EFFECTIVENESS OF SMART CONTROLLERS FOR WATER CONSERVATION IN RESIDENTIAL IRRIGATION

By

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To those who have supported me during this extended adolescence

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The ET controller has the potential to produce water savings without sacrificing landscape quality in Florida when implemented at residences that habitually irrigate excessively and programmed with settings that are appropriate for the landscape. The education provided as part of the education treatments was effective at reducing irrigation application in addition to water savings by the technology without education. Proper controller programming was essential to achieving maximum water savings while maintaining acceptable landscape quality. If the time and effort of proper programming is not achievable, other smart irrigation technologies that do not increase existing irrigation, such as soil moisture sensors, would be more appropriate.

The time-based treatments selected to represent actual homeowner practices in Florida resulted in excessive irrigation during the field plot study. Though the ET controllers decreased irrigation compared to 100% replacement of the net irrigation requirement, there were no additional water savings compared to 60% replacement. Additionally, the performance scores for the ET controllers were not different from the 60% replacement with all treatments experiencing over-irrigation. The ET controller should be implemented only in situations of excessive irrigation habits.

In efforts to better approximate water conservation potential, an hourly soil water balance (SWB) was developed as an alternative to the industry standard, the daily SWAT test, for evaluating irrigation adequacy, a measure of under-irrigation, and scheduling efficiency, a measure of over-irrigation. The hourly SWB better matched the deterministic soil water model compared to the daily SWAT test thus improving estimates of volumetric water content in a shallow root zone. Additionally, the hourly SWB was preferential to the daily SWAT test based on the combination of more accurate landscape programming required to obtain high performance scores and the realistic representation of soil water movement by hourly SWB resulting in a more accurate translation of SWAT scores to controller performance in the landscape. As a result, the hourly SWB should be used as an alternative method for testing ET controllers that will more accurately reflect true soil-water relationships thus allowing for the estimation of water conservation potential.

CHAPTER 1
INTRODUCTION

Historically, the primary purpose of irrigation was to produce better yield of agricultural crops by supplementing water when rainfall is inadequate to maintain sufficient soil moisture. Over time, irrigation technology has become affordable in the residential sector, thus providing an opportunity for more lush and vibrant residential landscapes. Turfgrass has become a $40 billion dollar industry and it's estimated that more than 30 million acres of land make up home lawns in the United States (National Turfgrass Federation, Inc. 2003). As of 2005, domestic water use, which includes both indoor and outdoor water consumption, accounted for 58% of the public water supply in the United States and 60% of the public water supply in Florida (Kenny et al. 2009). Florida was ranked fourth in domestic water use; the only states having higher consumption were California, Texas, and New York.

It is commonly assumed that access to potable water is a right and should be provided unconditionally with minimal costs. However, using the limited potable water supply to irrigate landscapes, which are typically considered ornamental in nature and not purposeful to sustain life such as in agriculture, may not be socially responsible. Additionally, the tariffs for potable water are generally low with an international average of \$2.03 per m^3 of combined water and wastewater calculated from a 276-city survey (GWI 2011). This rate does not cover the real costs associated with the water and wastewater treatment processes while maintaining the aging infrastructure used to provide clean water to most homes in the United States (USEPA 2002).

On the other hand, turfgrass can be a functional part of the landscape by reducing soil erosion, preventing particulate inhalation from excess dust, dissipating heat at the soil surface level, and providing a wildlife habitat. There are also recreational and aesthetic reasons for maintaining turfgrass landscapes such as providing cushioned support for sports and playground activities and improving mental health and quality of life (Beard and Green 1994). Finding better ways to preserve turfgrass-based landscapes through modernized irrigation techniques may be a good compromise.

Current Irrigation Practices

The Florida Water Resources Act of 1972 was enacted to address the water quantity and quality problems in the state of Florida (Chapter 373 Florida Statutes). The Water Resources Act specified that water-related decisions would be managed in the best interest of the public and established regional jurisdiction to five Water Management Districts supervised by the Florida Department of Environmental Protection (FDEP). In addition to creating the five districts, the Water Resources Act specified the activities of the districts (Carriker 2006).

- Water-related regulations such as consumptive use permitting and surface water management
- Providing flood control systems
- Monitoring and researching water-related activities paid for by taxes
- Developing regional water supply plans

The five Water Management Districts are Northwest Florida (NWFWMD), Suwannee River (SRWMD), St. Johns River (SJRWMD), Southwest Florida (SWFWMD), and South Florida (SFWMD). The boundaries of the districts were chosen based on hydrological features and did not fall within political boundary lines. A nine to eleven person board governs each district with members selected by the governor (Carriker 2006).

Chapter 373.62 of the Florida Statutes outlines the only irrigation system regulations common to the state with the possibility of additional restrictions at the district, county, municipality, or other local level. Irrigation watering restrictions are one well-known regulation mandated by the districts where irrigation is allowed only for certain times of day and days of week (Table 1-1). The enforcement in the form of warnings and fines for violating watering restrictions is typically carried out at the county level resulting in varying intensity throughout the state.

The American lawn became a fundamental part of the home after the Second World War when suburbanization exploded (Robbins and Birkenholtz 2003). In Florida, in-ground, automatic irrigation systems have become a standard installation for single-family homes with primarily turfgrass-based landscapes. The most popular type of turfgrass is St. Augustinegrass due to its potential for dark green color and moderate levels of drought tolerance, shade tolerance, and salt tolerance.

For homes with automatic irrigation systems, more than half of total household water use can be irrigation. In Nevada, Devitt et al. (2008) found that 66% of the total water used at all sites was outdoors for 27 residential sites. Similar results were also found in central Florida where 64% of the total household water use was determined to be irrigation (Haley et al. 2007).

Soil Water Modeling

Models are used to solve problems in the real world when actual data cannot be collected. In soil water modeling, mathematical representations are used to model hydrological processes in the variably saturated shallow soil profile known as the vadose zone. Soil water models can be used for various purposes.

- Exploratory tools to determine certain processes or interactions
- Management tools to make real-time water management decisions and control hydrological systems
- Predictive tools to planning decisions and contribute develop policy

Models can be described in a number of ways such as physically based vs. empirically based, temporal vs. spatial, or static vs. dynamic. The appropriate model should be created or selected based on the purpose of the model while factoring the types of available input data and ability to produce meaningful outcomes. Simple models typically use a soil water balance or tipping bucket approach to water movement (evapotranspiration exits, precipitation and irrigation enter) for a fixed, homogeneous soil profile whereas complex models evaluate continuous water movement through one-dimensional or two-dimensional flow through a vertically heterogeneous soil profile (Ranatunga et al. 2008). Complex models require intensive input data provided by the user, numerical approximation techniques, and intense computations compared to simple models that are generally easier to use (Jeong et al. 2010). However, simple models sometimes lack key biological and hydrological processes making the model less realistic (Ranatunga et al. 2008).

As watersheds experience urbanization, permeable surfaces become impervious from structures such as buildings, roads, and sidewalks that create small, individualized soil water systems located throughout the urban area (Jeong et al. 2010). The fragmentation of the watershed to many small, unconnected landscapes renders many large-scale models inapplicable. Additionally, building construction changes the natural soil properties found on soil maps and in other sources to the properties of a generic fill material that may not be represented in the model. For urban residential landscapes, a model that spatially addresses the hydrogeological properties of individual home lots would be most beneficial.

Soil water models are calculated on various timesteps depending on the desired outcome. Large watershed models typically run on an annual, monthly, or weekly basis to minimize calculation errors whereas smaller landscape models typically run on daily or sub-daily timesteps. For residential turfgrass systems, combining sub-daily and daily time intervals can be beneficial to better capture short-term hydrological processes such as individual rainfall and irrigation events while still evaluating long-term water movement (Jeong et al. 2010).

There are many considerations to modeling the hydrological processes of a turfgrass system such as turfgrass species, plant growth, climatic conditions, plant density, water table depth, and water availability. Turfgrass systems are unique compared to agricultural systems because the goal of turfgrass in the landscape is to be ornamental and not marketable. As a result, it is unfavorable to increase yield of turfgrass due to increased mowing and nutrient requirements without a return on investment (Rosenberg et al. 2011). Research studies have shown that turfgrass growing in water conservative conditions can provide a minimally acceptable aesthetic (Bonos and Murphy 1999; Davis et al. 2009; Fu et al. 2004; McCready et al. 2009; Peacock and Dudek 1984) while resulting in less plant growth (Banuelos et al. 2011; Biran et al. 1981; Carrow 2006; Hsiao and Acevedo 1974). As a result, climatic conditions (evapotranspiration) and water availability (soil water storage, irrigation, rainfall, drainage, and runoff) are the most important parameters in modeling a turfgrass system.

Soil Water Storage

The amount of water able to be stored in the soil column of interest (root zone) is dependent on the characteristics of the soil. The soil column consists of soil particles structured with pore spaces sized from soil type and the level of compaction. For example, sandy soils have larger pore spaces compared to clay soils because the soil particles for sand are larger. Air and water exist in the pore spaces, or storage, of the soil column.

Saturation of the storage occurs when the pore spaces consist of only water and no air (IA 2005). However, the gravitational forces are stronger than the surface tension forces (cohesive and adhesive) between the water molecules and the soil particles when saturated causing drainage to the next layer of soil assumed to be unsaturated (Richards 1931). At the point when gravitational forces are less than tension forces, drainage due to gravity ceases and the soil column holds the maximum amount of water that can be stored given the soil characteristics. When this phenomenon occurs, the volume of water in the soil column divided by the total volume of the soil column can be calculated as field capacity (FC) (IA 2005). Through evapotranspirative losses, water will continue to leave storage until the work required by the plant material to uptake water is too great (Richards 1931). This occurs at the permanent wilting point (PWP), also calculated as the volume of water in the soil column divided by the total volume of the soil column (IA 2005). Typically, plants cannot recover from water stress when PWP is reached.

The amount of water that can be stored in a specific soil column is the available water holding capacity (AWHC) calculated as the difference in FC and PWP (IA 2005). The plant available water (PAW) can be calculated from AWHC by multiplying by the volume of the soil column to convert to total storage. For plant management purposes, a maximum allowable depletion (MAD) level is selected to ensure that plants do not become water-stressed. Readily available water (RAW), calculated by multiplying PAW by MAD, is the amount of water above the MAD level that can be depleted while maintaining well-watered conditions (i.e. no water stress).

The amount of water in the soil column can be calculated using a soil water balance (IA 2005).

$$SWB_i = SWB_{i-1} - PWR + R_e + IWR_{net} \qquad (1\text{-}1)$$

The SWB is the soil water level (mm) for timestep i or i-1, PWR is the plant water requirement (mm) on day i, R_e is effective rainfall (mm) on day i, and IWR_{net} is the net irrigation water requirement (mm) on day i. The soil water balance level can fluctuate based on the storage parameters of the soil column that determines the AWHC.

Soil Parameters

The hydraulic conductivity and soil water retention parameters are important hydraulic properties used to determine water movement through a soil column. Hydraulic conductivity (K) is the rate that water can move through the soil column. Hydraulic conductivity primarily depends on soil moisture and pressure head, but can be affected by temperature and salinity of the soil column (Nielson et al. 1986). Temperature and salinity affect the bonding forces between the soil particles and water molecules, thus affecting capillary flow through the pores (Richards 1931). Soil water retention curves relate soil moisture and matric potential.

Empirical formulas exist to predict the soil water retention curves (Brooks and Corey 1964).

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(h/_{h_b}\right)^{\lambda}} \tag{1-2}$$

The θ(h) is soil moisture content, θ_s is soil moisture content at saturation, θ_r is soil moisture content at PWP, h is the pressure head (cm) at a certain depth in the soil profile, h_b is the bubbling pressure, and λ is a pore size distribution index. Another popular formula was developed by van Genuchten (1980).

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha|h|)^n]^m} \tag{1-3}$$

The α, m, and n are empirical constants. The λ in Brooks and Corey (1964) is equal to m minus n.

Hydraulic properties can be measured in the field with equipment such as tensiometers and soil moisture sensors (Nielson et al. 1986). Though the parameters would be most accurate when directly measured, it is typically not feasible due to time and cost. Many have developed theoretical approaches to determining hydraulic conductivity related to pore size distribution (Nielson et al. 1986). The equation developed by Childs and Collis-George (1950) were modified by Marshall (1958) to become the modified CCG equation.

$$K_r(\theta_i) = \Theta^{\beta} \sum_{i=1}^{k} \frac{[2(k-i)+1]}{h_i^2} \Big/ \sum_{i=1}^{l} \frac{[2(l-i)+1]}{h_i^2} \tag{1-4}$$

The i is a division, k is the number of divisions to a prescribed value of θ, and l is the total number of divisions of the soil profile. There is an alternate equation developed by Mualem (1976) and another equation proposed by Burdine (1953).

$$K_r(\Theta) = \Theta^{1/2} \left[\int_0^{\Theta} \frac{1}{h(x)} dx \Big/ \int_0^1 \frac{1}{h(x)} dx\right]^2 \tag{1-5}$$

$$K_r(\Theta) = \Theta^2 \int_0^{\Theta} \frac{1}{h^2(x)} dx \Big/ \int_0^1 \frac{1}{h^2(x)} dx \quad (1\text{-}6)$$

The x is the depth in the soil profile and Θ is the effective soil moisture content, ranging from 0 at PWP to 1 at saturation.

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (1\text{-}7)$$

In Europe, a widely used equation is the exponential Gardner relationship (Gardner 1958).

$$K(h) = K_s \cdot e^{\alpha h} \quad (1\text{-}8)$$

Hydraulic conductivity curves were further developed by van Genuchten (1980) using the Mualem relationship it can be expressed as a function of soil moisture or as a function of pressure head.

$$K_r(\Theta) = \Theta^{1/2}\left[1 - \left(1 - \Theta^{1/m}\right)^m\right]^2 \quad (1\text{-}9)$$

$$K_r(\mathrm{h}) = \frac{\{1 - (\alpha h)^{n-1}[1 + (\alpha h)^n]^{-m}\}^2}{[1 + (\alpha h)^n]^{m/2}} \quad (1\text{-}10)$$

The m ranges from 0 to 1 and can be estimated from n as m=1-1/n. Additionally, hydraulic conductivity from van Genuchten using the Burdine relationship can be expressed as a function of soil moisture or as a function of pressure head.

$$K_r(\Theta) = \Theta^2\left[1 - \left(1 - \Theta^{1/m}\right)^m\right] \quad (1\text{-}11)$$

$$K_r(\mathrm{h}) = \frac{1 - (\alpha h)^{n-2}[1 + (\alpha h)^n]^{-m}}{[1 + (\alpha h)^n]^{2m}} \quad (1\text{-}12)$$

The n is greater than 2 and m ranges from 0 to 1 and can be estimated from n as m=1-2/n.

Chu (1978) analyzed cylinder infiltrometer data collected by the Soil Conservation Service from field sites having multiple soil types to determine soil parameters (Table 1-2). Additionally, Rawls et al. (1982; 1983) developed various soil parameters for a variety of soil types (Table 1-3).

The soil moisture profile can be affected by the historical wetting patterns due to hysteresis, or the dependence of a system on its current and past environment. As a result, soil hydraulic properties can evolve based on the wetting pattern and effectively change the soil water retention curve (Izady et al. 2009). As a result, the wetting process may require a different soil water retention curve than the drying process. It can be attributed to geometric nonuniformity of pores, differences in spatial connectivity of pores, variation in the liquid-solid contact angle, and air entrapment (Izady et al. 2009). Though hysteresis can be neglected in soil water modeling, it is an important process for redistribution and long-term modeling.

Preferential flow can occur in soil profiles that have holes, cracks, or other larger pores that result in fast and uneven flow of water through the soil profile. Water movement in soil profiles that experience preferential flow may not be described with the same hydraulic properties as an isotropic soil profile.

Evapotranspiration

Evapotranspiration (ET) occurs as part of a balanced energy budget that exchanges energy for outgoing water at the surface of the plant, including both the evaporation from the soil surface and the transpiration through plant material (Allen et al. 1998). The components that affect the rate of ET are solar radiation, temperature, relative humidity, and wind speed (ASCE 2005).

Though there are various methods of estimating ET including field lysimeter experiments, soil water studies, and a long-term inflow-outflow water budget for large areas, it is more efficient and economical to predict ET of a reference plant material using climatic-based equations. The reference plant material is located around the sensors collecting the climatic data used to calculate reference ET (ET_o) and should be an actively growing, well-watered, dense green grass of uniform height (ASCE 2005).

The Penman-Monteith equation has been endorsed by many organizations including the American Society of Civil Engineers (ASCE), International Commission for Irrigation and Drainage (ICID), Food and Agriculture Organization of the United Nations (FAO), and the Irrigation Association (ASCE 2005). The most recent form of the Penman-Montieth equation is the ASCE standardized reference evapotranspiration equation.

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273}(e_s - e_a)u_2}{\Delta + \gamma(1 + C_d u_2)} \quad (1\text{-}13)$$

Variables defined.

$$\Delta = \frac{2503 e^{\frac{17.27T}{T+237.3}}}{(T+237.3)^2} \quad (1\text{-}14)$$

$$e_s = \frac{e^{\circ}(T_{max}) + e^{\circ}(T_{min})}{2} \quad (1\text{-}15)$$

$$e^{\circ}T = 0.6108 e^{\frac{17.27T}{T+237.3}} \quad (1\text{-}16)$$

$$e_a = \frac{e^{\circ}(T_{min})\frac{RH_{max}}{100} + e^{\circ}(T_{max})\frac{RH_{min}}{100}}{2} \quad (1\text{-}17)$$

$$R_n = R_{ns} - R_{nl} \quad (1\text{-}18)$$

$$R_{ns} = (1 - \alpha)R_s \quad (1\text{-}19)$$

$$R_{nl} = \sigma f_{cd}\left(0.34 - 0.14\sqrt{e_a}\right)\left[\frac{T_{Kmax}^4 + T_{Kmin}^4}{2}\right] \quad (1\text{-}20)$$

$$f_{cd} = 1.35\frac{R_s}{R_{so}} - 0.35 \quad (1\text{-}21)$$

$$R_{so} = (0.75 + 2 \times 10^{-5}z)R_a \quad (1\text{-}22)$$

$$R_a = \frac{24}{\pi} G_{sc} d_r[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \quad (1\text{-}23)$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \quad (1\text{-}24)$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (1\text{-}25)$$

$$\omega_s = \cos^{-1}[-\tan(\varphi)\tan(\delta)] \quad (1\text{-}26)$$

$$u_2 = u_z \frac{4.87}{ln(67.8z_w - 5.42)} \quad (1\text{-}27)$$

ET_o = reference evapotranspiration, mm/day
γ = psychrometric constant, 0.067 kPa/°C
Δ = slope of the saturation vapor pressure-temperature curve, kPa/°C
T = daily mean air temperature, °C

e_s = saturation vapor pressure, kPa
e^oT = saturation vapor pressure function, kPa
e_a = actual vapor, kPa
RH = relative humidity, %
R_n = net radiation, MJ/m^2/day
R_{ns} = net short-wave radiation, MJ/m^2/day
R_{nl} = net outgoing long-wave radiation, MJ/m^2/day
R_s = incoming solar radiation, MJ/m^2/day
α = albedo or canopy reflection coefficient, 0.23
σ = Stefan-Boltzmann constant, 4.901 x 10^{-9} MJ/K^4/m^2/day
f_{cd} = cloudiness function, $0.05 \leq f_{cd} \leq 1.0$
R_{so} = calculated clear-sky radiation, MJ/m^2/day
R_a = extraterrestrial radiation, MJ/m^2/day
z = station elevation above sea level, m
d_r = inverse relative distance factor for the earth-sun
δ = solar declination, rad
φ = latitude, rad
ω_s = sunset hour angle, rad
J = Julian day
G_{sc} = solar constant, 4.92 MJ/m^2/hr
G = daily soil heat flux density, 0 MJ/m^2/day
u_2 = wind speed at 2 m height, m/s

This equation takes into account net radiation, R_n (MJ m^{-2} d^{-1}); heat flux, G (MJ m^{-2} d^{-1}); vapor pressure, Δ (kPa °C^{-1}), e_s (kPa), e_a (kPa); temperature, T (°C); and wind speed, u_2 (m s^{-1}). The γ is the psychrometric constant and can be obtained from the measured mean atmospheric pressure (ASCE 2005). A grass reference crop rather than alfalfa is used for residential landscapes; for a grass reference, the constants of C_n and C_d are 900 and 0.34, respectively (ASCE 2005).

The ET of the irrigated crop (ET_C) is calculated from the ET of the reference plant material (ET_O) under the same climatic conditions using a ratio called a crop coefficient (K_C).

$$ET_c = K_c \cdot ET_o \tag{1-28}$$

The K_C accounts for differences in ground cover, canopy characteristics, and aerodynamic resistance from the reference grass (Jenson et al. 1990). Values of K_C can vary based on soil water availability, nutrient management, and overall turfgrass health (Gibeault et al. 1989); ideally, K_C values should be calculated from well-watered, properly managed turfgrasses. Though annual K_C values have been suggested (Gibeault et al. 1989; Allen et al. 1998), monthly K_C values should be used when available (Table 1-4).

In the soil water balance, the PWR equals the amount of water necessary to maintain healthy plant material (IA 2005). The PWR is calculated as the plant-specific evapotranspiration (ET_C).

In Florida, the maximum ET occurs in May when there is the least cloud cover, maximum vapor pressure deficit conditions, and the highest incoming solar radiation (Jia et al. 2009). Other summer months are not as high due to the rainy season occurring from Jun. through Nov. resulting in reduced ET rates due to frequent rainfall events and increased cloud cover. The K_C values in South Florida exceeded values for all other locations for all months except in Jun. and Jul. for Las Vegas, NV. The K_C values from California maximized in May, similar to the Florida locations, but at a much lower average.

Precipitation

Precipitation is considered to be the most variable input to hydrological models. It can come in the form of drizzle, rainfall, freezing rainfall, snow, or hail. In Florida, the primary type of precipitation is rainfall. Rainfall can vary spatially, with localized rainfall events, and temporally, with fluctuating intensities.

Effective rainfall is the amount of water from a rainfall event that can be stored in the soil profile. In the tipping bucket method of a soil water balance model, effective rainfall was limited to the portion of total daily rainfall that would cause the soil water storage to reach FC after PWR was taken into account (IA 2005). Rainfall that exceeded soil water storage was considered lost due to surface runoff or deep percolation. In a real soil water storage system, this assumption would be inaccurate because water can still enter the soil profile until reaching saturation, which is above field capacity, and may be able to temporarily store water on the soil surface depending on the landscape features such as depressions and slopes.

Urbanization of watersheds affected the way rainfall interacts with the soil profile. Impermeable surfaces may cause excess water to be directed onto the soil profile causing flooding when the volume exceeds the soil infiltration rate. Chang (2007) found that the impact of urbanization during individual storm events is more significant than mean annual runoff. This indicates that the short-term effects on soil water storage from rainfall may only be apparent at a small timestep.

A major effect of whether rainfall enters the soil water profile or becomes runoff is the intensity of the event. Intensity is determined by measuring the volume of rainfall occurring over a certain time period. Intensity has greater fluctuation and higher peaks when the timestep is small, thus allowing more accurate depiction of the soil water processes. However, when the timesteps are extremely small, such as a minute, it may be difficult to determine separate rainfall events that occur on the same day because intensities are so low. In the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model, rainfall events were considered independent when more than 180 minutes passed between measured rainfall (Knisel 1980).

Irrigation

Irrigation is the amount of water required to maintain plant health and should be applied only on days when the water level reaches the MAD level. The depth of irrigation required to increase soil water storage to field capacity, thus satisfying PWR, is the net irrigation (IWR_{net}) (IA 2005).

