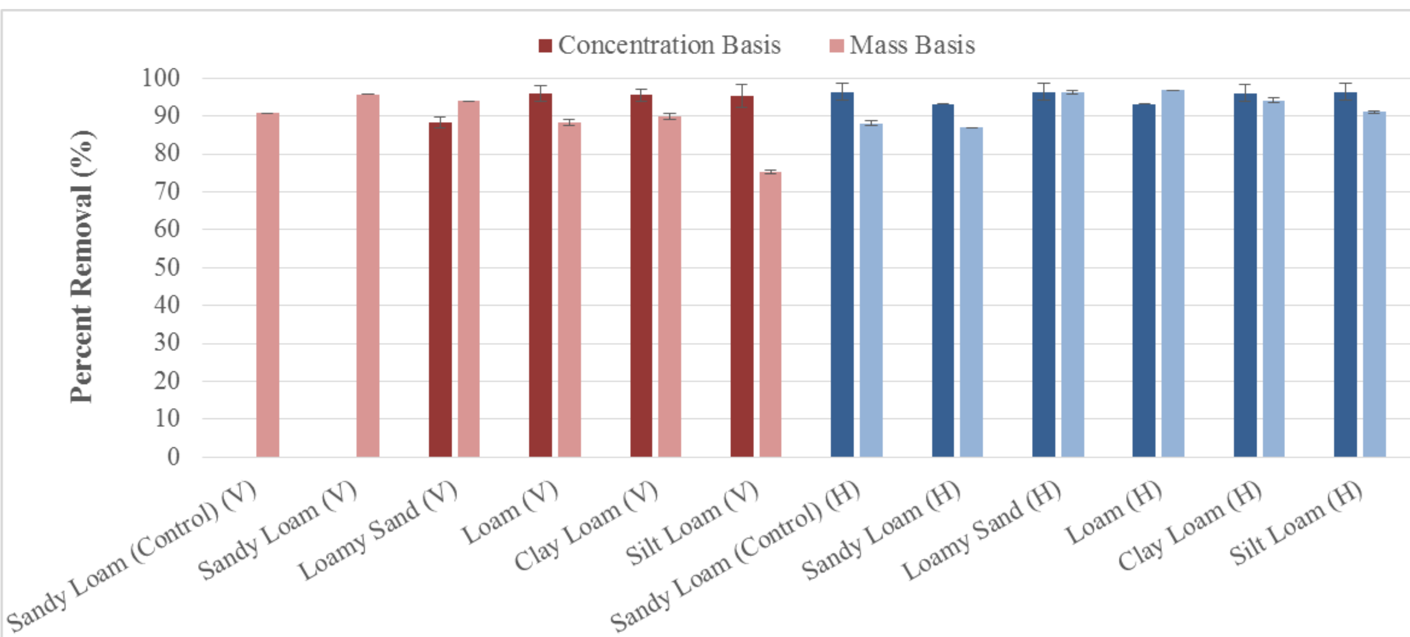

Figure A27: NH_3 Percent Removal on a Concentration and Mass Basis for All Lysimeters

