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Evaluating the Role of Evapotranspiration in the Hydrology of Bioinfiltration and Bioretention Basins Using Weighing Lysimeters

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Abstract

Stormwater runoff is a major contributor to the degradation of surface water quality in the United States. Low impact development (LID) is a stormwater management approach that attempts to halt surface water degradation by reducing peak flows, the volume of runoff, and improving the water quality of stormwater runoff to predevelopment conditions. Two important tools in LID are bioinfiltration and bioretention basins. However, scarce research exists concerning the specific hydrologic components of bioinfiltration and bioretention basins, particulary the evapotranspiration (ET) and outflows associated with such basins.

The goals of this research were to 1) quantify the individual components of the water budgets of bioinfiltration and bioretention basins, 2) determine the ability of the Food and Agriculture Organization (FAO) FAO-56 method (used for the prediction of ET in agriculture) to be applied in estimating ET from such basins, and 3) to determine if ET is a significant portion of the water loss from bioinfiltration and bioretention basins. Weighing lysimeters were constructed at Villanova University to represent a bioinfiltration basin and a bioretention basin. The ET and outflows from a bioinfiltration lysimeter were measured over the course of March through December of 2010, and the ET from a bioretention lysimeter was measured from August through December of 2010. The ET and outflows from the lysimeters were observed from both natural occurring precipitation and from storms that were simulated to mimic field conditions. The simulated storms imitated runoff generated from 13, 19, and 25 mm storm events that produced runoff from 5:1 and 10:1 impervious area to lysimeter area ratios. Storms were simulated May through July, and November through December 2010 in the bioinfiltration lysimeter. Storms were simulated in November through December 2010 in the bioretention lysimeter.

Two primary factors were observed to contribute to the ET measured from the lysimeters; the climate and the available soil moisture within the lysimeters. From March through December 2010, a total of 1,019 mm of precipitation was recorded. The bioinfiltration lysimeter during that period lost 358 mm of water to ET and 646 mm of water to infiltration without storm simulation. The corresponding ratio of ET to

precipitation was approximately 1:3, and the ratio of ET to infiltration was approximately 1:2. The low ratio of ET to infiltration was due to the almost constant state of low soil moisture in the bioinfiltration lysimeter throughout the year, without the addition of water from a surrounding impervious drainage area. Of the 337 mm of precipitation measured from August through December, the bioretention lysimeter lost 200 mm of water to ET. In comparing the bioretention lysimeter to the bioinfiltration lysimeter during the same time period of August through December, the bioretention lysimeter lost essentially twice the amount of water to ET. The increased ET performance is due to the internal water storage layer that was created in the bioretention lysimeter that served to provide more available soil moisture. From storm simulations the bioinfiltration lysimeter lost 133 mm of water to ET and 815 mm of water to infiltration, a ratio of ET to infiltration of 1:6. The high ratio of ET to infiltration is due to the simulated storm intensity which was greater than natural storm intensity typically observed in southeastern Pennsylvania. The bioretention lysimeter lost 9 mm of water from storm simulations which were performed in November and December 2010. The climate during this time period inhibited the ET performance. Overall the ET rates from storm simulations in both lysimeters were similar to those observed from naturally occurring precipitation.

The FAO-56 method for the estimation of ET in agriculture from the lysimeters was applicable in estimating the ET from the lysimeters, with preliminary coefficients for crop type and stress parameters for the bioinfiltration lysimeter resembling those for sugar beet and cotton. The measured ET from the lysimeters does initially seem to be a major portion of the water loss.

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Chapter 1: Project Overview

Stormwater runoff is a primary contributor to water quality impairments throughout the United States (USEPA 2007). In order to reduce the peak outflows, volume of runoff, and water quality problems associated with stormwater runoff, stormwater control measures (SCMs) are used. However, SCMs often require valuable land area to achieve these goals and return a developed site back to its predeveloped hydrology.

Consistently, residential land prices have risen across the country (Davis and Palumbo 2006). Hence the land devoted towards stormwater management is valuable and it is imperative that the technology be as efficient as possible. Stormwater control measure regulations in the past were created without a good understanding of the unit processes, and thus the recommended sizes for these systems may be overestimated. For example, Villanova University retrofitted a traffic island in 2001 into a bioinfiltration rain garden to accommodate a 2.5 cm (one inch) storm as prescribed in the Pennsylvania Stormwater Best Management Practices (PABMP) (PABMP 2006) manual (Emerson 2007). A maximum directly connected impervious drainage area to infiltration area of 5:1 is suggested by the PABMP manual, but the Villanova bioinfiltration rain garden effectively functions at a ratio of approximately 10:1 (Emerson 2007). With the basin performing at half of the recommended size, there is less expense in construction costs, and increased land use around the basin.

Infiltration SCMs are a comparatively new tool in stormwater management. Infiltration SCMs manage the volume of stormwater runoff rather than only the peak flows, acting to reduce the magnitude and frequency of flooding as well as stream channel erosion and sedimentation. Infiltrating stormwater runoff allows development to more closely resemble the natural predevelopment hydrology of a given area (Emerson 2007). Infiltrating SCMs typically allow water to pond and infiltrate within 72 hours, however, if soil and groundwater characteristics are unsuitable to infiltration, liners may be incorporated into the design such that volume reduction is achieved primarily through evapotraspiration (PABMP 2006). In both cases, evapotranspiration (ET) plays a role in how the runoff volume within the SCM is removed; it is presently unclear how large the role of ET is in these systems (Davis et al. 2009).

Evapotranspiration (ET) is the process by which water is withdrawn from the soil, transpired from the leaves of plants, and evaporated from the surface of plants and the soil. Evapotranspiration is fueled by energy, primarily solar radiation, temperature, the water vapor pressure gradient, and wind speed. However, plant and soil characteristics are also important in the ET process (Allen et al. 1998). Typical values for ET are plant/crop and climate specific. Wright (1988) measured ET values for alfalfa near the Snake River Conservation Research Center in Idaho (arid climate) ranging from 1.84 mm/day in October to 6.73 mm/day in July. Shih et al. (1982) measured the ET of rice during two growing seasons in the Florida Everglades (tropical climate), and found values ranging from 1.8 to 10.2 mm/day. While on the time scale of one day ET volume removal is small, over the course of a year this removal becomes increasingly important. For example, if an average of 2 mm/day were evapotranspired from a 28 m^2 bioretention basin over the course of a year, the resulting water loss would total approximately 20 m^3 of water or 20,000 L.

Research has been done to prove the effectiveness of bioinfiltration and bioretention basins regarding total volume reduction and water quality improvement (Davis 2008, Davis et al. 2009, Hunt et al. 2006, and Li et al. 2009). However, there is a lack of research concerning specific components of the water budgets in bioinfiltration and bioretention basins, as well as a lack of long-term data to support hypotheses concerning their design, operation, maintenance, and seasonal variations in performance. To obtain and maintain the optimum performance in reduction of stormwater volume with bioinfiltration and bioretention basins it is imperative to perform further research (Emerson 2007).

Therefore, the goal of the present study is to better understand the water budgets of bioinfiltration and bioretention basins by quantifying the ET and outflows that occur during the course of a year in the climate of southeastern Pennsylvania. The measurement of ET and outflow is done through experimentation with weighing lysimeters that have been constructed at Villanova University. The research will determine if ET is a significant portion of the water loss from bioinfiltration and bioretention basins and therefore can be given credit as volume reduction during the permitting process. The research will also examine a predictive equation for ET that can aid in the design of these basins in this climate.

1.1 The Stormwater Problem

Hydrology is the study of the distribution and circulation of water over a range of time and space (Wallender and Grismer 2002). The hydrologic cycle on an undeveloped parcel of land consists of precipitation falling, 40% of that precipitation is evapotranspired by the sun and plants, 25% infiltrated into the ground near the surface (interflow), another 25% infiltrated deeper into the ground, and only the remaining 10% becoming surface stormwater runoff (PCGM 1999). When that parcel of land is developed, or urbanized, the hydrologic cycle is altered. Impervious areas are introduced into the site resulting in increased surface runoff volumes with less evapotranspiration, infiltration, and interflow (PCGM 1999). Increasing surface runoff volumes results in greater flood risks, stream channel erosion that damages ecological habitats, and decreased recharge of groundwater resources (Davis 2008).

In the past, stormwater management involved removal of runoff from the site as quickly as possible. As stream degradation and water quality issues became apparent, this methodology evolved to removing the water from the site, holding it in temporary storage, then releasing it slowly into the receiving water body. The tools for this approach are detention basins and wet ponds (Gilroy and McCuen 2009). However, stream degradation and water quality issues have pervaded as detention controls only peak flows and their timing. Detaining stormwater does not confront the increased volume of runoff from a developed site, which when detained and gradually released creates a flow in the receiving water body still greater than predevelopment and for a longer duration (Holman-Dodds et al. 2003, Gilroy and McCuen 2009).

The latest evolution in thought regarding stormwater management is low impact development (LID). Low impact development seeks to manage stormwater by both detention and the reduction of runoff volume, in an attempt to mimic the predevelopment hydrologic conditions of a given site. The tools for this approach are often infiltration based SCMs, such as bioinfiltraton and bioretention basins (Davis 2008).

1.2 Bioinfiltration and Bioretention Basin Design

Bioretention is a lump term that embodies two separate but closely related infiltration SCMs. The first, a bioretention basin without a liner or underdrain, allows for stormwater infiltration to recharge the groundwater and provides an environment conducive to evapotranspiration. These are often referred to as rain gardens but will be referred throughout this text as bioinfiltration basins. The second are bioretention basins with underdrains, allowing for less infiltration, more detention, and evapotranspiration for volume reduction. Such basins will be referred to as bioretention basins.

Bioinfiltration basins are a structural SCM used in LID to reduce the volume of stormwater runoff, filter pollutants through capture in the soil and/or plant uptake, recharge the groundwater table through infiltration, and halt thermal pollution of stormwater runoff (PADEP 2006). Stormwater runoff is channeled into an inlet structure, and if the design capacity is exceeded, overflows are routed into existing storm sewers. The vegetation chosen for bioinfiltration basins range from small plants to large trees (Roy-Poirier et al. 2010).

When local soils do not have a sufficient infiltration rate, underdrains are installed to aid in the removal of ponded water, creating a bioretention basin (Roy-Poirier et al. 2010). The guideline for the minimum soil infiltration rate varies dependent on municipality and between Pennsylvania, Maryland, and North Carolina ranges from 0.25 cm/hr to 5.08 cm/hr (PABMP 2006, PCGM 2007, and NCDENR 2009). These guidelines are established to prevent ponded water from remaining in the basin long enough to allow for mosquito breeding that is often associated with stagnant water (Roy-Poirier et al. 2010, Dietz and Clausen 2005). Stormwater runoff enters the system in the same manner as a bioinfiltration basin, but typically only leaves the system via underdrain outflow, ET, and minimally through infiltration. When the basin is full, flows are bypassed around or through the system and into existing storm sewers (Hunt et al. 2006).

A current design consideration regarding bioretention basins has been the saturated internal water storage layer (IWS). While the conventional bioretention underdrain system uses a gravity fed outflow pipe that is directly connected to a storm sewer, the IWS is created by installing an upturned elbow before the flow enters the storm sewer. The upturned elbow is often 0.45 to 0.6 m tall and creates an IWS of that same size in the basin. Research has shown that the IWS creates an anaerobic zone conducive to the growth of bacteria that aid in the denitrification of stormwater runoff (Hunt et al. 2006). In addition to potential denitrification benefits, the IWS creates an area of storage in the bioretention basin before outflow is produced through the underdrain. The IWS is especially beneficial after periods without precipitation, during which the IWS dries out through ET and provides water for plants. The IWS enables the bioretention basin to completely capture small storm events without producing outflow, which is contrary to conventional design where outflow occurs as soon as water reaches the underdrain. The delayed outflow allows for increased infiltration in bioretention basins without impermeable liners. However, as soon as the IWS is full the bioretention basin functions as though there is no upturned elbow, and outflow develops in the same manner as a conventional underdrain system (Li et al. 2009).

1.3 Evapotranspiration

Evapotranspiration has been the subject of copious research due to its importance in maximizing water resource management with regards to irrigation in agriculture (Jia et al. 2006). Many rural areas of the world still use inefficient irrigation techniques. For example, in China there are areas using irrigation methods that lose up to 60% of their supplied water to ET and infiltration. By changing to drip irrigation techniques, these areas in China could increase irrigation efficiencies up to 75-95% (Liao et al. 2008). However, in order to obtain these efficiencies with the maximum agricultural yield, accurate crop specific ET information is needed. To quantify irrigation needs the United Nations Food and Agriculture Organization (FAO) and the American Society of Civil Engineers (ASCE) has adopted a method using a modified form of the Penman-Monteith (PM) equation to predict crop specific ET. The modified PM method requires the measurement of temperature, relative humidity, solar radiation, and wind speed. These climatological parameters are input into the modified PM equation, which yields the reference evapotranspiration (ET_0). The modified PM ET_0 is adjusted to the specific crop and soil moisture conditions needed through the use of established coefficients gained from prior research using weighing lysimeters (Allen et al. 1998). While ET and the associated parameters are well-established for the agricultural community, the use of the modified PM equation and the associated parameters have not been verified for use in SCMs; this is the goal of the present study. The applicability of the modified PM method must be tested as the goal in SCMs is the opposite of agriculture; that is knowing how much water is lost to ET to determine storm precipitation volume reduction, as opposed to determine how much water needs to be applied for irrigation.

1.4 Weighing Lysimeters

Weighing lysimeters are instruments used to measure ET. A weighing lysimeter uses a mass balance where the change in weight of the entire lysimeter system is equal to what comes in due to precipitation minus what leaves the system either through water draining out of the lysimeter or through ET. Weighing lysimeters are often designed as microcosms of field crops. For example, to measure the ET of field maize, weighing lysimeters are often placed within an actual crop field of maize.

Weighing lysimeters, if properly designed, instrumented, and interpreted, can provide accurate ET measurements that give insight to a variety of parameters that govern the ET process (Allen and Fisher 1990). While weighing lysimeters are often expensive, they provide important information regarding the reliability of predictive equations and water balance models (Xu and Chen 2005).

1.5 Research

Little research has been performed concerning the agricultural methodology for the estimation of ET and its application to stormwater SCMs. However, ET could prove to be a substantial mechanism for volume removal once it is quantified. Further, through the use of predictive equations, such as the modified PM equation, ET from bioinfiltration and bioretention SCMs could be incorporated into their design. Accounting for the ET volume reduction could create more spatially and cost effective SCMs, operating at maximum levels of performance. Therefore, two weighing lysimeters were constructed at Villanova University to measure the ET occurring in bioinfiltration and bioretention basins, as well as to gain insight into the parameters that guide the ET process. The measured ET from both lysimeters is compared to the modified Penman-Monteith reference ET_0 to establish coefficients for plant characteristics and water stress conditions in the method prescribed by the FAO and ASCE. The research is an attempt to aid in the prediction of ET in bioinfiltration and bioretention basins in climates similar to the humid subtropical of southeastern Pennsylvania.

Chapter 2: Literature Review

Bioinfiltration and bioretention basins are important tools in low impact development, but very little research has been done regarding the individual components involved in the water budgets of these devices. Quantifying the amount of evapotranspiration and groundwater recharge, and understanding the driving forces behind these components, is crucial in maximizing the effectiveness of bioinfiltration and bioretention basins. Understanding evapotranspiration and groundwater recharge is key to maximizing agricultural yield with water resource management, and as such significant research has been conducted to quantify and predict these components. Yet little research has been done to take the same methods of investigation used by agriculture and apply them to bioinfiltration and bioretention basins. The following provides an overview of research concerning bioinfiltration and bioretention design and hydrology. The review then investigates evapotranspiration principles, prediction, and the design of weighing lysimeters with regard to the agricultural community. Finally, the review will focus on research applying these methods to the prediction of evapotranspiration from bioinfiltration and bioretention basins in an attempt to increase the efficiency of these stormwater control measures.

2.1 Introduction

Hydrology is the scientific study of the distribution, circulation, and physical properties of water throughout the Earth and its atmosphere, over a range of time and space (Wallender and Grismer 2002). Figure 1 details the hydrologic cycle on a small parcel of land in both pre- and post-development stages. Before construction the hydrologic cycle is balanced where 40% of the precipitation that falls is evapotranspired by the sun and plants, 25% is infiltrated into the ground near the surface (interflow), another 25% is infiltrated deeper into the ground, and the remaining 10% becomes surface runoff (PCGM 1999). Construction alters this balance with the introduction of impervious area, causing increased surface runoff volumes with less evapotranspiration, infiltration, and interflow (PCGM 1999). The increased surface runoff volumes and the related peak flows increase flood risks and causes degradation to receiving waterbodies.

The degradation is due to stream and river bank erosion caused by scouring and loss of water quality with increased pollutant loads (Davis 2008).

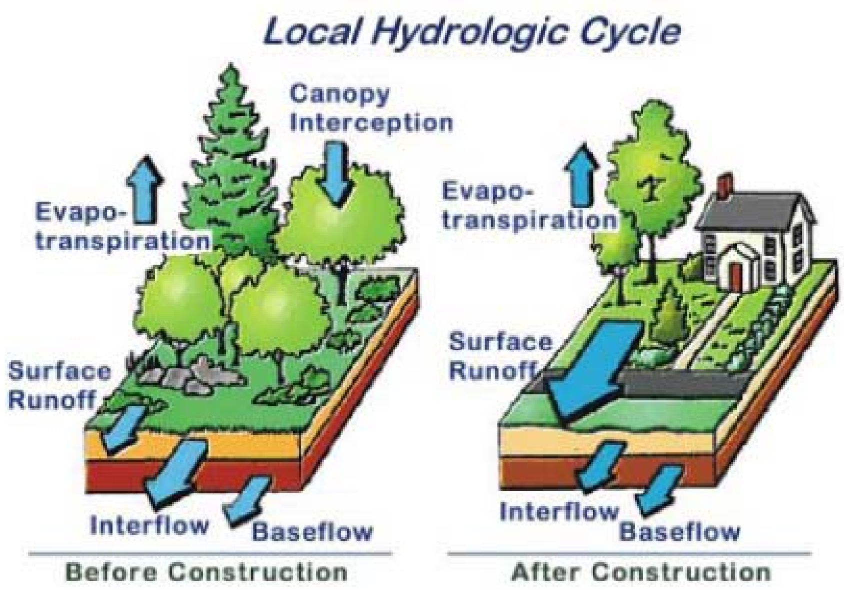

Figure 1 Hydrologic Cycle with Disturbance Due to Development (Maryland Department of the Environment 2011)

Low impact development (LID) is an environmental viewpoint that seeks to combat this degradation from the source. There are two LID perspectives that attempt to minimize the hydrologic impact of a developed area by mimicking predevelopment hydrology. The first perspective is to mimic the temporary detention, or storage, of the undeveloped site. The second perspective is to mimic the predevelopment infiltration qualities of the site (PGCM 1999), which can be done by maintaining the preexisting landscape and topography, disconnecting impervious areas, and increasing the flow lengths of a development. Two important tools for achieving these ends are on-site, vegetated, infiltration based SCMs known as bioinfiltraton and bioretention basins (Davis 2008).

The previous method of stormwater management was to remove the water from the site, to store it, and then release it gradually into the receiving water body. The primary tools of this methodology are detention basins and wet ponds (Gilroy and McCuen 2009). Detention basins and wet ponds control the peak flows and their timing but do nothing to control the increased volume of water input into receiving water bodies.

The increased volume is discharged more slowly, and although the peak discharge is lowered, the discharge is still greater than predevelopment and spread out over a longer duration. The longer duration of increased flow is still capable of moving large quantities of sediment that have damaging effects on stream stability and ecosystems (Holman-Dodds et al. 2003, Gilroy and McCuen 2009).

While LID methods are an improvement in the technology of stormwater management there is still a lack of research done to quantify this improvement and the mechanisms that drive LID SCMs, such as evapotranspiration and groundwater recharge. There is also not enough research concerning proper placement, spacing, quantity, the effects of land use types, and the return period of investment regarding LID SCMs. Until these aspects are better understood, the performance of these SCMs may be below their potential (Gilroy and McCuen 2009).

2.2 Bioinfiltration Basin Design

Bioinfiltration basins are a structural SCM that reduces the volume of stormwater runoff, filters pollutants by trapping them in the soil or through plant uptake, recharges the groundwater table by allowing for stormwater to infiltrate through the soil media, halts stormwater from thermally polluting downstream waterbodies, and provides an environment conducive to evapotranspiration (ET). In addition to these qualities bioinfiltration basins are also an aesthetically pleasing SCM in that they are gardens often planted with native species that provide a habitat to organisms (PADEP 2006). Figure 2 is an example diagram of a bioinfiltration basin.

Bioinfiltration systems are typically small basins that are excavated and backfilled with a blend of organics and highly permeable soil that provides both optimum water infiltration and native plant growth. An inlet structure is used to channel stormwater runoff from the drainage area into the basin and an overflow structure routes any flows above the ponding capacity out of the basin. The vegetation is often determined by the size of the bioinfiltration basin and can include anything from small plants and shrubs to large trees. However, the vegetation should be chosen based on the environmental stresses particular to the site (Roy-Poirier et al. 2010). For example, Villanova University retrofitted an existing traffic island into a bioinfiltration basin (Figure 3) in

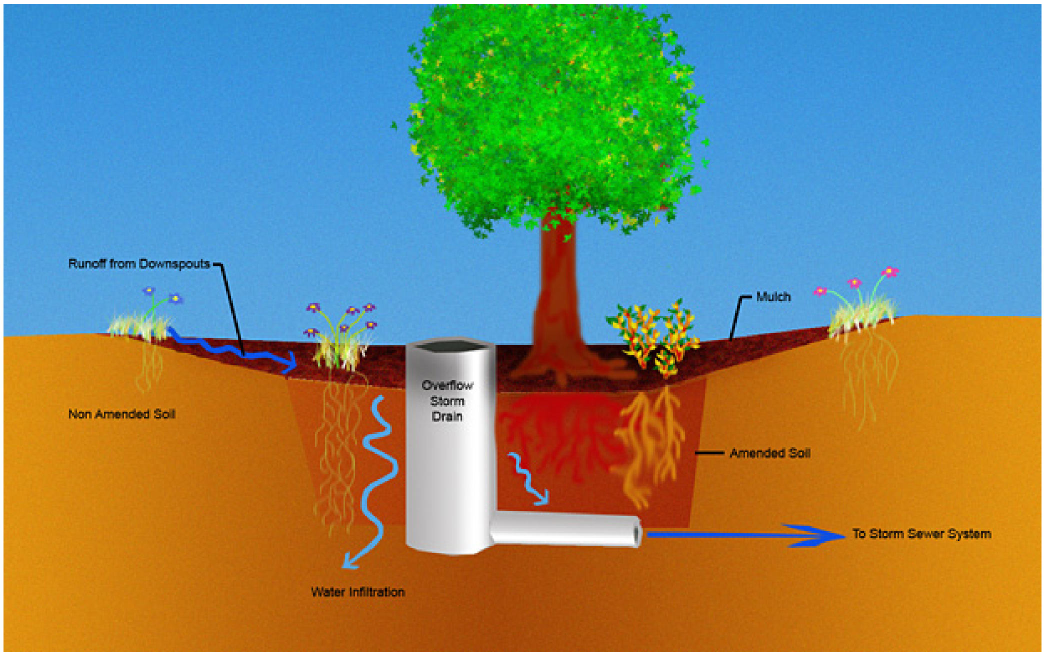

Figure 2 Example Diagram of a Bioinfiltration Basin (US Air Force 2011)

August 2001. The basin was constructed with a 50% native Glenelg silt loam soil and 50% sand mixture (by volume). The plants in the bioinfiltration basin are common to the New Jersey coast and were chosen for their ability to thrive in the local climate, as well as their ability to withstand the high salinity levels of stormwater runoff generated from salting of the surrounding parking lot in winter (Emerson 2007).

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Figure 3 Bioinfiltration Basin at Villanova University

There are varying design criteria dependent upon location and local government regulation. As an example, three design recommendations along the eastern seaboard are given. Prince George's County Maryland (PCGM) (2007), developers of bioinfiltration and bioretention technology, suggests that no more than 1-2 acres of drainage area is input into these basins with the most preferable drainage area being less than 1 acre. Flows from larger areas can achieve flow rate values greater than 0.14 m^3/s after a 10 year storm that may erode stabilized areas and require pipe enclosure. The PABMP (2006) manual states that bioinfiltration and bioretention basins should generally not exceed a loading ratio of 5:1 (impervious drainage area to infiltration area). The North Carolina Department of Environment and Natural Resources (NCDENR) (2009) requires that drainage area calculations take into account all stormwater runoff including off-site drainage, but gives no specific maximum drainage area values. PCGM (2007) requires that no more than 30.5 cm of ponding accrue within the basin, and ponded water should drain in 3 to 4 hours and the entire system in less than 48 hours. NCDENR (2009) states that the ponding depth within the basin must be no greater than 30.5 cm, however 22.9 cm is preferred. Further, NCDENR (2009) requires ponded water is to completely drain within 12 hours and to drain 61 cm below the soil surface within 48 hours.

2.3 Bioretention Basin Design

Bioretention basins are bioinfiltration basins with underdrains and sometimes lined by an impermeable membrane. Underdrains are installed in order to assist in draining ponded water from the basin in a timely fashion which is necessary when the soils used do not have a high infiltration rate (Roy-Poirier et al. 2010). When ponded water remains in the basin too long there is the potential for mosquito breeding, algal blooms, and odor issues associated with stagnant water (Roy-Poirier et al. 2010, Dietz and Clausen 2005). PCGM (2007) suggests that underdrains always be in implemented in design, however requires them when the soil infiltration rate is less than 1.27 cm/hr. The PABMP manual (2006) advises the use of an underdrain or oversizing a bioinfiltration basin if the soil infiltration rate is 0.25 cm/hr or lower. NCDENR (2009) recommends that an underdrain be installed when the soil drainage is less than 5.08 cm/hr.

Stormwater runoff enters the system in the same manner as a bioinfiltration basin, but typically only leaves the system through underdrain outflow, ET, and some infiltration. When the basin is full, flows are bypassed around or through the system (Hunt et al. 2006). Figure 4 is an example of a bioretention design.

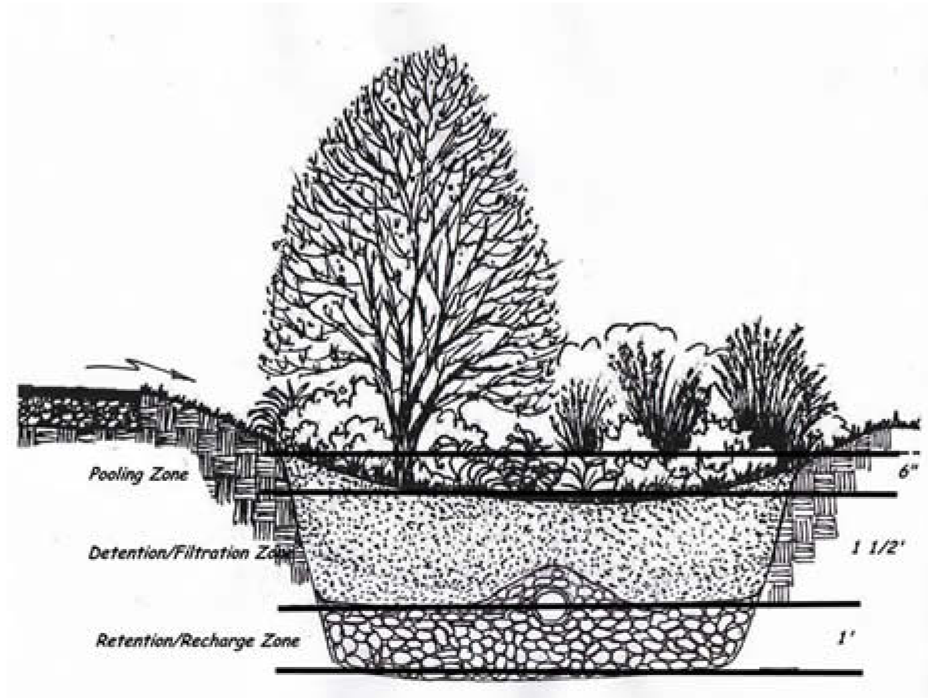

Figure 4 Example Diagram of a Bioretention Basin (Univeristy of Connecticut 2011)

A recent update in the design of bioretention basins has been the inclusion of a saturated internal water storage layer (IWS). The conventional underdrain system uses gravity to direct flow into an outlet box and on to a storm sewer. The IWS is created by modifying the conventional underdrain through placement of an upturned elbow before flow exits the system (Figure 5). An IWS is typically between 0.45 to 0.6 m (Hunt et al. 2006). The IWS creates an anaerobic zone within the bioretention basin, which enables denitrification, the conversion of nitrate-nitrogen to nitrogen gas. Hunt (2003) used 1.2 m deep soil columns with varying depths of saturation to demonstrate a total nitrogen and nitrate-nitrogen removal of 60 to 90%. Similar results have been difficult to reproduce in the field. Hunt et al. (2006) found that during June 2002 to May 2003 two comparison sites, one with a conventional underdrain system and one with an IWS, produced no statistically significant difference in outflow concentrations of total nitrogen.

There is also the hydrologic impact of the IWS design to consider. Li et al. (2009) studied the hydrology of the same two comparison sites investigated by Hunt et al (2006) over 46 storm events ranging from July 2003 to September 2004. The study revealed that while there was no impact on the outflow hydrographs for medium and large storm events (greater than 2.54 cm) the site with the IWS was able to completely capture many smaller events. The captured stormwater was then either infiltrated or evapotranspired. When an IWS is used without a liner, infiltration is promoted for smaller storm events. Li et al. (2009) explains that the performance of the IWS on small storms is due to the fact that 0.45 to 0.6 m of storage must be filled before water is allowed to leave the system through piped outflow. In conventional design outflow begins as soon as water reaches the underdrain outflow pipe at the bottom of the basin. With IWS design there is a point reached where the magnitude of the storm negates the basin's extra storage ability: when the IWS becomes full the outflows of both the IWS and conventional designs are identical. Multiple small storms during a short time period, which will fill the storage provided by the IWS, will result in the same outflows as the conventional design (Li et al. 2009).