Irrigation systems that are perfectly efficient may apply IWR_{net} directly. However, irrigation systems are not perfectly efficient thus requiring additional irrigation application to ensure IWR_{net} is received in the soil column. Because efficiency is difficult to quantify directly, distribution uniformity (DU) of the irrigation system is typically used as a substitute (Burt et al. 1997). The DU is typically measured using catch-can testing that involves placing a grid of buckets throughout the irrigated area and measuring the volume of water collected from an irrigation event. The lower quarter distribution uniformity (DU_{lq}) can be calculated as the ratio of the average of the lowest 25% of volumes (d_{lq}) to the average of all volumes measured (d_{avg}) (Burt et al. 1997).

$$DU_{lq} = \frac{d_{lq}}{d_{avg}} \tag{1-29}$$

The IA (2005) suggested that DU_{lq} overestimates the effect of non-uniform landscapes. Therefore, the DU_{lh} should be used for irrigation scheduling purposes and can be estimated from DU_{lq}.

$$DU_{lh} = 0.386 + 0.614 \cdot DU_{lq} \tag{1-30}$$

Using the DU_{lh}, the amount of additional water required to achieve IWR_{net} can be calculated as the RTM (IA 2005).

$$RTM = \frac{100}{DU_{lh}} \tag{1-31}$$

Multiplying the RTM by IWR_{net} produces the gross irrigation requirement (GIR), or the amount of water that should be scheduled in order to apply IWR_{net} to the soil column (IA 2005). Efficiency is typically affected by irrigation system design, such as not having head-to-head coverage, and pressure problems.

Additional considerations to take into account when scheduling irrigation include soil type, sprinkler type, and slope. Soil type and sprinkler type are important to determining the maximum runtime length, especially if the irrigation application rate of the sprinklers exceeds the infiltration rate of the soil type. Also, high slopes can decrease the infiltration rate, which will also affect the maximum runtime length. Irrigation events should be broken into multiple irrigation events where the cycle lengths are less than the maximum runtime, thus minimizing runoff. The length of time between irrigation events, or soak times, should also be determined based on these factors.

Infiltration

Infiltration of water through the soil profile is primarily dependent on soil parameters, pre-existing soil moisture conditions, and precipitation intensity. According to Mein and Larson (1973), infiltration is one of the largest influences on runoff, but is one of the most deficient processes in hydrological modeling. In the tipping bucket method of a soil water balance model, infiltration is considered instantaneous. Additionally, the total volume of infiltrated water is assumed to be equal to the available water storage of the soil profile and any excess water is lost to surface runoff or deep percolation. Though these assumptions simplify the soil water balance, it fails to follow physical responses to infiltration and can lead to compounding errors if applied over long time periods for small study sites.

Infiltration can observe three behaviors based on values of infiltration rate, rainfall intensity, and saturated hydraulic conductivity (Mein and Larson 1973). When rainfall intensity is less than saturated hydraulic conductivity, all water infiltrates into the soil column and there is no runoff. In this case, the soil moisture changes but does not exceed field capacity. When rainfall intensity exceeds saturated hydraulic conductivity but does not exceed the infiltration rate, all of the water infiltrates causing the soil moisture to exceed field capacity. However, if the rainfall intensity exceeds the infiltration rate, the infiltration rate declines while runoff is generated.

Many empirical equations have been suggested to better approximate infiltration processes. An infiltration equation suggested by Kostiakov and Horton was a simplistic representation that had the ability to fit most data (Childs 1969). The Holtan model (1961) expressed infiltration as a function of pore space and not as a function of time. However, these and other empirically based equations require parameters that are difficult to estimate (Mein and Larson 1973). The Philip equation (1957) was developed for ponded, homogeneous soils using more predictable parameters. However, this equation can only assume ponding conditions and cannot account for initial conditions when the infiltration capacity is infinite. An analytic infiltration model (Parlange et al. 1982) was expanded for redistribution with multiple rainfall events (Smith et al. 1993). Currently, the two most prominent methods for modeling infiltration are Richards equation (1931) and Green-Ampt equation (1911).

Richards

Richards equation (1931) was developed for the flow of water through unsaturated porous media, such as a soil column, from Darcy's Law for flow through porous media under saturated conditions and Poiselle's Law for the flow of liquids in capillary tubes.

$$q = -K\nabla\Phi \tag{1-32}$$

The q is flow rate over the surface area of the soil column, K is the hydraulic conductivity, and $\nabla\Phi$ is the total water-moving field that is based on the gravitational and pressure forces in the three dimensional plane. The primary difference between saturated flow and unsaturated flow is the dependency of water movement on capillary forces and hydraulic conductivity of the soil column.

Richards equation can be expressed based on pressure head (h), soil moisture content (θ), or a combination of both (Celia et al. 1990).

$$C(h)\frac{\partial h}{\partial t} - \nabla \cdot K(h)\nabla h - \frac{\partial K}{\partial z} = 0 \tag{1-33}$$

$$\frac{\partial \theta}{\partial t} - \nabla \cdot D(\theta)\nabla \theta - \frac{\partial K}{\partial z} = 0 \tag{1-34}$$

$$\frac{\partial \theta}{\partial t} - \nabla \cdot K(h)\nabla h - \frac{\partial K}{\partial z} = 0 \tag{1-35}$$

The C(h) is the specific moisture capacity function, D(θ) is the unsaturated diffusivity, and z denotes the depth of the soil column. The structure of these equations assumes positive vertical dimension is upward and the soil column is isotropic.

Richards equation is a nonlinear partial differential equation that cannot be solved analytically. Instead, numerical approximations such as the finite difference or finite element methods combined with iteration techniques such as Picard or Newton methods are required for discrete solutions (Celia et al. 1990).

Celia et al. (1990) found that despite widespread use, the h-based equation combined with a backward Euler time discretization, using any iteration method, produced large mass balance errors. Using the h-based equation, smaller timesteps are necessary to obtain convergence and reduce mass balance errors. A timestep of 120 s underestimated the infiltration depth by 20%. The θ-based equation, though perfectly mass conservative, produces discontinuous soil moisture content profiles that are not easily used. It was also found that the mixed form of Richards equation combined with a backward Euler time approximation and Picard iteration would alleviate these problems. Additionally, finite difference approximations were suggested as preferable to finite element approximations due to lack of mass lumping. Finite element approximations produced oscillatory solutions, larger mass balance errors, underpredicting infiltration depth, and exhibiting undershoot errors ahead of the infiltration front.

Green-Ampt

The Green-Ampt (GA) equation (1911) was developed to model infiltration in a homogeneous and isotropic soil profile during ponded conditions. It was a physically based empirical model that was derived from Darcy's Law for instantaneous ponding on the soil surface. Infiltration occurs as a sharp wetting front, sometimes referred to as a rectangular piston front, with the wetting front advancing through the lower portion of the soil profile. Water infiltrates completely until the soil surface reaches saturation, also known as infiltration capacity (Mein and Larson 1973). At infiltration capacity, conditions change from unponded to ponded.

In 1973, Mein and Larson contributed to the GA model by accommodating time periods where ponding was not instantaneous. The new model, referred to as GAML, had the ability to change from unponded to ponded conditions during steady rainfall events. The GAML was evaluated at several rainfall intensities and soil moisture contents on five types of soils (Mein and Larson 1973). Cumulative infiltration predicted by the Green-Ampt equation did not deviate significantly from cumulative infiltration computed using Richard's equation. Based on a study that evaluated the GAML equation for 47 rainfall events in seven locations, the most accurate results were obtained when analyzed at a ten-minute time interval (King 2000).

Continued development to GAML occurred when Chu (1978) further enhanced GAML to account for unsteady rainfall events that occur from multiple periods of rainfall intensity exceeding the infiltration rate. Chu suggested that the improved equation adequately modeled infiltration for a watershed due to total estimated runoff approximated measured runoff when replicated for three separate storm events.

In 1997, Ogden and Saghafian included the option of having two wetting fronts to account for hiatuses between pulses of a single rainfall event. They suggest that infiltration is significantly underestimated during the second pulse by not redistributing the soil water during the hiatus period. Compared to Richard’s equation, Green-Ampt with redistribution (GAR) performed well with only 2% error in cumulative infiltration for the first wetting front and 4.5% error for the second wetting front when evaluated for 6 h. However, coarser soils that have saturated hydraulic conductivity values greater than 1 cm/h had errors that increased logarithmically.

Gowdish and Muñoz-Carpena (2009) expanded on GAR proposed by Ogden and Saghafian (1997) with modifications to reduce the error seen when adding multiple rainfall events. The new method, titled MGAR, increased the total number of rainfall events possible from two to infinity thus creating the ability for long-term analyses of infiltration. Convergence of the model was obtained for all soil types when using the van Genuchten (1980) retention curves and Brooks and Corey (1964) unsaturated hydraulic conductivity curve. The relationship between error and soil texture was determined using a method for non-linear least squares curve-fitting resulting in the development of a correction factor termed the redistribution coefficient. The MGAR model better approximated Richard’s equation compared to GAR, especially for coarse textured soils, over the 365 h evaluation.

The Green-Ampt equation (1911) requires an iterative solution to calculate the infiltration capacity.

$$f_p = K_s\left[1 + \left(M_d\frac{S_{av}}{F}\right)\right] \tag{1-36}$$

f_p = infiltration capacity
K_s = saturated hydraulic conductivity
M_d = initial soil moisture deficit
S_{av} = capillary suction at the wetting front
F = cumulative infiltration

Integration of the above equation results in the expression for cumulative infiltration (Mein and Larson 1973). The capillary suction at the wetting front varies as the wetting front moves through the soil during a rain event. Though S_{av} can be determined experimentally, it can also be estimated from integrating Brooks and Corey (1964).

$$S_{av} = -\Psi_b\left(\frac{2+3\lambda}{1+3\lambda}\right) \tag{1-37}$$

The Ψ_b is the bubbling pressure and λ is the soil pore size distribution index. The parameters of K_s, M_d, and S_{av} are considered to be constant during a rainfall event because diffusion is assumed to be negligible (Chu 1978).

For calculation purposes, a temporary shift in the time scale so that ponding begins when time equals zero is necessary to account for cumulative infiltration and is expressed as a pseudotime (t_s).

$$t_s = \frac{F_{tp}}{K_s} - \frac{M_d S_{av}}{K_s}\ln\left(1 + \frac{F_{tp}}{M_d S_{av}}\right) \tag{1-38}$$

The F_{tp} is the cumulative infiltration at the time ponding occurs and t_p is the time at the start of ponding.

$$t_p = \left[\frac{K_s M_d S_{av}}{I - K_s} - P(t_{n-1}) + R(t_{n-1})\right] + t_{n-1} \tag{1-39}$$

The I (mm) is the rainfall intensity and t_{n-1} is the time at the beginning of the current rainfall intensity. The time to ponding calculation was substituted into an integrated form of Equation 1-36 to get the equation for cumulative infiltration.

$$F_p = K_s(t - t_p + t_s) + M_d S_{av} \ln\left(1 + \frac{F_p}{M_d S_{av}}\right) \tag{1-40}$$

After ponding, this equation requires an iterative procedure to obtain a solution because the cumulative infiltration term cannot be isolated on one side of the equation. However, t_s and t_p can be calculated implicitly.

Ponding will continue until a specified time when the rainfall intensity falls below the infiltration capacity and all of the ponded water has infiltrated or become runoff. The time this occurs is called time to end ponding (t_j).

$$t_j = t_p - t_s + \frac{1}{K_s}\left[I(t_j - t_{t-1}) + S + F_{t-1} - M_d S_{av} ln\left(1 + \frac{I(t_j - t_{t-1}) + S + F_{t-1}}{M_d S_{av}}\right)\right] \tag{1-41}$$

F_{t-1} = last calculated cumulative infiltration
t_{t-1} = the time when cumulative infiltration was last calculated

These equations are only valid when there are ponding conditions. If there are no ponding conditions because the rainfall intensity is less than the infiltration rate, then the infiltration rate for unponded conditions (f_u) equals the rainfall intensity. Additionally, cumulative infiltration (F_u) would be equal to the amount of rainfall occurring over time.

During periods of no rainfall, a differential equation for redistribution of water in the soil column was proposed by Ogden and Saghafian (1997).

$$\frac{d\theta_o}{dt} = \frac{1}{Z}\left[r_h - K_i - \left(K(\theta_o) + \frac{K_s G(\theta_i, \theta_o)}{Z}\right)\right] \tag{1-42}$$

The Z is the depth to the wetting front, r_h is the rainfall flux during hiatus, K_i is the unsaturated hydraulic conductivity under initial conditions, $K(\theta_o)$ is the unsaturated hydraulic conductivity after the rainfall event, and $G(\theta_i,\theta_o)$ is the integral of the capillary drive across the wetting front. Integration of $G(\theta_i,\theta_o)$ and continued derivations from assumptions from van Genuchten (1980) and Brooks and Corey (1964) relationships, where Θ is relative saturation.

$$G(\theta_i, \theta) = S_{av}\left(\frac{\Theta^{3+1/\lambda} - \Theta_i^{3+1/\lambda}}{1 - \Theta_i^{3+1/\lambda}}\right) \tag{1-43}$$

The redistribution coefficient (Γ) was used to correct for errors occurring over time for a wide range of soils.

$$\Gamma = a_1 + a_2 ln(T_R) + a_3/N_R \tag{1-44}$$

The T_R is the redistribution time and N_R is the redistribution number determined from the number of wetting fronts (Gowdish and Muñoz-Carpena 2009). The values of a_1, a_2, and a_3 were calculated using three intervals (Table 1-5).

$$a_i = \left(b_i + c_i K_s^{d_i}\right)^{(-1^i)} \ for\ i = 1,2,3 \tag{1-45}$$

Surface Runoff

In many hydrological models, the curve number method developed by the Natural Resources Conservation Service has been implemented to estimate surface runoff (Garen and Moore 2005). The curve number method is an empirical method designed for flood models, but has expanded for use in continuous models and varies based on soil moisture. It was developed to predict the amount of streamflow in addition to baseflow of a water body and does not correspond to overland flow. Because the soil water balance does not have a spatial component, estimating surface runoff based on the curve number would be inappropriate (Jeong et al. 2010).

Surface runoff, in terms of overland flow, can occur when the precipitation rate exceeds the infiltration rate of the soil column or the soil moisture is already at saturation (Garen and Moore 2005). As a result, surface runoff can be quantified based on the infiltration calculations in the model.

Calibration and Validation

The accuracy of a model is evaluated through calibration and validation procedures. Calibration is performed to minimize the differences between observed and predicted results and optimize models. Additionally, validation of the model can be completed to quantify its performance compared to the physical system being modeled. Data used to calibrate a model should not be used to validate it, thus requiring multiple datasets.

The combination of goodness-of-fit measures, absolute error measures, and graphical assessments can provide an adequate evaluation of model performance for calibration and validation purposes (Legates and McCabe Jr. 1999; Willmott et al. 1985; McCuen et al. 2006; Krause et al. 2005). Combining these three methods will result in overcoming the limitations inherent in each individual measure. Goodness-of-fit measures summarized here include the coefficient of determination (R^2) and Nash-Sutcliffe coefficient of efficiency (NSE). Absolute error measures include mean absolute error (MAE) and root mean square error (RMSE). Graphical assessments, though not detailed here, include 1:1 graphs and time series graphs.

The coefficient of determination, calculated as the square of the Pearson's product-moment correlation coefficient, is the proportion of the variability that can be explained in the model. It is calculated as a unitless measure of the colinearity of the residuals (Legates and McCabe, Jr. 1999; Jeong et al. 2010).

$$R^2 = \left\{\frac{\sum_{i=1}^{N}(O_i-\bar{O})(P_i-\bar{P})}{\left[\sum_{i=1}^{N}(O_i-\bar{O})^2\right]^{0.5}\left[\sum_{i=1}^{N}(P_i-\bar{P})^2\right]^{0.5}}\right\}^2 \tag{1-46}$$

O = observed value
P = predicted value
$\bar{O}$ = average of the observed values
$\bar{P}$ = average of the predicted values

N = number of observed or predicted values

Values of the coefficient of determination range from 0, indicating no agreement, to 1, indicating perfect linear agreement. Limitations to this model include inability to describe nonlinear systems, sensitivity to outliers, and biased results when the model accurately predicts extremes but not values near the mean (Legates and McCabe, Jr. 1999; McCuen et al. 2006). Models that systematically over- or under-predict measured data can result in high coefficients of determination (Krause et al. 2005).

The NSE is an alternate goodness-of-fit parameter to the coefficient of determination.

$$NSE = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \tag{1-47}$$

The numerator of the equation measures the variation in the data that was not explained by the model and the denominator measures the total variation in the observed data (McCuen et al. 2006). Values of the coefficient can range from -∞ to 1 where values of 0 to 1 indicate that the model, if linear, is unbiased. According to Jeong et al. (2010), NSE larger than 0 indicate minimally acceptable performance and greater than 0.65 on a daily basis is preferred. However, the NSE is subjective and may be lower for subdaily results and higher for monthly or annual outputs. Similar to the coefficient of determination, limitations to the NSE include sensitivity to sample size, outliers, magnitude bias, and time-offset bias.

The mean absolute error is a model prediction error that is expressed in the units of the variable of interest. It can be calculated to determine the magnitude of the differences between the predicted and observed values.

$$MAE = \frac{\sum_{i=1}^{n}|O_i - P_i|}{n} \tag{1-48}$$

The optimal value of MAE is 0 indicating that there is no error between the predicted and observed values. Willmott and Matsuura (2005) suggested that the MAE is the most natural and unambiguous measure of the magnitude of average error.

The root mean square error, also a dimensioned model prediction error, is a function of average error, squared errors, and $n^{1/2}$.

$$RMSE = \left[\frac{\sum_{i=1}^{n} |O_i - P_i|^2}{n}\right]^{1/2} \tag{1-49}$$

Though frequently used as a measure for environmental models, its meaning is often misinterpreted by researchers (Willmott and Matsuura 2005). Squaring the residual errors allows the magnitude to affect the metric and not the positive or negative difference. However, this exacerbates the influence of large errors allowing a few large errors to increase the RMSE value when there may be few small errors. As a result, RMSE will always be greater than MAE unless all residual errors are equal, in which case RMSE equals MAE. Due to MAE being only a function of average error, it is the preferred metric over RMSE for evaluating model performance (Legates and McCabe, Jr. 1999; Willmott and Matsuura 2005).

Sensitivity Analysis

A sensitivity analysis is performed to determine the influence of various parameters on the outcome of the model. It can also be used to test the logic and stability of the model by testing for extreme values, thus determining its limits (Jones and Luyten 1998; Saltelli et al. 2000). Sensitivity analysis can be local by evaluating an outcome based on varying input parameters individually. It can also be global by evaluating many parameters simultaneously.

Local sensitivity analysis, also called one-at-a-time (OAT) analysis, can be performed by varying the value of a single parameter while maintaining the original values for all other parameters and quantifying the difference in the outcome. Absolute sensitivity is a measure of the variation of the outcome of interest related to the change in the selected parameter.

$$\sigma(y|k) = \frac{y(k+\Delta k/2)-y(k-\Delta k/2)}{\Delta k} \tag{1-50}$$

The y is the outcome variable and k is the parameter selected to change (Jones and Luyten 1998). Normalizing the measure to other variables in the model can be done by calculating the relative sensitivity.

$$\sigma_r(y|k) = \sigma(y|k)\frac{k}{y} \tag{1-51}$$

Local sensitivity measures are appropriate for problems where parameters cannot be observed directly (Saltelli et al. 2000) or if the parameters produce linear output responses (Muñoz-Carpena et al. 2007).

Global sensitivity analysis involves varying many parameters and quantifying variation through probability distribution functions. Analytic approaches to calculating the variation include, but are not limited to, Taylor series approximations, First Order Approximations ([FOA], Morgan and Henrion 1992), and Monte Carlo simulations (Muñoz-Carpena et al. 2007). Global sensitivity methods can be used for determining the portions of the model that do not provide an adequate contribution to the results (Saltelli et al. 2000). This aids in simplifying the model to parameters that affect the outcome of interest and verifying the representation of the physical system. Additional benefits to global analysis include testing many parameters simultaneously, the ability to rank parameter importance, and determining interaction effects (Muñoz-Carpena et al. 2007).

Summary of Available Models

There are thousands of hydrological models in existence with a wide range of purposes such as vadose zone water movement, groundwater movement, and overland flow. Typically, hydrological models are used to predict agricultural water use, water availability, and water management issues like flooding and stream flow levels. Due to these large-scale issues, many models evaluate large-scale areas such as catchments, basins, and watersheds with varying timesteps such as daily, weekly, monthly, or even annually. Also, many models have multiple objectives in addition to the results of the hydrological model such as sediment transport, nutrient transport, and crop growth.

CHEMFLO-2000

This program, available through the EPA, uses Richards' equation to model one dimensional water movement in soil columns of finite length or semi-infinite length with uniform initial conditions (Nofziger and Wu 2003). Partial differential equations are solved using finite differences with backward Euler approximation and a Picard iteration scheme. Soil water retention curves can be selected from Brooks and Corey (1964), Simmons et al. (1979), and van Genuchten (1980) using the Mualem (1974) relationship. Hydraulic conductivity curves can be calculated using Brooks and Corey (1964), Gardner (1958), and van Genuchten (1980), also using the Mualem (1974) relationship. Acceptable ranges for parameters for soil water retention curves and hydraulic conductivity curves can be determined through extensive soil testing (Table 1-6). The user must specify the initial matric potential and boundary conditions at the soil surface expressed as a constant matric potential, constant flux density, or falling head.

Additional boundary conditions at some depth of the soil column for a finite soil system are expressed as constant matric potential, constant flux density, or free drainage. There are various limitations specific to the model.

- No source or sink terms for root water uptake
- No provisions for shrink/swell, preferential flow, and hysteresis
- Sensitivity to initial and boundary conditions
- Discretization errors increase as the mesh size increases

HYDRUS-1D

This model can be used to analyze one-dimensional water and solute movement in variably saturated porous media by numerically solving Richards' equation for water flow and the convection-dispersion equation for solute transport (USDA 2008). Richards' equation is solved by finite element schemes using either Gaussian elimination for banded matrices, conjugate gradient method for symmetric matrices, or the ORTHOMIN method (Mendoza et al. 1991) for asymmetric matrices. Implementing automatic time step adjustments, error checking, and minimizing numerical oscillations improve solution efficiency of the finite element method. Flow regions can be delineated by irregular boundaries and composed of non-uniform soils that have a variety of boundary conditions. Hydraulic properties were described by van Genuchten (1980), Brooks and Corey (1964), and modified van Genuchten functions where modifications were made to improve hydraulic properties near saturation.

SWAP

The Soil-Atmosphere-Plant (SWAP) model simulates the transport of water, solutes, and heat in variably saturated zone over growing seasons. SWAP consists of clearly defined modules for soil water flow, soil heat flow, solute transport, crop growth, macropore flow and interaction with groundwater and surface water systems (Kroes et al. 2008). It has been derived from previous versions, such as SWATR(E), SWACROP, and SWAP93, and integrated into other models for nutrient management, such as PEARL, ANIMO, and STONE. The upper system boundary is defined by the soil surface with or without a crop and the atmospheric conditions. The bottom is bounded by the unsaturated zone and describes the interaction with regional groundwater. Richards' equation is applied for water movement throughout the variably saturated zone, allowing the use of soil hydraulic functions from databases and simulation of all kinds of management options. Root water extraction at various depths is calculated from potential transpiration, root length density, and possible reductions due to wet, dry, or saline conditions. Though not standard, SWAP can be implemented on a regional scale within GIS.

WAVE

This FORTRAN-based model can be used to evaluate water movement using the SWATRER code, nitrogen movement using SOILN code, heat and solute modeling using LEACHN code, and crop growth using SUCROS. Soil water movement is determined using a soil water balance where one-dimensional flow is determined from Richards equation solved using the finite difference method. The upper boundary condition is specified by flux density or pressure head. The lower boundary can be specified based on the presence of a water table, pressure head, flux density, or free drainage. Hydraulic conductivity values are fitted using Gardner (1958) when measured values are not available. Additionally, if a soil water retention curve is not specified, van Genuchten (1980) with the Mualem (1974) relationship can be used. Hysteresis can be considered using Mualem second parametric model (Mualem 1974). Preferential flow can be considered by summing multiple soil water retention curves.

