Villanova University

The Graduate School

Department of Civil and Environmental Engineering

QUANTIFYING EVAPOTRANSPIRATION THROUGH A SENSITIVITY STUDY OF CLIMATE FACTORS AND WATER TABLE INTERACTIONS FOR A CONSTRUCTED WETLAND MESOCOSM

A Thesis In

Civil and Environmental Engineering

By Nha Truong

Submitted in partial fulfillment

of requirements

for the degree of

Master of Science in Civil Engineering

May 2012

QUANTIFYING EVAPOTRANSPIRATION THROUGH A SENSITIVITY STUDY OF CLIMATE FACTORS AND WATER TABLE INTERACTIONS FOR A CONSTRUCTED WETLAND MESOCOSM

By

Nha Truong

May 2012

Robert G. Traver, Ph.D., P.E., D.WRE Date
Professor, Department of Civil and Environmental Engineering
Director, Villanova Stormwater Partnership
Director, Villanova Center for the Advancement of Sustainable Engineering

---

Bridget M. Wadzuk, Ph.D. Date
Associate Professor, Department of Civil and Environmental Engineering

---

Ronald A. Chadderton, Ph.D., P.E., D.WRE Date
Professor, Department of Civil and Environmental Engineering
Chairman, Department of Civil and Environmental Engineering

Gary A. Gabriele, Ph.D. Date
Dean of the College of Engineering

A copy of this thesis is available for research purposes at Falvey Memorial Library

Acknowledgements

These past two years of attending the graduate school at Villanova University have truly been an experience that has allowed me to develop a passion for the field of water resource engineering. I am extremely fortunate to work with some of the hardest and caring colleagues and advisors that I will forever remember.

The opportunity to succeed in this demanding program could not have been possible if it was not for Dr. Andrea Welker. I would like to give my most sincere thank you to her for allowing me to be a teaching assistant for the undergraduate courses and then providing me with the opportunity to become a graduate research assistant. Her enthusiasm and belief in me provided the motivation and confidence I needed to excel through graduate school.

In addition, I would like to thank Dr. Robert Traver and Dr. Bridget Wadzuk for accepting me as a graduate research assistant and advising me through my research. I am very grateful for their enthusiasm for my research and patience to read my thesis.

I want to thank my fellow colleagues, Erin, Mike, Cara, Laura, Kaitlyn, Chelsa, and Sonali for helping me with my research and lab work when I needed it. It was a lot of fun working with all of you and I hope that we keep in touch.

I would also like to thank George Pappas for helping me with any constructing that I needed, his patience and craftsmanship is without equal. Also, I would like to thank Linda DeAngelis for all her help throughout these years with anything I needed; she had an answer for any questions.

Lastly, but most important, I want to thank my family. Mom, dad, Le, thank you for your love, support, and all that you have done and will do for me to continue through my journey.

Table of Contents

List of Figures

List of Tables

Abstract

In the design process of low impact development, evapotranspiration (ET) is traditionally overlooked due to both the difficulty of accurately estimating ET and the continued focus on post peak flow design criteria. Evapotranspiration involves two components, the evaporation of water into the atmosphere and plant uptake for biological processes (transpiration). These two components are controlled by temperature, solar radiation, relative humidity, wind speed, and water availability. The study of the evapotranspiration process requires measuring these climate components and relating them to the ET observed. In the past, these climate components were used in equations and methodologies that were developed to estimate ET for agricultural purposes. Therefore, these equations are difficult to relate to stormwater control measures (SCMs) as they operate under variety of water availability conditions.

In this study, a method to quantity evapotranspiration for a constructed stormwater wetland (CSW) SCM is constructed using a Mariotte bottle system. The system is designed to automatically measure ET in a CSW mesocosm in a controlled greenhouse, where the meteorological components are also measured with weather instruments.

The results are analyzed and relationships between ET and the meteorological components are compared using statistics to create a regression model as an estimation tool. Correlations between the climate elements and ET are examined to observe which factors are the driving forces. In addition, common predictive equations in practice are examined to study their applicability for a constructed stormwater wetland SCM. From this analysis, calibration coefficients based off of the Penman-Monteith reference crop coefficient are applied in order to fit the calculated values to the measured evapotranspiration results of the mesocosm.

The outcomes of this study are to demonstrate the significance of evapotranspiration in the water budget and show its impacts on the design process of low impact developments. With continued research using the techniques defined by this study, a more accurate relationship between climate factors and ET can be developed.

Problem Statement

This research will demonstrate the significance of evapotranspiration through quantifying daily values of ET in a CSW mesocosm and further, relate ET to the climate parameters. A sensitivity study is performed to relate ET to the effects of temperature, relative humidity, solar radiation, wind, and plant health. As a result of these climate factors, a new reference relationship is demonstrated for a CSW mesocosm so that it can serve as a tool for the stormwater practice.

The results of this research thesis will advance the practice of stormwater management. In the past few years, there has been major progress in the case for managing storm water through SCM, which aim to retain storm runoff on site. These systems consist of green roofs, rain gardens, wetlands, and even swales, all serving the purpose of slowing down the time in which storm water reaches the sewers and river contributories. A policy issue with many low impact developments is that they rarely incorporate ET as a factor to sustain the water budget. If ET is considered, runoff volume can be greatly reduced.

Although focusing on ET is beneficial to the design aspect, designers need to have an idea of how much volume can be reduced. Therefore, this research will present an estimation of an ET study for CSW mesocosm over a period of 165 days and how weather parameters affect the daily rate.

1. Introduction

A major challenge in sustainable stormwater management is to comprehend the components of the water budget and balance the components. The water budget on land surfaces consist of precipitation, infiltration, run off, and evapotranspiration (ET). Each component itself is difficult to measure but the ET process is the most challenging. Figure 1 illustrates the processes of the water budget.

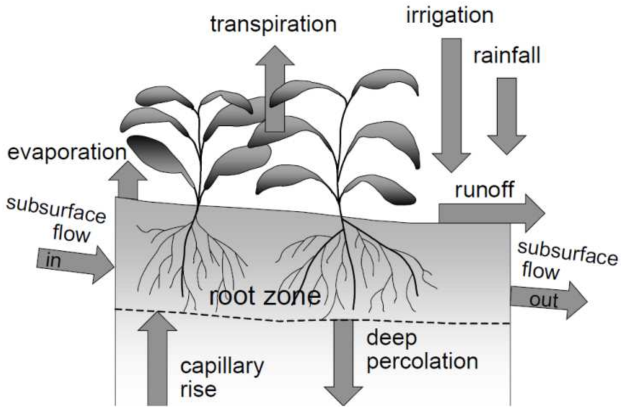

Figure 1: Water Budget on Land Surface (Allen et. al. 1998). Flow through the atmosphere, surface and subsurface is shown with arrows. Evaporation and transpiration are shown separately but are often combined as evapotranspiration

The first step is to measure the rainfall or any inflow that is present. A portion of the water is then infiltrated in to the soil and contributes to the groundwater system. The amount of infiltration is different depending on the characteristics of the sites. The remaining water is transpired or evaporated back to the atmosphere. Any excess water will contribute to the natural stream systems as runoff.

Sustainable management focuses on reducing this increased runoff. As human population expands exponentially, so does land development. With the increase in land development, the issue of managing stormwater becomes much more significant due to new constructions that create more impervious area. Therefore, when it rains, less water can be absorbed in to the ground or collected for evapotranspiration and more runoff is created. This runoff causes a higher concentration of flow and frequency of flooding in the natural water systems.

To reduce runoff, the field of stormwater management focuses on maximizing the designs of stormwater control measures (SCM), which on infiltrates water in the ground or retained water to reduce peak flow. Example of SCMs include bioretention, bioinfiltration, raingardens, pervious pavements, green roofs, and CSW, all of which focuses on reducing peak flows and through capturing runoff volume. Their effectiveness is dependent on how well they retain the increased inflow to prevent runoff higher than predeveloped conditions. There are methods available to accurately quantify the rate of infiltration and volume retained, but the most challenging part is quantifying ET. This research examines a CSW system with the use of a CSW mesocosm to quantify ET, and relate it to the individual weather components.

1.1 Constructed Stormwater Wetland

A constructed stormwater wetland system is similar to a wet pond that incorporates wetland plants in the design. When runoff flows through the CSW, pollutant removal is achieved through settling and biological uptake. Constructed stormwater wetlands are among the most effective stormwater practices in terms of pollutant removal and also offer aesthetic and habitat value (EPA 2006). Constructed stormwater wetlands are designed specifically for the purpose of treating runoff through elongated complex flow path that reduces peak flow over time. The CSW can also be utilized for volume reduction through evapotranspiration, but this process is often overlooked.

Although a CSW system can accommodate a higher volume of water than other SCMs, there are limitations that make the design challenging. The limitations include 1) relatively large amount of space the CSW consumes making it an impractical option on some sites 2) improper designed CSW might become a breeding area for mosquitos 3) CSW require careful design and planning to ensure that plants are sustained after the practice is in place 4) it is possible that CSW may release nutrients during the nongrowing season and 5) designers need to ensure that CSW do not negatively impact natural wetlands or forest during the design phase (EPA 2006).

The CSW on site at Villanova is the model for the mesocosm used in this study. The site is 0.78 hectares with three meanders and a sediment forebay. By having multiple meanders, the flow path is able to be extended for longer retention time. The CSW is planted with herbaceous and woody native plants (Pittman 2011) and is the source of the vegetation used in the mesocosm to quantify the ET.

1.2 Evapotranspiration Overview

Evapotranspiration is a combination of two separate processes where water is lost due to evaporation and used in plant uptake for biological processes (transpiration). Evaporation and transpiration occur simultaneously and are difficult to distinguish, and even more challenging to measure accurately. The rate of ET in a CSW is influenced by several factors which include temperature, relative humidity, solar radiation, wind speed (Allen et. al. 1993), and the availability of water.

1.3 Research and Methodology

There have been numerous empirical and semi-empirical equations published to estimate ET from meteorological data. The various empirical and semi-empirical equations were developed for agricultural crops, which include Thornthwaite, Priestley and Taylor, Penman, and modified Penman-Monteith equations. These equations are often restricted to specific conditions and may not be adaptable to various climate situations. There have been numerous researchers that have analyzed the performance of the various methods in different conditions. As a result, in 1990, the Expert Consultation mentioned by Allen et. al. (1998) determined that the FAO (Paper 56) Penman-Monteith (PM) method is the recommended standard method for definition and computation of ET. The PM defines a reference ET and uses a crop coefficient (K_c) that adjusts ET rates based on the health of agricultural crops throughout their growing seasons. Since the PM equation is used to determine the minimum water need for agricultural crops, it is a different application than a complex CSW environment that includes abundance availability of water and plant species selected for the purpose of up taking water. In this study, several of these equations are examined and adjusted to a CSW environment by calibrating the equations.

In order to perform a comparison on the merit of each predictive equation, evapotranspiration must be quantified to compare with the calculated results. One method is the use of lysimeters, which measures the weight of a mesocosm and any change in weight from the loss of water is equated to the rate of evapotranspiration. The use of weighing lysimeters for the CSW is difficult due to the precision required and the extension of the water table above the ground surface.

A Mariotte bottle is able to provide a solution for the complex goal of having an abundant water source and maintain a water table. The Mariotte bottle maintains a constant water head in the sink end and the source tank (Mariotte bottle) decreases in water level and can be measured to determine water loss.

1.4 Research Objectives

This research thesis focuses on three main goals.

I. *Quantify evapotranspiration in a constructed wetland mesocosm*

Using a Mariotte bottle system, it was possible to quantify the ET from the wetland mesocosm representing the CSW at Villanova University. This allowed for fully saturated soil with a water table that is observed throughout the CSW system. The volume displaced by ET was represented by the change in water level within the Mariotte bottle measured by an ultrasonic sensor.

II. *Use statistical analysis to develop an equation modeling the relationship between climate factors and ET*

A statistical approach is taken to compare how changes in temperature, relative humidity, solar radiation, and wind affected the rate of ET. First, a regression equation is developed for two depths, a 12.7 cm water table set up, and then another for the 7.6 cm water table. To verify if these equations do model successfully show a relationship between weather factors and ET, a calibration was performed. This calibration used a regression equation of the 12.7 cm water table for the first 50 days and then verified to see if the measured ET fits the calibrated equation over a 167 day period.

III. *Evaluate ET equations in current practice using the wetland mesocosm*

Predictive ET equations such as the Hargreaves and the widely used Penman-Monteith have been used for projecting the water demand of agricultural crops. Contrast that to a CSW, where the goal is to extract the volume of water given that there is always availability. In this situation, the goal of ET research is to see how much water is removed.

In order to apply the common practiced ET equations for the CSW, adjustments to the coefficients are calibrated based on a trial and error method. This research will mainly focus on the modified Penman-Monteith technique. First, a crop coefficient will be chosen based on research reviewed by the Food and Agricultural Organization. Next, the calculated results from the calculated values from the adjusted coefficients will be calculated and compared to the measured results. Lastly, the chosen coefficient will be applied to the PM calculated value to compare how well it fits the measured ET data.

1.5 Organization of Thesis

This thesis is organized in to six main chapters. They include the introduction, background and literature review, research methodology, results and discussion, and conclusion. The introduction section describes the background of the stormwater management field and why it is necessary to extend the study of evapotranspiration for constructed stormwater wetlands. In the background and literature review, the focus is on describing evapotranspiration and techniques to quantify it. The research methodology section also includes calculation methods used to predict evapotranspiration. The results and discussion section will go over the data collected over the length of the research project. It includes implementation of the data collected and forming regression models to predict ET along with adjusting the widely used Penman-Monteith equation to fit the results. The application of this study will be discussed and how the outcome of this study can be used to advance the field of stormwater management. Lastly, the conclusion will summarize the study and discuss further research that can be done to produce a more detailed analysis of ET.

2. Background and Lit Review

2.1 Evaporation

Evaporation is the process where liquid is converted to water vapor (vaporization) and removed from the evaporating surface, including lakes, rivers, pavements, soils, and wet vegetation (Allen 2000). For this process to occur, energy is required to change the state of the water molecules from liquid to water vapor. This process is driven mainly by solar radiation, and to a lesser extent, the ambient temperature of the air. The driving force to remove vapor from the evaporating surface is the gradient between the vapor pressure at the surface and that of the overlying atmosphere. As evaporation proceeds, the surrounding air becomes more humid and evaporation process will slow down if the humid air is not transferred to the atmosphere. The replacement of the saturated air with the drier air is a strong function of wind speed (Allen 2005). Therefore, solar radiation, air temperature, relative humidity, and wind speed are all climatological factors that need to be considered when examining the evaporation process.

2.1.1 Penman Method for Calculating Evaporation

Howard Penman developed a method to measure evaporation from an open water surface. Penman's equation (1948) requires daily mean temperature, wind speed, relative humidity and solar radiation.

$$\lambda ET = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}E_a \tag{2. 1}$$

Where Δ is the slope of saturation vapor pressure curve, γ is the psychometric constant, R_n is the net radiation, G is the soil heat flux, and E_a is the "drying power of air." E_a will be defined further in Chapter 3. The term λET represents the flux density of latent heat ($W/m^2 * d^{-1}$)in to the air, in this case evaporation and it is in units of energy (W/m^2) (Penman 1948).

2.2 Transpiration

Transpiration is the process where water is absorbed through the roots of plants and expelled in to the atmosphere. The water vapor is released through the stomata of the plant, which are mainly in the leaf (Figure 2).

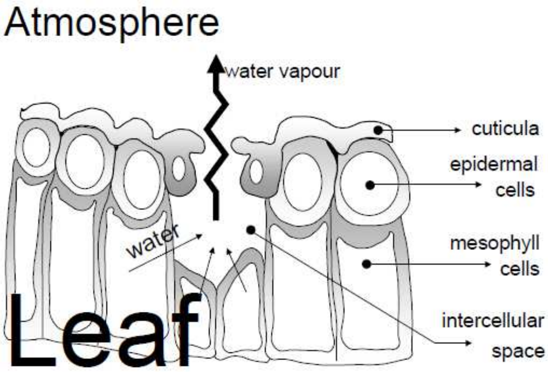

Figure 2: Schematic Representation of a Plant Stomata (Allen et. al. 1998)

Similar to evaporation, there is a vapor pressure gradient between the leaf and atmosphere, which dictates the rate at which water is extracted from the leaf. Different plant species can also affect the rate of evaporation due to the water demand and plant cell structures. In addition, transpiration is dependent on the energy supply consisting of solar radiation, air temperature, air humidity, and wind speed. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate (Allen and Pereira 2000).