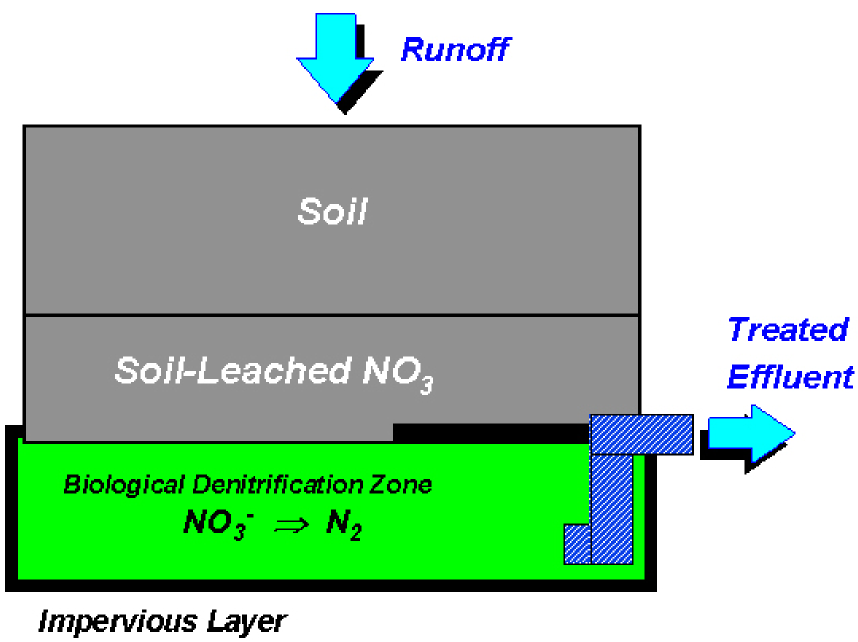

Figure 5 Internal Water Storage Layer Produced by Upturned Elbow (MWRRC 1999)

2.4 Bioinfiltration and Bioretention Hydrologic Performance

There is meager quantitative information available concerning the hydrologic impacts of bioinfiltration and bioretention technology. Much more research is needed concerning all aspects of these SCMs (Davis 2008, Davis et al. 2009). Li et al. (2009) reports that bioretention basins perform well for small rain events (less than 2.54 cm), but that performance is weakened by larger rain events. In a study of six bioretention basins

Li et al. (2009) details two of these basins in particular, one located in Greensboro, North Carolina (drainage to surface area ratios of 5:1) and the other in Silver Spring, Maryland (drainage to surface area ratios of 2:1). Each basin received 63 and 60 storm events during 14 months and the storm depths ranged from 0.25-12.47 cm and 0.3-5.82 cm, respectively. The basin in North Carolina was able to capture 63% of the storms without producing outflow; the captured water left the system through infiltration and ET. Similarly, the basin in Maryland captured 53% of the storms without outflow and removed this water via infiltration and ET. No quantitative information is provided concerning what portion of the water was infiltrated and what left through ET for either of the bioretention basins.

Another bioretention basin in the Li et al. (2009) study was evaluated over 27 storm events in 6 months ranging in depth from 0.18-5.84 cm. The basin had a drainage area to surface area ratio of 4.5:1, and reduced the total runoff volume by 19%. The basin, located in Louisburg, North Carolina, was lined with an impermeable membrane that allowed no water to leave by infiltration. The basin received 499 mm of water, of which 350 mm left as underdrain outflow, and 56 mm of water was bypassed as overflow (406 mm of water as total outflow). The remaining 93 mm of water is attributed to ET. Davis (2008) evaluated two bioretention basins in College Park, Maryland. Runoff was collected from 0.24 ha of asphalt parking lot and directed into two basins functioning together to form a combined bioretention surface area of 28 m^2. Out of 41 storm events over nearly 2 years, 18% of the events were small enough to be completely captured by the two bioretention basins. Both of these basins were lined with an impermeable polypropylene liner again halting infiltration, indicating that this water was evapotranspired. Hunt et al. (2006) collected data from a neighboring bioretention basin to the one studied by Li et al. (2009) in Greensboro, North Carolina. Data was collected from June 2002 to May 2003 and over 48 observed storm events 78% of the runoff was captured by the basin and infiltrated or evapotranspired. High seasonal variation was observed; 86% capture, 93% capture, 87% capture, and 46% capture were observed during spring, summer, fall, and winter, respectively.

Dietz and Clausen (2005) performed a study of two bioretention basins designed to collectively capture the first 2.54 cm of runoff from a 106.8 m^2 asphalt shingle roof in

Connecticut. The basins contained soil 0.6 m deep and three different native species of shrubs. Data was taken during December 2002 to December 2003 and during that time only 0.8% of the total inflow was released as overflow due to overcapacity of the basins. Both basins were lined by an impermeable membrane and contained an underdrain structure. Of the water captured by the basins, 98.8% exited through the underdrain. While this data is skewed by the inability of water to infiltrate due to the presence of the impermeable membrane, it does point to the lack of ET during the period where water remained within the basins.

2.5 Evapotranspiration

Evapotranspiration (ET) is the process by which water transpires from the leaves of plants and evaporates from the surface of plants and the soil; it is a process driven by energy, specifically heat in the form of solar radiation and temperature. The water vapor pressure gradient, plant and soil characteristics are also key components that drive ET (Allen et al. 1998).

2.5.1 Importance of Evapotranspiration in Agriculture

Evapotranspiration in an agricultural context has received much attention as understanding crop ET is the key to water resource management and irrigation timing (Jia et al. 2006). There are many regions of the world currently experiencing water shortage. Industrialization, urbanization, and population growth have increased the demand on existing supplies often removing available water from agriculture (Lopez-Urrea et al. 2006). Many of these rural areas still use inefficient irrigation techniques such as furrow or block surface irrigation. Several areas of China have irrigation efficiencies of 40% (the ratio of consumed water to supplied water) indicating that 60% of the water is lost to ET and infiltration (Liao et al. 2008).

Switching from furrow or block irrigation to drip irrigation (where water is applied at the root zone of the plant) can increase efficiencies up to 75-95%. In order to obtain this efficiency precise information is needed regarding crop specific ET, as the most efficient irrigation technique is that which only needs to replace water used by the crop (Liao et al. 2008). Precision irrigation limits evaporative effects and infiltration while maximizing crop transpiration.

2.5.2 FAO Method for Prediction of Crop Evapotranspiration using the Penman-Monteith Equation

In quantifying ET, an energy balance equation is associated with the water balance. The solar net radiation is equated to the vertical heat flux in the soil (soil heat flux), the vertical heat flux from the ground to the atmosphere (sensible heat flux), and the energy used in the ET process (latent heat flux). The horizontal transfer of energy is ignored making the energy balance appropriate only for large, extensive surfaces (Teixeira 2008). The energy equation is the basis for the Penman and Penman-Monteith equations. As the Penman equation involved multiple wind functions and calibrations it was considered difficult to use from a practical standpoint. However, the Penman-Monteith equation showed a strong correlation with lysimeter observations, and included more parameters governing ET, such as plant physiological and aerodynamic characteristics (Pereira et al. 1999). Therefore, the Food and Agriculture Organization (FAO) of the United Nations and the American Society of Engineers (ASCE) formally accepted the Penman-Monteith equation as the standard method for calculating ET for a reference crop. The FAO also provides a practical application for reference ET, by establishing coefficients with which ET_0 can be adjusted based on the specific plant type and water stress levels (Allen et al. 1998).

The method developed for the estimation of crop ET by the FAO involves first determining the local climatic parameters and those parameters effect on a reference surface; thus the reference ET is the ET due to climatic conditions alone. The reference surface is a hypothetical grass crop that is solely used to reflect the local climatic parameters' ability to promote ET. The parameters chosen for this crop serve to negate the differences in soil type, crop type, growth, and land management conditions worldwide. The reference crop covers an extensive area, is sufficiently watered, growing, and entirely shades the ground. The crop has a uniform height of 0.12 m, a constant surface resistance of 70 s/m, and an albedo of 0.23. The constant surface resistance of 70 s/m is chosen to reflect a moderately dry soil that receives water from irrigation once a week (Allen et al. 1998). The climatic parameters and reference surface information are input into the Penman-Monteith equation which yields the reference ET (ET_0). Figure 6 is a diagram of this process.

The second stage of the FAO method (Figure 7) incorporates the effects of the ground cover, canopy, and aerodynamic resistance that result from the height, roughness, and reflective properties of an actual crop of interest under standard conditions. Standard conditions imply that all crop variables are in optimal ranges for ideal growth. Ideal growth (under the given climatic conditions of stage one) is considered to result from large crop fields which are disease and pest free with optimal water. The differences that distinguish the crop of interest with the reference crop are represented by the crop coefficient (K_c). ET_0 is multiplied by K_c to obtain ET_c, the crop ET under standard conditions (Allen et al. 1998).

The final stage in the prediction of ET using the FAO method is depicted in Figure 8. The final stage is the inclusion of the water stress coefficient (K_s). The water stress coefficient accounts for lack of water or soil salinity that make less water available for plant root extraction. Wet soil has a high potential energy that allows for water to freely move within the soil medium providing less resistance to the uptake of plant roots. In contrast, dry soil has a stronger soil suction that resists the plant uptake of water. The crop is defined as water stressed when the soil water falls below a limit that is specific to each crop. To apply the effects of soil water stress into the prediction of ET for a particular crop, K_s is multiplied by ET_c. The resulting $ET_{c\ adj}$ is the predictive ET for a particular crop in specific climatic conditions under water stress (Allen et al. 1998).

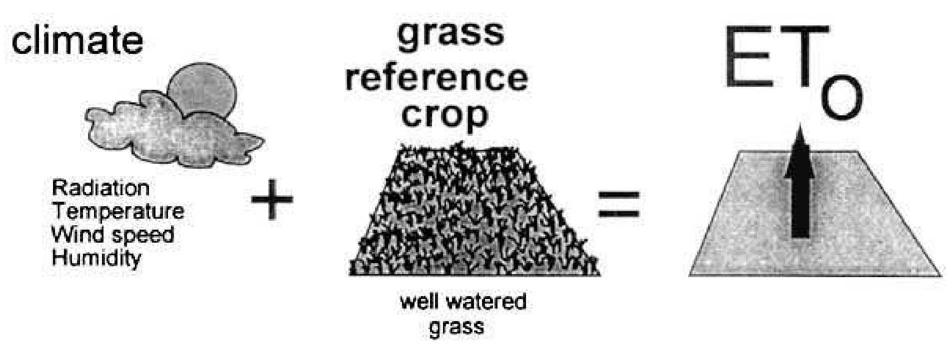

Figure 6 Development of Reference Evapotranspiration (Allen et al. 1998)

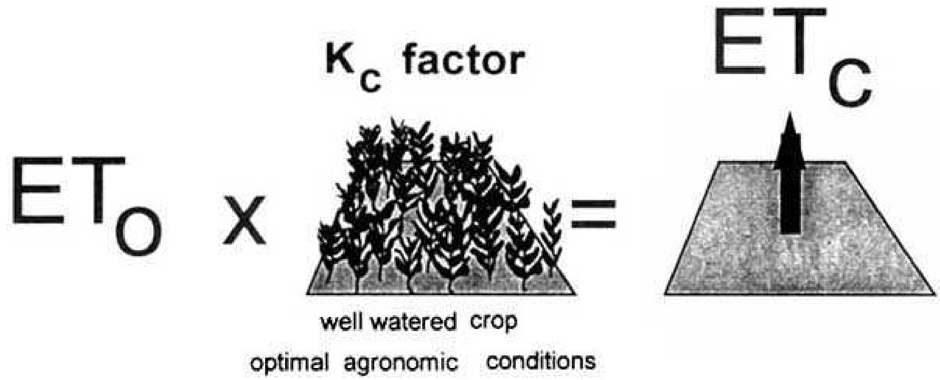

Figure 7 Adjustment of Reference Evapotranspiration to Crop ET Under Standard Condition with Introduction of K_c (Allen et al. 1998)

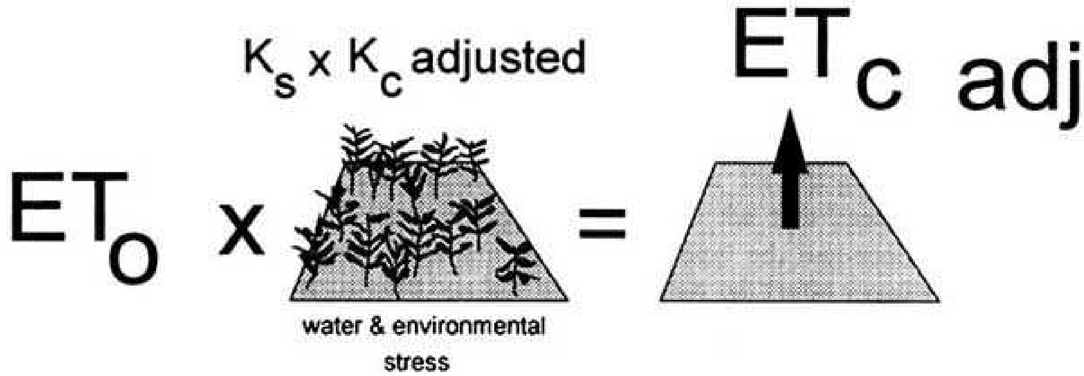

Figure 8 Adjustment of Crop Evapotranspiraton with Environmental Stress Factor (Allen et al. 1998)

2.5.3 Daily Evapotranspiration of Common Crops and K_c Values for Use in the Prediction of Evapotranspiration by Agriculture

The daily ET of specific crops is both climate and crop specific. Liu et al. (2002) used a large weighing lysimeter to measure the ET of winter wheat and field maize over five seasons (1995-2000) at Luancheng Station in the North China Plain. The study found that peak ET rates for winter wheat occurred in May, where the daily ET averaged over the month ranged from approximately 4.5-6 mm/day. An average of the climate data taken over the five seasons produced an ET_0 value of 3.8 mm/day for the month of May. The measured winter wheat lysimeter data (ET_c), similarly averaged over five seasons for the same month yielded 5.4 mm/day. The crop coefficient (K_c) back calculated for the month of May was determined to be 1.42. However, 1.42 is the peak K_c value and K_c values over the winter wheat growing season of October to June ranged from 0.38 to 1.42, with the average of all the data being 0.93. The peak ET rate for field maize occurred in August with daily ET values over the month ranging between approximately 4-5 mm/day. The average August ET_0 was 3.4 mm/day and the lysimeter measured ET_c was 4.7 mm/day. The K_c value for the month of August, averaged over five seasons, was calculated at 1.38. The daily K_c values averaged over each month of the growing season, June to September, ranged from 0.59-1.38. The average K_c value of all the data was determined to be 1.1.

Wright (1988) used weighing lysimeters to measure the ET from alfalfa over seven years ranging from 1969-1975 in Kimberly, Idaho. The ET consistently peaked in July where the daily ET averaged over the month, and the month of July again averaged over seven years was determined to be 6.73 mm/day. The minimum value of 1.84 mm/day occurred during October.

Shih et al. (1982) studied the ET of rice in the Everglades Agricultural Area of South Florida. The study took place from the summer of 1979 to the fall of 1980. The peak daily ET rate was found in the summer with an average value of 8.3 mm/day calculated from a range of 4.8 to 10.2 mm/day. The lowest average of 4.3 mm/day was observed in the fall, and the range was 1.8 to 5.3 mm/day.

There is relatively little information concerning K_c values in areas that are not water stressed. The FAO has established K_c values for well managed crops in subhumid environments, such as grassland and prairie climates. The values are split between the three main stages of the growing season: the initial, middle, and end (Allen et al. 1998). These values are listed in Appendix 1. Notable values are listed in Table 1.

Table 1 Example K_c Values for Common Crops (Allen et al. 1998)

Crop Name	$K_{c\ initial}$	$K_{c\ middle}$	$K_{c\ end}$
Winter Wheat (non-frozen soil)	0.70	1.15	0.25-0.40
Field Maize	N/A	1.20	0.35-0.60
Alfalfa (avg cutting effects)	0.40	0.95	0.90
Rice	1.05	1.20	0.60-0.90

2.6 Weighing Lysimeters

Weighing lysimeters are instruments that measure ET by utilizing a mass balance. The change in weight of the entire lysimeter system is equal to what comes in due to precipitation minus what leaves the system, either through water draining out of the lysimeter or through ET. Weighing lysimeters are designed to create a microcosm of an area of interest, with inflows and outflows controlled and measured. Figure 9 is an example schematic detailing load cells to measure the change in weight and a tipping bucket rain gauge to measure lysimeter outflow.

Weighing lysimeters are the best available means of measuring ET at the micro-scale (Grimmond and Oke 1999, Jia et al. 2006, and Xu and Chen 2005). Lysimeters, if they are designed, installed, instrumented, managed, and interpreted properly, provide ET measurements that accurately reflect the system that is being studied. The acquired ET data can also give insight to a variety of parameters that govern the ET process (Allen and Fisher 1990). Acquiring ET information can be costly, but defends the reliability of predictive equations and water balance models (Xu and Chen 2005).

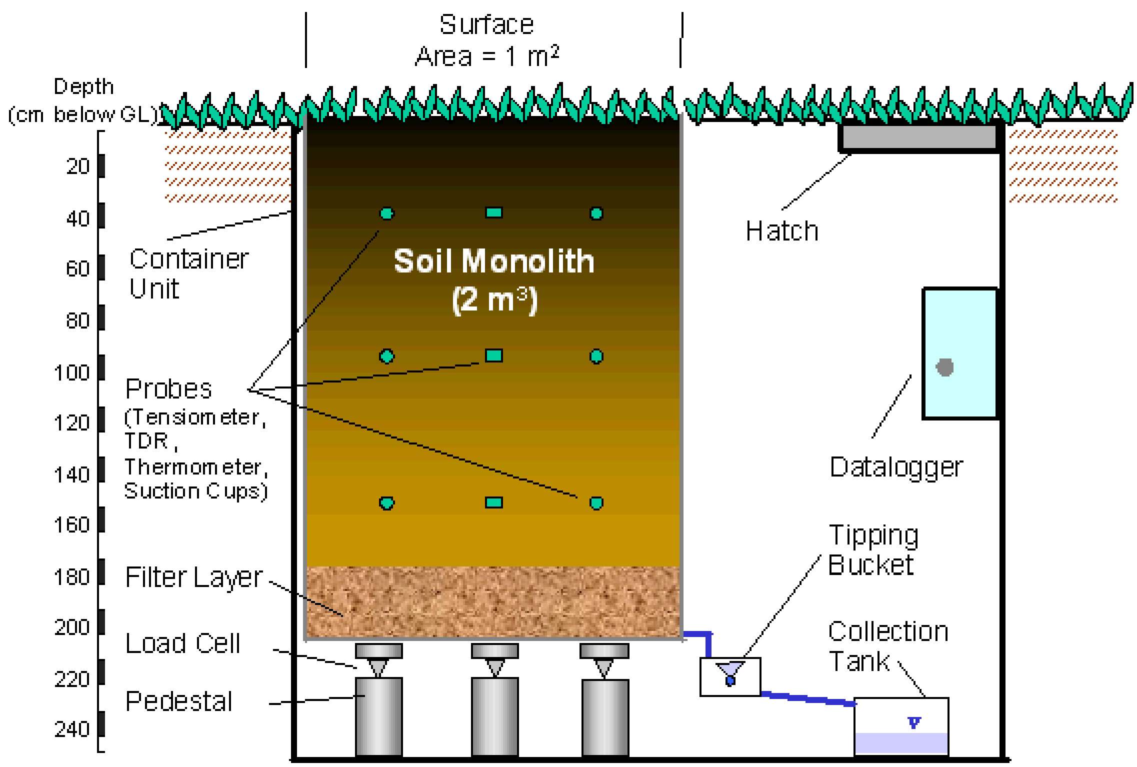

Figure 9 Example Schematic of a Weighing Lysimeter (Meissner and Seyfarth 2004)

De la Hire was the first recorded person to construct a weighing lysimeter in 1688 (Marek et al. 1988). The first monolithic weighing lysimeter in the United States was constructed by Sturtevant in 1875. However, it was not until 1958 that the first selfrecording monolithic weighing lysimeters were built at Coshocton, Ohio (Marek et al. 1988). The latter set the norm for agricultural lysimeter design for the next 25 to 30 years. These designs call for very large lysimeters that use balance beams, counterweight mechanisms, access tunnels for maintenance, undisturbed soil monoliths, and even air conditioning below the ground level. Currently, however, designs that make use of systems supported only by temperature compensated load cells, with no balance beams, counterweights, or other moving parts are common (Allen and Fisher 1990). There are also many lysimeters built with recreated soil profiles as an undisturbed soil monolith is often difficult to engineer and expensive (Marek et al. 1988).

While lysimeters have long been used to measure ET, throughout their history they have been beset with complications and designs that have not accurately represented the field conditions they were intended to mimic. The most important part of a weighing lysimeter, if it is to be used for quantifying ET for a particular type of vegetation, is that the soil mixture and plants be the same as the area being modeled (Allen et al. 1998). A typical problem with weighing lysimeters is that the depth is too shallow and does not allow for the plant root density at the bottom. The lack of depth does not correctly simulate field conditions due to differences in drainage, soil water availability, and thermal characteristics (Marek et al. 1988). Another common issue with weighing lysimeters is measuring percolation due to their tendency to clog, which creates a temporary saturated zone with anaerobic conditions that influence capillary rise (Weihermueller et al. 2007).

The measurement duration, lysimeter shape, weighing mechanisms, construction materials, and site maintenance all impact the accuracy of the ET measurement (Jia et al. 2006). For example, Guiting (1991) performed a two-fold comparison study of lysimeters in China used for the measurement of rice ET. The first comparison was between the ET measured from a lysimeter with a soil container composed entirely of concrete contrasted against a lysimeter with a soil container fabricated with 3 mm steel plate sidewalls. The study was conducted over five years from 1985 to 1989 and found that concrete lysimeters can measure up to 20% more ET than steel plate lysimeters. Guiting (1991) determined that the concrete sidewalls absorbed moisture while the steel walls did not. The thermal conductivity of the concrete walls was also greater than the steel walls. When the ambient temperature was 35.2°C, the temperature of the concrete lysimeter wall was measured to be 47.4°C, while the steel lysimeter wall was 41°C. Finally, the walls of the concrete lysimeter were approximately seven times thicker than the steel walled lysimeter. The tops of these walls, for both the concrete and steel plate lysimeters, were exposed at the ground level. The wider walls received greater solar radiation and temperature effects that aided in the promotion of ET.

The second comparison by Guiting (1991) was between lysimeters all composed with 3 mm steel plate walls but with areas of 0.132 m^2, 0.6m^2, 3.2 m^2, and 6 m^2. The results from each lysimeter, again obtained over five years ranging from 1985 to 1989, were compared by examining the ratio of ET from each lysimeter individually to the ET measured from the lysimeter with an area of 6 m^2. The average ET ratio values over five years were 1.23, 1.14, 1.04, and 1.00 for the area ratios 0.132 m^2/6 m^2, 0.6m^2/6 m^2, 3.2 m^2/6 m^2, and 6 m^2/6 m^2, respectively. The results indicate that the smaller the lysimeter area the larger the measured ET. It was determined that the smaller lysimeter area provided a greater proportion of the outside lysimeter wall to be exposed to the factors that drive ET, such as temperature and solar radiation.

Denich and Bradford (2010) constructed a cubic subsurface weighing lysimeter Ontario, Canada (Figures 10 and 11) for the purpose of measuring the ET occurring in a bioretention basin in an urban environment (62% impermeable and 38% permeable surfaces). The lysimeter has a surface area of 1.31 m^2 and depth of 1.02 m. One cubic meter of triple-mix soil media topped with shredded hardwood mulch and herbaceous perennial plants are housed in a medium density polyethylene (MDPE) pallet tank. The pallet tank rests on four temperature corrected, stainless steel shear beam type load cells that have a combined capacity of 5,000 kg (Figure 11). Encasing the pallet tank and load cells is a 5 mm outer steel tank (Figures 10 and 11). The entire assembly sits on a reinforced concrete pad. The percolated outflow is collected from the 40 L effluent storage tank (Figure 10). The Denich and Bradford (2010) lysimeter is designed only to receive direct precipitation. No drainage area is associated with the lysimeter and no simulations have been performed to simulate stormwater runoff from an attached drainage area. The initial data from the lysimeter taken over 11 sunny days with no precipitation at the end of July and during August measured an average ET rate of 4.2

mm/day. Another data set of 5 consecutive sunny days with no precipitation ranging from August 30 to September 3 recorded an average ET rate of 7.7 mm/day.

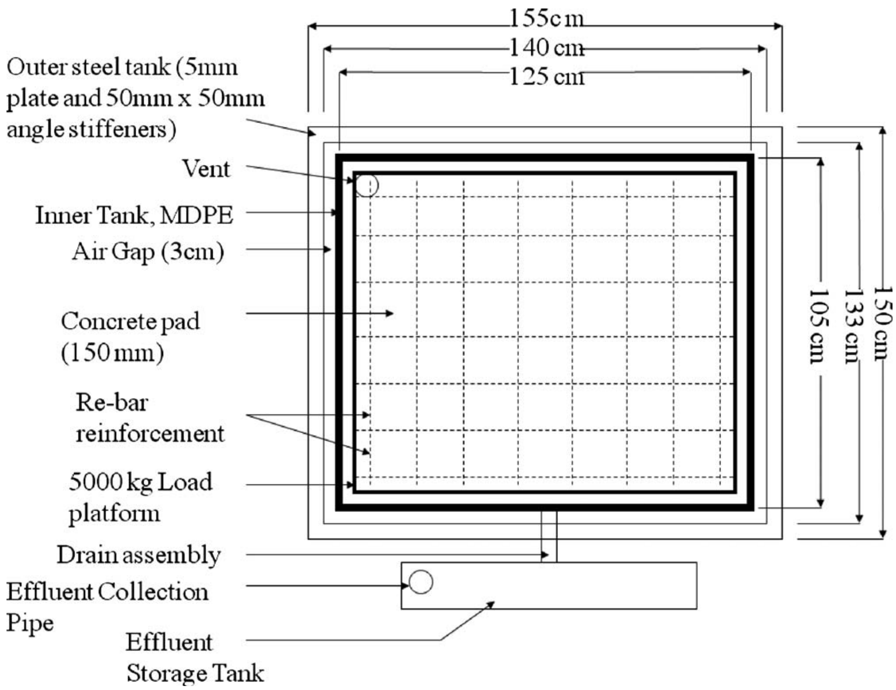

Figure 10 Top View of Weighing Lysimeter Design by Denich and Bradford (2010) for Study of Urban Evapotranspiration

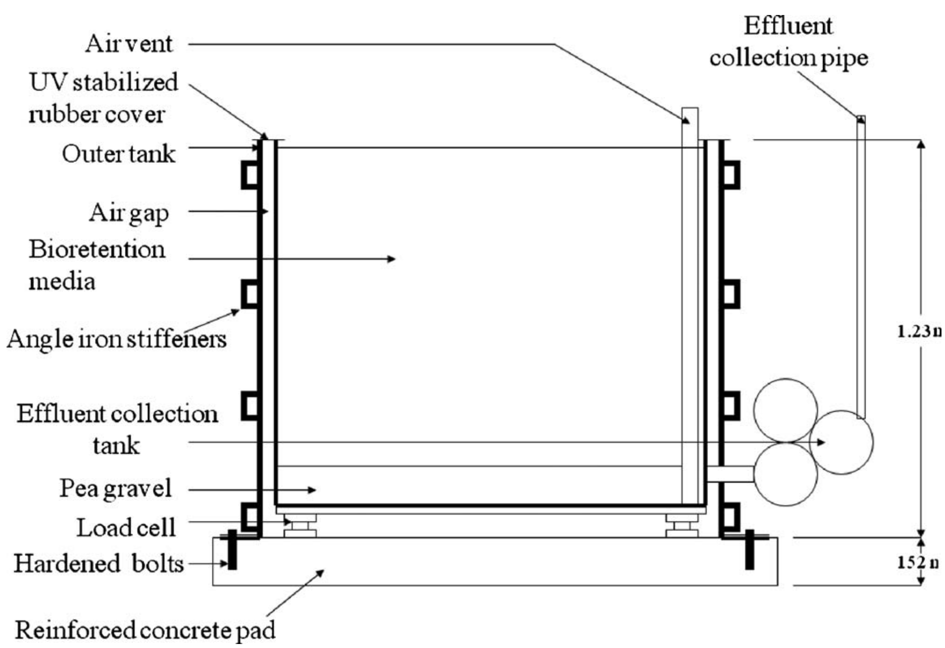

Figure 11 Side View of Weighing Lysimeter Design by Denich and Bradford (2010) for Study of Urban Evapotranspiration

Chapter 3 Methodology

3.1 Lysimeters

The Villanova ET study site (Figure 12) is geographically located at latitiude 40º 2' N and longitude 75º 20' W at an elevation of approximately 120 m above sea level. The site consists of three identical lysimeters (Figure 12). Each lysimeter is housed inside of a concrete well 1.83 m deep and 1.22 m square. There is a concrete ceiling with a 1.07 m diameter hole through which a 0.76 m diameter and 0.91 m deep galvanized steel weighing bucket hangs from an open 1.22 m cube galvanized steel structure. Four chains attach the bucket to the upper corners of the cube and converge at a Sentran S-beam tension load cell, with a listed combined error of 0.025% of the rated output. A Campbell Scientific CR1000 datalogger is located on site to record the lysimeter weights, total rainfall, lysimeter outflows, relative humidity, solar radiation, temperature, and wind speed at one minute intervals.

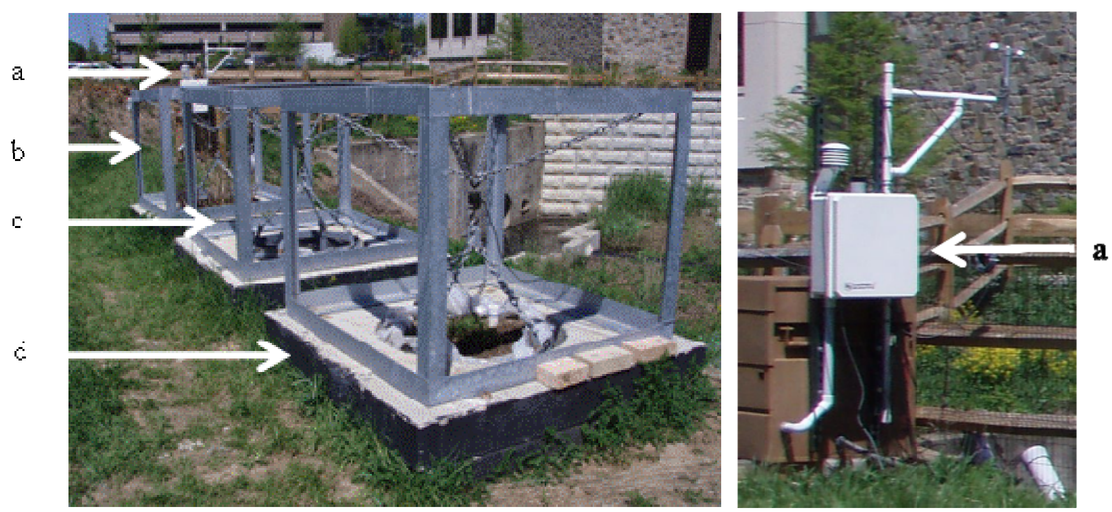

Figure 12 Lysimeters and Control Bucket with Weather Station. The weather station and datalogger is (a), the bioinfiltration lysimeter (b), the load cell control bucket (c), and the bioretention lysimeter (d).

The bioinfiltration lysimeter has twelve 2 cm diameter holes in the bottom of the weighing bucket covered by a geotextile fabric to allow percolated outflow to leave, but to prevent sediments from leaving. Beneath the lysimeter bucket is a funnel (Figure 13a) that directs percolated outflow into a tipping bucket rain gauge (Figure 13b) for measurement. The bioinfiltration lysimeter is designed as a microcosm of the Villanova bioinfiltration basin and uses the same vegetation and soil; plants native to the New Jersey coast, a 50% native Glenelg silt loam soil and 50% sand mixture (by volume) (Emerson 2007).