ET Controllers

ET controllers use evapotranspiration (ET) to estimate plant water needs. Though they vary in functionality based on model, most ET controllers use a soil water balance to determine how much irrigation is necessary and when to apply it. The controllers are designed to either replace the typical timer or act as an amendment to the timer. The primary differences in types of controllers are due to the methods for obtaining ET information that include: 1) historical pre-programming, 2) on-site calculation, and 3) provided by a signal service. More information about the types of ET controllers can be found in Davis (2008).

Evaluation Programs

The Irrigation Association developed the Smart Water Application Technologies (SWAT) Testing Protocol for Weather-Based Irrigation Controllers as a method to evaluate the ability of ET controllers to use ET for irrigation scheduling purposes (IA 2008). This testing protocol was established in 2002 and is now in its 8th draft. The protocol specifies a 30-day test to determine if ET controllers can maintain theoretical soil moisture for six diverse virtual landscapes (Table 1-7; Table 1-8).

The controllers were evaluated against the soil-water characteristics of the virtual landscapes to determine performance measured through scheduling efficiency and irrigation adequacy. Scheduling efficiency is a measure of over-irrigation and is quantified as scheduling losses combined from three sources: soil moisture rising above field capacity, too long cycle times, and too short soak times. It is calculated from 30-day totals.

$$E = \frac{I_n - SL}{I_n} * 100 \tag{1-52}$$

The E is scheduling efficiency (%), I_n is net irrigation (mm), and SL is scheduling losses (mm). Similarly, irrigation adequacy is a measure of under-irrigation and can be quantified from the periods when the virtual landscape would not be considered as well-watered conditions. It is calculated from 30-day totals.

$$A = \frac{ET_C - D}{ET_C} * 100 \quad (1\text{-}53)$$

The A is irrigation adequacy (%), ET_C is crop-specific evapotranspiration (mm), and D is the amount of deficit (mm). Deficit is calculated as the cumulative depth below well-watered conditions, or depth below the maximum allowable depletion level. Results of 100% for either score would indicate that the irrigation scheduling performance by the ET controller was effectively perfect over the 30-day test. Manufacturers program their own ET controllers and choose when to publish the results, sometimes resulting in repeated testing until nearly perfect scores are produced (Table 1-9).

In June 2006, the United States Environmental Protection Agency (USEPA) started the WaterSense program to add labels on product packaging of certified water-saving devices to aid consumers in choosing better products. By Jan. 2007, the first devices were labeled as a part of this program included high efficiency toilets that use less than 4.9 L per flush. Other products with WaterSense specifications include faucets, showerheads, and urinals. The first outdoor products eligible for the WaterSense label were ET controllers with the final specification released on Nov. 3, 2011 and the first ET controllers were officially labeled as water-saving devices in May 2012 (USEPA 2012).

The WaterSense testing specification was developed by expanding and adapting on the Irrigation Association's SWAT testing protocol. The modifications to the SWAT testing protocol include:

- Minimum of four rainfall events that exceed 2.54 mm
- Irrigation occurs before rainfall in the soil water balance
- Runtimes less than or equal to three minutes are not considered
- No more than 2 consecutive days and 3 total days of missing ET_O data in any 30-day testing period
- Backup rain gauge is only acceptable substitute for missing rainfall data

Manufacturers must become WaterSense partners, indicating a commitment to a high standard in water efficiency and performance, and work directly with an accredited certified licensing body (LCB) to have their ET controllers tested. The LCB inspects the overall production capabilities of each manufacturer to ensure products can be mass produced and available nationally. The LCB selects a single random sample from the production line after final packaging and cannot receive any additional materials to aid in interacting with the ET controller since those materials will not be available to the end user. Manufacturers must have no interaction with the product during testing.

Unlike the SWAT test, scores are counted from the first 30-day period that meets the weather requirements. The criteria for achieving the WaterSense label include:

- Irrigation adequacy score greater than or equal to 80% for every zone
- Scheduling efficiency score is greater than or equal to 90% for every zone
- Scheduling efficiency score is great than or equal to 95% averaged across zones

If these score thresholds are achieved, the LCB notifies the USEPA of the brand and model to add to the registry of WaterSense labeled devices (Table 1-10); however, quantitative score results are not made available to the USEPA or the public.

Previous Research

Multiple research studies in the forms of bench tests, plot studies, and cooperator studies have been performed in the U.S. The bench tests were conducted to determine the functionality of the ET controllers such as how the program settings determine the irrigation schedule, requirements for installation, and accuracy compared to theoretical water needs. The evaluation programs described above were performed as bench tests. Plot studies were conducted to assess the functionality as well, but to also evaluate the effect of the irrigation schedule calculated by the ET controller on actual landscapes. Cooperator studies were more complex and variable due to differences in landscapes and homeowner interactions, but were the most applicable for determining the performance of an ET controller in the real world.

Bench tests

In addition to the evaluation programs already discussed, there have been multiple bench tests performed to determine the effectiveness of ET controllers. Bench tests are good for determining the nuances of the controller model such as responses to different types of programming and irrigation scheduling techniques. However, it is impossible to determine the effects of the nuances because the test is conducted virtually where only the controller valve output signals are recorded which would result in irrigation if connected to an irrigation system.

In 2002, the Metropolitan Water District of Southern California (MWD 2004) conducted a bench test to compare irrigation scheduling of ET controllers to theoretical water needs for three types of landscapes (Table 1-11). The ET controllers selected for soil moisture depletion analyses were AquaConserve, WeatherTRAK, and Weatherset. All three controllers exhibited good performance, normally falling in the acceptable range of 30% to 70% depletion of the available water holding capacity (AWHC). However, the Weatherset controller irrigated for longer runtimes with fewer cycles per month that may have resulted in exceeding the available water holding capacity on irrigation days, causing runoff or deep percolation, and caused deficit conditions between irrigation days.

A bench test was conducted in 2003 using Aqua Conserve, WeatherSet, WeatherTRAK, and Calsense controllers (Pittenger et al. 2004) to determine the programming requirements, ease of setup and operation, and accuracy of matching irrigation needs to five types of landscapes: turfgrass, high water use mixed plantings, low water use mixed plantings, trees, and annuals. A real-time reference landscape was used to calculate ET_C for the turfgrass directly and was adapted using plant factors for the other virtual landscapes. Though all ET controllers adjusted irrigation schedules based on the ET_C trends, the magnitudes of the adjustments were not consistent. Consequently, none of the ET controllers achieved high accuracy in predicting irrigation needs for all types of virtual landscapes with the error usually resulting in too much irrigation. Programming required professional setup and monitoring with significant manual adjustments, thus making it difficult to properly program all of the controllers despite the level of technological complexity.

In 2008, Texas A&M University bench tested six ET controllers over a four-week period using the six landscapes described in the IA's SWAT protocol (Table 1-7) (Swanson and Fipps 2009). Comparisons were made to ET_O directly and irrigation recommendations provided by TexasET Network Landscape Plant Water Requirement Calculator (TexasET Network 2012). Irrigation application by the ET controllers exceeded ET_O at a frequency of 58%. Additionally, irrigation application exceeded the irrigation recommendations with 100% frequency for signal-based controllers and 75% frequency for standalone controllers with on-site sensors. All controllers failed to adequately adjust for rainfall, incorporating only 48.53% of the time for signal-based controllers and 56.25% of the time when sensed by onsite sensors.

Texas A&M University repeated testing for Year 2 on ten ET controller models tested for 13 weeks (Swanson and Fipps 2010). Over the season, only two ET controller models irrigated within the Texas recommendations with the remaining ET controllers applying 3-5 times the irrigation volumes. Over Year 2, the ET controllers exceeded ET_O 20% of the time, which is significantly less than Year 1 results, but the frequency of exceeding recommended irrigation amounts was 97% for signal-based controllers and 76% for standalone controllers which matched Year 1 results.

The third year of bench testing by Texas A&M University consisted of eight controllers tested for 34 weeks that were programmed with landscape characteristics found in Texas and not with the SWAT virtual landscapes (Swanson and Fipps 2011). Additional changes included testing two signal-based controllers with rain sensors and were no longer tested indoors. Though none of the controllers adequately met plant water requirements for the entire study period, all controllers still applied excessive amounts of irrigation during sporadic portions of the study period. However, ET controllers with onsite sensors typically performed better than signal-based controllers by applying irrigation similar to the recommendation more frequently.

In 2009 and 2010, UF-IFAS implemented a bench test to determine the reproducibility and transferability of the SWAT test if adopted for the EPA WaterSense program (Davis and Dukes 2012). Though not reproducible in the current form, UF-IFAS was able to recreate the testing software into a more understandable spreadsheet and provide training materials for future testing labs. The SWAT test was not considered transferrable due to the decreases in scheduling efficiency scores during periods of increased rainfall frequency. Some recommended changes to the SWAT test include longer testing periods, disclosing program settings with test results, and increasing the rainfall threshold.

Plot studies

Three ET controller models (Weathermatic Smartline 1600, Toro Intelli-Sense, and ETWater Smart Controller 100) were implemented on 60 m^2 St. Augustinegrass plots in southwest Florida (Davis et al. 2009; Davis and Dukes 2012). Two time-based treatments with rain sensors were also implemented to simulate UF-IFAS recommendations for Florida. The TIME treatment replaced 100% of the net irrigation requirement and the RTIME applied the same schedule with 60% replacement, both treatments restricted to two days per week. All treatments were compared to a simulated timed-based treatment without a sensor (TIME WOS) that included irrigation events bypassed by the rain sensor for the TIME treatment, which is closer to the irrigation habits of a Florida residential irrigator. Overall, the ET controllers produced 43% annual water savings with savings fluctuating throughout the year based on overall irrigation demand. The ET controllers had the highest water savings compared to TIME WOS in winter, 50%-60%, during the period of lowest irrigation demand. The least savings occurred in the spring, 9%-15%, during the highest irrigation demand.

Rainfall features for these three ET controllers were not sophisticated enough to account for localized rainfall typical to Florida (Davis and Dukes 2010). Similar to the results of the Florida SWAT test (Davis and Dukes 2012), periods of more frequent rainfall resulted in lower scheduling efficiency scores. Additionally, the values for various program settings were not available from the controller manufacturers. Therefore, it was difficult for the controllers to perform well against a soil water balance because the settings could not be matched.

A similar plot study was conducted in north Florida where the Toro Intelli-Sense and Rain Bird ET Manager ET controllers were used on 18.2 m^2 St. Augustinegrass plots using a two day per week irrigation schedule (McCready et al. 2009; Davis and Dukes 2012). Water savings were also calculated compared to a TIME WOS treatment with savings ranging from 25% during the spring to 63% during the fall. The ET Manager had an incorrect rainfall setting that caused the controller to under-irrigate in the spring, resulting in higher water savings, but at the expense of landscape quality. The researchers found that the default settings were not appropriate for all landscapes and were not representative of the study site. Programming, especially application rates, should be done by a qualified professional to maximize the benefits of using an ET controller.

Rutland and Dukes (2012) conducted a study using the Toro Intelli-Sense on 60 m^2 St. Augustinegrass plots in southwest Florida to test the effectiveness of the rainfall features used by the controller. This controller accepts a standard rain sensor as well as offers a rain pause feature that pauses irrigation for a number of days based on the depth of rainfall received. The algorithm used to calculate number of days for rain pause is proprietary and not clearly described in manufacturer documentation. Maximum water savings was achieved by combining a rain sensor and the rain pause feature, totaling 41%. Each rain feature that was independently tested achieved only 25% water savings. The rain sensor typically bypassed for localized rainfall events not sensed at the weather station(s) used by the ET controller. Conversely, the rain pause feature bypassed for longer time periods based on the amount of rainfall received whereas a rain sensor dries out within 24-48 hours (Cardenas-Lailhacar and Dukes 2008). Based on the current technology level, including rain sensors on ET controllers is preferable in Florida.

Grabow et al. (2012) reported on an evaluation of the Toro Intelli-Sense ET controller on 16 m^2 St. Augustinegrass plots planted on clay soils in North Carolina. The ET controller over-irrigated in 2007 11% compared to a time-based treatment, causing the soil water content to reach levels frequently above field capacity. They estimated that over-irrigation occurred due to high ET_O values broadcasted to the controller that averaged 30% higher than on-site calculations. Though not as drastic as the 2007 results, the ET controller over-irrigated compared to the timer treatment in 2008 as well.

Cooperator studies

A three-year study in three Colorado cities from 2000 to 2002 was conducted to determine the reliability and effectiveness of a WeatherTRAK-enabled ET controller (Aquacraft, Inc. 2002; Aquacraft, Inc. 2003). Participation included nine residences and one commercial property in 2001 with seven of the ten sites remaining in 2002. Due to voluntary participation in the program, five of the seven sites were historical under-irrigators that maintained their historical average during the study, thus resulting in no actual water savings. However, the ET controllers captured 88% (2001) and 92%

(2002) of potential water savings compared to evapotranspirative demand and was reliable in obtaining ET_O, responding to drought restrictions, and equipment durability.

In 2002, the Los Angeles Department of Water and Power assessed the performance of ET controllers by professionally installing 18 WeatherTRAK and 7 Water2Save controllers, totaling 25 sites (Bamezai 2004). Historical irrigation was determined from two years of water use prior to installation and was normalized for differences in weather during the study period. Water savings were calculated from data collected up to one year after installation. Combined, the ET controllers had 78% potential water savings compared to the theoretical irrigation demand and the water savings compared to historical irrigation application averaged 17.4% for the WeatherTRAK controllers and 28.3% for the Water2Save controllers. Although most cooperating homeowners reacted positively to the technology, education and outreach programs for landscapers and homeowners were strongly suggested.

A residential runoff reduction (R3) study was conducted in Irvine, CA to evaluate changes in water usage, dry weather runoff, water quality, and customer attitudes and awareness from implementing WeatherTRAK-enabled ET controllers or an education-only program (MWDOC and IRWD 2004). Treatments were separated into neighborhoods resulting in 112 residential and 15 commercial ET controller installations (one neighborhood), 225 homes and one school participating in the education group (one neighborhood), and the remaining three neighborhoods were selected as blind comparisons with no known changes to their irrigation practices. Each neighborhood had a single-point storm drain separate from other communities that was monitored for 12 to 18 months beginning in 2001. The educational materials consisted of postcards sent with change in weather conditions suggesting days of week and minutes per day of irrigation. Results showed that the ET controller neighborhood decreased water consumption by 156 L d^{-1} and dry weather runoff by 50% with significantly lower total nitrogen levels in runoff compared to all other treatments. The education households decreased water consumption by only 97 L d^{-1} and increased dry weather runoff during the study period.

A Las Vegas Valley study occurring over a 12 to 18 month period, ending in 2005, consisted of installing WeatherTRAK-enabled ET controllers at 17 residential sites and Rain Bird ESP timers at 10 control sites where 5 control sites received seasonal irrigation scheduling information (Devitt et al. 2008). On average, there was a 20% reduction from historical irrigation application by implementing an ET controller, which was significantly more water savings than both control groups that had no water savings, 9% increase by the control with educational programming and 2% increase by the control without educational programming.

Mayer et al. (2009) implemented a study in California that involved installing 3,112 ET controllers of varying models at residential and commercial properties through rebate and voucher programs, exchange programs, and direct installation programs. Overall, ET controllers reduced outdoor water use after one year by 6.1% compared to one year of pre-smart controller outdoor water use that was normalized for differences in weather. Though water savings were statistically significant, the resulting savings was lower than expected due to historical under-irrigators experiencing increases in irrigation application by implementing a smart controller. This indicates that smart controllers may not be applicable for broad implementation to the entire population.

Using a subset of 384 sites that had three years of data, a multi-year analysis showed that water savings increased over time from -6% after the first year to +16.4% after the third year.

Davis and Dukes (2012) performed an ET controller cooperator study in three cities located in Hillsborough County. The Toro Intelli-Sense was selected as the ET controller based on the positive results of the SWF plot study. There was a total of 21 ET controllers professionally installed and programmed by research personnel and 15 comparison homes that were representative of the area. Using only one year of data collected in 2009-2010, ET controller performance was compared to irrigation application from 15 representative comparison homes, historical irrigation application calculated from five years of billing records, and theoretical irrigation needs. The ET controllers applied significantly more monthly irrigation than the comparison groups in two locations, averaging 32 mm and 42 mm, while the comparison groups significantly decreased their irrigation application compared to their historical practices. At the third location, there were not significant differences from the comparison group, averaging 38 mm, or from the historical average. Cumulatively, the ET controllers ranged from 25.8% water savings to 1.1% increase from the historical totals over the same months. Also, the ET controllers reduced irrigation application in all locations compared to the theoretical requirement by 23.4% to 49.9%.

Table 1-1. Summary of restrictions on outdoor water use from the potable supply for each water management district

Water Management District	Restriction Days during Daylight Savings (d wk^{-1})	Restriction Days during Eastern Standard Time (d wk^{-1})	Restriction Times	Source
Northwest Florida	NA	NA	NA	NA
Suwannee River	2	1	10 am to 4 pm	SRWMD 2012
St. Johns River	2	1	10 am to 4 pm	SJRWMD 2012
Southwest Florida	2	1	8 am to 6 pm	SWFWMD 2013
South Florida	2	2	10 am to 4 pm	SFWMD 2012

Note: NA indicates that restrictions were not applicable to that district.

Table 1-2. The parameters of K and M_dS_{av} were estimated from Soil Conservation Service (1964) cylinder infiltrometer data by Chu (1978) to be used as guidelines for parameter estimates.

Soil Type	K^a (m/h)	$M_dS_{av}^b$ (m)
Clay	<0.0021	>0.061
Clay loam	0.0021 – 0.0067	0.043 – 0.0061
Silt loam	0.0067 – 0.0142	0.036 – 0.043
Sandy loam	0.0142 – 0.0247	0.027 – 0.036
Sand	>0.0247	<0.027

[a]Estimation of the hydraulic conductivity for specific soil types
[b]Initial soil moisture deficit and capillary suction at the wetting front, commonly expressed as one term

Table 1-3. Soil parameters originally put together by Rawls et al. (1982; 1983) and summarized by Ogden and Saghafian (1997).

Soil Type	Total Porosity	Effective Porosity	Residual water content	Wilting point water content	ψ_b (cm)	λ	K_s (cm/h)	H_c (cm)
Sand	0.437	0.417	0.020	0.033	7.26	0.694	23.56	9.62
Loamy Sand	0.437	0.401	0.035	0.055	8.69	0.553	5.98	11.96
Sandy Loam	0.453	0.412	0.041	0.095	14.66	0.378	2.18	21.53
Loam	0.463	0.434	0.027	0.117	11.15	0.252	1.32	17.50
Silt Loam	0.501	0.486	0.015	0.133	20.79	0.234	0.68	32.96
Sandy clay loam	0.398	0.330	0.068	0.148	28.08	0.319	0.30	42.43
Clay Loam	0.464	0.390	0.075	0.197	25.89	0.242	0.20	40.89
Silty clay loam	0.471	0.432	0.040	0.208	32.56	0.177	0.20	53.83
Sandy clay	0.430	0.321	0.109	0.239	29.17	0.223	0.12	46.65
Silty clay	0.479	0.423	0.056	0.250	34.19	0.150	0.10	57.77
Clay	0.475	0.385	0.090	0.272	37.30	0.165	0.06	62.25

Table 1-4. Warm season turfgrass crop coefficients calculated from various studies.

Month	North Florida[a]	South Florida[a]	California[b]	Las Vegas, NV[c]	Beijing, China[d]
January	0.35	0.71	0.55	0.44	NA
February	0.35	0.79	0.54	0.43	NA
March	0.55	0.78	0.76	0.67	NA
April	0.80	0.86	0.72	0.76	0.66
May	0.90	0.99	0.79	0.75	0.79
June	0.75	0.86	0.68	0.89	1.06
July	0.70	0.86	0.71	0.89	1.15
August	0.70	0.90	0.71	0.82	1.09
September	0.75	0.87	0.62	0.82	0.97
October	0.65	0.86	0.54	0.77	0.78
November	0.60	0.84	0.58	0.81	0.84
December	0.45	0.71	0.55	0.51	NA

[a]Values were found in Jia et al. (2009)
[b]Values were found in Gibeault et al. (1989)
[c]Values were found in Devitt et al. (1992)
[d]Values were found in Zhang et al. (2007)

Table 1-5. Parameters used to calculate the redistribution coefficient determined by Gowdish and Muñoz-Carpena (2009).

Iteration	b_i	c_i	d_i
1	4.2952	154.6101	-1.0
2	0.0020	-0.0010	0.5
3	-14.0032	-61.5429	-1.0

Table 1-6. Ranges of acceptable hydrological parameters for each method for calculating soil water retention curves and hydraulic conductivity curves available in the CHEMFLO-2000 model

Parameter	Symbol	Brooks and Corey (1964)		van Genuchten (1980)		Simmons et al. (1979)		Gardner (1958)	
		Min	Max	Min	Max	Min	Max	Min	Max
Residual water content	θ_r	0	0.15	0	0.15	0	0.15	NA	NA
Saturated water content	θ_s	0.25	0.60	0.25	0.60	0.25	0.60	NA	NA
Air entry value	h_b	-60.0	-1	NA	NA	NA	NA	NA	NA
Constant	λ	0.05	1.7	NA	NA	NA	NA	NA	NA
Constant	α	NA	NA	0.002	0.15	1.15	1.25	NA	NA
Constant	n	2	6	1.25	3	0.025	0.1	1.8	3.5
Saturated hydraulic conductivity	K_s	0	NA	0	NA	NA	NA	0	NA
Matric potential constant	h_c	NA	NA	NA	NA	NA	NA	-50	-5

Table 1-7. Description of virtual landscape zones used in the SWAT testing protocol (IA 2008)

Description	Units	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Soil Texture		Loam	Silty Clay	Loamy Sand	Sandy Loam	Clay Loam	Clay
Slope	%	6	10	8	12	2	20
Exposure		75% Shade	Full Sun	Full Sun	50% Shade	Full Sun	Full Sun
Vegetation		Tall Fescue	Bermuda	Ground Cover	Woody Shrubs	Trees & Ground Cover	Bermuda
Landscape Coefficient[a,b]		Varies Monthly (see Table 1-8)	Varies Monthly (see Table 1-8)	0.55	0.40	0.61	Varies Monthly (see Table 1-8)
Irrigation System		Pop-Up Spray Heads	Pop-Up Spray Heads	Pop-Up Spray Heads	Pop-Up Spray Heads	Surface Drip	Rotors
Precipitation Rate[c]	in/h	1.60	1.60	1.40	1.40	0.20	0.35
Application Efficiency	%	55	60	70	75	80	65
Gross Area	ft^2	1,000	1,200	800	500	650	1,600
Allowable Depletion	%	50	40	50	55	50	35
Available Water[a,d]	in./in.	0.17	0.17	0.09	0.13	0.18	0.17
Root Zone Depth[a,d]	in.	10.0	8.1	20.0	28.0	25.0	9.2
RZWWS[e]	in.	0.85	0.55	0.90	2.00	2.25	0.55
Soil Intake Rate[d]	in./h	0.35	0.15	0.50	0.40	0.20	0.10
Allowable Surface Accumulation[d,f]	in.	0.25	0.16	0.26	0.24	0.26	0.10

[a]Values selected based on vegetation description.
[b]Values selected based on exposure description.
[c]Values selected based on irrigation system description.
[d]Values selected based on soil texture description.
[e]Root zone working water storage (RZWWS) is calculated using the available water, root zone depth, and allowable depletion values.
[f]Values selected based on slope description.

Table 1-8. Crop coefficients for zones 1, 2, and 6 for the SWAT test (IA 2008).

Month	Zone 1	Zone 2	Zone 6
Jan.	0.41	0.52	0.52
Feb.	0.46	0.64	0.64
Mar.	0.52	0.70	0.70
Apr.	0.56	0.73	0.73
May	0.60	0.73	0.73
Jun.	0.62	0.71	0.71
Jul.	0.62	0.69	0.69
Aug.	0.60	0.67	0.67
Sep.	0.56	0.64	0.64
Oct.	0.50	0.60	0.06
Nov.	0.45	0.57	0.57
Dec.	0.40	0.53	0.53

Table 1-9. Summary results from the SWAT test.