Although the process of water vapor leaving the leaf is similar in all plants, the rate and time of day is dependent on the type of photosynthesis specific to the type of plant. The three main types of plants and their ideal conditions are C_3 (best under moist conditions, C_4 (under warm, sunny, dry conditions, and CAM (under desert conditions) (Marietta 2008). In a CSW, most of the plants are type C_3 photosynthesis due to the moist conditions that is ideal for their photosynthesis process.

2.3 Evapotranspiration

The combination of evaporation and transpiration is referred to as evapotranspiration (ET), due to the difficult in separating the two simultaneous processes. The evaporation from a soil surface containing plants is mainly determined by how much solar radiation reaches the soil surface. As plants mature and become denser, the effects of solar radiation on the surface decrease. At this point, transpiration through plants governs and becomes the main process (Figure 2.2).

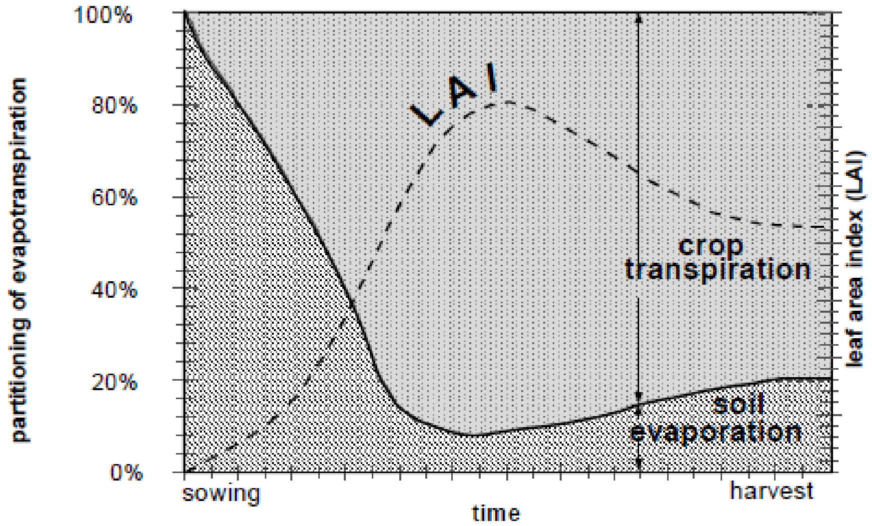

Figure 3: The Partitioning of Evapotranspiration into evaporation and transpiration over the growing period of an annual field crop (Allen et. al. 1998)

The sowing through harvest time can be representative of the plant growth cycle where seeds are planted at sowing and plants are past their maturity during harvest. During the peak mature stage of plant growth, crop transpiration is the highest and evaporation is the lowest. The leaf area index (LAI) at this point is also at its peak. For the periods in between, there is an inverse relationship between transpiration and soil evaporation due to the surface area available for evaporation.

2.4 Factors Affecting Evapotranspiration

There are many factors that must be considered when examining ET. They include atmospheric parameters, crop characteristics, management and environmental aspects.

2.4.1 Atmospheric Factors

The main atmospheric parameters are solar radiation, air temperature, humidity and wind speed. When temperature increases, evapotranspiration rates will increase, especially during the growing season. In the growing season stronger sunlight and warmer air masses along with higher temperatures will cause the plant cells which allow the stoma to open, releasing more water in to the atmosphere. Relative humidity has an inverse relationship with ET, such that higher humidity tends to result in lower ET rates because it is easier for water to evapotranspirate in to dryer air than in to more saturated air. An increase in wind and air speed will result in a higher ET rate because the air movement allows for the saturated air from the released water vapor to be moved. This will allow for drier air to replace the area, which will allow more space for water to be vaporized (USGS 2012). Soil moisture availability is also a factor that will affect ET where less available moisture will result in a decrease to ET. Due to the CSW environment, there is always a water table, which will result in a completed saturated soil with pore pressure.

2.4.2 Crop Characteristics

The development of the crop coefficients has been intensively studied by Richard Allen, co-author of the Food and Agricultural Organization Irrigation and Drainage Paper No. 56 (FAO 56).

There are four primary characteristics that are considered when developing a crop evapotranspiration that include: 1) crop cover density and total leaf area; 2) resistance of foliage epidermis and soil surface to the flow of water vapor; 3) aerodynamic roughness of the crop canopy; and 4) reflectance of the crop and soil surface to short wave radiation (Allen 2003). The crop ET coefficient, K_c, was developed and applied to agricultural situations, and is also generally valid for natural vegetation and conditions including open water, but can have large spatial variability. During the growing season, K_c varies as plants develop, so that the fraction of ground covered by vegetation changes, and the plants age and mature. In addition, K_c can vary according to the wetness of the soil surface, especially when there is little vegetation cover, such that the coefficient will have a high value when soil is wet and steadily decreases as the soil dries (Allen 2003). Figure 4 developed by Allen illustrate the change in K_c during the life cycle of crops and seasonal changes.

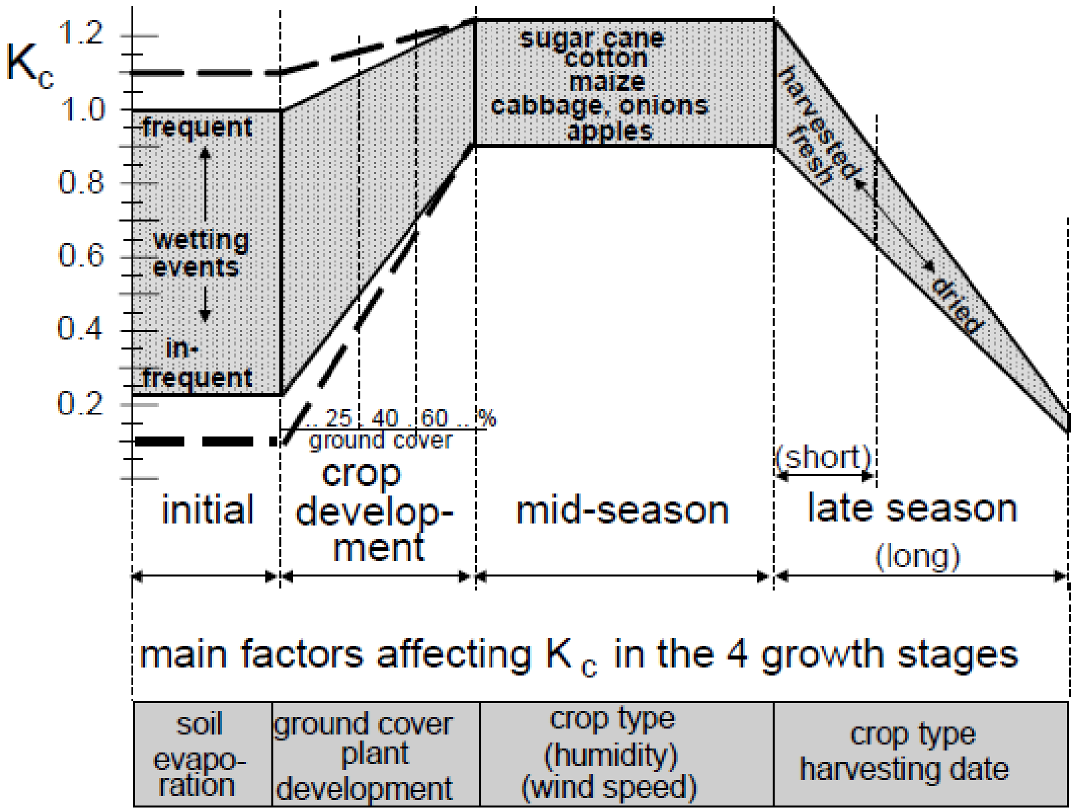

Figure 4: Typical Ranges expected in Kc for the Four Growth Stages (Allen et. al. 1998)

As illustrated in figure 4, the crop coefficient can vary substantially throughout the seasons. In general, at its peak, K_c can be 1.2 and as low as 0.2 during the late season. This crop coefficient serves as a multiplier for use with developed reference ET equations such as the Penman-Monteith.

$$ET_c = K_c ET_o \qquad (2.2)$$

ET_c	=	Crop evapotranspiration (mm/d)
K_c	=	Crop Coefficient
ET_o	=	Reference Crop ET (mm/d)

The steps to calculate ET_c consists of:

1) Identify the crop growth stages, determining their lengths, and selecting the corresponding K_c coefficients
2) Adjusting the selected K_c coefficients for frequent of wetting or climatic conditions during the stage
3) Construct the crop coefficient curve (identifying one K_c value for any period during growing season)
4) Calculate ET_c as the product of ET_o and K_c

In order to determine ETo, the FAO-56 paper recommends that the Penman-Monteith equation to be used, which takes in to consideration the climate parameters and seasonal changes.

2.5 Calculate Reference Crop Evapotranspiration, ETo

2.5.1 Actual, Potential and Reference Evapotranspiration

The three terms that are most commonly used in quantifying and calculating evapotranspiration are actual, potential and reference. There are common misconceptions between the three terms that relate to their description of evapotranspiration.

Actual ET is a function of surface, subsurface, and meteorological conditions. It is the quantity of water vapor evaporated from the soil and plants when the ground is at its natural moisture content (WMO 1992). The most common method to measure actual evapotranspiration is through weighing lysimeters, which use a mass balance method and measures water loss.

Potential and reference ET were developed to eliminate the crop specific changes in the evapotranspiration process (Irmak and Haman 2003). Penman defined potential evapotranspiration as the amount of water transpired by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. This definition of potential ET rate is not related to a specific crop; as a result, it is difficult to conclude a specific rate for ET since well watered agricultural crops may be as much as 10 to 30% greater than that occurring from the green grass (Irmak and Haman 2003).

Reference ET is defined as “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m (4.72 in), a fixed surface resistance of 70 sec m^{-1} (70 sec 3.2 ft^{-1}) and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground” (Irmak and Haman 2003). In other words, reference ET is a calculated value based off of weather conditions, seasonal changes, and type of crops, while potential ET eliminates the crop specific changes in the evapotranspiration process. The most common practice to quantify reference ET is through the Penman-Monteith calculation, which is followed by the Food and Agricultural Organization.

2.5.2 Penman-Monteith Equation

The original PM equation was developed in 1948. This equation combined the energy balance with the mass transfer method and derived an equation in order to compute the evaporation from an open water surface from collected weather data. Included in the PM equation are the aerodynamic resistance, r_a, and bulk surface resistance, r_s, terms that are crop specific (Howell and Evett 2004). The surface resistance describes the resistance of vapor flow through stomata openings, total leaf area and soil surface. The aerodynamic resistance describes the resistance from the vegetation upward and involves friction from air flowing over vegetative surfaces (Allen et. al. 1998). By including the resistance factors, the PM equation can be formed.

$$\lambda ET_o = \frac{\Delta(R_n - G) + \rho_a c_p \frac{e_s - e_a}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \tag{2. 3}$$

λETo	=	Latent-heat flux for ET ($W*m^{-2}$)
Rn	=	Net radiation at the crop surface ($MJ*m^{-2}*d^{-1}$)
G	=	Soil heat flux density ($MJ*m^{-2}*d^{-1)}$
ρ_a	=	Mean air density at constant pressure
c_p	=	Specific heat of the air
e_s	=	Saturation vapor pressure (kPA)
e_a	=	Actual vapor pressure (kPA)
e_s-e_a	=	Saturation vapor pressure deficit (kPA)
Δ	=	Slope vapor pressure curve ($kPA*°C^{-1}$)
γ	=	Psychrometric constant ($kPA*°C^{-1}$]
r_s	=	Bulk surface resistance
r_a	=	Aerodynamic resistance

The λET variable represents the energy required to evaporate water at the specified ET rate and it states that the net radiation input at land surface is used to heat the air, warm the soil, and evaporate water (Healy and Scanlon 2010). The variables that make up the PM equation include all the parameters that govern energy exchange and corresponding latent heat flux (evapotranspiration from uniform expanses of vegetation. These parameters can be measured or calculated from collected climate data.

2.5.3 Penman-Monteith Equation modified by Food and Agricultural Organization

In 1998, the Food and Agricultural Organization published a paper titled "*FAO Irrigation and Drainage Paper No. 56*" written by Richard Allen, Luis Pereira, Dirk Raes, and Martin Smith proposes a modified PM equation estimating reference evapotranspiration that overcomes shortcomings of the previous method and provides values more consistent with actual crop water use data worldwide. As a result, the FAO-56 PM equation is able to provide a standard to which evapotranspiration at different periods of the year or in other regions can be compared and a comparison between other crops.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2. 4}$$

ET_o	=	Reference evapotranspiration ($mm*d^{-1}$)
R_n	=	Net radiation at the crop surface ($MJ*m^{-2}*d^{-1}$)
G	=	Soil heat flux density ($MJ*m^{-2}*d^{-1}$)
T	=	Mean daily air temperature at 2 m height (°C)
U_2	=	Wind speed at 2 m height ($m*s^{-1}$)
e_s	=	Saturation vapor pressure (kPA)
e_a	=	Actual vapor pressure (kPA)
e_s-e_a	=	Saturation vapor pressure deficit (kPA)
Δ	=	Slope vapor pressure curve ($kPA*°C^{-1}$)
γ	=	Psychrometric constant ($kPA*°C^{-1}$)

For equation 2.4, standard climatological records with solar radiation, air temperature, humidity, and wind speed is needed. These measurements should be taken at 2 m above the soil surfaces, if not; a conversion equation will be needed. The FAO Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process (Allen et. al. 2003). By using the FAO PM definition for ET_o, a crop coefficient K_c is needed that is specific to research sites by relating the measured crop evapotranspiration with the calculated as previously discussed. While not necessary for a CSW application, there is also a stress coefficient, K_s, that considers drought and other stress conditions.

2.5.4 Hargreaves Equation

When climate data such as solar radiation, relative humidity, or wind speed are missing, an alternative method to calculate ET_o can be estimated using the Hargreaves equation:

$$ET_o = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a \quad (2.5)$$

Where T is temperature in Celsius and R_a is the extraterrestrial radiation calculated as described in Chapter 3. Both units for ET_o and R_a are in mm/d (Allen et. al. 1998) where the coefficient serves as a conversion factor.

Even though the Hargreaves equation does not require the same variables as the Penman-Monteith equation, there have numerous independent investigations comparing it to different models where it consistently produces accurate estimates of potential evapotranspiration. The comparisons examine methods such as energy balance techniques, the Penman combination equation, or lysimetric observations (Hargreaves and Samani, 1982; Mohan, 1991; Saeed, 1986). The Hargreaves equation especially has a high correlation with the Penman combination equation for estimates of average weekly evapotranspiration in humid regions (Mohan 1991).

2.6 Published Methods of Quantifying Evapotranspiration for SWW

Lysimeters

The most common method to quantify actual evapotranspiration in the field is through using weighing lysimeters. Weighing lysimeters measure changes in the mass a soil sample that may contain crops or plants selected for a study of evapotranspiration. However, lysimeter installations suffer from some serious drawbacks including disturbance of the soil profile, interruption of deep percolation and horizontal flow components and uneven management of lysimeters compared to field soil (Grebet and Cuenca 1991). In addition, there is a high cost associated with using lysimeters due to the load. Most important, the vegetation both inside and surrounding the lysimeter must be perfectly matched with the same height and leaf area index.

2.7 Background on Mariotte Bottle Device

For this research thesis, ET is quantified for a CSW environment that has a constant water table. Therefore, using a lysimeter is not possible. To make the CSW mesocosm set up possible, a device called a Mariotte bottle is used.

The Mariotte bottle allows for delivery of a liquid at a constant pressure. The design was first reported by E.L. McCarthy (McCarthy 1934), but invented by Edme Mariotte in the 17th century. It can be connected to a secondary container (sink) and in this case, it allows for an adjustable water table to the CSW mesocosm connected to the bottle (Cattle and George 1999). Figure 5 illustrates a Mariotte bottle connected to the CSW mesocosm.