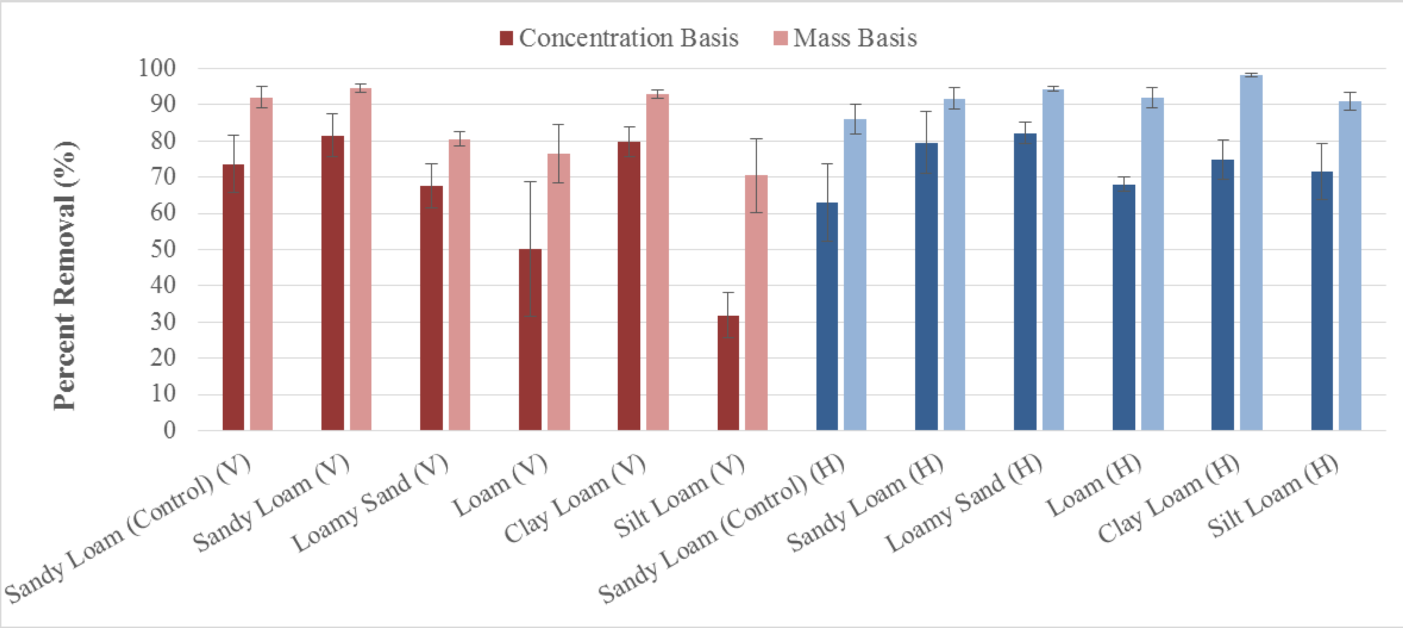

Figure A28: TKN Percent Removal on a Concentration and Mass Basis for All Lysimeters

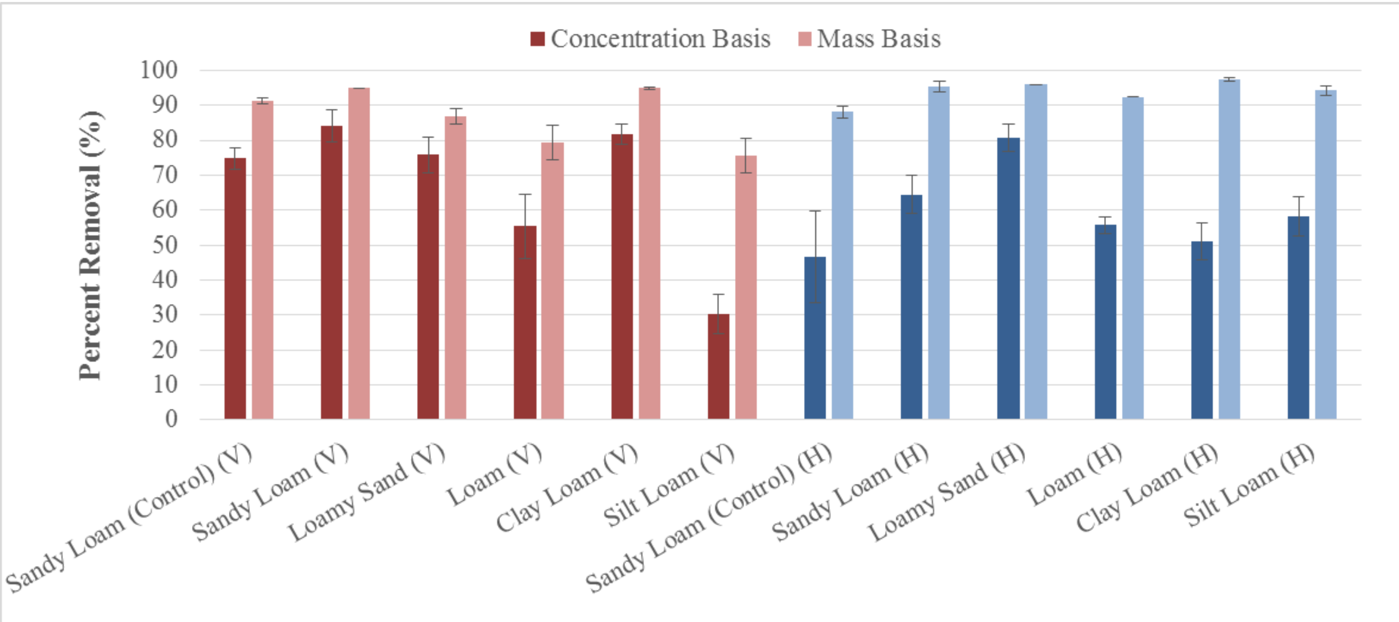

Figure A29: Total Nitrogen Percent Removal on a Concentration and Mass Basis for All Lysimeters