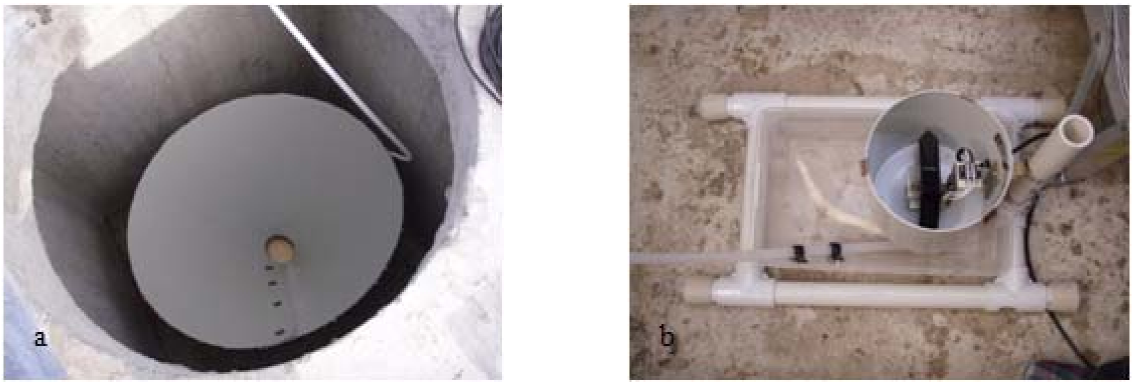

Figure 13 Outflow measurement system for Bioinfiltration Lysimeter. (a) is the funnel to direct flow to the rain gauge (b).

The galvanized steel bucket for the bioretention lysimeter is sealed at the bottom. Instead of allowing percolated outflow to leave the system, as is the case with the bioinfiltration lysimeter, an underdrain and upturned elbow system was constructed (Figure 14). The bioretention lysimeter bucket houses a made topsoil consisting of 63.6% sand, 32.4% silt/clay, and 4.0% organics.

Figure 14 Bioretention Lysimeter Design with the top view (a) and side view (b).

The underdrain was created using 10.16 cm PVC pipe with 2 mm slots drilled at 2 inch spacings. The underdrain drains to a 3.81 cm outflow pipe that angles around the side of the bucket with two 90 degree turns (Figure 14b). Figure 14 details the 3.81 cm cleanout pipe that was placed in the system in order to release accumulated sediment trapped in the underdrain. The underdrain system rests on 10.16 cm of coarse gravel, on top of the coarse gravel and directly under the 10.16 cm slotted PVC pipe is a 6 mm plastic liner. Wrapped around the 10.16 cm slotted PVC pipe is 10.16 cm more of coarse gravel. On top of the coarse gravel is 5.08 cm of fine gravel and above that is 5.08 cm of sand.

The purpose of the underdrain and upturned elbow is to create an internal water storage (IWS) layer for plants to draw moisture from during periods of low rainfall, as well as to recreate an anaerobic zone similar to bioretention designs of Hunt et al. (2006). The anaerobic zone with a carbon source provides an environment suitable to bacteria that assist in denitrification of stormwater runoff, improving the water quality of the outflow (Hunt et al 2006). The upturned elbow rises 45.72 cm up the side of the lysimeter bucket; this creates the boundary of the IWS layer. With the 30.48 cm of bed material at the bottom of the bucket, this creates a 15.24 cm layer of saturated soil to house denitrifying bacteria, and act as a reservoir for plants to draw from.

3.2 Load Cell Accuracy

A control cell (Figure 12c) is used to determine the accuracy of the weight measurements. The control cell, which has a drain, has a constant weight of 278.1 kg (613 lbs). During one day, over the course of one week of examination, the maximum recorded weight was 278.3 kg (613.5 lbs) and the minimum weight was 278.1 kg (613.1 lbs). The greatest percent range on record is 0.06% (0.4 mm of water) over 24 hours. The range accounts for the cumulative error of the datalogger and load cells, due to error in measurement and temperature change. The recorded weight varies directly with relative humidity (Figure 15); it is conjectured that the load cells are sensitive to the formation and dissipation of dew and therefore capable of accurate ET measurement over 24 hour time periods.

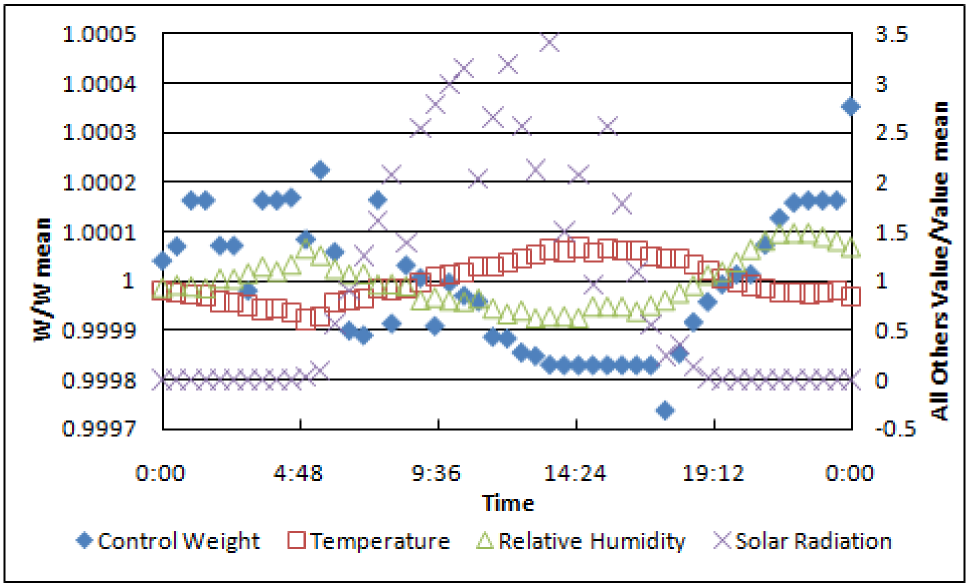

Figure 15 Normalized Control Bucket Weight, Temperature, Relative Humidity, and Solar Radiation. All values are normalized by the 24 hour mean for May 7, 2010.

3.3 Bioinfiltration Lysimeter with Direct Rainfall

Evapotranspiration resulting from only natural occurring precipitation falling within the lysimeter was calculated from March to December of 2010. The ET and infiltration from natural precipitation can be viewed as simulating the effects of a bioinfiltration basin with no drainage area. The analysis was done in order to facilitate an understanding of the ET effects due to the vegetation itself and to compare to existing crop lysimeter data. The analysis was also used to ensure the proper working of the equipment and calculation methods.

3.4 Simulated Storms

Bioinfiltration and bioretention basins are designed to receive runoff from drainage areas in order to assist in achieving predevelopment hydrologic conditions. Therefore, storm loading experiments with simulated impervious area loading ratios were performed in 2010 to replicate these field conditions. The simulations included 2.5 hour storm events of 13, 19, and 25 mm producing runoff occurring from both 5:1 and 10:1 impervious area to lysimeter area loading ratios (Table 2). The storm events and loading ratios were chosen based on their applicability to the Villanova bioinfiltration basin that the lysimeter was designed to mimic. The Villanova bioinfiltration basin was designed to capture a maximum of 25 mm of runoff from the surrounding 10:1 impervious area to basin area ratio. A loading ratio of 5:1 was also simulated due to the design recommendations of the PABMP manual (PADEP 2006).

The 2.5 hour storm duration was chosen for the convenience of being able to divide the storm water into six portions that could be poured slowly into the lysimeter at half hour increments. The simulations were conducted during the morning (started at 5:00 am) and evening (started at 7:00 pm) in the summer (May through July) and late fall (November through December). Tables 3 and 4 lists the storm event, loading ratios, and dates of the simulated storm loadings during the summer and late fall respectively.

The initial goal for the spacing of the simulated storms was to allow the bioinfiltration lysimeter to dry for 72 hours before loading. The goal became unattainable due to the frequent small storms that often occur during the summer in southeastern Pennsylvania. Therefore, the simulated storms were performed when 24-48 hours of dry weather was expected (regardless of prior rain) and the antecedent soil moisture of the lysimeter monitored. The modified procedure proved to have more interesting results as the soil moisture in the lysimeter prior to the simulated storms was an important factor in determining how much water remained in the lysimeter to be available for ET, and how much drained out as infiltration

In order to measure the ET occurring in the bioretention lysimeter, the lysimeter was filled with water to capacity. The maximum water storage of the lysimeter was obtained when water reached the top of the upturned elbow. Loading simulation experiments were performed in late fall.

Table 2 Storm Simulation Volumes

Storm Event (mm)	5:1 Loading Ratio Amount per 0.5 hr (L)	5:1 Loading Ratio Total Water Input (L)	10:1 Loading Ratio Amount per 0.5 hr (L)	10:1 Loading Ratio Total Water Input (L)
13	4.92	29.53	9.84	59.05
19	7.19	43.15	14.38	86.31
25	9.84	59.05	19.68	118.10

Table 3 Summer Storm Simulation Event, Loading Ratio, and Date Performed

Storm Event (mm)	Loading Ratio	Date
13	5:1 Evening	5-26-10
19	5:1 Evening	5-8-10
25	5:1 Evening	5-14-10
13	5:1 Morning	7-22-10
19	5:1 Morning	6-18-10
25	5:1 Morning	6-22-10
13	10:1 Evening	7-7-10
19	10:1 Evening	7-1-10
25	10:1 Evening	6-28-10
13	10:1 Morning	6-11-10
19	10:1 Morning	6-8-10
25	10:1 Morning	6-15-10

Table 4 Late Fall Storm Simulation Event, Loading Ratio, and Date Performed

Storm Event (mm)	Loading Ratio	Date
13	5:1 Morning	12-3-10
19	5:1 Morning	11-22-10
25	5:1 Morning	12-31-10
13	10:1 Morning	12-9-10
19	10:1 Morning	11-13-10
25	10:1 Morning	11-10-10

3.5 Soil-Water Characteristic Curve

In order to understand the relationship between antecedent soil moisture conditions and the performance of the bioinfiltration lysimeter in terms of infiltration and ET, a soil-water characteristic curve (SWCC), or graph of the gravimetric water content of the soil vs. the soil suction was created for the bioinfiltration lysimeter using the Fredlund et al. (2002) approach, which can be effectively used for a wide range of soils:

$$\theta(\psi, a, n, m) = \theta_S \left[1 - \frac{\ln\left(1 + \psi/\psi_r\right)}{\ln\left(1 + 10^6 kPa/\psi_r\right)} \right] \left[\frac{1}{\left[\ln\left(e + \left(\psi/a\right)^n\right)\right]^m} \right] \quad (1)$$

where θ is the gravimetric water content (%), ψ is the soil suction (kPa), ψ_r is the suction at the residual water content (kPa), θ_s is the saturated water content (%), 10^6 (kPa) is a theoretical maximum suction with zero moisture, and a, n, and m are the model parameters. A value of a = 100 was selected based on soil type.

Soil sieve analysis yields the effective grain size diameter (Fredlund et al. 2002):

$$\frac{1}{d_e} = \frac{3}{2}\frac{\Delta g_1}{d_1} + \sum_{i=2}^{i=n} \frac{\Delta g_i}{d_i} \qquad (2)$$

where d_e is the effective grain size diameter, d_i is the diameter of the current fraction of material (d_1 is the largest diameter), and Δg_i is the mass fraction of that segment of material. The d_e is used to determine the model parameters n and m:

$$n \text{ or } m = p_1 \left[\frac{1}{\ln\left\{ e + \left[\frac{10^{-\log(d_e)-1}}{p_2} \right]^{p_3} \right\}} \right]^{p_4} + p_5 \qquad (3)$$

where $p_{1\text{-}5}$ are coefficients of best fit. For n, $p_1 = 19$, $p_2 = 50$, $p_3 = 30$, $p_4 = 1$, and $p_5 = 1$. For m, $p_1 = 1.5$, $p_2 = 100$, $p_3 = 10$, $p_4 = 1$, and $p_5 = 0.5$.

3.6 ET Calculation Methods

3.6.1 ET Calculated from Direct Rainfall

Evapotranspiration from the bioinfiltration lysimeter resulting only from direct rainfall was measured using the mass balance:

$$ET_m = R - P - \Delta W \qquad (4)$$

where ET_m is the lysimeter measured ET (mm), R is the precipitation into the lysimeter (mm), P is percolated infiltration outflow (mm), and ΔW is the change in weight of the lysimeter (mm).

In order to avoid accounting for water in both the R and W terms of Equation 4, and due to the trivial amount of ET that occurs on days with precipitation, ET was measured only on days without precipitation. Removing the precipitation input reduces the R term of Equation 4 to zero. The measurement time period was midnight to 23:59, which was chosen for its consistency as ET is calculated over a ten month time span.

Evapotranspiration from the bioretention lysimeter was also measured from midnight to 23:59 on days without precipitation and when no percolated outflow was leaving the system. The method reduces both the precipitation (R), and outflow term (P) of Equation 4 to zero leaving the bioretention lysimeter ET_m to be calculated by equation 5:

$$ET_m = -\Delta W \quad (5)$$

3.6.2 ET Calculated from Storm Simulations in the Bioinfiltration Lysimeter

The mass balance Equation 4 was used to calculate ET resulting from storm simulation. During analysis of the preliminary data from the bioinfiltration lysimeter it was discovered that the tipping bucket rain gauge used to measure the infiltration was not able to accurately quantify the volume of water leaving the lysimeter. To circumvent this error, the 24 hour period from which ET was to be calculated began as soon as an accurately measurable amount of infiltration began to be recorded (usually three hours before all water left the lysimeter via infiltration). The percolation was then back calculated from the peak of the weight measurement after the simulated storm. The method was chosen to reduce to the precipitation term R in Equation 4 to zero. It is assumed that the soil within the lysimeter is saturated as there is still water leaving the system when the ET is measured.

3.6.3 ET Calculated from Storm Simulations in the Bioretention Lysimeter

The bioretention lysimeter ET_m calculation began after the lysimeter was filled to capacity with water. The beginning of the 24 hour ET calculation started once the outflow ceased and the weight stabilized. With no precipitation (R), and percolated outflow term (P), the ET for this lysimeter was again calculated using Equation 5.

3.7 Penman-Monteith Equation

To facilitate a complete understanding of processes that govern ET within the lysimeter, and in an attempt to find a predictive equation that accurately describes the amount of ET that can be expected, the FAO Penman-Monteith equation (equation 6) was used. The Penman-Monteith equation uses the measured local climatological parameters of temperature, relative humidity, solar radiation, and wind speed in addition to site specific parameters such as latitude, longitude, and elevation. These parameters are used to calculate the reference ET (ET_0) for a hypothetical reference crop that has a height of 0.12 m, a fixed surface resistance of 70 s/m, an albedo of 0.23, and is never short of water (Allen et al 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (6)$$

where R_n is the net radiation at the crop surface ($MJ/m^2/day$), G is the soil heat flux density ($MJ/m^2/day$), T is the mean daily air temperature at 2 m height (^oC), u_2 is the wind speed at 2 m height (m/s), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), (e_s - e_a) is the saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa/°C), and γ is the psychrometric constant dependant on altitude (kPa/^oC) (Allen et al 1998).

Once the reference ET_0 is calculated a crop coefficient (K_c) with water stress (K_s), based on this experimental setup, can be determined:

$$K_c K_s = \frac{ET_m}{ET_0} \quad (7)$$

where ET_m is the evapotranspiration measured in the lysimeter (mm/day). The goal of this study is to determine typical K_cK_s values for bioinfiltration and bioretention systems, which can then be used with the reference ET_0 to predict ET. However, the determination of K_c and K_s individually is beyond the scope of this study as this is the first analysis of the data generated for the year 2010.

Chapter 4 Results and Discussion

The evapotranspiration results from the bioinfiltration and bioretention lysimeters were calculated over the months of March through December 2010. During this time ET was measured from both direct rainfall entering the lysimeters and simulated storm events. The ET measured from direct rainfall was used to examine seasonal variations in ET performance. As bioinfiltration and bioretention basins receive stormwater runoff from a surrounding impervious area, storms were simulated that mimicked this effect, in 5:1 and 10:1 impervious area to lysimeter area ratios.

4.1 Soil-Water Characteristic Curve

A soil water characteristic curve was generated (Equation 1 and Figure 16) for the soil in the bioinfiltration lysimeter. Soil laboratory analysis was combined with field observations to establish the wilting point and field capacity of the lysimeter soil. The minimum lysimeter weight that allowed for infiltration to occur from natural precipitation (Figure 17) was used to determine the wilting point of the soil. The maximum weight of the bioinfiltration lysimeter during the summer storm simulations (Figure 18) from which soil storage ceased and additional water was lost to infiltration, was used to determine the field capacity of the soil. These observations indicate that when the lysimeter weight is approximately 565 kg the soil gravimetric water content is 2.6%, the soil suction is strong (approximately 100,000 kPa) and very little water is allowed to exit the lysimeter via infiltration. When the maximum weight is approximately 615 kg the soil gravimetric water content is 22.8%, the soil suction is estimated to be 10 kPa, and after this point there is little suction available, allowing more water to leave the lysimeter as infiltration.

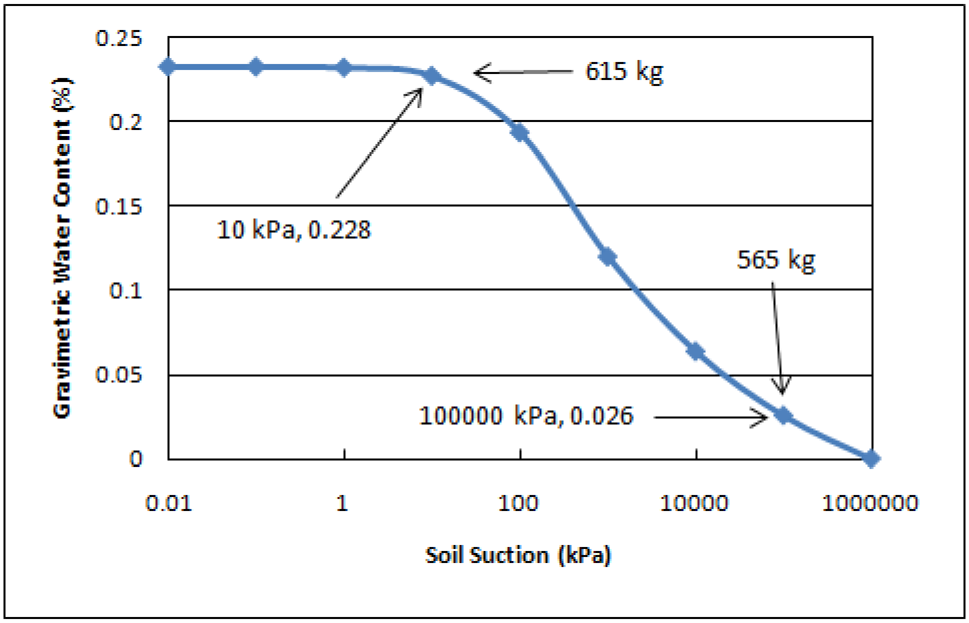

Figure 16 Soil Water Characteristic Curve for the Bioinfiltration Lysimeter

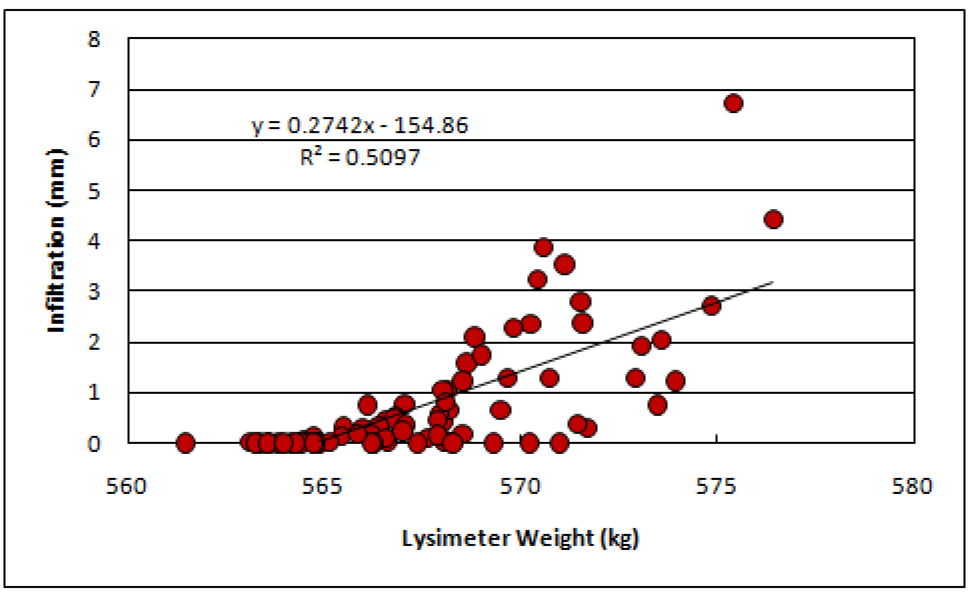

Figure 17 Minimum Bioinfiltration Lysimeter Weight that Allowed for Infiltration to Occur from Only Natural Precipitation Falling within the Lysimeter

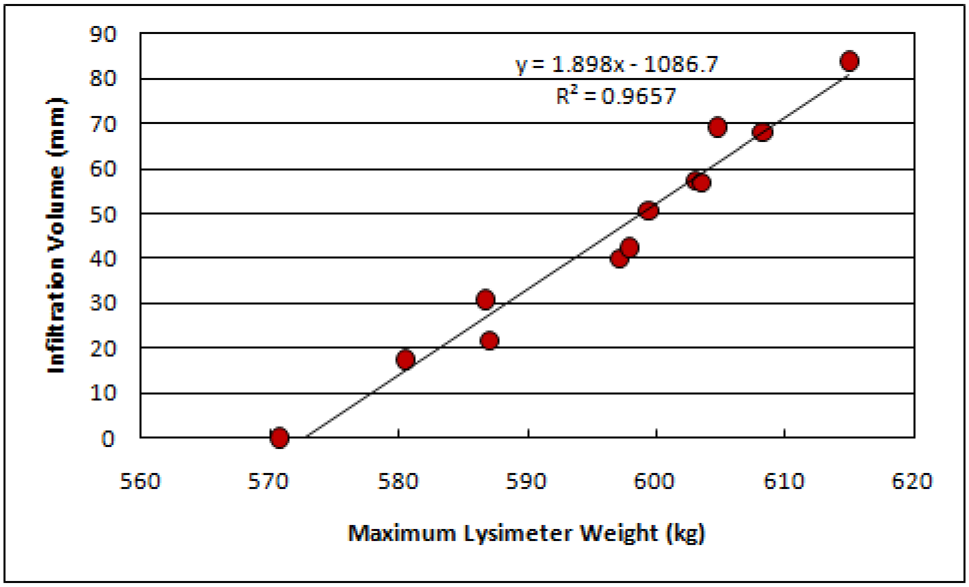

Figure 18 Maximum Lysimeter Weight from the Bioinfiltration Lysimeter during the Summer Storm Simulations

4.2 Lysimeter Data Resulting from Direct Rainfall

Evapotranspiration data resulting from naturally occurring precipitation falling within the bioinfiltration lysimeter was collected from March through December 2010, although throughout this time there were also simulated storms and short periods with no data collection due to instrumentation error. Bioretention lysimeter data for naturally occurring precipitation is available from mid-August to December 2010; simulated storms and short periods with instrumentation error occurred during this time.

4.2.1 Early Season (March and April)

The collected data for the bioinfiltration lysimeter in March and April 2010 (Figures 19 and 20) from days without precipitation (see Chapter 3.6 Methods Equation 4) is compared to the Penman-Monteith (PM) ET_0 (Equation 6). In order to avoid accounting for water in both the R and W terms of Equation 4, and due to the trivial amount of ET that occurs on days with precipitation, ET is reported only on days without precipitation.

The PM ET_0 is greater than the bioinfiltration lysimeter ET_m for March and April. The average K_cK_s (Equation 7) values for each month (Table 5) were nearly the same. Accordingly the average lysimeter weight for both months is very nearly the same indicating that the soil moisture conditions within the lysimeter on average were similar. Analysis of the bioinfiltration lysimeter data from March and April 2010, in attempt to determine whether the climate or the soil moisture conditions had more influence on the ET_m, was done by comparing the changes in slope between each ET_m data point relative to the changes in slope between each PM ET_0 and average daily lysimeter weight data point (Table 6, Appendix 2 and 3). The climate is reflected in the values of the PM ET_0 equation, which is a function of the temperature, relative humidity, solar radiation, and wind speed. The soil moisture conditions outlined in the SWCC (Figure 16) are reflected in the average daily lysimeter weight. Using Figure 19 as an example of the slope analysis, from the first data point (March 1) to the second data point (March 4), the slopes of the ET_m, the PM ET_0, and the average daily lysimeter weight are all in the same direction; down, or negative. The same change in slope between all three parameters indicates that both the climate (PM ET_0) and available soil moisture could have had an impact on the ET_m for March 4. However, from March 4 to March 5 the measured ET slope is negative (goes down) simultaneous with the available soil moisture while the PM ET_0 is positive (goes up), indicating that on March 5 the available soil moisture may have had more impact on the ET_m than the climate. Continuing with the analysis, from March 5 to March 6, the slopes of the ET_m and the PM ET_0 are both positive while the soil moisture is negative, indicating the climate had more influence on the measured ET than the soil moisture.

When this analysis is viewed over the entire month of March, the soil moisture conditions had a stronger influence on the rate of ET_m with the slope of the ET_m simultaneously changing positively or negatively with the average lysimeter weight in 87.50% of the data (Table 6). Indeed there are only two data points that do not change in the same direction as the daily average lysimeter weight during the entire month (Appendix 2). However, the climate still had a strong effect as the ET_m slope changed in the same direction with the PM ET_0 data 68.75% of the time. In comparing the actual values of the change in slopes when the changes went the same direction (to examine how close the ET_m followed either the climate or soil moisture), the PM ET_0 slope changes were closer to the ET_m than the daily average lysimeter weight (in order to compare this accurately the lysimeter weight was converted to mm of water). The same analysis for the month of April yields that both the PM ET_0 and average daily lysimeter weight had an equal influence on the ET_m with changes in slope occurring from both factors 57.89% simultaneously with the ET_m . The percent difference was lower for the values of changes in slope between the ET_m and the PM ET_0 indicating that when the climate had influence, that influence was more closely mirrored by the ET_m (Table 6).

There is greater fluctuation in the lysimeter soil moisture during March than in April, which can be seen by variations in the lysimeter weight. The lysimeter loses 10 kg of water during the first 11 days of March due to increased infiltration rates resulting from frequent small storms at the end of February. Rain occurs from March 12-15 refilling the lysimeter with 6 kg of water after which infiltration increases again and the lysimeter loses 5 kg mainly to infiltration and partially to ET. In contrast the soil moisture of the lysimeter in April is more constant due to an even distribution of precipitation. The lysimeter loses 6 kg of water in the first seven days of April, but never loses more than 3 kg after rain events that occur on April 8, 9, 13, 16, 21, 22, 24-27. These rain events produced 0.99, 0.76, 0.48, 0.66, 0.46, 0.03, and 3.71 cm, respectively.

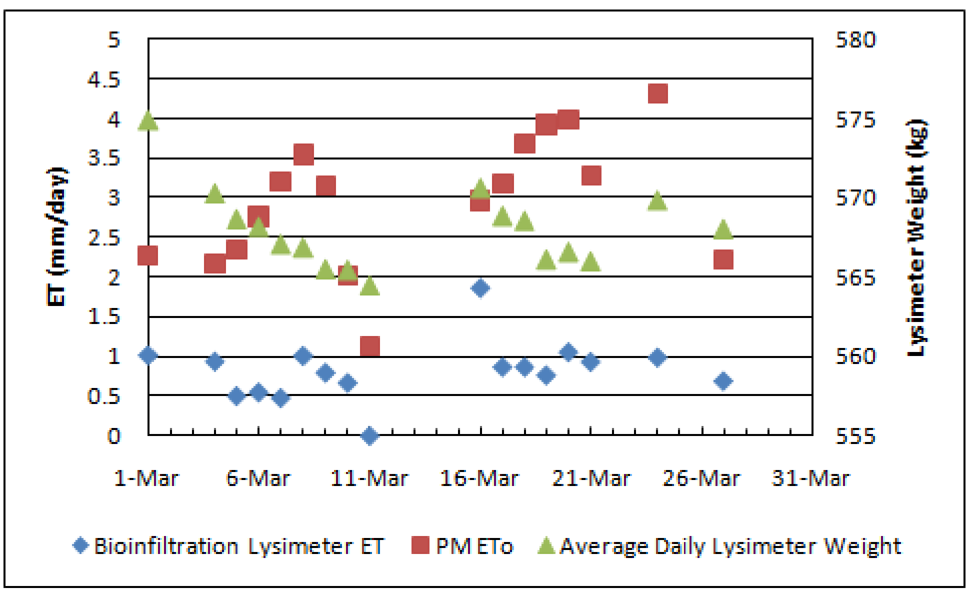

Figure 19 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight Data for March 2010

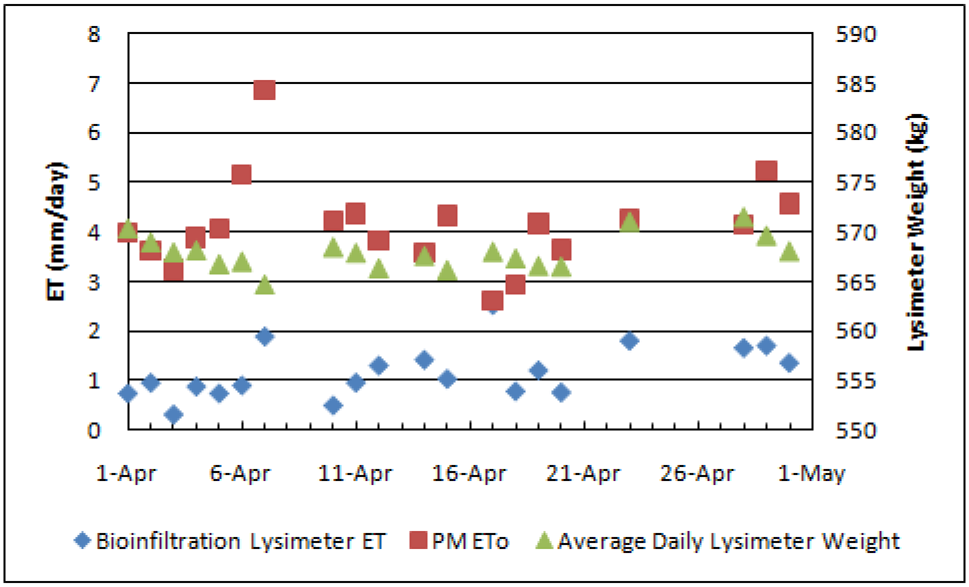

Figure 20 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight Data for April 2010

Table 5 Average Bioinfiltration Lysimeter ET, PM ET_0, K_cK_s Values, and Lysimeter Weight for March and April 2010

Month	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_cK_s	Average Bioinfiltration Lysimeter Weight (kg)
March	0.82	2.94	0.28	570.93
April	1.16	4.14	0.29	569.05

Table 6 Comparison of Bioinfiltration ET_m, PM ET_0, and Average Daily Weight Slope Characteristics for March and April

Month	Percentage of ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Percentage of ET_m and Avg. Weight Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and Avg. Weight Slopes Moving in the Same Direction (%)
March	68.75	87.50	98.47	127.03
April	57.89	57.89	72.86	124.93

The FAO has established K_c values for well managed crops in subhumid environments, such as grassland and prairie climates with an average relative humidity of approximately 45% and an average wind speed of around 2 m/s (Allen et al. 1998). (These values can be found in Appendix 1). The National Oceanic and Atmospheric

Administration (NOAA) lists the annual relative humidity average for Philadelphia, PA as 76% in the morning and 55% in the afternoon (2002a), and the average wind speed in Philadelphia as 4.25 m/s (2002b). The Philadelphia area may on average yield less ET than the FAO subhumid environments due to increased relative humidity; however the increased wind speed in the Philadelphia region may balance this effect enough for reasonable comparison. The evaluation is further marred however, by the fact that comparison is being made between K_c and K_cK_s values. There is some water stress, indicated by the average daily lysimeter weight for both March and April (Table 5) which compared to the SWCC (Figure 16) is only somewhat above the wilting point. The water stress would have the effect of making the lysimeter K_cK_s term lower than the lysimeter K_c term if it were solved for separately. K_s is equal to one if there is no water stress, and becomes less than one (greater than zero) when water stress begins. However, for the sake of future study the comparison between FAO K_c and the lysimeter K_cK_s is still made. The K_c values for crops that are comparable to the lysimeter K_cK_s for the spring/early growth are listed:

Table 7 Initial Growth Phase K_c Values Similar to Observed Bioinfiltration K_cK_s

Crop	K_c	Source
Sugar beet	0.35	Allen et al. (1998)
Sugar cane	0.40	Allen et al. (1998)
Cereal (barley, oats, spring wheat)	0.30	Allen et al. (1998)
Fibre and oil (cotton, flax, sesame, sunflowers)	0.35	Allen et al. (1998)
Alfalfa	0.40	Allen et al. (1998)
Winter wheat	0.38	Liu et al. (2002)
Bioinfiltration Lysimeter K_cK_s	0.29	

The vegetation in the lysimeter during mid-April is pictured in Figure 21. The new growth has just begun to sprout and there is still a large amount of dead plant stalks from the previous year; thus comparison to initial growth stages of the crops is reasonable. These dead stalks provide a canopy over the soil that protects the soil from direct evaporation caused by solar radiation and wind.