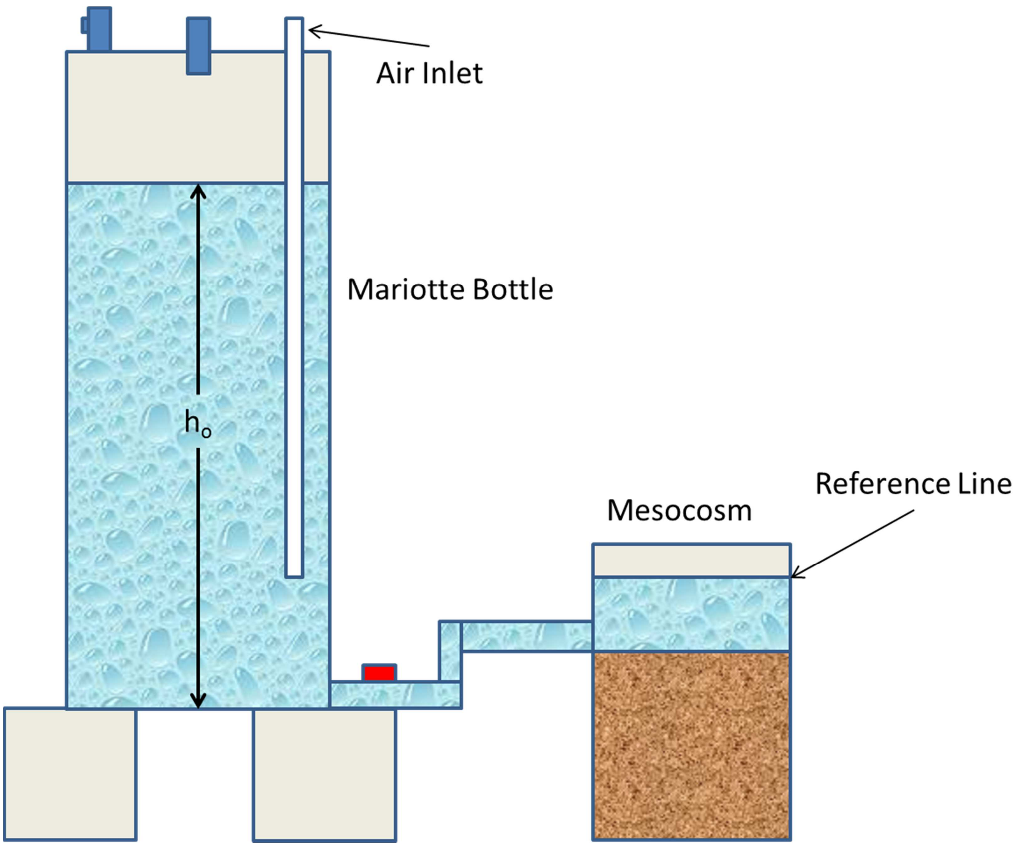

Figure 5: Mariotte Bottle Layout

The only change in pressure or water table is within the bottle, the water table in mesocosm is able to remain constant. The Mariotte bottle is constructed so that it is completely closed with an air inlet tube placed on top. A second opening serves as an outlet for the liquid to be delivered (Marian 2006). A reference line for pressure is established at the bottom of the inlet tube, $P_{ref,}$ and is calculated by:

$$P_{ref} = \rho g h_o + P_{space} \tag{2.6}$$

The variables are defined as ρ is the density of water, g is the acceleration of gravity, h_0 is the difference in height between the top of the water and the bottom of the tube and P_{space} is the pressure in the space above the water. When the outlet is opened, water flows out of the bottle until P_{space} falls to where it equals atmospheric pressure minus $\rho g h_0$, the pressure exerted by the water column. At this point, the water inside the tube has fallen to the bottom of the tube, and the pressure at its bottom opening equals atmospheric pressure. (h_0, decreases slightly during this process) (Marian 2006).

2.8 Statistical Approaches to Estimate Evapotranspiration

One of the objectives for this research thesis is to quantify ET within a CSW. From the measured values, a relationship is developed between the climate data collected to the resulting daily ET rates and compared to the calculated FAO-PM equation 2.4. In order to create a relationship, a statistical approach is taken using correlation and regression analysis.

A correlation analysis is a measure of linear association between two variables (Encyclopedia Britannica 2012). The results are always between -1 and +1 where a correlation coefficient of +1 indicates that two variables are perfectly related in a positive linear sense. A -1 value results in an inverse relationship; a value of zero indicates no linear relationships. Correlation analysis is necessary as it indicates which environmental factor has the highest impact on the resultant ET from the data collected.

A multiple linear regression analysis involves identifying the relationship between a dependent variable and one or more independent variables (Encyclopedia Britannica 2012). The analysis assigns a coefficient for every independent variable (x_i) and forms a linear equation which takes the following form:

$$y = ax_1 + bx_2 + cx_3 + dx_4 + Z$$

Each coefficient (a, b, c, d, etc...) are calculated to form a trend line of the dependent variable so that the best fit is possible. The equation calculates an intercept, Z, which is also important in forming the best fit line for the dependent variable.

This method of using regression analysis with ET as the dependent variable and the environmental factors as the independent is common throughout research studies. The following contains an example that utilizes this statistic approach.

Eagleman, J.R. (1971). An Experimentally Derived Model for Actual Evapotranspiration.

The study published by J.R. Eagle of the University of Kansas used a regression analysis approach to develop a relationship between experimental data from several different climatic regions to actual water loss rates from land surfaces. Three different environmental conditions were studied and combined in to a single model expressing the composite relationship. In addition, some investigation resulted in concluding that ET is also a function of the soil moisture, *MR*, (Demead and Shaw 1962). The author also studied published potential ET equations and assigned an independent variable, *PE.* A cubic function between the soil moisture, potential ET, and the three various environmental coefficients (*A, B, C)* were assigned to equate the actual ET, *AE*. From the data source collected, the author developed Table 1 that varied each coefficient to actual ET for each data set.

$$\frac{AE}{PE} = A + B(MR) + C(MR)^2 + D(MR)^3$$

Table 1: Comparable Regression Coefficients (Eagleman 1971)

A	*B*	*C*	*D*	*PE* (*mm/day*)	*Data source*
0.3440	3.36	−5.34	2.68	2.0	Denmead and Shaw (1962)
0.0870	3.40	−4.11	1.62	3.3	Denmead and Shaw (1962)
0.2180	2.78	−3.28	1.29	3.6	Pierce (1958)
0.0334	2.58	−1.83	0.185	4.1	Denmead and Shaw (1962)
0.2419	1.46	−1.23	0.553	5.1	Eagleman (1963)
0.0186	1.05	1.58	−1.69	5.6	Denmead and Shaw (1962)
0.0361	−0.412	1.93	−0.465	6.4	Denmead and Shaw (1962)
0.0599	−0.359	4.87	−3.62	9.0	Van Bavel (1967)

Concluding the paper, the author claims that a good relationship exists between climates B, C, and D (which are undefined) although there were several distinct different types of vegetation and climate conditions in the analysis. This implies that the general response of these different types of vegetation to their environment was quite similar (Eagleman 1971). He also states that since the moisture changes corresponding to different depths because of the differences in rooting characteristics of the plants, there will be an orderly relationship between actual evapotranspiration, potential evapotranspiration and soil moisture.

3. Research Methods

This section presents on the research methods used, which include the mesocosm set-up and experiment, as well as the statistical methods used to analyze observed data. The experimental procedure consisted of a CSW mesocosm coupled with a Mariotte bottle system that was instrumented to quantify ET. The correlation and multiple linear regression statistical methods were used to determine a predictive equation for ET, and compared to common methods currently employed. There was also calibration of the model regression equation to verify the model's applicability.

3.1 Mesocosm System

A mesocosm of a CSW was developed using a 46 cm diameter barrel filled with soil from Villanova University's CSW to a depth of 61 cm. Plants from the Villanova CSW were used in the mesocosm to simulate a CSW environment. The plants are made up of mostly Sagittarian Latifolia, also known as broadleaf arrowhead. A constant water level was maintained with a Mariotte bottle system to create constantly ponded conditions, replicating conditions found in the Villanova surface flow CSW. Figure 6 are pictures of the Sagittarian Latifolia plant in its early growing stage.

a) Initial Planting of Mesocosm

(June 28, 2012)

b) Two months after planting

(August 28, 2012)

Figure 6: CSW Mesocosm with Plants.

3.2 Mariotte Bottle System and Measuring Devices

The Mariotte bottle system is a device that provides the ability to maintain a constant output water head pressure as described previously. This Mariotte system (described in Chapter 2.8) fundamentally serves as the means for quantifying ET, as the changes in water depth within the Mariotte bottle system reflect the amount of ET from the CSW mesocosm. The Mariotte bottle consists of a closed container 152 cm high and 51 cm in diameter. An ultrasonic sensor (Senix ToughSonic “TSPC” Distance Sensors) threaded through the top of the Mariotte bottle measures the change in water level every 5 minutes. There is a connection for water to the CSW mesocosm connected to the Mariotte bottle bottom. Additionally, there is a pressure release used to release the air build up when the bottle is being filled and a valve used to enable the flow to the mesocosm.

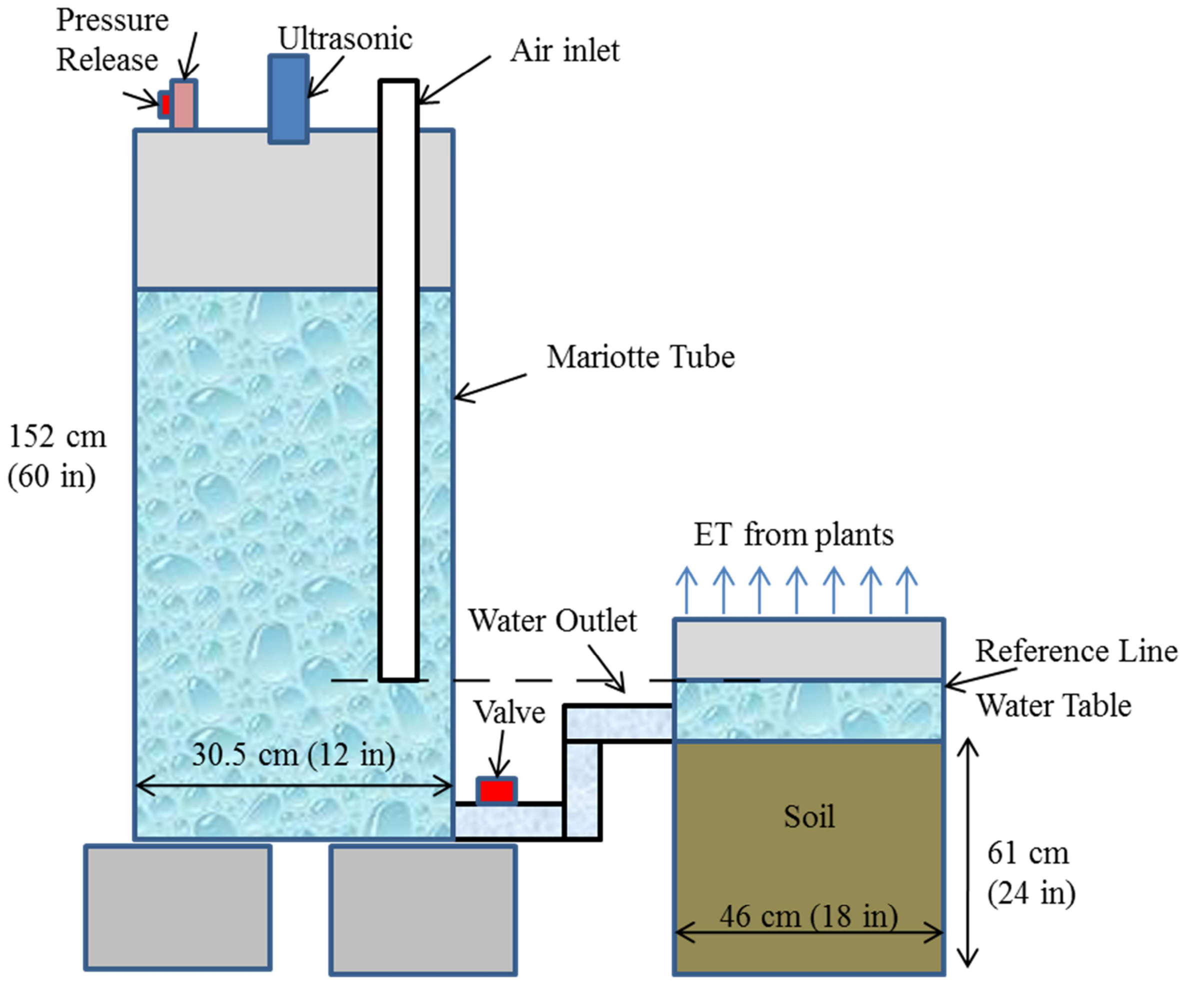

Figure 7: Constructed Stormwater Wetland Mesocosm Set Up

To convert the volume evapotranspirated into a depth over the mesocosm, the change in water level is multiplied by 0.444, which is the ratio of the water surface area in the Mariotte bottle to the water surface area of the CSW mesocosm. For example, a 1 mm depth change in height of the Mariotte bottle represents a 0.444 millimeter change in the mesocosm.

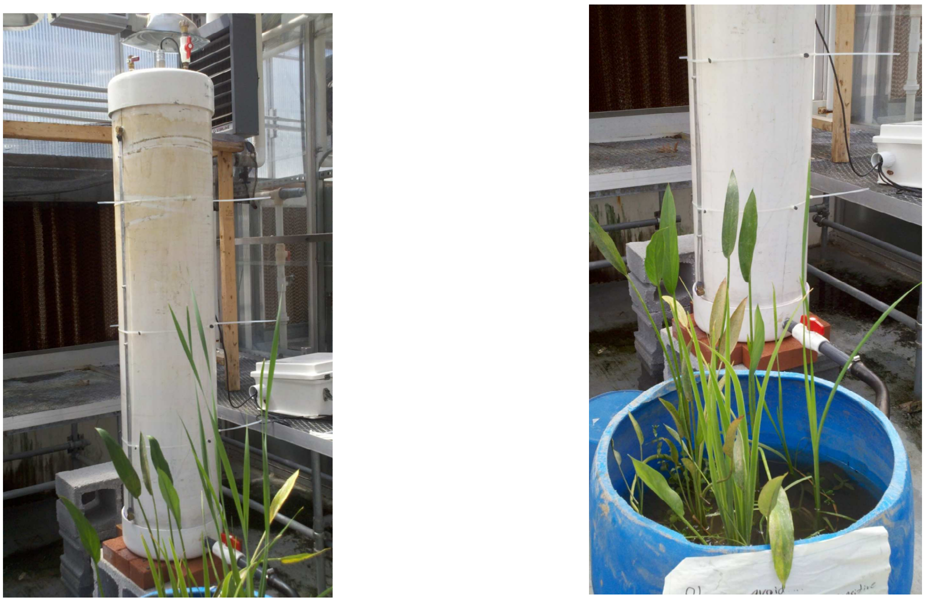

Figure 8: Photos of Mariotte Bottle and CSW Mesocosm (early plant growth)

Evapotranspiration is an energy driven process, in which the energy is derived from climatological parameters, such as temperature, relative humidity, solar radiation and wind. A weather station (*Relative Humidity and Temperature – C.S. HMP60 and I-Button, Solar Radiation – C.S. LI200X Silicon Pyranometer, Wind – 014A-L Anemometer*) was used to measure the different climatological parameters. A Campbell Scientific (CS) Data Logger (CR1000) was used as a central connection to the other instruments to record data continuously at 5 minute intervals. Figure 9 is a picture of where the weather instruments and data loggers were located.

