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Quantifying Evapotranspiration from a Green Roof Analytically

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Quantifying Evapotranspiration from a Green Roof Analytically

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ABSTRACT:

Green roofs are a common stormwater control measure used to help mitigate increased stormwater runoff caused by urbanization. Green roofs can retain upwards of 90% of rain given the appropriate conditions. Green roof design parameters, such as substrate composition and depth and plant type, affect the retention capabilities of green roofs by storing and allowing greater extraction of water by plants for evapotranspiration (ET). Evapotranspiration has been studied extensively in agriculture to be able to estimate irrigation demands, but ET in stormwater management infrastructure is poorly understood. Measurements from a weighing lysimeter consisting of a 10.2 cm deep, 45.7cm x 45.7 cm green roof replica on 3 Sentran load cells, was compared with results from the standardized reference Penman-Monteith equation to obtain crop coefficients (k_c) for future predictions of ET from green roofs. The years 2009 and 2010 contained very different weather patterns with 2009 being wet and mild and 2010 being dry and hot. The weight of the lysimeter was used to estimate the soil moisture content and determine the moisture stress (with stress coefficient, k_s). Ascertaining the level of stress quantifies the reduction expected in ET due to water shortage and proved to be critical to obtaining reasonable crop coefficient values. The average stress in 2009 was 1.0 with monthly crop coefficients ranging from 1.0 to 1.4; in 2010, the average stress coefficients were between 0.6 and 0.7 and dropped as low as 0.2 with estimated monthly crop coefficients ranging from 1.5 and 1.7. The high water stress levels present in 2010 made it difficult to separate k_c from k_s, but use of the 2009 crop coefficients in 2010 with estimated stress levels did not produce viable results, indicating that k_s may not be sufficient in representing severe stress conditions. Although the model $ET_{c,adj}$ in 2010 still compared well against the measured ET, ET_{lys}, it is believed that better results could be obtained using a dual-crop coefficient approach, where transpiration and evaporation are modeled individually, and results moer similar to those from 2009 would be obtained. The work presented is a preliminary attempt at establishing k_c values for use in future design work, and while still in need of validation, could prove useful for rough estimates of ET.

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Chapter 1

Introduction

Urbanization has drastically increased the amount of impervious surface and, consequently, changed the hydrology of the earth. The hydrologic cycle affects from where and how much water is available to society, as water is constantly cycling through the atmosphere. Precipitation becomes surface and ground water before it is evaporated into the atmosphere only to be precipitated again. A portion of the precipitation is absorbed and transpired by plants as they collect carbon dioxide to perform photosynthesis . The evaporation of water from the plant surface and soil together with the transpiration of water through the stomata of the plants is known as evapotranspiration (ET). The goal of this research is to gain a better quantitative understanding of the evapotranspiration process, specifically as it pertains to stormwater management in the urban setting.

1.1 Stormwater Management

Stormwater management uses a combination of structural and non-structural elements called Best Management Practices (BMPs) or Stormwater Control Measures (SCMs) to mitigate stormwater effects. The most recent BMPs target water quality and water quantity issues associated with increased development that causes rain to run off into streams often collecting pollutants along the way. Stormwater runoff is detrimental to the ecosystem when it changes the environment, such as temperature, pH, and sediment loading. Wildlife is acclimatized to its surrounding environment and significant changes to, for example, stream geometry and chemistry will disturb the habitat and disrupt the natural ecosystem. In order to reduce the impact that storm runoff can have, BMPs have been implemented in land development projects. Best Management Practices are designed to naturally treat rain water for both water quality and quantity before it turns into ground and surface water. Volume and peak flow reductions occur by infiltration and evapotranspiration in systems such as green roofs, rain gardens, and pervious pavement.

A new trend in urban areas with combined sewers is to charge property owners for stormwater runoff since the city is required to treat it once it is in the stormwater system. However, current BMP regulations were created without a good quantitative understanding of the water processes present and the volume capacity of BMPs in the Pennsylvania BMP Manual is highly dependent on infiltration capacity (PADEP 2006), which is difficult to achieve in urban environments. Evapotranspiration is considered significant for large time scales (months/years), but its influence at smaller scales (days/weeks) for stormwater BMP applications is still being quantified. The BMP of focus for this research is a green roof on Villanova University's campus that is instrumented with a weighing lysimeter and weather station for measurement and estimation of ET, respectively. Ultimately, it is hoped that this research will lead to improved urban stormwater management designs based on better quantification of ET.

1.2 Evapotranspiration

Evapotranspiration (ET) is the process by which water transpires from the leaves of plants and evaporates from the surface of plants and the soil. It is a process driven by energy, specifically solar radiation. As such, an energy balance equation can be associated with the water balance involved in the hydrologic cycle. The net radiation from the sun can be equated to the vertical heat flux in the soil (soil heat flux), the vertical heat flux from the ground to the atmosphere (sensible heat flux), and lastly the energy used in the evapotranspiration process (latent heat flux). The horizontal transfer of energy is generally ignored (Teixeira 2008).

The rate of ET varies widely based on land cover (Vörösmarty et al. 1998; Lu et al. 2005). Potential ET is often estimated instead of actual ET for use in hydrologic models because it is easier to estimate since it is based only on climate and vegetation type. Actual ET also depends on soil characteristics and moisture content and vegetation maturity (Douglas et al. 2009). Large complex areas with a range of land types, such as urbanized and mountainous, are more difficult to obtain accurate ET estimates. Urban and mountainous areas both have high spatial variability and distinct areas of impervious and pervious surfaces. Solar radiation cannot be assumed to affect the land uniformly due to large terrain shadow effects and, in urban areas, the heat island effect may further complicate estimating ET (Mészároš and Miklánek 2009; Denich and Bradford 2010). Of note, Denich and Bradford (2010) hope to improve regional and SCM ET estimates in urban areas by installing a system of weighing lysimeters and eddy correlation systems throughout Ontario and incorporating the variability in hydrologic models. Vegetation type also has significant influence on ET as is evident by the various vegetation parameters in the physical Penman-Monteith model and numerous land studies that have been performed (e.g. Zhang and Ross 2010; Mészároš and Miklánek 2009; Douglas et al. 2009; Verstraeten et al. 2008).

Quantifying ET has been a goal for years, specifically in agriculture because a better estimation of ET allows for better estimation of irrigation demands. Although over-irrigation will increase productivity if there is adequate sunshine, it can lead to water quality problems in areas where water is in short supply. In addition, water is costly and the marginal benefit of irrigation decreases after an optimum level (Teixeira 2008). The rigor used in calculating ET is often limited by the data available and the degree of accuracy required for the application. Analytical equations which model the physical process of ET, such as the Penman and Penman-Monteith equation, give superior point results over simpler empirical equations based on temperature (e.g. Thornwaite and Blaney-Criddle) and solar radiation (e.g. Priestly-Taylor and Makkink) when compared with lysimeter measurements (Kumar et al. 1987; Allen et al. 1998; Xu and Chen 2005). Both analytical and empirical equations assume sufficient water for ET to occur uninhibited and the empirical equations tend to over predict ET in humid climates (lower than expected vapor pressure gradient) and under predict ET in dry climates (higher than expected vapor pressure gradient) (Allen et al. 1998). Many of the studies evaluating the different methods compared results from small areas on which lysimeter or other actual ET data is available. However, on the larger watershed-scale, rainfall-runoff models have produced similarly accurate potential ET estimates using temperature-based equations when compared with a watershed balance (Oudin et al. 2005; Vörösmarty et al.

1998).

Each method considers slightly different meteorological variables and places different weight on each variable. The empirical equations based on temperature use a combination of average, minimum, and maximum daily temperature. Radiation based equations generally use incoming radiation (as opposed to net radiation) and both types of empirical equations also may use relative humidity, wind speed, and hours of daylight (Lu et al. 2005). Due to the empirical nature of these equations and natural variability of climatic conditions, local calibration is often required for accurate results and temperature based equations are often favored because of the readily available data worldwide. That said, these empirical equations produce different results at different scales (Lu et al. 2005) and are generally not recommended for large-scale hydrologic models although some success has been had (Allen et al. 1998; Douglas et al. 2009).

The analytical equations, of which the first widely accepted form was published in Penman (1948), are a combination of the mass transfer of heat and water vapor at the land-air interface and the energy balance of the atmosphere. The vapor pressure gradient is the driving factor behind the rate of ET and is usually estimated through measurements of the temperature and relative humidity (Allen et al. 1998). The Penman-Monteith equation (Monteith 1965) is an adjustment to the Penman equation that includes parameters that model specific plant characteristics. The disadvantage of the Penman and Penman-Monteith equations are the intensive data requirements and, in the case of the Penman-Montieth equation, the requirement for specific resistance parameters that change not only by plant but also time of year and time of day (Allen et al. 2000). To simplify the use of the Penman-Monteith equation, ET from a reference surface, or reference ET, is commonly used with predefined resistance parameters. Evapotranspiration for specific crops are estimated through a single coefficient (Jensen et al. 1990; Allen et al. 1998; Allen et al. 2000).

1.3 FAO56 Standardized

Much emphasis has been placed in the last 25 years on establishing a standard equation with which farmers, engineers, and scientists can accurately predict ET (Allen et al. 1998). The United Nations Food and Agriculture Organization (FAO) Irrigation and Drainage Paper No. 24 (FAO24) was published in 1977 (Doorenbos and Pruitt 1977) and presented four methods with which to calculate reference crop ET (ET_o). The methods were to be used for 10-day or one-month periods and varied in requirements as they meant to meet the needs of all potential users; a modified Penman equation and the Blaney-Criddle methods were among the suggested methods (Allen et al. 1998). An update to FAO24 came in 1998 in FAO56 in which a standardized reference Penman-Monteith equation (FAO56PM) was recommended as the sole method for estimating reference ET daily (ET_o). The reference ET calculated is the potential ET expected from a reference crop of a short turf grass assuming sufficient water (Allen et al. 1998).

The standardized equation aims to simplify the ET calculation by reducing the variables to two encompassing coefficients, one for specific crop characteristics and one for environmental stress conditions. The agricultural sector has developed these coefficients for a variety of crops, but little information is available for stormwater control measures. The standardized Penman-Monteith equations follow several assumptions that make them less applicable to stormwater control measures, such as green roofs and bioinfiltration rain gardens. For example, the Penman-Monteith equation assumes an expansive field of crops (at least 50 m in each direction) in which case the lateral energy losses can be ignored. Stormwater control measures are generally small areas that collect rain runoff from a larger, urban area. Consequently, the lateral energy losses may be far more significant than for an expansive field. The assumption of a uniform crop is also often violated in a BMP. Green roofs are often designed with multiple species of *Sedums* and rain gardens have a variety of plant species. Further, unlike agricultural fields, BMPs are not planted in such a way to ensure full ground coverage, another assumption of the Penman-Monteith equation. Best Management Practices are also not irrigated during drought periods, which can cause plants to wilt and die and soil to be exposed.

1.4 ASCE Standardized

The American Society of Civil Engineers (ASCE) also published a standardized reference equation but recognized two reference surfaces for monthly, daily and hourly timesteps: grass and alfalfa. One of the goals of the ASCE was to establish a single equation that produces consistent estimates of ET (ET_{ref}) for both agricultural and landscape needs while using the existing database of crop coefficients. ASCE accomplished this task by publishing an equation with a table of coefficients to be used for the appropriate reference surface and timestep (Allen et al. 2000). Both the FAO56PM and the ASCE Standardized PM are based on the ASCE-PM equation published by ASCE in 1990 (Jensen et al. 1990) but adjusted for a reference surface.

1.5 Research Objectives

The goal of this research is to examine the standardized FAO56 and standardized ASCE short reference Penman-Monteith equation for quantifying ET on a green roof at daily timesteps and compare it to direct measurements of ET from an on-site weighing lysimeter. A soil retention curve was created and used in conjunction with known soil moisture conditions to relate the rate of ET and the ability of the green roof to experience ET based on weather patterns.

Chapter 2

Literature Review

2.1 Green Roofs

Green roofs of different types have existed for centuries, but have only recently been evaluated for their benefits over more traditional grey roofs. The benefits of green roofs include stormwater volume and peak flow reduction, but also energy savings and air quality improvement (Mentens et al. 2006; Oberndorfer et al. 2007; Spolek 2008; Voyde et al. 2008). Urbanization has rapidly increased in major cities, and with it, a growth in impervious surfaces. The urban heat island effect is a direct result of heat being absorbed by impervious surfaces and being trapped in cities. Greener, less urban areas do not have the heat island effect because heat is used in the evapotranspiration process (Oberndorfer et al. 2007). In addition, stormwater management has become a major issue in cities, such as Portland and Philadelphia, where combined sewer overflows contaminate natural water supplies during large rain events (Spolek 2008). Best Management Practices can combat the urban heat island effect and stormwater overflows, except that BMPs require green space that may not be available in cities. Green roofs offer an advantage over other BMPs because they use traditionally impervious surfaces (Oberndorfer et al. 2007). Roof surfaces in cities range from 30% to 40% of all impervious surfaces, offering a distinct opportunity to convert impervious roofs to green space without losing functionality (Oberndorfer et al. 2007; Hutchinson et al. 2003). Models of Toronto, Canada have also indicated that greening 50% of roofs evenly throughout the city could result in an annual temperature reduction of 2°C (Oberndorfer et al. 2007) and greening 10% of roofs in Brussels, Belgium could reduce total runoff by almost 3% (Menten et al. 2006). Additionally, green roofs are known to mitigate certain pollutants such as acid rain and nitrate, but the planted systems may yield other contaminants such as phosphorous, potassium, calcium, and magnesium in the runoff (Berghage et al. 2009). The over-application of fertilizer may also add to phosphorous and nitrogen in the runoff (Rowe et al. 2006).

Numerous studies have been performed to examine the retention capabilities of green roofs and a wide range of results have been published. Green roof retention is complicated and a function of several factors including soil media depth, plant species, and rainfall pattern (Hutchinson et al. 2003; Moran 2004; Carter and Rasmussen 2006; Martin 2006; Spolek 2008; DiGiovanni et al. 2010). Green roof retention performance is generally given as a percent of total precipitation or the amount of rain retained, which is eventually lost by evapotranspiration. Storm, monthly, and yearly retention all vary from each other depending on the location and specific characteristics of the green roof and climate. Annual retention performance of green roofs has been reported as 16% to 29% in Vancouver, BC, Canada with substantially worse performance in winter when most of the years' rainfall occurs (Roehr and Kong 2010). However, in a similar climatic region in Portland, Oregon, average annual retention performance has been reported as 18% and 29% for one study and 48% for another despite each of the green roofs monitored in Vancouver and Portland having substrate depths of 4″-5″, which one might expect to strongly influence retention capabilities. Performance was also worse in winter than summer (Spolek 2008; Hutchinson et al. 2003). Other climatic regions experience different annual stormwater retention; Moran (2004) and Carter and Rasmussen (2007) reported retention values of 62%, 63%, and 78% for the southeastern United States, respectively, which is hot and humid in summer and mild in winter. The aforementioned locations and others also experience differences in monthly retention values, but from which two inferences can be made: smaller storms (< 2.54 cm) tend to have higher retention rates and the first 1.26 cm of rain is retained upwards of 100% (Spolek 2008; Moran 2004; Carter and Rasmussen 2007; Simmons et al. 2008; Villarreal and Bengtsson 2005). Based on literature, climate plays a role in retention performance of a green roof, with special note that areas with high precipitation in winter perform worse because ET rates are lower and therefore green roof retention recovery is slower as opposed to summer when retention recovery is quicker. However, climate may not affect green roof performance in sub-tropical climates, such as in Auckland, NZ where there is low variability in climate between seasons (Moran 2004; Hutchinson et al. 2003; Voyde et al. 2010a).

The research community has attempted to correlate a number of factors to the stormwater retention of the green roof. The most obvious factor is precipitation depth, and indeed Carter and Rasmussen (2007) found this to be the best single predictor of retention. In contrast, Moran (2004) cites precipitation depth and pattern as strongly influential; infrequent, small storms would undoubtedly yield complete precipitation retention, but frequent small storms could also yield high retention rates while infrequent large storms could yield the opposite (Moran 2004). Berghage et al. (2007) suggests that optimal performance would be achieved with 12.7 mm (0.5″) wetting events every 3-5 days. DiGiovanni et al. (2010) similarly was unable to discern a unique relationship between retention and precipitation depth, but did note 100% retention for storms with an antecedent dry period to precipitation depth ratio of 8 hr/mm; Moran (2004) also found consistently high retention related to antecedent dry period and precipitation depth. Additional considerations include storm duration and storm intensity, although differing conclusions have been published regarding these factors and no specific relationship has been established (Moran 2004; Carter and Rasmussen 2007; Voyde et al. 2010a; Villarreal and Bengtsson 2005). Ultimately, multiple elements of the weather patterns affect the retention performance of green roofs and climate will play a large role in the effectiveness of a green roof. Aside from the precipitation depth and pattern, climate, such as temperature and relative humidity, affects the storage recovery of a green roof and the location of the interest may well determine how effective a green roof can be at reducing runoff volume. Nonetheless, once the green roof design and performance expectations have been established, there is evidence to suggest that green roofs will perform similarly from year to year despite varying precipitation (Liesecke 1999 in Moran 2004; Köhler et al. 2001; Spolek 2008).

2.2 The Effect of Plant and Soil on Green Roof Performance

Traditionally, many studies examine ET as a single process from which heat and water are transferred away from the surface. The water available for ET is considered in two forms, Total Available Water (TAW) and Total Evaporable Water (TEW), and is defined by the soil characteristics as quantified by the field capacity and the wilting point. The field capacity is the moisture content of soil after it has been gravimetrically drained from saturation and the wilting point is moisture content at which point plants can no longer extract water. The TAW is water available to the plants for growth and eventual transpiration and is considered to be the quantity of water between the field capacity and the wilting point of the soil. The TEW refers to the water available for evaporation from a bare soil and is the water from the field capacity to one-half the wilting point. However, full ground cover of a plant implies that the soil beneath the plants is completely shaded and as such is negligible for the estimation of evaporation. The soil tension, or soil matric potential, increases as water is depleted and makes it more difficult to extract or evaporate water. The range from which water extraction by the plant is energy-limited is known as the Readily Available Water (RAW) and is dependent on the species but is usually between 0.3 and 0.7 of the TAW for shallow- and deep-rooted plants, respectively (Allen et al. 1998). Data published by Rezaei et al. (2005) suggests a change in rate of ET after 50%-60% of the total water evapotranspirated, indicating a threshold soil moisture condition for the 1:1 mixture of *Delosperma nubigenum* and *Sedum album* of about 0.5TAW after which the rate of ET decreases until the wilting point is reached and ET ceases. Berghage et al. (2009) commented on the same study and reported that average ET rates decreased substantially after 40% of the water content at field capacity was lost. This is not comparable to the percent of TAW without knowing the wilting point. In a greenhouse experiment in New Zealand, trays of *Sedum mexicanum* and *Disphyma austral* showed similar behavior with severe reduction of ET after about 60% of total water loss (Voyde et al. 2010a). A similar distinction between energy-limited and moisture-limited moisture content exists with bare substrate and data from both Rezaei et al. (2005) and Voyde et al. (2010a) indicate a similar threshold of 50%-60% of TEW for Readily Evaporable Water (REW).

2.2.1 Evaporation vs Transpiration

A few studies have directly examined the impact of plants for water retention and evaporation on a green roof compared to bare substrate. Berghage et al. (2007) found 40% better retention in planted substrate compared to bare substrate and Voyde et al. (2010) found a similar contribution to ET by transpiration from succulents in a greenhouse experiment. The day of watering initiates the largest and most similar rates of evaporation and transpiration, but transpiration and evaporation diverged on days 2-10. The onset of water stress around day 10 caused the plants to decrease transpiration to less than the rate of evaporation of the substrate. Succulents readily transpire available water and can store up to 1 mm water inside the leaf structure, from which they can use during drought conditions (Voyde et al. 2010). Other estimates of sedum water detention are as high as 10 mm (Jarrett et al. 2006) and Berghage et al. 2007 reported that *Sedum spurium* can weigh 1g/cm of roof surface with 80-90% of the weight being water. The ability for succulents to use water readily when available, but reduce water consumption upon stress conditions, further strengthens the argument for their advantageous uses on green roofs for increased stormwater retention.

2.2.2 Plants and Green Roofs

The ideal plant for a green roof is one which uses water quickly and in large amounts when available, but is tolerant to droughts as well. *Sedums* and other succulents are known to be drought resistant and it had been hypothesized that they may not be ideally suited for green roof applications because they are thought to conserve water all the time and provide little improvement for green roof retention performance compared to bare substrate (Berghage et al. 2007). However, greenhouse experiments have exhibited substantial contributions to ET with 20%-40% of measured ET being transpiration from plants such as sedums (Berghage et al. 2007; Voyde et al. 2010). Although *Sedums* were able to conserve water during drought, they also provided excellent retention recovery between wetting events (Voyde et al. 2010).

Further, it has been stated that *Sedums* perform well during droughts due to a Crassulacean acid metabolism (CAM), which allows them to close their stomata during the day and perform photosynthesis at night when it is cooler; this reduces the amount of moisture lost to the atmosphere (Black and Osmond 2003; Chen and Black 1983). Voyde et al. (2010) reported data that corroborates the belief that sedums close stomata during the day to reduce water consumption, but did not find increased ET during the nighttime compared to Disphyma species. Berghage et al. (2007) similarly found the greatest difference in ET between planted and unplanted trays to be in the early afternoon as opposed to at night for both Sedum and Disphyma species immediately following wetting, but after 10 days reported insignificant differences in ET.

The emphasis for green roofs has been placed on using succulents, such as sedum species, for their drought tolerance. However, an ecosystem generally contains multiple types of vegetation, and consequently, a mixture of herbaceous and succulents has been promoted as possibly improving green roof health (Dvorak and Volder 2010), and therefore improve green roof retention performance. Research has shown that succulents can do well in shallow, porous, unirrigated substrates, but herbaceous plants may need greater substrate depths and/or more irrigation to perform similarly (Dvorak and Volder 2010; Monterusso et al. 2005; Thuring et al. 2010). The de-facto standard for green roofs in the United States is the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) Richlinien für die Planung, Ausführung and Plege von Dachbegrünung (Guidelines for Planning, Implementation, and Maintenance of Green Roofs) published in Germany and accepted worldwide as a design standard. The FLL recommends different substrate depths for different types of plants and different mixes of plants with 10 cm being the shallow end for mixes with herbaceous and woody species (FLL 2002, Dvorak and Volder 2010). Monterusso et al. (2005) looked at plant growth and reported substantial death of native species in Michigan on a green roof once irrigation stopped; however, the substrate depth was only 10 cm and other studies found non-irrigated native herbaceous plants in northern climates to survive in substrates of 15 cm or more (Dvorak and Volder 2010). Lundholm et al. (2010) further found that a multicultural green roof benefited from inter-species relationships and reported increased temperature mitigation and retention performance using mixed native flora in a substrate only 6 cm deep; the plant species chosen were native to coastal Nova Scotia, where the plants chosen often endure drought and inundation in shallow soil. On the other hand, other studies have shown that sedum species were outperformed by herbaceous plants in substrates deeper than 10 cm, where conditions favor the growth of herbaceous species and cause shaded canopy cover to smaller sedum plants (Oberndorfer et al. 2007).

Herbaceous species can be especially affected by drought due to their metabolism although both herbaceous' and succulents' growth rates suffered during a two week drought. All the succulents were more sensitive to a drought immediately after planting instead of after two weeks of irrigation, likely due to the lack of development of a mature root system or maximum leaf area for photosynthesis; only *Sedum album* grown in clay showed particular good ability to recover from a two week drought (Thuring et al. 2010).

Native flora is generally preferred because they are adapted to local conditions and preserve the natural biodiversity (Oberndorfer et al. 2007). Furthermore, introducing non-native species, while beneficial for stormwater retention, may be invasive in a specific area and have detrimental effects to the ecosystem as a whole (Dvorak and Volder 2010). The individual conditions of a specific region and green roof may determine whether native species or imported succulents will be better suited for the environment of the green roof.

2.2.3 Plant Stomatal Resistance and ET_c Crop Coefficient k_c

Specific plant physiology, combined with climatological factors, is the driving force behind the rate of ET occurring on a green roof. The crop coefficient k_c used in the standardized PM equations to estimate ET is, among many things, a function of the stomatal resistance, the ability of the roots to absorb soil moisture, and the leaf coverage and density (Allen et al. 1998). It has been established that succulents are resistant to drought for their ability to control their stomata and therefore conserve water. Much of the research surrounding the PM equation has included quantifying the surface and aerodynamic resistances. Physiology of the plant dictates the stomatal resistance, r_l, and in conjunction with the typical Leaf Area Index (LAI), i.e. leaf area per unit area of the ground, determines the bulk surface resistance (Allen et al. 1996). However, it should be noted that r_l is also known to change based on water availability and climate. Increased radiation and increasing vapor pressure deficit both increase stomatal resistance. Decreasing soil moisture increases stomatal resistance (Allen et al. 1996; Allen et al. 1998). Estimates of r_l for CAM plants, such as sedums, range from 300-2000 s/m compared with C3 metabolism plants, such as corn and wheat, that range from 130 to 200 s/m (Spalding et al. 1980; Black and Osmond 2003).

Both the FAO and ASCE provide k_c values for crops, such as pineapple, that also utilize CAM, but pineapple and sedums have different physical characteristics and as such may not have comparable surface and aerodynamic resistances and k_c values. Further, it should be noted that the k_c values published in FAO56 are based on average r_l values that theoretically vary with each time step (Allen et al. 1996). For further details see 3.0 Theory and General Methodology.