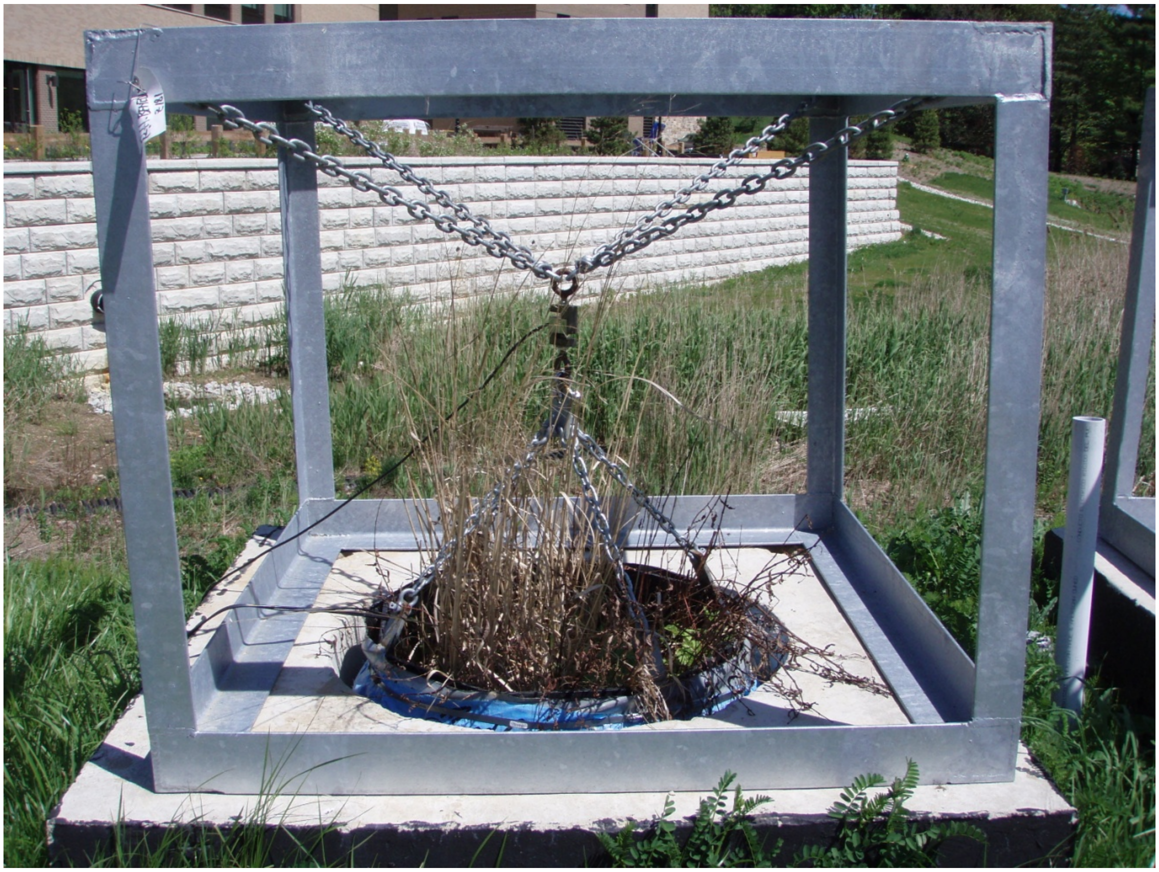

Figure 21 Bioinfiltration Lysimeter in Mid-April 2010.

4.2.2 Mid-Season (May – August)

The bioinfiltration lysimeter data for May (Figure 22), June (Figure 23), the first week of July (Figure 24), and August (Figure 25) display the ET trends of the summer months of 2010 (Table 9). The lysimeter ET data from May shows general governance by the climate reflected in the PM ET_0 values. The slopes of the ET_m data follow the same direction as the slopes of the PM ET_0 data in 75.00% of the measurements (Table 10, Appendix 4). In June the bioinfiltration lysimeter is overall affected equally by the climate and the soil moisture. The month of June displays the interconnected nature of the influence of climate and soil moisture on the measured ET rate. The first five ET_m data points generally follow the climate (via PM ET_0). However, on June 10 the PM ET_0 decreases, yet the ET_m increases in response to more soil moisture resulting from a 19 mm 10:1 (drainage to lysimeter area ratio) simulated storm loading of 86.31 L that took place on June 8 and 1.45 cm of rain on June 9. On June 14 the lysimeter weight increases again due to a 13 mm 10:1 storm simulation of 59.05 L and 63.8 mm (29.10 L) of direct rain over June 12 and 13. Analysis of the soil-water characteristic curve (Figure 16) shows that when the bioinfiltration lysimeter weight is below 565 kg, the soil suction is strong and the soil retains more water. The strong soil suction is the cause of the relatively small slope between June 10 and 14 relative to the larger slope between June 7 and 10. With the increase in available soil moisture on June 14 is a decrease in the PM ET_0 resulting from a decrease in solar radiation from 21.94 MJ/m^2/day on June 10 to 13.10 MJ/m^2/day on June 14. While on June 14 the soil moisture available for ET has increased, the climate is reduced in its ability to promote ET and the lysimeter ET_m is reduced. During the next three data points on June 17, 20, and 21 the ET_m consistently increases with the climate (PM ET_0), thereby decreasing the soil moisture.

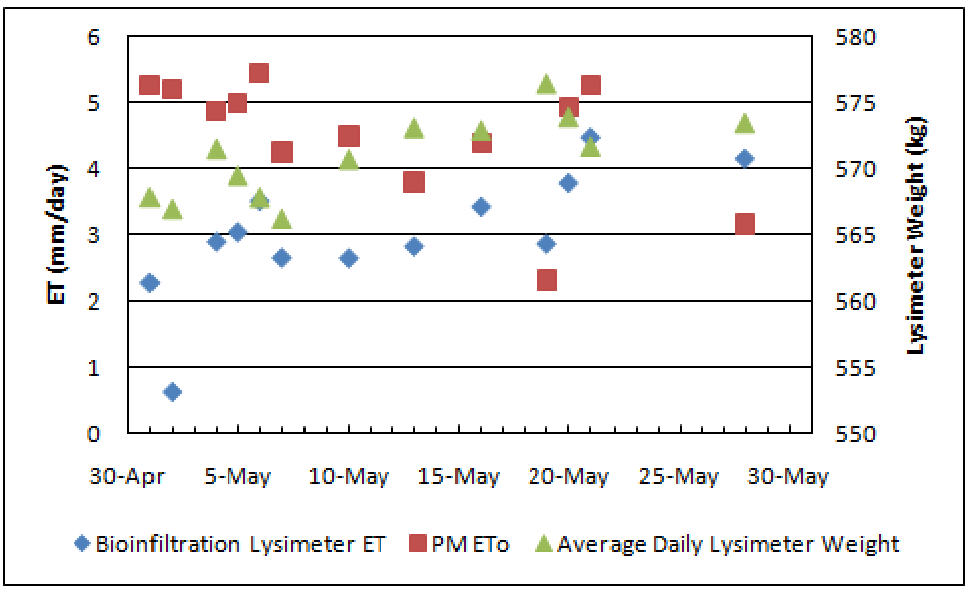

Figure 22 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight Data for May 2010

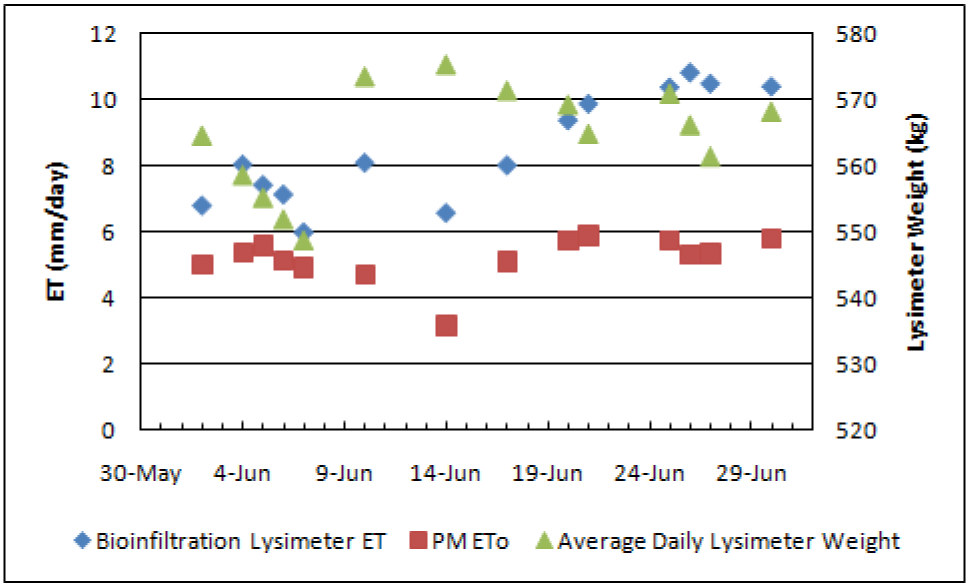

Figure 23 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight Data for June 2010

The PM ET_0 values are greater than the bioinfiltration lysimeter ET in May similar to the months of March and April 2010. However, this trend changes in June and July when the PM ET_0 is less than the bioinfiltration lysimeter ET, but returns during the end of August when the PM ET_0 is again greater than the lysimeter ET. Observations in May, June, July, and August yield daily average bioinfiltration lysimeter K_cK_s values at 0.72, 1.81, 2.17, and 0.50 respectively. These K_cK_s values average to a middle growth phase K_cK_s of 1.30 rising from the initial growth phase K_cK_s of 0.29. The fluctuation is inherent in the PM ET_0 equation and is evidenced in the FAO crop K_c values (Appendix 1). For example over the course of a growing season sugar cane K_c values are 0.40, 1.25, and 0.70 (Allen et al. 1998). The fluctuation of K_c points to PM ET_0 being greater than the measured ET during the initial growth phase with a K_c less than 1 (Equation 7), then the PM ET_0 being less than the measured ET during the middle growth phase with a K_c greater than 1, and finally the PM ET_0 being again greater than the measured ET with a K_c less than 1. The same changes would be observed with the water stress coefficient (K_s).

While the PM ET_0 data reflects the climatic parameters governing ET, the average lysimeter weight reflects the overall soil moisture conditions within the lysimeter. The available soil moisture over the summer months decreases continuously (Table 9). The decrease is stepwise during May, June, and the first week of July, with the bioinfiltration lysimeter losing roughly 5 kg every month. However, the daily average weight decreases sharply in August by nearly 50 kg relative to the first week of July. The decreasing soil moisture is due to increasing ET values during the summer until the soil moisture content of the lysimeter reaches an extreme low during August. For example, the climatic parameters for May and June are similar with an average daily PM ET_0 of 4.49 and 4.99 mm/day (Table 9). The June data has an average lysimeter weight that is 5.91 kg less than May and the lysimeter ET for June is on average 5.54 mm/day greater than May. Further, the four days in July have a daily average lysimeter weight 4.75 kg less than June. While the average daily PM ET_0 values for the days in July are 1.76 mm/day greater than that from June, the average daily ET is 6.12 mm/day greater than that from June. The trend ceases when the bioinfiltration lysimeter loses an extreme amount of soil moisture in August and reaches the wilting point. The natural precipitation events during July and August were relatively small (rain events occurred on August 12, August 15-16, and August 22-24, producing 0.76, 0.18, and 2.92 cm of rainfall, respectively) and there were no simulated storms during this time to add water to the system. The reaction of the lysimeter to the soil moisture deficit in August (Figure 25), is that the lysimeter weight guides the trend in the lysimeter measured ET until August 18 when the PM ET_0 value indicates poor climatic conditions for ET, and the measured ET decreases in relation. The solar radiation on August 17 is measured at 21.11 $MJ/m^2/day$, then decreases to 9.03 $MJ/m^2/day$ on August 18, but increases back to 25.11 $MJ/m^2/day$ on August 19. After August 18 the measured ET again follows the decreasing trend with the lysimeter weight until the 2.92 cm rain event increases the lysimeter soil moisture content. From August 25-30 the measured ET more closely follows the climate (PM ET_0). Overall, August is guided slightly more by available soil moisture than the PM ET_0 with 66.67% of the ET_m slopes changing with the lysimeter weight relative to 50.00% of the ET_m slopes changing with the PM ET_0 (Table 10).

The FAO K_c values for crops that are similar to the lysimeter K_cK_s for the summer/middle growth phase are listed:

Table 8 Middle Growth Phase K_c Values Similar to Observed Bioinfiltration K_cK_s

Crop	K_c	Source
Sugar beet	1.20	Allen et al. (1998)
Sugar cane	1.25	Allen et al. (1998)
Cereal (barley, oats, spring wheat)	1.15	Allen et al. (1998)
Fibre and oil (cotton, flax, sesame, sunflowers)	1.10-1.20	Allen et al. (1998)
Field Maize	1.20	Allen et al. (1998)
Field Maize	1.42	Liu et al. (2002)
Bioinfiltration Lysimeter K_cK_s	1.30	

Table 9 Average Bioinfiltration Lysimeter ET, PM ET_0, K_c Values, and Lysimeter Weight for May, June, the First Week of July, and August 2010

Month	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_cK_s	Average Daily Bioinfiltration Lysimeter Weight (kg)
May	3.01	4.49	0.72	571.06
June	8.55	4.99	1.81	565.15
July 3-6	14.67	6.75	2.17	560.40
August	1.93	4.05	0.50	510.80

Table 10 Comparison of Bioinfiltration ET_m, PM ET_0, and Average Daily Weight Slope Characteristics for May through August

Month	Percentage of ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Percentage of ET_m and Avg. Weight Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and Avg. Weight Slopes Moving in the Same Direction (%)
May	75.00	33.33	74.11	112.42
June	53.85	46.15	76.42	175.89
July 3-6	33.33	0	69.22	N/A
August	50.00	66.67	104.94	127.42

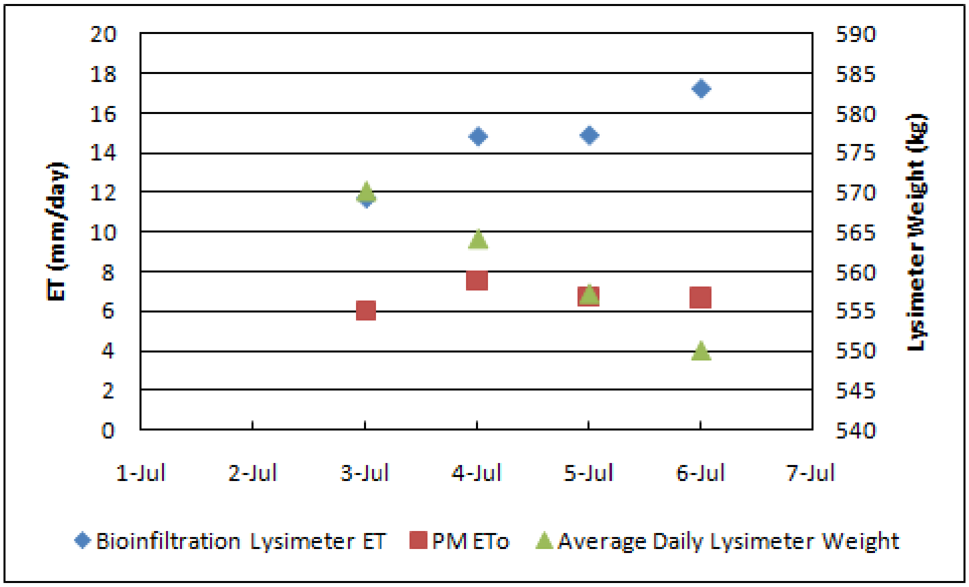

Figure 24 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight Data for Four Days during the First Week of July 2010

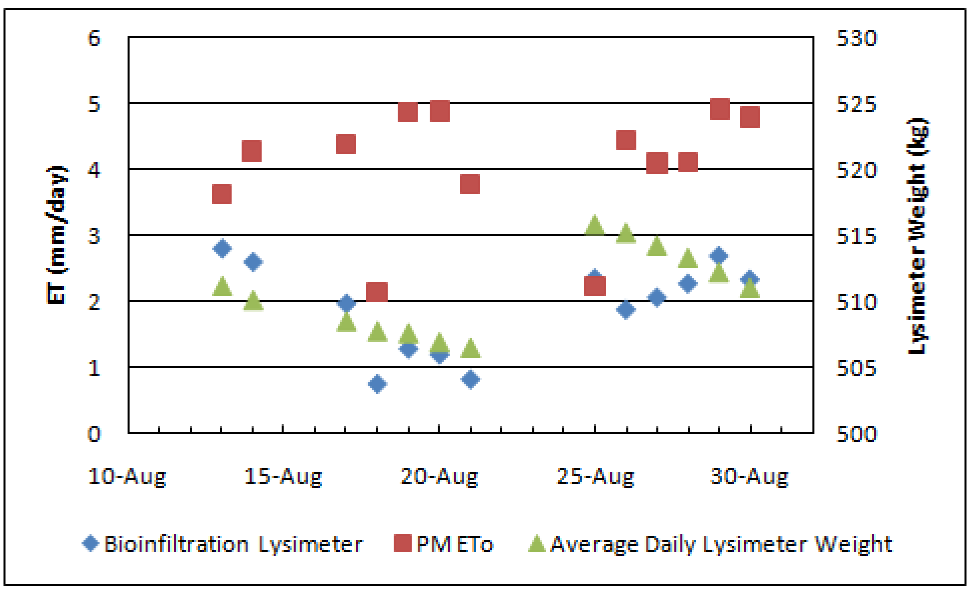

Figure 25 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight Data for August 2010

Figure 26 is a picture of the vegetation in the bioretention lysimeter during late June. The vegetation in the bioinfiltration lysimeter is similar in appearance to Figure 26, at approximately 0.75 m high, and providing a full canopy over the soil. The vegetation in both lysimeters were obtained from the same source; the bioinfiltration rain garden at Villanova University.

Figure 26 Vegetation in the Bioretention Lysimeter during Late June 2010. The Vegetation is Similar to the Vegetation in the Bioinfiltration Lysimeter

The available data for the bioretention lysimeter begins in August and goes through December 2010. Due to instrumentation troubles no storms were simulated during August and September 2010. Therefore the lysimeters dried out as the available water was evapotranspired. The reaction of the bioretention lysimeter to increasingly dry soil conditions was similar to that of an extended drought; a decrease in the rate of ET (Figure 27). Rain events occurred on August 12, over the period of August 15-16, and again on August 22-24 producing 0.76, 0.18 of rainfall, and 2.92 cm of rainfall, respectively. However, none of these events was enough to significantly increase the soil moisture in the lysimeter, and with the soil moisture so low, the climate had less of an influence on the bioretention lysimeter ET. The slope of the ET_m moves in the same direction as the slope of the average daily lysimeter weight in 75.00% of the data compared to with 41.67% of the PM ET_0 (Table 11). It is estimated that had the soil moisture conditions kept the lysimeter weight at approximately 560 kg, ET values of 15 mm/day would have been consistently observed. It is of note that the time period of late August is nearly the least that the bioretention lysimeter has ever weighed. The trend of decreasing weight continues unabated by a significant moisture input until September 11, 2010 at which the lowest point reached is 506.97 kg.

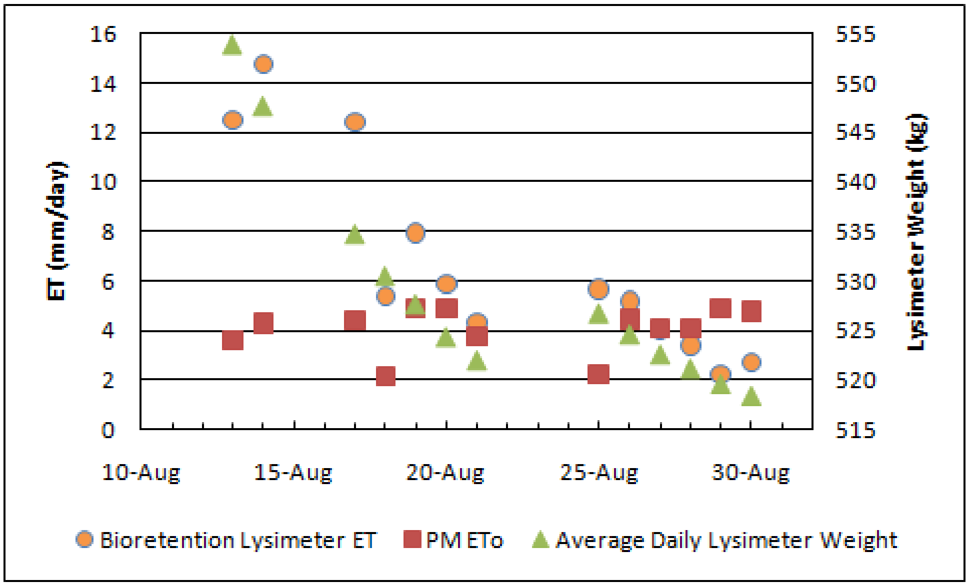

Figure 27 Bioretention Lysimeter ET, ET_0, and Average Lysimeter Weight Data for the Month of August

Table 11 Comparison of Bioinfiltration and Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weight Slope Characteristics for August

Lysimeter	Percentage of ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Percentage of ET_m and Avg. Weight Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and Avg. Weight Slopes Moving in the Same Direction (%)
Bioinfiltration	50.00	66.67	104.94	127.42
Bioretention	41.67	75.00	72.08	120.67

The bioinfiltration data compared to the bioretention data for August 2010 (Figure 28) with extreme soil moisture deficits shows that over eighteen days the lysimeters start with different ET measurements, the bioretention ET 9.68 mm/day greater than the bioinfiltration ET, but both converge to within 0.4 mm/day by the end of the month. The difference in ET_m values at the beginning of the August data set is due to the greater soil moisture stored in the bioretention lysimeter due to the IWS design. The greater available soil moisture is able to drive ET. Average K_cK_s values over the time period for the bioinfiltration lysimeter are 0.50 and 1.75 for the bioretention (Table 12). Again, the difference is due to the high ET rates measured at the beginning of the month when soil moisture within the lysimeter was much greater. By August 20 the bioretention measured ET was within close proximity of the PM ET_0 (Figure 27).

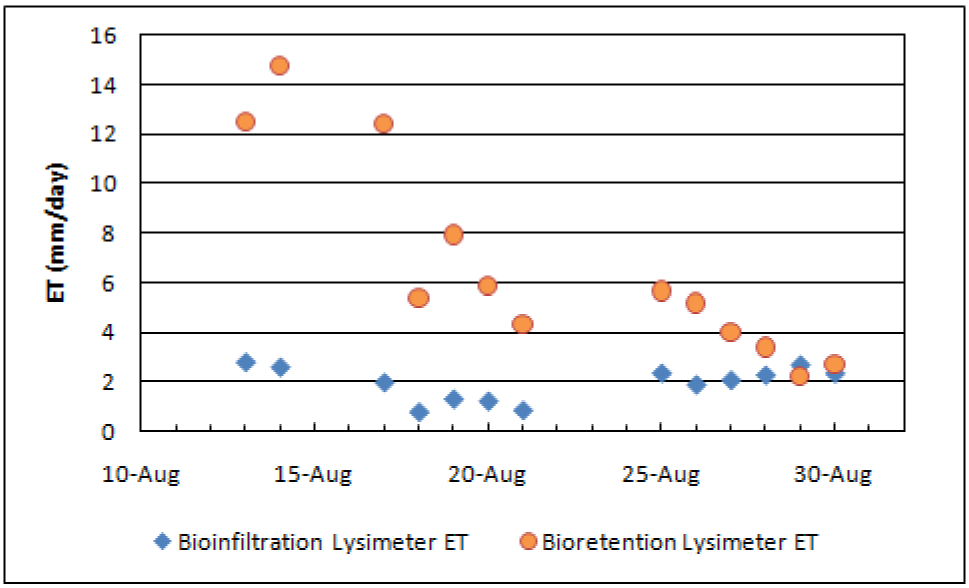

Figure 28 Bioinfiltration and Bioretention Comparison Data for August 2010

Table 12 Comparison of Bioinfiltration and Bioretention Lysimeter Data for August 2010

Lysimeter	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_cK_s	Average Daily Lysimeter Weight (kg)
Bioinfiltration	1.93	4.05	0.50	510.80
Bioretention	6.67	4.05	1.75	528.70

4.2.3 Late Season (September – October)

No storms were successfully simulated in the bioinfiltration lysimeter during September. Water was added to the lysimeters in order to salvage the vegetation which had reached the wilting point.

The bioinfiltration lysimeter (Figure 29) has observed ET that is less than the PM ET_0 in September. The daily average K_cK_s value (Table 13) is 0.27 over the course of the month. The same trend is true in the bioretention lysimeter (Figure 30) until 111 kg of water was poured into the lysimeter on September 17, taking the lysimeter from driest soil conditions on record to near its capacity. From this point forward the measured bioretention ET correlates very well with PM ET_0 with 60% of the ET_m slopes moving in the same direction as the PM ET_0 (Appendix 8). Further, all six of the ET_m data points are on average within 0.43 mm/day of the PM ET_0. The close proximity of the ET_m values with the PM ET_0 for the bioretention lysimeter near saturation agrees well with theory as the PM ET_0 equation is for a well watered reference crop experiencing no water stress (Allen et al. 1998).

Comparing the data obtained from both lysimeters over the month of September 2010 (Figure 31), the measured ET values are very similar until the bioretention lysimeter gains the 111 kg of water on September 17. From this point on, for the four data points that the lysimeters share in common (September 18-21) the bioinfiltration lysimeter averages 0.71 mm/day of ET while the bioretention lysimeter averages 3.29 mm/day. On average, both lysimeters are equally affected by the climate and available soil water (Table 14).

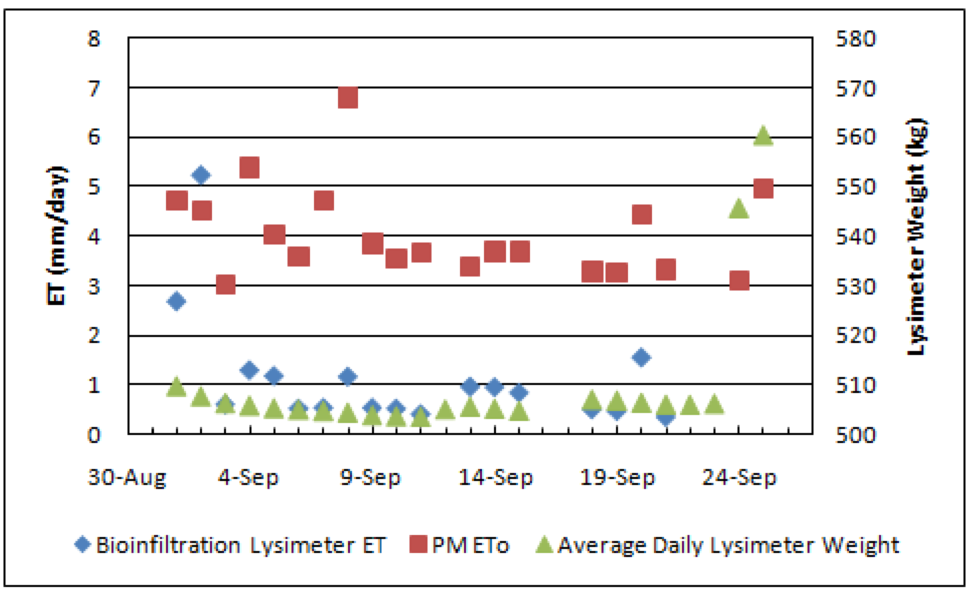

Figure 29 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight for September 2010

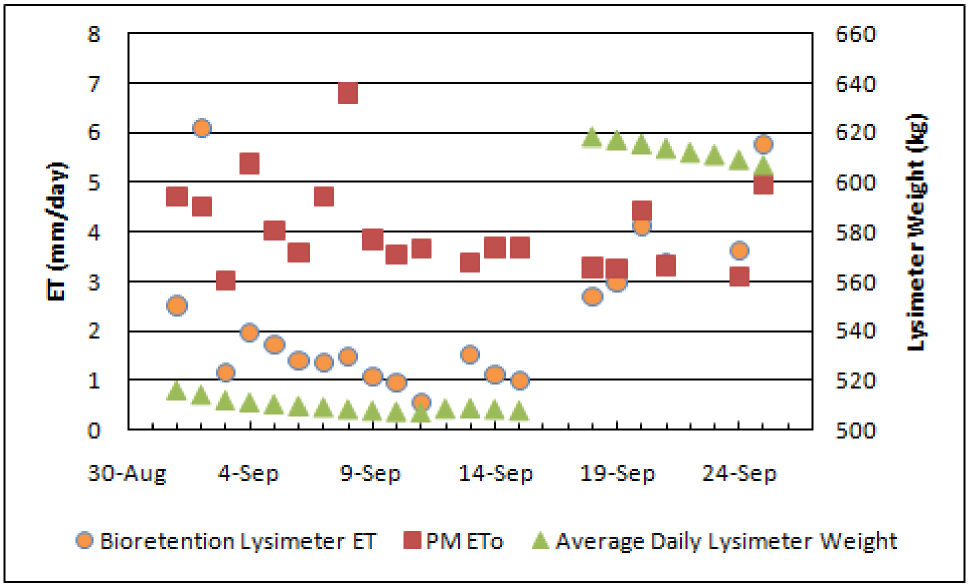

Figure 30 Bioretention Lysimeter ET, ET_0, and Average Daily Lysimeter Weight for September 2010

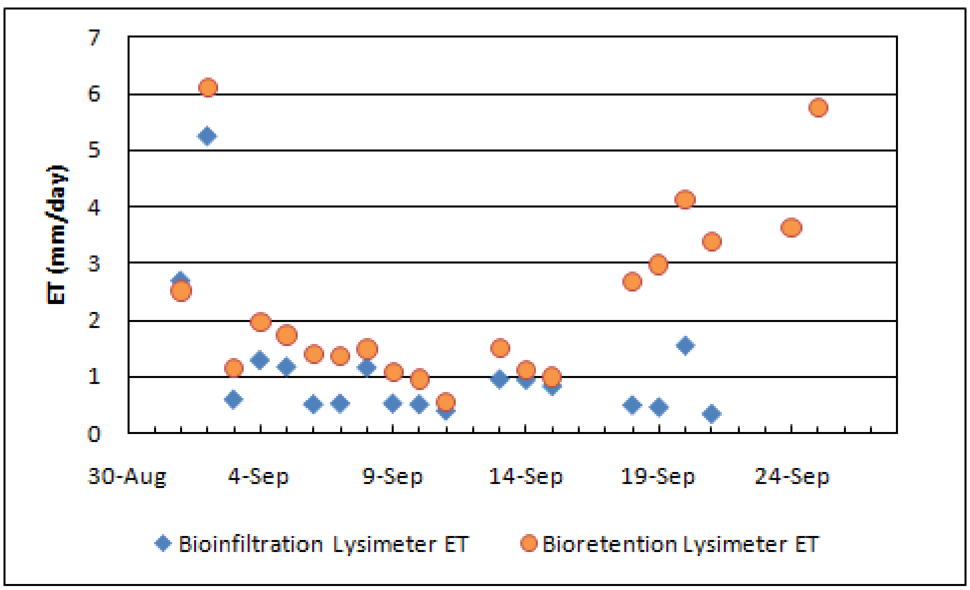

Figure 31 Bioinfiltration and Bioretention Comparison Data for the Month of September 2010

Table 13 Comparison of Bioinfiltration and Bioretention Lysimeter Data for September 2010

Lysimeter	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_cK_s	Average Daily Lysimeter Weight (kg)
Bioinfiltration	1.17	4.04	0.27	514.01
Bioretention	2.32	4.04	0.58	550.54

Table 14 Comparison of Bioinfiltration and Bioretention ET_m, PM ET_0, and Average Daily Weight Slope Characteristics for September

Lysimeter	Percentage of ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Percentage of ET_m and Avg. Weight Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and Avg. Weight Slopes Moving in the Same Direction (%)
Bioinfiltration	76.47	64.71	100.31	111.91
Bioretention	57.89	63.16	93.68	115.21

No storms were simulated during the month of October 2010. The bioinfiltration lysimeter (Figure 32) measured an average of 1.35 mm/day and the bioretention lysimeter (Figure 33) 2.53 mm/day (Table 15). The increased soil moisture within the bioretention lysimeter due to its ability to retain water compared to the bioinfiltration lysimeter with sandy soil and open infiltration created average weights at 629.18 to 564.03 kg respectively (Table 15). The ET results of the bioinfiltration lysimeter are more guided by the available soil moisture than by the climate (Table 16). However, the ET results of the bioretention lysimeter (Figure 33) display a strong guidance by the climate (Table 16), where the greatest difference between the measured ET and the PM ET_0 is 0.89 mm/day and the average difference is 0.31 mm/day. Again, the PM ET_0 values are for a hypothetical reference crop that is well watered and the bioretention lysimeter was near saturated capacity (lysimeter weight 635 kg) in October (Table 15). The saturation, due to the construction of the bioretention lysimeter allows for the ET rates to be more in line with those from the PM equation. The K_cK_s value, the ratio of ET_m to PM ET_0, is of 1.08 (Table 15).