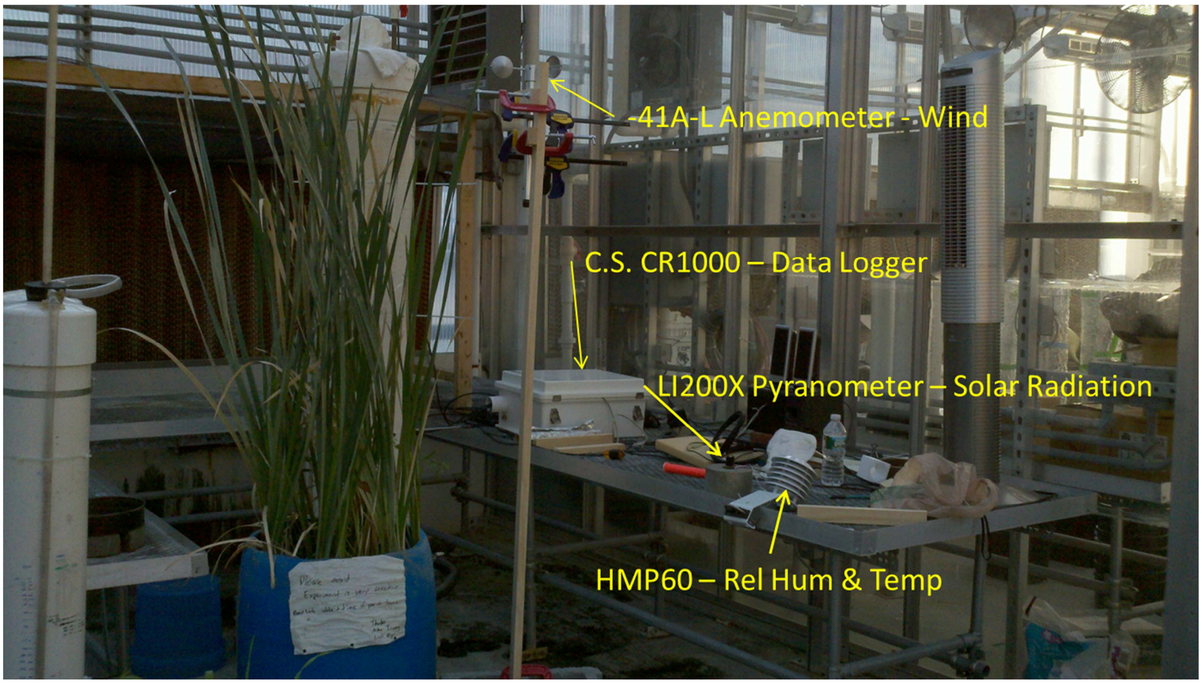

Figure 9: Location of Weather Instruments. Included in this picture is the fan used to apply wind. These instruments were connected to a data logger which collected data every five minutes.

Also, the growth of the plant shown is when the research was at day 36 (Figure 9), which was a little past its matured stage because it is showing a little bit of yellow, a sign of drying.

3.3 Calibration of Ultrasonic for Greenhouse Environment

Since the experimental set up is in a greenhouse environment, heat lamps are used to maintain a constant temperature. As seen in Figure 9, the ultrasonic sensor is on top of the Mariotte bottle, which was directly below a heat lamp. The ultrasonic sensor has internal temperature compensation since the speed of the ultrasonic sensor is dependent on the temperature; the equation 3.1 was used to calculate the speed of ultrasonic waves as a function of temperature (V_{adj}) (NDT 2008).

$$Vadj = 331 + 0.6 * (℃) \tag{3. 1}$$

However, the heat lamps above the ultrasonic sensor yields a temperature about 20 °F higher than the temperature inside the Mariotte bottle (recorded with a temperature probe, specifications are in Appendix A).Therefore, the internal compensation of the ultrasonic is inaccurate and has high fluctuation due to the high temperature caused by the heat lamps. To resolve this problem, the ultrasonic was shielded and the internal temperature compensation was disabled and a new compensation is calculated using the equation 3.2.

$$Hadj = H + (H * \frac{(Vadj - Vunadj)}{Vunadj}) \tag{3. 2}$$

Where H is the original height reading, V_{adj} is the adjusted velocity, V_{unadj} is the unadjusted velocity, and H_{adj} is the adjusted height. Using the new adjustment in height reading, the reading of the ultrasonic is substantially more stable and accurate. Figure 10 is an example of a comparison between unadjusted with the internal compensation temperature enabled and the adjusted reading with it disabled.

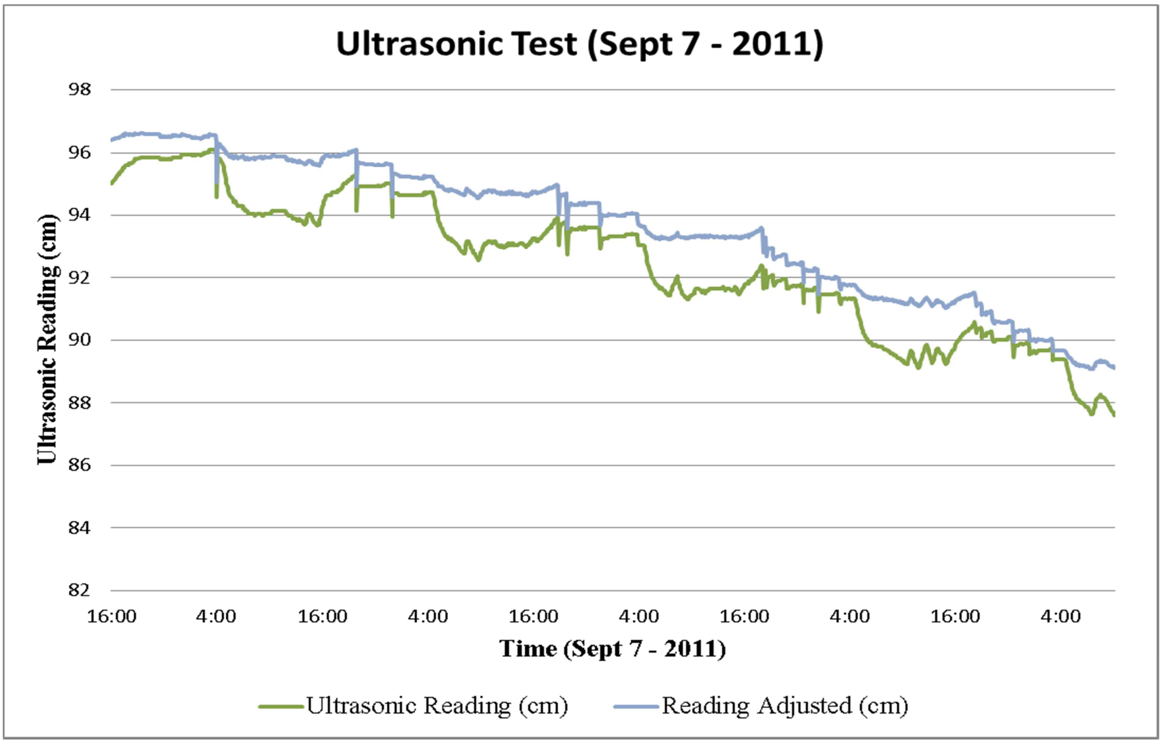

Figure 10: Comparing Ultrasonic Results of Adjusted vs. Nonadjusted

For the ultrasonic without using the equation adjustment for ultrasonic velocity, there is a higher variation in reading than when an adjustment was applied. By adjusting the ultrasonic reading, this allowed for more precise reading of ET so that the values are more consistent.

3.4 Examining Common Practiced Reference ET Equations for Comparison

The third objective of this research project consists of examining the current published equations that are in common use. They consist of the Penman-Monteith, Hargreaves, and Penman equation for evaporation. These predictive equations are based on weather parameters that can be measured from the instruments. Table 2 is a list of the weather parameters and their assigned variables for use in the reference evapotranspiration equations.

Table 2: Weather Parameters Needed For ET Equations

ET Equations	Weather Parameter			
	Temp	Rel. Hum.	Solar	Wind
Hargreaves	✓		✓	
Penman Evaporation	✓	✓	✓	
Penman Monteith	✓	✓	✓	✓

3.5 Using Weather Parameters to Calculate Evapotranspiration

The meteorological factors that determine evapotranspiration were weather parameter collected from the weather instruments. The weather provides the energy needed for vaporization and are a driving force for plant biological processes. The principal weather parameters are as follows.

Solar Radiation ($MJ*m^{-2}*d^{-1}$)

Solar radiation is the energy available to vaporize water and is an important factor in the rate of plant biological processes. The potential amount of radiation that is available is determined by the site location and time of the year. The actual solar radiation depends on the turbidity of the atmosphere and presence of clouds, which reflect and absorb major parts of the radiation.

Air Temperature (C)

An additional effect of solar radiation is when it becomes absorbed by the atmosphere, temperature rises. The sensible heat of the surrounding air transfers energy to the crop which influences the rate of ET. For example, in sunny, warm weather, the loss of water by the ET is greater than in cloudy and cool weather.

Air Humidity (%)

Also called relative humidity, it is the determining factor for the vapor removal. This vapor removal is the difference between the water vapor pressure at the evapotranspiring surface and the surrounding air. When more vapor is able to be removed in the atmosphere, then plants will have more space to excrete water vapor. For example, in hot dry arid regions, plants will consume large amounts of water due to the abundance of energy and the desiccating power of the atmosphere. In humid tropical regions, the high humidity of the air will reduce the amount of potential ET due to the smaller difference in water vapor between the atmosphere and plant surfaces.

Wind Speed (m/s)

The process of vapor removal depends on wind and air turbulence which transfers large quantities of air over the evaporating surface. During the vaporization of water, the air above the evaporating surface becomes gradually saturated with water vapor. If this air is not continuously replaced with drier air, the driving force for water vapor removal and ET rate will decrease. Figure 11 illustrates the effects of a combination of climate factors that will affect ET in a hot and dry and humid and warm climate condition.

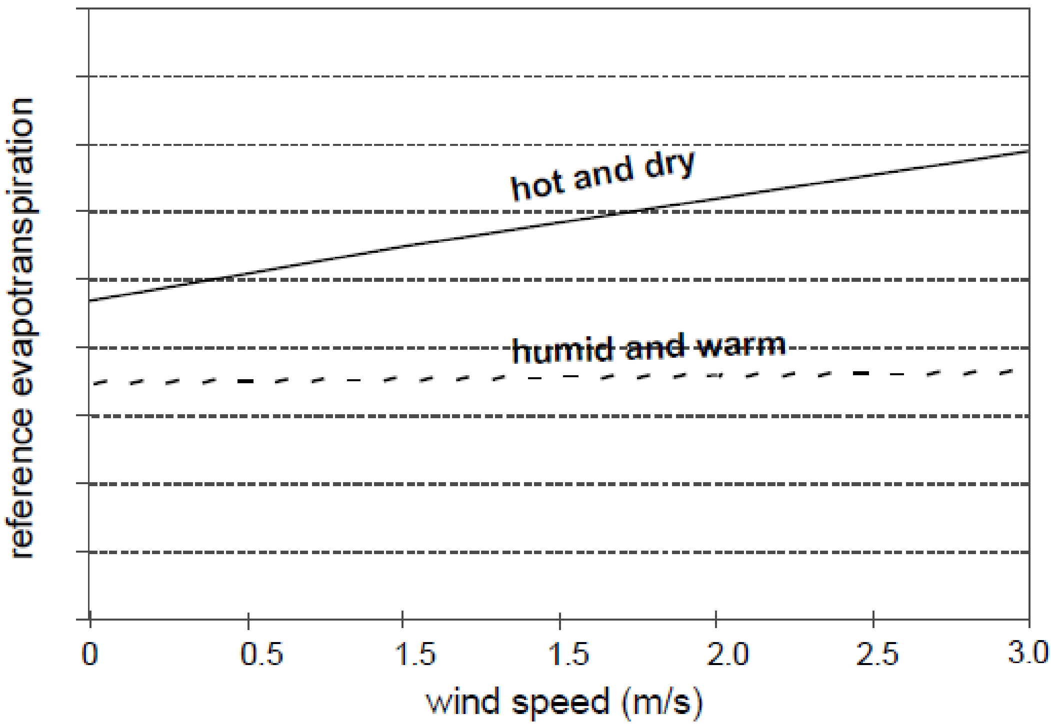

Figure 11: Effects of Wind speed on Evapotranspiration (Allen et. al. 1998)

Temperature, solar radiation, relative humidity, and wind speed all affect one another. Therefore, they are the four main weather components that serve as the basis for calculation of the commonly practiced evapotranspiration equations.

FAO-56 Penman Monteith Equation to Calculate Reference ET

The PM equation published by the Food and Agricultural Organization uses weather data that can be easily measured. The following calculations use different climate parameters to formalize the variables within the PM equation 2.4 described by Allen, et al. (1998).

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

Net Radiation, R_n

The net radiation is the difference between the incoming net short wave radiation, R_{ns}, and the outgoing net long wave radiation R_{nl}.

$$R_n = R_{ns} - R_{nl} \tag{3. 3}$$

Net solar or net shortwave radiation, R_{ns}

The net shortwave radiation is the result from the balance between incoming and reflected solar radiation.

$$R_{ns} = (1-\propto)R_s \tag{3. 4}$$

R_{ns}	=	net solar or shortwave radiation (MJ m^{-2} day^{-1})
α	=	albedo or canopy reflection coefficient, 0.23 typical grass
R_s	=	the incoming solar radiation (MJ m^{-2} day^{-1})

Net long wave radiation, R_{nl}

The net long wave radiation is proportional to the absolute temperature of the surface raised to the fourth power, expressed by the Stefan-Bolzmann law.

$$R_{nl} = \sigma \left[\frac{T_{max,K}^4 + T_{min,K}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \tag{3. 5}$$

R_{nl}	=	net outgoing long wave radiation (MJ m^{-2} day^{-1})
σ	=	Stefan-Boltzmann constant (4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1})
$T_{max,K}$	=	maximum absolute temperature during the 24-hour period (K = °C + 273.16)
$T_{min,K}$	=	minimum absolute temperature during the 24-hour period (K = °C + 273.16)
e_a	=	actual vapor pressure (kPa)
R_s/R_{so}	=	relative shortwave radiation (limited to < 1.0)
R_s	=	measured or calculated solar radiation (MJ m^{-2} day^{-1})
R_{so}	=	Calculated clear-sky radiation (MJ m^{-2} day^{-1})

Clear-sky solar radiation, R_{so}

$$R_{so} = (0.75 + 2 * 10^{-5} z) R_a \tag{3. 6}$$

R_{so}	=	extraterrestrial radiation
z	=	station elevation above sea level (m)
R_a	=	Soil heat flux density (MJ*m-2*d-1)

Extraterrestrial radiation, Ra

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \tag{3. 7}$$

Ra	=	extraterrestrial radiation (MJ m^{-2} day^{-1})
Gsc	=	solar constant = 0.0820 (MJ m^{-2} min^{-1})
dr	=	inverse relative distance Earth-Sun
ωs	=	sunset hour angle (rad)
φ	=	latitude (rad)
δ	=	solar declination (rad)

$$d_r = 1 + 0.33 \cos\left(\frac{2\pi}{365} J\right)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)$$

J	=	Number of the day in year (1-365 or 366)

$$\omega_s = \arccos(-\tan(\varphi)\tan(\delta))$$

Atmospheric Parameters, P

The atmospheric pressure is the pressure that is exerted by the weight of the earth’s atmosphere, where evaporation at high altitudes is promoted due to low atmospheric pressure.

$$P = 101.3 \left(\frac{293 - 0065z}{293}\right)^{5.26} \tag{3. 8}$$

P	=	Atmospheric Pressure (kPA)
z	=	Elevation above sea level (m)

Latent heat of vaporization, λ

The latent heat of vaporization is the energy required to change a unit mass of water from liquid to water vapor in a constant pressure and temperature process. Since it only varies slightly over normal temperature ranges, a single value is used.

$$\lambda = 2.45 \frac{MJ}{kg} \tag{3. 9}$$

Psychrometric Constant, γ

The psychrometric constant is the relationship between partial pressure of water vapor in the air to the actual air temperature. It is derived using constant variables established by past research as published by Allen, et. al. (1998).