Brand Name	Model Name	Published Date	Scheduling Efficiency (%)			Irrigation Adequacy (%)		
			Min	Max	Mean	Min	Max	Mean
ETwater	Smart Controller	9/9/05	100	100	100	93.7	100	98.5
Irritrol	Smart Dial	1/9/06	100	100	100	100	100	100
Toro	Intelli-Sense	1/9/06	100	100	100	100	100	100
Hydropoint	WeatherTRAK	1/9/06	100	100	100	100	100	100
Rain Bird	ET Manager	6/27/06	100	100	100	100	100	100
Calsense	ET2000e	4/11/07	100	100	100	100	100	100
Hunter	ET System	4/11/07	100	100	100	97.7	100	99.5
Weathermatic	SL1600	4/11/07	100	100	100	97.7	100	99.6
Alex-Tronix	Enercon Plus	5/17/07	100	100	100	96.4	100	99.0
Alex-Tronix	Smart Clock	5/17/07	100	100	100	98.9	100	99.8
Aqua Conserve	Aqua ET-9	9/10/07	100	100	100	98.7	100	99.8
Hydrosaver	ETIC	10/8/07	94.8	100	98.9	93.1	100	98.5
Cyber-Rain	XCI	4/11/08	100	100	100	79.5	100	88.4
Rain Master	RME Eagle	4/11/08	100	100	100	100	100	100
SMG Superior Controls	Sterling 8	7/15/08	79.5	100	92.9	100	100	100
Rain Bird	ESP-LX with ET Manager	5/11/09	100	100	100	95.5	100	98.5
WaterOptimizer	WaterOptimizer	5/11/09	100	100	100	100	100	100
Tucor	RKS with Tipping Rain Bucket	5/13/09	68.0	100	92.0	100	100	100
Rain Bird	ESP-SMT	6/1/09	100	100	100	93.2	100	98.5
NDS Raindrip	WeatherSmartPro	1/5/10	96.2	100	98.4	100	100	100
Alex-Tronix	Universal Smart Module	4/15/10	99.1	100	99.9	94.4	100	97.8
ETwater	Hermit Crab	3/22/11	100	100	100	100	100	100
Hunter	Solar Sync Module	3/22/11	100	100	100	87.8	100	95.7
Hunter	Solar Sync Sensor	3/22/11	100	100	100	95.4	100	98.8
Rain Bird	SST Smart Controller	4/5/11	99.0	100	99.8	97.8	100	99.3
Toro	EC-XTRA w Smart Pod	4/5/11	100	100	100	87.0	100	94.7

Table 1-9. Continued

Brand Name	Model Name	Published Date	Scheduling Efficiency (%)			Irrigation Adequacy (%)		
			Min	Max	Mean	Min	Max	Mean
Irritrol	KwikDial Climate Logic	4/20/11	100	100	100	94.4	100	97.8
Irritrol	MC48E Climate Logic	4/20/11	100	100	100	95.8	100	98.6
Irritrol	RainDial Climate Logic	4/20/11	100	100	100	98.2	100	99.4
Irritrol	Total Control Climate Logic	4/20/11	100	100	100	92.1	100	95.5
Toro	TMC-212 Climate Logic	4/20/11	100	100	100	87.7	100	94.2
Toro	TMC-424E-ID Climate Logic Kit	4/20/11	100	100	100	94.7	100	98.4
DIG	Leit 2 ET	6/21/11	99.0	100	99.7	100	100	100
Rain Master	RME Eagle Plus	6/21/11	89.5	100	95.4	96.7	100	98.9
Tucor	RKD-WS	5/9/12	96.5	100	98.9	100	100	100

Table 1-10. List of EPA WaterSense labeled ET controllers.

Brand Name	Model Name	Maximum Zone Capacity	Weather Data Source
Cyber-Rain	Pro System	16	Signal
Cyber-Rain	Standard System	16	Signal
Cyber-Rain	Long Range	24	Signal
Irritrol Rainmaster	RME Eagle	36	Signal
Rain Bird	ESP-SMT	13	Sensor
Rain Bird	Simple-To-Set	12	Sensor
Raindrip	Weather Smart Pro	6	Sensor
Toro	XTRA Smart EC-XTRA	10	Sensor

Table 1-11. Landscape descriptions adapted from MWD (2004).

Characteristic	Scenario A	Scenario B	Scenario C
Plant Type	Cool Season Turfgrass	Annuals	Acacia and Myoporum
Crop Coefficient	0.8	1.0	0.3
Root Depth (in)	4	4	12
Soil Type	Loam	Sand	Clay
Slope	Flat	Flat	>20°
Exposure	Full Sun	Shady Most of Day	Full Sun
Sprinkler Type	Pop-up Sprays	Pop-up Sprays	Rotors
Application Rate (in/hr)	1.58	1.94	0.56
Irrigation Efficiency	0.625	0.55	0.70

CHAPTER 2
PERFORMANCE OF WEATHER-BASED IRRIGATION CONTROLLERS IN SOUTHWEST FLORIDA LANDSCAPES

Introduction

In 2005, Florida ranked fourth in domestic water use trailing only California, Texas, and Michigan[*] (Kenny et al. 2009). Daily per capita indoor water use has been found to be constant across the United States with a mean of 0.262 m^3 d^{-1} (Mayer et al. 1999). Conservation programs targeted to outdoor water use should be able to achieve reductions in domestic water use in Florida, where annual rainfall averages 1,340 mm (Romero and Dukes 2013). A study in central Florida found that 64% of domestic water use was for irrigation (Haley et al. 2007). The potential for reduction in the public water supply demand by better irrigation scheduling techniques is substantial.

The Irrigation Association (IA 2008) defined smart controllers as technologies that "…estimate or measure depletion of available plant soil moisture in order to operate an irrigation system, replenishing water as needed while minimizing excess water use." One type of smart controller is the weather-based or evapotranspiration (ET) controller that determines irrigation schedules based on estimates of plant water needs determined from weather measurements. This information can be obtained in one of three ways: through satellite signal, measured on-site, or programmed with historical data (Dukes 2012).

The Municipal Water District of Orange County and Irvine Ranch Water District (IRWD) conducted a study in Irvine, CA to evaluate WeatherTRAK-enabled ET controllers compared to an education-only program (MWDOC and IRWD 2004).

[*] With permission from ASCE

WeatherTRAK ET Everywhere™ is a signal service that broadcasts estimated ET and rain pauses to the ET controller on a daily basis. Treatments were separated into neighborhoods resulting in 112 residential and 15 commercial ET controller installations (one neighborhood), 225 homes and one school participating in the education group (one neighborhood), and the remaining three neighborhoods were selected as blind comparisons with no known changes to their irrigation practices. The educational materials consisted of postcards sent that suggested days of week and minutes per day of irrigation. Results showed that the ET controller decreased neighborhood-wide water consumption by 0.156 $m^3\ d^{-1}$ whereas water consumption in the education households decreased by only 0.097 $m^3\ d^{-1}$ during the twelve to eighteen month study period.

A Las Vegas Valley study occurring over a 12 to 18 month period, ending in 2005, consisted of installing WeatherTRAK-enabled ET controllers at 17 residential sites and Rain Bird ESP timers at 10 control sites where half of the controls received seasonal irrigation scheduling information (Devitt et al. 2008). On average, the ET controller treatment reduced irrigation by 20% compared to historical irrigation application. This was the only treatment to have water savings; there was a 9% increase by the control with educational programming and 2% increase by the control without educational programming.

Mayer et al. (2009) analyzed data from 3,112 ET controllers of varying models at residential and commercial properties throughout California. Overall, ET controllers reduced irrigation use after one year by 6.1% compared to one year of pre-smart controller outdoor water use that was normalized for differences in weather. Though water savings were statistically significant, the resulting savings was lower than expected due to historical under-irrigators that had increased irrigation with the ET controllers. This result indicates that smart controllers may not be applicable for broad implementation to the entire population with the expectation of irrigation reduction. Using a subset of 384 sites that had three years of data, a multi-year analysis showed that irrigation use decreased over time from +6% after the first year to -16.4% after the third year.

In 2006-2007, a field plot study of ET controllers in southwest Florida resulted in irrigation savings of 43% compared to a time-based schedule of 100% replacement of the net irrigation requirement without a rain sensor (Davis et al. 2009; Davis and Dukes 2012). Higher water savings were seen during the fall and winter seasons with a maximum of 60% savings. However, this plot study was conducted in a controlled setting and may not translate to actual savings for homeowners. The objective of this study was to determine the effectiveness of an ET controller in real-world conditions, based on adequate performance during the field plot study.

Materials and Methods

Potential participants located in the southwest Florida communities of Apollo Beach, Riverview, and Valrico and in the top 50th percentile of water users based on a county-wide analysis completed by Romero and Dukes (2010) were solicited by a letter from Hillsborough County Water Resource Services. Potential participants were directed from the mailed letter to an online questionnaire as the primary method for volunteering for the study. Additionally, potential participants could respond to the questionnaire by phone if averse to providing personal information on the internet. Participation in the study was completely voluntary.

Thirty-six cooperators were selected across the three communities after undergoing irrigation evaluations conducted by University of Florida, Institute of Food and Agricultural Sciences (UF-IFAS). Evaluations were conducted to assess study eligibility based on the following: presence of a functional automatic irrigation system, good landscape quality, and commitment to long term participation to the study. As part of the on-site evaluation, irrigation distribution uniformity was measured in one representative zone of the landscape by the catch can test (IA 2013) using 16-24 collectors when wind conditions were low and soil moisture measurements from a FieldScout TDR 300 (Spectrum Technologies, Inc.) when soil moisture was below field capacity.

Cooperators were separated into two treatment groups: 21 cooperators were outfitted with Toro Intelli-Sense™ TIS-612 (Riverside, CA) ET controllers (ET treatment) that used WeatherTRAK ET Everywhere™ signal service (Hydropoint DataSystems, Inc., Petaluma, CA), and the remaining 15 formed a comparison group with no added technology. In addition to ET controllers, rain sensors were installed on the ET treatment homes. The Intelli-Sense™ (Toro Company, Riverside, CA) was chosen as the ET controller based on results from a field plot study also conducted in southwest Florida (Davis et al. 2009; Davis and Dukes 2012).

The ET Everywhere™ signal service provided reference evapotranspiration (ET_O) and rainfall information to the Intelli-Sense that required an annual subscription. According to the manufacturer, daily ET_O and rainfall information were interpolated by modeling software using data collected at multiple off-site weather stations triangulated in proximity to the controller location (The Toro Company 2011). The ET Everywhere™

signal service used the American Society of Civil Engineers ET_O equation (ASCE 2005) for calculating ET_O and required multiple weather parameters including temperature, relative humidity, solar radiation, and wind speed.

We programmed the ET controllers using the landscape and irrigation system information obtained during the irrigation evaluation. Most settings were chosen based on descriptions, thus using default values, except for application rates that were customized by zone and irrigation system efficiency that were based on measured lower half distribution uniformity (DU_{lh}) values (IA 2005) based on the catch-can test results. Cooperators that received the ET controller also received exemptions from day-of-the-week watering restrictions. The ET controllers were programmed to allow irrigation with a 12 am to 6 am water window unless otherwise specified by the cooperator.

Automatic meter reading (AMRs) devices (FIREFLY, Datamatic, LTD., Plano, TX) were installed on household water meters in January 2009 and collected sub-hourly water meter data through January 2011. The AMRs were equipped with an optical sensor that attached to the face of the water meter to record every sweep of the dial, signifying 0.038 m^3 of water consumption. Indoor water use was separated from irrigation by removing any water accumulated for a single sub-hourly time period that was less than the minimum volume capable by the irrigation system which was determined during the initial irrigation system evaluation. The average per capita indoor water use for the cooperators ranged from 0.054 m^3 d^{-1} to 0.530 m^3 d^{-1}, averaging 0.260 m^3 d^{-1}, which matches the average that was found in a U.S. study covering twelve cities (Mayer et al. 1999).

Irrigation was converted from volume to depth using an estimated irrigated area. In the initial analysis presented in Davis and Dukes (2012), property appraiser landscape square footage totals were used as estimated irrigated areas for all cooperating homes. However, established ornamental plants do not require irrigation in southwest Florida to maintain acceptable quality (Schieber et al. 2008; Gilman et al. 2009) allowing for decreases from total landscape area to turfgrass area only. The percentage of turfgrass was estimated visually during the irrigation evaluation. Additionally, the cooperators in Riverview were not traditionally landscaped with parts of the properties left as natural, non-irrigated areas. As a result, all property borders were redefined using Geographical Information Systems (GIS) to determine more accurate irrigated areas. The adjusted turfgrass area estimates in Riverview resulted in higher irrigation depths. New area estimates using GIS in the other two locations resulted in relatively no change in estimations. The presented results were calculated from areas found using GIS for the Riverview location and property appraiser areas for the other two locations.

Historical irrigation use (2001 to 2009) was determined for each cooperator from total metered data provided by the regional water wholesaler, Tampa Bay Water. Irrigation water use was estimated for this period by subtracting the estimated average monthly indoor estimate from the sub-hourly AMR data during the study period from the total metered values. This method assumes that indoor water use generally remains constant throughout the year (Dziegielewski and Keifer 2010).

Additional comparison homes were identified and billing records from 2001 to 2011 were obtained for 46 neighbors with comparable landscapes to the ET controller treatment. There were 3-5 neighbors identified for every cooperator that received an ET controller. Neighbors were chosen if residing on the same or immediately adjacent street, similar size of irrigable area, and had an acceptable landscape quality. These billing records were included as additional comparisons in the C+E treatment. Sub-daily water meter data was not available for these homes; instead, indoor water use was assumed as the calculated average of 0.260 m^3 d^{-1} and 2.59 persons per household obtained from the 2007-2011 American Community Survey for Hillsborough County, FL (United States Census Bureau 2013). Using these assumptions, indoor water use totaled 20.2 m^3 mo^{-1}, which was similar to the average monthly volume of 20.4 m^3 mo^{-1} calculated from the AMR data. The method of using billing records, assumed indoor water use, and property appraiser data for estimating irrigation was used by Friedman et al. (2013).

The GIR was used as a comparison for irrigation application by the treatments over the study period. The GIR is an estimate of theoretical irrigation needs calculated by multiplying the net irrigation water requirement (IWR_{net}) by a scheduling multiplier (SM). The IWR_{net} is defined as the amount of irrigation required to increase soil water storage to the maximum water level that can be stored before gravitational drainage (IA 2005). The IWR_{net} was determined from mass conservation of soil water content (IA 2005).

$$IWR_{net} = PWR - R_e \tag{2-1}$$

The PWR is the plant water requirement (mm) and R_e is effective rainfall (mm). The IWR_{net} was accumulated daily, but was applied only on days when the soil water level fell below management allowable depletion (MAD), taken as 50% of the available water holding capacity determined for each soil type from the soil survey map for Hillsborough County (National Resource Conservation Service 1989). Values for the available water holding capacity ranged from 23 mm to 28 mm per 305 mm of soil, which was the assumed root zone for turfgrass. Once IWR_{net} was applied, the soil water level increased to the maximum storage capacity and IWR_{net} was reset to zero. Deep percolation and surface runoff, also typically part of the soil water balance, were considered negligible since deep percolation and runoff can be avoided with proper design and management of the irrigation system. The PWR is the amount of water necessary to maintain healthy plant material (IA 2005). The PWR is calculated as the plant-specific evapotranspiration (ET_C) for any given plant material by applying a crop coefficient (K_C) using Equation 1-28 (Allen et al. 1998). The K_C values for turfgrass ranged monthly from 0.45 (December through February) to 0.90 (May) based on the location of the field study (Jia et al. 2009). It was assumed that established ornamental plants did not require irrigation in southwest Florida (Schieber et al. 2008; Gilman et al. 2009) thus using turfgrass K_C values was appropriate for this analysis. The ET_O is reference ET calculated using Equation 1-13 (ASCE 2005). Effective rainfall was limited to the portion of total daily rainfall that caused the soil water level to reach the maximum soil storage capacity after PWR was taken into account. Rainfall that exceeded the soil storage capacity was considered lost due to surface runoff or deep percolation.

Weather data were collected from three weather stations installed in the communities associated with the study. The weather stations were equipped to provide temperature, relative humidity, solar radiation, and wind speed at 15 minute intervals to calculate ET_O. Weather station distances from the cooperating homes varied but were not greater than 4 km. Weather stations were also equipped with rain gauges to determine rainfall totals. Two additional rain gauges were added to ensure rainfall measurements occurred within 500 m of all cooperating homes. Historical weather data was collected from two Florida Automated Weather Network (FAWN) stations located in the communities of Balm and Dover within Hillsborough County, FL. When data was available for both stations, ET_O and rainfall values were averaged.

The SM was determined using an approximation of the lower half distribution uniformity (DU_{lh}) from the lower quarter distribution uniformity (DU_{lq}) determined from catch-can tests using Equation 1-30 (IA 2013). The measured DU_{lq} for all 36 cooperating homes ranged from 0.45 to 0.79. There was no discernible pattern to distribution uniformity values of homes assigned to specific treatments indicating that treatment results were not biased based on this factor. The average DU_{lh} of 0.80 obtained from on-site irrigation evaluations was assumed as the average efficiency for all 46 neighbors that did not receive evaluations.

Turfgrass quality ratings were taken a minimum of every three months using National Turfgrass Evaluation Program (NTEP) procedures (Shearman and Morris 1998). The rating scale ranged from 1 to 9, where 1 represents dead turfgrass or bare ground, and 9 represents the highest possible quality and 5 was the minimal level for acceptable landscape quality. A baseline turfgrass quality rating was taken prior to the implementation of treatments to determine the change in quality during the study period. Turfgrass quality was judged primarily based on color and density. Though turfgrass quality can be affected by factors other than irrigation, the practice of assessing turfgrass quality as a way to validate that the decline in quality was not due to irrigation has been used in multiple peer-reviewed studies (Cardenas-Lailhacar and Dukes 2012; Davis et al. 2009; Davis and Dukes 2012; Haley et al. 2007; Haley and Dukes 2012).

Of the 21 cooperators that received ET controllers as a part of the study, there were 15 respondents to a post-study survey concerning their opinion of the technology and how it affected their irrigation system and landscape. The survey was administered online using the same methods employed for the sign-up questionnaire. There were approximately twenty questions that addressed various topics such as their knowledge of the functionality of the controller, overall satisfaction with performance, and likelihood of continuing to use the controller.

Statistical analyses were performed using Statistical Analytical Systems (SAS) software (Cary, NC). Irrigation applied and turfgrass quality were analyzed using the glimmix procedure in which irrigation application required a log transformation, and comparisons were made using the least mean square differences by treatment and location. Significance was determined at a 95% confidence level.

Results and Discussion

The annual ET_O, averaging 1,483 mm for the two-year study period, was not significantly different from the previous nine years of annual ET_O, averaging 1,423 mm (Table 2-1). Rainfall was significantly lower during the study period with an annual average of 1,210 mm, compared to the previous nine years average of 1,306 mm. Rainfall during the study period was the second lowest observed year from the years of data analyzed. A severe drought was declared by the U.S. Geological Survey from 1998 to 2002 (Verdi et al. 2006), which includes the period of lowest annual rainfall observed. Given that annual rainfall was significantly less than the average and the only other period with less rainfall was under drought conditions, the study period was considered a dry period. However, the frequency of rainfall events, averaging 112 events per year, was not different from the historical average of 117 events per year.

Total irrigation applied varied across the treatment areas with significance in the statistical model based on location (P-value < 0.0001) and location by treatment (P-value = 0.0001) effects. Irrigation application by the ET treatment, averaging 38 mm mo^{-1}, was significantly less than the comparison treatment that averaged 51 mm mo^{-1} in Apollo Beach (Table 2-2). In contrast, the ET treatment in Riverview applied significantly more than the comparison treatment, 36 mm mo^{-1} compared to 24 mm mo^{-1} respectively. Results were not significantly different in Valrico where the ET treatment applied 41 mm mo^{-1} and the comparison treatment applied 36 mm mo^{-1} during the study period.

The average monthly gross irrigation requirement (GIR) varied across the study locations from 51 mm to 65 mm depending on soil type and irrigation DU_{lh} measured at each cooperating home (Table 2-2). Only the Apollo Beach comparison homes had no significant difference between irrigation application (51 mm mo^{-1}) and the GIR (53 mm mo^{-1}). As a result, comparison homes in this location applied 3% more than the GIR over the study period (Table 2-3), which was a negligible increase considering the monthly averages. All other treatments had significantly less irrigation application than their respective GIR, with differences of 23% to 57%, indicating deficit irrigation conditions during the study period.

The historical average irrigation calculated from 2001 to 2008 ranged from 46 mm mo^{-1} in Riverview to 70 mm mo^{-1} in Apollo Beach (Table 2-2). All treatments applied significantly less irrigation than their historical average with cumulative reductions ranging from 23% to 48% (Table 2-4). Reductions in average irrigation application by comparison treatments in all three communities indicated that there was a fundamental change in irrigation habits, but the reason is unknown.

Many possibilities exist for this fundamental change that may include any combination of: the decline in economic conditions causing more efficient water use practices, well-publicized drought conditions in the area, or initial homeowner interaction with researchers that included suggested maintenance fixes that turned cooperator attention to the irrigation system. Irrigation was influenced by drought conditions due to temporary extreme irrigation restrictions (4 hours only, 1 d wk^{-1}) that were in place from Apr. 3, 2009 through Jun. 30, 2009. It is possible that the perception of the drought and increased watering restrictions during spring 2009 could have promoted deficit irrigation practices at the beginning of the study and a shift in priorities from high landscape quality to reducing water use. The ET controller homes were exempt from day of the week restrictions but were asked to change their irrigation start times to correspond with the water window of the comparison homes. Despite the possibility for effects due to researcher interaction, typical interaction with the cooperators in the comparison treatment occurred only once during the initial evaluation in 2008 and this extreme of a response (significant decline from historical average) was not observed in other homeowner cooperative studies (Haley et al. 2007; Haley and Dukes 2012).

The comparison treatments historically over-irrigated in Valrico and Apollo Beach when compared to the GIR. The historical irrigation of the ET treatment homes in these two locations were not different from the GIR indicating that they were already irrigating similarly to plant water needs. Despite acceptable irrigation practices, the addition of the ET controller further decreased their monthly average irrigation application. Additionally, water savings of 24% occurred in Apollo Beach (Table 2-3). Irrigation on ET homes in Valrico was not significantly different than their respective comparison treatments. In Riverview, the cooperators in both treatments were already historical under-irrigators compared to the GIR. The most significant reduction in historical irrigation from GIR occurred by the comparison treatment in Riverview with an additional significant decrease in irrigation over the study period from the historical average. Due to this significant reduction, ET controllers resulted in a 54% increase in irrigation relative to the comparison treatment. Despite this increase, significant reductions in average irrigation from historical averages occurred by using an ET controller (Table 2-2).

It was determined that the cooperators in Riverview and the ET controller treatments in Apollo Beach and Valrico historically maintained or applied less than the GIR, thus were not considered over-irrigators prior to the start of the study. It was not the intention to have under-irrigating cooperators in the study due to the limitations of potential water savings as a result of imposed treatments. These three locations were initially selected due to identifying a large number of potential participants in the top 50th percentile of water users compared to other communities in the county (Romero and Dukes 2010). However, Romero and Dukes (2010) showed that utility customers who meet these criteria may still under-irrigate compared to GIR determined for well-watered conditions.

In Valrico, the turfgrass quality of the comparison homes averaged 5.1 whereas the ET controller group was able to maintain a significantly better turfgrass quality rating, averaging 7.4 (Table 2-2). Despite significant differences in turfgrass quality, average monthly irrigation application by each treatment was not significantly different. This may indicate that the ET controllers were more effective at applying irrigation when necessary based on plant water needs rather than using a rigid day-of-the-week restricted schedule. However, irrigation application in Apollo Beach by the comparison treatment was higher than its corresponding ET treatment with no difference in turfgrass quality, averaging 5.7. Thus, this observation was not conclusive and could be due to other uncontrolled factors affecting a landscape such as fertilizer application and pest management differences inherent in a “real world” study.