2.2.4 Substrate Depth

Theoretically, root-water uptake is time and space dependent including factors such as soil property, crop characteristics, soil moisture, and weather conditions. Root systems are complex and uptake capabilities vary from top to bottom with the maximum occurring at the top near the surface and the minimum occurring at the bottom of the root (Ojha et al. 2009). Correspondingly, considerable research has been performed regarding the effect of substrate depth on plant growth on a green roof (VanWoert et al. 2005a; Thuring et al. 2010; Durham et al. 2007; Getter and Rowe 2007, 2008, 2009). General agreement exists that media depths of 7 cm – 10 cm (3.1 inches – 4 inches) provides significant improvement of plant establishment and growth over time compared to shallower media depths (Dvorak and Volder 2010; Getter and Rowe 2007, 2008; Thuring et al. 2010). Substrate depth did not influence survival of Sedum plant species when compared to season of planting (Getter and Rowe 2007) and the difference in plant growth was negligible the first

2 months, but as the roots grow and mature, the deeper substrate depths substantially improved plant growth. This is perhaps because the deeper substrate is able to store more water that is not accessed by the plants until the roots are longer, which is important during drought periods (Durham et al. 2007; VanWoert et al. 2005a). The plant selection will also affect the implications of substrate depth as succulents, such as stonecrops, will not benefit from depths greater than 10 cm but herbaceous plants will (Thuring et al. 2010). Congruently, VanWoert (2005a) found that irrigation could offset the effects of shallow substrate and Getter and Rowe (2009) found that mean volumetric moisture content over 48 months corresponded with absolute coverage rates of the plants. Additionally, colder climates benefit from at least 10 cm (4 inch) substrate to prevent frostbite of the roots of plants, which hinders water uptake and growth the next year (Dvorak and Volder 2010; Durham et al. 2007).

There have only been limited studies on the effect of substrate depth on stormwater retention and it is difficult to compare different studies on stormwater retention due to varying environmental conditions and green roof characteristics. VanWoert et al. (2005a) and Uhl and Schiedt (2008) both found a positive relationship between substrate depth and retention while, on the other hand, Berghage et al. (2007) report that a doubling in substrate depth from 4 cm (1.6 inches) to 7.9 cm (3.9 inches) produced almost no noticeable retention increases. Similarly, Voyde et al. (2010a) reports no statistically significant difference in stormwater retention when increasing soil depth from 5 cm to 7 cm with the exception of one of 6 plots, which had a pre-grown sedum mat as opposed to planted plugs; however, it was stated that plant cover improved with the deeper substrate. Possible hypothesis for these differences between the four studies includes substrate composition, filter fabric, and plant species present. The use of a retention fabric is thought to improve retention beyond the substrate's abilities but the results of various studies are inconclusive (Uhl and Schiedt 2008; Voyde et al. 2010a; VanWoert et al. 2005a). Several studies have also examined the effect of green roof slope in combination with substrate depth and again results are varied. German studies have concluded annual retention to be similar for a large range of roof slopes from 2% to 9% (Van Woert et al. 2005a). VanWoert et al. (2005a) found no difference for heavy rainfalls (>6 mm, as defined by the author) and only minor differences overall. For a given substrate depth, however, retention was higher for a 2% slope than a 6.5% slope. Villareal and Bengtsson (2005) also found substantial differences in runoff between roof slopes when categorized into rain intensity; higher slopes saw greater runoff. Again, seasonal differences were observed in runoff when distributed by slope, which can possibly be attributed to the slope and orientation of the green roof positioning it to obtain more solar radiation energy, thereby potentially increasing ET (Uhl and Schiedt 2008). Uhl and Schiedt (2008) observed larger differences in runoff in warmer weather, possibly because of increased lateral flow due to higher conductivity.

One would expect stormwater retention to increase with increased substrate depth (more water-holding capacity) and more established vegetation (higher transpiration rates) but as can be seen, this is not so clear. The earlier discussion of monthly and annual stormwater retention yielded variability that was widely hypothesized to be a factor of rainfall depth and timing and it appears the relationship between retention and substrate depth is similarly complicated.

2.2.5 Substrate Composition

Composition is an important consideration for water retention, plant growth and water quality of runoff. Studies have shown that increased organic content can aid plant growth, but its decomposition over time leads to loss of soil volume and water-holding capacity. Furthermore, organic matter can leach nutrients into the runoff and as such organic content is suggested to be a maximum of 15% by volume (Rowe et al. 2006).

The substrate used on an extensive green roof is usually a unique blend of materials designed to retain water and be lightweight. Common material composition includes minerals, such as shale, slate, clay or volcanic materials, and a variety of fines and organics. Large aggregate materials, such as shale and slate, are preferred for green roofs because of their lightweight and drainage abilities but suffer from low water-holding capacity; the ideal green roof media will hold a large amount of water, but upon capacity drain so as to not pond at the surface (Rowe et al. 2006). Little research has been performed to specifically improve the physical properties of substrate. Mixed aggregates with fines and organics, such as peat and compost (compost is a recycled material that has numerous sources including mushroom and poultry) have been analyzed to improve plant growth (Rowe et al. 2006; Thuring et al. 2010). Other sources of organics include Polyacrylamide gel (PAG) and Urea-formaldehyde resin foam (UFRF), which have been used to decrease bulk density, increase water-holding capacity of soils, and improve plant growth in horticulture and agriculture (Nguyen et al. 2009). Experimental substrate design to improve plant performance on green roofs is in its infancy and could be found in only three instances in the literature. Contrary to literature, Panayiotis et al. (2003) did not find an increase in water-holding capacity with the addition of UFRF to a sandy loam despite increasing the air-filled porosity, and subsequently failed to observe improved growth of Lantana camara on a green roof. On the other hand, despite realizing increases in water-holding capacity, Nguyen et al. (2009) did not find these increases to increase plant available water (presumably TAW) for *Orthosiphon aristatus*, albeit a species not likely to be found on a green roof. Rowe et al. (2006) tested various green roof substrate mixtures with increased and reduced water-holding capacities and found different plant growth behavior for herbaceous and succulent species. Substrate depth and organic content also played a substantial role in plant growth, especially for the herbaceous species.

Studies with regards to plant growth and viability in various substrates are limited too. *Sedum album* has been the only plant among both herbaceous and succulents found to be affected by substrate type when water was available in clay and shale; however, during droughts, plants in clay did better than shale likely due to the water holding ability of clay. It is hypothesized by Thuring et al. (2010) that the performance of shale could likely be improved with the addition of fines or organic material because substrates used were under the organic content recommended by the FLL. The addition of fines or organics would improve the water-holding capacity of the soil closer to that of clay and therefore improve drought performance (Thuring et al. 2010), but from the limited research available this may not be true. Monterusso et al (2005) and Rowe et al. (2006) similarly found that herbaceous plants in particular needed additional irrigation to offset the lower water-holding capacity of slate, which has similar characteristics to expanded shale (Thuring et al. 2010).

Higher water holding capacity is important as evident by the performance of clay, however plants prefer to grow in medias with large proportions of large-sized aggregates, such as shale and slate, assuming adequate water supply (Thuring et al. 2010; Rowe et al. 2006). As such, clay-based media may be better in areas affected by drought due to water retaining capacity of the media while shale-based media may be better for areas subject to more frequent precipitation, especially acid rain, which is better neutralized and the ability to dry out quicker (Berghage et al. 2007). Regardless, the most suitable soil may be based on local plant availability because this will determine the growth requirements. While high organic content should be limited on a green roof because of the maintenance it incurs, it is important to provide plants the opportunity to thrive in order to promote transpiration, which affects green roof performance (Voyde et al. 2010; Berghage et al. 2007) and provide the aesthetic and ecological benefits associated with green roofs.

2.3 Measuring ET

2.3.1 Weighing Lysimeters

Weighing lysimeters have often been used to determine ET successfully because they depend on a simple mass balance where ET is equal to total water input minus percolation and change in water storage (measured as the change in weight). However, measured percolation and irrigation are included in the measured weight change and therefore must be added back to the weight before ET can be calculated (Schwaerzel & Bohl 2003). Although generally accurate, lysimeters require a significant financial investment, maintenance, and a long study period (Meissner et al. 2008). The most important part of a weighing lysimeter, if it is to be used for quantifying ET for a particular type of vegetation, is that the soil mixture and plants be the same as the area being modeled (Allen et al. 1998). Lysimeter applications in poorly watered vegetation prove to be particularly problematic due to differences in soil texture, soil depth profile, fertility, salinity, and thermal conditions inside and outside lysimeters (ASCE 1996) and ET may fall outside the limits of the resolution of the lysimeter. Lysimeter design and operation details will also affect measured ET (Vaughan 2007). A common issue with weighing lysimeters is measuring percolation. A funnel with a tipping bucket can be used to measure the percolation, but the bottom of the lysimeter has a tendency to clog and a water saturated zone at the bottom can cause temporary anaerobic conditions influencing capillary rise during evapotranspiration (Weihermueller et al. 2007); additionally, high percolation rates my exceed the capacity of the rain gauge. Another method to measure change in water storage and to corroborate the lysimeter data are tensiometer and TDR probes; a tensiometer probe contains a small vacuum with which it detects changes in soil tension and TDR probes emit an electric current whose response changes based on the water content of the soil around it (Schwarzel 2003). TDR probes were found to more accurately measure the change in soil moisture than tensiometers (Schwarzel 2003), although their high cost prevents widespread installation (Denich and Bradford 2010). Nonetheless, redundancy in soil moisture measurements is a good thing and can only lead to more accurate data. Considerable improvement in ET measurements has also been shown with the use of post processing of data, such as with a Savitsky-Golay filter (Vaughan et al. 2006).

2.3.2 Energy Flux Measurements

The strenuous installation requirements of weighing lysimeters have lead to more advanced direct measurements of ET. The Bowen Ratio Method and Eddy Correlation Method require the measurement of the individual components of the atmospheric energy and mass balances to find actual ET.

The Bowen Ratio Method relies on the ratio of the sensible heat flux to the latent heat flux, which can be further defined as a psychrometric constant times the ratio of the change in temperature to the change in water vapor pressure for two different heights. The Eddy Correlation Method determines the sensible and latent heat fluxes by measuring the vertical windspeed, temperature, and vapor density instantaneously and averaging the results over a specified time. However, success varies using these two methods. Certain times of the day are not well suited for measurements using Eddy Correlation because of condensation that develops inside the instrumentation, especially in the early morning hours. Other times the vapor pressure gradients are simply too weak to be accurately determined. It is imperative to use instruments that sample with high frequency and high sensitivity, especially for times with low humidity (Bidlake et al. 1996; Harrington et al. 2004; Jia et al. 2009). Regardless, numerous applications of Eddy Correlation measurements have successfully been applied in Florida using care to abide by fetch requirements and systematic data processing (Jia et al. 2009) and in other water-limited agricultural areas such as Africa (Kakane and Agyei 2006). Still, despite the advances made in sensor technology in the last 20 years, both Harrington et al. (2004) and Bidlake et al. (1996) concluded that the methods did not account for all the energy as estimated by the measured total solar radiation minus the subsurface heat flux and rate of heat storage in the canopy (if applicable).

Given the variability of results from both the Bowen Ratio Method and Eddy Correlation Method, a weighing lysimeter used in conjunction with either of these methods is expected to give good corroboration of ET specific to stormwater BMPs. An attempt would also need to be made to correct any skewed results from the micrometeorological methods that occur during dry periods. An advantage to these direct energy flux measurements is they have minimal theoretical assumptions and may be able to provide ET measurements on a larger scale than individual weighing lysimeters. Denich and Bradford (2010) ultimately hope to implement eddy covariance measurements of ET for the city scale and relate the network of lysimeter ET measurements to these larger scale findings.

2.4 Equations to Predict Evapotranspiration

2.4.1 Empirical Evapotranspiration Equations

There are many empirical ET models available, some of which are still frequently used for their simplicity (e.g. 1985 Hargreaves-Samani, Priestly-Taylor, Thornwaite Method, Turc, Makkink). Each method considers slightly different meteorological variables, and places different weight on each variable. For example, the Thornwaite and 1985 Hargreaves methods are based on daily temperature values (average and min/max, respectively) and the Priestly-Taylor, Turc, and Makkink equations are based solely on solar radiation. These methods can produce variable estimates of ET depending on temporal and spatial scales and as such, require local calibration for proper estimates (Lu et al. 2005; Jensen et al. 1990; Allen et al. 1998); even with local calibration, methods, such as Thornwaite, underestimate ET in arid conditions and overestimate ET in wet climates due to lack of a representation of the vapor deficit (Pereira and Pruitt 2004). Perhaps one of the most important misuses of these empirical methods is the time step at which they are applied. For example, the FAO24 Blaney-Criddle was recommended for one month or longer and the pan evaporation method was recommended for ten or more days. These limits are not always respected because ET estimates are often needed on smaller timescales for irrigation requirements (Allen et al. 1998).

The multitude of choices led organizations such as ASCE and the FAO to recommend a preferred method to estimate ET. In 1977, in FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt 1977), the Blaney-Criddle method was recommended as an alternative to the analytical modified Penman equation and pan evaporation method for instances where only air temperature was available. Subsequent studies revealed the necessity for an update and the ASCE published Manual of Practice No. 70 (Jensen et et al. 1990) in which the analytical Penman-Monteith equation was recommended as the sole method for estimating ET. However, where data was limited to temperature, the 1985 Hargreaves equation was recognized as providing the best estimates with the widest range of validity of the available empirical equations (Allen et et al. 1998). In 1998 and 2000, the FAO and ASCE, respectively, discouraged the use of empirical equations, instead recommending standardized Penman-Monteith equations with methods for estimating the necessary parameters from simple climate data sets (Allen et al. 1998; Walter et al. 2000).

2.4.2 Penman and Penman-Monteith Equations

The Penman Equation (Eqn 2.4.1) was first developed in 1948 and was the first method to combine the energy balance and mass transfer functions for determining ET (Penman 1948):

$$E_h = \frac{\Delta}{\Delta + \gamma} Q_N + \frac{\gamma}{\Delta + \gamma} E_a \tag{2.4.1}$$

where E^h = flux of latent heat due to evaporation, Δ = slope of the curve saturation vapor pressure (at water surface) vs Temperature, γ = psychometric constant, Q_N = net radiation absorbed, and E_a = the drying power of the air (Vieux, 2008).

The Penman-Monteith equation (Eqn 2.4.2) was developed in 1965 (Monteith 1965) and combines the Penman equation with vegetative parameters that include an aerodynamic resistance and surface resistance (Allen et al. 1996).

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \dfrac{e_s - e_a}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \tag{2.4.2}$$

where R_n is the net radiation, G is the soil heat flux, (e_s - e_a) represents the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapor pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances.

Each of the energy components in equations 2.4.1 and 2.4.2 is broken down into parameters that can be approximated by meteorological factors that include mean temperature, mean wind speed, relative humidity, and solar radiation. A complete set of procedures for estimating these parameters can be found in Allen et al. (1998). The Penman and Penman-Monteith equations should not require local calibration because they model the physical process of ET, although substantial improvement of ET estimates have been found for the Penman equation with a locally calibrated wind function (Walter et al. 2000; Allen et al. 1996). The Penman-Monteith equation incorporates the effects of plant physiology (r_a and r_s) and while improving the estimate, adds complexity to the equation. The most significant change between the Penman and Penman-Monteith equation is the replacement of the linear wind function with the surface resistance parameter r_s, which changes with windspeed and causes calculated ET to vary curvilinearly, decreasing with increasing windspeed. On the contrary, the Penman equation has been shown to overpredict ET in moderate to high winds (Allen et al. 1996).

Substantial research is required to quantify the plant characteristics because they are not yet fully understood (Black and Osmond 2003; Chen and Black 1983; Pittenger and Shaw 2004, 2007). Feller (2011) attempted to calibrate the Penman-Monteith equation using lysimeter data from an extensive green roof containing a variety of sedums. The lysimeter data was used to fit the direct Penman-Monteith equation for values of r_a and r_s. The aerodynamic resistance parameter, r_a, is based on the roughness length governing momentum transfer and are estimated with a series of relationships that are based on crop height (Allen et al. 1998). Sedum's are low lying vegetation generally shorter than the reference crop height of 0.12 m; reducing the height used to calculate r_a increases r_a. Feller (2011) used standard methods from FAO56 to estimate the aerodynamic resistance with two changes to the reference variables; the height of the crop, h, was changed to 0.1 m and the height at which the humidity measurements were taken was 0.5 m instead of 2 m. This yielded a r_a of $\frac{176}{u_2}$, where u_2 is the average windspeed 2 m above the surface. The parameter r_s was taken to be 100 s/m. Reduction coefficients were found by minimizing the sum of the squared errors between the measured lysimeter ET and the Penman-Monteith equation (2.4.2). The reduction coefficients 0.62 and 0.81 were found for r_a and r_s, respectively, using data from April to November 2009. The parameter r_a was ultimately taken to be $\frac{109}{u_2}$ and r_s was 81 s/m (Feller 2011), compared to the reference parameters $\frac{208}{u_2}$ and 70 s/m (Allen et al. 1998).

These values for r_s and r_a are difficult to compare to accepted values for other crops or to values of k_c because of the unique physiology and physical characteristics of sedums. However, r_s can be otherwise estimated from Eqn 2.4.3 (Allen et al. 1998).

$$r_s = \frac{r_l}{LAI_{active}} \tag{2.4.3}$$

where r_l is the average stomatal resistance of a leaf [s/m] and LAI_{active} is the active Leaf Area Index, which is defined as the sunlit surface area of leaf per area of ground [m^2/m^2]. Depending on the maturity of the plant, LAI is usually taken to be between three and five with LAI_{active} estimated at half. If r_l is assumed to be 1000 s/m (see 2.2.3) and LAI is four, then r_s can be approximated at 500 m/s, which is substantially higher than Feller (2011). The parameter r_a calculated by Feller (2011) was also substantially different from the reference value, indicating that the zero displacement heights and roughness lengths that determine aerodynamic resistance may not be the same for a sedum green roof compared to a field of turf grass. More work needs to be performed in this area, but the resistance parameters from Feller (2011) may not be a realistic representation of sedum physiology although it is also unknown what type of complicating factors might affect the presented results. Determining r_s and r_a is obviously a tedious task that may vary considerably based on the green roof location and the variety of vegetation present.

As a result, the concept of reference ET was developed to provide a consistent measure of ET. Reference ET is ET from a reference surface (reference crop with no environmental stresses), usually taken to be short turf grass or the taller alfalfa plant. Modification of reference ET to match actual environmental conditions and plant selection is accomplished with crop and stress coefficients.

There are numerous implementations of the Penman and Penman-Monteith equations that may include modifications for wind function and mean daily vapor pressure deficit and are formatted to match the inclinations and requirements of individual types of users: California Irrigation Management Information Systems (CIMIS), Natural Resources and Conservation Service (NRCS), Holdridge, British Meteorological Office of Rainfall and Evaporation Calculation system (MORECS). The standardized reference equations as promoted by the FAO and ASCE were developed to provide a standard, unified approach for all types of users worldwide (Allen et al. 2000).

2.4.3 FAO56 Standardized Reference ET Equation

In 1998, the FAO of the United Nations published FAO56 as an update to FAO24 (Doorenbos and Pruitt 1977), promoting a standardized reference Penman-Monteith equation as the sole method for calculating reference ET (Eqn 2.4.4). The publication was a result of an international commission that reviewed the then-currently accepted methods for calculating reference ET (from FAO24) and concluded that advances in research and technology allowed for improved reference ET measurements. FAO56 defined the reference crop as having a height of 0.12 m, a surface resistance (r_s) of 70 s/m, and aerodynamic resistance (r_a) of $\frac{208}{u_2}$ s/m and an albedo of 0.23; it is assumed the crop is of uniform height, actively growing, and with adequate water. The equation for reference ET is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2.4.4}$$

where ET_o is reference ET [mm/day], R_n is net radiation at the crop surface [MJ/m^2/day], G is soil heat flux density [MJ/m^2/day], T is mean daily air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m/s], e_s is saturation vapor pressure [kPa], e_a is actual vapor pressure [kPa], e_s-e_a is saturation vapor pressure deficit [kPa], Δ is slope vapor pressure curve [kPa/°C], γ is psychrometric constant [kPa/°C].

Since the FAO56 reference ET has pre-established plant parameters, a single crop coefficients, k_c, is used to modify the reference ET for specific crops (ET_c). The coefficient k_c is based on the crop characteristics and changes throughout the growing season. A second coefficient, k_s, is used to account for stress conditions that arise from drought, salinity, management practices, and disease and is the final step in estimating actual ET ($ET_{c,adj}$).

Fairly little effort has been placed in specifying the stress coefficient (k_s) and crop coefficient (k_c) for stormwater applications despite the potential benefit of accurately predicting ET. The stress coefficient k_s will vary from year to year and would be difficult to predict. The stress coefficient is better suited to real-time monitoring and estimation of irrigation demands. For stormwater BMPs, several values may be recommended for various climatic years: wet, average, and dry.

Allen et al. (1996) provides some guidelines for estimating ET from natural vegetation and includes a discussion on parameter k_c. In general, k_c should not exceed 1.3 for grass reference because the "reference crop provides a nearly maximum sink for short-wave radiation and has large LAI and roughness to promote energy and vapor transfer." Additionally, the Penman-Monteith equation assumes a large field of vegetation (>50m diameter) for lateral energy fluxes to be negligible. Field calibrated values of k_c higher than 1.3 may indicate a problem with field measurements including a miscalculation of vegetation leaf area, a significant lateral energy transfer to/from the lysimeter, or bad weather data. It is noted, however, that smaller areas of vegetation may exhibit k_c values of 150%-180% of 1.25, which is a range of 1.9 to 2.3 (Allen et al. 1996). Two studies that quantify the crop coefficient, k_c, for green roofs include one in Italy and one at Penn State University, State College, PA. Lazzarin et al. (2005), in Italy, used soil hygrometer measurements and potential ET as calculated by a form of the modified Penman Equation to develop a curve for k_c against soil relative humidity, which is defined as the ratio of the water content to saturated water content. In 2002, there was relatively little water stress and the curve ranged from 0.32 to 0.52 with the average close to 0.5, but in 2003, the curve was more variable and ranged from <0 to 0.35 (Lazzarin et al. 2005), likely including the effects of water stress. Rezaei et al. (2005) performed a green house experiment with four trays each of soil and a mixed bed of *Delosperma nubigenum* and *Sedum album* at a 1:1 ratio. The trays were irrigated and set to dry for 21 days during which time the weight of each tray was monitored and compared to ET_o to determine crop coefficient values. It is unclear which methodology was used to determine ET_o. The experiment was performed twice, once for winter conditions, which produced a combined $k_s k_c$ coefficient of 0.74, and once for fall/spring conditions, which produced a $k_s k_c$ coefficient of 1.97 (Rezaei et al. 2005). The variable results of the studies above exhibit the need for more green roof specific estimation of crop coefficients; more discussion on estimating k_c and k_s is presented in 3.0 Methodology.

2.4.4 ASCE Standardized Reference ET Equation

In 2000, the ASCE standardized a slightly different reference ET equation, splitting the Penman-Monteith equation into one for a short reference crop and one for a tall reference crop by issuing a table of constants to accompany the ASCE PM equation (Eqn 2.4.5) (Allen et al. 2005).

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{2.4.5}$$

where ET_{sz} is standardized reference crop ET for short or tall surfaces [mm/day or mm/hr], C_n is a numerator constant that changes with reference type and calculation time step [K mm s^3/Mg/day or K mm s^3/Mg/hr], C_d is denominator constant that changes with reference type and calculation time step [s/m], and the other variables are similar to FAO56.

The coefficients C_n and C_d are based on the timestep desired for ET calculations and the reference crop chosen. The reference crops defined by ASCE are the same 0.12 m high grass as in FAO56 as well as a taller plant, 0.5 m high alfalfa. Reference ET for each of these crops is designated ET_{os} and ET_{rs}, respectively. Allen et al. (2005) felt that a single equation was least confusing but desired to represent both types of reference ET that were commonly used and for which crop coefficients were available.

Perhaps the most important contribution of the ASCE PM equation is the different constants for both daily and hourly calculations. While the FAO56 PM can be applied at hourly time steps by using 37 instead of 900 in the numerator (Eqn 2.4.5) along with hourly weather data, Itenfisu et al. (2003) showed improvement in the ASCE PM over FAO56 PM for hourly calculations during both daytime and nighttime when comparing sum-of-hourly vs daily ET; the ASCE PM equation provides different resistance parameters for daytime and nighttime. The ASCE PM equation also provides clear guidelines for use of the alfalfa reference crop. The crop coefficients applied to ET_o are distinct depending on the type of reference ET. Allen et al. (1998) estimates the alfalfa family of crop coefficients to be 1.05-1.3 of the grass family crop coefficients, depending on humidity and wind conditions; predictive equations exist to convert ET_{rs} to ET_{os} based on these conditions (Allen et al. 1998). However, it should be noted that the crop coefficients published in Allen et al. (1998) for FAO56 PM can be used with ET_{os} from the ASCE PM equation (Itenfisu et al. 2003).

2.5 Sub-daily Evapotranspiration Measurements

Daily-calculated ET may misrepresent the ET occurring due to changes in humidity, wind speed and temperature throughout the day. Both evaporative power and plant stomatal resistance change with weather conditions (Allen et al. 1996, 1998; Irmak et al. 2005). Research has shown that using surface resistance of 70 s/m for reference grass will under-predict ET during the daytime and over-predict ET during the nighttime. Several studies have confirmed 50 s/m for daytime and 100 s/m for nighttime to be more appropriate on an hourly basis (Itenfisu et al. 2003; Irmak et al. 2005). The use of 70 s/m is, however, still considered appropriate for daily time steps (Allen et al. 2006). The energy ground flux may also affect ET on an hourly time step, as it is generally highest during the dawn and dusk hours; it is often approximated to be zero on a daily basis (Allen et al. 1996). Procedures for approximating the ground flux hourly can be found in Allen et al. (1996, 1998). Changes in incident radiation from morning to evening could also explain differences in daily vs sum-of-hourly ET as the sunlight hits the leaves at different angles.

Some applications, such as stormwater BMPs, may benefit from hourly or smaller time steps due to the small time scale in which they operate. Rain events often occur only for short amounts of time (hours) and the retention recovery implications of ET are critical to understanding how BMPs such as green roofs are affected by changes in weather conditions. Daily time step ET may not present enough detail for research into understanding the behavior of the coefficients k_c and k_s but would certainly be accurate enough for implementation in SCM design.

Studies validating the FAO56 PM and ASCE PM have included hourly comparisons with lysimeter measured ET and each study revealed relatively good accuracy with the highest rates of ET early afternoon (Irmak et al. 2005; Itenfisu et al. 2003; Howell and Evett 2005; Allen et al. 2006). Voyde et al. (2010) and Berghage et al. (2005) similarly determined the highest rate of ET to be between 12pm and 3pm immediately after irrigation in a greenhouse simulation of a green roof comprised of sedums. An hourly time step for calculating ET would capture this daily peak and could have substantial implications for a green roofs retention recovery if one considers the lower soil tension present after a rainfall.