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665 * 10^{-3} P \tag{3. 10}$$

γ	=	Psychrometric constant (kPa °C^{-1})
P	=	Atmospheric pressure (kPa) (eq. 3.8)
λ	=	Latent heat of vaporization, 2.45 (MJ kg^{-1}) (eq. 3.9)
c_p	=	Specific heat at constant pressure, 1.013*10^{-3} (MJ kg^{-1} °C^{-1})
ε	=	ratio molecular weight of water vapor/dry air = 0.622

Slope of the saturation vapor pressure curve, Δ

$$\Delta = \frac{4098 \left[0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \tag{3. 11}$$

Δ	=	Slope of saturation vapor pressure curve at air temperature T (kPA °C^{-1})
T	=	Temperature (°C)

Mean Saturation vapor, e_s

$$e^o\,(T) = 0.6109 exp\frac{17.27T}{T + 237.3} \tag{3. 12}$$

$e^o(T)$	=	Saturation vapor pressure at the air temperature T (kPA)
T	=	Air temperature (°C)

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \tag{3. 13}$$

e_s	=	Mean saturation vapor (kPA)

Actual Vapor pressure, e_a

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2} \tag{3. 14}$$

e_a	=	Actual vapor pressure (kPA)
RH	=	Relative Humidity (%) (daily max, min)

4. Results and Discussion

Based on the methodology presented, ET was measured on a total of 167 days and compared with current predictive ET calculation equations. The measured ET from the CSW mesocosm, as previously outlined, was measured by the change in water level of the Mariotte bottle as recorded by the ultrasonic sensor. The water level change in the Mariotte bottle was converted into a volume change that was converted to the ET from the mesocosm, which is done by a ratio of surface areas (i.e. 0.444).

$$ET_{mesocosm}\left(\frac{mm}{d}\right) = 0.444 * \Delta H_{Mariotte} \tag{4. 1}$$

In addition to the results of the ET observed in the mesocosm, this chapter will discuss the observed ET related to the climate data recorded, the development of a relationship of climate factors to ET results using regression analysis, and calibration of commonly practiced equations in order to fit measured ET results

4.1 Quantified Results

The first phase consisted of a 12.7 cm (5 in.) water table and ran for 68 days. During the second phase the water table level was adjusted to 7.6 cm (3 in.) for 45 days. For the third phase the water table level was restored to 12.7 cm for to make a comparison between the seasonal changes and plant livelihood. Throughout these phases, wind is controlled between an insignificant presence to a measured speed of about 2 m/s. In between these phases, the plant maturity was observed in order to develop a performance adjustment similar to that of the crop coefficient K_c from the Penman-Monteith equation. Table 3 shows which parameters could be varied or were naturally part of the study.

Table 3: Varying Parameters of ET Study

	Varying Parameters					
	Temp	Rel. Hum.	Solar	Wind	Water Depth	Plant Health
Controllable				✓	✓	
Uncontrollable	✓	✓	✓			✓

The uncontrollable parameters allow a simulation of the variation in weather parameters, which is important in order to provide as much of a natural condition as possible. There was a change in daily ET when wind and water depth was adjusted throughout the study. Figures 12-14 illustrates the daily ET along with measured weather parameters for each individual phases. Daily average pan evaporation result is also shown from using a load cell is also shown so that a comparison between evaporation and transpiration can be developed.

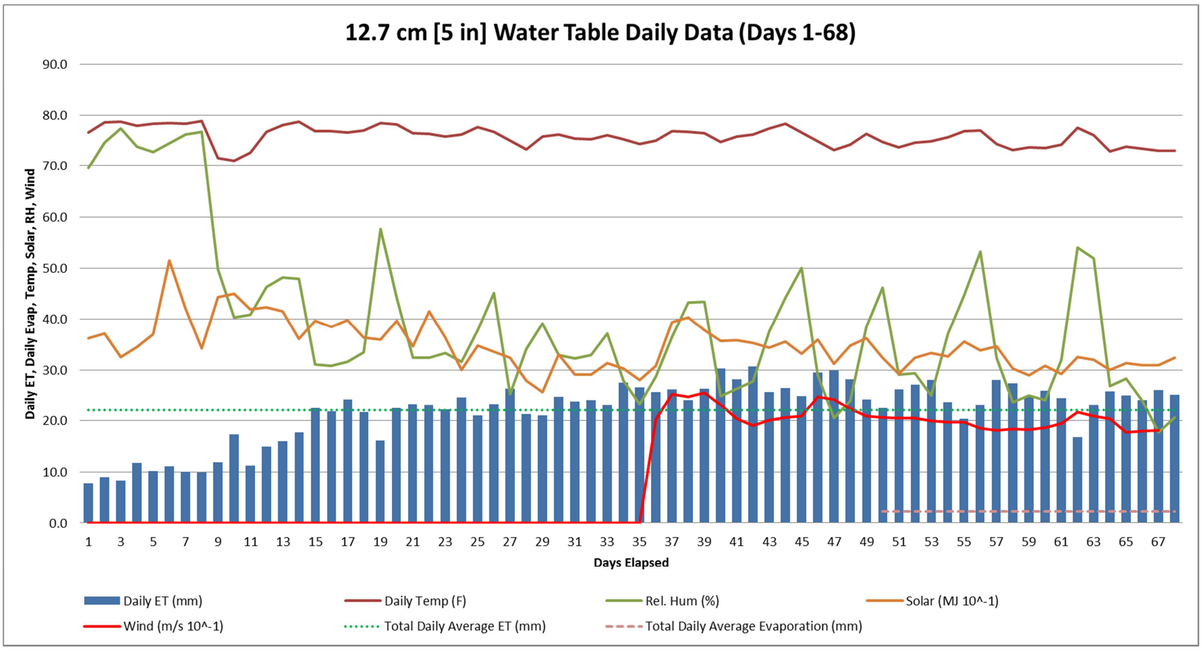

Figure 12: Results for Phase 1 (Days 1-68)

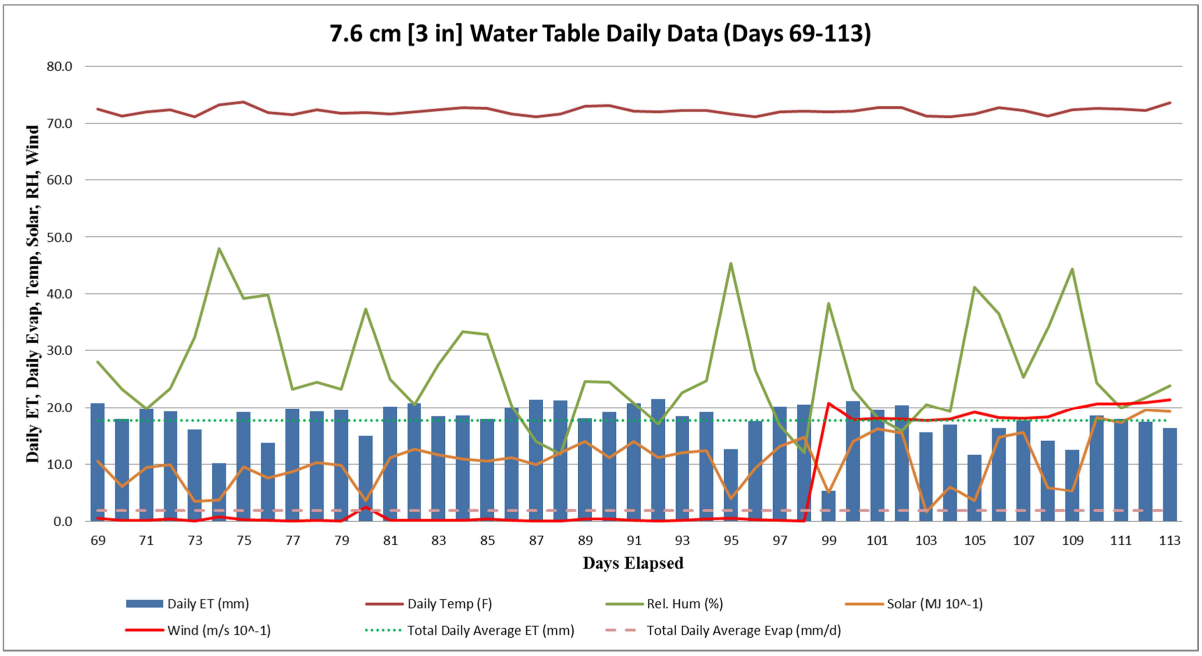

Figure 13: Results for Phase 2 (Days 69-113)

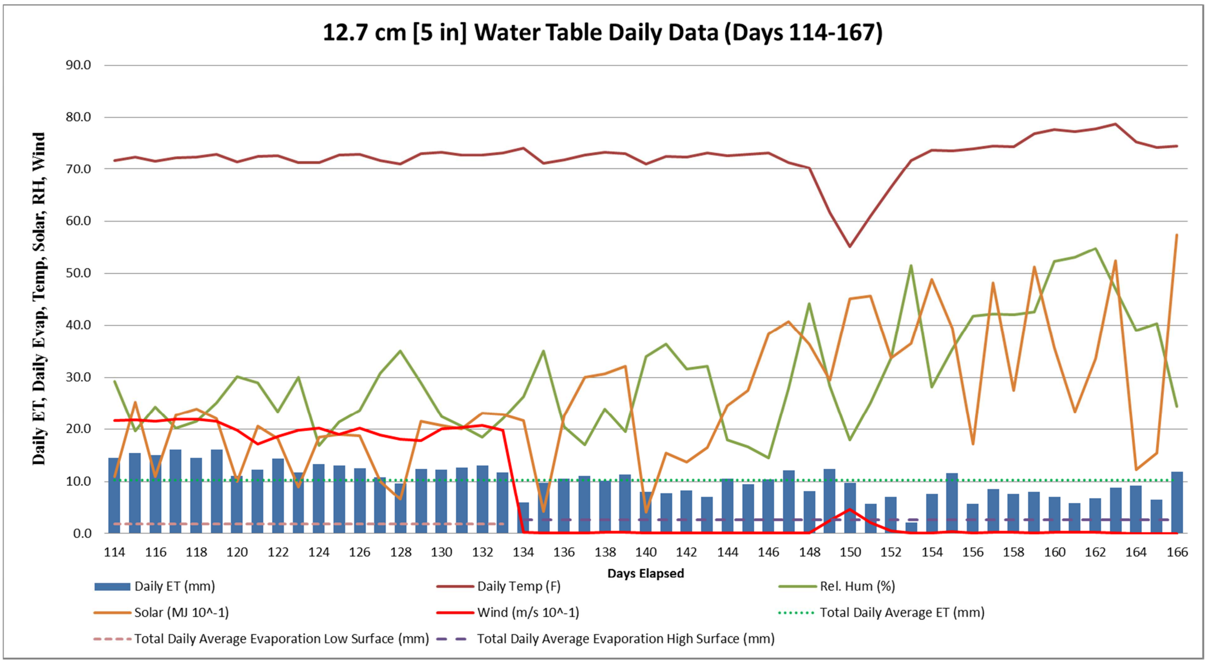

Figure 14: Results for Phase 3 (Days 114-167)

Temperature throughout the study did not vary substantially, staying around 70 through 80 degrees Fahrenheit (294 to 300 Kelvin). The steady rate was due to the experiment being set up within a greenhouse that maintains a constant temperature for plant growth throughout the year.

Relative Humidity varied over a large high range except during the first few days of the research. These high relative humidity values are a result of the cooling system of the greenhouse, which uses a water cooling system that has fans spreading the water vapor. Therefore, the water vapor will cause the air to be more saturated, resulting in an increase in relative humidity.

Solar Radiation during phase1 was around 3.5 $MJ*m^{-2}*d^{-1}$ but declined in phase 2. The decline of phase 2 decreased because the heat lamps used in the greenhouse was turned off during the winter months, in addition to the shorter daylight hours. In the middle of phase 3 around day 140, solar radiation increased again as Spring began.

Wind is added on day 35 of the experiment in order to develop a relationship between ET and the presence of wind and without. The wind is created by using a tower fan that generates average wind speed (between 1.5 to 2.5 meters per second), which is taken from the data of a green roof at Villanova University..

Table 4 shows the maximum and minimum and average for each parameter to show how conditions differ throughout each phase.

Table 4: Average, Maximum, and Minimum of Weather Conditions

	Temp (F)			**Rel. Hum (%)**			**Solar ($MJ*m^{-2}*d^{-1}$)**		
	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Phase 1	76	79	71	40	77	18	3	5	3
Phase 2	72	74	71	26	48	12	1	2	0
Phase 3	72	79	55	30	55	15	3	6	0

Evaporation averaged around 2 mm/d during phase 1, but in phase 2 and 3 daily average value was approximately 3.5 mm/d. The increase in evaporation for phase 3 was due to filling up the pan evaporation bucket an inch from the top, rather than a couple of inches from the bottom in. The higher water elevation allowed for the water surface to be exposed to wind and drier air. When the surface level was a couple inches from the bottom, the average evaporation was 1.8 mm/d comparing to 2.7 mm/d when it was filled to the top.

There is a noticeable difference in the daily ET between each phase with phase 1 having the highest at an average of 22 mm/d while phase 2 and phase 3 were approximately 18 mm/d and 10 mm/d, respectively. Although a change in the water table from 12.7 cm to 7.6 cm from phase 1 to 2 could have contributed to the decrease, further investigation of the data concluded that it was mainly the plant growth cycle. As phase 2 began in December 2011, the plants started showing signs of dryness, representing maturity. Therefore, when the plants are past their growth, ET starts to decrease because they do not need as much water for growth. The next section illustrates the health of the plants throughout the research.

4.2 Plant Health and Growth

Visual observations were made about the plant maturity. During the first phase of the experiment the plants were at the height of the growing season, as seen in Table 5 (phase 1) with full, dense plants. During the second and third phase the plants started to die due to the natural plant cycle and a bug infestation that was noted on day 118 (February 6, 2012). Note in Table 5 (phase 2) that the plants are not as lush as in phase 1 and there are several brown stalks. A slight difference in the daily average ET (around 5 mm/d) between the water tables is demonstrated at phase 2. Once it switched back to 12.7 cm in phase 3, the daily ET showed a drastic drop as the majority of the plants showed signs of dryness.

Table 5: Picture Timeline of Plants (Phase 1-3)

Picture Timeline of Plants – Phase 1 (September 21 2011 thru December 12 2011)		
		
September 29, 2011 Day #8	October 17, 2011 Day #17	November 29, 2011 Day #56

Table 5: Picture Timeline of Plants (cont.)

Picture Timeline of Plants – Phase 2 (December 16 2012 thru February 2 2012		
		
December 22, 2011 Day #75	January 5, 2012 Day #88	January 23, 2012 Day #105

Picture Timeline of Plants – Phase 3 (February 2 2012 thru March 26 2012)		
		
February 7, 2012 Day #119	March 1, 2012 Day #141	March 27, 2012 Day #166

The difference in ET throughout the life of the plants is previously discussed and can be represented with the Penman-Monteith crop coefficient K_c. For the different ET results between the two water tables (21 mm/d for 12.7 cm and 17 mm/d for 7.6 cm), a hypothesis that can be drawn is that more pore water pressure allows for a faster plant uptake process, which will be difficult to prove. Based on the picture timeline, the difference in the average ET rate through the phases is most likely due to the maturity of the plants. When the plants are more matured, they do not require as much water as their growth stage.

4.3 Statistical Analysis to Develop Relationship Equation of Results

In order to develop a relationship between the climate factors measured to the quantified ET, statistical analysis methods must be used. The first step is to see how the weather parameters affect ET through a correlation analysis. Following, a multiple linear regression model is developed.

4.3.1 Correlation Analysis

In a correlation analysis, two numbers are produced. First, a value is given on the magnitude of the association, which is similar to a sensitivity relationship, and this is the correlation value. Next, a percentage is given for each independent variable (temperature, relative Humidity, solar Radiation, and wind Speed) that identifies their individual contribution to the dependent variable, in this case, the ET measured. This correlation analysis is presented in Figures 15 and 16 for the 12.7 cm (5 in.) during the growing season, the 7.6 cm (3 in.), and the 12.7 cm water table as plants are past their matured stage.