Turfgrass quality ratings in Riverview were not different and were well above the acceptability threshold of 5, averaging 6.0 and 6.7 for the comparison and ET treatments, respectively (Table 2-2). The decline in irrigation application in Riverview failed to negatively impact turfgrass quality despite a noticeable decrease in irrigation application by both treatment groups. The comparison group consisted of only three cooperators who did not have the full-sun landscapes common to many planned development communities in Florida. These homes had established, tree-covered landscapes that would have contributed to lower irrigation and acceptable quality ratings. High water tables could have been present at two of the homes; one home continually experienced periods of poor drainage, with standing water in the vegetated culvert, and another home was located along a creek. As a result, turfgrass quality was unaffected by the decline in irrigation application during the study period.

Changes in irrigation behavior due to implementing an ET controller caused a reduction of 23% to 34% compared to the historical average (Table 2-4). These reductions were generally less than the water savings observed in field plot studies conducted in central and southwest Florida that showed 25%-63% seasonal savings (McCready et al. 2009) and 43% annual savings (Davis et al. 2009). Although the cooperators ultimately had complete control over the ET controllers and were not in a managed research environment, these cooperators received complimentary site-specific adjustments of their ET controllers from UF-IFAS when requested without relying on irrigation contractors or other technical support options. If this service had not been provided, the reductions might have been even less substantial. These results suggest that implementing ET controllers in the real world without considering previous irrigation habits may result in lower water savings than expected.

Given the deficit irrigation of the comparison homes, we were concerned that the small sample size could be misrepresenting irrigation practices of “typical” homes in the study areas. Thus, additional homes in close proximity to cooperators in the ET treatment that exhibited comparable landscapes were analyzed from billing records as additional cooperators in the comparison treatment, creating the “comparisons plus estimations” treatment. This additional group was created to assess the potential bias of the small number of comparison homes that were recruited for this study. Using these new observations, average irrigation for the comparison treatment in Apollo Beach declined from 51 mm mo^{-1} to 39 mm mo^{-1} whereas the comparison treatment in Riverview increased from 24 mm mo^{-1} to 33 mm mo^{-1} (Table 2-5). Average historical irrigation application declined in all three locations with cooperators in Apollo Beach, averaging 47 mm mo^{-1}, and Riverview, averaging 39 mm mo^{-1}, applying significantly less than the GIR in those locations (59 mm mo^{-1} for Apollo Beach and 60 mm mo^{-1} for

Riverview). Despite the reduced historical averages, irrigation application during the study period was still significantly less than the GIR and historical averages, further reinforcing the fundamental change in irrigation habits during the study period that was originally observed with the initial comparison homes. In Valrico, the comparison plus estimations treatment group irrigated more than the comparison treatment group, averaging 43 mm mo^{-1}, which was significantly different from both updated averages of the GIR and the historical average. There were no differences in irrigation application between the comparison plus estimations group and ET controller treatments in any location during the study period despite significant decline in irrigation application compared to the historical average for the ET treatment.

Fifteen of the 21 cooperators with ET controllers participated in a post-test survey concerning their experiences. There were two respondents (13%) that were unable to identify the name of the smart technology installed at their home based on multiple-choice answers. Of these two respondents, one indicated that they were unsure of the name of the technology, but knew they were using a smart controller and one indicated that they were unaware of a smart technology at their home at all.

The respondents were asked questions to determine if they understand the basis of the ET controller technology. When asked to select the major influence to determining irrigation runtimes by an ET controller, 80% correctly selected weather conditions whereas three respondents (20%) incorrectly thought that ET controllers were based on soil moisture. The two respondents who were unable to identify an ET controller installed at their home were also a part of the 20% that made this incorrect choice. The respondents were also asked about their trust in the ET controller and whether they felt comfortable interacting with the technology. Twelve respondents (80%) trusted that the ET controller irrigated properly and 11 respondents (73%) felt that they could make changes to the controller settings. Two of the three respondents that did not trust the ET controller also responded with lack of trust of rain sensors indicating that the respondents were possibly leery of overall irrigation automation.

To determine overall satisfaction from using an ET controller, respondents were asked about their satisfaction with their irrigation system, landscape, and specifically about their controller. All respondents were indifferent, somewhat satisfied, or extremely satisfied with their irrigation practices, which included the use of an ET controller. More specifically, all respondents rated the performance of the ET controller on a 1 to 5 scale as a 3 or higher except for one respondent who also indicated extreme dissatisfaction with their landscape appearance. This one respondent was also the only cooperator that provided a negative answer when asked if the irrigation system was adequately irrigating the landscape. Communication with the cooperator that responded as extremely dissatisfied occurred throughout the study period where the cooperator was convinced that the controller did not apply irrigation at all. Their irrigation system and ET controller were checked multiple times for functionality and their sub-daily water data was verified through manual meter readings to ensure irrigation was occurring. The most prevalent issue with turfgrass quality was weed management, which cannot be fixed by using a smart controller. There were 12 respondents (80%) that indicated they were at least somewhat satisfied with their landscape appearance with the remaining respondents indicating some dissatisfaction and indifference.

Overall, a majority of the cooperators were satisfied with the ET controller and felt it maintained their irrigation scheduling practices or improved them. Eleven cooperators (73%) responded that they plan to continue using the ET controller and eight of those respondents planned to pay the annual $48 signal fee for the ET Everywhere™ service. The remaining seven respondents planned to switch the controller to a basic time clock with user-selected runtimes instead of paying the fee.

Despite the relatively dry conditions and the design of an ET controller to maintain well-watered conditions, the ET controllers decreased outdoor water use compared to the historical trends. The comparison treatment also reduced water use from historical trends, but the comparison homeowners accomplished reductions manually whereas the ET controller performed automatically and without water restrictions. An ET controller should produce significant savings if used by a homeowner who historically irrigated more than 576 mm yr^{-1} in this region. This value was estimated from annual historical irrigation of the ET controller treatment that had the lowest average irrigation application and was significantly less than the historical average (Table 2-2). Based on the results of this study, cooperators historically irrigating similarly to or more than GIR in southwest Florida with a minimum annual estimate of 696 mm (based on the minimum estimate of 58 mm mo^{-1}) would produce substantial irrigation savings using the Intelli-Sense™. Other brands of ET controllers use their own proprietary algorithms for scheduling irrigation that may have different performance. However, most of the cooperators in this study only irrigated a fraction of the gross requirement on average.

ET controllers are designed to maximize efficient irrigation for landscapes without sacrificing quality in the name of water conservation. Mayer et al. (2009) found that homes already irrigating less than GIR saw an increase in irrigation application when implementing a smart controller, whereas those irrigating more than GIR saw a significant decrease in irrigation application. In this study, irrigation savings were not as significant due to cooperators who did not necessarily irrigate more than GIR prior to the study.

Conclusions

When irrigation above the estimated GIR is typical this study showed that ET controllers have the potential for water conservation in Florida. Irrigation applied was 23%-41% less than GIR and 23%-34% less than the historical average irrigation. Irrigation amounts applied by the ET controllers were adequate to maintain good landscape quality.

Homeowners who already irrigate less than GIR (i.e. well-watered conditions) or accept declines in landscape quality on a regular basis will not benefit from using an ET controller in terms of water savings. In fact, their irrigation use may increase with an ET controller. However, homeowners who set their time clocks to a peak irrigation schedule without updating the controller settings throughout the year may see significant reductions in irrigation by implementing an ET controller, specifically during the fall and winter seasons. In southwest Florida, an Intelli-Sense™ would be recommended for residential properties that irrigate at least the GIR and would produce significant savings if irrigating more than 696 mm annually. Adequate performance by other ET controllers may occur at different thresholds due to the variability in irrigation scheduling techniques across brands.

Proper controller programming was essential to achieving maximum water savings while maintaining acceptable landscape quality. Although the cooperators ultimately had complete control over the ET controllers, their primary interaction with UF-IFAS through the study period was to receive complimentary programming adjustments. If this service had not been provided, any lasting effect of the ET controllers may have been less substantial.

If irrigation was conservative prior to ET controller implementation, the ET controller increased irrigation. In addition to seeing this trend in the cooperator study, this conclusion was also found by Mayer et al. (2009), in which the sites already irrigating less than the GIR did not experience water savings with an ET controller. Other smart irrigation technologies that do not increase existing irrigation, such as soil moisture sensors, would be more appropriate in that situation.

Table 2-1. The ET_O and rainfall for the historical time period (2001-2009) and the study period (2009-2010).

Period	ET_O (mm)	Rainfall (mm)	Days with Rainfall
2001	1,436	764	82
2002	1,388	1,425	154
2003	1,318	1,334	132
2004	1,438	1,900	114
2005	1,401	1,764	141
2006	1,481	1,499	112
2007	1,519	1,393	116
2008	1,453	1,261	117
Historical Average	1,423 *a*	1,306 *a*	118 *a*
2009	1,471	1,280	117
2010	1,495	1,141	107
Study Period	1,483 *a*	1,210 *b*	112 *a*

Note: Values followed by different letters within the same columns are different at the 95% confidence level.

Table 2-2. Average monthly irrigation application from February 2009 through January 2011 as compared to average monthly historical irrigation and average gross irrigation determined using Equations 2-1 and 2-3.

Location	Treatment[a]	Number of Homes	Irrigation Application[b] (mm mo^{-1})	Gross Irrigation Requirement (mm mo^{-1})	Historical Irrigation Application (mm mo^{-1})	Turfgrass Quality[c]
Apollo Beach	C	6	51 *c*	53 *c*	70 *a*	5.7 BC
	ET	7	38 *d*	58 *bc*	60 *b*	5.6 BC
Riverview	C	3	24 *e*	57 *b*	46 *c*	6.0 ABC
	ET	5	36 *d*	65 *a*	48 *c*	6.7 AB
Valrico	C	6	36 *c*	51 *b*	62 *a*	5.1 C
	ET	9	41 *c*	58 *ab*	60 *a*	7.4 A

[a]Labels of C and ET represent the comparison treatment and ET controller treatment, respectively.
[b]Values within each location followed by lowercase letters are different at the 95% confidence level;
[c]Values followed by uppercase letters are different at the 95% confidence level.

Table 2-3. Cumulative irrigation application over the 2009-2010 study period as compared to cumulative gross irrigation requirement calculated using Equations 2-1 and 2-3.

Location	Treatment	Cumulative Irrigation (mm)	Difference from C (%)	Cumulative Gross Irrigation Requirement (mm)	Difference from Gross Irrigation Requirement (%)
Apollo Beach	C	1,166	0	1,132	3
	ET	891	-24	1,240	-28
Riverview	C	531	0	1,225	-57
	ET	820	54	1,395	-41
Valrico	C	830	0	1,086	-24
	ET	950	14	1,238	-23

Note: Labels of C and ET represent the comparison treatment and ET controller treatment, respectively.

Table 2-4. Cumulative irrigation application as compared to cumulative historical irrigation application calculated from 9 years of billing data, when available.

Location	Treatment	Cumulative Irrigation (mm)	Cumulative Historical Irrigation (mm)	Difference from Historical (%)
Apollo Beach	C	1,166	1,580	-26
	ET	891	1,350	-34
Riverview	C	531	1,013	-48
	ET	820	1,068	-23
Valrico	C	830	1,397	-41
	ET	950	1,338	-29

Note: Labels of C and ET represent the comparison treatment and ET controller treatment, respectively.

Table 2-5. Average monthly irrigation application from February 2009 through January 2011 as compared to average monthly historical irrigation and average gross irrigation where additional cooperators were added to the comparison treatment through billing records.

Location	Treatment[a]	Number of Homes	Irrigation Application[b] (mm/month)	Gross Irrigation Requirement (mm/month)	Historical Irrigation Application (mm/month)
Apollo Beach	C+E	18	39 *c*	59 *a*	47 *b*
	ET	7	38 *c*	58 *a*	60 *a*
Riverview	C+E	13	33 *d*	60 *a*	39 *c*
	ET	5	36 *cd*	65 *a*	48 *b*
Valrico	C+E	30	43 *d*	50 *c*	52 *bc*
	ET	9	41 *d*	58 *ab*	60 *a*

[a]Labels of C+E and ET represent the comparison plus estimations treatment and ET controller treatment, respectively.
[b]Values within each location followed by different letters are different at the 95% confidence level.

CHAPTER 3
IMPLEMENTING SMART CONTROLLERS ON SINGLE FAMILY HOMES WITH EXCESSIVE IRRIGATION

Introduction

Previous research has shown that at least half of total household water use goes toward irrigation when homes have automatic irrigation systems. In Nevada, Devitt et al. (2008) found that outdoor water use was 66% of total water used at 27 residential sites. Similar results were also found in central Florida where 64% of the total household water use was irrigation (Haley et al. 2007). When faced with potential population growth, limited water resources, and installation of automatic irrigation systems becoming the standard practice, efficient automatic irrigation has become increasingly important.

Smart controllers are technologies designed to adjust or override irrigation based on weather or soil conditions thus limiting over-irrigation (Dukes 2012). Based on the current products available on the market, smart controllers include weather-based irrigation controllers, or evapotranspiration (ET) controllers, and soil moisture sensor (SMS) controllers. Though there are many variations, ET controllers typically use weather information, user-selected program settings, and proprietary algorithms to determine the irrigation schedule instead of relying on manually selected runtimes. Soil moisture sensor controllers bypass irrigation events when the measured soil moisture is greater than a threshold, generally selected based on available water holding capacity.

A cooperator study conducted in Pinellas County, FL using Acclima TDT RS500 (SMS treatment) showed reductions in irrigation application of 65% after 26 months compared to homes with typical automatic irrigation systems. Additional treatments of automatic irrigation system with rain sensor and automatic system with rain sensor and educational materials did not have statistically significant reductions.

Recent research has shown that smart technologies are most effective for homeowners that have excessive irrigation. A two year study in Colorado showed no water savings due to five of the seven cooperators being historical under-irrigators (Aquacraft, Inc. 2002; Aquacraft, Inc. 2003). Mayer et al. (2009) found only 6% water savings from 3,112 ET controllers in California using one year of pre-installation to one year of post-installation. When further breaking down the analysis, 42% of the participants were historical under-irrigators that experienced increased irrigation application as a result of the technology thus decreasing overall savings. Davis and Dukes (in press) recommended that the Toro Intelli-Sense ET controller would be appropriate for homeowners with average irrigation totals greater than 696 mm annually in southwest Florida.

As evidenced by previous research studies, smart controllers are most effective at water conservation when implemented by historical over-irrigators. However, relying on volunteers that may have conservative irrigation tendencies prior to study participation can dampen the impact of smart controllers when targeted to the correct audience. The objective of this study was to determine the water conservation potential of implementing smart controllers on single family homes with excessive irrigation in Orange County, FL.

Materials and Methods

Participant Selection

Historical monthly water billing records were provided by Orange County Utilities for all single-family residential accounts in their service area over a seven-year period.

Since actual indoor water use was unknown prior to the study period, it was estimated using the per capita method (Mayer et al. 1999) with the assumptions of 0.25 m^3 d^{-1} per person and 2.25 persons per account (U.S. Census Bureau 2009), totaling 16.9 m^3 mo^{-1}. This method is frequently used to separate indoor and outdoor water uses when only total account data area available (Friedman et al. 2013; Mayer et al. 1999; Romero and Dukes 2013; Davis and Dukes, in review).

Estimated irrigation was evaluated against monthly gross irrigation requirement (GIR) totals determined from a daily soil water balance, thus creating monthly landscape irrigation ratios (LIR) (Davis and Dukes, in review). Frequent LIR values greater than 1 indicate over-irrigation practices whereas frequent LIR values less than 1 indicate under-irrigation practices. Accounts with LIR values that were greater than 1.5 for at least 3 months per year for three consecutive years were considered over-irrigators. The threshold of 1.5 was chosen to account for the variability inherent in the assumptions used for the calculations and to increase the probability to identifying customers with excessive irrigation.

The 7,408 accounts that met the criteria as an excessive irrigator were solicited by Orange County Utilities through a mailed letter to respond via an on-line questionnaire provided by University of Florida-Institute of Food and Agricultural Sciences (UF-IFAS). There were 843 unique responses to the solicitation letter.

To aid in participant selection, irrigation system evaluations were performed in geographic areas with many respondents to increase the likelihood of meeting the statistical requirements for treatment replications while minimizing spatial variability. Irrigation systems were checked for functionality and problems were reported to the homeowner. Due to the large number of evaluations required for this study, visual inspections of irrigation system efficiency were substituted for quantitative distribution uniformity measurements.

Treatment Description

A total of 167 participants were selected in nine locations across Orange County, FL (Table 3-1). Five treatments were replicated four times in each location except for three locations where securing 20 participants was not a viable option. The Keene's Pointe location had only three replications of one treatment (19 participants).   Only three of the five treatments were implemented in Apopka (13 participants) and North Tanner Road (15 participants) locations to maintain sufficient replications.

Of the five treatments, four treatments included the addition of an irrigation technology to the already existing irrigation system. Two treatment groups received ESP-SMT ET controllers (Rain Bird Corporation, Azusa, CA) and two treatment groups received WaterTec S100 SMSs (Baseline Inc., Boise, ID). Two treatments, one for each technology, were installed using methods determined solely by the installing contractor without UF-IFAS intervention. The remaining two technology treatments included UF-IFAS training for the contractor prior to installations, site-specific programming of the smart technology, and cooperator education of the technology installed at their home. All participants that received a technology also received a variance for day-of-the-week water restrictions. The final treatment was a comparison treatment that did not receive interventions to their normal irrigation practices.

Data Collection and Analysis

Weather data were collected from three weather stations installed by UF-IFAS in the communities of Hunters Creek, Keene's Pointe, and Waterford Lakes. Weather data for the cooperators in Apopka were collected from the Florida Automated Weather Network (FAWN) weather station located at the Mid-Florida Research and Education Center in Apopka, FL. The weather stations provided temperature, relative humidity, solar radiation, and wind speed at fifteen minute intervals. Weather stations were also equipped with rain gauges to measure rainfall totals. Maximum distances between the representative station and cooperating homes was 10.8 km. Two rain gauges monitored by UF-IFAS and one rain gauge monitored by Orange County Utilities were used to better approximate rainfall in Turtle Creek, Waterford Lakes, and North Tanner Road locations. Historical average rainfall and ET_O were determined using thirty years of data (1980-2010) from a weather station located at the Orlando International Airport (NCDC 2009).

All 167 participants received E-Coder R900i (Neptune Technology Group, Inc., Tallassee, AL) flow meters installed on dedicated irrigation lines. These flow meters had automatic meter recording (AMR) capability built into the meter that recorded irrigation volumes per hour throughout the study. The minimum volume recognized by the meter was 379 cm^3. Volumes were converted to depth of irrigation applied using irrigated areas measured during the initial on-site evaluation.

Turfgrass quality ratings were taken seasonally using National Turfgrass Evaluation Program (NTEP) procedures (Shearman and Morris 1998). The rating scale ranged from 1 to 9, where 1 represents dead turfgrass or bare ground, 9 represents the highest possible quality, and 5 was the minimal level for an acceptable single-family landscape. Turfgrass quality was judged primarily based on color and density.

Statistical analyses were performed using Statistical Analytical Systems (SAS) software (Cary, NC). Irrigation application and turfgrass quality were analyzed using the glimmix procedure and comparisons were made using the least mean square differences by treatment, soil type, and season. Significance was determined at a 95% confidence level. The study was conducted from Nov. 2011 through Aug. 2013.

Gross Irrigation Requirement

The GIR, an estimate of theoretical irrigation needs calculated using a daily soil water balance, was used as a comparison to irrigation by the treatments in this study. The GIR was calculated by multiplying the net irrigation water requirement (IWR_{net}) by a scheduling multiplier (SM). The IWR_{net} is defined as the amount of irrigation required to increase soil water storage to field capacity (FC), or the maximum water level that can be stored before gravitational drainage (IA 2005). The IWR_{net} was determined from mass conservation of soil water content using equation 2-1 (IA 2005). The PWR is the plant water requirement (mm) and R_e is effective rainfall (mm). The IWR_{net} was accumulated daily, but was applied only on days when the soil water level fell below management allowable depletion (MAD), calculated as 50% of the difference between FC and permanent wilting point (PWP) where PWP is the water level where plants can no longer extract water from the root zone (IA 2005). The PWP and FC were selected as 9 mm and 52 mm (43 mm available water) for the locations classified as flatwoods soils and 9 mm and 33 mm (24 mm available water) for the locations classified as sandy soils (USDA 1989a, USDA 1989b). Both PWP and FC were calculated based on a root zone depth of 305 mm for turfgrass. Once IWR_{net} was applied, the soil water level increased to field capacity and IWR_{net} was reset to zero. Deep percolation and surface runoff, also typically part of the soil water balance, were considered negligible since deep percolation and runoff can be avoided with proper design and management of the irrigation system.

The PWR equals the amount of water necessary to maintain healthy plant material (IA 2005) and was calculated as the plant-specific evapotranspiration (ET_C) using Equation 1-28 (Allen et al. 1998). Reference evapotranspiration (ET_O) is the estimated evapotranspiration of a short reference crop assumed to be a dense, well-watered, cool-season turfgrass maintained at a 0.12 m height. The ET_O was calculated using Equation 1-13 using the collected weather station data. The crop coefficient (K_C) values are ratios of average crop-specific evapotranspiration to average reference evapotranspiration. These values incorporate distinguishing characteristics of the specific crop to the reference crop such as crop height, crop-soil surface resistance, and albedo of the crop-soil surface (Allen 2000). The K_C values selected for these studies were updated monthly for turfgrass with values of 0.45 (December-February), 0.65 (March), 0.80 (April), 0.90 (May), 0.75 (June), 0.70 (July-August), 0.75 (September), 0.70 (October), and 0.60 (November) (Jia et al. 2009).

Effective rainfall was limited to the portion of total daily rainfall that caused the soil water level to reach the maximum soil storage capacity after PWR was taken into account. Rainfall that exceeded the soil storage capacity was considered lost due to surface runoff or deep percolation.

A scheduling multiplier (SM) based on the average distribution uniformity of the irrigation system was used to convert IWR_{net} to GIR. The SM was estimated as 1.00, 1.25, and 1.67 to represent irrigation system efficiencies of 100%, 80%, and 60%, respectively. The GIR was calculated as a range of acceptable irrigation application by multiplying IWR_{net} (Equation 2-1) by each SM (IA 2013) resulting in two irrigation target ranges of achievable efficiency as 60% to 80% and high efficiency as 80% to 100%.

Results

Weather Patterns

The monthly ET_O and rainfall totals fluctuated throughout the study period with minimums of 72 mm (Jan. 2013) and 1.4 mm (Nov. 2012) and maximums of 177 mm (May 2012) and 236 mm (Aug. 2012), respectively (Figure 3-1). There was little variation in ET_O calculated across the location clusters as evidenced by relatively narrow error bars throughout the study period. Rainfall was much more variable across locations, especially during periods of frequent rainfall, indicating the occurrence of some localized rainfall events.

Using Figure 3-1, periods of similar weather patterns were identified to account for differences in treatments based on weather. Though ET_O fluctuated throughout the study period, differences in ET_O between winter and summer months were not as extreme as differences in rainfall. As a result, four periods of wet (summer) and dry (winter) seasons were classified based on rainfall patterns (Table 3-2). The dry seasons were selected as months where rainfall did not meet ET_O indicating very little rainfall. The wet seasons were selected as months where rainfall met or exceeded ET_O considering the high variability in the rainfall measurements. Further analysis of historical rainfall confirmed that the seasons defined as dry received less rainfall than periods defined as wet (Table 3-2). Due to average rainfall having such high variability, there was no significant difference at the 95% confidence level between rainfall during the study period and historical average for each season. This was also true for the number of rainfall events.

Irrigation Application

In all weekly statistics evaluated, location cluster was not significant to the statistical model during the study period. However, the soil type and seasonal period were significant resulting in the need to separate results by these factors. The treatment effect was also significant (P-value < 0.0001) indicating differences in irrigation applied by the various technologies and implementation approaches.