2.6 Sensitivity of ET Estimates

It is widely accepted that accurate ET estimates from any of the Penman-Monteith equations is dependent on good weather data; Allen et al. (1996, 1998) provides helpful quality assurance procedure for weather station data (Irmak et al. 2005; Itenfisu et al. 2003). Additionally, the PM equation functions under the assumption of a large expanse (>50 m in all directions) of vegetation to negate lateral energy fluxes and expects the vegetation to be healthy, well-watered, and actively growing. Violations of each of these expectations can result in poor results (Allen et al. 1996).

Studies have shown ET predictions to be volatile in high-advection, high vapor pressure deficit conditions (Howell and Evett 2004; Allen et al. 2005; Irmak et al. 2005; El Khoury 2010); various wind functions have been employed with the Penman and Penman-Monteith equations in the past to improve estimates. Wind affects ET by transporting water vapor away from the crop surface and change the aerodynamic and surface resistances of the vegetation (Itenfisu et al. 2003; Jensen et al. 1990; Allen et al. 2006). In fact, El Khoury (2010) found PM estimates of ET to be an order of magnitude more sensitive to wind than any other climatic variable and suggests that an anemometer at any site requiring ET estimates would greatly reduce the uncertainty of estimates for relatively little expense; in contrast, Martin (2009) reported greater sensitivity to relative humidity for simulated green roof runoff. ET estimates are also especially sensitive to the coefficients used with ET_o, especially low k_c values (Martin 2009; El Khoury 2010; Allen et al. 2005). The FAO56 values for crop coefficient k_c are considered valid for an average minimum relative humidity of 45% and average wind speed conditions of 2 m/s (Allen et al. 1998, 2005). Although the standardized PM equations account for wind speed when calculating ET_o, vegetation with a different aerodynamic resistance would respond differently and k_c does not incorporate changes in wind speed (El Khoury 2010). Additionally, k_c coefficients were determined under ideal growing conditions, which may be atypical of actual conditions, although the dual crop coefficient method was found to be more robust than the single crop coefficient method (Allen et al. 2005). Lastly, the stress coefficient k_s may vary based on vegetation and substrate type and depth for a given soil water content (El Khoury 2010).

Chapter 3

Theory and General Methodology

3.1 Villanova Green Roof

The Villanova green roof is a retrofit of the roof that is situated on part of the Center for Engineering, Education, and Research (CEER) building on Villanova University's campus. The building abuts Spring Mill Road (PA State RT 320) in Villanova, Pennsylvania. The green roof is considered extensive and was built in July 2006 and is 53.4 m^2 (575 ft^2). The roof was designed to capture the direct rainfall and according to the designer has a rain capacity of 4.7 cm (1.85”). The Villanova green roof, from bottom to top, consists of an impermeable membrane, a drainage layer, absorbent filter fabric, 10 cm (4”) of soil media, and a variety of *Sedums* (Appendix A). A typical cross section for an extensive green roof can be seen in figure 3.1.1. The soil media used for the Villanova green roof is the rooflite® extensive mc made by Skyland USA, LLC (Appendix B) and is designed to be lightweight and to have a high water content when water is available but also drain to avoid ponding at the surface. *Sedums* were planted for their ability to thrive in a diverse set of conditions that include both saturation and periods of drought. *Sedums* are particularly well suited for the highly porous rooflite® media. More information regarding Villanova's green roof and current green roof design standards can be found in Feller (2011), PADEP (2006), and FLL (2002).

Additionally, the green roof includes a full weather station that measures solar radiation, wind speed, rainfall, temperature, and relative humidity (Figure 3.1.2, Table 3.1.1, Appendix C). These parameters are measured for use in the Penman-Monteith equation, which is used to model ET to compare to the results from the weighing lysimeter.

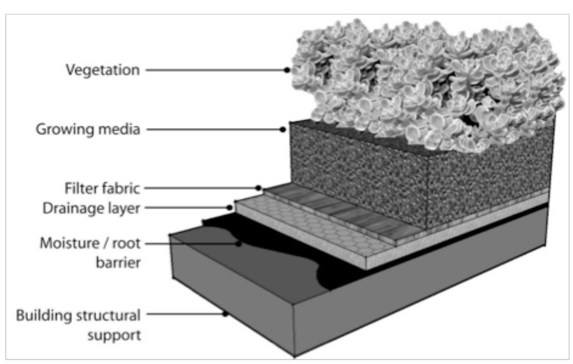


Figure 3.1.1: Typical Extensive Green Roof Cross Section (Martin 2009)

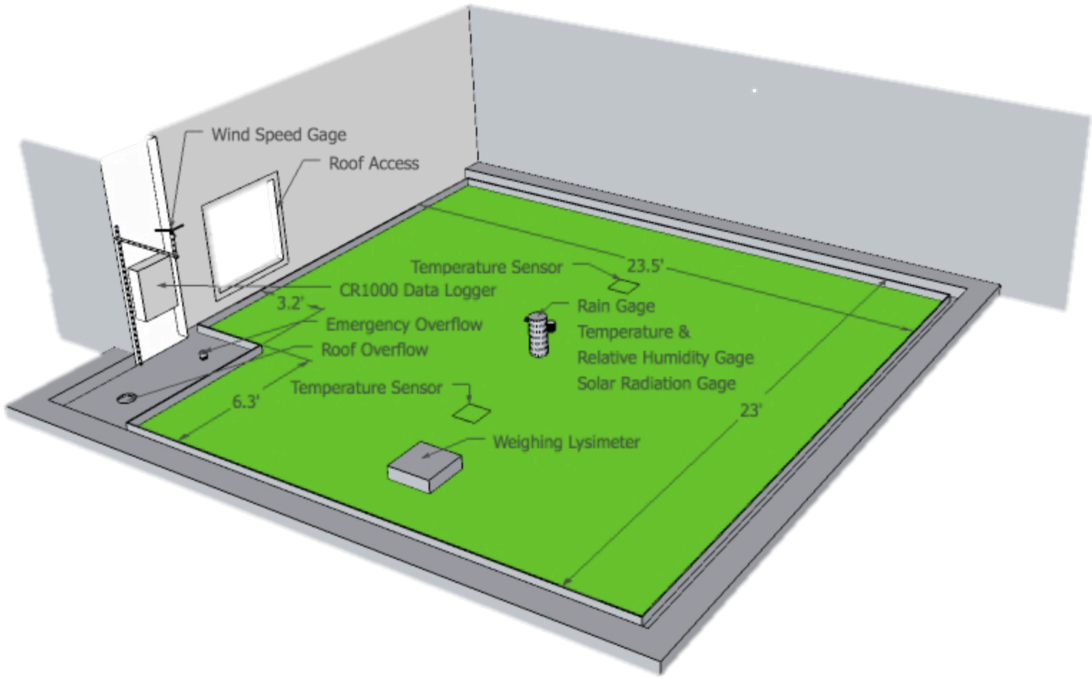


Figure 3.1.2: Schematic of green roof and current instrumentation (Feller 2011)

Table 3.1.1: Weather Instrumentation used at the green roof (Feller 2011)

Parameter	Product No.	Instrument
Temperature	HMP50	Vaisala Temperature and RH Probe
Relative Humidity	HMP50	Vaisala Temperature and RH Probe
Wind Speed	014A	Met One Anemometer
Solar Radiation	LI200X	LI-COR Silicon Pyranometer
Rainfall	2149	American Sigma Rain Gauge
Datalogger	CR1000	Measurement Control Sys

3.1.1 Weighing Lysimeter

The weighing lysimeter on the green roof is a cubic structure made of CPVC with the inner dimensions 45.7 cm x 45.7 cm x 10 cm (18″x18″x4″) (LxWxH) (Figure 3.1.3). The weighing lysimeter box is situated on top of three Sentran load cells (model PF; capacity 45.5 kg (100 lbs); accuracy 0.25%; compensated temperature range 4.4°C to 60°C (40°F to 140°F)), which are connected to a Campbell Scientific CR1000 datalogger. Both the green roof and the weighing lysimeter consist of the same layers as mentioned previously. The lysimeter box sits on top of the green roof. Additionally, the lysimeter, despite having a drainage layer, has no opening from which water can drain. As a result, the lysimeter will overflow out the top in cases where it rains more than there is storage in the box where as the green roof itself has an underdrain with an outflow pipe.

Figure 3.1.3: Picture and schematic of weighing lysimeter used in this research. The lysimeter is 45.7 cm x 45.7 cm x 10.2 cm deep (18″x18″x4″). (Feller 2010)

3.1.2 Load Cell Data

Previous research using data from the green roof lysimeter included a calibration analysis of the load cell data by Feller (2011). A 23 day calibration period was observed with a static weight of about 66 kg. Although data was collected every five minutes, fluctuations due to solar radiation and/or temperature forced the analysis of only midnight data points to eliminate solar induced variations. The 23 midnight data points from the calibration period were assumed to be a normal distribution with a mean of 66.20 kg and a standard deviation of 0.09 kg. Ninety percent of the data, with 95% confidence, was observed to fall within 1.04 mm (0.04 in) ET. More discussion regarding the error of the weighing lysimeter can be found in Feller (2011).

3.1.3 Water Balance

The ASCE Hydrology Handbook (Allen et al. 1996) describes the general soil water balance (Eqn 3.1.1):

$$\Delta\Theta * z_s = P - Q_r - ET_a - DP + GW \tag{3.1.1}$$

where $\Delta\Theta$ is the average moisture content change of the soil [cu. m/cu. m], z_s is the depth of the soil [mm], P is precipitation and irrigation [mm], Qr is surface runoff [mm], ET_a is actual evapotranspiration [mm], DP is deep percolation losses [mm], and GW is movement of ground water into the soil column [mm]. The green roof is not connected to ground water, i.e. there are no DP or GW fluxes, therefore the equation can be rearranged and solved for ET_a (Eqn 3.1.2).

$$ET_a = P - Q_r - \Delta\Theta z_s \tag{3.1.2}$$

where P is precipitation as measured by a tipping bucket rain gauge [mm] (American Sigma Rain Gauge Product# 2149) located on the green roof (Figure 3.1.2). The runoff (Q_r) was measured by an Omega flow meter and a 12" Thelmar Weir with a Senix ultrasonic transducer, although these were not in operation for the majority of this study. The change in moisture content in the soil is modeled by the weighing lysimeter and is measured as the change in weight of the system (ΔW). Since the weighing lysimeter was built without an outflow for runoff, it has a possibility to overflow during heavy rain events. In order to estimate the overflow, the lysimeter weight was evaluated for each day and the daily maximum weight was noted. Additionally, the maximum weight recorded for each growing year was also noted. The largest observed weights in 2009 and 2010 were 44.1 kg (97.0 lbs) and 43.5 kg (95.7 lbs), respectively, and are indicative of the lysimeter being at full capacity. It is theorized that the difference between the observed maximum weights is a result of external factors e.g. rain intensity being greater than the infiltration rate of the soil.

Both the daily maximum weights and yearly maximum weights were used as an indication of the lysimeter being at maximum capacity to estimate overflow. The difference between the expected maximum weight (by adding the rain to the minimum weight of the day of the rain event) and the actual maximum weight on the day of the rain event was estimated to be the lower bound of the overflow estimate. The difference between the maximum weight of the entire dataset each year instead of the daily maximum was used to estimate the upper bound of the overflow estimate. Negative overflow results were considered a product of noise and were estimated as zero.

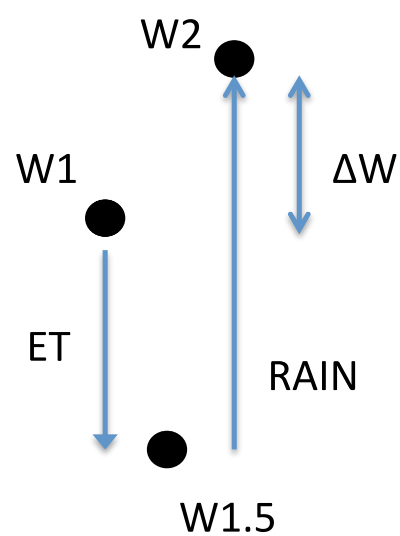


Figure 3.1.4: Demonstration how the change in weight (ΔW) recorded over one day can mislead conclusions about ET. If ET is calculated simply as the change in weight from midnight (W1) to midnight (W2), ET would be considered 0 for the day because the rain (more than) compensates the weight loss due to ET. In this case, ET is the difference between W1 and the lowest weight of day 1 (W1.5). This is equivalent to rain (P) minus change in weight from midnight to midnight (ΔW) (Eqn 3.1.2)

Some questions were also raised about the validity of Eqn 3.1.2 depending on the time scale. On a daily time scale, it is important to include both rainfall, ET, and overflow in the mass balance because both processes could have affected the resulting weight the next day (Figure 3.1.4). However, on a five-minute timescale, it can be assumed that only one process is occurring at a time. As such, the change in weight is indicative of rain or ET depending on the sign. Possible complication in this situation occurs during overflow where the lysimeter weight is no longer changing despite both rain and overflow happening. Visual inspection of the data would need to be used to determine whether additional computation is required on the mass balance. Vaughan et al. (2007) addressed a similar issue and suggested that the irrigation and percolation amount be added back to the weight of the system at the one hour time intervals to avoid double counting this measure of water. In the case of the Villanova green roof, the daily ET mass balance is performed as per Eqn 3.1.2.

3.1.4 Green Roof Soil Characteristics

Although ET is primarily a function of solar radiation, it can be limited by soil moisture availability. It is difficult to determine how much water is available in the soil for ET, but understanding the soil characteristics of the rooflite® extensive mc media will help interpret the patterns of ET as they relate to rain patterns and soil moisture content. A general analysis of the media's soil characteristics were provided by the manufacturer and included a soil distribution curve along with a table of various ranges of values for soil properties such as dry and saturated density, porosity, water holding capacity, pH and salt content, organic matter content, and nutrients (Appendix B). However, in order to better understand the water available to the plants on the green roof, laboratory work was performed to more specifically determine the soil properties. The dry bulk density was found to be 0.71 g/cm^3 (44.3 lb/ft^3), which is within the range provided for rooflite® extensive mc for the Mid-Atlantic region (0.7-0.85 g/cm^3, 44-53 lb/ft^3). The specific gravity, G_s, was estimated using a procedure based on ASTM D 854, the standard test for specific gravity of soil solids using a water pycnometer. The procedure made use of a 500 mL flask in which dry soil (baked 24 hrs at 105°C) was weighed. Slurry was created with Milli-Q water and a vacuum applied to remove any air from within the slurry. After 10 minutes of applying the vacuum, water was added to the slurry until 200 mL of mixture was present. The 200 mL slurry was weighed and replaced with 200 mL of Milli-Q water, which was also weighed. Specific gravity was computed based on several trials and shall be considered to be 1.5 (Eqn 3.1.3).

$$G_s = \frac{m_s}{m_s + m_{fw} - m_{fws}} \tag{3.1.3}$$

where m_s is mass of dry soil [g], m_{fw} is mass of flask and Milli-Q water [g], and m_{fws} is mass of flask, Milli-Q water, and dry soil [g].

A soil moisture curve was found experimentally to help identify the range of moisture content available to the plants by applying a continuously increasing pressure head to a soil column and measuring the amount of water lost at each step. A soil sample is weighed, baked for 24 hours at 105°C, and weighed again to obtain the initial moisture content for the experiment. Meanwhile, a soil column is saturated by pouring water into a burette that is connected to the soil column with a tube (Figure 3.1.5). The initial water level is read from the burette and the soil column is raised in

2-inch increments. The water drained from the soil column will result in a new water level in the burette, which is noted after 5-10 minutes and the procedure is repeated.

Eventually, an air pocket will form at the top of the tube just below the soil column. This indicates water is no longer draining from the soil column at the rate at which water is moving from the tube to the burette. At this point, the change in water level in the burette is not representative of water draining from the soil column but rather of water leaving the tube as it is raised; this occurs at about 32 inches of head.

Knowledge of the porosity (n) of the soil (53%, Eqn 3.1.4, Eqn 3.1.5) allows estimation of the saturated volumetric water content (Θ_s) using the specific gravity and dry unit weight determined in the lab (Eqn 3.1.6).

$$e = G_s \frac{\gamma_w}{\gamma_d} \tag{3.1.4}$$

$$n = \frac{e}{1+e} \tag{3.1.5}$$

$$\Theta_s = 0.8n \tag{3.1.6}$$

where e is the void ratio [unitless], G_s is the specific gravity [unitless], γ_w is the unit weight of water [g/cm^3], γ_d is dry unit weight of soil [g/cm^3], n is porosity [unitless], Θ_s is the saturated water content of the soil [cm^3/cm^3].

The saturated water content was estimated based on the ratio (about 0.8) of maximum water holding capacity to maximum porosity provided on the material data sheet (Appendix B) and was measured to average 42%, which is within range of 40-55% listed for the maximum water-holding capacity of rooflite® extensive mc.

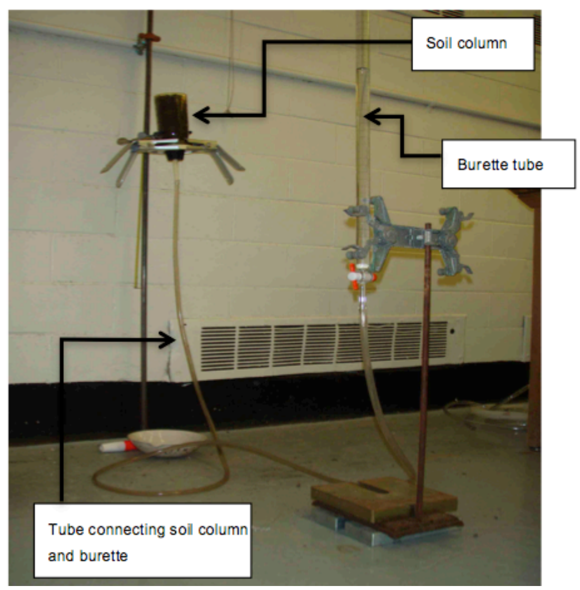


Figure 3.1.5: Test setup for determining the soil moisture curve of the green roof growing media. A soil column is connected by a tube to a burette, which measures the amount of water that drains from the soil column as it is raised incrementally.

The field capacity and wilting points of different soils can be varied based on the characteristics of the soil, but the available water for plant (i.e. the difference between the water contents at the field capacity and the wilting point) is very similar for fine to moderately coarse soils (Allen et al. 1996). The soil water retention curve (Figure 3.1.6) shows the range of moisture content available for plant uptake on the green roof. The field capacity is approximated at 0.39 cm^3/cm^3, where the slope changes on the right end of the curve and the wilting point is estimated at about 0.18 cm^3/cm^3, where the slope changes on the left end of the curve. As such, the available water is 0.21 cm^3/cm^3, which is slightly higher than most published values (Allen et al. 1996); however, this result may be appropriate since rooflite® substrate is designed to have a high water holding capacity.

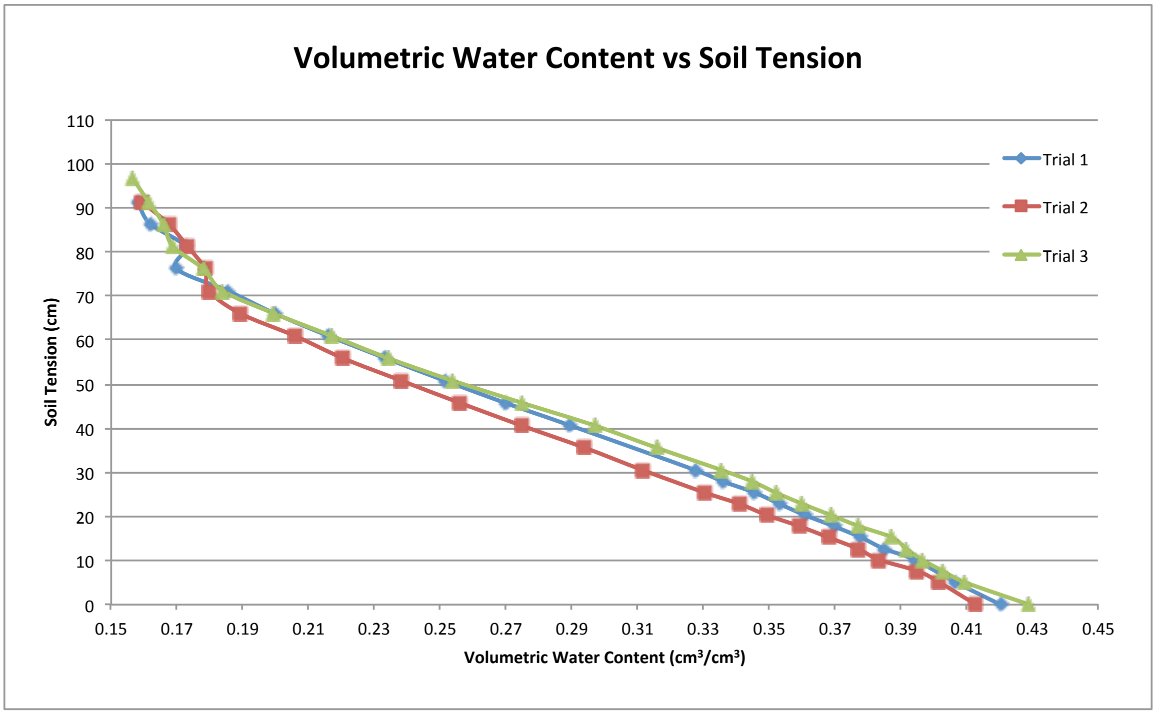


Figure 3.1.6: Volumetric Water Content vs. Soil Tension. Reproducible results show an upper drained limit of about 0.39 (see change of slope on the right) and a lower limit of about 0.18 (see change in slope on the left).

3.2 Estimating ET using FAO56

Actual ET ($ET_{c,adj}$) is computed using two coefficients to correct reference ET (ET_o) for the vegetation and the environmental conditions present. The first coefficient (k_c) is a crop specific parameter based on the aerodynamic resistance through the foliage of the plant and the stomatal resistance of the leaf (Eqn 3.2.1) and the second coefficient (k_s) is based on the environmental stress such as salinity and water availability (Eqn 3.2.2) (Allen et al. 1998).

$$ET_c = k_c ET_o \tag{3.2.1}$$

$$ET_{c,adj} = k_s ET_c \tag{3.2.2}$$

3.2.1 Determining ET_o by FAO56

Reference ET for the green roof was calculated using the standardized FAO56 Penman-Monteith equation (Eqn 2.4.4, Eqn 3.2.3) using on-site meteorological data. Data is recorded in five-minute intervals but summed/averaged as a daily value for computation of ET_o. The input parameters include minimum, maximum, and average daily temperature at 0.5 m; minimum and maximum relative humidity at 0.5 m; average daily wind speed at 2 m above the surface; and daily solar radiation. Daily estimates of ET were used instead of hourly estimates because comparison was being made against the lysimeter, which only measures to within one mm (4-5 hours worth of ET); additionally, original procedures followed were from Allen et al. (1998), which details daily timestep computations.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3.2.3}$$

Since ET_o is computed using predetermined characteristics of a reference plant, many of the variables in the direct Penman-Monteith equation (Eqn 2.4.2) can be calculated and combined into the coefficients seen in Eqn 3.2.3 and result in a simpler equation. Parameters T and u_2 are daily averages while R_n is a daily computation based on the sum of incoming solar energy (see Allen et al. 1998). The saturation vapor pressure (e_s) is approximated using temperature data and relative humidity data (Eqn 3.2.4) where $e_o(T_{max})$ is the vapor pressure at the maximum daily temperature (Eqn 3.2.5) and $e_o(T_{min})$ is the vapor pressure at the minimum daily temperature (Eqn 3.2.6).

$$e_s = \frac{1}{2}(e_{oTmax} + e_{oTmin}) \tag{3.2.4}$$

$$e_{oTmax} = 0.6108e^{\frac{17.27T_{max} - 116.9}{T_{max} + 237.2}} \tag{3.2.5}$$

$$e_{oTmin} = 0.6108e^{\frac{17.27T_{min} - 116.9}{T_{min} + 237.2}} \tag{3.2.6}$$

Using the average daily temperature to estimate e_s tends to underpredict the saturation vapor pressure and in turn underpredicts ET_o. As such, the average of $e_o(T_{max})$ and $e_o(T_{min})$ should be used when possible (Allen et al. 1998), as in eqn 3.2.4.

The parameter Δ is the slope of the saturation vapor pressure curve and is estimated for the day using the mean daily temperature (Eqn 3.2.7,Eqn 3.2.8).

$$\Delta = \frac{4098e_{oTmean}}{(T_{avg} + 237.2)^2} \tag{3.2.7}$$

$$e_{oTmean} = 0.6108e^{\frac{17.27T_{mean} - 116.9}{T_{mean} + 237.2}} \tag{3.2.8}$$

The actual vapor pressure (e_a) (as opposed to the saturation vapor pressure) is estimated by using the extreme vapor pressure (Eqns 3.2.5, 3.2.6) and relative humidity values (Eqn 3.2.9).

$$e_a = \frac{e_{oTmin}RH_{max} + e_{oTmax}RH_{min}}{200} \tag{3.2.9}$$

Lastly, γ is the psychometric constant estimated by (Eqn 3.2.10) and is taken to be 0.0666 kPa/°C.

$$\gamma = \frac{c_p P}{\epsilon\lambda} \tag{3.2.10}$$

where c_p is the specific heat of water at a constant pressure $[1.013 * 10^{-3}$MJ/kg/°C], P is atmospheric pressure [kPa] as estimated by Eqn 3.2.11, ε is the ratio of the molecular weight of water vapor to dry air at 0.622, and λ is 2.45 MJ/kg and is known as the latent heat of vaporization of water.

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{3.2.11}$$

where z is the elevation above sea level [m]. This was approximated to be 140 m for the research site using Google Earth®.