Comparing the ET data from both lysimeters (Figure 34) reveals the same changes in slope during the beginning and end of the month with the exception being the middle, from October 21-26. During this period of data the bioinfiltration lysimeter is more controlled by available soil moisture with five out of six ET_m slopes moving in the same direction as the average daily lysimeter weight (Appendix 9), and the bioretention lysimeter ET_m is more controlled by the climate with five out of six slopes following the PM ET_0 (Appendix 9).

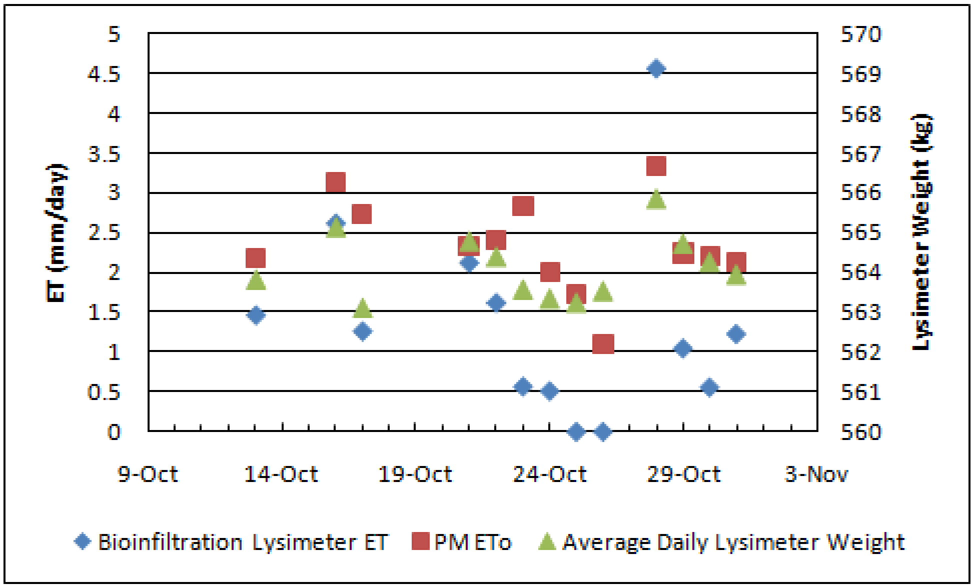

Figure 32 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight Data for October 2010

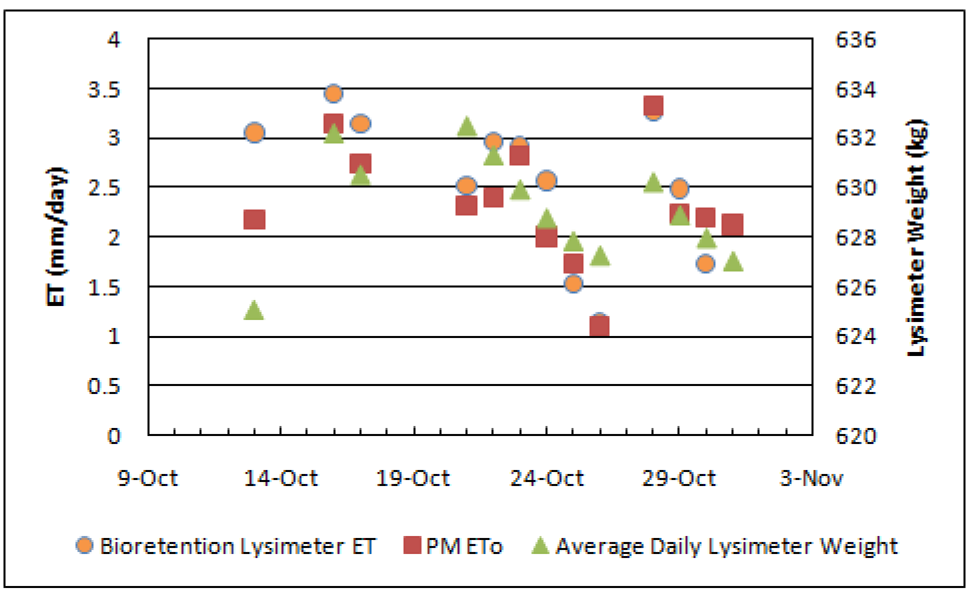

Figure 33 Bioretention Lysimeter ET, ET_0, and Average Daily Weight Data for October 2010

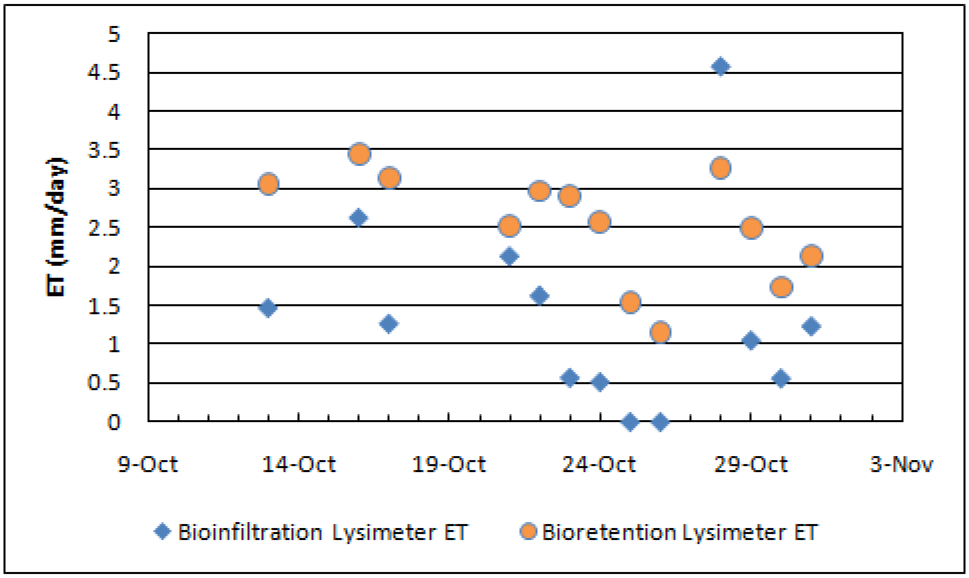

Figure 34 Bioinfiltration and Bioretention Comparison Data for the Month of October 2010

Table 15 Comparison of Bioinfiltration and Bioretention Lysimeter Data for October 2010

Lysimeter	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_cK_s	Average Daily Lysimeter Weight (kg)
Bioinfiltration	1.35	2.33	0.61	564.03
Bioretention	2.53	2.33	1.08	629.18

Table 16 Comparison of Bioinfiltration and Bioretention ET_m, PM ET_0, and Average Daily Weight Slope Characteristics for October

Month	Percentage of ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Percentage of ET_m and Avg. Weight Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and Avg. Weight Slopes Moving in the Same Direction (%)
Bioinfiltration	58.33	83.33	100.99	76.74
Bioretention	83.33	75.00	76.31	131.79

4.2.4 Senescence (November and December)

Simulated storm loading resumed in November. Storms were simulated in both lysimeters (Figures 35 and 36) on November 10, 13, and 22. Rain events took place on November 4, 16-18, 25-26, and 30. The ample soil moisture conditions in both lysimeters are conducive to prediction by the PM ET_0, with the average daily K_cK_s values (Table 17) at 1.35 and 1.09 for the bioinfiltration and bioretention lysimeters, respectively. The bioinfiltration lysimeter ET_m is guided more by the soil moisture than the climate as the ET_m follows the same direction as the average daily lysimeter weight in 87.50% of the data (Table 18). The bioretention lysimeter is guided more by the climate than the soil moisture with the ET_m changing direction with the PM ET_0 in 81.25% of the data. The average daily difference between the bioinfiltration measured ET and the PM ET_0 is 1.05 mm/day. The average daily difference between the bioretention measured ET and the PM ET_0 is 0.44 mm/day. The measured ET from both lysimeters (Figure 37), with each being near to the PM ET_0, yield similar values. The average daily difference in ET measured from both lysimeters over the month of November 2010 is 0.89 mm/day. The average daily PM ET_0 dropped to 1.47 mm/day during this time of year (Table 17). The bioinfiltration lysimeter measured an average daily ET of 1.71 mm/day compared to 1.47 mm/day measured by the bioretention lysimeter (Table 17).

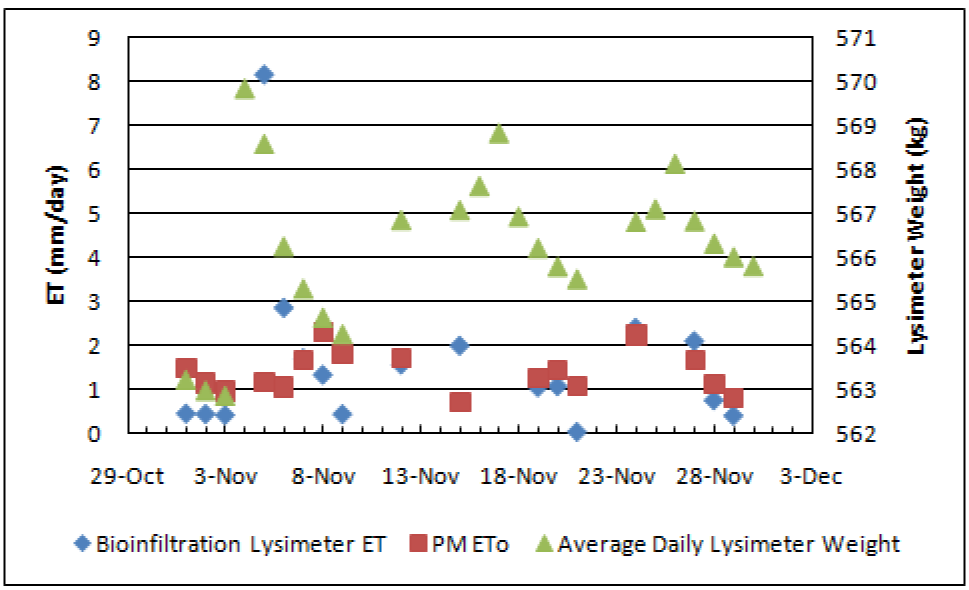

Figure 35 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight for November 2010

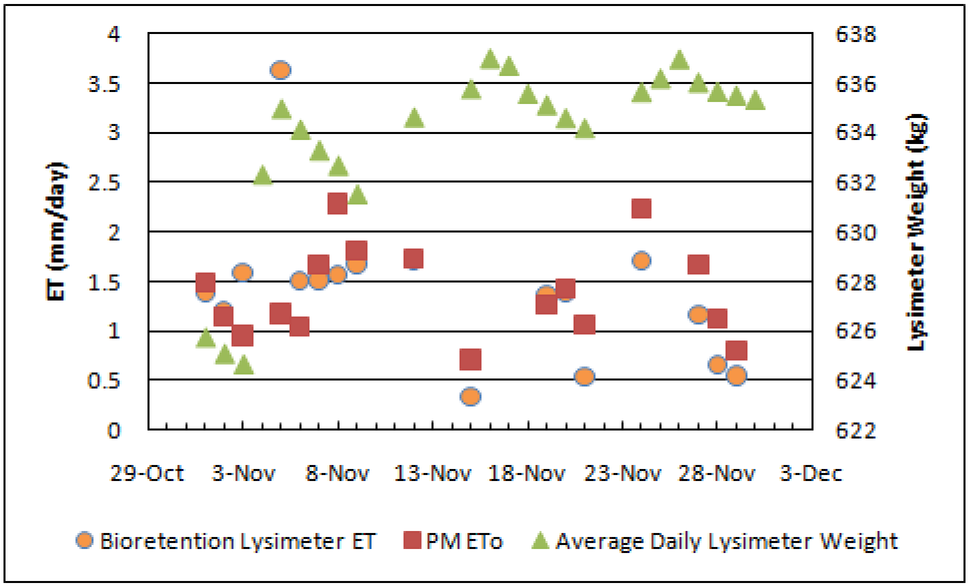

Figure 36 Bioretention Lysimeter ET, ET_0, and Average Daily Lysimeter Weight for November 2010

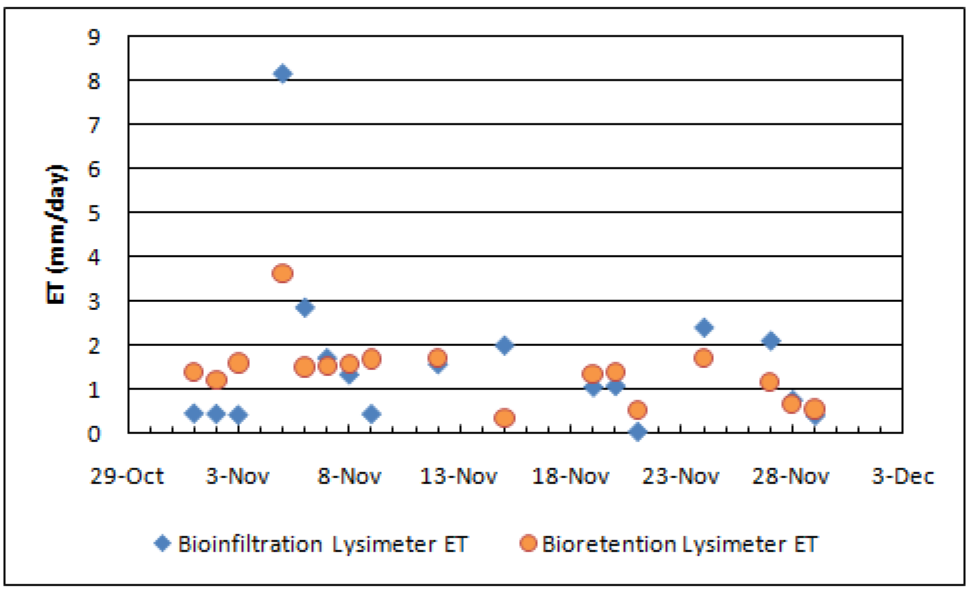

Figure 37 Bioinfiltration and Bioretention Comparison Data for the Month of November 2010

Table 17 Comparison of Bioinfiltration and Bioretention Lysimeter Data for November 2010

Lysimeter	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_cK_s	Average Daily Lysimeter Weight (kg)
Bioinfiltration	1.71	1.47	1.35	566.22
Bioretention	1.47	1.47	1.09	633.74

Table 18 Comparison of Bioinfiltration and Bioretention ET_m, PM ET_0, and Average Daily Weight Slope Characteristics for November

Lysimeter	Percentage of ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Percentage of ET_m and Avg. Weight Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and Avg. Weight Slopes Moving in the Same Direction (%)
Bioinfiltration	68.75	87.50	112.85	68.39
Bioretention	81.25	50.00	92.03	98.12

Storms were simulated December 3, 9, and 31. Precipitation events occurred on the 12-13, 16, 26-27. The tipping bucket rain gauge outflow measurement for the bioinfiltration lysimeter is located at the bottom of the 1.83 m deep concrete well that houses the lysimeter. Although temperatures were dropping below the freezing point of water for every day that ET was measured, the concrete well provided insulation from the ambient air temperature, keeping the tipping bucket rain gauge from freezing until December 26. On December 26 and 27 rain events occur and no outflow is measured although soil moisture conditions within the bioinfiltration lysimeter are such that infiltration should be present. Infiltration data returns on December 29 (Appendix 11) and continues until the end of the time period used to measure ET from the simulated storm loading on December 31, 2010. It is due to the freezing of the outflow measurement device, and the relatively little ET that occurs during extreme cold weather, that the months of January and February are not investigated for 2010 or 2011.

The average daily PM ET_0 for the month is 1.06 mm/day (Table 19), which is greater than the ET measured from each lysimeters (Figures 38 and 39). The average daily K_cK_s values are 0.67 and 0.56 for the bioinfiltration and bioretention lysimeters respectively. The ET values measured from both lysimeters (Figure 40) are very near each other despite being less than the PM ET_0. The bioinfiltration lysimeter is more influenced by the climate than the soil moisture, and conversely the bioretention is more influenced by the available soil moisture (Table 20). The average daily difference between ET measured from both lysimeters is 0.33 mm/day.

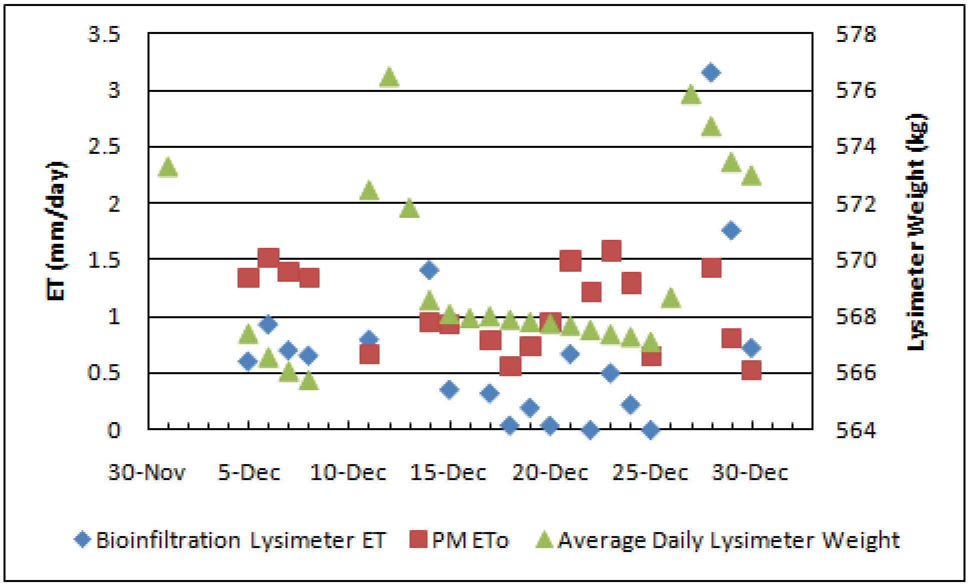

Figure 38 Bioinfiltration Lysimeter ET, ET_0, and Average Daily Lysimeter Weight for December 2010

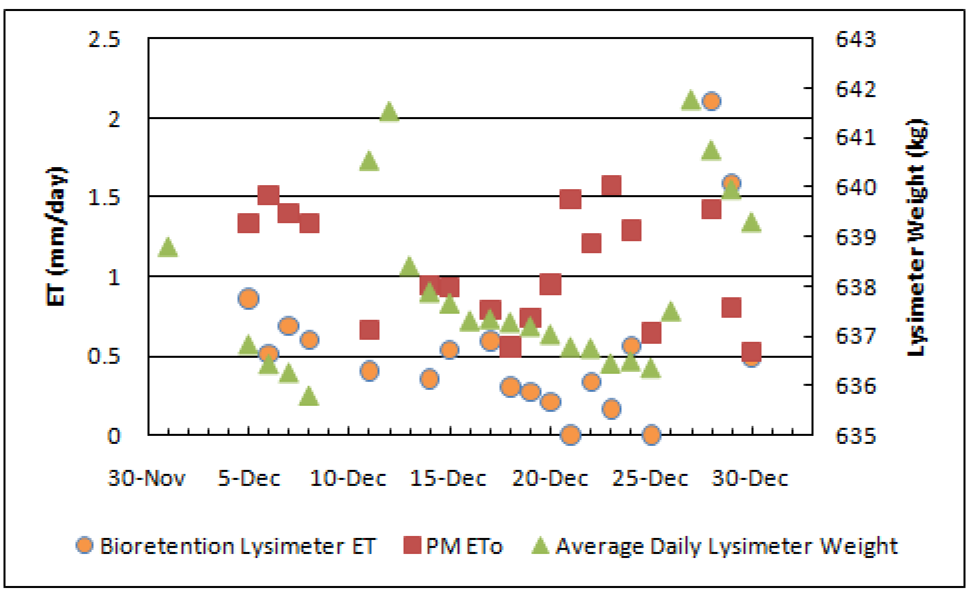

Figure 39 Bioretention Lysimeter ET, ET_0, and Average Daily Lysimeter Weight for December 2010

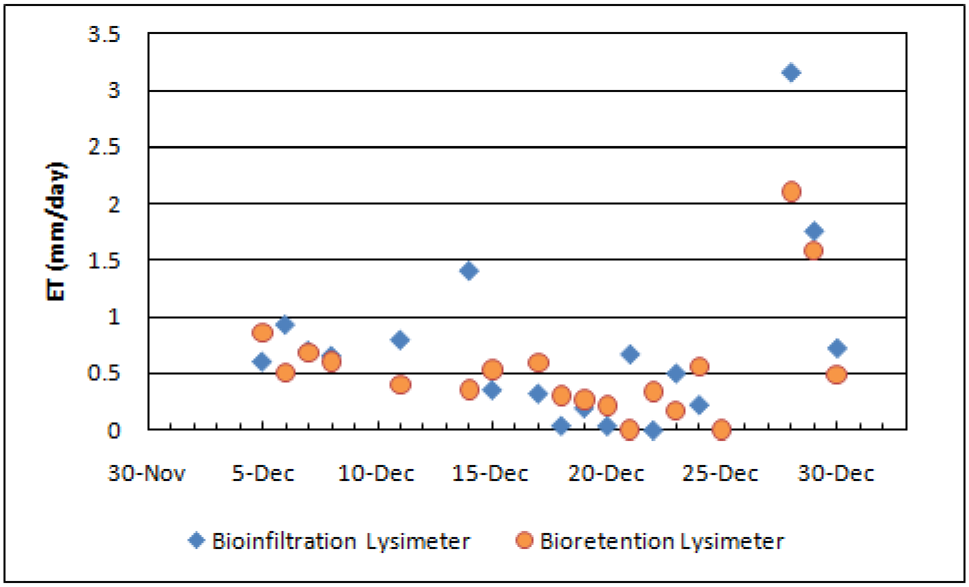

Figure 40 Bioinfiltration and Bioretention Comparison Data for the Month of December 2010

Table 19 Comparison of Bioinfiltration and Bioretention Lysimeter Data for December 2010

Lysimeter	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_c	Average Daily Lysimeter Weight (kg)
Bioinfiltration	0.69	1.06	0.67	569.56
Bioretention	0.56	1.06	0.56	637.93

Table 20 Comparison of Bioinfiltration and Bioretention ET_m, PM ET_0, and Average Daily Weight Slope Characteristics for December

Month	Percentage of ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Percentage of ET_m and Avg. Weight Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and PM ET_0 Slopes Moving in the Same Direction (%)	Average Percent Difference between ET_m and Avg. Weight Slopes Moving in the Same Direction (%)
Bioinfiltration	88.88	72.22	17.54	19.39
Bioretention	38.88	81.25	14.57	27.65

4.2.5 Summarized Lysimeter Data Resulting from Direct Rainfall

The summarized data for the ET resulting from direct rainfall obtained from the bioinfiltration lysimeter for March through December 2010 (Table 21 and Figure 41) yields a bell curve for both the measured ET and PM ET_0 data that peaks in July. In general the PM ET_0 is greater than the lysimeter ET March through May, less than the lysimeter ET during June and July, greater than the ET_m in August through October, and then more closely predicts November and December. The ability of the PM ET_0 to predict the ET_m is reflected in the average daily K_cK_s values (Table 21), which are the ratio of lysimeter measured ET to the predicted PM ET_0 (Equation 7). A value of 1 would indicate exact daily average prediction by the PM ET_0. The closest predictions of the lysimeter ET by the PM ET_0 occurred in May, October, November, and December. The K_cK_s values computed for these months are 0.72, 0.61, 1.35, and 0.67 respectively. The percent differences between the measured ET and the PM ET_0 for May, October, November, and December are 39, 53, 15, and 42% respectively. The nearest prediction occurred in November, where the K_cK_s of 1.35 was calculated, but the measured and predicted ET had only a 15% difference.

It should be noted that, due to datalogger battery problems, the available data for the month of July is limited to four days at the beginning of the month. It is estimated however, that this month would have remained the peak of the measured ET data and that the general bell curve of the data would have remained the same if more July data would have been available, only the peak may have been lower with more data to average. The assumption seems appropriate due to the removal of large amounts of water from the lysimeter during the month of July. The average daily lysimeter weight for the four days of July (Table 21) is 560.40 kg yet the average drops in August to 510.80 kg (Figure 25). Further, three storms were simulated on July 1, 7, and 22, with the last storm simulation bringing the peak lysimeter weight up to 570.76 kg. For the lysimeter to have lost this water from July 22 to August 13 an average ET rate of 5.72 mm/day would be required. Considering the ET_m averages to 8.30 mm/day over July and August this appears to be a reasonable assumption.

The average daily bioinfiltration lysimeter weight during each month remained mostly between 564.03 and 571.06 kg (Table 20 and Figure 30) indicating a fairly constant soil moisture condition within the lysimeter, that hovers above the wilting point indicated on the SWCC (Figure 16). The exceptions are for three months during July, August, and September, particularly August and September, where no storm loadings were performed. Here the lysimeter was in extreme soil moisture deficit and limits the amount of ET that occurs. The PM ET_0 indicates conditions favorable to ET with average daily values of 4.05 and 4.04 mm/day for August and September, respectively (Table 21). Naturally occurring precipitation in amounts only falling on the lysimeter were not enough to maintain the soil moisture within the lysimeter against the ET rates present. It is speculated that had the soil moisture conditions within the lysimeter been similar to those during June, the average ET rate for the month of August would have been closer to the June value. Similarly, if the soil moisture conditions during September had been near the May level then the ET rates measured during September would have more closely resembled May. More constant available soil moisture would have created a smoother bell curve within the overall yearly data.

Table 21 Bioinfiltration Lysimeter Data March through December of 2010

Month	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Coefficient K_cK_s	Average Daily Bioinfiltration Lysimeter Weight (kg)
March	0.82	2.94	0.28	570.93
April	1.16	4.14	0.29	569.05
May	3.01	4.49	0.72	571.06
June	8.55	4.99	1.81	565.15
July 3-6	14.67	6.75	2.17	560.40
August	1.93	4.05	0.50	510.80
September	1.17	4.04	0.27	514.01
October	1.35	2.33	0.61	564.03
November	1.71	1.47	1.35	566.22
December	0.69	1.06	0.67	569.56

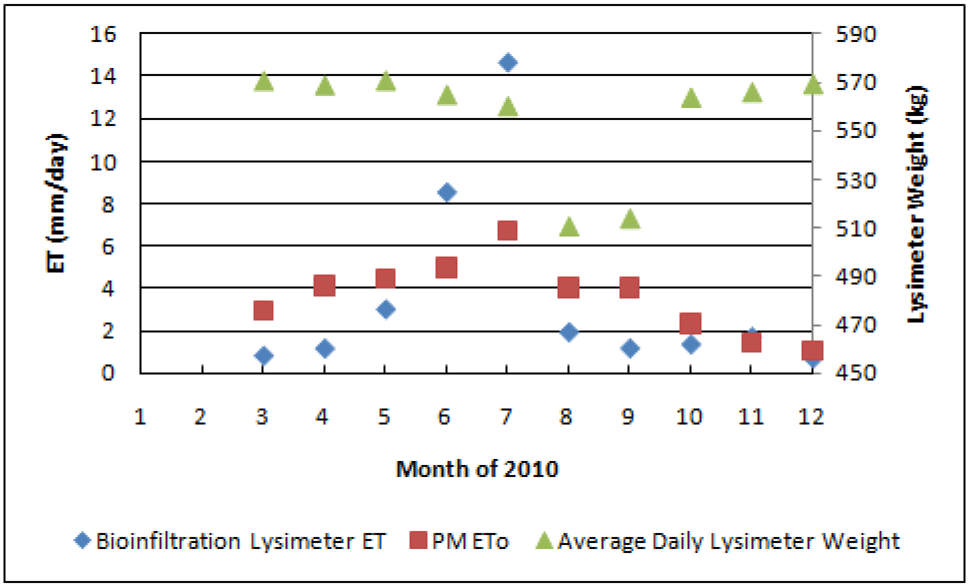

Figure 41 Bioinfiltration Lysimeter ET Performance Compared to ET_0 and Average Daily Lysimeter Weight for 2010

For the bioretention lysimeter (Table 22 and Figure 42), the PM ET_0 equation is less than the measured ET in August, greater than September, almost equal to in October and November, but greater than December. The same information is reflected in the K_cK_s values (Table 22). The average daily K_cK_s value in August was found to be 1.75, in September 0.58, October 1.08, November 1.09, and December 0.56. The closest predictions of the ET_m by the PM ET_0 were in October and November where the percent difference of the average daily measured ET and the average daily predicted ET were 8 and 0%.