Dry 2012

Weekly irrigation application ranged from 12 mm (SMS+Edu) to 25 mm (MO) in the flatwoods locations (Table 3-3). There was no significant difference in weekly irrigation application between SMS and ET treatments, applying 19 mm and 20 mm, respectively. The MO applied the most irrigation per event, averaging 12 mm. The ET applied the least per event, averaging 5 mm, but applied irrigation the most often with 3.6 events per week. Only 1.2 events occurred per week for SMS+Edu combined with only 6 mm per event resulting in the low weekly application.

In these same locations, all treatments applied more irrigation than GIR, representing the irrigation required, regardless of efficiency (Figure 3-2). Cumulative irrigation application ranged from 291 mm (SMS+Edu) to 460 mm (SMS). Both technology treatments that received education applied less irrigation compared to the other three treatments, totaling 1% (SMS+Edu) and 11% (ET+Edu) more than the achievable GIR range of 60% to 80% efficiency. However, there was still uncaptured potential water savings by all treatments during this season with over-irrigation by as much as 52% (SMS).

Irrigation was the highest in the sand locations with weekly irrigation application ranging from 20 mm (SMS, SMS+Edu) to 32 mm (MO). The MO treatment also applied the most irrigation per event, averaging 16 mm, which was applied 1.9 times per week. There was no significant difference in weekly irrigation application between any of the technology treatments during this period. However, irrigation per event was 9 mm for ET+Edu, SMS, and SMS+Edu, which was significantly different from 7 mm for ET. The ET treatment had more events per week, averaging 3.1, which was more than the other treatments resulting in similar weekly totals to the other technology treatments.

Cumulative irrigation in the sand locations ranged from 383 mm (SMS+Edu) to 592 mm (MO) (Figure 3-3). Both the SMS and ET+Edu treatments irrigated similarly to SMS+Edu with totals of 416 mm and 385 mm, respectively, whereas ET irrigated similarly to MO, totaling 553 mm. The MO and ET treatments over-applied by 34% and 25%, respectively, considering GIR with 60% efficiency. The three treatments with the lowest cumulative irrigation application still had over-irrigation during the months of February and March, but fell within the achievable GIR range assuming 60% to 80% efficiency.

Wet 2012

The weekly irrigation average for the flatwood locations was significantly different for all treatments, ranging from 11 mm (SMS+Edu) to 27 mm (MO) (Table 3-3). The technology with education treatments tended to irrigate less than the technology only treatments on a weekly basis. The MO treatment applied 13 mm per event, similar to the previous season, which was significantly more than all other treatments. The ET treatment applied the least irrigation per event at 5 mm, but applied the most times per week with 3.8 events.

Cumulative irrigation application in the flatwoods locations ranged from 304 mm (SMS+Edu) to 629 mm (MO) (Figure 3-4). Compared to the previous season, the technology treatments began to separate from MO with decreases of 14% by ET and 26%-30% by SMS and ET+Edu. Though SMS+Edu had the best results, falling within the preferred GIR range assuming 80% to 100% efficiency at the end of the season, some under-irrigation occurred by this treatment in July. The ET+Edu began the season in the acceptable GIR range, but steadily increased during the last three months of the season resulting in over-irrigation.

The MO treatment for the sand locations continued to irrigate similarly to the dry 2012 period, applying 36 mm per week at 16 mm per event and 1.8 events per week, despite frequent rainfall. Weekly irrigation statistics for the technology treatments also had similar trends to dry 2012 in irrigation per event, ranging from 6 mm to 9 mm. The education treatments and SMS applied 17 mm (SMS) to 21 mm (SMS+Edu) across 1.9 (both SMS treatments) to 2.2 (ET+Edu) events per week. The biggest difference from dry 2012 was that the technology treatments began to have significant differences with the ET treatment applying more per week than the other three technology treatments. Irrigation per event remained relatively the same for all treatments between these two seasons, but events per week increased to 4.1 events for ET resulting in higher overall irrigation.

In the sand locations, cumulative irrigation ranged from 457 mm (SMS+Edu) to 858 mm (ET) (Figure 3-5). This is the first season and soil type where a technology treatment applied more irrigation than MO, resulting in an 8% increase. The remaining three technology treatments irrigated similarly throughout the entire season resulting in a maximum difference of 2% and a minimum reduction of 42% from MO. Assuming no residential irrigation system is 100% efficient, slight under-irrigation occurred by these three treatments during the beginning of the season, but increased in July to just outside the high efficiency GIR range thus following the 80% efficiency trend. The ET treatment also increased steeply in July resulting in 43% more irrigation than the irrigation required using an irrigation system with 60% efficiency.

Dry 2013

In the flatwoods locations, weekly irrigation application by MO averaged 26 mm, which was applied in 15 mm events on an average of 1.7 events per week (Table 3-3). Education was important to the SMS technology for this season, with significantly less irrigation by SMS+Edu (11 mm) compared to SMS (18 mm). Both ET treatments applied 15 mm per week, which were significantly different from both SMS treatments. After MO, SMS applied the most irrigation per event, averaging 10 mm, with the remaining treatments averaging 5-6 mm. Once again, the ET treatment applied the least per event, 5 mm, but irrigated the most times per week at 3.8 events.

All treatments irrigated more than what was required throughout these winter months in the flatwoods locations, ranging from 264 mm to 551 mm by SMS+Edu and MO, respectively (Figure 3-6). There was no difference in cumulative irrigation between the ET treatments, applying 328 mm (ET+Edu) to 335 mm (ET) with reductions of 39%-40% compared to MO. The SMS applied the most out of the technology treatments, resulting in 29% reduction from MO compared to a 52% reduction by SMS+Edu.

Both ET treatments applied the least on the sand soil, averaging 17 mm for ET and 18 mm for ET+Edu. The remaining three treatments were not significantly different from each other with averages ranging from 21 mm (SMS, SMS+Edu) to 23 mm (MO). Irrigation application by MO was significantly less than previous periods, indicating that there was a change in behavior by this treatment group due to an unknown outside factor. This treatment still applied the most irrigation per event, 15 mm, but was only applied 1.4 times per week. The ET treatment continued to apply the least per event, 5 mm, but irrigated most often at 3.1 events per week.

Similar to the flatwoods locations, cumulative irrigation in the sand locations was much higher than required during these winter months, applying 370 mm (ET+Edu) to 515 mm (MO) (Figure 3-7). Though ET+Edu had the largest reduction in irrigation application from MO (28%), this treatment still over-irrigated by 37% assuming 60% irrigation system efficiency. All other technology treatments reduced irrigation application from MO by 4% to 17%, indicating that there were uncaptured potential savings during the period.

Wet 2013

In the flatwoods locations, weekly irrigation application for MO, SMS, and both ET treatments was not different with averages ranging from 21 mm to 22 mm (Table 3-3). Similar to other seasons, the application schedule within the week varied across all treatments. Irrigation per event ranged from 5 mm (ET) to 9 mm (SMS) and events per week ranged from 1.2 events (SMS+Edu) to 3.6 events (ET). The SMS+Edu treatment applied the least amount of irrigation per week (13 mm).

All treatments fell within or just outside of the achievable and high efficiency GIR ranges during this season for the flatwoods soils, ranging from 264 mm to 472 mm by SMS+Edu and ET, respectively (Figure 3-8). All treatments except SMS+Edu applied irrigation within the achievable efficiency GIR range with only the ET treatment applying 2% more than the range maximum. The SMS+Edu constantly fell just below the high efficiency range indicating that there were deficit conditions by this treatment throughout this season.

Weekly irrigation application in the sand locations was highest by MO and ET, applying 28-29 mm, but had very different scheduling techniques as was seen in other seasons (Table 3-3). The MO treatment averaged 14 mm per event with 1.6 events per week compared to 6 mm per event by ET with 4.7 events per week. Similar to most other seasons, there were no differences in irrigation application between both SMS treatments, applying 16-17 mm per week. The SMS treatments applied similar irrigation per event at 8-9 mm compared to ET+Edu, but weekly irrigation was different for ET+Edu due to averaging 2.6 events per week compared to 1.3 events (SMS+Edu) and 1.6 events (SMS).

Cumulative irrigation ranged from 328 mm (SMS+Edu) to 570 mm (ET) in the sand locations (Figure 3-9). The two SMS treatments applied just less than the achievable GIR range for the first half of the season, but declined in irrigation application over the second half of the season resulting in final irrigation totals falling in the high efficiency GIR range, reducing irrigation by 34%-40% compared to MO. The ET+Edu treatment also followed the GIR at 60% efficiency, but declined in irrigation application by a smaller amount compared to the SMS treatments during the second part of the season, reducing irrigation by 21% compared to MO. Since ET applied the most irrigation during this season, irrigation application was 4% more than MO and outside of the achievable GIR range.

Turfgrass Quality

Turfgrass quality ratings by treatment were not significantly different prior to the start of the study, ranging from 6.3 to 6.8 (Table 3-4). Additionally, treatments were not significantly different within each of the seasons that occurred during the study indicating that quality did not suffer as a result of treatments. However, there were differences across seasons, ranging from 6.4 occurring during dry 2012 to 7.1 occurring during both wet seasons. It is likely that quality increased during the wet seasons due to ideal temperature conditions and lack of water stress that promoted better growth performance compared to the dry seasons. Other unmeasured factors could have affected turfgrass quality such as disease, fertilizer application, mowing practices, and irrigation system maintenance.

Discussion

Overall, there was a trend of water savings due to installing a smart technology with additional savings from education and detailed programming. This was evidenced by the Edu treatments consistently averaging similar or less irrigation than their non-education counterparts (Table 3-3). However, only a few treatments were able to maintain irrigation totals within acceptable GIR ranges and none of the treatments performed with maximum efficiency throughout all seasons. The SMS+Edu treatment was the only treatment to irrigate efficiently on both soil types, falling within the high efficiency GIR range, but this occurred during the wet 2013 season only (Figure 3-8; Figure 3-9). The SMS treatment also fell within the high efficiency GIR range during the wet 2013 season, but only for the sand soil type. The ET+Edu generally performed better in the sand locations compared to the flatwoods locations, falling within the achievable efficiency GIR range during most seasons.

There were instances when weekly irrigation averages did not match the multiplication of irrigation per event by events per week with a maximum difference of almost 8 mm. There would likely be 1-3 mm attributable to rounding thus further exploration into the data was required. Some treatments during some seasons had cooperators that irrigated unusually large amounts resulting in inflated weekly averages compared to the median. These instances skew the distribution from normal to non-normal, causing a discrepancy in the two totals. These outliers are likely due to circumstances outside of the treatment, but were not removed because they are part of the variability in performing irrigation studies in real world, uncontrolled environments. A transformation of the data was not performed since this problem affected only 38% of the averages and the minimum sample size of any one combination of treatment, season, and soil type was 289.

Sometime between the wet 2012 and dry 2013 seasons, there was a decrease in average weekly irrigation application by MO in the sand locations (Table 3-3). Interaction between UF-IFAS and the cooperators in MO had not occurred since the initial on-site irrigation evaluation, prior to the beginning of the dry 2012 season, indicating that the change in behavior was due to an external factor unrelated to the study. The most likely factor affecting irrigation totals was a water rate increase that became effective in Oct. 2012. Though the water rate increase was small, maximum increase of \$0.33 per 3.78 m^3 for the highest tier, the perceived increase can affect behavior. This was shown in Whitcomb (2005) where survey respondents were found to be concerned about the cost of water, especially irrigation, but were not knowledgeable about the details of true water rates such as price, size, and number of tiers.

There was a general trend of higher weekly irrigation application for all treatments located in sand soils compared to flatwoods soils. Sandy soils generally have smaller soil water holding capacities compared to the flatwoods soils resulting in the need for more irrigation. This was seen in the GIR ranges where the irrigation applied assuming 100% efficiency, representing IWR_{net}, was 28% greater for the sand locations (1,099 mm) than the flatwoods locations (858 mm) (Figure 3-2; Figure 3-3). However, the ET treatment in sand locations was not different from MO, a group shown to be excessive irrigators (Davis and Dukes, in review). Since the only major difference between the ET treatments was the programming of “sand” on the controllers for the sand locations compared to “loamy sand” for the flatwoods locations, the available water holding capacity may have been inappropriate for the actual soil characteristics, causing over-irrigation despite the default setting description matching the soil type.

Though none of the treatments achieved GIR with good efficiency throughout all seasons, the SMS+Edu consistently had better results compared to the other treatments. In addition to site-specific zone runtimes, this technology required a proper burial location in a representative portion of the landscape and an estimation of the threshold based on field capacity of the soil that could be selected through automatic calibration as opposed to user selection. Once these requirements were met, the SMS directly measured soil moisture resulting in bypassing unnecessary irrigation events. The ET+Edu had acceptable results in some seasons, but generally applied more irrigation than SMS+Edu. The success of an ET controller required more complex programming and detailed knowledge of both the technology and soil water characteristics of the landscape. The ET controller uses a model as an estimation of soil moisture which is only as good as the model inputs. The complexity of accurate programming in one on-site evaluation was an obstacle for maximizing water savings when using ET controllers. It is likely that the amount of water savings achieved from determining more accurate model inputs would not justify the increased costs to obtaining the information due to other limitations on the technology, such as the accuracy of the weather monitor.

In addition to the importance of program settings for ET controllers, there should have been higher accuracy in rainfall accountability in efforts to achieve water savings. Since most of the irrigation scheduling relies on modeling, rainfall was one of the only on-site measurements taken by the ET controller. However, there was a lack of response to rainfall during wet seasons, where frequency of irrigation events remained constant or increased in wet months compared to dry months (Table 3-3), resulting in increased application during wet seasons when ET_O was higher. Some increase would be expected, as was seen in the higher GIR totals from dry to wet seasons. However, the ET+Edu and SMS+Edu applied similar irrigation depths per event, but ET+Edu always applied more events per week than SMS+Edu in the flatwoods locations (Table 3-3) despite no differences in turfgrass quality (Table 3-4). The direct measurement of effective rainfall by the SMS technology allowed the technology to regulate the timer schedule resulting in more efficient irrigation application than the ET controller. Advances to the ET controller technology must occur to address this issue.

The benefits received as a part of one of the technology with education treatments included adjusted program settings and a single, on-site cooperator education session that lasted no more than five minutes. Education is extremely important to the success of smart controllers so that they become a trusted device with proper maintenance to achieve long term water conservation. In the case of this study, it is likely that the single educational on-site visit was not as influential to water savings as was the detailed program settings. One setting specific to the education treatments was restricting irrigation opportunities to three events per week. This was an effective limitation for the ET controller where irrigation savings were not as substantial for the ET treatment due to averaging more than 3 events per week. Though SMS did not average above two events per week, thus regularly bypassing unnecessary irrigation events, the SMS+Edu frequently averaged fewer events per week than SMS. As a result of restricting irrigation to only three specific days, SMS+Edu was delayed until the next available irrigation day when falling below the soil moisture threshold, allowing either effective rainfall or short periods of deficit conditions between irrigation events.

Conclusions

The overall trend of water savings occurred due to installing a smart technology with additional savings from education and detailed programming. Results suggest that water savings were greatest for the SMS with education on the flatwoods soils, applying 11-13 mm per week. However, both SMS were relatively as effective as the ET controller with education on the sand soils. Despite the uncontrolled environment, cooperator interactions did not increase irrigation application to previously excessive levels thus water savings were achieved by introducing a smart technology.

Despite positive results based on trends in irrigation application, only a few treatments were able to maintain irrigation totals within the defined GIR ranges, resulting in 21%-52% water savings by those treatments compared to MO, and none of the treatments performed efficiently in all seasons. A majority of the savings occurred by the cooperators within the sand soils by the SMS, ET+Edu, and SMS+Edu treatments. In the flatwoods soils, only the SMS+Edu fell within the GIR ranges during the wet seasons resulting in water savings of 52% in 2012 and 42% in 2013. None of the treatments fell within either achievable or high efficiency GIR ranges during the dry 2013 season.

The SMS+Edu treatment performed better than the other treatments, falling within the achievable efficiency GIR range during dry 2012 and the high efficiency GIR range for both wet seasons regardless of soil type. The performance of SMS+Edu can be attributed to bypassing unnecessary irrigation events based on measured soil moisture and site-specific runtimes as a part of education that limited over-irrigation on an irrigation day. The ET+Edu treatment also had promising performance results in the sand locations, falling within the achievable efficiency range during dry 2012 and wet 2013 and within the high efficiency range during wet 2012. Irrigation was greater than the achievable efficiency range in the flatwoods locations during both 2012 seasons due to more events occurring per week.

Both technologies were able to reduce irrigation application when implemented on sites with historical excessive irrigation. In general, there was higher consistency in efficient irrigation application by the SMS technology than the ET technology. The SMS was able to produce water savings in both soil types and during most seasons whereas the ET controller was less predictable. The ET controllers may require technological advancement combined with additional educational opportunities to achieve the same amount of water savings as the SMS.

Table 3-1. Number of cooperators by location and treatment.

Group Name	Soil type	ET[a]	ET+Edu[b]	SMS[c]	SMS+Edu	MO[d]	Total
Hunters Creek A	Flatwoods	4	4	4	4	4	20
Hunters Creek B	Flatwoods	4	4	4	4	4	20
Keenes Pointe Area	Sand	4	4	4	4	3	19
North Tanner Road Area	Sand	0	5	0	5	5	15
Turtle Creek Area	Sand	4	4	4	4	4	20
Waterford Lakes – East	Flatwoods	4	4	4	4	4	20
Waterford Lakes – South	Flatwoods	4	4	4	4	4	20
Waterford Lakes –West	Flatwoods	4	4	4	4	4	20
Sweetwater Apopka Area	Sand	0	5	0	5	3	13
Total		28	38	28	38	35	167

[a]ET designates cooperators that received a Rain Bird ESP-SMT ET controller
[b]Edu designates cooperators that received an on-site educational training and optimized programming
[c]SMS designates cooperators that received a Baseline WaterTec S100 SMS
[d]MO designates cooperators that did not receive a technology

Table 3-2. Description of seasonal periods used to account for various dry/wet periods occurring throughout the study period.

Season	Start Date	End Date	Number of Weeks	Cumulative Rainfall (mm)		Number of Rainfall Events	
				Study Period Average[a]	Historical Average[b] (s.d.)	Study Period Average	Historical Average (s.d.)
Dry 2012	Nov. 2011	Apr. 2012	25	123	428 (169)	30	46 (9)
Wet 2012	May 2012	Oct. 2012	26	705	895 (170)	75	85 (11)
Dry 2013	Nov. 2012	Mar. 2013	22	76	354 (168)	22	39 (9)
Wet 2013	Apr. 2013	Aug. 2013	20	782	730 (164)	79	68 (10)

[a]Averages during the study period were calculated using rain gauges installed for the study across all locations.
[b]Historical averages were calculated using a rain gauge installed at the Orlando International Airport (NCDC 2009).

Table 3-3. Statistics for irrigation application by each treatment over the study period.

	Flatwoods			Sand		
Treatment	Irrigation Per Week (mm)	Irrigation Per Event (mm)	Events Per Week (#)	Irrigation Per Week (mm)	Irrigation Per Event (mm)	Events Per Week (#)
			Dry 2012			
MO	25 *a*	12 *a*	1.8 *c*	32 *a*	16 *a*	1.9 *c*
ET	20 *b*	5 *c*	3.6 *a*	22 *b*	7 *c*	3.1 *a*
ET+Edu	16 *c*	6 *c*	2.6 *b*	21 *b*	9 *b*	2.3 *b*
SMS	19 *b*	8 *b*	1.4 *d*	21 *b*	9 *b*	2.0 *c*
SMS+Edu	12 *d*	6 *c*	1.2 *e*	20 *b*	9 *b*	2.0 *c*
			Wet 2012			
MO	27 *a*	13 *a*	1.9 *c*	32 *a*	16 *a*	1.8 *c*
ET	23 *b*	5 *d*	3.8 *a*	26 *b*	6 *c*	4.1 *a*
ET+Edu	17 *d*	7 *c*	2.6 *b*	19 *cd*	8 *b*	2.2 *b*
SMS	20 *c*	9 *b*	1.4 *d*	17 *d*	8 *b*	1.9 *c*
SMS+Edu	11 *e*	5 *d*	1.3 *e*	21 *c*	9 *b*	1.9 *c*
			Dry 2013			
MO	26 *a*	15 *a*	1.7 *c*	23 *a*	15 *a*	1.4 *e*
ET	15 *c*	5 *c*	3.0 *a*	17 *b*	5 *d*	3.1 *a*
ET+Edu	15 *c*	6 *c*	2.5 *b*	18 *b*	8 *c*	2.4 *b*
SMS	18 *b*	10 *b*	1.5 *d*	21 *a*	9 *bc*	2.0 *c*
SMS+Edu	11 *d*	6 *c*	0.97 *e*	21 *a*	10 *b*	1.6 *d*
			Wet 2013			
MO	22 *a*	10 *a*	1.6 *c*	29 *a*	14 *a*	1.6 *c*
ET	21 *a*	5 *e*	3.6 *a*	28 *a*	6 *c*	4.7 *a*
ET+Edu	22 *a*	8 *c*	3.0 *b*	22 *b*	9 *b*	2.6 *b*
SMS	21 *a*	9 *b*	1.8 *c*	17 *c*	9 *b*	1.6 *c*
SMS+Edu	13 *b*	6 *d*	1.2 *d*	16 *c*	8 *b*	1.3 *d*

Note: Values within each column and season followed by different lowercase letters are different at the 95% confidence level.

Table 3-4. Turfgrass quality ratings for each treatment[a] were evaluated seasonally[b]

Treatment	Evaluation Period Turfgrass Quality	Dry 2012 Turfgrass Quality	Wet 2012 Turfgrass Quality	Dry 2013 Turfgrass Quality	Wet 2013 Turfgrass Quality
MO	6.3 *a*	6.4 *a*	7.0 *a*	6.6 *a*	6.9 *a*
ET	6.8 *a*	6.5 *a*	7.3 *a*	6.9 *a*	7.2 *a*
ET+Edu	6.6 *a*	6.3 *a*	7.0 *a*	6.8 *a*	7.2 *a*
SMS	6.7 *a*	6.3 *a*	7.0 *a*	6.9 *a*	7.1 *a*
SMS+Edu	6.7 *a*	6.4 *a*	7.0 *a*	6.6 *a*	7.0 *a*
Mean	6.6 *C*	6.4 *D*	7.1 *A*	6.7 *B*	7.1 *A*

[a]Ratings within each season followed by different lowercase letters are different at the 95% confidence level.
[b]Mean seasonal ratings followed by different uppercase letters are different at the 95% confidence level.