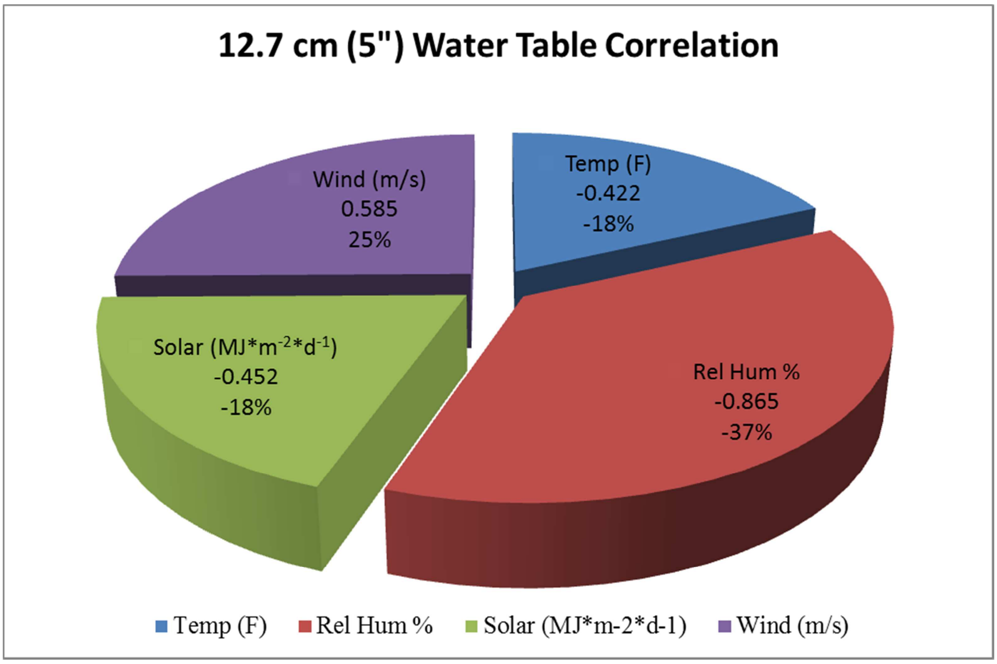

Figure 15: 12.7 cm WT Correlation Analysis

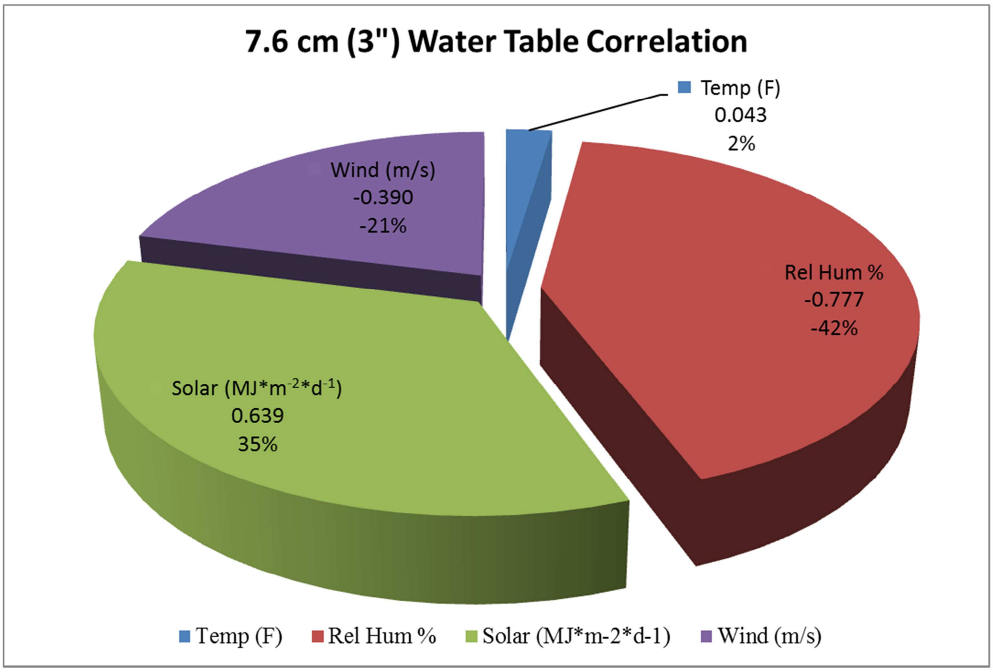

Figure 16: 7.6 cm WT Correlation Analysis

The correlation for the 12.7 cm (5 in) water table shows that relative humidity has the highest contribution with a sensitivity magnitude of -0.865, which supports the conclusion that it is the governing climate factor of ET, as previously discussed. This calculation agrees with the Penman-Monteith equation where the actual air vapor pressure variable, e_a, which is calculated by relative humidity data, is subtracted and causes ET to be less. Therefore, with higher relative humidity, there will be a decrease in ET due to a smaller water vapor gradient.

Temperature and solar radiation are very similar in sensitivity and have a contribution of 18% (but have a negative value). In the instances where the correlation coefficient is expected to have a positive impact on ET, a driving factor such as relative humidity causes it to have an inverse relationship. This is due to days where solar radiation and temperature increases, but relative humidity does also. Since relative humidity has an inverse role, it causes the ET to be low even though temperature and solar radiation increased relatively. Wind has a sensitivity value of 0.585, which is relatively high and shows a significant contribution of 25%. All of these factors may play a role in reducing the effects of temperature due to their stronger influence on ET.

For the 7.6 cm (3 in) water table, relative humidity is similar to the 12.7 cm water table, where it is the prevailing factor with a sensitivity value of -0.777. With the water table at 7.6 cm, temperature has an insignificant sensitivity of 0.043 and only a 2% contribution. A theory is that the heat lamps in the green house were off but the temperature was maintained steady at 72°F. Therefore, the insignificant contribution is a result from the lack of variation in the environment temperature. The temperature during phase 2 was a steady 73 °F with only a 2 degree variation. The average temperature during phase 1 was 76 °F but could vary 5 degrees. The higher variation is the reason why the contribution percentage for temperature in phase 1 was higher than phase 2.

Solar radiation in the 7.6 cm water table has a similar sensitivity to the 12.7 cm water table but shows a positive relationship with a higher contribution percentage. The positive association demonstrated is similar to the commonly practiced reference ET equation such as the Penman-Monteith. In addition, it has a higher role compared to the 12.7 cm water table, which can be due to the inactivity of the heat lamps during the dates of which the 7.6 cm water table was set up. Since the heat lamps are off, the variation in solar radiation day by day is small (approximately 0.5 $MJ*m^{-2}*d^{-1}$), and the only source is from the sun. The sun radiation has a much stronger effect than heat lamps, the small differences plays a significant contribution. In the case where heat lamps were turned on, the instrument that is used detects the high degree of radiation which is shown in the high variation but the heat lamps do not have as much of an impact on plant processes when compared to the sun radiation. The solar radiation from the pyranometer measured a max of 5 $MJ/m^2/d$ and a minimum of 3 $MJ/m^2/d$ in phase 1 but only 1 MJ/m2/d for max and 0 for minimum for phase 2. Therefore, the maximum in phase 1 is due to the lights but the lighting might not have as much effect as just the sun but the instrument does not know the difference between artificial and natural solar radiation which has a greater effect. From the correlation analysis, the percentage of contribution for solar radiation is greater in phase 2 than 1, therefore showing that the artificial lighting does not have as much as effect as natural lighting.

Wind shows a 22% contribution but a negative sensitivity value of -0.383, which is the opposite of the 12.7 cm water table set up. An explanation is since these are during the winter months and the plants showed maturity past their growing peak and are drying out, they do not need as much water for biological processes. Therefore, as the plants become more mature, ET values become smaller, and although wind is added, it is unable to keep up with the rate at which ET is slowed from plant maturity.

The difference in sensitivity and contribution magnitudes when comparing the 12.7 cm and 7.6 cm water tables is due to climate factors that are governing, such as relative humidity, or from the maturity of the plant performance. In order to demonstrate better support for this theory, a contribution analysis is performed using the Penman-Monteith Equation in the FAO-56. Figure 17 is an illustration of the role of temperature, relative humidity, solar radiation, and wind speed from a correlation analysis of the Penman-Monteith reference ET equation using measured data.

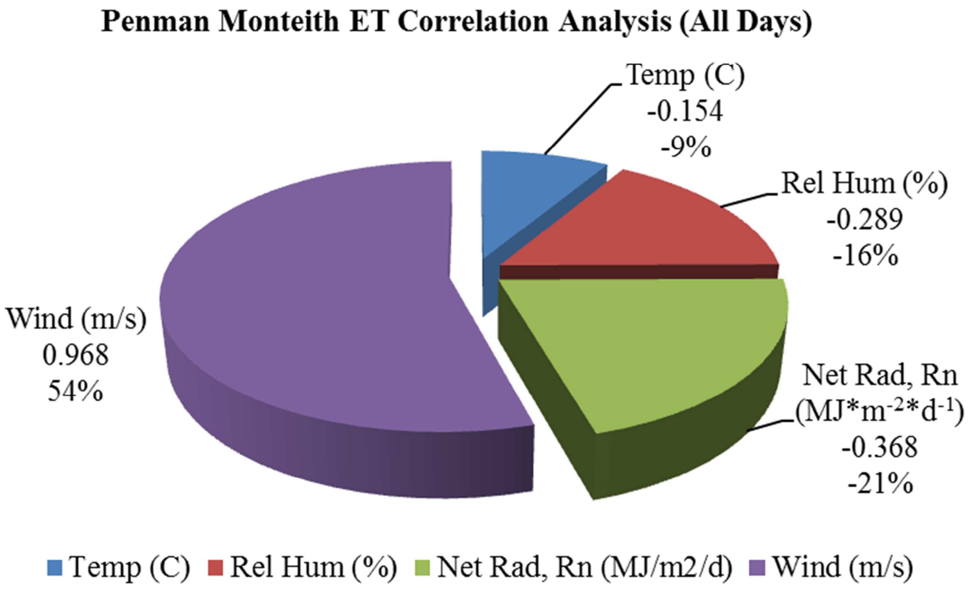

Figure 17: Correlation Analysis of PM using Measured Data

The correlation analysis of the Penman-Monteith reference ET equation shows that temperature has a negative correlation but also the smallest lowest sensitivity. This can be caused by more significant parameters, such as relative humidity, that reduces ET even when temperature is increasing as was seen in the previous correlation analysis. Relative humidity has a negative correlation and a significant contribution value, similar to the correlation analysis of actual measured ET results. The major difference is that the PM equation weighs wind speed much more than the actual data results of the experiment.

Wind speed demonstrates a high sensitivity and contribution percentage (0.97, 54%) for the Penman-Monteith equation. Reasoning for this is due to the agriculture purposes of the PM equation, there is always a presence of wind on crop fields. Since the experiment uses a tower fan, wind does not spread as evenly as it would on the field, which may affect the correlation of the different water table analysis. Also, since crop fields are outside, the data for the PM equation may only be measured when plants are in their growing seasons. From this, wind does have a positive and significant contribution as seen from the phase 1 with a 12.7 cm water table which took place when plant growth prospered.

The net radiation (R_n) is used because this not only accounts for the solar radiation but also for the day of the year. Naturally, plant processes are slowed during the colder seasons because they are unable to survive the cold, therefore a later day of the year will result in less ET. For this research, since it was in a greenhouse, the plant processes is slow when they are past their maturity regardless of the day of the year but instead the growth cycle is accounted for. From this conclusion, in the PM equation, the amount of measured solar radiation is not as important as the day of the year but this concept will prove inapplicable for this research since the plants have a different cycle.

An analysis is illustrated (Figure 18) to demonstrate this theory, which shows that the measured solar radiation (R_s) is indeed, has less of an impact when comparing to the impacts from the day of the year.

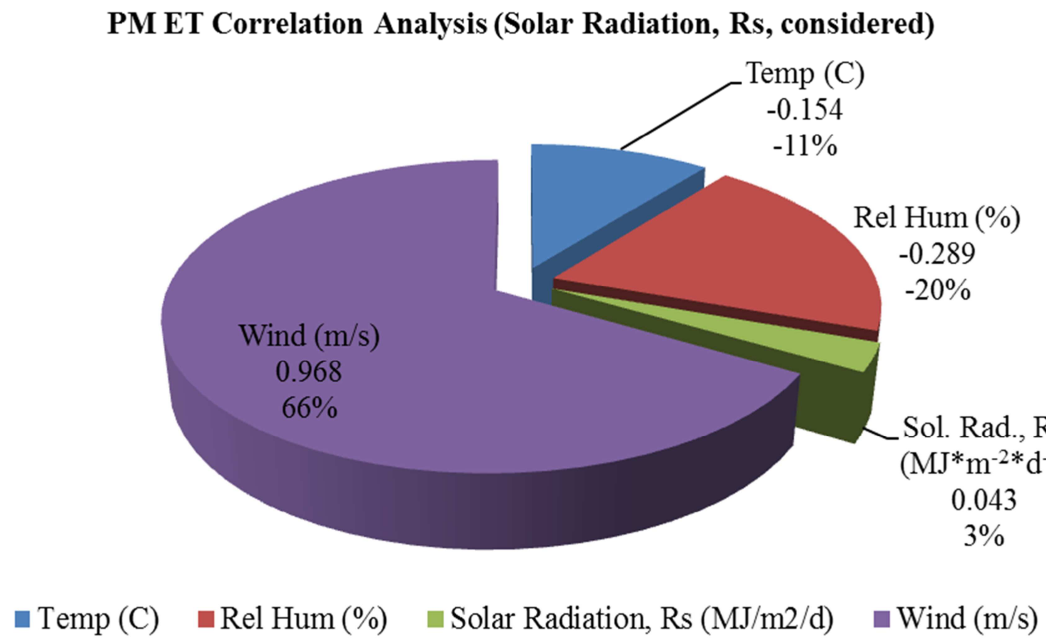

Figure 18: Correlation Analysis of PM using Measured Incoming Solar Radiation

Overall, relative humidity shows a significant impact on ET. Solar radiation is also a major factor, but it is heavily influenced by day of the year when analyzing ET with the PM equation. Temperature does not show a significant impact whereas wind speed does have an impact, but is also affected by the maturity of the plants. By understanding the sensitivity and impact of each climate factors to evapotranspiration from a correlation analysis, ET can be roughly estimated based solely on climate factor. In order to have a better prediction of ET, a multiple linear regression model is created to serve as a calculation tool for evapotranspiration based on climate factors.

4.3.2 Multiple Linear Regression Modeling

As previously discussed, a multiple linear regression model develops a relationship between two or more independent variables to a dependent variable by fitting a linear equation to the observed data. Every independent variable (climate factors), x, is associated with a dependent variable, y, as ET. A regression model assigns a best fitting coefficient for each variable to make a linear line. The second part of the regression model is the intercept point, which dictates the outcome of the data set. Below is a model of the results of a multiple linear regression model with the measured data identified.

$$y = ax_1 + bx_2 + cx_3 + dx_4 + Z \tag{4. 2}$$

y	=	Daily Reference ET (mm/d)
x_1	=	Temperature (F)
x_2	=	Relative Humidity (%)
x_3	=	Solar Radiation ($MJ/m^2/d$)
x_4	=	Wind Speed (m/s)
Z	=	Intercept of Regression Line
a,b,c,d	=	Coefficients of independent Variables

Figures 19 and 20 illustrate the results of the regression modeling for phase 1 and 2. The ET regression coefficients on the x-axis is the sum of the climate factors multiplied by their according coefficients developed by the regression analysis; that is the first four terms on the right hand side of equation 4.2. In order to calculate the daily ET, the intercept is added to the reference ET regression coefficient. The calculated reference equation is then compared to the measured ET to illustrate how well the calculated ET fits the measured. Table 6 shows the results of the regression analysis of the 12.7 cm and the 7.6 cm water table. Also, the results of the calibrated version of the 12.7 cm water table are shown, which will be elaborated in the next section.