The average daily bioretention lysimeter weight increased progressively throughout the five months of data. August and September were months of extreme soil moisture deficit, however October through December represent essentially maximum soil moisture conditions. Three storm loading simulations in November keep the soil in the lysimeter saturated for longer, explaining the increase in average daily lysimeter weight between October and November. The maximum bioretention lysimeter weight that is achieved during both of those months is roughly 635 kg. There is cooling between October and November during which the highs were 12.7 to 21.4ºC and the lows reach 3.5 to 16.0ºC in October compared to highs of 5.5 to 18.0ºC and lows of -3.4 to 7.1ºC in November. Yet this trend is not as drastic as that between November and December where the December highs range from -4.0 to 8.0ºC and the lows between -9.1 to -2.1ºC.

During December, similar to November, there were three storm simulation events that kept the lysimeter soil saturated, but the average daily lysimeter weight in December is greater than that of November. Also interesting to note is the fact that the maximum weight achieved after the simulated storm loadings generally increases with decreasing temperature. For example, of the three storm loadings during November, which took place on November 10, 13, and 22, the average temperature for the day was 10.05, 9.23, and 9.64ºC respectively. Also the peak weight reached after filling the lysimeter to capacity, which was the method of storm simulation for the bioretention lysimeter, was 635.94, 636.39, and again 636.39 kg on November 10, 13, and 22 respectively. The average temperatures during the December storm loadings on December 3, 9, and 31, were 1.32, -4.05, and 1.95ºC respectively. The lysimeter weight at capacity during these temperatures was 637.30, 640.47, and 648.64 kg respectively. The last date, December 31, was a warm day after a two week period of consistent cold where the highs ranged from -4.4 to 4.0ºC and the lows from -2.3 to -9.1ºC. It is conjectured that this decrease in temperature increased the density of water within the bioretention lysimeter soil causing an increase in the maximum lysimeter weight at capacity, and is also the cause of the increased daily averaged weight for the month of December.

Table 22 Bioretention Lysimeter Data August through December of 2010

Month	Average Daily Bioretention Lysimeter ET (mm/day)	Average Daily Penman-Monteith ET_0 (mm/day)	Average Daily Crop Coefficient K_cK_s	Average Daily Bioretention Lysimeter Weight (kg)
August	6.67	4.05	1.75	528.70
September	2.32	4.04	0.58	550.54
October	2.53	2.33	1.08	629.18
November	1.47	1.47	1.09	633.74
December	0.56	1.06	0.56	637.93

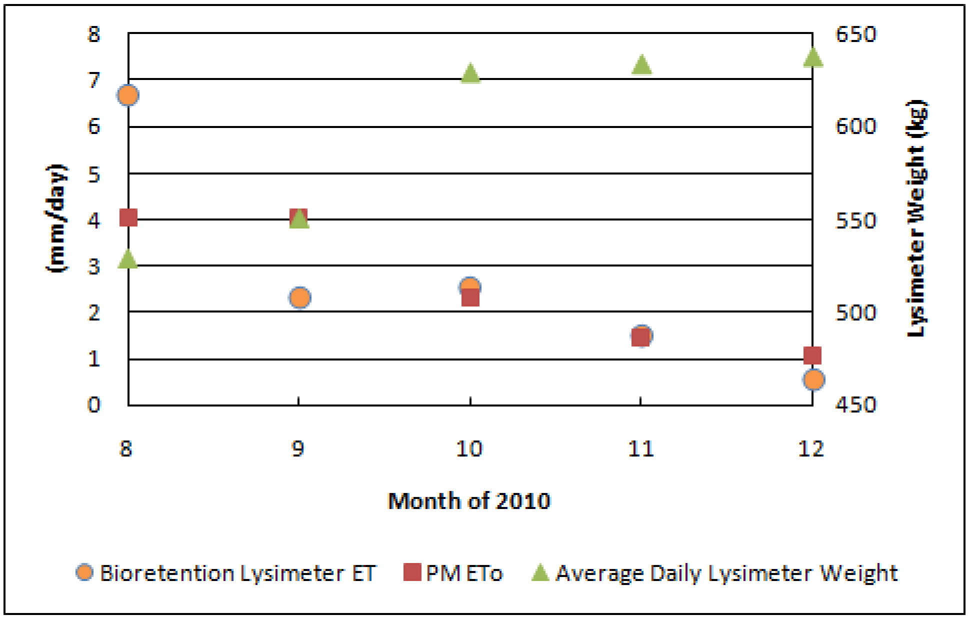

Figure 42 Available Bioretention Lysimeter ET Performance Compared to ET_0 and Average Daily Lysimeter Weight for 2010

The ET measurement obtained from the bioinfiltration and bioretention lysimeter for the months of August to December were similar (Figure 43). During months with climatic conditions that are more conducive to ET, the bioretention lysimeter produced greater average daily ET rates. During November and December when the PM ET_0 dropped to 1.47 and 1.06 mm/day, respectively, the lysimeters performed essentially the same. The increased performance of the bioretention lysimeter over the bioinfiltration lysimeter is due to more soil moisture in the bioretention lysimeter. Analysis of the daily averaged lysimeter weights for the months of August to December for each lysimeter (Tables 21 and 22) reveal a consistently greater bioretention soil moisture. The increased soil moisture is due to both the liner and upturned elbow that keeps water stored in the IWS layer until that reservoir is used by ET.

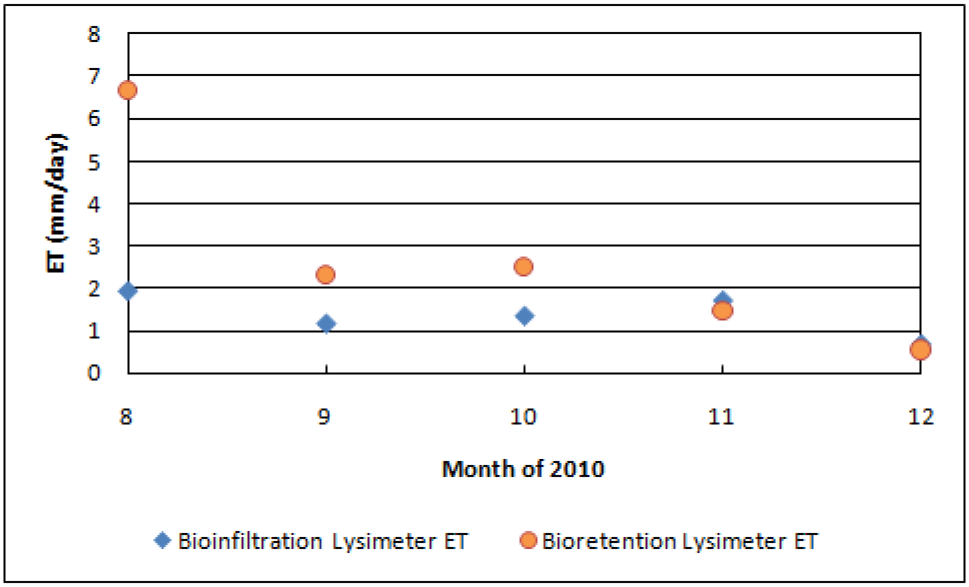

Figure 43 Comparison of Bioinfiltration and Bioretention Lysimeter Data for 2010

The K_cK_s values obtained for both lysimeters (Table 23 and Figure 44) show no direct relationship between each other. The lack of relationship is due to the difference in ET measured in each lysimeter in relation to the PM ET_0. The lysimeters were both identical in all aspects except for the soils and the ability, or lack of, to drain water. The water storage created by the liner and upturned elbow in the bioretention lysimeter kept the soil moisture available for ET longer than in the bioinfiltration lysimeter, where the high sand content and open drainage removed water quickly. The greater amount of available water in the soil produced greater than or roughly equal amounts of ET in the bioretention lysimeter compared to the bioinfiltration lysimeter in all of the available data for 2010 (Figure 43), also the bioretention lysimeter average daily K_cK_s values are always greater or essentially equal to the bioinfiltration lysimeter (Table 23 and Figure 44). The K_cK_s values for November seem to break this trend at first glance, however the higher K_cK_s for the bioinfiltration lysimeter is due to the small daily ET measurements divided into the small daily PM ET_0 during this month. When such values are inserted into Equation 7, slight differences create larger fluctuations in percentages. For example, the average daily ET measured in November was 1.71 mm/day from the bioinfiltration lysimeter compared to 1.47 mm/day from the bioretention lysimeter. The difference is small, 0.24 mm/day, yet the daily K_cK_s values are 1.35 and 1.09 for the bioinfiltration and bioretention lysimeters respectively, a difference of 0.26.

Table 23 K_cK_s Value Comparison for Bioinfiltration and Bioretention Lysimeters

Month	Bioinfiltration Average Daily Crop Coefficient K_cK_s	Bioretention Average Daily Crop Coefficient K_cK_s
August	0.50	1.75
September	0.27	0.58
October	0.61	1.08
November	1.35	1.09
December	0.67	0.56

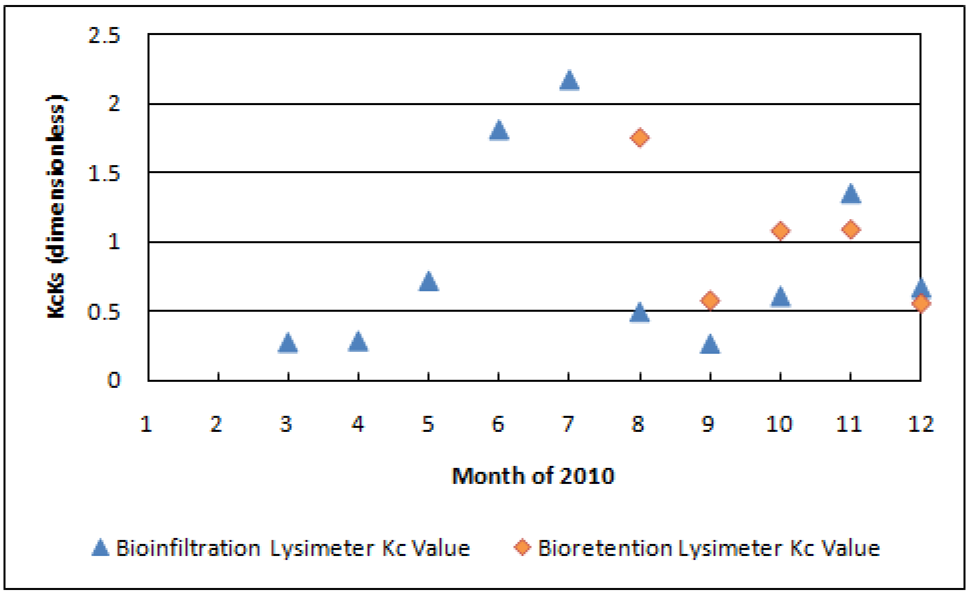

Figure 44 Comparison of K_cK_s Values between Bioinfiltration and Bioretention Lysimeters for the Year of 2010

As the bioretention lysimeter did not begin to collect data until August, the bioinfiltration lysimeter was the only lysimeter from which to compare K_cK_s values to known crop K_c values. Due to agricultural water resource management being more of an issue in drier climates, there is not a lot of available research into ET and K_c values in humid continental climates such as Pennsylvania (Allen et al. 1998). Therefore, the K_cK_s values obtained from the bioinfiltration lysimeter are compared to known crop coefficients in subhumid environments (Table 24). The four crops that are the most similar to those measured in the bioinfiltration lysimeter are sugar beet, sugar cane, cereals, and cotton. A complete list of crops in a subhumid environment is found in Appendix 1.

The bioinfiltration and bioretention lysimeters housed vegetation that was approximately 0.75 m. Of the four crops with similar K_c values, sugar beet is chosen as the most representative of these crops as it has an average crop height of 0.5 m compared to the sugar cane with an average height of 3 m. The cereal crops such as barley, oats, and spring wheat are given a crop height of 1 m but do not have late season K_c values as high as those measured in the bioinfiltration lysimeter. Cotton produces K_c values that are very similar to the bioinfiltration lysimeter but has a crop height of 1.2-1.5 m.

Table 24 Season Averaged K_cK_s Values for the Bioinfiltration and Bioretention Lysimeters Compared to Known Crop K_c Values (Allen et al. 1998)

	Early Season (Spring)	Mid Season (Summer)	Late Season (Fall)
Bioinfiltration Lysimeter	0.29	1.30	0.74
Bioretention Lysimeter	Unavailable	Unavailable	0.92
Sugar Beet	0.35	1.20	0.70
Sugar Cane	0.40	1.25	0.75
Cereals	0.30	1.15	0.4
Cotton	0.35	1.15-1.20	0.50-0.70

4.3 Storm Simulations

Storm events were simulated in the bioinfiltration lysimeter in the morning (Table 25) and evening (Table 26) of summer 2010, and in the morning of late fall 2010 (Table 27). As bioinfiltration and bioretention basins receive stormwater runoff from surrounding impervious area, in typical loading ratios of 5:1 or greater (impervious area to basin area), these storms were simulated in 5:1 and 10:1 loading ratios to more accurately mimic field conditions. The resulting ET measurements are compared to the PM ET_0, the resulting K_cK_s values, and to the soil moisture conditions within the lysimeter.

Table 25 Results for Summer Morning Storm Simulations

mm Storm	Loading Ratio	ET_m (mm)	Infiltration (mm)	ET_0 (mm/day)	K_cK_s	Initial Weight (kg)	Maximum Weight (kg)
13	5:1	31.5	0.0	5.6	5.61	545.9	570.7
19	5:1	9.3	39.9	5.3	1.75	569.3	597.1
25	5:1	10.3	42.4	4.9	2.11	562.2	597.9
13	10:1	6.9	50.6	4.6	1.49	570.9	599.4
19	10:1	4.4	69.2	4.8	0.91	547.0	604.7
25	10:1	4.4	83.9	4.7	0.94	571.5	615.0

Table 26 Results for Summer Evening Storm Simulations

mm Storm	Loading Ratio	ET_m (mm)	Infiltration (mm)	ET_0 (mm/day)	K_cK_s	Initial Weight (kg)	Maximum Weight (kg)
13	5:1	5.9	21.7	4.9	1.20	572.8	587.1
19	5:1	2.6	30.7	3.5	0.75	569.5	586.8
25	5:1	4.5	57.4	5.6	0.81	578.7	603.1
13	10:1	9.5	17.3	4.0	2.38	539.1	580.6
19	10:1	10.3	57.0	5.2	1.98	562.1	603.5
25	10:1	14.3	68.0	6.3	2.27	554.7	608.3

Table 27 Results for Late Fall Storm Simulations

mm Storm	Loading Ratio	ET_m (mm)	Infiltration (mm)	ET_0 (mm/day)	K_cK_s	Initial Weight (kg)	Maximum Weight (kg)
13	5:1	0.9	No Data	1.2	0.76	<568.3[1]	>573.7[2]
19	5:1	5.3	41.7	0.9	5.69	565.1	589.9
25	5:1	0.3	61.6	0.5	0.51	572.7	617.2
13	10:1	1.8	46.0	0.7	2.45	565.5	595.7
19	10:1	3.2	62.9	1.0	3.13	566.3	597.9
25	10:1	7.3	64.3	1.7	4.40	563.8	601.1

[1]There is gap in the data record. The value listed is the weight 14 hours before loading.
[2]Value is the maximum weight 6 hours after what would be the actual peak weight.

The ET_0 and ET_m (Figure 45) for the bioinfiltration lysimeter are positively correlated for the summer storm simulations ($R^2 = 0.63$; Figure 45) and for the late fall ($R^2 = 0.51$; Figure 46), suggesting a strong correlation between the climate represented by the Penman-Monteith equation and the measured lysimeter ET values. However, this does not completely describe the conditions that govern the measured ET. There is also a relationship between the weight of the lysimeter and the amount of ET_m (Tables 25, 26, and 27), indicating that the lysimeter soil moisture conditions have some effect on the amount of ET. The data demonstrates the strong linear relationship (R^2 = 0.97) between the total infiltration and the maximum lysimeter weight after the simulated storm loadings (Figures 47 and 48). When the maximum bucket weight during the summer storm simulations was approximately 570 kg, the lysimeter had strong soil suction and released very little water to infiltration. Conversely, when the lysimeter weight was 615 kg there was very little soil suction and the majority of added water went to infiltration (Figure 47). The relationship is altered somewhat by the colder temperatures present during the late fall storm simulations (Figure 48 and Table 27). When applying the linear equation from the summer storm simulations with R^2 = 0.97 to predict the infiltration volume from the bioinfiltration lysimeter during late fall (in order to test the applicability of the equation generated from summer on other seasons) there is an average discrepancy of 11.8 mm of water (Table 28). The linear equation underpredicts the measured infiltration from the late fall in four out of five applications. The underprediction is due to the fact that the colder temperatures promote less ET and more water infiltrates out of the lysimeter. The one instance where the equation overpredicts it does so by a large amount; 23.1 mm. The day the storm was simulated was December 31, a warm day following a two week period of cold where the highs ranged from -4.4 to 4.0ºC and the lows from -2.3 to -9.1ºC. It is conjectured that this decrease in temperature increased the density of water within the bioinfiltration lysimeter soil causing an increase in the maximum lysimeter weight at capacity, and could increase the viscosity of the water creating less infiltration than could be predicted from an equation generated from the warmer summer months.

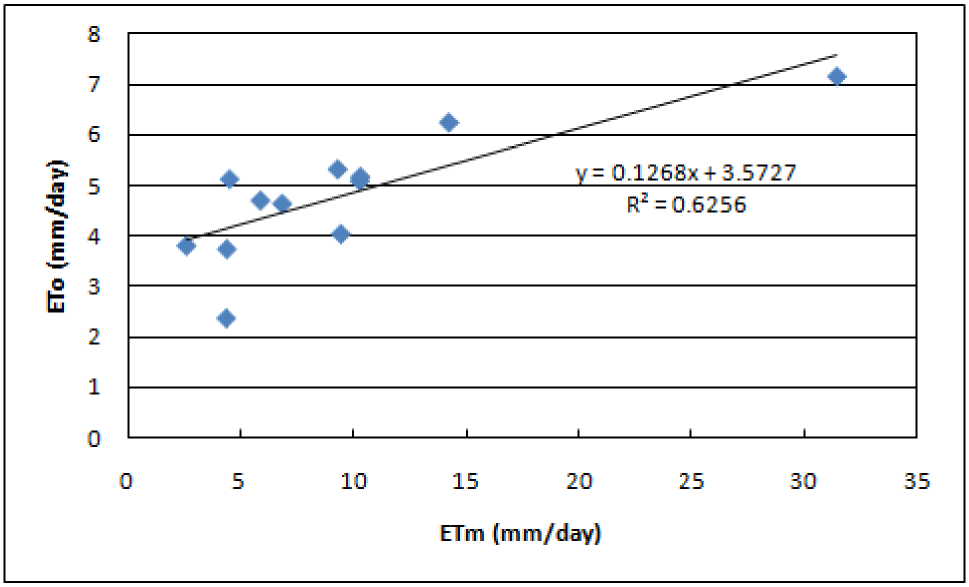

Figure 45 Bioinfiltration Lysimeter ET_0 vs. ET_m for Summer Morning and Evening Storm Simulations

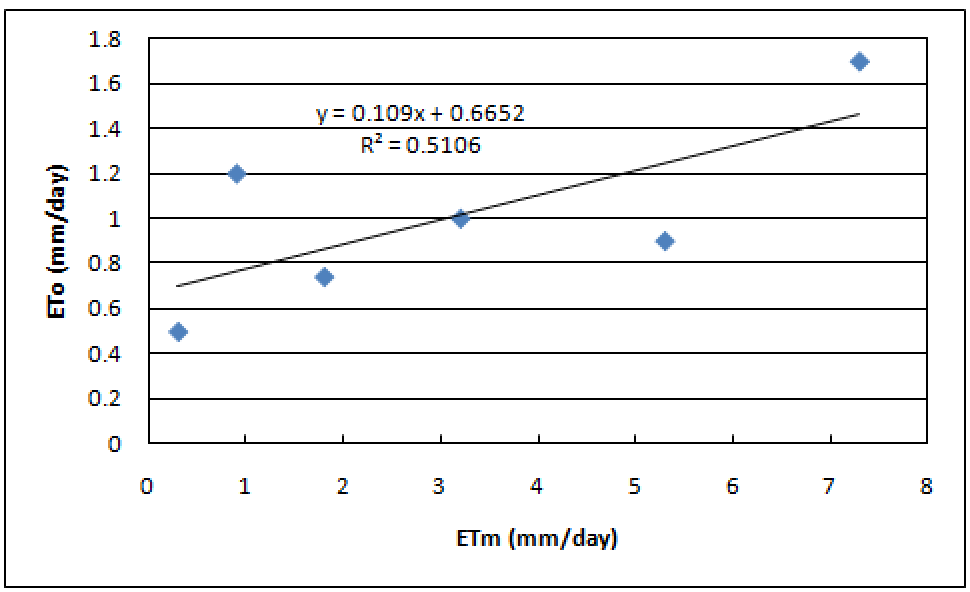

Figure 46 Bioinfiltration Lysimeter ET_0 vs. ET_m for Late Fall Storm Simulations

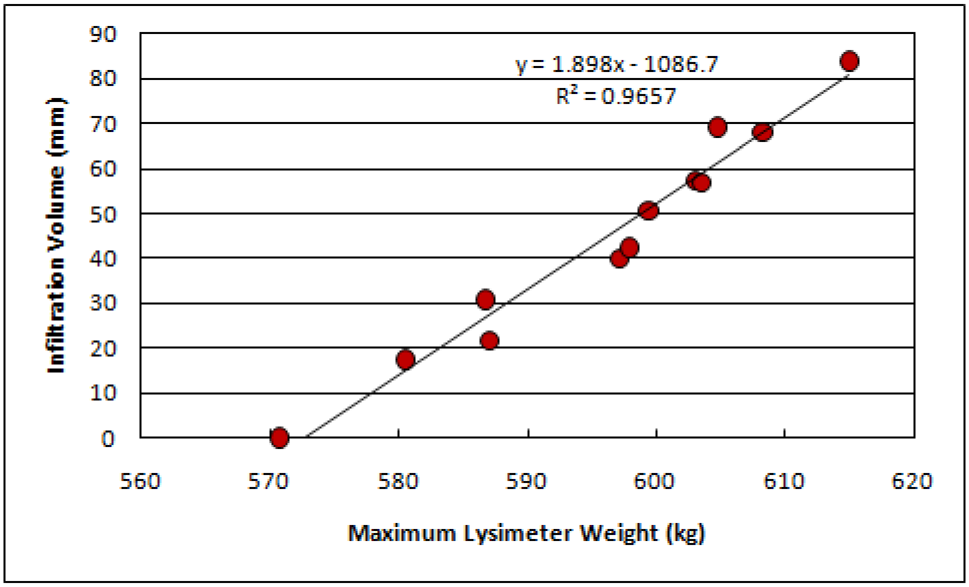

Figure 47 Infiltration Volume vs. Maximum Bioinfiltration Lysimeter Weight from Summer Morning and Evening Storm Simulations

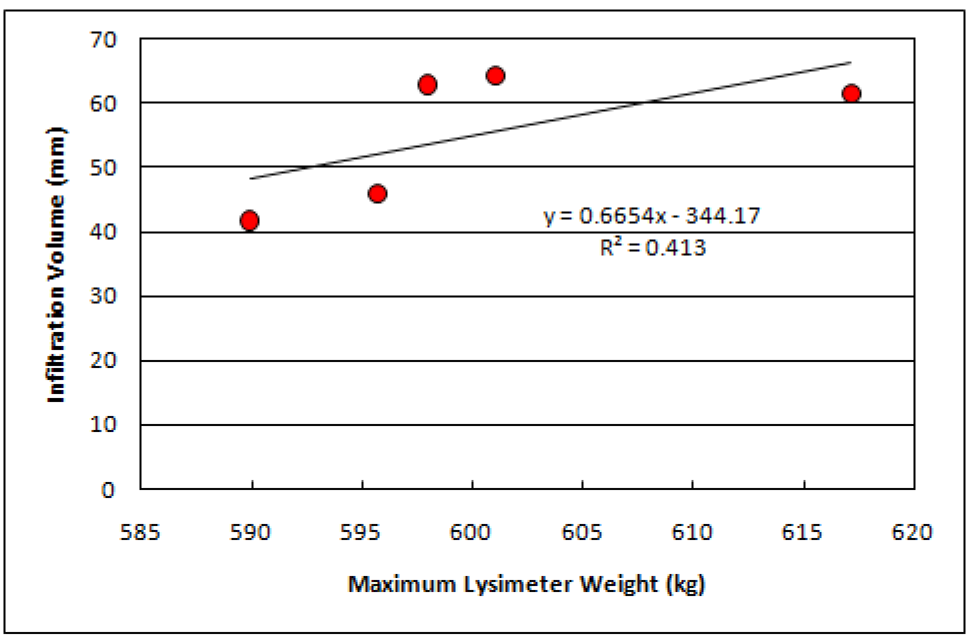

Figure 48 Infiltration Volume vs. Maximum Bioinfiltration Lysimeter Weight from Late Fall Storm Simulations

Table 28 Linear Equation from Summer Storm Simulation Maximum Lysimeter Weight to Infiltration Volume Applied to Late Fall Storm Simulations

Maximum Lysimeter Weight (kg)	Actual Infiltration Volume (mm)	y = 1.898x-1086.7 (mm)	Difference (mm)
589.92	41.7	33.0	8.7
617.17	61.6	84.7	23.1
595.70	46.0	43.9	2.1
597.94	62.9	48.2	14.7
601.07	64.3	54.1	10.2
		Average Difference	11.8

Storm events were simulated in the bioretention lysimeter by filling the lysimeter with water to capacity and measuring the resulting ET after 24 hours. The ET measured from this lysimeter (Table 29) has a strong correlation to the average temperature during the 24 hour period after storm simulation (R^2 = 0.66; Figure 49). The ET_m is also influenced by the climate parameters input into the PM ET_0 as the ET_m follows the slope of the PM ET_0 in 100% of the data (Figure 49). Here the relationship of the ET_m with the PM ET_0 agrees with theory as temperature is one of the parameters of the PM ET_0, and the PM ET_0 is for a reference crop that is not short of water (Allen et al. 1998).

Table 29 Bioretention ET from Storm Simulations during Late Fall Compared to the PM ET_0

Date	Average Temperature (ºC)	Bioretention ET (mm)	ET_0 (mm)	Difference (mm)
11-10-10	10.05	2.8	1.6	1.2
11-13-10	9.23	2.4	1.3	1.1
11-22-10	9.64	1.2	0.9	0.3
12-3-10	1.32	0.9	1.1	0.2
12-9-10	-4.05	0.5	0.6	0.1
12-31-10	1.95	0.8	0.6	0.2

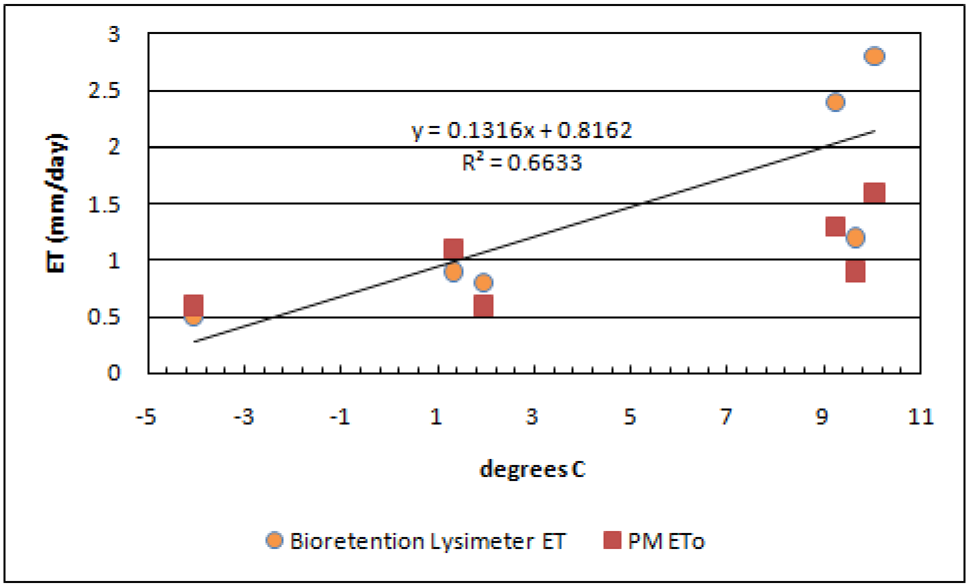

Figure 49 Trendline of Bioretention ET from Storm Simulations during Late Fall Compared and PM ET_0 vs. Temperature

4.4 Comparison of Lysimeter Performance with and without Storm Simulations

The data from storm simulations were averaged based on the months in which they took place and compared to the averaged data without storm simulations for the bioinfiltration lysimeter (Table 30) and the bioretention lysimeter (Table 31) individually. The bioinfiltration lysimeter had higher ET rates with storm simulations than without for all of the months except for June. The difference between the ET rates observed in the bioinfiltration lysimeter with and without storm simulations is minor except for during the month of November. It is estimated that this minor difference in ET rates is due to the simulations themselves providing more available soil moisture to the lysimeter. June had six storm simulations, twice as many as any other month, taking place on June 8, 11, 15, 18, 22, and 28. The repeated storm simulations had the effect of constantly recharging the soil moisture with available water for ET. Indeed after the storm simulations began the ET rates for the rest of month increased relative to before the simulations (Figure 23). November was the month most affected by the storm simulations where the ET rose from 1.7 mm/day without storm simulation to 5.3 mm/day with the simulations. The effect of the storm simulations during November could be due to the larger of the storm simulations were performed during that month and the fact that the climate was still conducive to ET.

The bioretention lysimeter ET was essentially the same with and without storm simulation due to the fact that the lysimeter soil water without simulation was already near capacity. The average daily lysimeter weights of 633.74 and 637.93 kg for the months of November and December, respectively (Table 22), are the maximum bioretention lysimeter weights on record.

Table 30 Average Bioinfiltration Lysimeter Performance with and without Storm Simulations

Month	Average Daily Bioinfiltration Lysimeter ET (mm/day)	Average Daily PM ET_0 (mm/day)	Average Daily K_cK_s	Average ET from Storm Simulation (mm/day)	Average PM ET_0 during Storm Simulation (mm/day)	Average K_cK_s from Storm Simulation
May	3.0	4.5	0.72	4.3	4.7	0.92
June	8.6	5.0	1.81	8.3	5.1	1.58
July	14.7	6.8	2.17	17.1	4.8	3.32
November	1.7	1.5	1.35	5.3	1.2	4.41
December	0.7	1.1	0.67	1.0	0.8	1.24

Table 31 Average Bioretention Lysimeter Performance with and without Storm Simulations

Month	Average Daily Bioretention Lysimeter ET (mm/day)	Average Daily PM ET_0 (mm/day)	Average Daily K_cK_s	Average ET from Storm Simulation (mm/day)	Average PM ET_0 during Storm Simulation (mm/day)	Average K_cK_s from Storm Simulation
November	1.5	1.5	1.09	2.1	1.3	1.63
December	0.6	1.1	0.56	0.7	0.8	0.97

4.5 Evapotranspiration Totals

A total of 1,019 mm of precipitation was recorded from March through December of 2010. During that period the bioinfiltration lysimeter without storm simulation lost 358 mm of water (0.16 m^3 or 160 L) to ET and 646 mm of water (0.29 m^3 or 290 L) to infiltration (Appendix 2 – 11). Fifteen mm of water is unaccounted for perhaps due to error in measurement of the tipping bucket rain gauges (used to measure precipitation and infiltration) over the course of the year. The observed ratio of ET to rain was approximately 1:3, while the observed ratio of ET to infiltration was approximately 1:2.