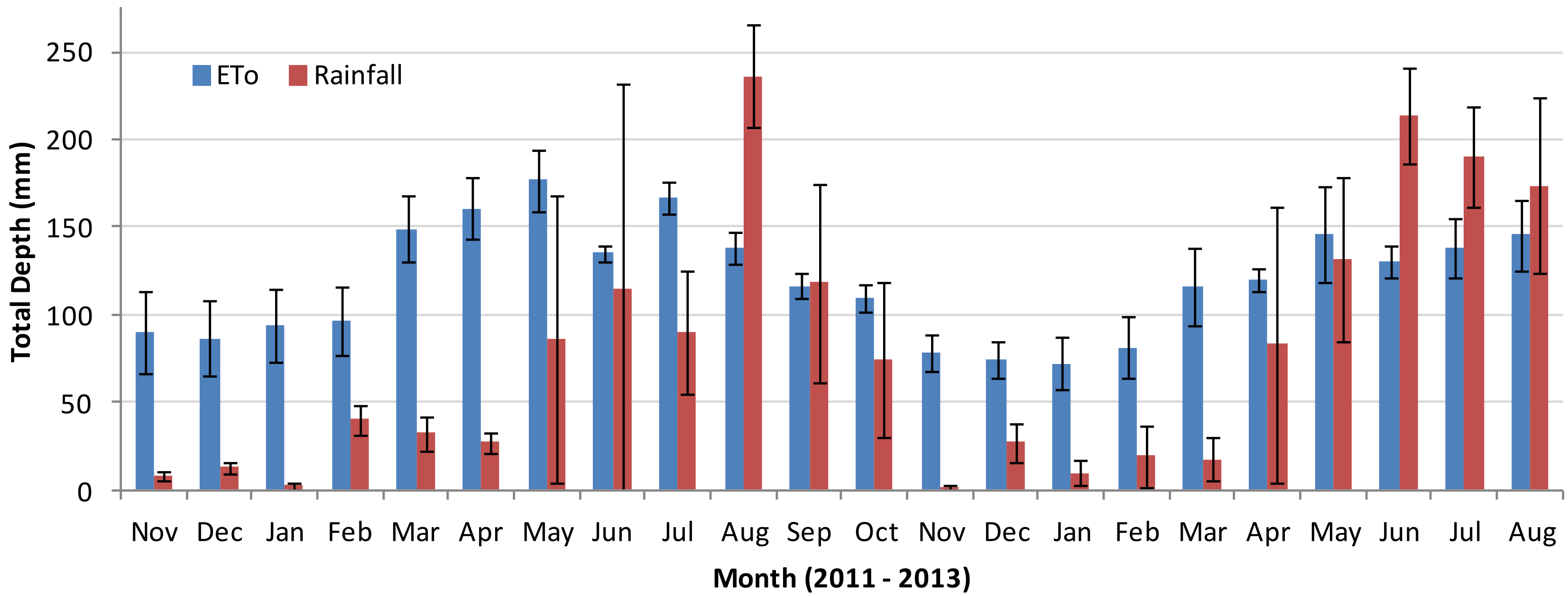

Figure 3-1. Monthly ET_O and rainfall for all locations during the study period with error bars representing the standard error of measurements across all study locations.

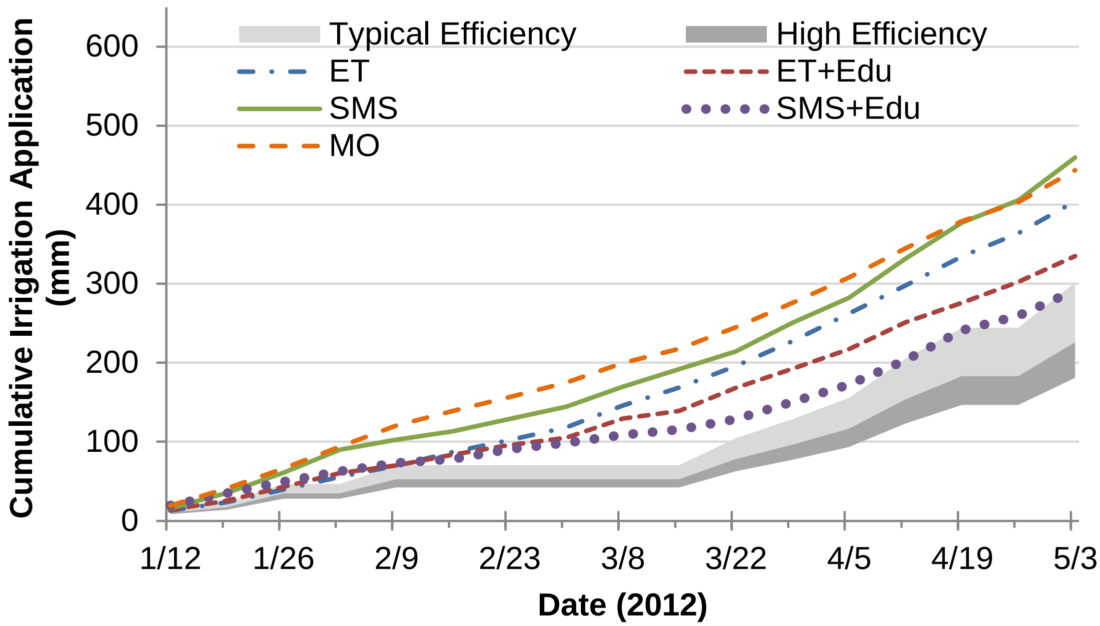

Figure 3-2. Cumulative irrigation application for all five treatments occurring on the flatwoods locations during the dry 2012 season compared to the estimated irrigation requirement assuming achievable and high efficiency ranges.

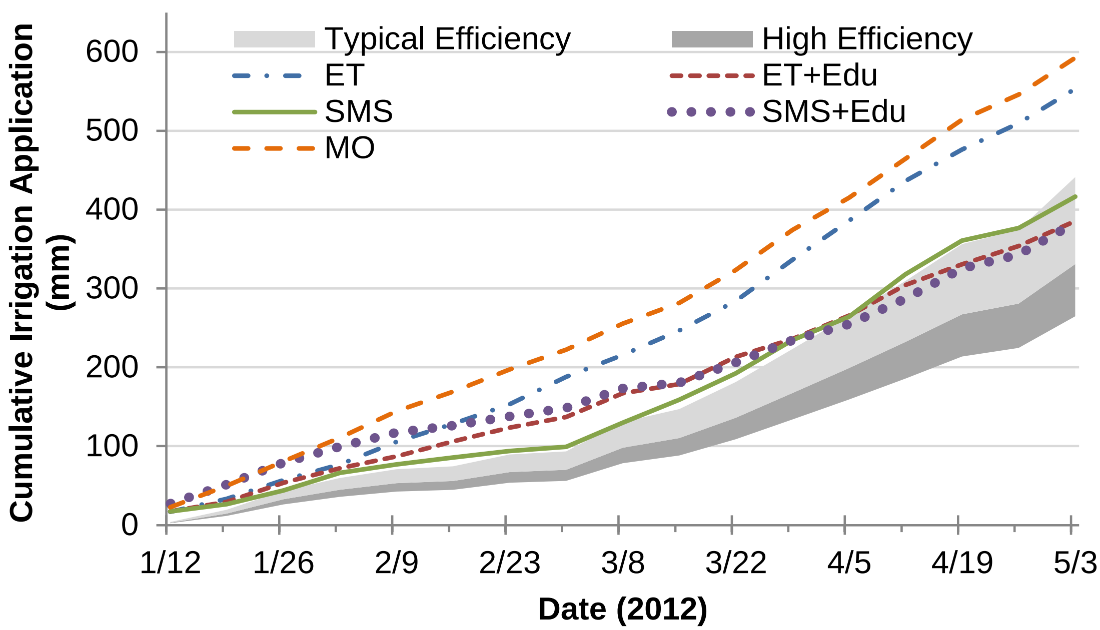

Figure 3-3. Cumulative irrigation application for all five treatments occurring on the sand locations during the dry 2012 season compared to the estimated irrigation requirement assuming achievable and high efficiency ranges.

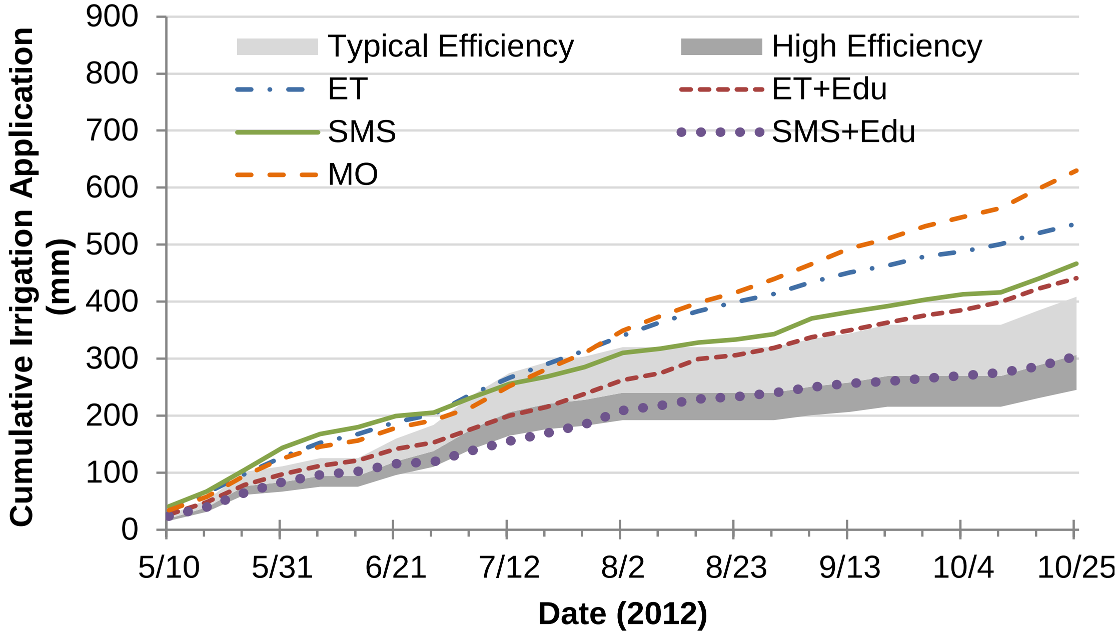

Figure 3-4. Cumulative irrigation application for all five treatments occurring on the flatwoods locations during the wet 2012 season compared to the estimated irrigation requirement assuming achievable and high efficiency ranges.

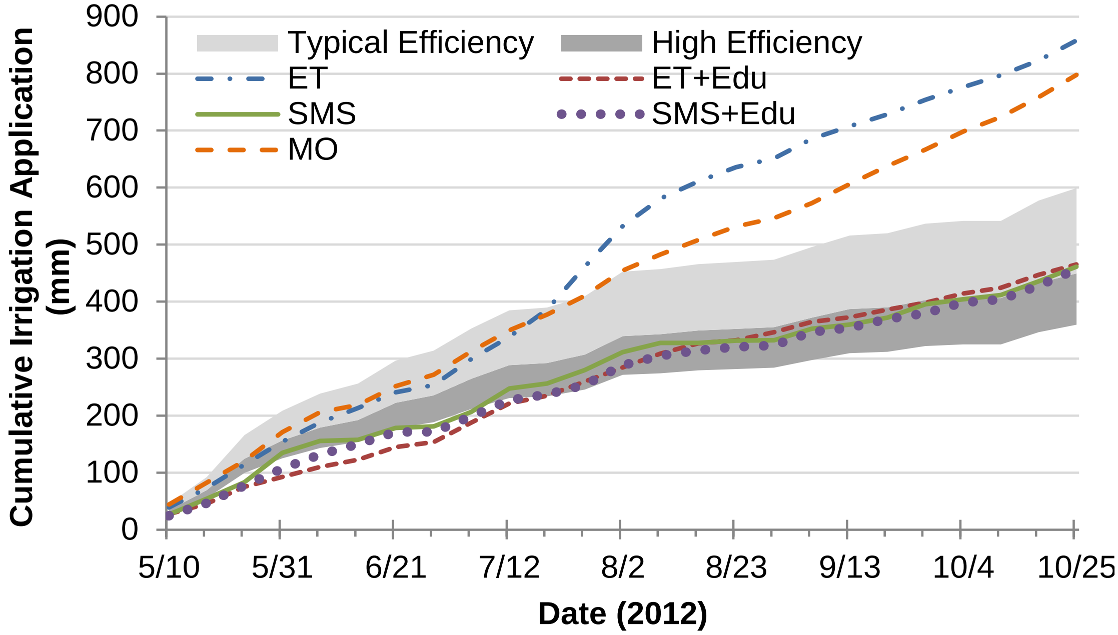

Figure 3-5. Cumulative irrigation application for all five treatments occurring on the sand locations during the wet 2012 season compared to the estimated irrigation requirement assuming achievable and high efficiency ranges.

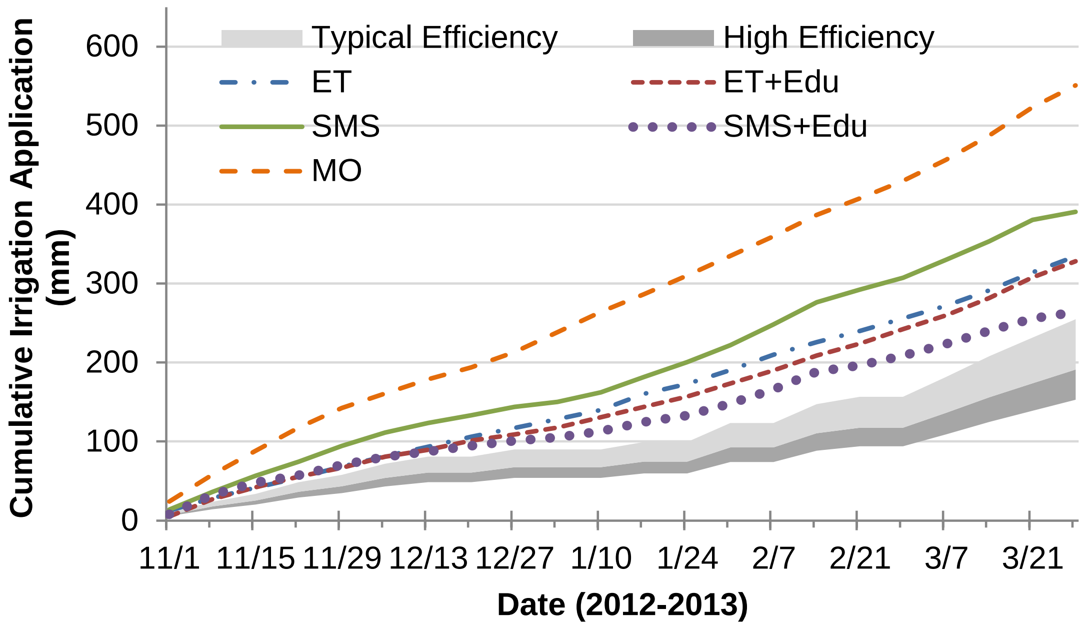

Figure 3-6. Cumulative irrigation application for all five treatments occurring on the flatwoods locations during the dry 2013 season compared to the estimated irrigation requirement assuming achievable and high efficiency ranges.

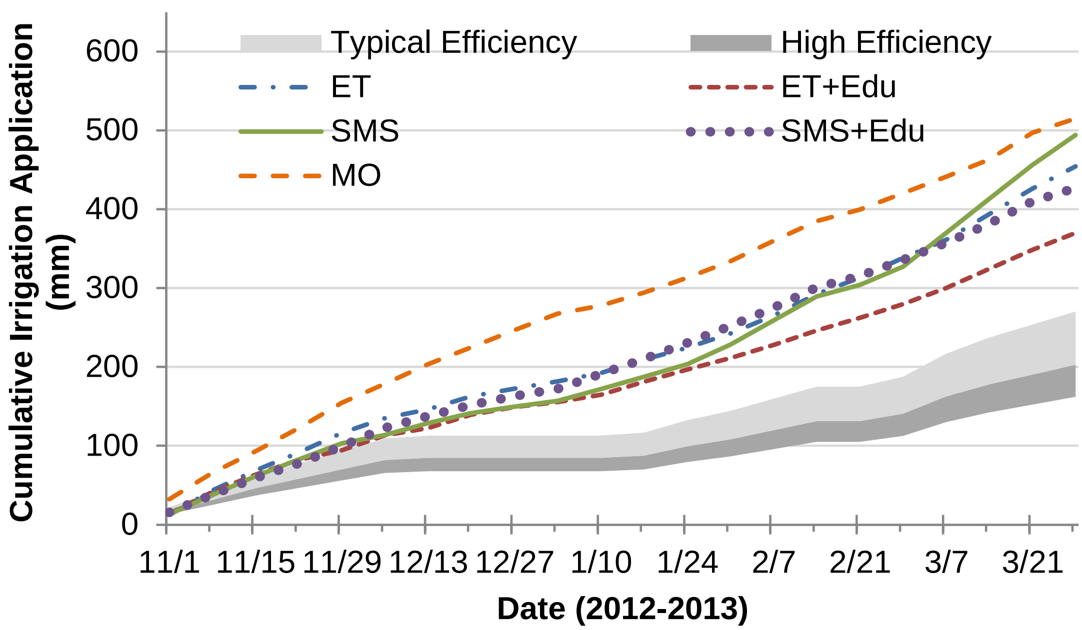

Figure 3-7. Cumulative irrigation application for all five treatments occurring on the sand locations during the dry 2013 season compared to the estimated irrigation requirement assuming achievable and high efficiency ranges.

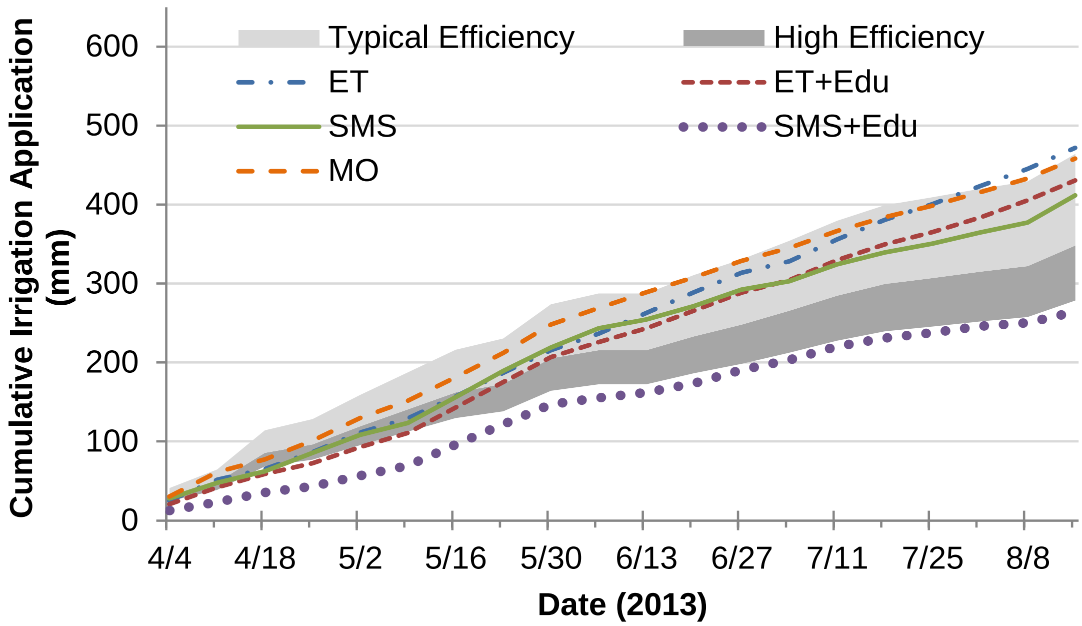

Figure 3-8. Cumulative irrigation application for all five treatments occurring on the flatwoods locations during the wet 2013 season compared to the estimated irrigation requirement assuming achievable and high efficiency ranges.

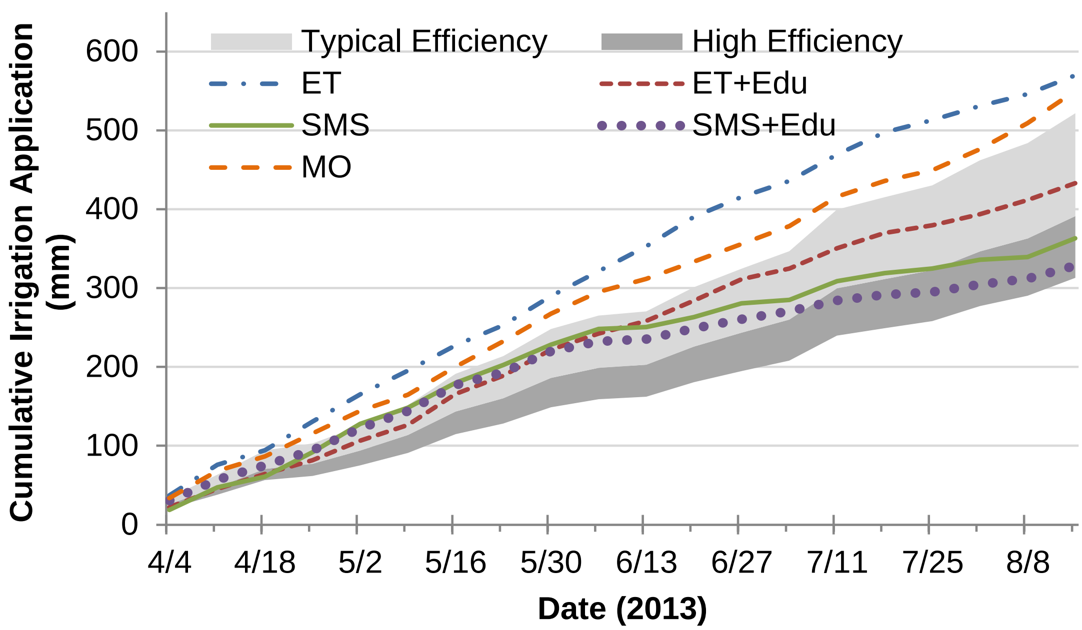

Figure 3-9. Cumulative irrigation application for all five treatments occurring on the sand locations during the wet 2013 season compared to the estimated irrigation requirement assuming a and high efficiency ranges.

CHAPTER 4
COMPARISON OF MODELING METHODS TO ESTIMATE SOIL WATER CONTENT IN TURFGRASS BASED LANDSCAPES

Introduction

The American lawn became a fundamental part of the home landscape after the Second World War when suburbanization exploded (Robbins and Birkenholtz 2003). Turfgrass can be a functional part of the landscape by reducing soil erosion, preventing particulate inhalation from excess dust, dissipating heat at the soil surface level, and providing a wildlife habitat. There are also recreational and aesthetic reasons for maintaining turfgrass landscapes such as providing cushioned support for sports and playground activities and improving mental health and quality of life (Beard and Green 1994).

Florida was ranked fourth in domestic water use in 2005; the only states having higher consumption were California, Texas, and Michigan (Kenny et al. 2009). Using the limited water supply to irrigate landscapes, which are typically considered ornamental in nature and not purposeful to sustain life such as in agriculture, may not be socially responsible. Finding better ways to preserve turfgrass-based landscapes through modernized irrigation techniques may be a good compromise.

One modern technology currently promoted for water conservation is a weather-based irrigation controller that uses reference evapotranspiration (ET_O) to estimate plant water needs. Though they vary in functionality by brand and model, most ET controllers use a soil water balance (SWB) to determine how much irrigation is necessary and when to apply it. Research has shown that ET controllers have the potential to produce water savings when implemented in scenarios with frequent excessive irrigation (Mayer et al. 2009; Davis and Dukes, in review). They have also been shown to increase irrigation at homes that historically irrigate at or below the theoretical irrigation requirement (Mayer et al. 2009; Davis and Dukes 2014).

The Irrigation Association developed the Smart Water Application Technologies (SWAT) Testing Protocol for Weather-Based Irrigation Controllers as a method to evaluate the ability of ET controllers to schedule irrigation (IA 2008). This testing protocol, established in 2002 and now in its 8th draft, specifies a daily soil water balance occurring over a 30-day period to determine if ET controllers can maintain theoretical soil moisture. The protocol specifies that testing results are valid when 30-day totals of rainfall and ET_O reached 10.2 mm and 63.5 mm, respectively. Publishing SWAT test results are at the discretion of the manufacturer and can be continually tested until achieving acceptable scores during a valid testing period.

The USEPA WaterSense program was developed to encourage the adoption of efficient water-related products into the consumer market thus ultimately increasing water conservation practices. Through this program, ET controllers are identified to consumers through product labeling after undergoing the SWAT test conducted by an independent testing facility (USEPA 2012). Prior to adoption of the SWAT test by USEPA, it was evaluated for transferability, or applicability of scores to different areas of the country, and reproducibility, or the ability to obtain identical results using the same input information by various testing labs (Davis and Dukes 2010). During these evaluation efforts, the primary deficiency of the SWAT test was identified as declining scheduling efficiency scores during periods of frequent rainfall resulting and the lack of transferability (Davis and Dukes 2012). Other significant deficiencies included the low rainfall and ET_O requirements for a valid test, penalized scores due to the mandate that rainfall must be taken into account before irrigation despite when irrigation occurred prior to rainfall on the same day, and inconsistencies in controller programming compared to theoretical landscape characteristics to achieve high scores.

Based on these deficiencies, it was hypothesized that an hourly soil water balance would better match deterministic soil water models and improves estimates of soil water content compared to a daily soil water balance. The objective of this study was to evaluate an hourly soil water balance to determine its ability to estimate soil water content compared to Richards' equation, a deterministic model, and the current SWAT test using a daily soil water balance.