Table A10: Statistical Paired T-Test Comparison between Effluent Pollutant Concentrations in the Vertical and Horizontal Soil Lysimeters for the Same Soil Types

Soil Media		**NO_2**	**NO_3**	**NO_X**	**TKN**	**TN**	**PO_4**	**TKP**
p-value	**Control**	0.607	0.479	0.490	0.346	0.082	0.134	0.380
Statistically different?		NO	NO	NO	NO	NO	NO	NO
p-value	**Sandy Loam**	0.254	0.234	0.314	0.340	0.903	0.346	0.313
Statistically different?		NO	NO	NO	NO	NO	NO	NO
p-value	**Loamy Sand**	0.025	0.754	0.285	0.037	0.327	0.808	0.211
Statistically different?		YES	NO	NO	YES	NO	NO	NO
p-value	**Loam**	0.502	0.088	0.546	0.036	0.111	0.567	0.356
Statistically different?		NO	NO	NO	YES	NO	NO	NO
p-value	**Clay Loam**	0.307	0.353	0.790	0.343	0.281	0.445	0.245
Statistically different?		NO	NO	NO	NO	NO	NO	NO
p-value	**Silt Loam**	0.677	0.120	0.009	0.215	0.229	0.107	0.006
Statistically different?		NO	NO	YES	NO	NO	NO	YES

Table A11: Statistical Paired T-Test Comparison between Effluent NO_2 Concentrations in the Vertical and Horizontal Lysimeters

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.064	0.653	0.281	0.732	0.040
Statistically different?			NO	NO	NO	NO	YES
p-value	**B**			0.017	0.080	0.148	0.045
Statistically different?				YES	NO	NO	YES
p-value	**C**				0.049	0.498	0.041
Statistically different?					YES	NO	YES
p-value	**D**					0.716	0.025
Statistically different?						NO	YES
p-value	**E**						0.026
Statistically different?							YES
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.119	0.208	0.508	0.306	0.722
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.111	0.337	0.462	0.941
Statistically different?				NO	NO	NO	NO
p-value	**I**				0.117	0.270	0.166
Statistically different?					NO	NO	NO
p-value	**J**					0.406	0.336
Statistically different?						NO	NO
p-value	**K**						0.636
Statistically different?							NO

Table A12: Statistical Paired T-Test Comparison between Effluent NO_3 Concentrations in the Vertical and Horizontal Lysimeters

Vertical Lysimeters								
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.266	0.156	0.749	0.268	0.557
Statistically different?			NO	NO	NO	NO	NO
p-value	**B**			0.535	0.131	0.654	0.262
Statistically different?				NO	NO	NO	NO
p-value	**C**				0.113	0.077	0.135
Statistically different?					NO	NO	NO
p-value	**D**					0.725	0.158
Statistically different?						NO	NO
p-value	**E**						0.194
Statistically different?							NO

Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.927	0.380	0.350	0.450	0.997
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.203	0.338	0.175	0.287
Statistically different?				NO	NO	NO	NO
p-value	**I**				0.729	0.199	0.218
Statistically different?					NO	NO	NO
p-value	**J**					0.275	0.177
Statistically different?						NO	NO
p-value	**K**						0.185
Statistically different?							NO

Table A13: Statistical Paired T-Test Comparison between Effluent NO_X Concentrations in the Vertical and Horizontal Lysimeters

Vertical Lysimeters								
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.329	0.085	0.964	0.135	0.081
Statistically different?			NO	NO	NO	NO	NO
p-value	**B**			0.415	0.358	0.354	0.044
Statistically different?				NO	NO	NO	YES
p-value	**C**				0.094	0.270	0.017
Statistically different?					NO	NO	YES
p-value	**D**					0.510	0.013
Statistically different?						NO	YES
p-value	**E**						0.017
Statistically different?							YES

Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.579	0.095	0.131	0.537	0.584
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.092	0.935	0.061	0.317
Statistically different?				NO	NO	NO	NO
p-value	**I**				0.243	0.034	0.021
Statistically different?					NO	NO	YES
p-value	**J**					0.130	0.294
Statistically different?						NO	NO
p-value	**K**						0.126
Statistically different?							NO

Table A14: Statistical Paired T-Test Comparison between Effluent TKN Concentrations in the Vertical and Horizontal Lysimeters

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.355	0.841	0.465	0.642	0.017
Statistically different?			NO	NO	NO	NO	YES
p-value	**B**			0.583	0.387	0.850	0.012
Statistically different?				NO	NO	NO	YES
p-value	**C**				0.520	0.084	0.066
Statistically different?					NO	NO	NO
p-value	**D**					0.208	0.375
Statistically different?						NO	NO
p-value	**E**						0.020
Statistically different?							YES

Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.595	0.172	0.582	0.203	0.687
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.628	0.832	0.967	0.552
Statistically different?				NO	NO	NO	NO
p-value	**I**				0.137	0.179	0.159
Statistically different?					NO	NO	NO
p-value	**J**					0.708	0.759
Statistically different?						NO	NO
p-value	**K**						0.588
Statistically different?							NO

Table A15: Statistical Paired T-Test Comparison between Effluent Total Nitrogen Concentrations in the Vertical and Horizontal Lysimeters

Vertical Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.067	0.869	0.448	0.412	0.004
Statistically different?			NO	NO	NO	NO	YES
p-value	**B**			0.671	0.337	0.868	0.003
Statistically different?				NO	NO	NO	YES
p-value	**C**				0.181	0.286	0.035
Statistically different?					NO	NO	YES
p-value	**D**					0.094	0.217
Statistically different?						NO	NO
p-value	**E**						0.014
Statistically different?							YES
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.604	0.111	0.299	0.912	0.533
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.017	0.901	0.365	0.407
Statistically different?				YES	NO	NO	NO
p-value	**I**				0.207	0.004	0.000
Statistically different?					NO	YES	YES
p-value	**J**					0.025	0.941
Statistically different?						YES	NO
p-value	**K**						0.175
Statistically different?							NO

Table A16: Statistical Paired T-Test Comparison between Effluent PO_4 Concentrations in the Vertical and Horizontal Lysimeters

Vertical Lysimeters								
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.391	0.391	0.676	0.391	0.391
Statistically different?			NO	NO	NO	NO	NO
p-value	**B**			0.294	0.099	0.717	0.235
Statistically different?				NO	NO	NO	NO
p-value	**C**				0.060	0.182	0.131
Statistically different?					NO	NO	NO
p-value	**D**					0.357	0.580
Statistically different?						NO	NO
p-value	**E**						0.237
Statistically different?							NO
Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.794	0.441	0.478	0.213	0.337
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.306	0.281	0.400	0.464
Statistically different?				NO	NO	NO	NO
p-value	**I**				0.291	0.057	0.213
Statistically different?					NO	NO	NO
p-value	**J**					0.724	0.849
Statistically different?						NO	NO
p-value	**K**						0.841
Statistically different?							NO

Table A17: Statistical Paired T-Test Comparison between Effluent TKP Concentrations in the Vertical and Horizontal Lysimeters

Vertical Lysimeters								
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**A**	**B**	**C**	**D**	**E**	**F**
p-value	**A**		0.423	0.314	0.123	0.423	0.325
Statistically different?			NO	NO	NO	NO	NO
p-value	**B**			0.317	0.085	0.278	0.150
Statistically different?				NO	NO	NO	NO
p-value	**C**				0.595	0.865	0.066
Statistically different?					NO	NO	NO
p-value	**D**					0.615	0.089
Statistically different?						NO	NO
p-value	**E**						0.047
Statistically different?							YES

Horizontal Lysimeters							
Soil Media		**Sandy Loam (Control)**	**Sandy Loam**	**Loamy Sand**	**Loam**	**Clay Loam**	**Silt Loam**
Lysimeter		**G**	**H**	**I**	**J**	**K**	**L**
p-value	**G**		0.426	0.662	0.389	0.189	0.642
Statistically different?			NO	NO	NO	NO	NO
p-value	**H**			0.398	0.929	0.322	0.588
Statistically different?				NO	NO	NO	NO
p-value	**I**				0.392	0.338	0.155
Statistically different?					NO	NO	NO
p-value	**J**					0.383	0.417
Statistically different?						NO	NO
p-value	**K**						0.075
Statistically different?							NO