Table 6: Statistical Analysis Results

Regression Statistics			
Statistics	**12.7 cm**	**7.6 cm**	**12.7 cm Cal**
Multiple R	0.945	0.885	0.963
R Square	0.892	0.783	0.928
Adjusted R Square	0.885	0.760	0.921
Standard Error	2.024	1.665	1.852
Observations	68	43	49

Regression Coefficients			
Graph	**12.7 cm**	**7.6 cm**	**12.7 cm Cal**
Intercept	-36.601	10.438	-22.058
Temp (F), a	0.983	0.149	0.820
Rel Hum (%), b	-0.349	-0.204	-0.348
Solar (MJ/m^2/d), c	-1.093	2.782	-1.673
Wind (m/s), d	1.875	-1.373	2.187

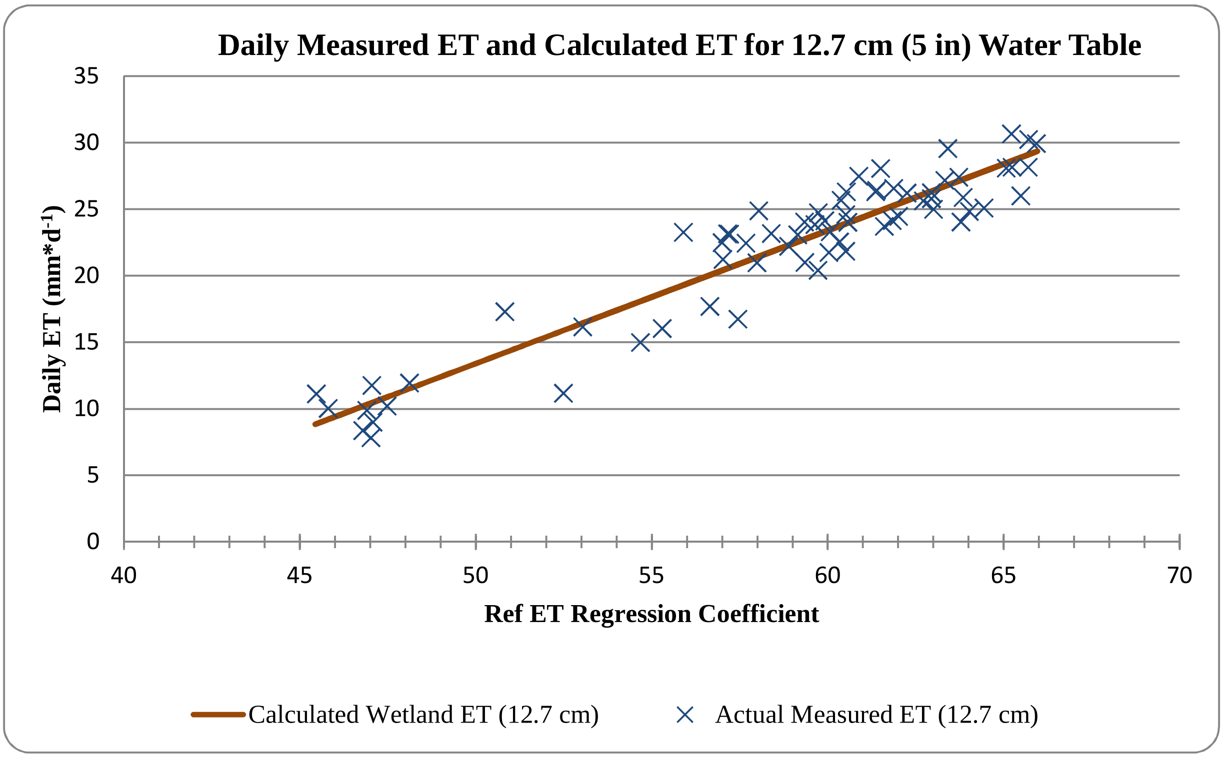

Figure 19: Daily Measured ET and Calculated ET for 12.7 cm (5 in.) Water Table

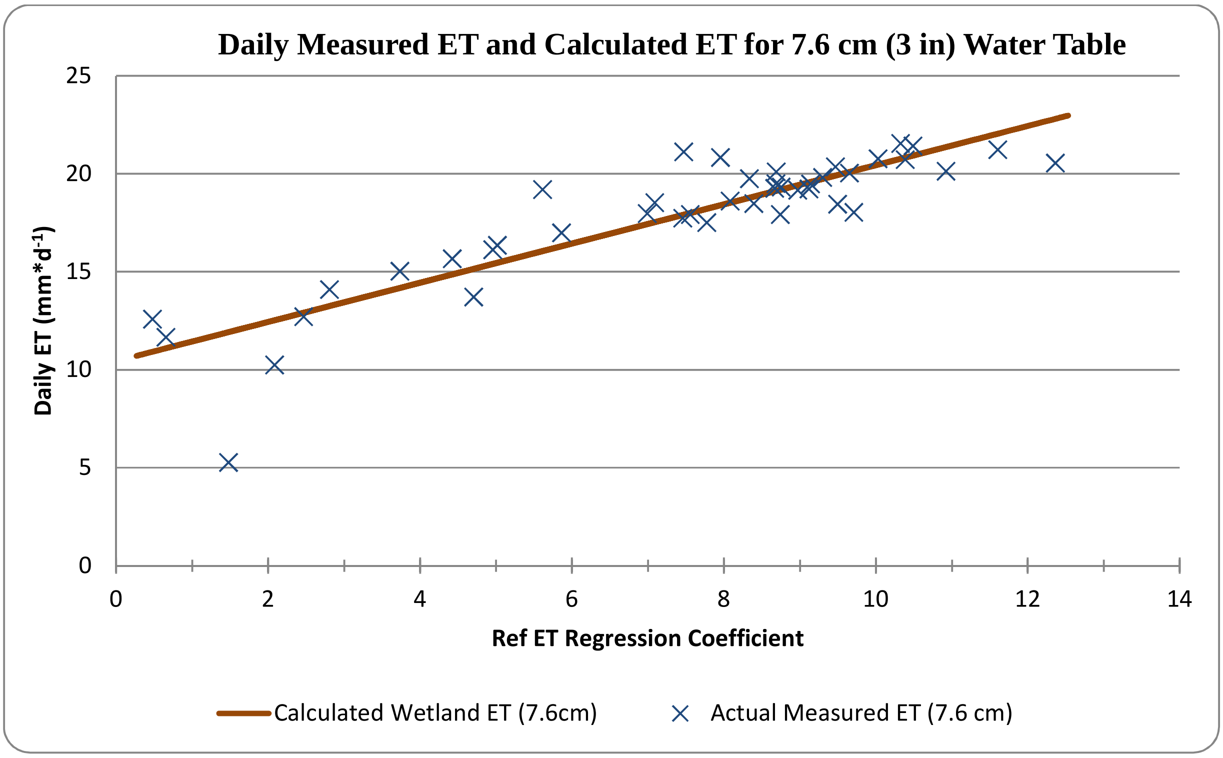

Figure 20: Daily Measured ET and Calculated ET for 7.6 cm (3 in.) Water Table

From Figures 19 and 20, the observed data shows that it has a highly fitted linear relationship based on the R^2 value with the daily measured ET. This means that the independent variables (climate factors) have a relatively defined relationship with ET.

To calculate the expected ET, the coefficients of the weather parameters and intercept are used to develop a best fit line. As shown in Figures 19 and 20, the line of best fit considers the variation of measured weather data and the resulting ET, to develop the closest trend. The equation for the best fit line of the 12.7 cm water table (phase 1) is:

$$Calc\ ET\ = 0.983(T) - 0.349(RH) - 1.093(Solar) + 1.875(Wind) - \ 36.601 \quad (4.3)$$

Similar to the trend of the correlation analysis, the 7.6 cm water table (phase 2) shows different linear relationship demonstrated below.

$$Calc\ ET = 0.149(T) - 0.204(RH) + 2.782(Solar) - 1.373(Wind) + 10.44 \quad (4.4)$$

Comparing the two different water table sets of coefficients, the most noticeable difference is the intercepting point in addition to signs and magnitude of coefficients. Some explanation behind these differences is the water table may have an effect on the rate of ET as previously described. Also, since the duration of the 7.6 cm water table was set up after the 12.7 cm test set up, the plants began to experience a declining stage which resulted in small quantities of ET per day, therefore affecting the regression coefficients.

4.3.3 Calibration of Regression Model

In order to confirm that regression model can serve as a prediction tool, a calibration of the equation was investigated. For the calibration, the 12.7 cm water table data was used and a regression equation is developed for the first 49 consecutive days, with 36 days without wind and another 13 with wind. This calibrated equation is then used to input collected climate data and the calculated ET is then compared to the measured ET for days 50-68 and days 114-166 as verification. For the days of 114-166, a crop coefficient of 0.42 (selected based on observed maturity of plants from the Penman-Monteith crop coefficient) was applied following the instructions of Allen et. al (1998) to add a crop coefficient as plants mature. During this later time period, the plants were in their late maturity; therefore, ET is not as high. The statistical results of the calibration are in the Table 7 for the calibration for days 1-49.

Table 7: Statistic Results for the Calibrated Data (Days 1-49)

Statistics	5" Calibration
Multiple R	0.963
R Square	0.928
Adjusted R Square	0.921
Standard Error	1.852
Observations	49.000

The selected calibration of days 1-49 was chosen because it produced the highest R^2 value of 0.92 and has a variety of days where wind was applied and not. The result of the regression analysis produced the following equation that serves as the best fit line for the measured ET for days 1 thru 49.

$$Calc\ ET\ = 0.82(T) - 0.35(RH) - 1.67(Solar) + 2.187(Wind) - 22.06 \qquad (4.\ 5)$$

Equation 4.5 was then applied to the weather data sets for verification using days 50-68 and days 114-166 with a crop coefficient of 0.42, all of which had a 12.7 cm water table. Comparing equation 4.5 with equation 4.2 for the 12.7 cm water table, they are only have a slight variation in coefficients. Figure 21 illustrates a comparison between calculated and measured ET.

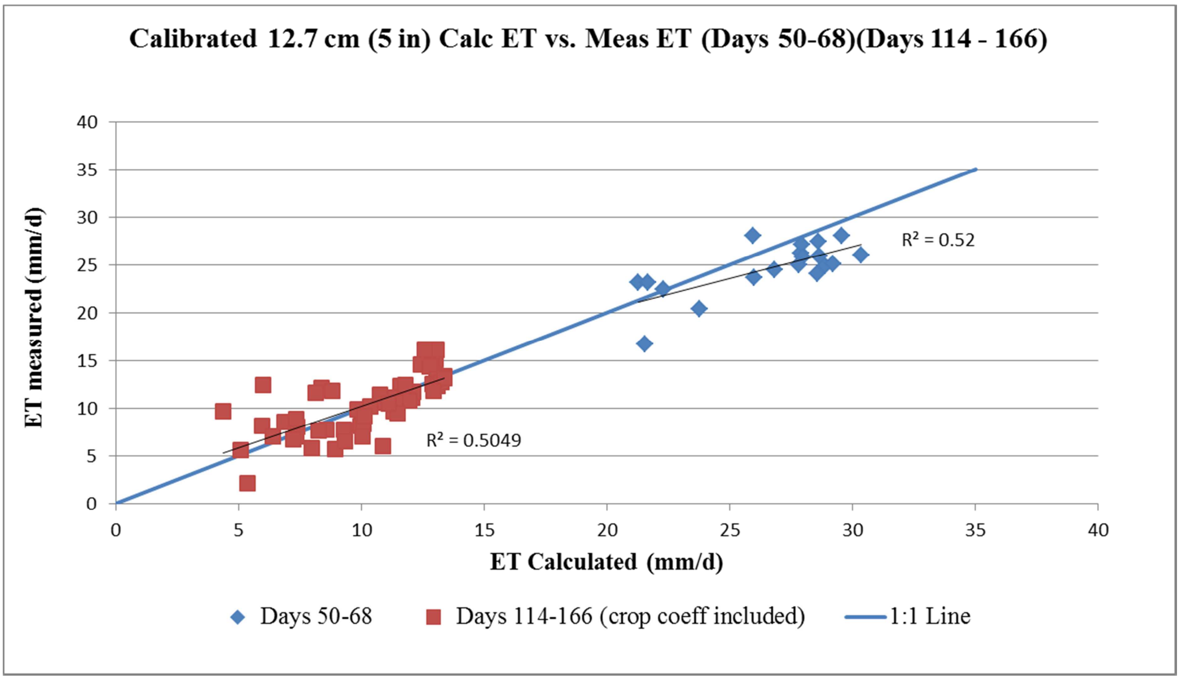

Figure 21: Calibrated 12.7 cm (5 in.) Calc ET vs. Meas ET (Days 50-68) (Days 114-166)

Verification of equation 4.5 for weather data from days 50-68 shows that it fits very well with the 1:1 line when compared to the actual measured ET. Although it overpredicts ET by approximately 5, the maximum error is approximately 10 mm/d. The higher calculated results can be due to the plants reaching its matured stage and does not utilize as much water, therefore further investigation is needed to adjust the crop coefficient value. Although the developed equation through regression analysis fits well with the data for verification, it should serve as a reference equation to be further developed through more data collection. There should be a higher variation and combination of changes of weather parameters so that a more accurate equation can be developed that accounts for the changes.

One of the necessary considerations for reference ET equation 4.5 is the growth cycle of the plants. The plants were observed to be the healthiest during September through November and showed signs of maturity starting in December. Phase 3 started on February 2^{nd} and was the initial date for the second set of data for verification of equation 4.5. The second data set lasted until day 166, or March 26^{th} 2012. During this time, the health of the plants significantly declined, as a result, ET will be greatly reduced. Therefore, a K_c value of 0.42 is multiplied to equation 4.5. As shown in Figure 21, days 114-166 fits the trend of the 1:1 line between calculated and measured data. It can be seen that there is an approximate division between higher and lower results but are closely clustered together. The crop coefficient, K_c, adjustment is only one consideration to making a more accurate calibrated model. Other considerations can include height of the water table, time of the year, and different plant species similar to the FAO-56 Penman-Monteith adjustment.

4.4 Comparing Reference Evapotranspiration and Measured Evapotranspiration

In order to further investigate the pattern of ET, a comparison amongst the Penman, Penman-Monteith and Hargreaves equation was performed to see the relationship between weather climates and seasonal changes of the reference ET established. Calculating the reference ET of the PM and Hargreaves equations, the results are plotted with the actual ET that was measured daily. Evaporation was also examined to see if there is any similarity with the Penman evaporation equation. Figure 21 below shows the PM, PM on days with wind only, Hargreaves, and Penman evaporation comparison.

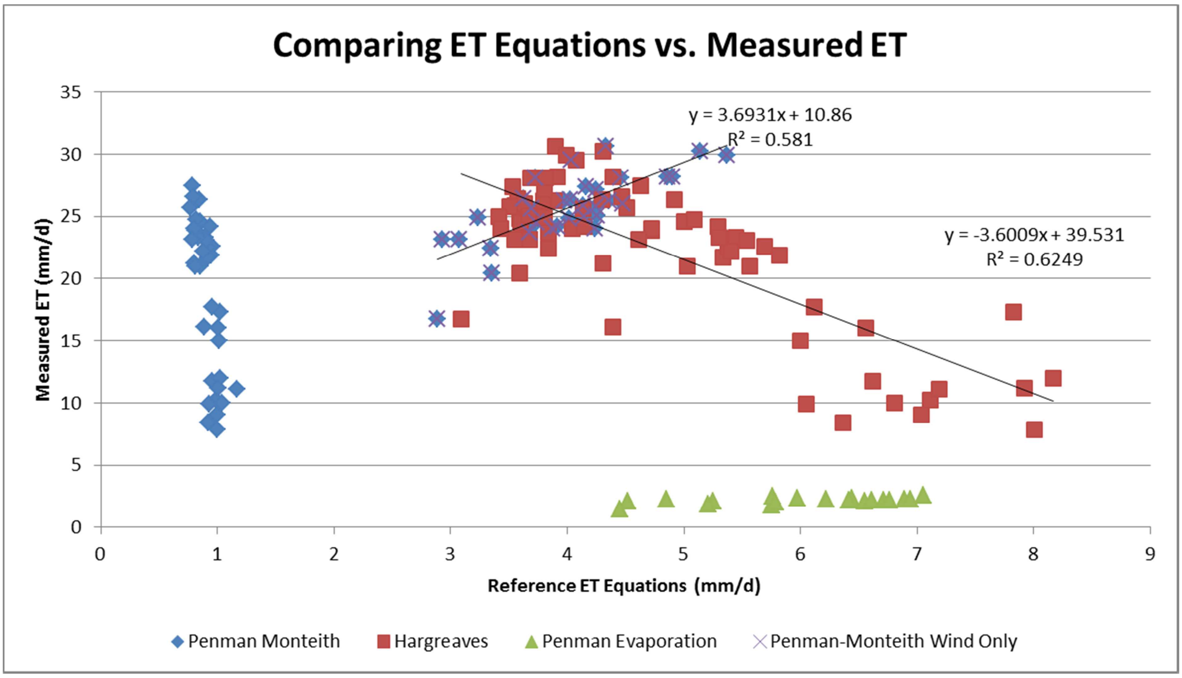

Figure 22: Comparing Practiced ET Equations with Measured Data

In the PM comparison, the calculated reference ET shows a scattered pattern with that of the actual ET. When the reference ET is around 1 mm/d, the measured ET varies from a range of 7 and 28 mm/d, with almost a vertical slope. At the points where the reference ET is between 3 and 6 mm/d, there is some linearity between the calculated and measured values.

One of the main reasons discovered for this scattered pattern is that the PM has a high emphasis on wind in the equation. Days where wind was not applied, the PM equation resulted in very low values comparing to the measured ET. On days where there is wind, the reference ET and measured ET shows a relationship that is linear.