3.2.2 Determining Crop and Stress Coefficients k_c and k_s for Agriculure by FAO56

FAO56 (Allen et al. 1998) outlines two procedures that can be used to determine k_c for various crops. The first is a single estimate of k_c and the second is a dual-crop coefficient approach (Eqn 3.2.12) that separates the transpiration portion (k_{cb}) and the evaporation portion (k_e) (Allen et al. 1998):

$$k_c = k_{cb} + k_e \tag{3.2.12}$$

The method chosen for determining k_c depends on the data and resources available. The single coefficient method is sufficient where the immediate effects of soil wetting events are not important, but rather the time averaged performance of the system is important. As such, the single crop coefficient method is recommended for use in planning and design where the timesteps are daily, 10-day, and monthly. The dual crop coefficient can be more accurate if detailed soil and hydrologic water balance data is available; it is recommended when daily and sub-daily estimates of ET are required either for real-time irrigation demands or for research. The largest difference between k_c and k_{cb} occurs at the beginning of the growing season when there is still significant evaporation from exposed soil (Allen et al. 1998).

The coefficient k_c changes during the various crop growth stages, which vary for each crop but are broken down into the initial (k_{cini}), development (k_{cdev}), middle (k_{cmid}), and late (k_{cend}) stages. The coefficient k_{cdev} is interpolated as a straight line between k_{cini} and k_{cmid} (Figure 3.2.1). The stage lengths vary based on crop characteristics and weather conditions, especially mean daily temperature. Local observation, communication with farmers and horticulturalists, remote sensing, or sophisticated plant growth models are suggested for determining growth stage lengths. On-site observations of the length of each growing stage (initial, development, mid, and late) were not performed at Villanova. However, as a result of the dry conditions during the summer of 2010, it is suspected that the green roof spent most of the summer in the initial and development stages, the former being defined as having approximately 10% ground coverage; consequently, the initial and development stages may not be applicable in 2010. Allen et al. (1998) provides k_c values for an assortment of non-stressed (i.e. well-watered), well-managed crops in a sub-humid climate, where the daily minimum relative humidity (RH_{min}) is 45% and average wind speed two meters above the surface (u_2) is 2 m/s at mean maximum plant height. Additionally, several protocols are provided to localize k_{cini} (based on wetting frequency), k_{cmid} (based on mean plant height, RH_{min} and u_2), and k_{cend} (based on mean plant height, RH_{min}, u_2, and irrigation practices).

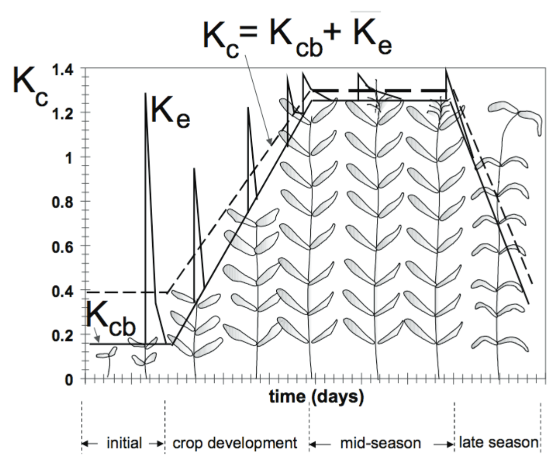


Figure 3.2.1: Theoretical variation in k_c during the growing season (Allen et al. 1998)

The dual-crop coefficient approach is more complicated because in addition to determining k_{cb} (similar to k_c but lower values, Figure 3.2.1) at the various stages, k_e is calculated following each wetting event (i.e. after gravity drains the soil down to the field capacity, see Section 2.2). At this point, the coefficient k_e is at a maximum and evaporation from the soil occurs at a maximum rate given the climatic conditions, limited only by the energy available. Once the Readily Evaporable Water (REW) is evaporated, the evaporation occurs at a decreasing rate until the soil moisture content is one-half the wilting point. The total amount of moisture evaporated is known as the Total Evaporable Water (TEW). It should be noted that the effect of k_e diminishes as vegetation cover increases because evaporation from soil beneath the vegetation cover is incorporated in k_{cb} (Allen et al. 1998). In the case of an extensive green roof, where coverage is theoretically 100% but not necessarily known due to a lack of maintenance, the dual crop coefficient may not be necessary or feasible.

The procedure for determining the coefficient k_c and k_{cb} is based on the assumption of adequate water supply. The coefficient k_s is used to further reduce the estimated ET (Allen et al. 1998). If it is assumed that a rain event saturates the soil, the following day the soil will drain due to gravity until the water content of the soil reaches field capacity, also known as the upper drained limit (Θ_{DU}). Plants have access to the water stored between the field capacity and the wilting point, also known as the lower limit of extractable water (Θ_{LL}). The region of moisture conditions between the upper drained limit and the threshold moisture content is known as the Readily Available Water (RAW) during which there is no stress to the plants and k_s is one. Readily Available Water is considered to be a fraction of TAW between 0.3 for shallow rooted plants and 0.7 for deep-rooted plants. The end of the RAW stage brings the soil to a threshold moisture condition at which point k_s decreases linearly to zero at the wilting point. Transpiration is the dominant process in ET during the mid-season with full cover and the single-coefficient k_c is intended to incorporate any evaporation. Under the single-crop coefficient scheme, ET ceases at the wilting point, however the dual-crop coefficient method would estimate more evaporation because k_s is only applied to k_{cb} (Eqn 3.2.13) (Allen et al. 1998).

$$ET_{c,adj} = (k_s k_{cb} + k_e) ET_o \tag{3.2.13}$$

Chapter 4

Applied Methodology and Results

4.1 Measured ET and Overflow

Evapotranspiration from the Villanova green roof was observed with a weighing lysimeter during the growing season (April – November) of 2009 and 2010. The year 2009 was a particularly wet and mild year with 1129 mm of rain and an average temperature of 17.5 $^{\circ}C$ compared with 772 mm and 19.1 $^{\circ}C$ in 2010, a dry and hot year (Table 4.1.1, Appendix B). Adjusting for overflow during heavy rain events, 2009 saw 756 mm of ET and 2010 saw 724 mm of ET (Table 4.1.1); this resulted in 67% retention and 94% retention, respectively. The Penman-Monteith equation is used in the standardized reference form to model ET and compared to results from the weighing lysimeter to determine the crop and stress coefficients that accompany the standardized reference ET equation. An on-site weather station was used to obtain the parameters necessary to calculate reference ET (ET_o) (Table 4.1.1).

ET varied considerably between months and years and overflow was a substantial factor in 2009 (366 mm), often accounting for 20% to 50% of the measured ET each month, with August and September having considerably more overflow. Much less overflow was estimated in 2010 (143 mm) when only July and November had substantial overflow (Table 4.1.1). The lysimeter data adjusted for overflow based on the daily maximum weight (see 3.1.1 Weighing Lysimeter) is used in all calculations unless otherwise noted.

4.2 FAO56 applied to Green Roofs

For natural or non-pristine vegetation, Allen et al. (1996) recommend the use of the dual-crop coefficient because of the adjustments to k_c that are considered. For example, the coefficient k_{cbfull} (Eqn 4.2.1) is an estimate of k_{cb} (transpiration coefficient) at peak plant size with adjustments for climate and mean plant height.

$$k_{cb\,full} = k_{cb,h} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \qquad (4.2.1)$$

The coefficient $k_{cb\,full}$ can be used as an approximation for k_{cbmid} when LAI is greater than three (typical values are 3-5) (Allen et al. 1998). Additionally, it is assumed that $k_{cb\,full}$ is a good estimate for k_{cb} for the lysimeter due the lack of an underdrain; the plants in the lysimeter consistently have a high LAI and did not suffer as much wilting as the rest of the green roof in 2010. Allen et al. (1998) also suggests that the single crop coefficient k_c can be derived from k_{cb} by accounting for wetting frequency. If it is assumed that, on average, southeastern PA sees approximately one wetting event

Table 4.1.1: Monthly Rain, Temperature and ET Data for 2009 and 2010. ET_{lys} is the measured ET from the lysimeter. Data (daily overflow adjusted) is ET_{lys} adjusted for overflow by computing overflow using the daily maximum and expected weights based on rainfall. See Section 3.1.3

	2009	Measured Data			Data (daily overflow adj)	2010	Measured Data			Data (daily overflow adj)
	Rain (mm)	Avg T (°C)	ET_o (mm)	ET_{lys} (mm)	ET_{lys} (mm)	Rain (mm)	Avg T (°C)	ET_o (mm)	ET_{lys} (mm)	ET_{lys} (mm)
Apr	119	12.9	86	126	101	65	14.6	71	103	102
May	144	17.5	93	144	100	106	19.0	103	139	138
Jun	118	20.6	92	117	98	92	24.5	133	107	107
Jul	131	23.1	120	114	114	152	26.6	132	161	129
Aug	268	24.3	100	268	127	38	24.7	110	46	46
Sep	130	18.7	70	129	90	105	21.5	95	41	26
Oct	166	12.6	48	167	75	161	13.9	57	215	123
Nov	54	10.0	34	54	50	54	8.0	36	55	53
Sum (Avg)	1129	(17.5)	643	1122	756	772	(19.1)	737	867	724

per week, k_c can be considered k_{cbfull} + 0.10 where $k_{cb,h} = 1.0 + 0.1h$ and h is plant height [m] (Allen et al. 1998).

Mid-season k_{cb} and k_{cbfull} values should also be adjusted based on stomatal control. A resistance correction factor, Fr, (Eqn 4.2.2) is used to modify k_{cb} for vegetation that has different internal properties than the reference grass, which has a mean stomatal resistance of 100 s/m along with many other agricultural crops (Allen et al 1998).

$$F_r = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma(1 + 0.34u_2 \frac{r_l}{100})} \tag{4.2.2}$$

The coefficient k_{cbfull} is an upper estimate of k_{cb} and k_{cb}+0.10 even more so. Based on the methods provided in FAO56, k_c will be estimated as $F_r k_{cbfull}$ + 0.10 with $k_{cb,h}$ = 1.01. The stomatal resistance, r_l, was initially estimated to be 1200 s/m, a mean of the range of values published in literature. The coefficient k_s was modeled to be the residual from ET_{lys}/ET_c and both 2009 and 2010 yielded monthly k_s values greater than one, which of course is not feasible. The monthly values for k_c ranged from 0.8 to 1.1 for both 2009 and 2010.

It is noted in FAO56 that small isolated stands of vegetation often have micro-scale meteorological conditions due to a lack of fetch that can cause an increase in the effect of k_c by 50%-80%. The previous results support this statement and therefore to decrease residual k_s values, k_c was increased by a factor of 1.8. Results for k_s again did not prove viable, indicating the need to adjust another parameter such as stomatal resistance.

The first model for determining k_c and k_s was based on the procedure outlined above and detailed in Allen et al. (1998). Henceforth, the model is denoted $k_c(fao56)$ to signify the methodology used to determine k_c and estimate $ET_{c,adj}$; similar notation is used for the other methods evaluated (e.g. $k_s(wgt)$ denotes k_s estimated based on lysimeter weight) and a coefficient with no parenthetical specification indicates a residual value from fitting the model to the data.

The model $k_c(fao56)$ was fit to ET_{lys} using opposite daily and monthly time scales (superscript d and m, respectively) for k_c and k_s. Computing $ET_{c,adj}$ with k_c and k_s on the same time scale would simply regurgitate ET_{lys}. Initial guesses for r_l of 100 s/m and 2000 s/m were used (range of expected outcome) but results proved to be unrealistic. The yearly sum of the $k_c(fao56)^m * k_s^d$ model was fit to ET_{lys}, which resulted in solutions for r_l in 2009 of 1580 s/m and 18 s/m (for the respective initial guesses for r_l), the former with an average k_s of 1.7 and the latter below accepted values for r_l. Fitting the model using $k_c(fao56)^d * k_s^m$ did not converge. In 2010, the model using $k_c(fao56)^m * k_s^d$ converged to r_l= 606 s/m and 28 s/m, respectively, the former with an average k_s of 0.9 but with k_s greater than 1.0 for two months and the latter below accepted values for r_l. The model using $k_c(fao56)^d * k_s^m$ did converge in 2010 but to r_l= 691 s/m and r_l= -22 s/m, the former again with an average k_s of 0.9 but with k_s greater then 1.0 for three months and the latter below physical possibilities. Based on these results, it seemed necessary to constrain k_s based on the data in order to calibrate r_l and obtain reasonable estimates of $ET_{c,adj}$ and its parameters.

4.3 Finding k_s Using Lysimeter Weight

The weight of the lysimeter is representative of the moisture content and was used to determine the threshold at which k_s is no longer one. Previous efforts to estimate k_c using FAO56 yielded incompatible results with k_s so it was reasoned that determining k_s first would allow for a better understanding of k_c.

Using the soil water retention curve, the available moisture content on the green roof had been estimated to be 0.21 with an upper drained limit (field capacity) of 0.39 and lower limit (wilting point) of 0.18 based on an average porosity of 0.53. The range of available moisture content was related to the range of weight seen in the lysimeter over the course of the two-year study. The maximum and minimum weights were 44.1 kg (97.0 lbs) and 31.7 kg (69.7 lbs) in 2009 and 43.5 kg (95.7 lbs) and 27.3 kg (60.1 lbs) in 2010, respectively. It is believed that 2009 did not experience completely dry conditions unlike 2010; for the purpose of comparing lysimeter weight to moisture content, 43.6 kg (96 lbs) and 27.3 kg (60 lbs) were used as the maximum and minimum weights, respectively.

Since the green roof lysimeter does not have an outflow, "drained" water will remain in the system until it is either evapotranspirated or overflowed over the sides and thus in the lysimeter TAW extends from the saturated moisture condition (Θ_s) to a threshold soil moisture condition (Θ_t), represented as a percent p of TAW (Eqn 4.3.1).

$$\Theta_t = p(\Theta_s - \Theta_{LL}) + \Theta_{LL} \tag{4.3.1}$$

Based on this threshold, the moisture stress reduction coefficient (k_s) for transpiration can be computed (Eqn 4.3.2).

$$k_s = \frac{\Theta - \Theta_{LL}}{\Theta_t - \Theta_{LL}} \tag{4.3.2}$$

Θ_t is the threshold soil moisture content taken to be between the saturated moisture condition and wilting point and Θ is the average soil moisture content of the lysimeter (Allen et al. 1996). Allen et al. (1996, 1998) cite typical RAW values to be between 30% and 70% of TAW with 50% commonly used. However, in estimating k_s and k_c, this value is critical to avoid muddling the effect of the two coefficients. Despite literature reports of RAW to be approximately 50%-60% of TAW for sedums, visual inspection of the data deemed it necessary to estimate the threshold for the circumstances found at Villanova.

The average weight of each day (Appendix D) was evaluated as if it were the soil moisture content and if the weight was less than a threshold weight (W_t) (Eqn 4.3.1), $k_s(wgt)$ was interpolated between W_t and W_{min} as per Eqn 4.3.2. Different scenarios were simulated in which the threshold percent moisture deficit (i.e. weight) varied in 10% increments from 10% to 60%. The crop coefficient k_c was calculated as the residual based on $k_s(wgt)$, ET_o, and ET_{lys} on a daily and monthly basis for both 2009 and 2010 (Tables 4.3.1).

There is a wide range of resulting k_s and k_c values with the lowest k_s values found at the highest weight threshold (10%, 92.4 lbs). This is intuitive; as the threshold is lowered, more days will be considered stressed and the monthly average will decrease below one. Consequently, k_c decreases with a decreasing threshold. To determine which of these is most appropriate, each $k_s(wgt)$ and k_c pair was multiplied with ET_o and the monthly $ET_{c,adj}$ was compared with ET_{lys}. The sum of the squared errors was calculated in an attempt to determine the least erroneous estimate. However, as k_s approaches one, the model simplifies and essentially becomes a single coefficient model, which has no problem calibrating with ET_{lys}; k_c depends on k_s so the math is circular. Instead, the monthly k_c values were compared year to year. Better use of the Penman-Monteith equation for stormwater management purposes requires the use of a single crop coefficient (per month) regardless of the yearly stress conditions. The values for k_c for 2009 and 2010 for each scenario were

Table 4.3.1: $k_s(wgt)$ and residual k_c values for various water stress thresholds

(a) 2009. Above the 81.6 lb (40%) threshold $k_s(wgt)$ is consistently one because the lysimeter weight did not go below this weight. k_c decreases with decreasing weight threshold.

2009	10% 92.4 lbs		20% 88.8 lbs		30% 85.2 lbs		40% 81.6 lbs		50% 78 lbs		60% 74.4 lbs		70% 70.8 lbs	
	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c
Apr	0.9	1.3	0.9	1.2	1.0	1.1	1.0	1.1	1.0	1.1	1.0	1.1	1.0	1.1
May	0.8	1.5	0.8	1.4	0.9	1.3	0.9	1.2	1.0	1.2	1.0	1.1	1.0	1.1
Jun	0.9	1.4	0.9	1.3	0.9	1.2	1.0	1.2	1.0	1.2	1.0	1.2	1.0	1.2
Jul	0.7	1.4	0.7	1.3	0.8	1.1	0.9	1.0	1.0	0.9	1.0	0.9	1.0	0.9
Aug	0.9	1.5	1.0	1.5	1.0	1.4	1.0	1.4	1.0	1.4	1.0	1.4	1.0	1.4
Sep	0.9	1.5	0.9	1.4	1.0	1.4	1.0	1.3	1.0	1.3	1.0	1.3	1.0	1.3
Oct	0.9	1.9	0.9	1.9	1.0	1.8	1.0	1.8	1.0	1.8	1.0	1.8	1.0	1.8
Nov	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5

(b) 2010. $k_s(wgt)$ indicates stress even at 70% threshold and k_c decreases with decreasing threshold weight.

2010	10% 92.4 lbs		20% 88.8 lbs		30% 85.2 lbs		40% 81.6 lbs		50% 78 lbs		60% 74.4 lbs		70% 70.8 lbs	
	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c	$k_s(wgt)$	k_c
Apr	0.6	2.4	0.6	2.2	0.7	1.9	0.8	1.7	0.9	1.5	0.9	1.4	1.0	1.3
May	0.6	2.2	0.7	2.0	0.8	1.7	0.9	1.6	0.9	1.4	0.9	1.3	1.0	1.3
Jun	0.3	2.5	0.4	2.3	0.4	2.0	0.4	1.7	0.5	1.5	0.6	1.3	0.7	1.0
Jul	0.4	2.4	0.5	2.2	0.5	2.0	0.6	1.8	0.6	1.6	0.7	1.4	0.7	1.2
Aug	0.2	2.5	0.2	2.2	0.2	1.9	0.2	1.7	0.3	1.4	0.4	1.1	0.5	0.9
Sep	0.1	2.3	0.2	2.0	0.2	1.8	0.2	1.5	0.2	1.3	0.3	1.0	0.4	0.8
Oct	0.7	3.1	0.8	2.8	0.8	2.6	0.9	2.4	0.9	2.2	1.0	2.1	1.0	2.1
Nov	0.4	3.5	0.5	3.1	0.5	2.7	0.6	2.4	0.7	2.0	0.8	1.7	1.0	1.5

Table 4.3.2: Correlation statistics for k_c for 2009 and 2010 based on varying thresholds for stress

	k_c correlation statistic from daily maximum weight overflow	k_c correlation statistic from yearly maximum weight overflow
10% - 92.4 lbs	0.457	0.247
20% - 88.8 lbs	0.544	0.318
30% - 85.2 lbs	0.627	0.400
40% - 81.6 lbs	0.664	0.475
50% - 78.0 lbs	0.655	0.540
60% - 74.4 lbs	0.586	0.548
70% - 70.8 lbs	0.498	0.521

correlated and it was determined that the 40% threshold had the strongest relationship. The correlation statistics using daily maximum weight exhibit a unimodal trend with a slight skew towards the lower threshold weights (Table 4.3.2). For comparison, k_c coefficients were calculated based on ET_{lys} with overflow calculated from the yearly maximum weight (Appendix E) (as opposed to daily maximum weight, see Section 3.1.3) and correlated between years (Table 4.3.2). The yearly maximum based overflow produced a larger range of values especially in 2009, decreased the fit between 2009 and 2010, and yielded an upward trend in correlation as the threshold weight was decreased (Table 4.3.2).

The coefficients k_s and k_c are substantially different between 2009 and 2010, which can mainly be attributed to the drought in 2010 that killed off a large amount of vegetation on the green roof. The lysimeter plants were not as affected but saw some thinning as well and may have contributed to an increased effect of k_e, which is not modeled here (Figure 4.3.1). The drought in 2010 (i.e. continuous low lysimeter weight) caused a large decrease in $k_s(wgt)$ and in turn increased the residual k_c compared to 2009. ET_{lys} (adjusted for overflow with daily maximum weight) measured only 32 mm less in 2010 than in 2009 compared with ET_{lys} (adjusted for overflow with yearly maximum weight), which measured 76 mm less in 2010 than in 2009. The green roof was substantially dryer in 2010 than 2009 with an average lysimeter weight of 33.6 kg (74 lbs) (0.21 moisture content; 39% TAW) compared with 40 kg (88 lbs) (0.29 moisture content; 70% TAW). Crop ET under non-standard conditions ($ET_{c,adj}$) was estimated in 2009 to be 758 mm with $k_s(wgt)^d * k_c^m$ and 785 mm with $k_s(wgt)^m * k_c^d$ (the difference is a result of the timescale at which they are being averaged); in 2010, $ET_{c,adj}$ was 692 mm and 751 mm, respectively (Table 4.3.3). The percent difference in 2009 was less using $k_s(wgt)^d * k_c^m$ (0.3%), but in 2010 the percent difference was less using $k_s(wgt)^m * k_c^d$ (3.7%); all estimates were less than 5% different from ET_{lys} (using daily maximum weight to calculate overflow).

(a) June 2009. Wet conditions kept the plants and healthy and growing with almost full coverage.

(b) October 2010. Summer drought killed much of the vegetation although the lysimeter made out better than the rest of the green roof.

Figure 4.3.1: Green Roof Vegetation Condition

Table 4.3.3: Estimated $ET_{c,adj}$ using $k_s(wgt)$ and residual k_c at daily and monthly time scales.

40% deficit 81.6 lbs	2009		$k_s(wgt)^d$ k_c^m ET_o	$k_s(wgt)^m$ k_c^d ET_o	2010		$k_s(wgt)^d$ k_c^m ET_o	$k_s(wgt)^m$ k_c^d ET_o
	$k_s(wgt)$	k_c	$ET_{c,adj}$	$ET_{c,adj}$	$k_s(wgt)$	k_c	$ET_{c,adj}$	$ET_{c,adj}$
Apr	1.0	1.1	93	102	0.8	1.7	94	104
May	0.9	1.2	107	101	0.9	1.6	134	154
Jun	1.0	1.2	106	100	0.4	1.7	100	105
Jul	0.9	1.0	108	115	0.6	1.8	126	138
Aug	1.0	1.4	142	127	0.2	1.7	40	45
Sep	1.0	1.3	93	89	0.2	1.5	25	28
Oct	1.0	1.8	86	75	0.9	2.4	120	124
Nov	1.0	1.5	51	50	0.6	2.4	53	54
Sum (Avg)	(1.0)	(1.3)	758	785	(0.6)	(1.8)	692	751

4.4 Using $k_s(wgt)$ and $k_c(fao56)$ to Estimate $ET_{c,adj}$

Both the $k_s(wgt)$ and $k_c(fao56)$ models individually produced substantially different values for the coefficients depending on month and year. Each of the parameters found were fit to produce results that agree with the measured ET_{lys}, but their validity is not known. There are still considerable assumptions being made for each method and variables that require better definition. The two models were fit together in a further attempt to establish r_l and eliminate a variable. In this case, $k_s(wgt)$ and $k_c(fao56)$ are independent parameters therefore they could be modeled at the same timescale. Also, $k_s(wgt)$ is set using 81.6 lbs (40%) as the threshold based on the earlier results and initial guesses for r_l were 100 s/m and 2000 s/m. For 2009, the model $k_c(fao56)^d * k_s(wgt)^d$ converged from both starting points to r_l=707 s/m and k_c resulted between 1.0 and 1.4. The only other model evaluated was $k_c(fao56)^m * k_s(wgt)^d$ because it was thought that the model would be more sensitive to daily changes in k_s than k_c, which should not change as drastically from day to day. For the model $k_c(fao56)^m * k_s(wgt)^d$, fitting from both initial values resulted in r_l=681 s/m with k_c between 1.1 and 1.4. For 2010, the model $k_c(fao56)^d * k_s(wgt)^d$ converged only to r_l=153 s/m with k_c equal to 1.9 for the first seven months and 1.8 for November. The model $k_c(fao56)^m * k_s(wgt)^d$ similarly converged to a single value of r_l=151 s/m with congruent results to before for k_c. The second highest correlation for k_c between 2009 and 2010 was at a threshold of 50% or 78 lbs. Fitting the model $k_c(fao56)^d * k_s(wgt)^d$ to ET_{lys} with $k_s(wgt)$ based on 78 lbs results in a r_l=254 s/m and changed values of k_c to a unimodal distribution ranging from 1.6 to 1.8. Using $k_c(fao56)^m * k_s(wgt)^d$ yielded almost the same results for r_l at 254 s/m (Table 4.4.1).

Of note is the increasing range of monthly k_c as the threshold is reduced. It would seem that the lower k_s values associated with a high weight threshold are forcing high values of k_c, but as the threshold weight is decreased, the highest stressed months (June – August) maintain high values of k_c and the less stressed months towards the beginning and end of the growing year exhibit lower, more appropriate k_c values; this trend is continued using a 74.4 lbs (60%) threshold too (Table 4.4.1a). Further, the stomatal resistance associated with each set of k_c and k_s values increases with decreases in the threshold weight. The trend continues in 2010 for the 60% threshold (Table 4.4.1b). Lower stomatal resistance increases k_c as water vapor more easily escapes from the leaves to the atmosphere. The difference in resistance values between 2009 and 2010 is likely a function of a decrease in vegetation density and increased influences of k_e, on which r_l and k_s have no influence.