The low amount of infiltration is due to the low soil moisture as indicated by the lysimeter weight remaining around 570 kg throughout the year which is only slightly above the wilting point indicated on the SWCC (Figure 16).

The bioinfiltration lysimeter from storm simulations May through December lost 133 mm of water (0.06 m^3) to ET and 815 mm of water (0.37 m^3) to infiltration. The observed ratio of ET to infiltration was approximately 1:6. The higher ratio of ET to infiltration observed from storm simulations is expected to be more representative of field conditions due to the increased soil moisture brought about by an impervious drainage area loading ratio. However, the 1:6 ratio of ET to infiltration could be inaccurately skewed towards infiltration due to the manner in which the storms were simulated. Water was poured into the lysimeter in one to two minute durations every half hour for two and a half hours, in essence mimicking storms with short bursts of great intensity. Had a more even distribution of rainfall been simulated with a lower intensity over the same two and a half hours, then perhaps an ET to infiltration ratio of 1:4 or 1:5 would have been observed.

The bioretention lysimeter ET without storm simulation was measured from August through December. During that time 337 mm of precipitation was recorded and the lysimeter lost 200 mm of water to ET. By comparison, the bioinfiltration lysimeter lost 103 mm of water to ET, essentially half of the ET measured from the bioretention lysimeter. Due to the IWS creating more available soil moisture available for ET, the ET rates in the bioretention lysimeter was essentially twice that of the bioinfiltration lysimeter August through December (Tables 21 and 22).

The bioretention lysimeter was filled to capacity during November and December and subsequently lost 9 mm of water to ET. The temperature during storm simulation had decreased enough at this point in the year to limit ET (Figure 49).

4.6 Extrapolation of Bioinfiltration Lysimeter ET to the Bioinfiltration Basin at Villanova University

The bioinfiltration lysimeter was created as a microcosm of the approximately 405 m^2 bioinfiltration basin at Villanova University. The bioinfiltration lysimeter lost 358 mm of water to ET over the course of March through December 2010 without storm simulation. Applying this ET total to the area of the bioinfiltration basin yields a potential water loss of approximately 145 m^3 (145,000 L) from March through December 2010. The water loss estimation for the bioinfiltration basin could be low as the basin receives runoff from a 10:1 impervious area to basin area loading ratio. The increased soil moisture due to increased runoff could provide more available water to drive ET, particularly if the soil moisture content was low before the storm. With low antecedent soil moisture conditions within the bioinfiltration basin, the basin could effectively capture small storms and increase the ET to infiltration ratio from the 1:6 observed from storm simulations closer to the 1:3 ratio observed from natural precipitation.

Chapter 5 Conclusions

Evapotranspiration was measured from naturally occurring precipitation in the bioinfiltration lysimeter from March through December 2010. Simulated storms mimicking drainage area to lysimeter area ratios of 5:1 and 10:1 were performed in the summer (May, June, July), and in the late fall (November and December). Evapotranspiration data from natural precipitation within the bioretention lysimeter was collected mid-August to December 2010, with storms simulated during the late fall.

5.1 Lysimeter Data from Naturally Occurring Precipitation

The ET resulting from direct rainfall measured from the bioinfiltration lysimeter and the PM ET_0 calculated for March through December 2010 (Table 21 and Figure 41) both yield a bell curve that peaks in July. The PM ET_0 is greater than the lysimeter ET March through May, less than the lysimeter ET during June and July, greater than the ET_m in August through October, and then most nearly predicts November and December. The PM ET_0 most closely predicted the ET_m in May, October, November, and December. The K_cK_s values computed for these months are 0.72, 0.61, 1.35, and 0.67 respectively. The percent differences between the measured ET and the PM ET_0 for May, October, November, and December are 39, 53, 15, and 42% respectively, indicating the most reasonable prediction occurred in November.

The average daily bioinfiltration lysimeter weight during March through December 2010 remained generally consistent between 564.03 and 571.06 kg (Table 21 and Figure 41). When compared to the SWCC and infiltration data from storm simulations, the lysimeter appears to remain at a point of strong soil suction at approximately 100,000 kPa. The July ET_m is 14.67 mm/day, a rate that drains the soil moisture from the lysimeter and by August and September, when no storm simulations were performed to refill the lysimeter with larger than natural amounts of water, the lysimeter enters a period of extreme soil moisture deficit. While the PM ET_0 indicates favorable conditions for ET with calculated values of 4.05 and 4.04 mm/day for August and September, respectively, the average daily ET measured for August and September are 1.93 and 1.17 mm/day, respectively. The lack of ET from the lysimeter points to the strength of the soil suction, which inhibits the ET rate from 14.67 mm/day in July when the soil moisture brings the average daily lysimeter weight to 560.40 kg to August where the measured ET rate fell to 1.93 mm/day with an average lysimeter weight of 510.80 kg. It is conjectured that ET decreased the soil moisture content, such that the lysimeter weight neared 570 kg in August, ET rates would have been measured at approximately 6-8 mm/day closer in value to the month of June. Similarly, if the soil moisture content been near 570 kg in September, the measured ET would have been roughly 3-4 mm/day. The increased soil moisture content would have created a smoother bell curve within the overall yearly data (Figure 30).

The PM ET_0 for the bioretention lysimeter (Table 22 and Figure 42) was less than the measured ET in August, greater than September, approximately equal in October and November, and again was greater than December. The average daily K_cK_s value in August was 1.75, 0.58 in September, 1.08 in October, 1.09 in November, and 0.56 in December. The PM ET_0 most nearly resembled the measured ET in October and November where the percent difference of the average daily measured ET and the average daily PM ET_0 were 8 and 0%.

The average daily bioretention lysimeter weight increased throughout the five months of data (Table 22) indicating greater available soil moisture. While August and September were months of extreme soil moisture deficit, October through December were roughly maximum soil moisture conditions owing to storm simulations in which the lysimeter was filled to capacity in November and December. It is conjectured that the decreasing temperatures in November and December also increased the density of water within the bioretention lysimeter soil. The effect was an increase in the maximum lysimeter weight at capacity which was greatest at the end of December.

During the months in which ET was measured from both lysimeters, August through December, similar ET rates were observed. In August, September, and October, the bioretention lysimeter measured higher average daily ET rates. However, during November and December the lysimeters performed essentially the same. Greater soil moisture conditions within the bioretention lysimeter, due to the liner and IWS layer, allowed for greater sustained soil moisture that increased the ET performance over the bioinfiltration lysimeter. The increased soil moisture, likewise, had the effect of increasing the bioretention lysimeter average daily K_cK_s values relative to the bioinfiltration lysimeter except for November and December where they are essentially the same (Table 23 and Figure 44).

The bioinfiltration lysimeter was the only lysimeter from which a long enough data record was measured to compare the K_cK_s values to known crop values. Research is unavailable concerning ET and K_cK_s values in humid continental climates such as Pennsylvania (Allen et al. 1998). Therefore the K_cK_s values obtained from the bioinfiltration lysimeter are compared to known crop coefficients in subhumid environments such as grasslands and prairies. Four crops were determined to be the most similar to those measured in the bioinfiltration lysimeter; sugar beet, sugar cane, cereals, and cotton. The crop most representative of the bioinfiltration lysimeter was sugar beet chosen for its average crop height of 0.5 m, the closest to the 0.75 m vegetation within the lysimeter. The ability of the K_cK_s values to compare with known crop K_c values, through the use of the PM ET_0, demonstrates the ability of the FAO method (for the prediction of agricultural crop ET) to translate to the prediction of ET from bioinfiltration and bioretention basins. However, data from a longer time span is needed to verify the K_cK_s values obtained from this research. Further, more research is needed to separate the coefficients K_c and K_s in order to more accurately compare the lysimeter K_c values to known crop K_c values.

From March through December 2010, a total of 1,019 mm of precipitation was measured at the lysimeter site. The bioinfiltration lysimeter during that time lost 358 mm of water to ET and 646 mm of water to infiltration without storm simulation. The resulting ratio of ET to precipitation was 1:3, and the ratio of ET to infiltration was 1:2. The low ratio of ET to infiltration is due to the limited available soil moisture within the lysimeter which remained only just above the wilting point for most of March through December. The data suggests that when the antecedent soil moisture conditions are low within a bioinfiltration basin, that the basin is able to completely capture small storm events, and remove the water through a greater ET to infiltration ratio.

The bioretention lysimeter received 337 mm of precipitation from August to December, of which 200 mm of water was lost to ET. The bioinfiltration lysimeter during this time period lost 103 mm of water to ET, essentially half that of the bioretention lysimeter. The increase in ET measured from the bioretention lysimeter is due to the IWS layer providing a reservoir of available soil moisture for ET. The results indicate that bioretention basins with the IWS design provide better ET removal than bioinfiltration basins, and perform well at capturing small rain events, to the point of filling the IWS layer.

5.2 Lysimeter Data from Storm Simulations

Storms were simulated within the lysimeters to more accurately mimic field conditions in which bioinfiltration and bioretention basins receive stormwater runoff from surrounding drainage areas. The bioinfiltration lysimeter received simulations mimicking 13, 19, an 25 mm storms generating runoff from both 5:1 and 10:1 impervious area to lysimeter area ratios. These storms were simulated in the morning and evening of May through July, and November through December. During the same time as the November through December simulations in the bioinfiltration lysimeter, the bioretention lysimeter received storm simulations that filled it to capacity.

There is a positive correlation (R^2 = 0.63) between the PM ET_0 and the measured ET for the summer storm simulations (Figure 45) and the late fall (R^2 = 0.51; Figure 46), indicating a strong correlation between the climate and the measured lysimeter ET rate. There is also a strong linear relationship between the total measured infiltration and the amount of ET_m (R^2 = 0.97) after the simulated storm loadings (Figure 47). Essentially no infiltration occurred when the maximum lysimeter weight during the storm simulation was approximately 570 kg. The maximum amount of infiltration occurred when the lysimeter weight peaked at 615 kg after the storm simulation. The soil water content was great enough to reduce the soil suction, allowing for the majority of the water exit as infiltration. A soil-water characteristic curve (Figure 16) was generated for the soil in the lysimeter and compared to the infiltration results from the summer storm simulations. When the lysimeter weighed 570 kg the soil gravimetric water content was estimated at 3%, the soil suction 100,000 kPa, and very little water was allowed to leave the lysimeter through infiltration. When the lysimeter weight was 615 kg, the soil gravimetric water content was estimated to be near saturated at 23%, the soil suction to be low at 10 kPa, and the majority of the water went to infiltration.

Application of the linear equation from the summer storm simulations with R^2 = 0.97 to the late fall storm simulations in the bioinfiltration lysimeter, in order to test the accuracy of the equation on other seasonal weather conditions, generated an average discrepancy of 11.8 mm of water. The colder temperatures and lowered amount of solar radiation promote less ET and therefore greater infiltration rates, causing the equation to underpredict the infiltration in four out of five applications. The one application where the equation did overpredict, it did so by 23.1 mm, a sizable amount. The storm simulation for this event took place on December 31, an unseasonably warm day after a two week period of cold where the highs ranged from -4.4 to 4.0ºC and the lows from -2.3 to -9.1ºC. While the ambient temperature increased for December 31, the conditions within the lysimeter, which sits underground, would not have had time to warm. Therefore it is speculated that the decrease in temperature increased the density of water within the bioinfiltration lysimeter, and increased the viscosity of the water, creating less infiltration than could be predicted by an equation generated from the warmer summer months.

Storm events were simulated in the bioretention lysimeter during November and December. The lysimeter was filled to capacity and the ET measured after 24 hours. The ET measured (Table 29) has a strong correlation to the average temperature during the 24 hour period after storm simulation (R^2 = 0.66) and is influenced by the climate parameters input into the PM ET_0 (Figure 49). The data aligns with theory as temperature is one of the parameters of the PM ET_0, and the PM ET_0 is for a reference crop that is not short of water (Allen et al. 1998).

Storm simulations in the bioinfiltration lysimeter resulted in 133 mm of water lost to ET and 815 mm of water lost to infiltration. The observed ET to infiltration ratio was 1:6. The method of storm simulation created unrealistic storm intensities that had the effect of increasing the infiltration values relative to the amount of ET past what would be commonly observed in the field. It is estimated that the 1:6 ratio of ET to infiltration represents an extreme that would only result from large storm events with great intensity. Therefore it is suggested that more common ET to infiltration ratios are 1:4 to 1:5, depending on impervious drainage area, storm size, storm intensity, and surface area to depth ratios of the bioinfiltration basin.

5.3 Comparison of Data with and without Storm Simulations

The bioinfiltration lysimeter yielded higher ET rates after storm simulations in every month of comparison except for June (Table 30). As June had six storm simulations, twice as many as any other month, the soil was constantly being recharged with available soil moisture, thereby on average increasing the rate of ET during the days without storm simulations. The month of November had the largest percent increase with ET rising from 1.7 mm/day without storm simulations to 5.3 mm/day with simulations. During the late fall storm simulations, the month of November received the two largest water inputs, providing more available soil moisture to a month that still had enough of the climate factors to promote ET.

The bioretention lysimeter ET was essentially unaltered by storm simulations as the lysimeter soil water without simulation was already near capacity due to reduced ET rates in November and December. The average daily lysimeter weights of 633.74 and 637.93 kg for the months of November and December respectively (Table 21), are the most massive recorded.

The results confirm that the available soil moisture is a key component in driving ET, along with the climate. While the bioretention lysimeter loses more water to ET in August through October, during November and December the ET measured from both lysimeters was essentially the same. However, the bioretention lysimeter loses its ability to capture small storms due to the IWS remaining at capacity during November and December. Without the climate to produce the energy to drive ET, the lysimeter remains full of water, and therefore diminished in ability to accept runoff without producing outflow.

5.4 Extrapolation of Bioinfiltration Lysimeter ET to the Bioinfiltration Basin at Villanova University

The bioinfiltration lysimeter from March through December 2010 lost 358 mm of water to ET without storm simulation at an ET to precipitation ratio of 1:3 and an ET to infiltration ratio of 1:2. Extrapolation of the 358 mm ET total to the area of the bioinfiltration basin yields a potential water loss of approximately 145 m^3 (145,000 L). The results of the storm simulation yield an extreme ET to infiltration ratio of approximately 1:6, with more representative field ratios likely to be 1:4 to 1:5. Considering the potential volume of water removed through ET, and the ET to infiltration ratio range (depending on storm size from 1:2 to 1:6) it appears that ET could be a significant portion of the water budget of bioinfiltration systems in terms of volume and relationship to infiltration. Further research is needed to determine if credit should be given to ET for volume reduction in the design of bioinfiltration basins.

5.5 Recommendations for Future Study

The most important aspect of the evapotranspiration study site, regarding the future, is the continued collection of data for both naturally occurring precipitation falling within the lysimeters and storm simulations. With data from multiple years added to this work, a more comprehensive analysis can take shape, through the averaging out of parameters such as wet and dry years, hot and cold years, years with high and low wind speeds, variations in infiltration from identical storm simulations, etc.

The K_cK_s terms should be individually isolated and solved. Seperating the terms can be done by examining lysimeter data that is known to be water sufficient, setting the K_s term equal to one and solving for K_c using Equation 7. Analysis over the course of several years of data will provide average K_c values for the initial, middle, and final growth stages of the lysimeter vegetation. Once done, the K_c information can be used to solve for K_s values during each of the growth stages, providing valuable insight into the performance of the lysimeters, and hence the SCMs they are intended to mimic.

A key aspect in the performance of lysimeters in terms of both ET and infiltration is the available soil moisture. In order to further isolate the effects of the abundance and lack of soil moisture, the lysimeters should be forced into extreme stages of both. Once the extreme stages of soil moisture are obtained, storm simulations should be performed and the data analyzed in reference to SWCCs for both lysimeters.

A more accurate outflow measurement system for the bioretention lysimeter should be designed and installed. Once done, storm simulations at varying levels of soil moisture could be used to study the hydrologic performance of the IWS layer, providing information about the level of storms that can be absorbed by the lysimeter at varying levels of IWS and soil moisture conditions. Also storm simulations including known concentrations of nutrients, such as nitrates and phosphates, could be performed in the bioretention lysimeter, and laboratory analysis of the outflow examined to determine any possible reduction of nutrients by the IWS layer.

Finally, the data obtained from both lysimeters should be directly applied to existing bioinfiltration and bioretention sites at Villanova University. The information can be used to validate the experimental data obtained from the lysimeters in terms of ET, infiltration/outflow, nutrient reduction, and seasonal performance.

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Appendix 1

Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non stressed, well-managed crops in subhumid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o (Allen et al. 1998).

Crop	$K_{c\,ini}$[1]	$K_{c\,mid}$	$K_{c\,end}$	Maximum Crop Height (h) (m)
a. Small Vegetables	**0.7**	**1.05**	**0.95**	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions				
- dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables - Solanum Family *(Solanaceae)*	**0.6**	**1.15**	**0.80**	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05[2]	0.90	0.7
Tomato		1.15[2]	0.70-0.90	0.6
c. Vegetables - Cucumber Family *(Cucurbitaceae)*	**0.5**	**1.00**	**0.80**	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber				
- Fresh Market	0.6	1.00[2]	0.75	0.3
- Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4
Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	**0.5**	**1.10**	**0.95**	
Beets, table		1.05	0.95	0.4
Cassava				

- year 1	0.3	0.80[3]	0.30	1.0
- year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6
Sugar Beet	0.35	1.20	0.70[5]	0.5
e. Legumes *(Leguminosae)*	**0.4**	**1.15**	**0.55**	
Beans, green	0.5	1.05[2]	0.90	0.4
Beans, dry and Pulses	0.4	1.15[2]	0.35	0.4
Chick pea		1.00	0.35	0.4
Fababean (broad bean)				
- Fresh	0.5	1.15[2]	1.10	0.8
- Dry/Seed	0.5	1.15[2]	0.30	0.8
Grabanzo	0.4	1.15	0.35	0.8
Green Gram and Cowpeas		1.05	0.60-0.35[6]	0.4
Groundnut (Peanut)		1.15	0.60	0.4
Lentil		1.10	0.30	0.5
Peas				
- Fresh	0.5	1.15[2]	1.10	0.5
- Dry/Seed		1.15	0.30	0.5
Soybeans		1.15	0.50	0.5-1.0
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)	**0.5**	**1.00**	**0.80**	
Artichokes	0.5	1.00	0.95	0.7
Asparagus	0.5	0.95[7]	0.30	0.2-0.8
Mint	0.60	1.15	1.10	0.6-0.8
Strawberries	0.40	0.85	0.75	0.2
g. Fibre Crops	**0.35**			
Cotton		1.15-1.20	0.70-0.50	1.2-1.5
Flax		1.10	0.25	1.2
Sisal [8]		0.4-0.7	0.4-0.7	1.5
h. Oil Crops	**0.35**	**1.15**	**0.35**	
Castorbean (*Ricinus*)		1.15	0.55	0.3
Rapeseed, Canola		1.0-1.15[9]	0.35	0.6
Safflower		1.0-1.15[9]	0.25	0.8
Sesame		1.10	0.25	1.0

Sunflower		1.0-1.15[9]	0.35	2.0
i. Cereals	**0.3**	**1.15**	**0.4**	
Barley		1.15	0.25	1
Oats		1.15	0.25	1
Spring Wheat		1.15	0.25-0.4[10]	1
Winter Wheat				
- with frozen soils	0.4	1.15	0.25-0.4[10]	1
- with non-frozen soils	0.7	1.15	0.25-0.4[10]	
Maize, Field (grain) *(field corn)*		1.20	0.60-0.35[11]	2
Maize, Sweet *(sweet corn)*		1.15	1.05[12]	1.5
Millet		1.00	0.30	1.5
Sorghum				
- grain		1.00-1.10	0.55	1-2
- sweet		1.20	1.05	2-4
Rice	1.05	1.20	0.90-0.60	1
j. Forages				
Alfalfa Hay				
- averaged cutting effects	0.40	0.95[13]	0.90	0.7
- individual cutting periods	0.40[14]	1.20[14]	1.15[14]	0.7
- for seed	0.40	0.50	0.50	0.7
Bermuda hay				
- averaged cutting effects	0.55	1.00[13]	0.85	0.35
- Spring crop for seed	0.35	0.90	0.65	0.4
Clover hay, Berseem				
- averaged cutting effects	0.40	0.90[13]	0.85	0.6
- individual cutting periods	0.40[14]	1.15[14]	1.10[14]	0.6
Rye Grass hay				
- averaged cutting effects	0.95	1.05	1.00	0.3
Sudan Grass hay (annual)				
- averaged cutting effects	0.50	0.90[14]	0.85	1.2
- individual cutting periods	0.50[14]	1.15[14]	1.10[14]	1.2
Grazing Pasture				
- Rotated Grazing	0.40	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.30	0.75	0.75	0.10

Turf grass				
- cool season [15]	0.90	0.95	0.95	0.10
- warm season [15]	0.80	0.85	0.85	0.10
k. Sugar Cane	**0.40**	**1.25**	**0.75**	**3**
l. Tropical Fruits and Trees				
Banana				
- 1st year	0.50	1.10	1.00	3
- 2nd year	1.00	1.20	1.10	4
Cacao	1.00	1.05	1.05	3
Coffee				
- bare ground cover	0.90	0.95	0.95	2-3
- with weeds	1.05	1.10	1.10	2-3
Date Palms	0.90	0.95	0.95	8
Palm Trees	0.95	1.00	1.00	8
Pineapple [16]				
- bare soil	0.50	0.30	0.30	0.6-1.2
- with grass cover	0.50	0.50	0.50	0.6-1.2
Rubber Trees	0.95	1.00	1.00	10
Tea				
- non-shaded	0.95	1.00	1.00	1.5
- shaded [17]	1.10	1.15	1.15	2
m. Grapes and Berries				
Berries (bushes)	0.30	1.05	0.50	1.5
Grapes				
- Table or Raisin	0.30	0.85	0.45	2
- Wine	0.30	0.70	0.45	1.5-2
Hops	0.3	1.05	0.85	5
n. Fruit Trees				
Almonds, no ground cover	0.40	0.90	0.65[18]	5
Apples, Cherries, Pears [19]				
- no ground cover, killing frost	0.45	0.95	0.70[18]	4
- no ground cover, no frosts	0.60	0.95	0.75[18]	4
- active ground cover, killing frost	0.50	1.20	0.95[18]	4
- active ground cover, no frosts	0.80	1.20	0.85[18]	4
Apricots, Peaches, Stone Fruit [19, 20]				
- no ground cover, killing frost	0.45	0.90	0.65[18]	3
- no ground cover, no frosts	0.55	0.90	0.65[18]	3
- active ground cover, killing frost	0.50	1.15	0.90[18]	3
- active ground cover, no frosts	0.80	1.15	0.85[18]	3
Avocado, no ground cover	0.60	0.85	0.75	3

Citrus, no ground cover [21]				
- 70% canopy	0.70	0.65	0.70	4
- 50% canopy	0.65	0.60	0.65	3
- 20% canopy	0.50	0.45	0.55	2
Citrus, with active ground cover or weeds [22]				
- 70% canopy	0.75	0.70	0.75	4
- 50% canopy	0.80	0.80	0.80	3
- 20% canopy	0.85	0.85	0.85	2
Conifer Trees [23]	1.00	1.00	1.00	10
Kiwi	0.40	1.05	1.05	3
Olives (40 to 60% ground coverage by canopy) [24]	0.65	0.70	0.70	3-5
Pistachios, no ground cover	0.40	1.10	0.45	3-5
Walnut Orchard [19]	0.50	1.10	0.6518	4-5
o. Wetlands - temperate climate				
Cattails, Bulrushes, killing frost	0.30	1.20	0.30	2
Cattails, Bulrushes, no frost	0.60	1.20	0.60	2
Short Veg., no frost	1.05	1.10	1.10	0.3
Reed Swamp, standing water	1.00	1.20	1.00	1-3
Reed Swamp, moist soil	0.90	1.20	0.70	1-3
p. Special				
Open Water, < 2 m depth or in subhumid climates or tropics		1.05	1.05	
Open Water, > 5 m depth, clear of turbidity, temperate climate		0.6525	1.2525	

[1] These are general values for $K_{c\ ini}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2. $K_{c\ ini}$ is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 29 and 30, or Equation 7-3 in Annex 7, or using the dual $K_{cb\ ini} + K_e$.

[2] Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased K_c values need to be taken. For green beans, peppers and cucumbers, 1.15 can be taken, and for tomatoes, dry beans and peas, 1.20. Under these conditions h should be increased also.

[3] The midseason values for cassava assume non-stressed conditions during or following the rainy season. The $K_{c\ end}$ values account for dormancy during the dry season.

[4] The $K_{c\ end}$ value for potatoes is about 0.40 for long season potatoes with vine kill.

[5] This $K_{c\ end}$ value is for no irrigation during the last month of the growing season. The $K_{c\ end}$ value for sugar beets is higher, up to 1.0, when irrigation or significant rain occurs during the last month.

[6] The first $K_{c\ end}$ is for harvested fresh. The second value is for harvested dry.

[7] The K_c for asparagus usually remains at $K_{c\ ini}$ during harvest of the spears, due to sparse ground cover. The $K_{c\ mid}$ value is for following regrowth of plant vegetation following termination of harvest of spears.

[8] K_c for sisal depends on the planting density and water management (e.g., intentional moisture stress).

[9] The lower values are for rainfed crops having less dense plant populations.

[10] The higher value is for hand-harvested crops.

[11] The first $K_{c\ end}$ value is for harvest at high grain moisture. The second $K_{c\ end}$ value is for harvest after complete field drying of the grain (to about 18% moisture, wet mass basis).

[12] If harvested fresh for human consumption. Use $K_{c\ end}$ for field maize if the sweet maize is allowed to mature and dry in the field.

[13] This $K_{c\ mid}$ coefficient for hay crops is an overall average $K_{c\ mid}$ coefficient that averages K_c for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

[14] These K_c coefficients for hay crops represent immediately following cutting; at full cover; and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods (Figure 35).

[15] Cool season grass varieties include dense stands of bluegrass, ryegrass, and fescue. Warm season varieties include bermuda grass and St. Augustine grass. The 0.95 values for cool season grass represent a 0.06 to 0.08 m mowing height under general turf conditions. Where careful water management is practiced and rapid growth is not required, K_c's for turf can be reduced by 0.10.

[16] The pineapple plant has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation from the soil. The $K_{c\ mid} < K_{c\ ini}$ since $K_{c\ mid}$ occurs during full ground cover so that soil evaporation is less. Values given assume that 50% of the ground surface is covered by black plastic mulch and that irrigation is by sprinkler. For drip irrigation beneath the plastic mulch, K_c's given can be reduced by 0.10.

[17] Includes the water requirements of the shade trees.

[18] These $K_{c\ end}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end}$ » 0.20 for bare, dry soil or dead ground cover and $K_{c\ end}$ » 0.50 to 0.80 for actively growing ground cover (consult Chapter 11).

[19] Refer to Eq. 94, 97 or 98 and footnotes 21 and 22 for estimating K_c for immature stands.

[20] Stone fruit category applies to peaches, apricots, pears, plums and pecans.

[21] These K_c values can be calculated from Eq. 98 for $K_{c\ min} = 0.15$ and $K_{c\ full} = 0.75$, 0.70 and 0.75 for the initial, mid season and end of season periods, and $f_{c\ eff} = f_c$ where f_c = fraction of ground covered by tree canopy (e.g., the sun is presumed to be directly overhead). The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. The midseason value is lower than initial and ending values due to the effects of stomatal closure during periods of peak ET. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

[22] These K_c values can be calculated as $K_c = f_c\ K_{c\ ngc} + (1 - f_c)\ K_{c\ cover}$ where $K_{c\ ngc}$ is the K_c of citrus with no active ground cover (calculated as in footnote 21), $K_{c\ cover}$ is the K_c, for the active ground cover (0.95), and f_c is defined in footnote 21. The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. Alternatively, K_c for citrus with active ground cover can be estimated directly from Eq. 98 by setting $K_{c\ min} = K_{c\ cover}$. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

For non-active or only moderately active ground cover (active indicates green and growing ground cover with LAI > about 2 to 3), K_c should be weighted between K_c for no ground cover and K_c for active ground cover, with the weighting based on the "greenness" and approximate leaf area of the ground cover.

[23] Confers exhibit substantial stomatal control due to reduced aerodynamic resistance. The K_c, can easily reduce below the values presented, which represent well-watered conditions for large forests.

[24] These coefficients represent about 40 to 60% ground cover. Refer to Eq. 98 and footnotes 21 and 22 for estimating K_c for immature stands. In Spain, Pastor and Orgaz (1994) have found the following monthly K_c's for olive orchards having 60% ground cover: 0.50, 0.50, 0.65, 0.60, 0.55, 0.50, 0.45, 0.45, 0.55, 0.60, 0.65, 0.50 for months January through December. These coefficients can be invoked by using $K_{c\ ini} = 0.65$, $K_{c\ mid} = 0.45$, and $K_{c\ end} = 0.65$, with stage lengths = 30, 90, 60 and 90 days, respectively for initial, development, midseason and late season periods, and using K_c during the winter ("off season") in December to February = 0.50.

[25] These K_c's are for deep water in temperate latitudes where large temperature changes in the water body occur during the year, and initial and peak period evaporation is low as radiation energy is absorbed into the deep water body. During fall and winter periods ($K_{c\ end}$), heat is released from the water body that increases the evaporation above that for grass. Therefore, $K_{c\ mid}$ corresponds to the period when the water body is gaining thermal energy and $K_{c\ end}$ when releasing thermal energy. These K_c's should be used with caution.