For the Hargreaves equation, there is a consistent negative slope between the reference and measured ET. This relationship is the result of the Hargreaves equation being dependent on the extraterrestrial solar radiation coefficient, R_a. The Hargreaves equation also contains only temperature as the other variable. Since R_a is dependent on the time of the year, as the season progresses and the experiment goes in to the winter season, the Hargreaves reference ET will begin to decline. This decline does not show up as drastic in the measured ET due to the greenhouse environment that the experimental setup is placed. Also, the Hargreaves equation other variable is temperature, but this was not one observed in the experiment. In the daily measured ET results, relative humidity has a governing role in the daily rate. Therefore, a low or high temperature will drastically change the Hargreaves ET. The Hargreaves ET does not correlate changes in daily rates from due to relative humidity and thus misses part of what was observed.

The daily evaporation rate shows a slope of almost zero when compared with the Penman evaporation equation. This is caused by many factors such as the size of the bucket that was used as an open water surface container. The rates in this container might not correlate to that of a body of water. Since the pan evaporation was relatively much smaller, effects of weather climate might not have that much of an effect.

Calibrating Penman-Monteith reference ET

The PM equation was developed for agriculture so that farmers can estimate how to water their crops; it is different in stormwater management practices where the purpose is to estimate the maximum water extraction from ET to lower runoff volume. Based on the relationships between ET and weather parameters observed, a calibration to increase the coefficients of the PM equation was performed in order to fit the calculated results with those measured.

In the first set of variables of the PM ($0.408*\Delta*(R_n\text{-}G)$), equation 2.4, the net solar radiation is included and so is the slope vapor pressure. The soil flux, G value is neglected since temperature has an insignificant effect, therefore zero. Based on the correlation analysis, it was observed that solar radiation and temperature showed an impact on the daily ET rate. The importance of these variables were emphasized for the PM calibration so that they have a higher impact, as a result, the coefficient 0.408 was increased to 13, based on a trial and error approach.

In Figure 22, there is a wide separation for the PM, between the daily ET on days with wind applied and on those that it is not. The presence of wind shows an increase of magnitude in the calculated results for daily ET in comparison to the rate at which ET is under 1 mm/d on days without wind. By increasing wind, it allows for the saturated air to be replaced by drier air which creates a steeper gradient for ET to occur. Therefore, the original form of the PM equation underestimates the observe wind factor of the observed data.

To make adjustments to the coefficients so that wind has more of an impact, the coefficient of 900 within the PM equation 2.4 was increased to 2355 in order to enhance the effect of wind on the ET rate. This adjustment also allows for temperature within the term e_s, the saturation vapor pressure, to have a greater influence and also for relative humidity within the term e_a, the actual vapor pressure, to have the same but inverse effect observed. Below is the PM equation with the adjusted coefficients.

$$ET_o = \frac{13\Delta(R_n - G) + \gamma \frac{2355}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4. 6}$$

Not only were the coefficients adjusted for the measured data, as the experiment entered a phase in which the plants were maturing, the crop coefficient, K_c, was applied to see if the calibrated PM equation still showed a similarity to the actual data. The crop coefficient was chosen to be 0.42 based on the maturity of the plants and this coefficient was multiplied to the calibrated PM equation 4.6 on February 2, 2012. This was the date in which phase 3 where the water table was set back to 12.7 cm and the plants had matured over the months in which the 7.6 cm was used. Figure 23 shows the comparison between the calibrated PM equation and the measured ET.

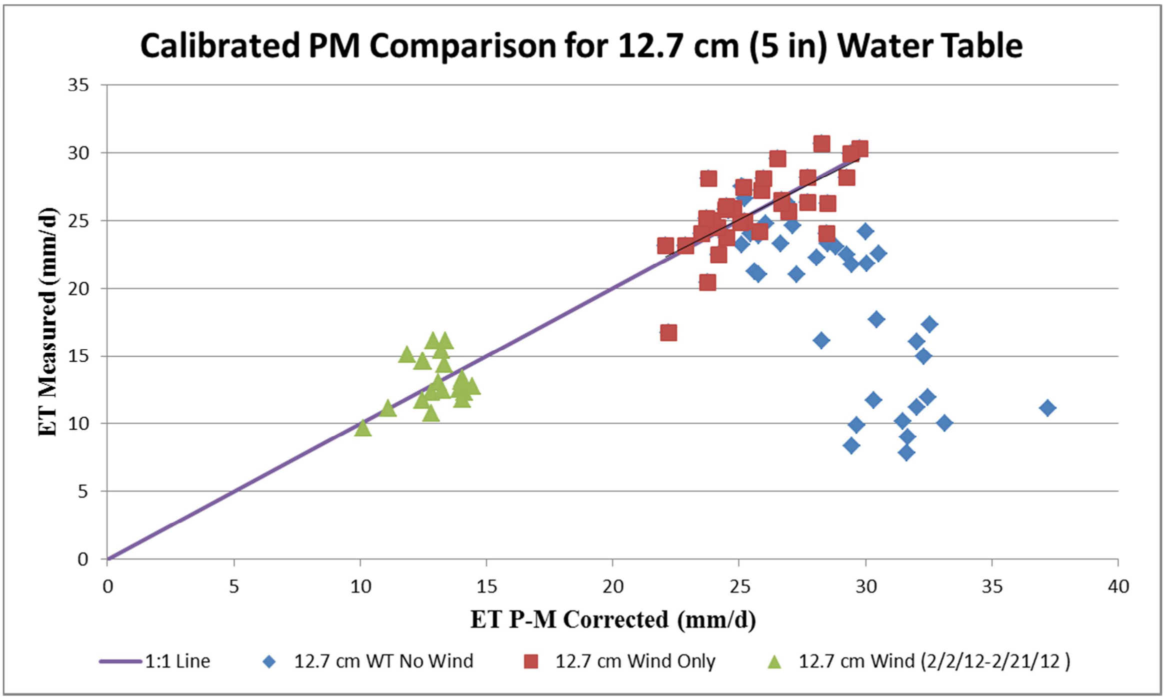

Figure 23: Calibrated PM Comparison for 12.7 cm (5 in.) Water Table

The calibrated PM equation was plotted for only days where wind was applied because this represents the natural environment where wind is present. As illustrated, days without wind shows scattered data points. On days with wind, the calibrated PM equation is observed to be based around the trend of the 1:1 line.

Results from February 2nd through February 21st are during the time period where the plants are past their matured stage so they do not have the ability to transpire as much water. During this time period, a crop coefficient of 0.42 was multiplied to the new calibrated PM calculations. This calculation is similar to the crop reference ET calculation shown in the FAO-56 paper written by Allen et. al 1998. The results of the calibrated PM including a crop coefficient of 0.42 show a very good relationship when compared with the measured data. The biggest difference between calculated and measured data was around 5 mm/d. Although the comparison between the calculated reference and measured ET results are precise, the coefficient of 0.42 used was only for the particular type of plants and stage of maturity. In order to develop a more accurate calibration of the PM equations, the crop coefficient should be adjusted depending on combination of plants, stage of maturity, and the water table.

5. Application of Study

The findings of the research project to quantify ET in a CSW mesocosm can serve as a useful tool for the stormwater management practice to effectively balance the water budget discussed in Chapter 1. During the height of the growing season, the plants demonstrated that it can transpire over 20 mm of water per day and evaporate approximately to 3 mm per day.

When considering the most frequent design storm, which is the 2-yr storm, producing precipitation of about 50.8 mm (2 in.) per event, given a well-developed CSW, ET alone can reduce almost half of the runoff in one day. The remaining volume can be infiltrated in to the ground, or slowly discharged resulting in less runoff volume over time.

By reducing the amount of runoff through taking advantage of ET, design costs of a CSW can be greatly cut. Since a CSW requires a large area to handle its design capacity, there can be more emphasis on the design to promote plant growth in order to maximize the effectiveness of ET. In addition, improving the plant type and increasing density will cost much less than expanding a CSW to handle more volume.

Additionally, the focus to develop the CSW through plant selection and increasing density can greatly help with pollutant removal. For wastewater treatment wetlands, the particular species selected are less important than establishing a dense stand of vegetation. Meanwhile, CSW plants should be chosen to mimic the communities of emergent plants of nearby natural wetlands. Both in wastewater and stormwater wetlands, native, local species should be used because they are adapted to the local climate, soils, and surrounding plant and animal communities (EPA 2011).

6. Conclusion

The evolution of stormwater management is growing towards the use of low impact developments in order save the cost of redesigning combined sewers and detention basins to mitigate stormwater runoff. Therefore, it is important to consider the role of evapotranspiration since much of the design focus of LIDs is based on vegetation and soil type. Since it is a complex process that varies dependent on climate factors, plant growth, and water availability, it is difficult to accurately estimate how much runoff volume it can reduce. For this reason, the results of this research are aimed to give the practice of stormwater management a better understanding how much quantity ET is which was observed to as high as 30 mm/d during the peak of the plant growth cycle or an average of 10 mm/d when plants are matured. In addition, this research provides a better understanding of factors that drives ET and formulates a reference equation to provide estimation.

6.1 Factors that affect ET

Temperature

Observing each climate factor, temperature did not have a noticeable impact throughout the research. The greenhouse where the experiment took place maintained a relatively constant temperature throughout the year between (294 – 300 K or 70 to 80 °F). In the Penman-Monteith equation for reference ET temperature is calculated to have a positive impact on ET. The Penman-Monteith equation yields a relationship where a higher temperature will result in a faster ET rate. Since temperature is maintained in the greenhouse environment, there is no conclusive evidence that this is the case.

Relative Humidity

The main driving factor observed in this experiment in the ET rate is relative humidity. As illustrated in the results, relative humidity has an inverse relationship with ET, meaning, the higher relative humidity there is, the less the ET rate will be. The relative humidity is an indication of the amount of moisture that is in the air. Transpiration can be referred to as "plant sweat" where if there is less moisture, meaning a low relative humidity, then drying power is greater allowing for more ET to take place. On the other hand, where there is high moisture content in the air, the drying power is less since there is already excessive moisture around the environment; therefore a lower ET rate is needed for balance.

Solar Radiation

Solar radiation is observed to be a positive factor of ET. Meaning, the higher the daily solar radiation is, the more ET will take place. This relationship is due to the plants having a faster biological process if there is more energy available. In addition, a higher solar radiation will allow for more water vapor to be processed, therefore increasing evaporation. Throughout this research, there are instances where solar radiation has in inverse relationship; this is caused by other factors that have a more significant impact, such as relative humidity.

Wind Speed

The relationship between ET and wind shows that wind have a positive relationship where other parameters are similar. In some instances, wind shows a negative relationship, but that is due to other climate factors governing, such as relative humidity. The function of wind in ET is that it allows for removal of the saturated air and replaces it with drier air. This process allows for a higher gradient of water pressure which increases the rate of ET.

Water Table

In this research, the water table was adjusted between 12.7 cm and 7.6 cm to investigate if this change could have an effect on ET. Although the 12.7 cm water table had a greater rate of approximately 5 mm/d, further investigation is needed for conclusion. Part of the reason being that the 7.6 cm water table (phase 2) started in December when plants showed signs of dryness, which is an indication maturity. Therefore, the plant health could be the reason why there was an average difference.

Plant Health

As described by Richard Allen (1998), the rate of ET through the growth cycle of plants can greatly differentiate. To accommodate for the growth stages, a crop coefficient factor (k_c), is applied. The coefficient varies between plant types, with those who prosper in wet conditions, have a value higher than 1, and vice versa. This coefficient can also be over 1 during the growth stages where water essential, but will reduce the rate of ET when plants are in their decline stages. Therefore, to provide a more accurate estimation of ET, the k_c value should be set to a combination of plant types and growth stages for each variation; this is an extensive study project that can sustain itself.

6.2 Further Research

The ability to measure the climate factors accurately is important in developing a collective relationship to the quantified evapotranspiration results. Using this data, a multiple linear relationship was developed in order to create a predictive ET equation. This equation was calibrated based on a set of measured data and then verified and compared with measured ET results to illustrate accurately. The comparison showed that the calculated results matched well with the measured, even when a crop coefficient of 0.42 was applied to accommodate the plant cycle. Although the calculated results were well representative of the measured, the research took place in a greenhouse and only considered its limited environment. Further research is needed to accommodate all of the variation in climate parameters similar to a natural wetland environment. Overall, this research provides the community of stormwater management an idea of the quantity of evapotranspiration in a constructed stormwater wetland so that it will be a substantial consideration in design requirements.

References

Allen, R.G., Pereira, L.S., Raes D., Smith M. (1998). “Crop Evapotranspiration - Guideline for Computing Crop Water Requirements - FAO Irrigation and Drainage Paper 56.” Rome, Italy, FAO. Food and Agriculture Organization of the United Nations.

Allen, R.G., W.O. Pruitt, et al. (1996). Chapter 4: "Evaporation and Transpiration". ASCE Handbook of Hydrology. New York, American Society of Civil Engineers**:** pp. 125-252.

Allen, R. G., and Pereira, L. S. (2009). "Estimating crop coefficients from fraction of ground cover and height." Irrigation Science, 28, 17-34.

Allen, R. G., Pruitt,W. O., Businger, J. A., Fritschen, L. J., Jensen, M. E., and Quinn, F. H. (1996). "Evaporation and transpiration." Chpt 4 in Hydrology Handbook: ASCE Manuals and Reports on Engineering Practice No. 28, ASCE, New York, 125-252.

Cattle S.R. and George B.H. (1992). “Describing, Analysing and Managing Our Soil”. Proceeding of the DAMOS ’99 workshop held at the University of Sydney, November 22nd-26, 1999

Denmead, O.T. and Shaw, R.H. (1962). “Availability of soil water to plants as affected by soil moisture content and meteorological conditions.” Agron, J. 54: 385-390.

Eagleman, J.R. (1971). “An experimentally derived model for actual evapotranspiration.” Agricultural Meteorology. 8: 385-394. Elsevier Publishing Company.

Encyclopedia Britannica. (2012). “Statistics.” Encyclopedia Britannica Inc. April 6 2012.

Grebet, R., and R.H. Cuenca. (1991). “History of lysimeter design and effects of environmental disturbances.” Pp. 10-18 in Lysimeters for evapotranspiration and environmental measurements, Proceedings of the International Symposium on Lysimetry, July 23-25, 1991, Honolulu, Hawaii. ASCE, 345 E. 47th St., NY, NY 10017-2398.

Howell, T. A., and Evett, S. R. (2004). "The Penman-Monteith Method." Proc., Section 3 in Evapotranspiration: Determination of Consumptive Use in Water Rights Proceedings, Continuing Legal Education in Colorado, Inc., 1-14.

Irmak, S., Howell, T., Allen, R., Payero, J., and Martin, D. (2005). Standardized asce penman-monteith: Impact of sum-of-hourly vs. 24-hour timestep computations at reference weather station sites. Transactions of American Society of Agricultrual Engineers, 48(3):1063.

Itenfisu, D., Elliott, R. L., Allen, R. G., andWalter, I. A. (2003). "Comparison of Reference Evapotranspiration Calculations as Part of the ASCE Standardization Effort." Journal of Irrigation and Drainage Engineering, 129, 440-448.

Kires, Marian. (2006). “The Physics Teacher”. 44. 388-389.

Marietta College. (2008). “Photosynthesis – An Overview”.

McCarthy, E.L. (1934). “Mariotte’s Bottle”. Science, 80:100.

NDT. (2008). “Temperature and the Speed of Sound”. NDT Resource Center.

Penman, H.L. 1948. Natural evaporation from open water, bare soil, and grass. Proceedings, Royal Society, London 193, pp. 120-146.

Pidwirny, M. (2006). "Actual and Potential Evapotranspiration." *Fundamentals of Physical Geography, 2nd Edition*. Date Viewed. http://www.physicalgeography.net/fundamentals/8j.html

Schneider, D. (2010). Personal Communication.

World Meteorological Organization, (1992): *International Meteorological Vocabulary*. Second edition, WMO-No. 182, Geneva.

Appendix A – Specifications of Measurement Instruments

Appendix B – Overall Illustration of Evapotranspiration Study

Appendix C – Daily Data Tables for Measured Weather and Evapotranspiration

Appendix D – Data Table of Calculated Regression Comparison

Appendix E – Data Table of Modified Penman-Monteith Comparison