$ET_{c,adj}$ as found using $k_c(fao56)^d$ and $k_s(wgt)^d$ was plotted against ET_{lys} for both 2009 (Figure 4.4.1a) and 2010 (Figure 4.4.1b). In 2009, using a weight threshold of 81.6 lbs, it is immediately clear that there may have been more overflow events than accounted for as there are several outliers where ET_{lys} is more than four times greater than $ET_{c,adj}$ (bottom right side of Figure 4.4.1a). Interestingly, despite the increased difficulty in separating k_s and k_c in 2010, the 2010 model better predicts ET with weight thresholds of 81.6 lbs (r^2 = 0.64), 78 lbs (r^2 = 0.66) (Figure 4.4.1b), 74.4 lbs (r^2 = 0.65), and 70.8 lbs (r^2 = 0.57) compared to 2009 with weight thresholds of 81.6 lbs (r^2 = 0.45) (Figure 4.4.1a) and 78 lbs (r^2 = 0.45). In 2009, the 78 lb threshold yielded a k_s of one for all months, therefore no lower thresholds were examined in 2009. See Appendix F for figures not shown.

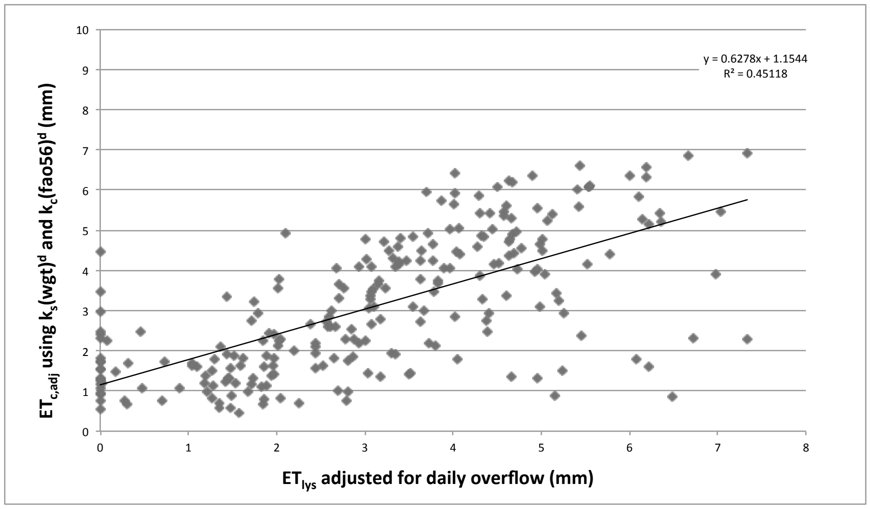
Table 4.4.1: The effect of different weight thresholds on r_l, k_c, and k_s

(a) Resulting k_c and k_s from fitting the $k_c(fao56)^m$ model to ET_{lys} with $k_s(wgt)^d$

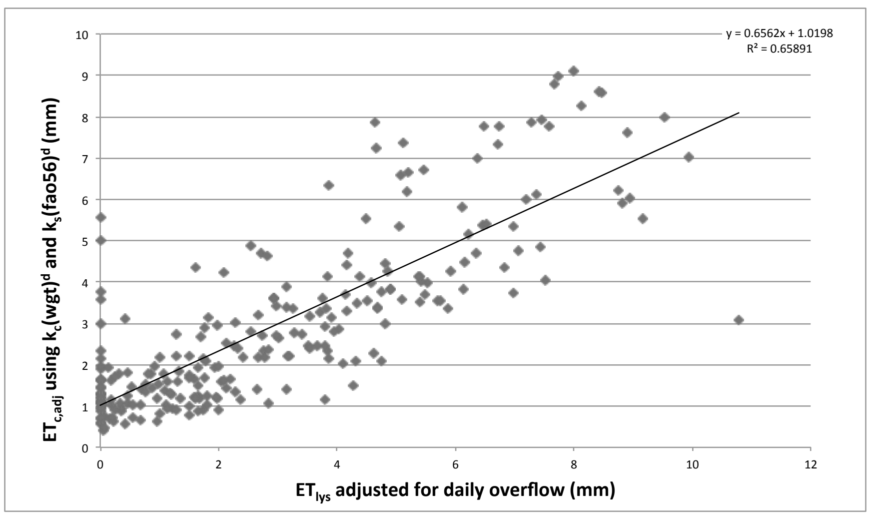
	2009				2010					
	40% - 81.6 lbs		50% - 78 lbs		40% - 81.6 lbs		50% - 78 lbs		60% - 74.4 lbs	
	$k_c(fao56)$	$k_s(wgt)$	$k_c(fao56)$	$k_s(wgt)$	$k_c(fao56)$	$k_s(wgt)$	$k_c(fao56)$	$k_s(wgt)$	$k_c(fao56)$	$k_s(wgt)$
Apr	1.0	1.0	1.0	1.0	1.9	0.8	1.7	0.9	1.5	0.9
May	1.1	0.9	1.1	1.0	1.9	0.9	1.7	0.9	1.5	0.9
Jun	1.2	1.0	1.2	1.0	1.9	0.4	1.7	0.5	1.6	0.6
Jul	1.3	0.9	1.3	1.0	1.9	0.6	1.8	0.6	1.7	0.7
Aug	1.4	1.0	1.3	1.0	1.9	0.2	1.8	0.3	1.6	0.4
Sep	1.3	1.0	1.2	1.0	1.9	0.2	1.7	0.2	1.5	0.3
Oct	1.1	1.0	1.1	1.0	1.9	0.9	1.7	0.9	1.5	1.0
Nov	1.1	1.0	1.1	1.0	1.8	0.6	1.6	0.7	1.4	0.8
(Avg)	(1.2)	(1.0)	(1.2)	(1.0)	(1.9)	(0.6)	(1.7)	(0.6)	(1.5)	(0.7)

(b) Resulting r_l from fitting the $k_c(fao56)$ model to ET_{lys} with $k_s(wgt)$

	40% - 81.6 lbs		50% - 78 lbs		60% - 74.4 lbs		70% - 70.8 lbs	
	$k_c(fao56)^d$ $k_s(wgt)^d$	$k_c(fao56)^m$ $k_s(wgt)^d$	$k_c(fao56)^m$ $k_s(wgt)^d$	$k_c(fao56)^d$ $k_s(wgt)^d$	$k_c(fao56)^m$ $k_s(wgt)^d$	$k_c(fao56)^d$ $k_s(wgt)^d$	$k_c(fao56)^m$ $k_s(wgt)^d$	$k_c(fao56)^d$ $k_s(wgt)^d$
	2009							
r_l(s/m)	707	681	752	725	746	772	753	779
	2010							
r_l(s/m)	153	151	254	252	375	378	533	539



(a) 2009. Threshold weight is 81.6 lbs (40%).



(b) 2010. Threshold weight is 78.0 lbs (60%).

Figure 4.4.1: ET estimated by $ET_{c,adj}$ using $k_c(fao56)$ and $k_s(wgt)$. Note different threshold values used each year.

Theoretically, the coefficient k_c should not change from year to year, as it is expected to be used for any vegetated plot with plants identical or similar to those at Villanova. Assuming a weight threshold of 81.6 lbs (40%), the moisture stress in 2009 was estimated to be non-existent almost every month. As such, it should be possible to use k_c calculated in 2009 to estimate the moisture stress in 2010. However, Table 4.4.2 shows that the residual k_s produces values greater than one, unrealistic for a stress coefficient. $ET_{c,adj}$ was estimated using monthly values of k_c from 2009 with monthly values of $k_s(wgt)$ with various thresholds from 2010 and the results were well below measured ET. The lowest percent error was found with a 70% threshold in 2010 because the stress coefficients were highest, but still underestimated ET by more than 10%. The stress experienced in 2010 caused substantial loss of groundcover, which causes a discontinuity between k_c and k_s compared to 2009. While the relationship between k_c and k_{cb} is not entirely known, it is likely that a dual-crop coefficient is more appropriate because of the ground cover loss; k_e is unaffected by k_s and including k_e would likely increase estimates of ET.

Table 4.4.2: Monthly k_c estimated in 2009 from $k_s(wgt)$ with 40% threshold and $k_c(fao56)$ is used to:
1. Estimate residual k_s in 2010 at a daily timestep (column 3).
2. Compute $ET_{c,adj}$ with $k_s(wgt)$ in 2010 at thresholds 50%, 60%, and 70% (columns 4-6).

Residual coefficent k_s^d is greater than one 4 of 8 months which is not possible and using $k_s(wgt)$ to compute $ET_{c,adj}$ greatly underestimates ET.

	$k_c(2009)$	k_s^d	$k_s(50\%)$	$k_s(60\%)$	$k_s(70\%)$
April	1.0	1.2	0.9	0.9	1.0
May	1.1	1.1	0.9	0.9	1.0
June	1.2	0.7	0.5	0.6	0.7
July	1.3	0.8	0.6	0.7	0.7
August	1.4	0.3	0.3	0.4	0.5
September	1.3	0.2	0.2	0.3	0.4
October	1.1	1.9	0.9	1.0	1.0
November	1.1	1.3	0.7	0.8	1.0
Sum $ET_{c,adj}$ (mm)	-	-	519	575	643
% Error	-	-	-28%	-21%	-11%

4.5 Iterative Determination of Coefficients k_c and k_s

In addition to the more analytical models used in Using $k_s(wgt)$ and $k_c(fao56)$ to Estimate $ET_{c,adj}$, the dataset was also examined on a daily basis to separate days when ET is likely to occur at the maximum rate and when it is likely to be limited by water availability. One through seven days were evaluated for water availability following a rain event. Consequently, ET was considered energy limited if the previous day contained rain (P) that was greater than $0.2 * ET_o$ ('wet' conditions), which is recognized as the minimum amount needed to affect the soil moisture (Allen et al. 1998). Consider the following logic for the first two scenarios (Eqn 4.5.1, Eqn 4.5.2):

$$\sum ET_{o\,i},\ when\ P_{i-1} > 0.2 ET_{o\,i} \tag{4.5.1}$$

$$\sum ET_{o\,i},\ when\ P_{i-2} > 0.2 ET_{o\,i-1} \tag{4.5.2}$$

where ET_{oi} is reference ET each day, i is the day index, and P is precipitation. ET_o and ET_{lys} (with overflow from maximum daily weight) were both tabulated using these criteria and an average monthly k_c was established (Eqn 4.5.3).

$$k_c = \frac{ET_{lys}}{ET_o} \tag{4.5.3}$$

The stress coefficient k_s was averaged for any remaining days in each inter-event period. The monthly k_c values were multiplied with daily ET_o to obtain daily ET_c. ET_{lys} and ET_c were summed for each of the days following the initial 'wet' days of an inter-rain event period, up to and including the next day of rain and the coefficient k_s was computed (Eqn 4.5.4); if k_s was equal to or greater than one, that day was assigned a value of one and the process was repeated for any remaining days in the inter-rain event period until k_s was less than one (at which point the rest of the days in the inter-event period were assigned this value) or the next day of rain was reached.

$$k_s = \frac{ET_{lys}}{ET_o} \tag{4.5.4}$$

The coefficient k_s was averaged monthly and then multiplied with ET_c. The results of this method were that the monthly and yearly estimates of ET got better as more days were added to the k_c computation (Appendix G). It was thought that the increased number of data points was removing variability and thus improving the estimate.

In response, moving averages of k_c for two, three, four, and six days were calculated. The moving averages were computed up to three, four and six days after each rain event using a forward differencing scheme and executed so as not to include days outside the maximum range; e.g. for the 3 day moving average with a 6 day maximum, an average was only calculated up to the fourth day (so as to include days 4-6) and then continued only following another rain event. It should also be noted that monthly boundaries were not respected so the average of the last few days of a month may include data from the beginning of the next month. The coefficient k_c is dynamic and as such this is thought to be the most representative despite later compilation into monthly values.

The values obtained for k_c are quite low compared with the previous results with the average ranging from 0.4 to 1.1 (Table 4.5.1). More importantly, a distinctive trend can be seen in both 2009 and 2010 in which increasing the maximum number of days after a rain event increased average k_c, regardless of the span of the moving average. Again, this may be a function of dampening the variability. On the other hand, increasing the span of the moving average while maintaining the maximum number of days beyond the rain event generally produced a decrease in k_c, with the exception of the 4-day max scenario in 2009 where the average remained similar. This is in line with expectations where the average would be encroaching on stressed conditions after some time.

In an attempt to isolate the effect of moisture stress, each inter-event period was broken down into smaller two-day and three-day segments as opposed moving averages. Multiple k_c values were computed for each month corresponding with the two-and three-day segments. Some months did not experience inter-event periods long enough to compute the later (past 3, 4 days, etc.) k_c values. The data shows a fairly clear trend of a decreasing k_c as the day is farther out from the rain event. Both 2009 and 2010 show similarity in monthly k_c values 1-2 days after a rain event and 1-3 days after rain event. In 2009, both monthly and average k_c for Days 3-4 is also similar to those of the previous days, but in 2010 shows more variability in the monthly values and the yearly average drops as k_s exerts its influence. Past four days there is a more substantial drop in k_c, especially in 2010 with the exception of November 2010, and past six days both years experience a considerable drop (Table 4.5.2).

Table 4.5.1: Results for k_c using a moving average for various amounts of unstressed days

(a) 2009. k_c results are almost all less than one and increases as more days are averaged

2009	2 day moving 2 day max	2 day moving 4 day max	4 day moving 4 day max	3 day moving 3 day max	3 day moving 6 day max	6 day moving 6 day max
Apr	0.5	0.5	0.6	0.6	1.0	0.9
May	0.7	0.7	0.7	0.7	0.9	0.7
Jun	0.7	0.9	0.9	0.7	1.0	0.9
Jul	0.4	0.6	0.6	0.5	0.9	0.8
Aug	0.6	0.6	0.5	0.5	1.1	0.9
Sep	0.6	0.7	0.6	0.6	0.9	0.7
Oct	0.9	1.4	1.3	1.2	1.7	1.7
Nov	0.7	0.9	0.9	0.8	1.5	1.4
Sum(Avg)	(0.6)	(0.8)	(0.8)	(0.7)	(1.1)	(1.0)

(b) 2010. k_c results are mostly less than one and increase as more days are averaged.

2010	2 day moving 2 day max	2 day moving 4 day max	4 day moving 4 day max	3 day moving 3 day max	3 day moving 6 day max	6 day moving 6 day max
Apr	0.4	1.0	0.7	0.5	1.2	1.0
May	0.7	1.1	1.1	1.0	1.3	1.3
Jun	0.3	0.6	0.4	0.4	0.7	0.5
Jul	0.6	0.9	0.7	0.6	1.0	0.8
Aug	0.2	0.3	0.2	0.2	0.3	0.3
Sep	0.3	0.3	0.4	0.3	0.4	0.5
Oct	0.9	1.5	1.1	0.9	1.8	1.8
Nov	0.3	0.6	0.5	0.3	0.7	0.3
Sum(Avg)	(0.4)	(0.8)	(0.6)	(0.5)	(0.9)	(0.8)

Table 4.5.2: Values for k_c using 2 and 3 day segments of the inter-rain event periods during which $k_s = 1$

(a) 2009. k_c begins to diverge after about 4 days post rain event.

2009	k_c 1-2 days	k_c 1-3 days	k_c 3-4 days	k_c 3-6 days	k_c 4-6 days	k_c 6-8 days	k_c 6-9 days
Apr	1.3	1.3	1.3	1.3	1.2	0.8	-
May	1.1	1.0	1.0	1.1	1.1	1.1	0.9
Jun	1.1	1.1	1.1	1.1	1.1	1.0	-
July	1.0	1.1	1.1	1.1	1.1	0.8	0.5
Aug	1.2	1.1	1.0	1.0	1.1	1.7	-
Sep	1.1	1.3	1.1	1.4	1.4	1.0	1.1
Oct	1.5	1.4	1.3	-	-	-	-
Nov	1.5	1.4	1.5	1.0	0.5	-	-
(Avg)	(1.2)	(1.2)	(1.2)	(1.1)	(1.1)	(1.1)	(0.8)

(b) 2010. k_c begins to diverge after 3 days post rain event.

2010	k_c 1-2 days	k_c 1-3 days	k_c 3-4 days	k_c 3-6 days	k_c 4-6 days	k_c 6-8 days	k_c 6-9 days
Apr	1.5	1.5	1.7	2.0	2.0	1.6	-
May	1.4	1.3	1.1	1.4	-	-	-
Jun	1.1	1.2	0.8	0.5	0.4	0.3	-
July	1.6	1.6	1.1	0.5	0.4	0.1	0.2
Aug	0.8	0.8	0.5	0.4	0.3	0.3	0.3
Sep	0.6	0.4	0.1	-	-	-	-
Oct	1.9	2.2	2.3	2.0	2.1	1.0	-
Nov	1.5	1.6	1.8	1.4	1.1	2.5	3.1
(Avg)	(1.3)	(1.3)	(1.2)	(1.2)	(1.1)	(1.0)	(1.2)

Chapter 5

Discussion and Conclusions

5.1 Green Roofs

Stormwater Control Measures such as green roofs are used as a sustainable approach to stormwater management. Green roofs have been shown to effectively retain stormwater depending on their construction and the climate in which they are located. The most popular type of green roof is extensive, which includes a shallow substrate depth of less than 15 cm and low-lying, drought-resistant vegetation. Contrarily, intensive roofs have much greater substrate depths and can include a greater variety of vegetation such as trees. Extensive roofs are generally preferred because they require less structural support and can often be added as a retrofit to existing roofs to decrease a building's impervious footprint. Much of the research on green roofs has been performed in Europe where they are more common, but they are gaining in popularity in North America. The last ten years has seen increased research into the effect of substrate composition with emphasis on sourcing local materials as well as using native plants. Green roofs require a unique substrate, one that holds water well but does not allow ponding, which would drown the succulent plants frequently found on extensive green roofs. The research has been performed in two formats, first looking at plant establishment and growth based on the extreme conditions often found on green roofs and second, the stormwater retention capabilities of various green roofs. Greater substrate depths have been shown to increase both plant growth and stormwater retention, and plant diversity provides improved stormwater retention performance although succulents, such as sedums, are the most robust, being able to survive in wet and dry conditions. Substrate composition can immensely affect green roof performance by limiting or facilitating plant growth; attempts to improve the water-holding capacity of mineral-based substrates with organics and fines has had mixed success, but is important in order to help encourage the use of locally available minerals such as shale and slate. Retention performance has been reported throughout the world as a wide range from 10% to 90%, affected by rain volume and timing, climate, and the individual green roof characteristics; areas where precipitation is evenly distributed throughout the year report greater benefit than areas where rain falls only part of the year. Temperature patterns also play a critical role in retention performance because of the potential recovery that is obtained. More work is still required to completely understand the benefits of green roofs and how and when to implement them, but it is clear that when used properly they can be an effective stormwater management tool in some parts of the world.

5.2 Evapotranspiration

Stormwater management design is based on the retention capabilities of stormwater control measures such as green roofs and the losses associated with them. Green roofs, in particular, have no means of infiltration and therefore rely completely on ET for retention recovery. Despite this, ET is poorly quantified and is usually based on rough estimates that come from older methods such as pan evaporation or empirically based models. Unfortunately, both pan evaporation methods and empirically based models require local calibration for reliable results at smaller time scales. Evapotranspiration was monitored on a green roof on Villanova's campus using a weighing lysimeter in order to obtain a better understanding of the quantity of losses occurring and how different climatic parameters affect ET.

Evapotranspiration is the latent heat flux component of the atmospheric energy balance and energy from the sun is the driving force behind the vaporization of water; the vapor gradient between the vegetation canopy and the atmosphere dictates how easily ET can occur assuming sufficient water. Measuring ET has been an important task in agriculture for understanding irrigation needs and a typical technique is the use of a weighing lysimeter. Weighing lysimeters are common for measuring ET because of their accuracy, assuming they are built to be representative of their surroundings; however, they can be expensive to install. Pan evaporation systems are also commonly used techniques because they are inexpensive to obtain and maintain but they require a coefficient specific to vegetation to accurately represent ET. More recent methods of measuring ET include Eddy Correlation and Bowen ratio in which the mass fluxes from vegetation are directly measured. Although they can be highly accurate, they require extremely sensitive instruments and proper knowledge for use. Empirical equations, such as those based on temperature or solar radiation, can assist in assessing ET, but require local calibration and even then may over- and under-estimate ET in hot/humid climates and cool/dry climates, respectively, because they are not modeling the physical processes. The more recent Penman-Monteith (PM) equation combines mass transfer and energy balance methods and includes vegetative resistances to model ET; it is based on the earlier Penman equation and was officially recognized by the ASCE and the FAO as the sole recommended method for calculating ET. The ASCE and FAO both standardized a similar form of the equation in a reference format in which the vegetation parameters are predefined for a short turf grass and a single crop coefficient is used to adjust ET for other vegetation; a second coefficient is used to adjust for environmental stresses. The PM reference equations are intended to simplify the use of the Penman-Monteith equation so that all types of potential users could accurately predict ET.

The primary focus of past ET research was to predict irrigation needs in agriculture so as to prevent unnecessary depletion of water supplies. One objective of this research is to assess the appropriateness of predicting ET in stormwater control measures such as a green roof using the PM equation. ET is more difficult to predict for green roofs than for irrigated fields because the water is supplied only by rain and is therefore unpredictable. The appropriateness of the PM equation for stormwater control measures is questionable because of the assumptions it requires: sufficient water; healthy, actively growing crop; fully shaded ground; uniform crop height; and large expanse of crop to minimize lateral energy fluxes. The biggest violation is probably the large expanse of crop and on a green roof especially, microclimate conditions may discredit the PM equation; PM estimates of ET are particularly sensitive to unusual wind patterns associated with urban areas were green roofs are found. Sufficient water is also a critical point in stormwater control measures and could easily lead to poor ground coverage and senescing instead of growing crops. The crop coefficient changes seasonally based on growth stages, but it is unclear if the stress coefficient is enough to account for stressed plants should the cover start to thin. Although there is some mention of the effect of decreasing ground cover in FAO56, little research has been performed providing a clear picture of how to predict ET based on the highly variable moisture conditions found in stormwater management where there is no irrigation.

One advantage the ASCE standardized PM equation has are the coefficients for both daily and hourly timesteps. When applied at an hourly timestep, superior results are obtained when the surface resistance used in the equation is different at night than during the day; an average of 70 s/m is recommended for daily timestep but 50 s/m and 100 s/m for daytime and nighttime, respectively. Although stormwater management is likely to be considered at a monthly or even yearly timescale, rain events happen for sometimes only a couple of hours, therefore it may be crucial to evaluate days with rain on a smaller scale to understand the patterns of k_c, k_s, and ET; this could be especially important depending on the timing of the rain and the ensuing weather pattern.

5.3 Green Roof Coefficients for the Standardized Reference Penman-Monteith Equation: Experimental Findings

Measurements of ET using a weighing lysimeter on a green roof were compared to the reference Penman-Monteith equation as standardized by the FAO in 1998 (Allen et al. 1998). Estimates were considered on a daily, monthly, and yearly basis in an attempt to identify appropriate crop and stress coefficients for the green roof. The lysimeter is not an exact replica of the green roof as it lacks an underdrain, which may have increased average moisture conditions compared to the actual green roof, but the plants and substrate are similar and therefore should still provide a good estimate of applicable crop coefficients. To keep with common engineering practice and due to the lack of notes regarding growth stages (the FAO56 suggested scale for k_c), the crop coefficient k_c was extracted on a monthly basis. Theory indicates that k_s would equal one for a range of moisture conditions and it is during this time that k_c could be estimated by ET_{lys}/ET_o . However, there is little research quantifying the moisture range, although recommendations for shallow- and deep-rooted plants are between 30% and 70%, respectively, of the total available water to the plants (usually the moisture content between the field capacity and the wilting point). Rain events occur in different magnitudes, some saturating and others barely wetting the surface and as such were counted only if the quantity of rain was greater than 20% of the estimated reference ET the next day. Still, the effect of the rain on ET will differ depending on antecedent moisture conditions. Several methods were used to determine k_c, but unless the moisture conditions were directly considered, irregular estimates were observed. The coefficient k_c is highly variable on a daily basis and even employing various averaging schemes did not stabilize estimates of k_c. The most difficult task was understanding when k_s was one. Evaluating k_s as one after each rain event was not suitable due to differences in rain volume and antecedent moisture conditions. Even in situations when it could be considered one, moisture conditions warranted different lengths for which k_s could be one, further complicating the estimation of k_c. Also, the year 2009 was very different than 2010 in rain patterns and temperature and as such did not necessarily respond well to the same methods of analysis. For example, in 2009 there were only four inter-event periods greater than six days and one greater than eight days while in 2010 there were seven periods greater than six days and three greater than ten days. Simply choosing a certain number of days after each rain event to include in an average k_c did not work because it was constantly changing and increasing the data used to estimate k_c dampened the variability and resulted in circular calculations with ET_o, ET_{lys}, and k_c (with k_s = 1). Evaluating k_c in two and three day segments provided better results than continuous or moving averages. Table 4.5.2 shows that in 2009 k_c tended to be affected by k_s after two to four days depending on the month. Compared to 2009, the months of August and September in 2010 were almost certainly constantly stressed and as such k_c was estimated much lower (Table 4.5.2). Interestingly though, in April and October 2010 k_c was estimated much higher up to nine days after a rain event than in 2009 and inexplicably increased farther away from the previous rain event. In general though, 2010 experienced decreases in k_c after two to three days, which is in line with the lower moisture contents seen in 2010 compared to 2009. Despite the strange increases in k_c during some months, the yearly average for k_c followed very similar trends in 2009 and 2010, starting at 1.3 and 1.2, respectively, and decreased as the soil dried out. Relating the average weight of the lysimeter to the average moisture condition of the soil required some detailed knowledge of the soil characteristics but proved reasonably successful in identifying stressed soil moisture conditions. Once again, determining the threshold at which soil was stressed proved vital to obtaining viable findings. Since in theory the soil should have the same threshold for stress regardless of moisture conditions, k_c was estimated by dividing ET_o into ET_{lys} but only for days during which the average weight was above the threshold. An uncertainty analysis was performed to decide at which point stress was initiated; moisture conditions at 10% through 70% of the total available water to plants were evaluated and the resulting k_c values for 2009 and 2010 were correlated by month. The percent found to yield the most similar results was 40%, which is in agreement with estimates of 30% to 50% for shallow-rooted crops in Allen et al. (1996). The results for average k_c based on stress beyond 40% moisture deficit (81.6 lbs) yielded very similar results, with more consistent monthly values, to other methods employed, potentially indicating the findings to be in the right ballpark. The values in 2010, however, were substantially higher and oddly increased at the end of the growing season. The only thoughts on this phenomenon are that $k_e$was exerting its influence on k_c.