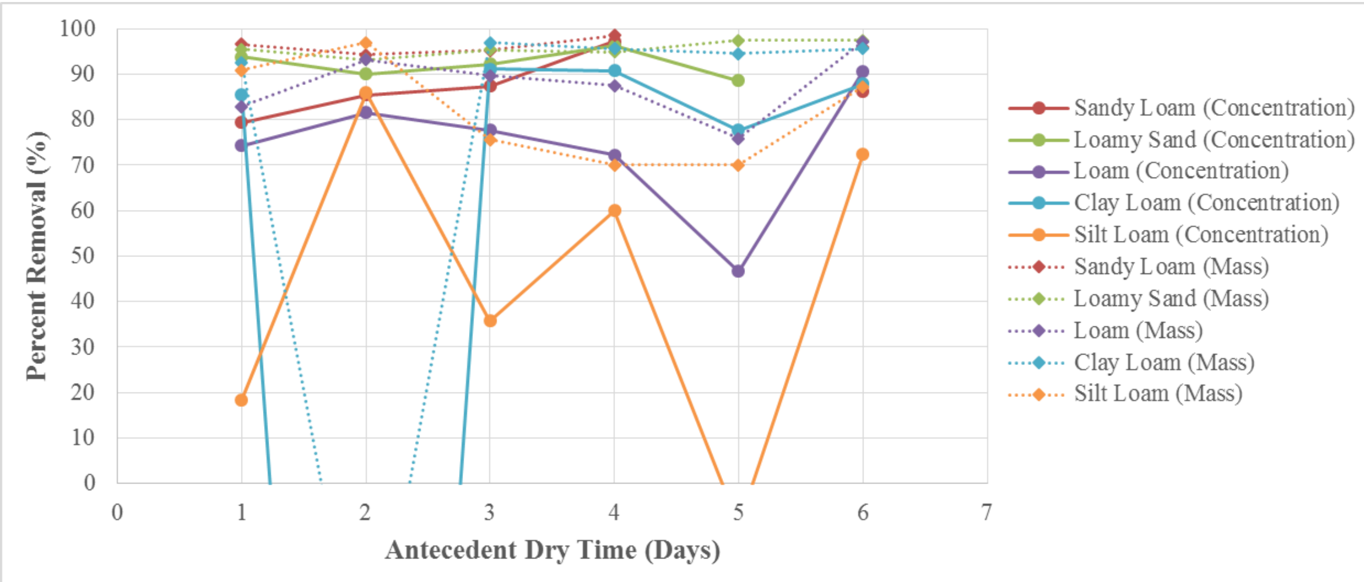

Figure A30: Relationship between Antecedent Dry Time and Percent Removal for NO_2 in the Vertical Lysimeters

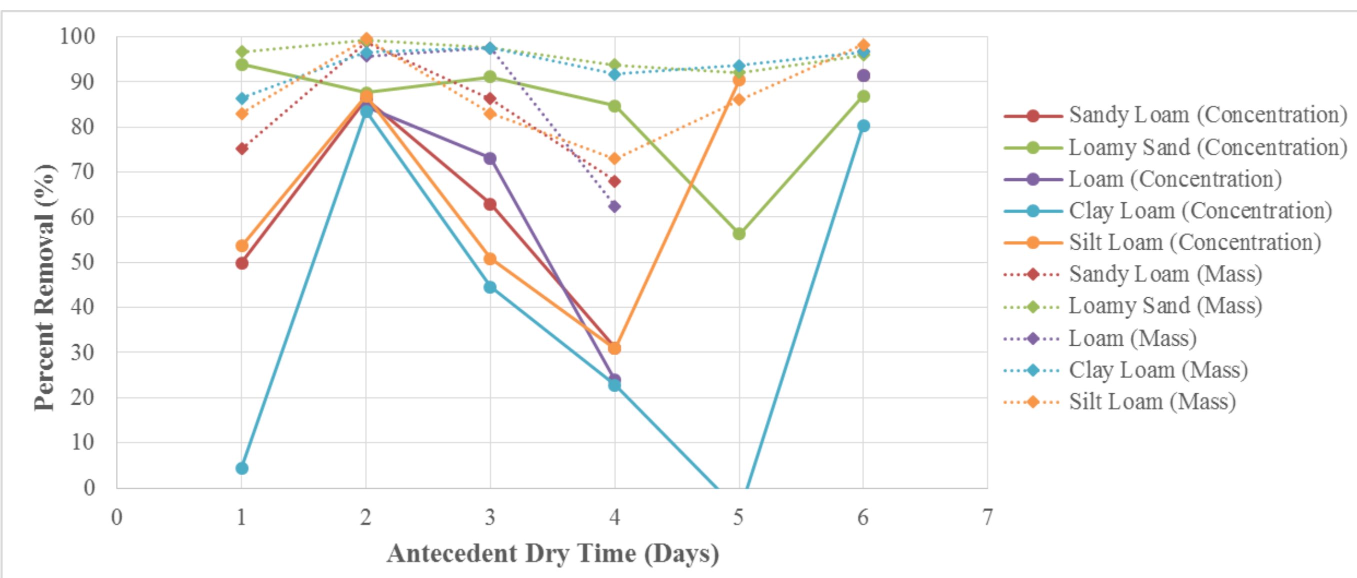

Figure A31: Relationship between Antecedent Dry Time and Percent Removal for NO_2 in the Horizontal Lysimeters