Appendix 2 March 2010 Raw Bioinfiltration Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for March

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
1-Mar	1.016598	2.70506	2.271567	0.447532	574.8461
4-Mar	0.938687	2.363041	2.168142	0.432945	570.2511
5-Mar	0.502981	1.585725	2.334123	0.21549	568.6245
6-Mar	0.547939	1.05715	2.759082	0.198595	568.142
7-Mar	0.4775	0.777316	3.19263	0.149563	567.05
8-Mar	1.00943	0.538939	3.539805	0.285165	566.8248
9-Mar	0.796615	0.310926	3.14607	0.25321	565.4785
10-Mar	0.667894	0.145099	2.004871	0.333136	565.4318
11-Mar	0	0.062185	1.124685	0	564.462
16-Mar	1.859347	3.855488	2.961075	0.62793	570.5793
17-Mar	0.868415	2.103936	3.182135	0.272903	568.8241
18-Mar	0.868301	1.233342	3.683975	0.235697	568.5198
19-Mar	0.764332	0.746224	3.92335	0.194816	566.0948
20-Mar	1.055525	0.456026	3.982172	0.265063	566.5639
21-Mar	0.933601	0.26947	3.276948	0.2849	565.9741
24-Mar	0.989175	2.269763	4.304073	0.229823	569.8045
27-Mar	0.691565	0.424933	2.209782	0.312956	568.0099

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weight for March

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
-0.02597	-0.03447	-3.36001	Yes	Yes	28.13956	196.932
-0.43571	0.165981	-1.18942	No	Yes		92.7579
0.044958	0.424959	-0.35282	Yes	No	161.7308	
-0.07044	0.433548	-0.79851	No	Yes		167.5746
0.53193	0.347175	-0.16467	Yes	No	42.03248	
-0.21281	-0.39374	-0.98446	Yes	Yes	59.65565	128.9002
-0.12872	-1.1412	-0.03415	Yes	Yes	159.4554	116.1327
-0.66789	-0.88019	-0.70915	Yes	Yes	27.42636	5.991875
0.371869	0.367278	4.473171	Yes	Yes	1.242363	169.299
-0.99093	0.22106	-1.28346	No	Yes		25.72366
-0.00011	0.50184	-0.22251	No	Yes		199.794
-0.10397	0.239375	-1.77324	No	Yes		177.8461
0.291193	0.058822	0.343021	Yes	Yes	132.7778	16.34406
-0.12192	-0.70522	-0.43128	Yes	Yes	141.0389	111.8419
0.018525	0.342375	2.800914	Yes	Yes	179.4683	197.3719
-0.0992	-0.6981	-1.31227	Yes	Yes	150.2303	171.8865

Appendix 3 April 2010 Raw Bioinfiltration Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for April

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
1-Apr	0.727841	3.233635	3.9818	0.182792	570.4139
2-Apr	0.944575	1.741188	3.622783	0.260732	568.9946
3-Apr	0.296594	1.046786	3.237397	0.091615	568.0013
4-Apr	0.867974	0.642581	3.886761	0.223316	568.201
5-Apr	0.725735	0.46639	4.076214	0.178041	566.7949
6-Apr	0.889496	0.352383	5.164642	0.172228	567.0564
7-Apr	1.888708	0.124371	6.846162	0.275878	564.7322
10-Apr	0.481567	0.176192	4.242277	0.113516	568.5217
11-Apr	0.947076	0.580396	4.372301	0.216608	567.9352
12-Apr	1.295909	0.342019	3.836513	0.337783	566.3747
14-Apr	1.412302	0.093278	3.578319	0.394683	567.6337
15-Apr	1.02149	0.186556	4.326465	0.236103	566.1985
17-Apr	2.532856	0.041457	2.599597	0.974326	568.0578
18-Apr	0.769209	0	2.933615	0.262205	567.3776
19-Apr	1.197269	0.020728	4.174224	0.286824	566.616
20-Apr	0.746996	0.082914	3.648763	0.204726	566.5427
23-Apr	1.801919	3.523833	4.274904	0.421511	571.1085
28-Apr	1.654742	2.373405	4.141748	0.399528	571.5682
29-Apr	1.702115	1.285163	5.228613	0.325539	569.6771
30-Apr	1.349954	0.808409	4.569823	0.295406	568.0976

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for April

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
0.216734	-0.35902	-3.11352	No	No		
-0.64798	-0.38539	-2.179	No	Yes		108.3147
0.571381	0.649365	0.438082	Yes	Yes	12.77646	26.40989
-0.14224	0.189453	-3.08456	No	Yes		182.3678
0.163761	1.088428	0.573652	Yes	Yes	147.6881	111.1699
0.999212	1.681519	-5.09859	Yes	No	50.90457	
-0.46905	-0.86796	8.313021	Yes	No	59.67266	
0.465509	0.130024	-1.2866	Yes	No	112.6673	
0.348833	-0.53579	-3.42327	No	No		
0.058197	-0.1291	2.761866	No	Yes		191.7453
-0.39081	0.748146	-3.1484	No	Yes		155.8306
0.755683	-0.86343	4.078744	No	Yes		137.4749
-1.76365	0.334018	-1.49215	No	Yes		16.67751
0.42806	1.240609	-1.67072	Yes	No	97.38891	
-0.45027	-0.52546	-0.1608	Yes	Yes	15.41177	94.74338
0.351641	0.208714	10.01599	Yes	Yes	51.01309	186.4331
-0.02944	-0.02663	1.008443	Yes	No	10.00262	
0.047372	1.086865	-4.1485	Yes	No	183.2936	
-0.35216	-0.65879	-3.46495	Yes	Yes	60.66146	163.0966

Appendix 4 May 2010 Raw Bioinfiltration Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for May

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
1-May	2.267545	0.456032	5.262111	0.430919	567.875
2-May	0.618491	0.238379	5.20963	0.118721	566.9908
4-May	2.89202	2.78798	4.863254	0.594668	571.5163
5-May	3.038438	0.663321	4.999189	0.607786	569.4924
6-May	3.513446	0.155473	5.442228	0.64559	567.8688
7-May	2.647944	0	4.247591	0.623399	566.2538
10-May	2.642058	1.295527	4.492694	0.588079	570.7247
13-May	2.82225	1.927733	3.796907	0.743303	573.087
16-May	3.425028	1.274801	4.37859	0.782222	572.9028
19-May	2.860968	4.415155	2.303419	1.242053	576.4238
20-May	3.788313	1.222985	4.941671	0.766606	573.9256
21-May	4.481857	0.300558	5.268583	0.850676	571.7024
28-May	4.159587	0.746227	3.154606	1.318576	573.4652

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for May

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
-1.64905	-0.05248	-1.93951	Yes	Yes	187.6628	16.18792
1.136764	-0.17319	4.963801	No	Yes		125.465
0.146418	0.135935	-4.43994	Yes	No	7.425606	
0.475008	0.443039	-3.56175	Yes	No	6.964695	
-0.8655	-1.19464	-3.54281	Yes	Yes	31.95261	121.4663
-0.00196	0.081701	3.269275	No	No		
0.060064	-0.23193	1.727414	No	Yes		186.5589
0.200926	0.193894	-0.13473	Yes	No	3.561934	
-0.18802	-0.69172	2.574713	Yes	No	114.5114	
0.927346	2.638253	-5.48032	Yes	No	95.96745	
0.693544	0.326911	-4.87693	Yes	No	71.85663	
-0.04604	-0.302	0.55242	Yes	No	147.0875	

Appendix 5 June 2010 Raw Bioinfiltration Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for June

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
2-Jun	6.814982	0.010363	5.02979	1.354924	564.586
4-Jun	8.065814	0.010363	5.355054	1.506206	558.6572
5-Jun	7.440314	0	5.595044	1.329804	555.2258
6-Jun	7.150328	0.010363	5.12208	1.395981	551.928
7-Jun	5.993448	0	4.929396	1.215858	548.7298
10-Jun	8.118567	2.03139	4.719844	1.720092	573.5867
14-Jun	6.58897	6.726377	3.150372	2.09149	575.4015
17-Jun	8.041981	0.383464	5.109752	1.573849	571.4359
20-Jun	9.399653	0	5.728246	1.64093	569.2914
21-Jun	9.902175	0	5.887861	1.681795	564.8516
25-Jun	10.4047	0	5.730086	1.815801	570.9981
26-Jun	10.85547	0	5.325038	2.038572	566.2112
27-Jun	10.51814	0	5.337693	1.97054	561.4576
30-Jun	10.42758	0	5.810246	1.794689	568.2582

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for June

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
0.625416	0.162632	-6.50298	Yes	No	117.4506	
-0.6255	0.23999	-7.52759	No	Yes		169.3122
-0.28999	-0.47296	-7.23423	Yes	Yes	47.96619	184.5839
-1.15688	-0.19268	-7.01598	Yes	Yes	142.8902	143.3794
0.708373	-0.06985	18.17618	No	Yes		184.9957
-0.3824	-0.39237	0.99527	Yes	No	2.573334	
0.484337	0.653127	-2.89975	Yes	No	29.67828	
0.452558	1.206165	-1.56813	Yes	No	90.86599	
0.502522	0.159616	-9.73965	Yes	No	103.5756	
0.125631	-0.03944	3.370933	No	Yes		185.6281
0.450777	-0.40505	-10.5011	No	No		
-0.33734	0.012654	-10.4279	No	Yes		187.4657
-0.03018	0.157518	4.972814	No	No		

Appendix 6 July 2010 Raw Bioinfiltration Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for July

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
3-Jul	11.73713	0	6.047119	1.940945	570.2157
4-Jul	14.8259	0	7.547526	1.964339	564.1625
5-Jul	14.88162	0	6.743414	2.206838	557.2202
6-Jul	17.23203	0	6.678246	2.580323	550.0068

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for July

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
3.08877	1.500407	-13.279	Yes	No	69.22215	
0.055725	-0.80411	-15.2293	No	No		
2.350411	-0.06517	-15.8241	No	No		

Appendix 7 August 2010 Raw Bioinfiltration Data, Bioretention Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for August

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
13-Aug	2.814124	0	3.630256	0.775186	511.1674
14-Aug	2.61013	0	4.282788	0.609447	510.0796
17-Aug	1.975261	0	4.395326	0.4494	508.4916
18-Aug	0.753286	0	2.145764	0.351057	507.7318
19-Aug	1.287651	0	4.879764	0.263876	507.5753
20-Aug	1.202073	0	4.888211	0.245913	506.8857
21-Aug	0.822942	0	3.778525	0.217795	506.4624
25-Aug	2.359367	0	2.24042	1.053091	515.8131
26-Aug	1.884707	0	4.447791	0.42374	515.1915
27-Aug	2.07079	0	4.099567	0.505124	514.2309
28-Aug	2.280754	0	4.110633	0.554843	513.2965
29-Aug	2.701679	0	4.919103	0.549222	512.1876
30-Aug	2.343445	0	4.790856	0.48915	511.037

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for August

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
-0.20399	0.652531	-2.38625	No	Yes		168.4981
-0.21162	0.037513	-1.16121	No	Yes		138.3396
-1.22197	-2.24956	-1.6667	Yes	Yes	59.20072	30.79073
0.534365	2.734	-0.34333	Yes	No	134.6015	
-0.08558	0.008447	-1.51282	No	Yes		178.584
-0.37913	-1.10969	-0.92859	Yes	Yes	98.13904	84.03324
0.384106	-0.38453	5.128136	No	Yes		172.1271
-0.47466	2.207372	-1.36363	No	Yes		96.71736
0.186082	-0.34822	-2.10722	No	No		
0.209965	0.011066	-2.04969	Yes	No	179.9735	
0.420925	0.80847	-2.43262	Yes	No	63.0466	
-0.35823	-0.12825	-2.5242	Yes	Yes	94.55102	150.2873

Raw Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weight Data for August

Date	Bioretention ET_m (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
13-Aug	12.49439	3.630256	3.441738846	553.8524
14-Aug	14.74828	4.282788	3.443617079	547.62
17-Aug	12.4327	4.395326	2.828617879	534.6537
18-Aug	5.400372	2.145764	2.516759924	530.4112
19-Aug	7.945821	4.879764	1.628321018	527.6153
20-Aug	5.896924	4.888211	1.206356269	524.2878
21-Aug	4.352539	3.778525	1.151914686	521.9266
25-Aug	5.664072	2.24042	2.528130161	526.6769
26-Aug	5.182447	4.447791	1.16517312	524.558
27-Aug	4.029134	4.099567	0.982819335	522.5217
28-Aug	3.400234	4.110633	0.82718025	521.0838
29-Aug	2.254882	4.919103	0.458392852	519.544
30-Aug	2.735512	4.790856	0.570986047	518.3208

Comparison of Slopes between Data Points of Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weights for August

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
2.253887	0.652531	-13.6719	Yes	No	110.1944	
-0.77186	0.037513	-9.48144	No	Yes		169.8883
-7.03233	-2.24956	-9.30663	Yes	Yes	103.0558	27.83904
2.545449	2.734	-6.13333	Yes	No	7.142813	
-2.0489	0.008447	-7.29951	No	Yes		112.3317
-1.54439	-1.10969	-5.1798	Yes	Yes	32.75719	108.1295
0.327883	-0.38453	2.605186	No	Yes		155.2846
-0.48163	2.207372	-4.64824	No	Yes		162.4454
-1.15331	-0.34822	-4.46718	Yes	Yes	107.2352	117.9209
-0.6289	0.011066	-3.15413	No	Yes		133.5031
-1.14535	0.80847	-3.37805	No	Yes		98.71753
0.48063	-0.12825	-2.68317	No	No		

Appendix 8 September 2010 Raw Bioinfiltration Data, Bioretention Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for September

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
1-Sep	2.684762	0	4.711786	0.569797	509.9352
2-Sep	5.24324	0.072542	4.517904	1.160547	507.8516
3-Sep	0.593076	0	3.021278	0.1963	506.5037
4-Sep	1.287651	0	5.376887	0.239479	505.9966
5-Sep	1.171225	0	4.023468	0.291098	505.4655
6-Sep	0.507498	0	3.587031	0.141481	505.154
7-Sep	0.522424	0	4.704505	0.111048	504.9089
8-Sep	1.156299	0	6.805477	0.169907	504.5715
9-Sep	0.522424	0	3.845383	0.135857	504.0362
10-Sep	0.506503	0	3.548862	0.142723	503.8503
11-Sep	0.392067	0	3.65356	0.107311	503.7072
13-Sep	0.951309	0	3.37752	0.281659	505.7555
14-Sep	0.942354	0	3.682897	0.255873	505.3347
15-Sep	0.829908	0	3.680815	0.225469	504.929
18-Sep	0.493153	0.010363	3.277689	0.150458	507.2157
19-Sep	0.455921	0.020726	3.253939	0.140114	507.019
20-Sep	1.546213	0.010363	4.441977	0.348091	506.5617
21-Sep	0.336923	0.010363	3.326458	0.101286	506.1941

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for September

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
2.558478	-0.19388	-4.57082	No	No		
-4.65016	-1.49663	-2.95678	Yes	Yes	102.6077	44.52209
0.694575	2.355609	-1.11254	Yes	No	108.9137	
-0.11643	-1.35342	-1.16506	Yes	Yes	168.3161	163.659
-0.66373	-0.43644	-0.68336	Yes	Yes	41.31928	2.914786
0.014926	1.117475	-0.53768	Yes	No	194.7275	
0.633875	2.100972	-0.74006	Yes	No	107.2892	
-0.63387	-2.96009	-1.17442	Yes	Yes	129.4513	59.7854
-0.01592	-0.29652	-0.40777	Yes	Yes	179.6167	184.9686
-0.11444	0.104697	-0.31382	No	Yes		93.11426
0.279621	-0.13802	1.164936	No	Yes		122.5725
-0.00896	0.305377	-0.9232	No	Yes		196.1569
-0.11245	-0.00208	-0.89001	Yes	Yes	192.7277	155.132
-0.11225	-0.13438	1112.678	Yes	No	17.941	
-0.03723	-0.02375	-0.4315	Yes	Yes	44.21526	168.2279
1.090292	1.188038	-1.00313	Yes	No	8.580513	
-1.20929	-1.11552	-0.80634	Yes	Yes	8.066964	39.98305

Raw Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weight Data for September

Date	Bioretention ET_m (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
1-Sep	2.517587	4.711786	0.534317	515.8838
2-Sep	6.098928	4.517904	1.349946	514.0443
3-Sep	1.151323	3.021278	0.381072	511.8418
4-Sep	1.957349	5.376887	0.36403	511.0054
5-Sep	1.731463	4.023468	0.430341	510.2671
6-Sep	1.403082	3.587031	0.391154	509.5121
7-Sep	1.363278	4.704505	0.289781	508.9352
8-Sep	1.49065	6.805477	0.219037	508.1329
9-Sep	1.082662	3.845383	0.281548	507.5933
10-Sep	0.9533	3.548862	0.268621	507.2207
11-Sep	0.559243	3.65356	0.153068	506.8912
13-Sep	1.510552	3.37752	0.447237	508.6928
14-Sep	1.109529	3.682897	0.301265	508.1954
15-Sep	0.997084	3.680815	0.270887	507.6403
18-Sep	2.686752	3.277689	0.819709	618.7333
19-Sep	2.970354	3.253939	0.912849	617.4616
20-Sep	4.122672	4.441977	0.928117	615.8351
21-Sep	3.371377	3.326458	1.013503	614.0719

Comparison of Slopes between Data Points of Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weights for September

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
3.581341	-0.19388	-4.0352	No	No		
-4.9476	-1.49663	-4.83153	Yes	Yes	107.1029	2.373938
0.806026	2.355609	-1.83492	Yes	No	98.02419	
-0.22589	-1.35342	-1.6197	Yes	Yes	142.7885	151.043
-0.32838	-0.43644	-1.65612	Yes	Yes	28.25677	133.8108
-0.0398	1.117475	-1.26552	No	Yes		187.8027
0.127372	2.100972	-1.7601	Yes	No	177.136	
-0.40799	-2.96009	-1.18362	Yes	Yes	151.5465	97.46536
-0.12936	-0.29652	-0.81735	Yes	Yes	78.49981	145.3426
-0.39406	0.104697	-0.72292	No	Yes		58.88432
0.475655	-0.13802	0.537951	No	Yes		12.29197
-0.40102	0.305377	-1.09127	No	Yes		92.50841
-0.11245	-0.00208	-1.21774	Yes	Yes	192.7277	166.1866
0.563223	-0.13438	1357.314	No	Yes		199.8341
0.283602	-0.02375	-2.78957	No	No		
1.152318	1.188038	-3.56813	Yes	No	3.052505	
-0.7513	-1.11552	-3.86796	Yes	Yes	39.02085	134.9423
0.2637	-0.23833	-3.32983	No	No		
2.128505	1.880738	-4.80284	Yes	No	12.35979	

Appendix 9 October 2010 Raw Bioinfiltration Data, Bioretention Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for October

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
13-Oct	1.467763	0	2.170028	0.67638	563.8389
16-Oct	2.622653	0.010363	3.140276	0.835166	565.1357
17-Oct	1.265346	0.010363	2.739604	0.461872	563.1308
21-Oct	2.12751	0	2.321718	0.916352	564.7887
22-Oct	1.622997	0	2.396126	0.677342	564.4023
23-Oct	0.569193	0	2.826128	0.201404	563.5876
24-Oct	0.513468	0	2.001679	0.256519	563.3604
25-Oct	0	0	1.730817	0	563.2569
26-Oct	0	0	1.098276	0	563.5491
28-Oct	4.569991	0.186563	3.328415	1.373023	565.8465
29-Oct	1.049824	0	2.239358	0.468806	564.7293
30-Oct	0.560238	0	2.199507	0.254711	564.2725
31-Oct	1.231926	0	2.128029	0.578905	563.9614

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for October

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
0.577445	0.485124	1.422417	Yes	Yes	17.37697	84.503
-1.35731	-0.40067	-4.3981	Yes	Yes	108.8336	105.6673
0.215541	-0.10447	0.909222	No	Yes		123.3471
-0.50451	0.074408	-0.84778	No	Yes		50.76806
-1.0538	0.430002	-1.7871	No	Yes		51.62417
-0.05573	-0.82445	-0.49852	Yes	Yes	174.6754	159.7828
-0.51347	-0.27086	-0.22687	Yes	Yes	61.86319	77.4235
0	-0.63254	0.640809	No	No		
2.284995	1.11507	2.519951	Yes	Yes	68.81786	9.779746
-3.52017	-1.08906	-2.4508	Yes	Yes	105.4889	35.81907
-0.48959	-0.03985	-1.00201	Yes	Yes	169.8918	68.70817
0.671688	-0.07148	-0.6826	No	No		

Raw Bioretention ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for October

Date	Bioretention ET_m (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
13-Oct	3.055932089	2.170028	1.408245	625.0566
16-Oct	3.445013641	3.140276	1.097042	632.1789
17-Oct	3.141510129	2.739604	1.146702	630.4988
21-Oct	2.518581608	2.321718	1.084792	632.4656
22-Oct	2.966373676	2.396126	1.237987	631.2849
23-Oct	2.911643534	2.826128	1.030259	629.9033
24-Oct	2.571321563	2.001679	1.284582	628.7371
25-Oct	1.530453778	1.730817	0.884238	627.8217
26-Oct	1.146347693	1.098276	1.04377	627.2312
28-Oct	3.269877188	3.328415	0.982413	630.1981
29-Oct	2.491714084	2.239358	1.112691	628.8627
30-Oct	1.734447943	2.199507	0.788562	627.9442
31-Oct	2.126514775	2.128029	0.999289	627.0103

Comparison of Slopes between Data Points of Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weights for October

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
0.194541	0.485124	7.812098	Yes	Yes	85.5078	190.281
-0.3035	-0.40067	-3.68565	Yes	Yes	27.59775	169.5671
-0.15573	-0.10447	1.078629	Yes	No	39.40026	
0.447792	0.074408	-2.5901	Yes	No	143.0039	
-0.05473	0.430002	-3.03091	No	Yes		192.9052
-0.34032	-0.82445	-2.55826	Yes	Yes	83.12827	153.0361
-1.04087	-0.27086	-2.008	Yes	Yes	117.403	63.44209
-0.38411	-0.63254	-1.29555	Yes	Yes	48.87341	108.5274
1.061765	1.11507	3.254294	Yes	Yes	4.897456	101.5987
-0.77816	-1.08906	-2.92941	Yes	Yes	33.3002	116.0461
-0.75727	-0.03985	-2.01497	Yes	Yes	180.0024	90.73554
0.392067	-0.07148	-2.0488	No	No		

Appendix 10 November 2010 Raw Bioinfiltration Data, Bioretention Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for November

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
1-Nov	0.463714	0	1.489057	0.311414	563.2025
2-Nov	0.451772	0	1.139147	0.396588	562.9562
3-Nov	0.42789	0	0.95522	0.447949	562.8364
5-Nov	8.166528	1.627175	1.171447	6.971319	568.5697
6-Nov	2.86538	0.062179	1.047623	2.735124	566.2336
7-Nov	1.718526	0	1.66443	1.032501	565.2727
8-Nov	1.343376	0	2.287564	0.587252	564.6207
9-Nov	0.449782	0	1.811452	0.248299	564.239
12-Nov	1.577412	0.818769	1.725289	0.914288	566.8367
15-Nov	2.0047	0.010363	0.708863	2.828051	567.0616
19-Nov	1.057953	0.020726	1.264969	0.836347	566.198
20-Nov	1.085816	0.020726	1.433256	0.757587	565.7805
21-Nov	0.045774	0	1.058715	0.043236	565.4936
24-Nov	2.410867	0.03109	2.234056	1.079143	566.7956
27-Nov	2.109614	0.124358	1.665128	1.266938	566.8113
28-Nov	0.763237	0	1.120476	0.681172	566.3037
29-Nov	0.413959	0	0.800579	0.517074	565.9946

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for November

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
-0.01194	-0.34991	-0.54035	Yes	Yes	186.7999	191.3516
-0.02388	-0.18393	-0.26273	Yes	Yes	154.0306	166.6701
3.869319	0.108113	6.288512	Yes	Yes	189.1273	47.63207
-5.30115	-0.12382	-5.12464	Yes	Yes	190.8701	3.386091
-1.14685	0.616807	-2.10802	No	Yes		59.06037
-0.37515	0.623134	-1.43021	No	Yes		116.8806
-0.89359	-0.47611	-0.83732	Yes	Yes	60.95918	6.502222
0.375877	-0.02872	1.899497	No	Yes		133.9227
0.142429	-0.33881	0.164499	No	Yes		14.3808
-0.23669	0.139027	-0.47365	No	Yes		66.71764
0.027863	0.168287	-0.91584	Yes	No	143.1809	
-1.04004	-0.37454	-0.62946	Yes	Yes	94.0915	49.18575
0.788364	0.39178	0.952055	Yes	Yes	67.20941	18.81049
-0.10042	-0.18964	0.011514	Yes	No	61.52185	
-1.34638	-0.54465	-1.11349	Yes	Yes	84.79257	18.93455
-0.34928	-0.3199	-0.67818	Yes	Yes	8.781207	64.02294

Raw Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weight Data for November

Date	Bioretention ET_m (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
1-Nov	1.393131	1.489057	0.93558	625.714
2-Nov	1.211029	1.139147	1.063101	625.0501
3-Nov	1.595135	0.95522	1.669914	624.6115
5-Nov	3.636072	1.171447	3.103916	634.988
6-Nov	1.503586	1.047623	1.435236	634.1491
7-Nov	1.519508	1.66443	0.91293	633.3059
8-Nov	1.567272	2.287564	0.685127	632.7029
9-Nov	1.681708	1.811452	0.928376	631.5371
12-Nov	1.723502	1.725289	0.998964	634.6448
15-Nov	0.336342	0.708863	0.474481	635.8022
19-Nov	1.361288	1.264969	1.076143	635.1414
20-Nov	1.38318	1.433256	0.965061	634.6093
21-Nov	0.534365	1.058715	0.50473	634.1952
24-Nov	1.711561	2.234056	0.766123	635.6713
27-Nov	1.17023	1.665128	0.702787	636.059
28-Nov	0.656762	1.120476	0.586145	635.6918
29-Nov	0.549292	0.800579	0.686118	635.5331

Comparison of Slopes between Data Points of Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weights for November

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
-0.1821	-0.34991	-1.4562	Yes	Yes	63.08401	155.5389
0.384106	-0.18393	-0.96218	No	No		
1.020468	0.108113	11.38139	Yes	Yes	161.6817	167.0866
-2.13249	-0.12382	-1.84015	Yes	Yes	178.0485	14.71747
0.015921	0.616807	-1.84987	Yes	No	189.9347	
0.047764	0.623134	-1.32279	Yes	No	171.5221	
0.114436	-0.47611	-2.55732	No	No		
0.013931	-0.02872	2.272422	No	Yes		197.5627
-0.46239	-0.33881	0.846345	Yes	No	30.84838	
0.256237	0.139027	-0.36243	Yes	No	59.30736	
0.021892	0.168287	-1.16707	Yes	No	153.9549	
-0.84881	-0.37454	-0.90846	Yes	Yes	77.53661	6.788775
0.392399	0.39178	1.079359	Yes	Yes	0.157718	93.3524
-0.18044	-0.18964	0.283499	Yes	No	4.971317	
-0.51347	-0.54465	-0.80555	Yes	Yes	5.89409	44.28771
-0.10747	-0.3199	-0.34821	Yes	Yes	99.41191	105.661

Appendix 11 December 2010 Raw Bioinfiltration Data, Bioretention Data and Comparison of Slopes Data

Raw Bioinfiltration ET_m, Infiltration, PM ET_0, and Average Daily Lysimeter Weight Data for December

Date	Bioinfiltration ET_m (mm/day)	Infiltration (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
5-Dec	0.607858	1.451	1.336917	0.454672	567.4086
6-Dec	0.934566	0.694411	1.512051	0.618078	566.5656
7-Dec	0.705293	0.155473	1.393807	0.506019	566.0658
8-Dec	0.658752	0	1.332011	0.494554	565.7526
11-Dec	0.800352	1.015695	0.664012	1.205328	572.4856
14-Dec	1.411677	1.057148	0.942796	1.49733	568.5791
15-Dec	0.357239	0	0.928498	0.384749	568.1082
17-Dec	0.3244	0	0.78873	0.411295	568.0228
18-Dec	0.039804	0	0.558863	0.071223	567.9004
19-Dec	0.196033	0	0.73723	0.265905	567.8216
20-Dec	0.037814	0	0.949146	0.03984	567.761
21-Dec	0.672683	0	1.486004	0.452679	567.6888
22-Dec	0	0	1.209262	0	567.5296
23-Dec	0.503517	0	1.575146	0.319664	567.3781
24-Dec	0.223896	0	1.291411	0.173373	567.2793
25-Dec	0	0	0.644032	0	567.1115
28-Dec	3.160417	0	1.426734	2.215141	574.7533
29-Dec	1.762479	0.020726	0.807335	2.183083	573.4876
30-Dec	0.727	0.010363	0.523379	1.389052	573.0116

Comparison of Slopes between Data Points of Bioinfiltration ET_m, PM ET_0, and Average Daily Lysimeter Weights for December

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
0.326707	0.175134	-1.84924	Yes	No	15.10171	
-0.22927	-0.11824	-1.09637	Yes	Yes	15.97472	32.70481
-0.04654	-0.0618	-0.68716	Yes	Yes	7.04063	43.6567
0.0472	-0.22267	4.923392	No	Yes		49.05041
0.203775	0.092928	-2.85659	Yes	No	18.6798	
-1.05444	-0.0143	-1.03291	Yes	Yes	48.66219	0.515674
-0.01642	-0.06988	-0.09369	Yes	Yes	30.97518	35.08862
-0.2846	-0.22987	-0.26844	Yes	Yes	5.319062	1.460513
0.15623	0.178368	-0.17288	Yes	No	3.308158	
-0.15822	0.211916	-0.13287	No	Yes		4.354486
0.63487	0.536858	-0.15844	Yes	No	4.182365	
-0.67268	-0.27674	-0.34927	Yes	Yes	20.85166	15.82337
0.503517	0.365884	-0.33234	Yes	No	7.91544	
-0.27962	-0.28373	-0.2167	Yes	Yes	0.365056	6.338444
-0.2239	-0.64738	-0.36826	Yes	Yes	24.30248	12.18956
1.053472	0.260901	5.587968	Yes	Yes	30.15019	34.13789
-1.39794	-0.6194	-2.77656	Yes	Yes	19.2962	16.51245
-1.03548	-0.28396	-1.04412	Yes	Yes	28.47896	0.207685

Raw Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weight Data for December

Date	Bioretention ET_m (mm/day)	PM ET_0 (mm/day)	K_cK_s	Avg. Daily Weight (kg)
5-Dec	0.859761	1.336917	0.643092	636.8199
6-Dec	0.510483	1.512051	0.33761	636.4229
7-Dec	0.68761	1.393807	0.493332	636.2509
8-Dec	0.601036	1.332011	0.451225	635.7847
11-Dec	0.404008	0.664012	0.608434	640.5309
14-Dec	0.356243	0.942796	0.377858	637.8757
15-Dec	0.534365	0.928498	0.575515	637.6488
17-Dec	0.596061	0.78873	0.755723	637.3384
18-Dec	0.304499	0.558863	0.544854	637.2661
19-Dec	0.26967	0.73723	0.365789	637.1854
20-Dec	0.21096	0.949146	0.222263	637.0213
21-Dec	0	1.486004	0	636.7684
22-Dec	0.336342	1.209262	0.278138	636.7443
23-Dec	0.167176	1.575146	0.106133	636.4381
24-Dec	0.560238	1.291411	0.433818	636.4855
25-Dec	0	0.644032	0	636.3479
28-Dec	2.105618	1.426734	1.475831	640.7411
29-Dec	1.588169	0.807335	1.967175	639.9446
30-Dec	0.484611	0.523379	0.925927	639.2856

Comparison of Slopes between Data Points of Bioretention ET_m, PM ET_0, and Average Daily Lysimeter Weights for December

Slope between ET_m Data Points (mm/day)	Slope between PM ET_0 Data Points (mm/day)	Slope between Avg. Weight Data Points (mm/day)	Movement in the Same Direction between ET_m and PM ET_0	Movement in the Same Direction between ET_m and Avg. Weight	Percent Diff. ET_m and PM ET_0 Slopes Moving in Same Direction (%)	Percent Diff. ET_m and Avg. Weight Slopes Moving in Same Direction (%)
-0.34928	0.175134	-0.87093	No	Yes		21.37551
0.177127	-0.11824	-0.37724	No	No		
-0.08657	-0.0618	-1.02274	Yes	Yes	8.349867	42.19582
-0.06568	-0.22267	3.470596	Yes	No	27.22286	
-0.01592	0.092928	-1.94157	No	Yes		49.18664
0.178122	-0.0143	-0.49791	No	No		
0.030848	-0.06988	-0.34042	No	No		
-0.29156	-0.22987	-0.1586	Yes	Yes	5.915944	14.7676
-0.03483	0.178368	-0.17711	No	Yes		33.56682
-0.05871	0.211916	-0.3598	No	Yes		35.97165
-0.21096	0.536858	-0.55486	No	Yes		22.45324
0.336342	-0.27674	-0.05288	No	No		
-0.16917	0.365884	-0.67164	No	Yes		29.88043
0.393062	-0.28373	0.103982	No	Yes		29.08
-0.56024	-0.64738	-0.30187	Yes	Yes	3.60799	14.98462
0.701873	0.260901	3.212406	Yes	Yes	22.90114	32.06891
-0.51745	-0.6194	-1.74722	Yes	Yes	4.483907	27.1512
-1.10356	-0.28396	-1.4456	Yes	Yes	29.53491	6.708951