The applicability of current theory on k_c is important for future use on green roofs and as such the method described in FAO56 for determining k_c for natural vegetation was applied in conjunction with the stress coefficients based on moisture conditions. Perhaps the most uncertain variable in the proposed method was the stomatal resistance of the vegetation. Little research was found regarding this value and the range provided in the literature was quite high from 300 s/m to 2000 s/m. Rather than guessing on this resistance parameter, the stomatal resistance was fit based on k_s at 40% deficit and experimental data and in 2009 very favorable results were obtained. Reference grass assumes a stomatal resistance of 100 s/m but the sedums on this green roof were exhibiting an average stomatal resistance of 750 s/m, which is well within the range reported in the literature. Additionally, the values for k_c trend as expected with a unimodal distribution ranging from 1.0 to 1.4, fitting the distribution depicted in Figure 3.2.1. An average of 1.2 also compares favorably with results from other methods used in this study. Results from 2010 were not as clear probably due to the high stress conditions found throughout the year; results for k_c were constant at 1.9, which is considerably higher than for 2009 but again similar to results from other methods used. When 2009 and 2010 are compared, 2010 experienced a higher average temperature than 2009 and drought conditions. It is possible that the stress threshold for this green roof may be lower but only reachable at extremely high energy levels. Accordingly, both 2009 and 2010 were analyzed using 50% deficit (78 lbs) instead of 40% (81.6 lbs) and 2010 was much more sensitive to this change. In 2009, only July saw a decrease in k_c, which was probably due to the fact that only July would have experienced substantial moisture conditions below 81.6 lbs. On the other hand, all of 2010 experienced stressed conditions and as a result all monthly k_c values decreased as a result of the change in the threshold condition. Even so, values for k_c appear to be higher for 2010, which may be an effect of the increased energy present and decreasing ground cover (i.e. increase in k_e); correspondingly, the stomatal resistances in 2010 for 40%, 50%, 60% and 70% deficits increased from 150 s/m to 540 s/m when fit to ET_{lys}.

Most notably, perhaps, is the strong fit observed in 2010 between $ET_{c,adj}$ and ET_{lys}. Despite the difficulties in separating k_c and k_s, 2010 is remarkably well predicted (Figure 4.4.1b). In contrast, 2009 is only moderately well predicted due to several outliers with high ET_{lys} values and low ET_o (Figure 4.4.1a). Possible explanations for these values include overflow not properly accounted for and compounding effects of uplift on the lysimeter from wind; the lysimeter sits above the green roof (Figure 3.1.3) and some of these days experienced higher than average wind speeds.

While more work should be performed for the sake of establishing k_c for a green roof of mixed sedums, this analysis indicates that 1.4 may be a reasonable estimate for k_{cmid} with full cover and it is in line with expectations for natural vegetation as stated in Allen et al. (1996). Furthermore, water stress can be expected to occur after four days during wet and mild conditions but only after three days during hot and dry periods (Table 4.5.2).

Choosing the appropriate methodology for determining k_c on a green roof is difficult because instead of estimating how much water needs to be provided to maintain healthy crop that is evapotranspirating at an energy-limited rate as in agriculture, the estimate focuses on determining ET based on how much water may or may not be available. Lack of irrigation can cause cover to disappear increasing the effect of k_e and decreasing k_{cb} during periods of drought such as was the case in 2010. The data provides a strong argument that k_c varies significantly between the milder, wetter 2009 and the hot and dry 2010 and that simply adjusting k_s does not compensate for the full range of stress conditions observed in 2010. In fact, using k_c from the 2009 $k_s(wgt) * k_c(fao56)$ model to estimate k_s in 2010 yielded results greater than one. Additionally, when these 2009 k_c were combined with $k_s(wgt)$ with varying thresholds in 2010, ET was grossly underestimated by $ET_{c,adj}$ (Table 4.4.2).

It would also seem reasonable that the physiology of the plants changes with increased heat and vapor pressure gradient as a response to environmental conditions. These are circumstances that agriculture would not deal with often because irrigation keeps the crops actively growing. However, for stormwater control measures, it may be crucial to understand these interactions so as to provide an appropriate range of parameters for use in design. For now, it is suggested that average conditions be considered and that an appropriate range of k_c values are between 1.1 and 1.4 throughout the year. Additionally, average stress conditions can be estimated to be between 0.6 and 0.8, keeping in mind that retention performance might actually be highest during years with the highest stress (i.e. least rainfall).

5.4 Future Work

Estimating ET is a complicated task with many variables that have been simplified in past exercises. However, the availability of water is a crucial component of ET that can drastically alter the ET process and possibly also the interactions between ET and the affecting factors. Further work to be done includes a separation of k_c in 2010 into k_{cb} and k_e to model the effects of ground cover lost. It would be especially interesting to fit k_c from 2009 to the dual crop coefficient for 2010 considering that using the 2009 single crop coefficients with $k_s(wgt)$from 2010 did not produce accurate estimates of ET in 2010. Additionally, analysis of ET for the purpose of developing standard crop coefficients should be performed on a rain event scale to understand the changes in k_c and k_s and the timing with which these changes take place. For design purposes, localized estimates of $ET_{c,adj}$ would require local predictions of k_s, so it would be imperative to be able to estimate average k_s from weather data such as average rainfall per month or average number of rain events per month. Furthermore, the sensitivity of the Penman-Monteith equation to remote data needs to examined, especially in urban areas with complex microclimates. From a biology point of view, more work regarding the stomatal resistance of sedums at the plant physiology level could provide insight to the effects of weather and extreme conditions. Lastly, continued collection of data, including accurate measurements of overflow, is planned at Villanova so it will be interesting to see how predictions based on results from 2009 and 2010 turn out; another year of data, perhaps not at such opposite extremes, should help validate the model and its associated parameters.

5.5 Closing Thoughts

Given the complexity of the surface and aerodynamic resistances, the raw Penman-Monteith equation is generally impractical to use, but the standardized equations and their associated publications do an excellent job of simplifying the parameters and facilitating its use. However, the availability of data is still crucial and it is unclear if remote data can provide viable esimates of ET. Numerous studies have compared the applicability of different methods of measuring and estimating ET in different situations and in circumstances where lack of moisture is not an issue, many of the techniques available provide accurate results. However, in more arid circumstances, or where moisture conditions are not inherently known, more research is needed to improve ET estimates. In the attempt to quantify ET for stormwater management purposes, potential ET should be compared to the measured results using a weighing lysimeter as opposed to other techniques so that microscale climates can be considered. Clearly, subsequent studies should be done to calibrate the Penman-Monteith model for use in stormwater BMPs, but I believe the results presented can be used to roughly estimate ET. The hope is that this research will further the understanding of ET as it relates to green roofs and assist in producing appropriate stormwater management designs. Additionally, quantifying ET from stormwater control measures may be the impetus needed for changing the current standards to include ET as a volume-reducing portion of the water balance for stormwater management.

Bibliography

[1] Aad, M. P. A., Suidan, M. T., and Shuster, W. D. (2010). "Modeling Techniques of Best Management Practices: Rain Barrels and Rain Gardens Using EPA SWMM-5." Journal of Hydrologic Engineering, 15, 434-443.

[2] Acreman, M. C., Harding, R. J., Lloyd, C. R., and McNeil, D. D. (2003). "Evaporation characteristics of wetlands: experience from a wetgrassland and a reedbed using eddy correlation measurements." Hydrology and Earth System Sciences, 7, 11-21.

[3] Al-Darby, A. M. (1996). "The hydraulic properties of a sandy soil treated with gel-forming soil conditioner." Soil Technology, 9, 15-28.

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

[5] Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements, Publication No. 56. Food and Agriculture Organization of the United Nations, Rome.

[6] Allen, R. G., Pereira, L. S., Smith, M., Raes, D., and Wright, J. L. (2005). "FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions." Journal of Irrigation and Drainage Engineering, 131, 2-13.

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

[8] 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.

[9] Allen, R. G., Walter, I., Elliott, R., Mecham, B., Jensen, M., Itenfisu, D. et al. (2000)"Issues, requirements and challenges in selecting and specifying a standardized ET equation." Proc., 4th National Irrigation Symp, 201-208.

[10] Andre, C. (2007). "Evaporation from Soils." Encyclopedia of Water Science, Second Edition, CRC Press.

[11] Asleson, B. C., Nestingen, R. S., Gulliver, J. S., Hozalski, R. M., and Nieber, J. L. (2009). "Performance Assessment of Rain Gardens." JAWRA Journal of the American Water Resources Association, 45, 1019-1031.

[12] Bedient, P. B., Huber, W. C., and Vieux, B. E. (2008). Hydrology and Floodplain Analysis. Prentice Hall, Upper Saddle River, NJ 07458.

[13] Berghage, R., Beattie, D., Jarrett, A., Thuring, C., Razaei, F., and O'Connor, T. (2009). "Green Roofs for Stormwater Runoff Control." EPA/600/R-09/026, Environmental Protection Agency, Cincinnati, OH, EPA/600/R-609/026.

[14] Berghage, R., Jarrett, A., et al. (2007). "Quantifying Evaporational and Transpirational Water Losses in Green Roofs and Green Roof Media Capacity for Neutralizing Acid Rain." National Decentralized Water Resources Capacity Development Project (NDWRCP). Center for Green Roof Research at Pennsylvania State University. State College, Pennsylvania.

[15] Berndtsson, J. C., Emilsson, T., and Bengtsson, L. (2006). "The influence of extensive vegetated roofs on runoff water quality." Science of The Total Environment, 355, 48-63.

[16] Bidlake, W. R., Woodham, W. M., Lopez, M. A., Southwest Florida Water Management District, and West Coast Regional Water Supply Authority. (1996). Evapotranspiration from areas of native vegetation in West-Central Florida, U.S. G.P.O.; Denver, CO.

[17] Black, C., and Osmond, C. (2003). "Crassulacean acid metabolism photosynthesis: working the night shift'." Photosynthesis Research, 76, 329-341.

[18] Black, P. E. (2007). "Revisiting the Thornthwaite and Mather Water Balance." JAWRA Journal of the American Water Resources Association, 43, 1604-1605.

[19] Bormann, H. (2010). "Sensitivity analysis of 18 different potential evapotranspiration models to observed climatic change at German climate stations." Climatic Change, 104, 729-753.

[20] Brutsaert, W. (1982). Evaporation into the Atmosphere. Theory, History, and Applications. Reidel, Dordrect, The Netherlands.

[21] Carter, T., and Jackson, C. R. (2007). "Vegetated roofs for stormwater management at multiple spatial scales." Landscape and Urban Planning, 80, 84-94.

[22] Carter, T., and Rasmussen, T. C. (2007). "Hydrologic Behavior of Vegetated Roofs." JAWRA Journal of the American Water Resources Association, 42, 1261-1274.

[23] Chen, F., and Robinson, P. J. (2009). "Estimating Reference Crop Evapotranspiration with ETgages." Journal of Irrigation and Drainage Engineering, 135, 335-342.

[24] Chen, S.-S., and Black, C. C. J. (1983). "Diurnal Changes in Volume and Specific Tissue Weight of Crassulacean Acid Metabolism Plants." Plant Physiology, 71, 373-378.

[25] Chen, X. (2009). Study of water dynamics in the soil-plant-atmospheric continuum in a water-control led ecosystem. PhD Dissertation, University of California, Berkeley, Berkeley, California.

[26] Cote, F., Folliot, M., and Andre, M. (1993). "Photosynthetic Crassulacean Acid Metabolism in Pineapple: Diel Rhythm of CO2 Fixation, Water Use, and Effect of Water Stress." Proc., I International Pineapple Symposium, ISHS Acta Horticulturae 334, 113-130.

[27] DeGaetano, A., Eggleston, K., and Knapp, W. W. (1994). "Daily Evapotranspiration and Soil Moisture Estimates for the Northeastern United States."Ithaca, NY, 11p.

[28] Denich, C., and Bradford, A. (2010). "Estimation of Evapotranspiration from Bioretention Areas Using Weighing Lysimeters." Journal of Hydrologic Engineering, 15, 522-530.

[29] DiGiovanni, K., Gaffin, S., and Montalto, F. (2010). "Green Roof Hydrology: Results from a Small-Scale Lysimeter Setup (Bronx, NY)." Proc., Low Impact Development 2010: Redefining Water in the City. ASCE, 114.

[30] Dong, A., Grattan, S., Carroll, J., and Prashar, C. (1992). "Estimation of Daytime Net-Radiation Over Well-watered Grass." Journal of Irrigation and Drainage Engineering, 118, 466.

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

[32] Douglas, E. M., Jacobs, J. M., Sumner, D. M., and Ray, R. L. (2009). "A comparison of models for estimating potential evapotranspiration for Florida land cover types." Journal of Hydrology, 373, 366-376.

[33] Dunnett, N., Nagase, A., Booth, R., and Grime, P. (2008). "Influence of vegetation composition on runoff in two simulated green roof experiments." Urban Ecosystems, 11, 385-398.

[34] Durhman, A. K., Rowe, D. B., and Rugh, C. L. (2007). "Effect of Substrate Depth on Initial Growth , Coverage , and Survival of 25 Succulent Green Roof Plant Taxa." HortScience, 42, 588-595.

[35] Durhman, A. K., Rowe, D. B., and Rugh, C. L. (2006). "Effect of Watering Regimen on Chlorophyll Fluorescence and Growth of Selected Green Roof Plant Taxa." HortScience, 41, 1623-1628.

[36] Dvorak, B., and Volder, A. (2010). "Green roof vegetation for North American ecoregions: A literature review." Landscape and Urban Planning, 96, 197-213.

[37] El Khoury, L. (2010). Modeling the uncertainty of evapotranspiration estimates. Master's Thesis, Oregon State University.

[38] Elhaddad, A., Garcia, L., and Chávez, J. (2011). "Using a Surface Energy Balance Model to Calculate Spatially Distributed Actual Evapotranspiration." Journal of Irrigation and Drainage Engineering, 17-26.

[39] Feller, M. (2011). "Draft Master's Thesis." Master's Thesis, Villanova University, Villanova, Pennsylvania, USA.

[40] FLL (2002). "Ricktlinie für die Planung, Ausführung und Pflege von Dachbegrünungen (Guidelines for Planning, Implementation, and Maintenance of Green Roofs).", Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau EV, Bonn, Germany.

[41] Gavin, H., and Agnew, C. T. (2003). "Evaluating the reliability of point estimates of wetland reference evaporation." Hydrology and Earth System Sciences, 7, 3-10.

[42] Getter, K.L., and Rowe, D.B. (2008). "Media depth influences Sedum green roof establishment." Urban Ecosystems, 11, 361-372.

[43] Getter, K.L., Rowe, D.B., and Andresen, J. (2007). "Quantifying the effect of slope on extensive green roof stormwater retention." Ecological Engineering, 31, 225-231.

[44] Getter, K. L., and Rowe, D. B. (2009). "Substrate Depth Influences Sedum Plant Community on a Green Roof." HortScience, 44, 401-407.

[45] Getter, K. L., and Rowe, D. B. (2008). "Selecting Plants for Extensive Green Roofs in the United States." Extension Bulletin E-3047, Michigan State University, E. Lansing, MI.

[46] Getter, K. L., and Rowe, D. B. (2007). "Effect of Substrate Depth and Planting Season on Sedum Plug Survival on Green Roofs." Journal of Environmental Horticulture, 25, 95-99.

[47] Getter, K. L., and Rowe, D. B. (2006). "The Role of Extensive Green Roofs in Sustainable Development." HortScience, 41, 1276-1285.

[48] Getter, K. L., Rowe, D. B., and Cregg, B. M. (2009). "Solar radiation intensity influences extensive green roof plant communities." Urban Forestry & Urban Greening, 8, 269-281.

[49] Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M., and Andresen, J. (2009). "Carbon Sequestration Potential of Extensive Green Roofs." Environmental Science & Technology, 43, 7564-7570.

[50] Hamlet, A. F., Mote, P. W., Clark, M. P., and Lettenmaier, D. P. (2007). "Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States." Journal of Climate, 20, 1468-1486.

[51] Haque, A. (2003). "Estimating actual areal evapotranspiration from potential evapotranspiration using physical models based on complementary relationships and meteorological data." Bulletin of Engineering Geology and the Environment, 62: 57.

[52] Harrington, R., Steinwand, I. A., Hubbard, P., and Martin, L. D. (2004). "Evapotranspiration from Groundwater-Dependent Plant Communities: Comparison of Micrometeorological Measurements and Vegetation-based Measurements."Los Angeles, CA.

[53] Heine, R. W. (1976). "Comparison of methods for estimating potential evapotranspiration in Canterbury." N.Z. J. Sci. , 19, 255 - 264.

[54] Hickman, J., Schneider, D., Wadzuk, B. M., and Traver, R. G. (2010). "Determination of Evapotranspiration in SCM's Using a Weighing Lysimeter: an Experimental Approach." Proc., World Environmental and Water Resources Congress 2010: Challenges of Change. Providence, RI.

[55] Hobbins, M. T. (2001). "The complementary relationship in estimation of regional evapotranspiration: An enhanced advection-aridity model." Water Resources Research, 37, 1389.

[56] Holdridge, L. R. (1947). "Determination of World Plant Formations from Simple Climatic Data." Science, 105, 367-368.

[57] 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.

[58] Hutchinson, D., Abrams, P., Retzlaff, R., and Liptan, T. (2003). "Stormwater monitoring two ecoroofs in Portland, Oregon, USA." Proc., 1st Greening Rooftops for Sustainable Communities Conference, Chicago, IL. 372-389.

[59] 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.

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

[61] Jamieson, P. D., Francis, G. S., Wilson, D. R., and Martin, R. J. (1995). "Effects of water deficits on evapotranspiration from barley." Agricultural and Forest Meteorology, 76, 41-58.

[62] Jensen, M. E., Burman, R. D., Allen, R. G. (1990). Evapotranspiration and Irrigation Water Requirements: Manual 70, ASCE. Committee on Irrigation Water Requirements. New York, NY.

[63] Jia, X., Dukes, M. D., and Jacobs, J. M. (2009). "Bahiagrass crop coefficients from eddy correlation measurements in central Florida." Irrigation Science, 28.

[64] Johnston, C., McCreary, K., and Nelms, C. (2004). "Vancouver public library green roof monitoring project." Proc., 2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Portland, OR. 391-403.

[65] Kakane, V. C. K., and Agyei, E. K. (2006). "Determination of Surface Fluxes Using a Bowen Ratio System." West Africa Journal of Applied Ecology, 9, 1-9.

[66] Köhler, M., Laar, M., Schmidt, M., Grimme, F. W., and Gusmao, F. (2001). "Urban Water Retention by Greened Roofs in Temperate and Tropical Climate." Proc., 38th International Federation of Landscape Architects World Congress, Singapore, Singapore.

[67] Kumar, K. K., Kumar, K. R., and Rakhecha, P. R. (1987). "Comparison of Penman and Thornthwaite methods of estimating potential evapotranspiration for Indian conditions." Theoretical and Applied Climatology, 38, 140-146.

[68] Lazzarin, R. M., Castellotti, F., and Busato, F. (2005). "Experimental measurements and numerical modelling of a green roof." Energy and Buildings, 37, 1260-1267.

[69] Lee, K.-H. (2010). "Relative Comparison of the Local Recalibration of the Temperature-Based Evapotranspiration Equation for the Korea Peninsula." Journal of Irrigation and Drainage Engineering, 136, 585-594.

[70] Lu, J., Sun, G., McNulty, S. G., and Amatya, D. (2005). "A comparison of six potential evapotranspiration methods for regional use in the Southeastern United States." Journal of American Water Resources Association, 41, 621-6733.

[71] Lundholm, J., Macivor, J. S., Macdougall, Z., and Ranalli, M. (2010). "Plant species and functional group combinations affect green roof ecosystem functions." PloS one, 5, e9677.

[72] Marcel, F. (2007). "Evapotranspiration." Encyclopedia of Water Science, Second Edition (Print Version), CRC Press.

[73] Martin, B. K. (2009). "The dynamic stormwater response of a green roof." Master's Thesis, University of Guelph, ON, Canada.

[74] Mastrorilli, M., Katerji, N., Rana, G., and Nouna, B. B. (1998). "Daily actual evapotranspiration measured with TDR technique in Mediterranean conditions." Agricultural and Forest Meteorology, 90, 81-89.

[75] Meissner, R., Rupp, H., and Seyfarth, M. (2008). "Advances In Out Door Lysimeter Techniques." Water, Air, & Soil Pollution: Focus, 8, 217-225.

[76] Mentens, J., Raes, D., and Hermy, M. (2006). "Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?" Landscape and Urban Planning, 77, 217-226.

[77] Mészároš, I., and Miklánek, P. (2009). "Influence of vegetation cover on evapotranspiration patterns in mountainous areas." Biologia, 64, 610-614.

[78] C. Miller. (2004). Green Roofs as Stormwater Best Management Practices: Preliminary Computation of Runoff Coefficients. Technical report, Roofscape: Green Technology for the Urban Environment, Philadelphia, PA. http://www.roofmeadow.com/technical/publications.php Date Accessed 3/31/2011.

[79] Milly, P. C. D. (1991). "A refinement of the combination equations for evaporation." Surveys in Geophysics, 12(1), 145-154.

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

[81] Monterusso, M. A., Rowe, D. B., and Rugh, C. L. (2005). "Establishment and Persistence of Sedum spp. and Native Taxa for Green Roof Applications." HortScience, 40, 391-396.

[82] Moran, A. C. (2004). "A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff Quality, and Plant Growth." Master's Thesis, North Carolina State University. Raleigh, NC.

[83] Morton, F. I. (1978). "Estimating Evapotranspiration from Potential Evaporation: Practicality of an Iconoclastic Approach." Journal of Hydrology, 38(1).

[84] Nagase, A., and Dunnett, N. (2010). "Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity." Landscape and Urban Planning, 97, 318-327.

[85] National Renewable Energy Laboratory (2004). "Green Roofs." Federal Energy Management Program: Federal Technology Alert, DOE/EE-0298 U.S. Dept of Energy, 32p.

[86] Nguyen, T.-T., Joyce, D. C., and Dinh, S.-Q. (2009). "Effects of artificial amendments in potting media on Orthosiphon aristatus growth and development." Scientia Horticulturae, 123, 129-136.

[87] Oberndorfer, E., Lundholm, J., Bass, B., et al. (2007). "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services." BioScience, 57, 823-833.

[88] Ojha, C. S. P., Prasad, K. S. H., Shankar, V., and Madramootoo, C. A. (2009). "Evaluation of a Nonlinear Root-Water Uptake Model." Journal of Irrigation and Drainage Engineering, 135, 303-312.

[89] Ortega-Farias, S., Irmak, S., and Cuenca, R. (2009). "Special issue on evapotranspiration measurement and modeling." Irrigation Science, 28, 1-3.

[90] PADEP (2006). "Pennsylvania Stormwater Best Management Practices Manual." http://www.elibrary.dep.state.pa.us/dsweb/View/Collection-8305 Date Accessed: 4/18/2011

[91] Palla, a., Gnecco, I., and Lanza, L. G. (2009). "Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof." Journal of Hydrology, 379, 193-204.

[92] Panayiotis, N., Panayiota, T., and Ioannis, C. (2003). "Soil Amendments Reduce Roof Garden Weight and Influence the Growth Rate of Lantana." HortScience, 38, 618-622.

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

[94] Pereira, A., and Pruitt, W. O. (2004). "Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration." Agricultural Water Management, 66, 251.

[95] Pittenger, D. R., and Shaw, D. A. (2007). "A Review of Literature on the Water Use of Plants." Proc., Symposium on Efficient Water use in the Urban Landscape. Las Cruces, New Mexico.

[96] Pittenger, D. R., and Shaw, D. A. (2004). "What We Know About Landscape Water Requirements." CO-HORT: A Cooperative Extension, University of California, 6, 1-4.

[97] Poss, J. A., Russell, W. B., Shouse, P. J., Austin, R. S., Grattan, S. R., Grieve, C. M., Lieth, J. H., and Zeng, L. (2004). "A volumetric lysimeter system (VLS): An alternative to weighing lysimeters for plant-water relations studies." Computers and Electronics in Agriculture, 43, 55-68.

[98] Rana, G., and Katerji, N. (1998). "A Measurement Based Sensitivity Analysis of the Penman-Monteith Actual Evapotranspiration Model for Crops of Different Height and in Contrasting Water Status." Theoretical and Applied Climatology, 60, 141-149.

[99] Rana, G., Katerji, N., and Mastrorilli, M. (1997). "Environmental and soil-plant parameters for modelling actual crop evapotranspiration under water stress conditions." Ecological Modelling, 101, 363-371.

[100] Rana, G., Katerji, N., Mastrorilli, M., and Moujabber, M. (1997). "A model for predicting actual evapotranspiration under soil water stress in a Mediterranean region." Theoretical and Applied Climatology, 56, 45-55.

[101] Raven, J. A., and Edwards, D. (2001). "Roots: evolutionary origins and biogeochemical significance." Journal of Experimental Botany, 52, 381-401.

[102] Rezaei, F., Jarrett, A., Beattie, D., and Berghage, R. (2005). "Defining Stormwater Attenuation on a Green Roof." Proc., 2005 Villanova Urban Stormwater Partnership Symposium. Villanova, PA.

[103] Rezaei, F., Jarrett, A., Berghage, R., and Beattie, D. (2005). "Evaporation Rates from Extensive Green Roof Plant Species." Proc., 2005 American Society of Agricultural Engineers International Meeting. Tampa, Florida.

[104] Robert, B. (2007). "Evapotranspiration." Encyclopedia of Water Science, Second Edition (Print Version), CRC Press.

[105] Roehr, D., and Kong, Y. (2010). "Runoff reduction effects of green roofs in Vancouver, BC, Kelowna, BC, and Shanghai, P.R. China.(Report)." Canadian Water Resources Journal, 35.

[106] Rowe, D. B. (2010). "Green roofs as a means of pollution abatement." Environmental Pollution, in press, 1-11.

[107] Rowe, D. B., and Getter, K. L. (2010). "Green Roofs and Garden Roofs." Urban Ecosystems Ecology, J. Aitkenhead-Peterson, and A. Volder, eds., American Society of Agronomy/Crop Science Society of America/ Soil Science Society of America, Madison, WI, 391-412.

[108] Rowe, D. B., Monterusso, M. A., and Rugh, C. L. (2006). "Assessment of Heat-expanded Slate and Fertility Requirements in Green Roof Substrates." HortTechnology, 16, 471-477.

[109] Schwaerzel, K., and Bohl, H. P. (2003). "An easily installable groundwater lysimeter to determine water balance components and hydraulic properties of peat soils." Hydrology and Earth System Sciences, 7, 23-32.

[110] Shaw, D. A., and Pittenger, D. R. (2004). "Performance of landscape ornamentals given irrigation treatments based on reference evapotranspiration." Proc., IV International Symposium on Irrigation of Horticultural Crops, 607-614.

[111] Silva, D., Meza, F. J., and Varas, E. (2010). "Estimating reference evapotranspiration (ETo) using numerical weather forecast data in central Chile." Journal of Hydrology, 382, 64-71.

[112] Simmons, M. T., Gardiner, B., Windhager, S., and Tinsley, J. (2008). "Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate." Urban Ecosystems, 11, 339-348.

[113] Snyder, R. L., and Eching, S. O. (2005). "Microclimate corrections for urban landscape evapotranspiration." Proc., World Water and Environmental Resources Congress: Impacts of Global Climate Change, ASCE, 544-556.

[114] Spalding, M. H., Edwards, G. E., and Ku, M. S. B. (1980). "Quantum Requirement for Photosynthesis in Sedum praealtum during Two Phases of Crassulacean Acid Metabolism." Plant Physiology, 66, 463-465.

[115] Spolek, G. (2008). "Performance monitoring of three ecoroofs in Portland, Oregon." Urban Ecosystems, 11, 349-359.

[116] Suleiman, A. A., and Hoogenboom, G. (2009). "A comparison of ASCE and FAO-56 reference evapotranspiration for a 15-min time step in humid climate conditions." Journal of Hydrology, 375, 326-333.

[117] Teixeira, A. H. d. C. (2008). "Measurements and modeling of evapotranspiration to assess agricultural water productivity in basins with changing land use patterns: a case study in the São Francisco River basin, Brazil." Doctoral Dissertation, Wageningen University, The Netherlands. 2008.

[118] Teixeira, A. H. d. C., Bastiaanssen, W. G. M., Ahmad, M. D., Moura, M. S. B., and Bos, M. G. (2008). "Analysis of energy fluxes and vegetation-atmosphere parameters in irrigated and natural ecosystems of semi-arid Brazil." Journal of Hydrology, 362, 110.

[119] Thornthwaite, C., and Mather, J. R. (1951). "The role of evapotranspiration in climate." Theoretical and Applied Climatology, 3, 16-39.

[120] Thuring, C. E., Berghage, R., and Beattie, D. J. (2010). "Green Roof Plant Responses to Different Substrate Types and Depths under Various Drought Conditions." HortTechnology, 20, 395-401.

[121] Uhl, M., and Schiedt, L. (2005). "Green Roof Storm Water Retention–Monitoring Results." Proc., 11th International Conference on Urban Drainage, Edinburgh, Scotland. 1-10.

[122] USDA (2010). "Welcome to the PLANTS Database | USDA Plants." http://plants.usda.gov/ Date Accessed 3/31/2011.

[123] USEPA (2010). "Wetlands - Wetland Types."http://water.epa.gov/type/wetlands Date Accessed 3/31/2011.

[124] VanWoert, N. D., Rowe, D. B., Andresen, J. a., Rugh, C. L., Fernandez, R. T., and Xiao, L. (2005). "Green roof stormwater retention: effects of roof surface, slope, and media depth." Journal of environmental quality, 34, 1036-1044.

[125] VanWoert, N. D., Rowe, D. B., Andresen, J. A., Rugh, C. L., and Xiao, L. (2005). "Watering Regime and Green Roof Substrate Design Affect Sedum Plant Growth." HortScience, 40, 659-664.

[126] Vaughan, P. J., and Ayars, J. E. (2009). "Noise Reduction Methods for Weighing Lysimeters." Journal of Irrigation and Drainage Engineering, 135, 235-240.

[127] Vaughan, P. J., Trout, T. J., and Ayars, J. E. (2007). "A Processing Method for Weighing Lysimter Data and Comparison to Micrometeorological ETo Predictions." Agricultural Water Management, 88, 141-146.

[128] Verstraeten, W. W., Veroustraete, F., and Feyen, J. (2008). "Assessment of Evapotranspiration and Soil Moisture Content Across Different Scales of Observation." Water, 70-117.

[129] Villarreal, E. L., and Bengtsson, L. (2005). "Response of a Sedum green-roof to individual rain events." Ecological Engineering, 25, 1-7.

[130] Vörösmarty, C. J., Federer, C. A., and Schloss, A. L. (1998). "Potential Evaporation Functions Compared on US Watersheds: Possible Implications for Global-Scale Water Balance and Terrestrial Ecosystem Modeling." Journal of Hydrology, 207, 147-169.

[131] Voyde, E., Fassman, E., and Simcock, R. (2010). "Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand." Journal of Hydrology, 394, 384-395.

[132] Voyde, E., Fassman, E., Simcock, R., and Wells, J. (2010). "Quantifying Evapotranspiration Rates for New Zealand Green Roofs." Journal of Hydrologic Engineering, 15, 395.

[133] Vu, S. H., Watanabe, H., and Takagi, K. (2005). "Application of FAO-56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan." Agricultural Water Management, 76, 195-210.

[134] Walter, I. A., Allen, R. G., Elliott, R., Jensen, M. E., Itenfisu, D., Mecham, B., et al. (2000). "ASCE's Standardized Reference Evapotranspiration Equation." Proc., Watershed Management & Operations Management 2000, ASCE, 126-137.

[135] Weihermueller, L., Siemens, J., Deurer, M., Knoblauch, S., Rupp, H., Goettlein, A., and Puetz, T. (2007). "In Situ Soil Water Extraction: A Review." Journal of Environmental Quality, 36, 1735-1748.

[136] Xu, C., and Chen, D. (2005). "Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany." Hydrological Processes, 19, 3717-3734.

[137] Xu, C., and Singh, V. (2005). "Evaluation of three complementary relationship evapotranspiration models by water balance approach to estimate actual regional evapotranspiration in different climatic regions." Journal of Hydrology, 308, 105-121.

[138] Zhang, J., and Ross, M. A. (2010). "Modeling Evapotranspiration of Two Land Covers Using Integrated Hydrologic Model." Journal of Irrigation and Drainage Engineering, 136, 511.

[139] Zhang, X. (2010). Shallow-layer soil water moisture changes in response to rainfall on green roof media. Master's Thesis, Beijing University of Technology, Beijing, China.

[140] Zhou, L., and Zhou, G. (2009). "Measurement and modelling of evapotranspiration over a reed (Phragmites australis) marsh in Northeast China." Journal of Hydrology, 372, 41-47.

Appendix A

Original Green Roof Plant Design

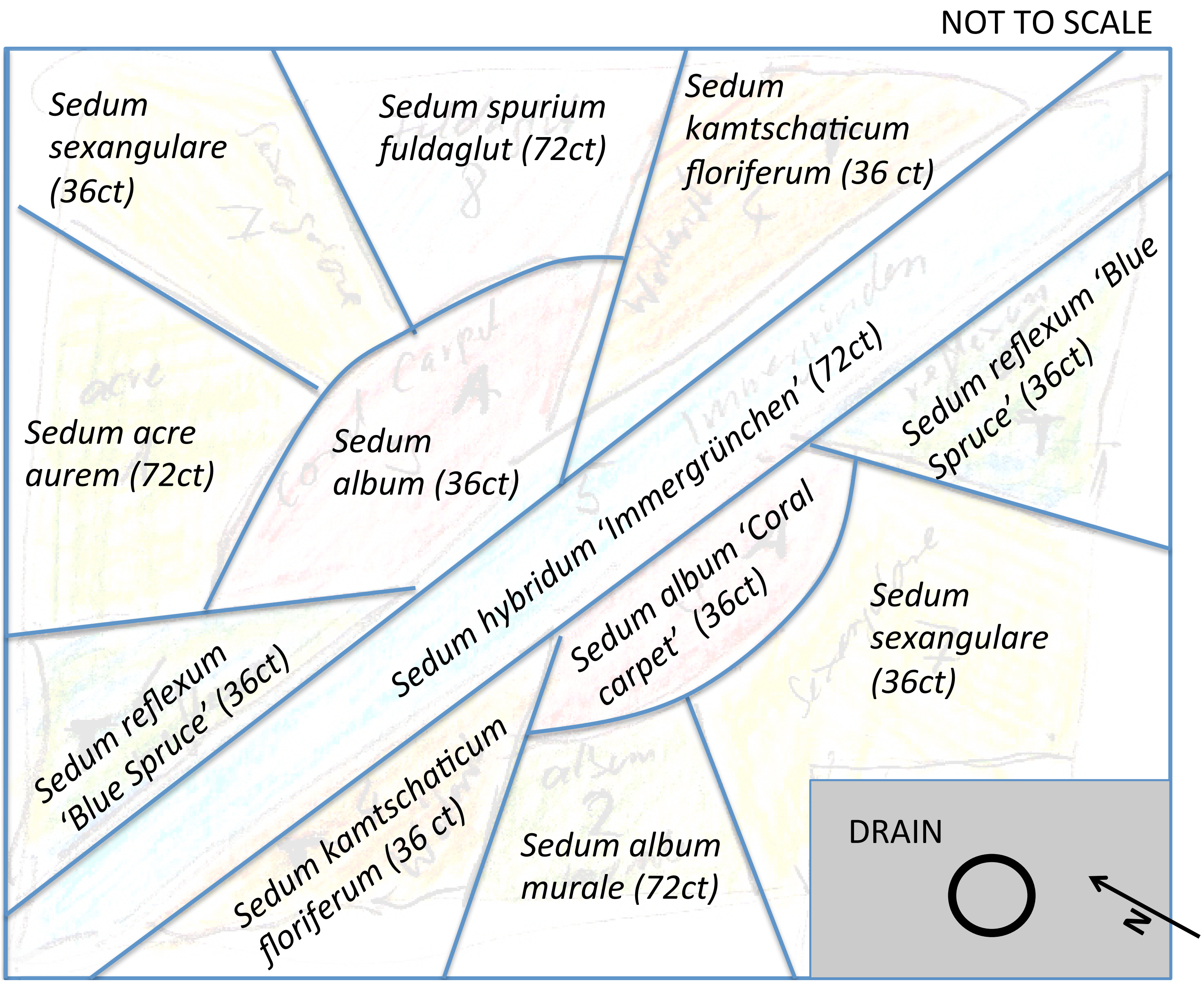


Figure A.1: In Spring 2011, new plugs were planted to replace the sections that had died in the drought in 2010, mostly in the north and south corners.

Appendix B

Soil Characteristics and Distribution Curve

rooflite®
Certified Green Roof Media

Typical Green Roof Media Analysis for rooflite® extensive mc

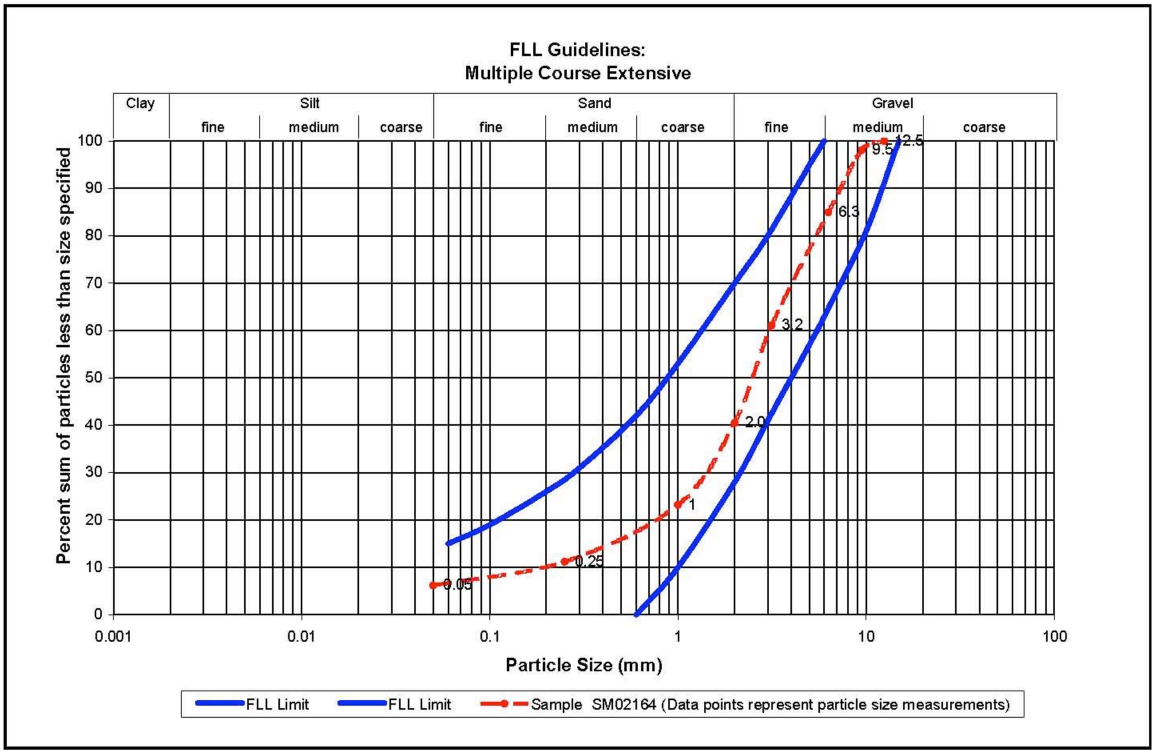
Results on dry weight basis unless specified otherwise

Analysis	Units	Results*	FLL** Requirements
Particle Size Distribution (See accompanying graph)			
Proportion of silting components (d < 0.063 mm)	mass %	5 - 10	< 15
Density Measurements*			
Bulk Density (dry weight basis)	g/cm^3	0.70 – 0.85	
Bulk Density (dry weight basis)	lb/ft^3	44 - 53	
Bulk Density (at max. water-holding capacity)	g/cm^3	1.15 – 1.35	
Bulk Density (at max. water-holding capacity)	lb/ft^3	72 - 85	
Water/Air Measurements			
Total Pore Volume	Vol. %	65 - 75	
Maximum water-holding Capacity	Vol. %	40 - 55	$\geq$ 35 $\leq$ 65
Air-Filled Porosity (at max water-holding capacity)	Vol. %	15 - 25	$\geq$ 10
Water permeability (saturated hydraulic conductivity)	cm/sec	0.02 – 0.08	0.001 – 0.12
Water permeability (saturated hydraulic conductivity)	in/min	0.47 – 1.89	0.024 – 2.83
pH and Salt Content			
pH ($CaCl_2$)		7.5 – 8.5	6.0 - 8.5
Soluble salts (water extract)	g /L	1.5 – 3.0	< 3.5
Organic Measurements			
Organic matter content	g/L	30 - 45	< 65
Nutrients			
Phosphorus, P_2O_5 (CAL)	mg/L	150 - 200	$\leq$ 200
Potassium, K_2O (CAL)	mg/L	400 - 700	$\leq$ 700
Magnesium, Mg (CaCl2)	mg/L	150 - 200	$\leq$ 200
Nitrate + Ammonium (CaCl2)	mg/L	10 - 40	$\leq$ 80

** Listed range of values is typical for the Mid Atlantic region*
*** All values are based on compacted materials according to laboratory standards and testing methods defined by the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.(FLL)*
Landscape Development and Landscaping Research Society e.V.
Guidelines for the Planning Construction and Maintenance of Green Roofing, Green Roofing Guideline, 2008

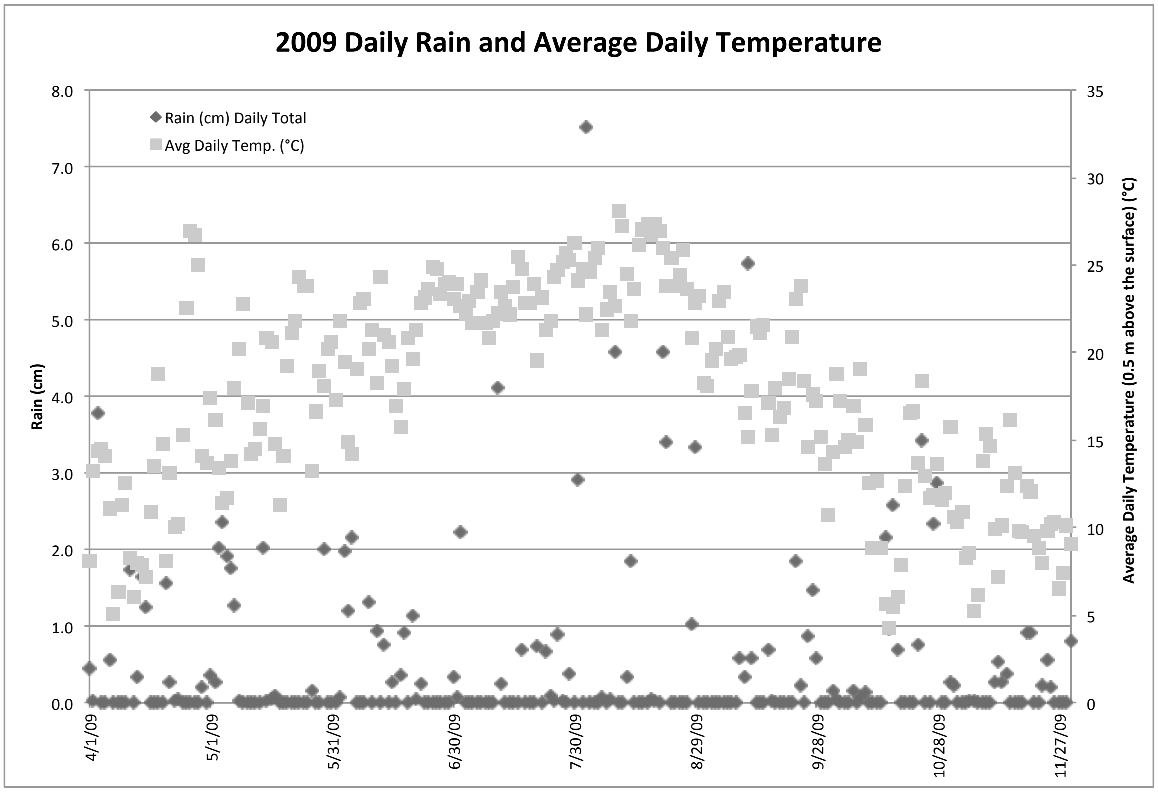
Certified Green Roof Media

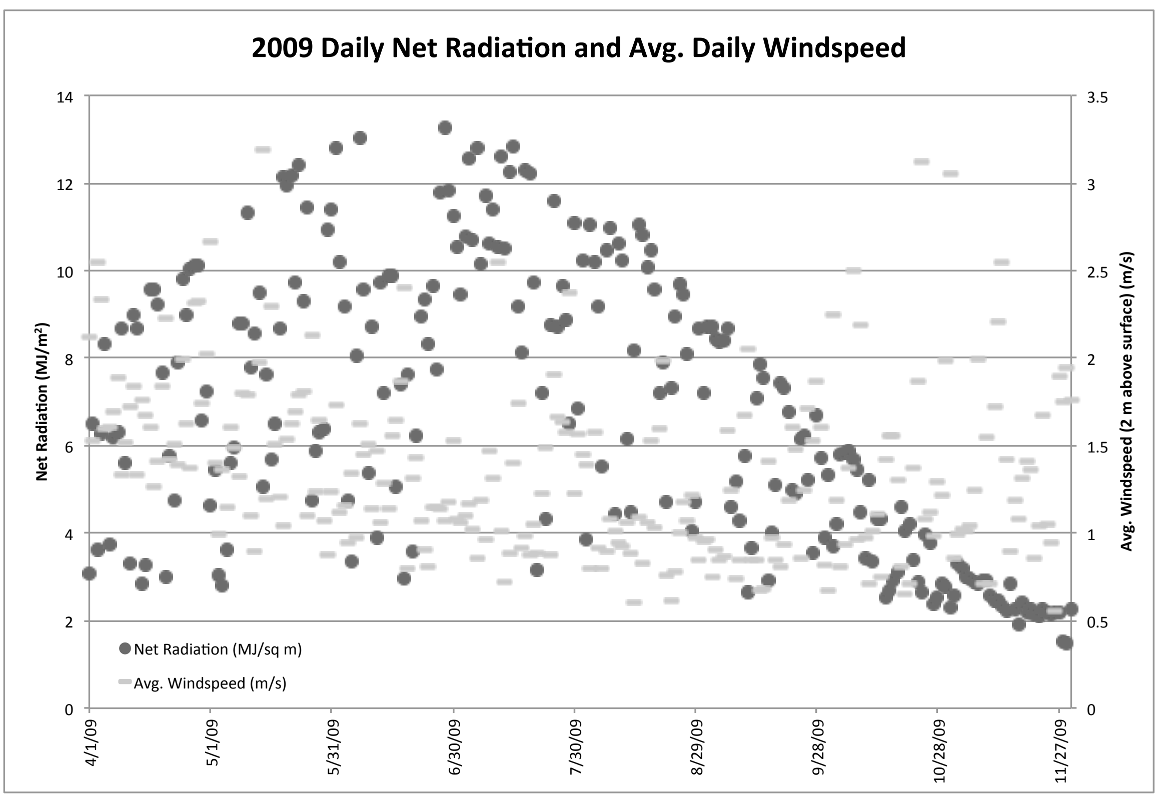
Typical Particle Size Distribution for rooflite® extensive mc

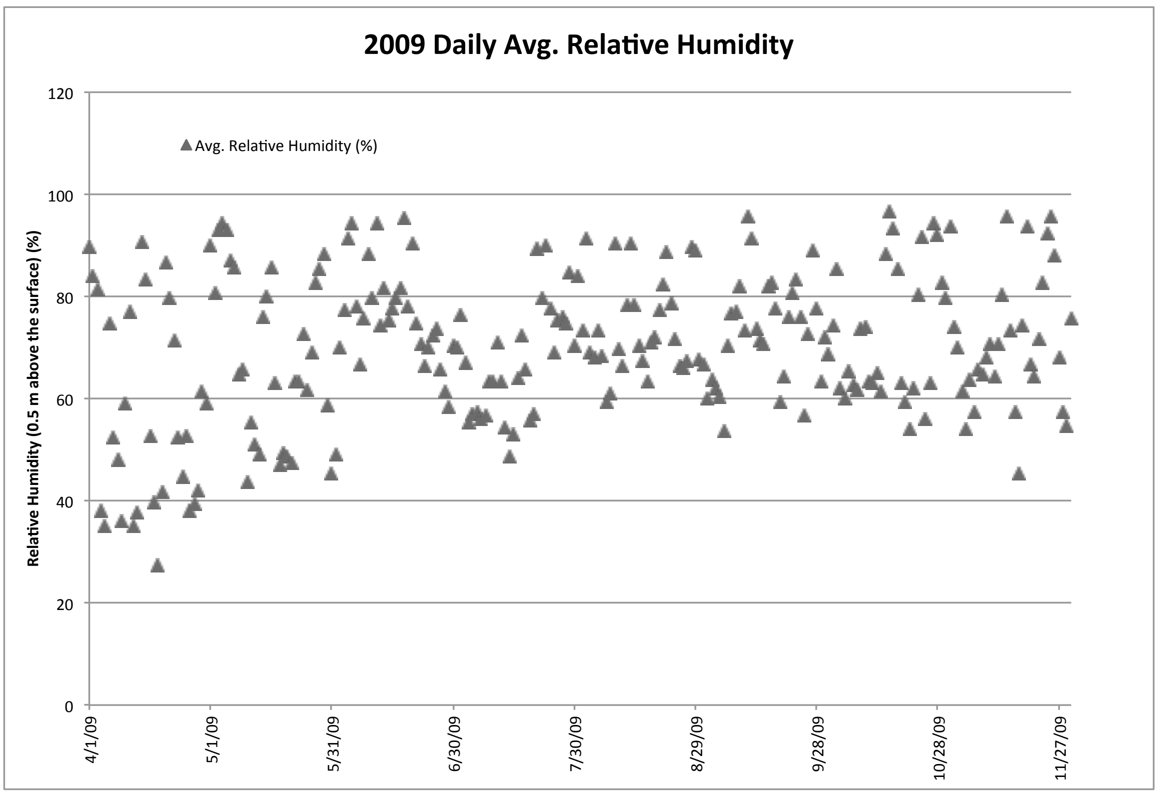


Appendix C

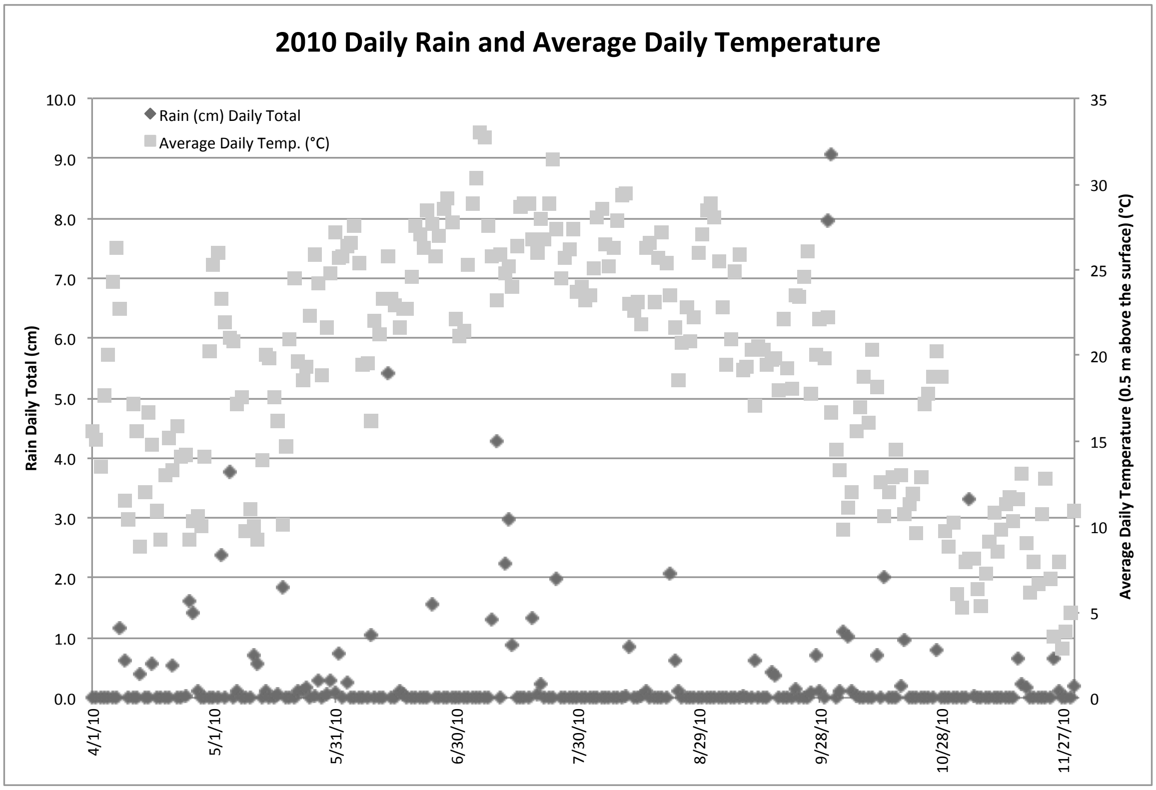
Weather Data for 2009 and 2010

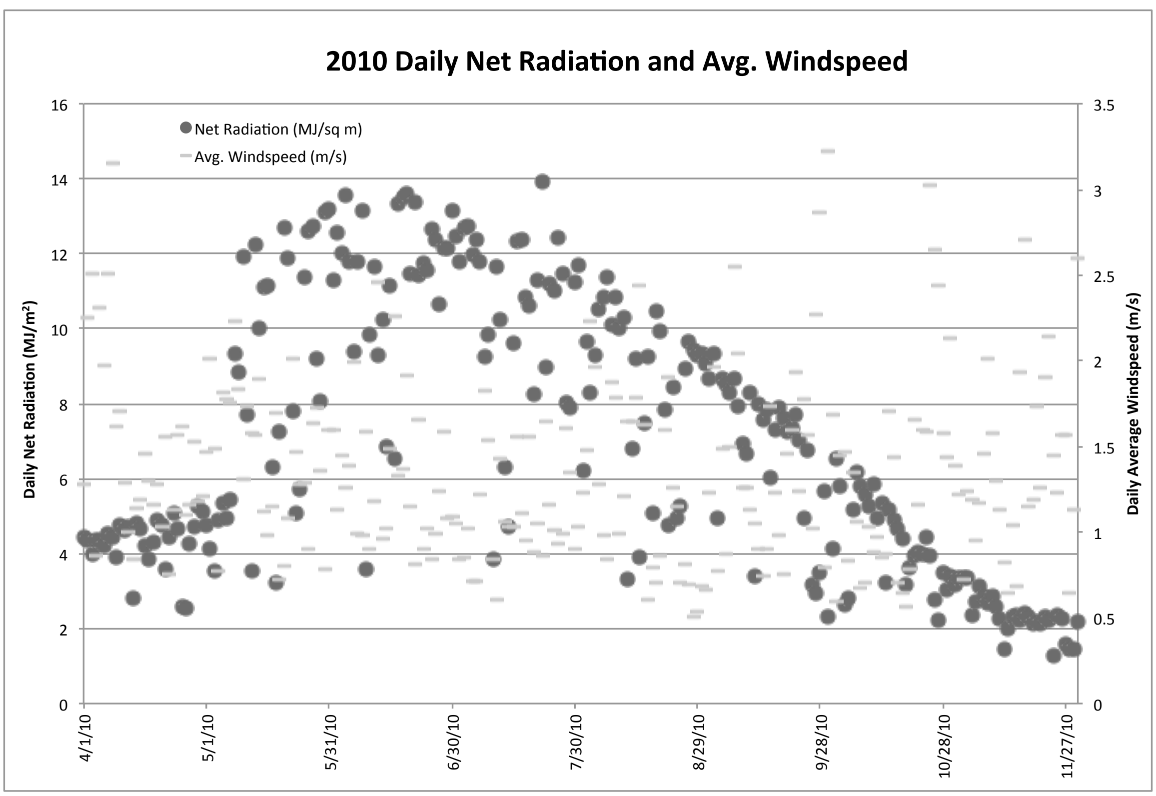

2009 Daily Rain and Average Daily Temperature
Rain (cm) Daily Total
Avg Daily Temp. (°C)
Rain (cm)
Average Daily Temperature (0.5 m above the surface) (°C)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
35
30
25
20
15
10
5
0
4/1/09
5/1/09
5/31/09
6/30/09
7/30/09
8/29/09
9/28/09
10/28/09
11/27/09

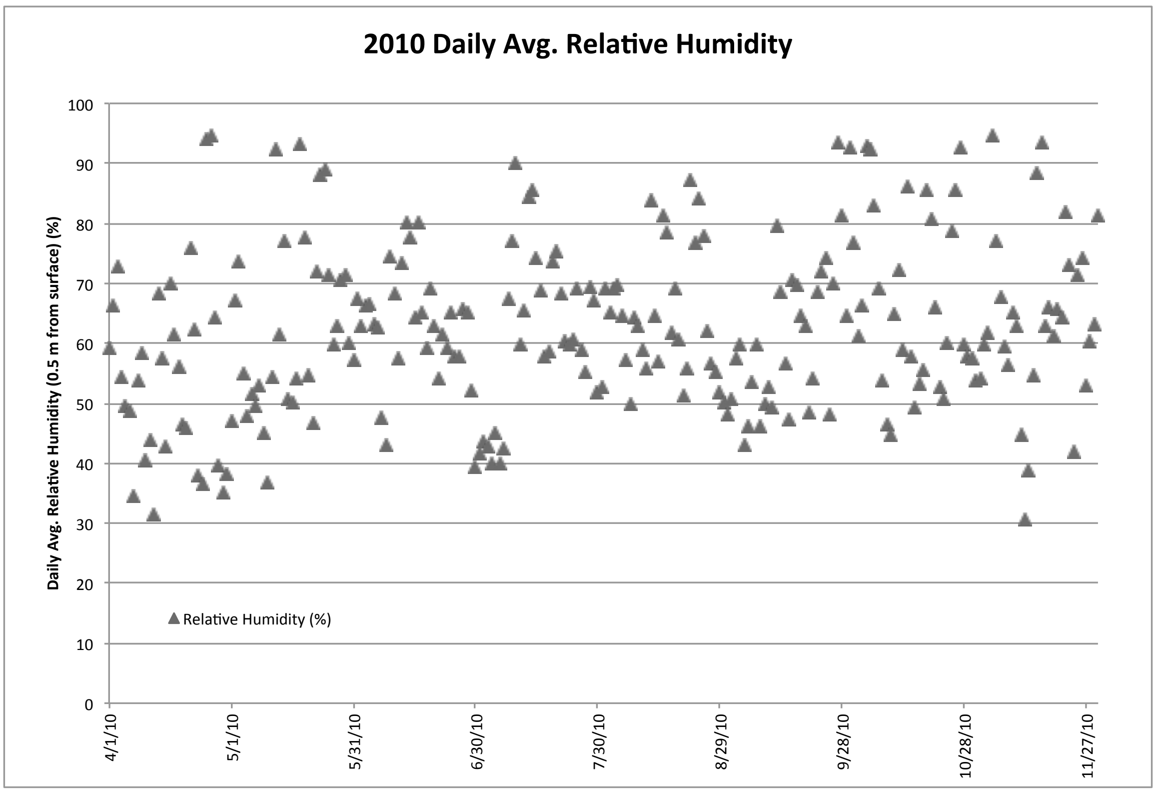

2009 Daily Net Radiation and Avg. Daily Windspeed
Net Radiation (MJ/sq m)
Avg. Windspeed (m/s)
Net Radiation (MJ/m²)
Avg. Windspeed (2 m above surface) (m/s)
14
12
10
8
6
4
2
0
3.5
3
2.5
2
1.5
1
0.5
0
4/1/09
5/1/09
5/31/09
6/30/09
7/30/09
8/29/09
9/28/09
10/28/09
11/27/09



2009 Daily Avg. Relative Humidity
Avg. Relative Humidity (%)
Relative Humidity (0.5 m above the surface) (%)
0
20
40
60
80
100
120
4/1/09
5/1/09
5/31/09
6/30/09
7/30/09
8/29/09
9/28/09
10/28/09
11/27/09

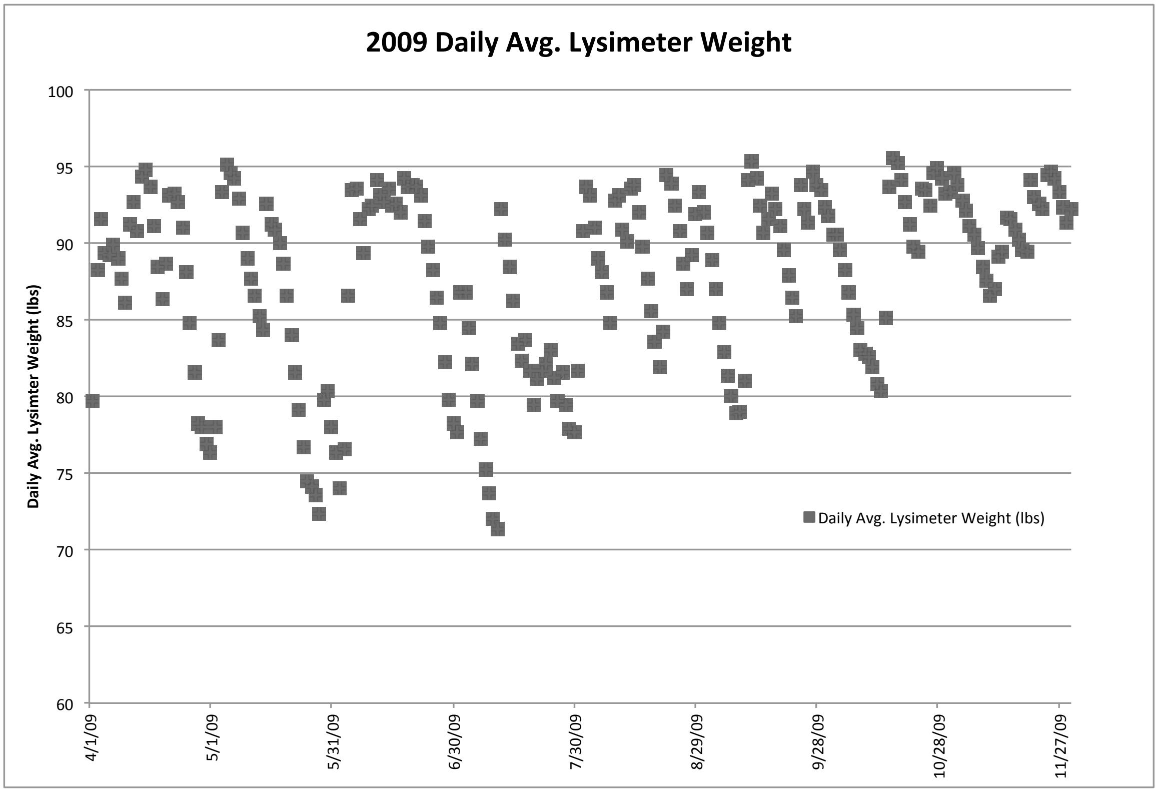

2010 Daily Rain and Average Daily Temperature
Rain (cm) Daily Total
Average Daily Temp. (°C)
Rain Daily Total (cm)
Average Daily Temperature (0.5 m above the surface) (°C)
4/1/10
5/1/10
5/31/10
6/30/10
7/30/10
8/29/10
9/28/10
10/28/10
11/27/10

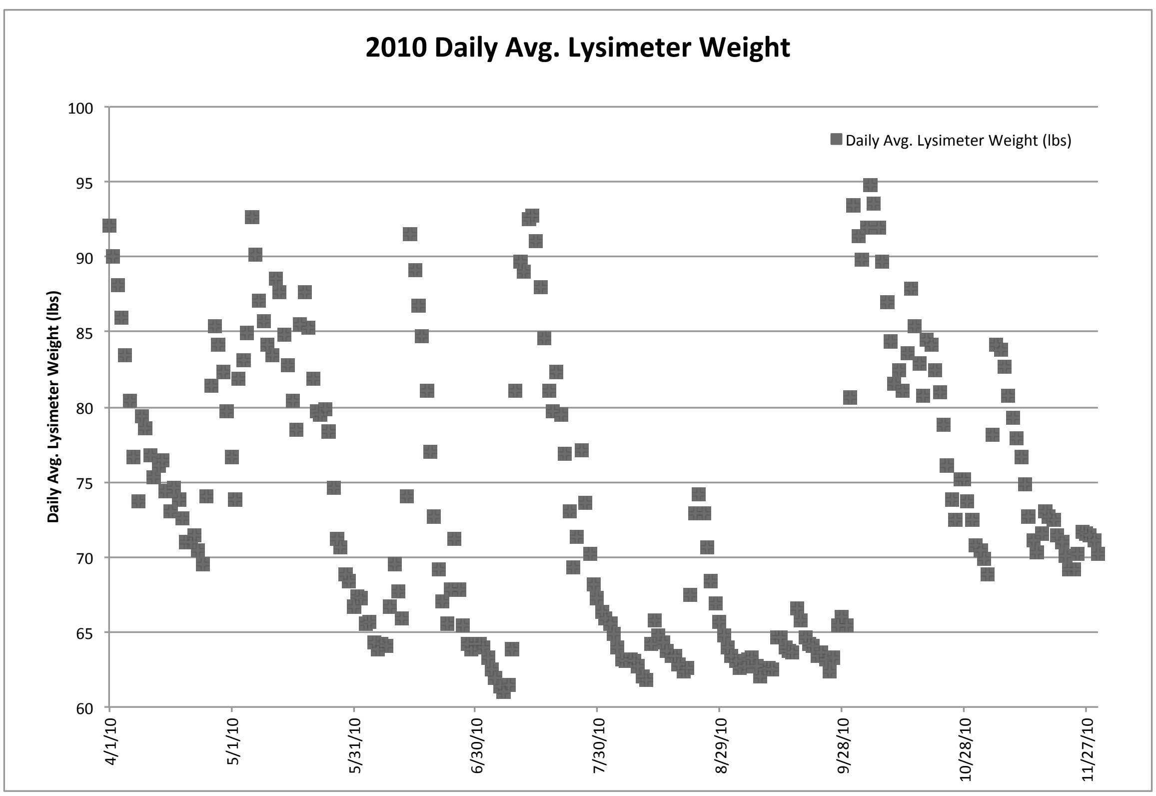

2010 Daily Net Radiation and Avg. Windspeed
Net Radiation (MJ/sq m)
Avg. Windspeed (m/s)
Daily Net Radiation (MJ/m²)
Daily Average Windspeed (m/s)
4/1/10
5/1/10
5/31/10
6/30/10
7/30/10
8/29/10
9/28/10
10/28/10
11/27/10


2010 Daily Avg. Relative Humidity
Daily Avg. Relative Humidity (0.5 m from surface) (%)
100
90
80
70
60
50
40
30
20
10
0
Relative Humidity (%)
4/1/10
5/1/10
5/31/10
6/30/10
7/30/10
8/29/10
9/28/10
10/28/10
11/27/10

Appendix D

Daily Avg. Lysimeter Weight for 2009 and 2010


2009 Daily Avg. Lysimeter Weight
Daily Avg. Lysimter Weight (lbs)
100
95
90
85
80
75
70
65
60
Daily Avg. Lysimeter Weight (lbs)
4/1/09
5/1/09
5/31/09
6/30/09
7/30/09
8/29/09
9/28/09
10/28/09
11/27/09


2010 Daily Avg. Lysimeter Weight
Daily Avg. Lysimeter Weight (lbs)
100
95
90
85
80
75
70
65
60
Daily Avg. Lysimeter Weight (lbs)
4/1/10
5/1/10
5/31/10
6/30/10
7/30/10
8/29/10
9/28/10
10/28/10
11/27/10

Appendix E

Crop Coefficients k_c based on $k_s(wgt)$ Derived using the Yearly Maximum Weight to Calculate Overflow

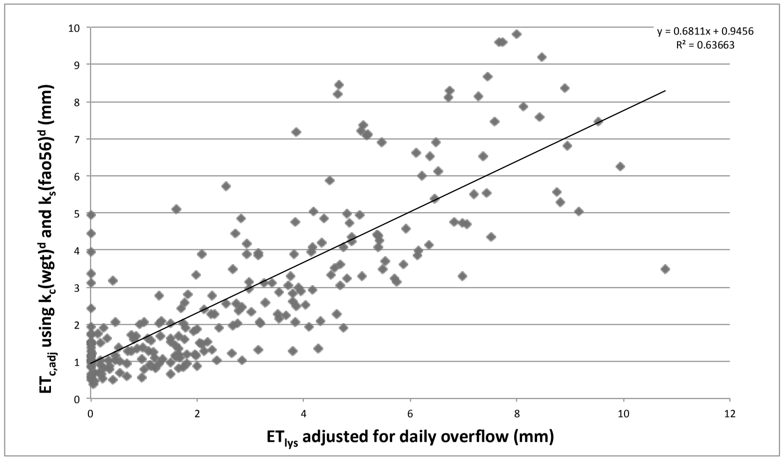
Table E.1: Crop coefficients k_c based on $k_s(wgt)$ derived using the yearly maximum weight to calculate overflow

2009	10% 92.4 lbs		20% 88.8 lbs		30% 85.2 lbs		40% 81.6 lbs		50% 78 lbs		60% 74.4 lbs		70% 70.8 lbs	
	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c
April	0.9	1.7	0.9	1.6	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5
May	0.8	1.8	0.8	1.7	0.9	1.6	0.9	1.5	1.0	1.4	1.0	1.4	1.0	1.4
June	0.9	1.8	0.9	1.7	0.9	1.7	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6
July	0.7	1.4	0.7	1.3	0.8	1.1	0.9	1.0	1.0	0.9	1.0	0.9	1.0	0.9
Aug	0.9	1.7	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6
Sept	0.9	1.7	0.9	1.6	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5	1.0	1.5
Oct	0.9	2.4	0.9	2.3	1.0	2.3	1.0	2.2	1.0	2.2	1.0	2.2	1.0	2.2
Nov	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6	1.0	1.6
Avg	0.9	1.7	0.9	1.7	0.9	1.6	1.0	1.6	1.0	1.5	1.0	1.5	1.0	1.5

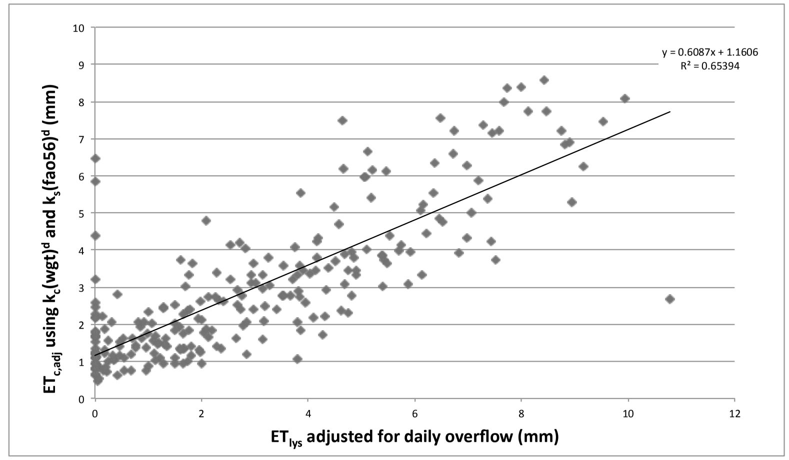
2010	10% 92.4 lbs		20% 88.8 lbs		30% 85.2 lbs		40% 81.6 lbs		50% 78 lbs		60% 74.4 lbs		70% 70.8 lbs	
	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c	k_s(wgt)	k_c
April	0.6	2.4	0.6	2.2	0.7	1.9	0.8	1.7	0.9	1.5	0.9	1.4	1.0	1.3
May	0.6	2.2	0.7	2.0	0.8	1.7	0.9	1.6	0.9	1.4	0.9	1.3	1.0	1.3
June	0.3	2.5	0.4	2.3	0.4	2.0	0.4	1.7	0.5	1.5	0.6	1.3	0.7	1.0
July	0.4	2.6	0.5	2.3	0.5	2.1	0.6	1.9	0.6	1.7	0.7	1.5	0.7	1.4
Aug	0.2	2.5	0.2	2.2	0.2	1.9	0.2	1.7	0.3	1.4	0.4	1.1	0.5	0.9
Sept	0.1	2.4	0.2	2.2	0.2	1.9	0.2	1.6	0.2	1.4	0.3	1.1	0.4	0.8
Oct	0.7	3.1	0.8	2.9	0.8	2.6	0.9	2.4	0.9	2.3	1.0	2.2	1.0	2.1
Nov	0.4	3.7	0.4	2.2	0.5	1.9	0.5	1.7	0.6	1.5	0.6	1.3	1.0	1.5
Avg	0.4	2.7	0.5	2.3	0.5	2.0	0.6	1.8	0.6	1.6	0.7	1.4	0.8	1.3

Appendix F

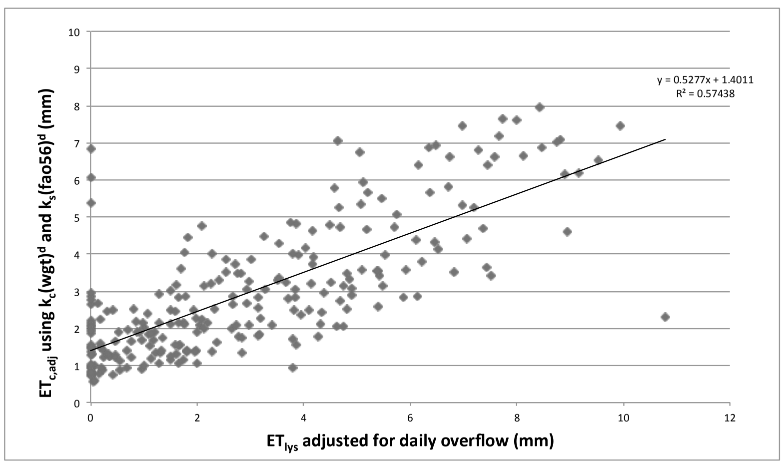
Model $ET_{c,adj}$ vs. ET_{lys} for Different Thresholds



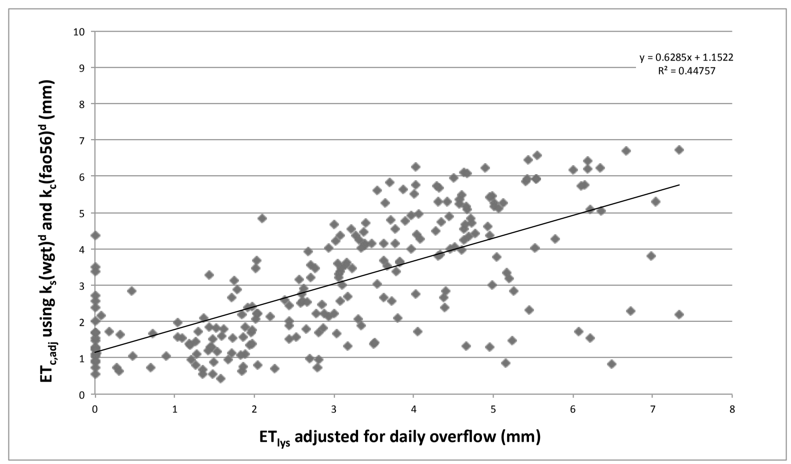
(a) 2010 with threshold at 81.6 lbs (40%)



(b) 2010 with threshold at 74.4 lbs (60%)



(c) 2010 with threshold at 70.8 lbs (70%)



(d) 2009 with threshold at 78 lbs (50%)

Figure F.1: $ET_{c,adj}$ using $k_s(wgt)^d * k_c(fao56)^d$ vs. ET_{lys}

Appendix G

Crop coefficient k_c derived for 1-7 day segments after each rain event

Table G.1: Results using 1-7 day segments after each rainfall to compute k_c with any remaining days in an inter-event period used to compute k_s. In general, the estimates of ET improved and k_c decreased as more days were incorporated. The crop coefficient did not vary unimodally as expected.

(a) 2009. The range of values found for k_c was within those expected, but steadily decrease from 1 day to 7 days; k_c should vary unimodally. k_s increases with increasing days and converges to one. The estimated ET consistently overestimates ET up to 6 days with decreasing magnitude. The 7 day segment underestimates ET. The percent error of the estimate improves with more days, likely due to the convergence of k_s, which results in a single coefficient model.

2009	Average k_c	Average k_s	Yearly Sum $ET_{c,adj}$ (mm)	Yearly Sum ET_{lys} (mm)	% Error
1 day	1.5	0.8	758	756	0.37%
2 day	1.4	0.9	766	756	1.34%
3 day	1.3	0.9	761	756	0.77%
4 day	1.3	1.0	765	756	1.22%
5 day	1.3	1.0	760	756	0.57%
6 day	1.3	1.0	758	756	0.27%
7 day	1.2	1.0	754	756	-0.19%

(b) 2010. The range of values for k_c ranges from 1.3 to 1.1 and is not unimodal in nature. $ET_{c,adj}$ does not consistently over- or underestimate ET but the magnitude of the percent error decreases with increasing number of days. k_s is less than one for each scenario, but increases towards one with increasing number of days. The estimate improves as k_s approaches one becuase the model becomes a single coefficient model.

2010	Average k_c	Average k_s	Yearly Sum $ET_{c,adj}$ (mm)	Yearly Sum ET_{lys} (mm)	% Error
1 day	1.3	0.8	663	724	-8.49%
2 day	1.3	0.8	705	724	-2.72%
3 day	1.3	0.8	727	724	0.39%
4 day	1.1	0.9	701	724	-3.21%
5 day	1.2	0.9	694	724	-4.14%
6 day	1.2	0.9	726	724	0.31%
7 day	1.2	0.9	739	724	2.01%