Materials and Methods

Soil Water Balance

The volumetric soil water content (θ) is calculated as the ratio between the volume of water to total volume (water, air, and soil particles) of the root zone. In a natural landscape system, θ can range from residual water content (θ_r), where additional energy is required to remove water from the profile, to saturation (θ_s), where all pore spaces are filled with water. Field capacity (θ_{FC}) is achieved when gravitational forces equal surface tension forces (cohesive and adhesive) between water molecules and soil particles resulting in no drainage due to gravity (Richards 1931). Water storage at water contents between θ_{FC} and θ_s is temporary and drains to θ_{FC} over time based on soil hydraulic properties. To reduce water stress on the plant material, the water content should be maintained above θ_r at a maximum allowable depletion (θ_{MAD}) typically selected as 50% between θ_r and θ_{FC} (IA 2013).

The soil water balance is a simple model that uses a tipping bucket approach to soil water movement in a homogeneous soil profile (i.e. depth per unit area of root zone) over a specified timestep (Ranatunga et al. 2008). The model is based on the principle that soil water at the current timestep (i) was affected by the soil water at the previous timestep (i-1) and inputs and outputs occurring at i.

$$Z_i = Z_{i-1} - ET_{C,i} + R_i + I_i - RO_i - D_i \quad (4\text{-}1)$$

The Z (mm) is the depth of water within the soil profile measured from the bottom of the root zone and is related to θ, ET_C (mm) is the plant-specific ET, R (mm) is rainfall, I (mm) is irrigation, RO (mm) is runoff from excess rainfall or irrigation, and D (mm) is deep percolation from excess rainfall or irrigation.

Plant-specific evapotranspiration (ET_C) is calculated for any given plant material by applying a crop coefficient (K_C) using Equation 1-28 (Allen et al. 1998). In this study, K_C values were selected monthly for warm season turfgrass located in central and southwest Florida (Jia et al. 2009), depending on the origin of the measured soil moisture data (Table 4-1).

Rainfall and irrigation are utilized similarly in the model where the depth equals the total that fell (R) or was applied (I) over the unit area during the timestep of interest. Events that cause θ to exceed θ_s result in separating total depth into effective depth, which is considered available for plant use, and a combination of runoff and deep percolation losses. When total depth results in θ that is less than θ_s, total depth equals effective depth.

Runoff and deep percolation are two different physical processes that both potentially occur when θ exceeds θ_{FC} resulting in water losses from the soil profile. Generally, runoff occurs due to improper cycle/soak scheduling of irrigation and landscape inclines whereas deep percolation occurs due to excess rainfall or irrigation.

It is difficult and unnecessary to separate these losses because they are quantified outside of the soil profile and the variable of interest is the change in depth of water within the soil profile.

Daily SWAT Test

The SWAT test, specified in the SWAT Climatologically Based Controllers 8th Testing Protocol (IA 2008) and used by USEPA WaterSense as a test specification for labeling (USEPA 2012), uses a soil water balance to simulate water movement in a landscape plant system using a daily timestep. It was developed as a tool to evaluate the ability of ET controllers to adequately and efficiently schedule irrigation. The SWAT test specifies six diverse virtual landscapes tested over a thirty day period during valid weather conditions that met minimums of 63.5 mm of ET_O and 10.2 mm of R over the testing period.

The soil water balance specified by the SWAT test was modified to restrict water movement to between θ_{MAD} to θ_{FC}. The range is referred to as the root zone working water storage (RZWWS) (IA 2008). In addition to new terminology, water level fluctuations were limited to zero and RZWWS, or the maximum value able to be stored depending on the tested zone. A water level of zero does not equate to the absence of water in the soil column. Therefore, the soil water balance used for the SWAT test does not represent the actual water level in the soil profile, but the level under which the plant material will no longer be considered well-watered. An additional modification included an arbitrary reduction of total daily rainfall by 20% citing losses to non-uniformity and runoff (IA 2008).

In the SWAT test, runoff and deep percolation were defined as scheduling losses consisting of direct runoff when irrigation cycles exceed maximum runtimes based on infiltration rates, soak runoff when irrigation cycles occur prior to minimum soak times based on infiltration rates, and surplus that occurred when the irrigation cycle causes θ to exceed θ_{FC}.

Hourly SWB Model

An hourly soil water balance was developed in efforts to address some deficiencies in the SWAT test such as lack of transferability and penalized scores due to mandating that rainfall occurred before irrigation despite actual order of events. All calculations specified in the daily version were maintained so that soil water movement within the RZWWS occurred in the same way. However, the soil water balance was updated to incorporate soil water movement above θ_{FC} and below θ_{MAD}. These simplifications may benefit the controllers during the test by not continually penalizing for deficit or surplus conditions. However, soil water levels in real systems can frequently exceed θ_{FC} until reaching saturation with deep percolation naturally occurring during each timestep until returning to equilibrium at θ_{FC}. Additionally, water levels falling below θ_{MAD} resulting in deficit conditions can occur in real systems and should be observed in the model.

To account for soil water levels higher than field capacity, an exponential decay function was incorporated into each timestep using a stepwise equation.

$$Z_i = \begin{cases} Z_0 * e^{-\lambda t}, & Z_0 > Z_{FC} \\ Z_{i-1}, & Z_0 \leq Z_{FC} \end{cases} \tag{4-2}$$

The Z_0 (mm) is the soil water level at the first instance it exceeds Z_{FC} (mm) as field capacity, λ is the decay constant, and t is the number of hours that the moisture balance remained above field capacity. The λ was calculated by rearranging Equation 4-3.

$$\lambda = \frac{\ln\left(\frac{\theta(t)}{\theta_0}\right)}{-t} \tag{4-3}$$

The λ is dependent on the magnitude of the depth of water exceeding field capacity thus affecting the amount of time it should take to drain to equilibrium. It was assumed that the maximum time to reach field capacity from saturation was 24 h. Thus, λ was calculated by substituting field capacity for θ(t), saturation for θ_0, and 24 h for t. The depth of water removed from the soil profile using the exponential decay function, calculated as the difference between Z_i and Z_{i-1} when $Z_0>Z_{FC}$, was considered lost through deep percolation.

The hourly SWB was adapted to incorporate layers within the root zone to evaluate the model at various depths. When more than one layer was evaluated, only the top-most layer received rainfall and irrigation as inputs to the soil profile. Each additional layer received only the deep percolation losses calculated using the exponential decay function from the upper adjacent layer. The ET_C was separated into evaporation and transpiration. Evaporation was assumed to be 10% of the ET_C and was removed from the top layer only (Hanks and Ritchie 1991). Transpiration was linearly proportioned into each layer so that a majority of ET_C occurred from the top layers in relation to root density.

When the soil water level falls below θ_{MAD} and deficit conditions occur, transpiration decreases due to the increases in energy required to remove water from the soil by the plant material. To account for this phenomenon, a stress coefficient (K_S) was introduced to the ET_C calculation using a linear relationship (Allen 2000):

$$K_s = \begin{cases} \frac{Z_{i-1}-Z_{PWP}}{Z_{MAD}-Z_{PWP}}, & Z_{i-1} < Z_{MAD} \\ 1, & Z_{i-1} \geq Z_{MAD} \end{cases} \tag{4-4}$$

The Z_{PWP} (mm) is the soil water level that permanent wilting occurs and θ_{MAD} (mm) is the soil water level at maximum allowable depletion.

HYDRUS-1D

Richards' equation (1931) was developed to estimate the flow of water through unsaturated porous media, such as a soil column, from Darcy's Law for flow through porous media under saturated conditions and Poiselle's Law for the flow of liquids in capillary tubes. Richards' equation can be expressed by pressure head (h) (Equation 1-33), soil moisture content (θ) (Equation 1-34), or a combination of both (Equation 1-35) (Celia et al. 1990). Richards' equation is a nonlinear partial differential equation that cannot be solved analytically. Instead, numerical approximations such as the finite difference or finite element methods combined with iteration techniques such as Picard or Newton methods are required for discrete solutions (Celia et al. 1990).

HYDRUS-1D Version 4.0 (PC-Progress, Prague, Czech Republic) was selected as the model used for calculating soil moisture using Richards' equation. This software has been established as a stable and reliable mechanism for predicting water movement in variably saturated porous media such as a soil column (Šimůnek et al. 2012). The Windows-based program was designed to simulate one-dimensional movement of soil water, heat, and solutes in a variably saturated soil profile (Šimůnek et al. 2008). For the purposes of this research, only soil water movement was considered. HYDRUS-1D numerically solves Richards' equation using Equation 1-35 by using Galerkin type linear finite element schemes where integration occurs using an implicit backwards finite difference scheme for both unsaturated and saturated conditions.

Field Measured Data

PSREU

Volumetric water content was collected from a bahiagrass pasture located in Block 4 at the Plant Science Research and Education Unit (PSREU) in Citra, FL. Time domain reflectometry (TDR) sensors (Campbell Scientific, Logan, UT) were buried in profile at the depths of 150 mm, 300 mm, 450 mm, 600 mm, 750 mm, and 900 mm. Volumetric water content was collected at 15 minute intervals from Jan. 1, 2004 to Jun. 23, 2004 totaling 174 days with data.

Irrigation of the turfgrass pasture was accomplished using a linear move system with an irrigation schedule determined by farm management. Irrigation and rainfall were both measured using an Onset Computer Corporation (Bourne, MA) tipping bucket rain gauge. The gauge utilized a Hoboware data logger that recorded each instance when 2.54 mm was collected in the tipping bucket. The rain gauge was mounted at a low height to catch both rainfall and irrigation thus these events were not distinguishable in this dataset.

Weather data during this time period was collected from the Florida Automated Weather Network (FAWN) weather station located at the PSREU. Weather parameters included temperature, relative humidity, solar radiation, wind speed, and rainfall collected at 15 minute intervals. Daily and hourly reference evapotranspiration (ET_O) was calculated using the ASCE standardized ET_O equation (ASCE 2005).

The soil type located in Block 4 at the PSREU was determined from soil survey maps to be Arredondo Fine Sand at 5 to 8 percent slopes (ArC), which is a well-drained soil having an available water capacity ($\theta_{FC} – \theta_{PWP}$) of 0.05 mm^3 mm^{-3} to 0.17 mm^3 mm^{-3} and a permeability rate of 152-508 mm/h (SCS 1979). On-site soil testing occurring on

Aug. 11, 2006 showed that the soil consisted of 94% sand, 3% silt, and 3% clay with surface saturated hydraulic conductivity, related to permeability, averaging 317 mm/h. Soil testing also provided additional estimations required for Richards' Equation that included θ_r (0.062 $mm^3\ mm^{-3}$), θ_s (0.329 $mm^3\ mm^{-3}$), n (3.86), and α (0.020 mm^{-1}).

GCREC

Twenty St. Augustinegrass plots measuring 7.6 m by 7.9 m were established at the Gulf Coast Research and Education Center (GCREC) in Balm, FL. These plots were created to evaluate the ability of ET controllers to schedule irrigation in southwest Florida. Results concerning these treatments can be found in Davis et al. (2009), Davis and Dukes (2010), and Davis and Dukes (2012). Each plot was maintained using an individualized irrigation system with dedicated 114 mm V100 w/ Pulse Output flow meter (AMCO Water Metering Systems, Ocala, FL) to measure volumes of irrigation application per plot. The flow meters were connected to a CR-10X data logger (Campbell Scientific, Logan, UT) that recorded sub-daily irrigation to easily separate irrigation system maintenance activities and treatment-related irrigation.

The twenty plots were separated into five treatments resulting in four replications of each treatment. There were hardware issues with one of the technologies being tested, so that treatment was removed from this analysis. Therefore, the treatments were: A) Weathermatic SL1600, B) Toro Intelli-Sense, C) TIME treatment based on 100% replacement of the net irrigation requirement (Dukes and Haman 2002), and D) RTIME treatment that was 60% of the TIME treatment. The variable of interest for these treatments was irrigation application only; thus, all plot maintenance and nutrient management remained constant across all treatments based on University of Florida –

Institute of Food and Agricultural Sciences (UF-IFAS) recommendations (Sartain 1991; Black and Ruppert 1998).

Soil moisture was measured using a TDR sensor buried diagonally at a 76 mm to 178 mm depth. Each plot received a sensor located in the middle of the southeast quadrant of the plot so that it was equidistant from all sprinkler heads ensuring good sprinkler application at the measurement site. Volumetric water content was collected at 15 minute intervals from Aug. 13, 2006 to Nov. 12, 2007.

The soil type for this study was Zolfo fine sand according to the soil survey (SCS 1989). The Zolfo series is described as a sandy, siliceous, hyperthermic Grossarenic Entic Haplohumods that is somewhat poorly drained. The θ_{FC} and θ_{PWP} for Zolfo fine sand was determined from laboratory samples to be 0.13 mm^3 mm^{-3} and 0.03 mm^3 mm^{-3}, respectively (Carlisle et al. 1985).

Model Parameterization, Calibration, and Validation

Each model was parameterized to best represent the conditions of the actual soil profile. HYDRUS-1D was used to determine the best fit of hydraulic characteristics for both studies and all layers using an inverse solution. At the PSREU, initial values and ranges of hydraulic parameters for each layer were selected based on soil core sampling conducted at the site. The inverse solution was repeated for each layer until volumetric water content of all layers generally approximated the measured data (Table 4-2; Table 4-3; Table 4-4; Table 4-5; Table 4-6; Table 4-7). Detailed soil sampling was not conducted at the GCREC; the hydraulic characteristics were initially selected based on soil survey information and educated guesses that were also fitted using an inverse solution in HYDRUS-1D (Table 4-8; Table 4-9; Table 4-10; Table 4-11).

The accuracy of the models was evaluated through validation procedures using a subset of the collected data from each study. Validation of the model was completed to quantify its performance compared to the physical system being modeled. The combination of goodness-of-fit measures, absolute error measures, and graphical assessments provide adequate evaluations of model performance (Legates and McCabe Jr. 1999; Willmott et al. 1985; McCuen et al. 2006; Krause et al. 2005). Combining these three methods will result in overcoming the limitations inherent in each individual measure.

The Nash Sutcliffe coefficient of efficiency (NSE) was selected to determine the goodness-of-fit (Equation 1-47). The numerator of the equation measures the variation in the data that was not explained by the model and the denominator measures the total variation in the observed data (McCuen et al. 2006). Dimensionless values of the coefficient can range from $-\infty$ to 1 where values of 0 to 1 indicate that the model, if linear, is unbiased. According to Jeong et al. (2010), NSE values larger than 0 indicate minimally acceptable performance and greater than 0.65 on a daily basis is preferred. Ritter and Muñoz-Carpena (2013) suggested NSE ranges of unsatisfactory (<0.650), acceptable (0.650 – 0.799), good (0.800 – 0.899), and very good (0.900 – 1.000). However, the NSE is subjective and may be lower for sub-daily results and higher for monthly or annual outputs. Limitations to the NSE include sensitivity to sample size, outliers, magnitude bias, and time-offset bias.

The root mean square error (RMSE) was selected to measure the absolute error (Equation 1-49). The root mean square error, also a dimensioned model prediction error, is a function of average error, squared errors, and $n^{1/2}$. Though frequently used as a measure for environmental models, its meaning is often misinterpreted by researchers (Willmott and Matsuura 2005). Squaring the residual errors allows the magnitude to affect the metric and not the positive or negative difference. However, this exacerbates the influence of large errors allowing a few large errors to increase the RMSE when there may be few small errors.

The FITEVAL software was used to determine the strength and appropriateness of the models evaluated in this paper (Ritter and Muñoz-Carpena 2013). This software uses a block bootstrap method for stationary dependent data (Politis and Romano 1994) resulting in a probability distribution of NSE and RMSE scores. FITEVAL was an important tool in determining whether the single values calculated from Equation 1-47 and Equation 1-49 using the entire dataset is representative of all parts of the dataset. Additionally, this software had the ability to incorporate uncertainty based on error inherent in the measured soil moisture estimated by the manufacturer of the TDR sensors as within +/-2.5% by volume of true soil moisture (Campbell Scientific 2014). The models were evaluated against measured soil moisture based on absolute measurements and uncertainty ranges resulting in two sets of NSE results.

Results

PSREU

There were a total of 70 days that received rainfall or irrigation during the 175 day study period located at the PSREU. Out of the daily totals, 38 days had depths greater than 2.54 mm with a maximum depth of 88 mm occurring on Feb. 24, 2004. These events translated to 167 h with water inputs across the 4,175 h period with 61 h that had water inputs greater than 2.54 mm. The maximum intensity of 3.63 mm h^{-1} occurred as a single event on May 18, 2004.

This study was separated into two sets of data for calibration and validation purposes. The calibration period was selected as the first 1,000 h of the study period, occurring from Jan. 1, 2004 through Feb. 11, 2004. There were 15 h of rainfall or irrigation with only 4 h where rainfall was greater than 2.54 mm. The largest event of 35.1 mm occurred in one hour on Feb. 1, 2004. The validation period occurred from Feb. 12, 2004 through Jun. 22, 2004 that included the remaining 3,175 h of the data and 152 h of rainfall or irrigation.

Calibration period

Out of the six layers representing observation points that occurred every 15 cm until the final depth of 90 cm, the best agreement occurred by HYDRUS-1D with NSE ranging from 0.629 to 0.855 across layers (Table 4-12). Results were also in an acceptable range for hourly SWB in the top two layers, with NSE calculated as 0.659 for the first layer and 0.663 for the second layer. However, NSE declined for each additional layer occurring below the second layer with bias occurring in the sixth layer for hourly SWB. When matching results by layer, the RMSE for HYDRUS-1D (0.004 $mm^3\ mm^{-3}$ – 0.009 $mm^3\ mm^{-3}$) was either the same or lower than RMSE for hourly SWB (0.007 $mm^3\ mm^{-3}$ – 0.011 $mm^3\ mm^{-3}$) indicating slightly less error when using HYDRUS-1D. Taking the measurement error of the sensor into consideration using the block bootstrapping method, average NSE increased to minimums of 0.989 for hourly SWB and 0.994 for HYDRUS-1D and remained above 0.900 for all iterations of all layers indicating acceptable model results with no bias.

The daily SWAT is a specific version of a daily soil water balance that does not accommodate layers thus only the surface layer was evaluated for this dataset. The NSE for the daily SWAT was 0.514 for this top layer, which was below the limit of acceptable performance (Ritter and Muñoz-Carpena 2013). The RMSE was also highest of the three models, estimated as 0.008 mm^3 mm^{-3}, indicating that the daily SWAT had the highest error.

In general, both multi-layer models best approximated the measured data during periods of declining VWC within the first layer while responding to rainfall or irrigation events by over-predicting the increased VWC (Figure 4-1). There were two instances when both models responded to an increase in VWC due to a rainfall or irrigation event that was not reflected in the observed data. An over-estimated response in VWC occurred by both models on Jan. 10. After this event, the hourly SWB declined at a faster rate than the measured data resulting in slight under-estimation before the next peak occurring on Jan. 19. However, it appeared that HYDRUS-1D declined at an appropriate rate resulting in continued over-estimation of VWC over these ten days.

Results for the hourly SWB in the second layer (NSE = 0.663) were similar to the results in the first layer (NSE = 0.659) whereas NSE results declined for the second layer from 0.756 to 0.629 for HYDRUS-1D, thus falling just below the threshold for acceptable performance of 0.65 (Table 4-12). In general, VWC was over-estimated by HYDRUS-1D over the calibration period compared to the hourly SWB that under-estimated VWC at the beginning of the period but slightly overestimated VWC for the remainder of the period (Figure 4-2). Both models responded appropriately to the three sharp increases observed in the measured VWC data with the exception of the last instance where the hourly SWB had a small change in soil moisture. Due to this discrepancy, the hourly SWB did not exhibit the curved decline to field capacity and overestimated VWC for the remainder of the calibration period.

Both models best approximated the measured VWC during the first 20 days of the calibration period when there was no rainfall or irrigation events indicating that ET_C losses were accurately predicted for the third layer (Figure 4-3). However, the volume of water entering the layer from the upper adjacent layer during rainfall or irrigation was under-estimated for two of the events by the hourly SWB resulting in an NSE of 0.454. The HYDRUS-1D better approximated the infiltration of water entering the layer resulting in an NSE of 0.855.

In the remaining layers, the hourly SWB maintained RMSE ranging from 0.009 mm^3 mm^{-3} (Layer 5) to 0.011 mm^3 mm^{-3} (Layer 4) and NSE ranging from -0.299 (Layer 6) to 0.224 (Layer 5) thus performance was unacceptable (Table 4-12). There was little difference in RMSE and NSE results between the third, fourth, and fifth layers for the hourly SWB model. Similar to the results of the third layer, the hourly SWB best approximated the measured VWC during the first portion of the calibration period for the fourth (Figure 4-4) and fifth (Figure 4-5) layers, but increased only slightly in response to rainfall or irrigation events compared to the measured VWC. The sixth layer was the only layer to exhibit signs of model bias as indicated by a negative NSE score where the error between the observed and predicted values was greater than the error in the observed values and average of observed values. However, the NSE results were always acceptable when taking into account measurement error with an average NSE score of 0.989 for the final layer. The VWC was not influenced by rainfall and irrigation events for the hourly SWB in the sixth layer (Figure 4-6).

The model results obtained by using HYDRUS-1D ranged from 0.004 mm^3 mm^{-3} (Layer 6) to 0.006 mm^3 mm^{-3} (Layer 4) in RMSE and 0.743 (Layer 5) to 0.849 (Layer 6) in NSE (Table 4-12). These results indicate that the HYDRUS-1D was consistent in estimating VWC at all depths evaluated as a part of this study. Considering measurement error, 100% of NSE remained above 0.9 with averages above 0.998 for the fourth through sixth layers, respectively. Graphical results showed that the HYDRUS-1D continued to under-estimate VWC during the last observed rainfall or irrigation event for all three of the lower layers. This resulted in over-estimated VWC occurring after the peak in the fourth layer (Figure 4-4). In the fifth and sixth layers, VWC determined by HYDRUS-1D closely approximated measured VWC with the only deviation occurring in the final peak (Figure 4-5; Figure 4-6).

Validation period

Despite good results during the calibration period, HYDRUS-1D failed to adequately predict VWC for all layers during the validation period with RMSE ranging from 0.020 mm^3 mm^{-3} (Layer 3 and 5) to 0.035 mm^3 mm^{-3} (Layer 2) and NSE ranging from -0.452 (Layer 1) to -2.703 (Layer 6) (Table 4-12). Over-estimation of VWC occurred for all six layers indicating that the calibration results were not adequate in representing the validation period for this model. Alternative periods were evaluated to determine if the soil hydraulic parameters could have been better approximated based on better model agreement, but model outcomes remained consistent to the results presented here.

The RMSE for the hourly SWB model ranged from 0.012 mm^3 mm^{-3} (Layers 3 and 6) to 0.018 mm^3 mm^{-3} (Layers 1, 2, and 4) while the NSE ranged from -0.729 (Layer 5) to 0.383 (Layer 1), respectively (Table 4-12). The results of the first two layers were similar for this model, indicating consistent approximations of VWC in the top 37.5 cm. However, the NSE for all layers were below 0.65 thus resulting in unacceptable approximations of the field-measured VWC. In the first layer, there were over-estimations in peak VWC that occurred in response to rainfall or irrigation events (Figure 4-7). In the second layer, VWC was under-estimated multiple times, but did not have the large errors in peak VWC observed in the first layer (Figure 4-8). The bottom four layers did not have good agreement with the measured VWC primarily due to no response to at least six rainfall or irrigation events in layer 3 (Figure 4-9), seven events in layer 4 (Figure 4-10), five events in layer 5 (Figure 4-11), and all events in layer 6 (Figure 4-12). These results indicate that there was model error in the assumptions used to determine percolation to lower layers.

Model bias occurred for HYDRUS-1D in all six layers resulting in negative values of NSE. However, the NSE averages assuming measurement error ranged from 0.907 (Layer 2) to 0.954 (Layer 4) during this period. Though the averages fell within the “very good” range defined as greater than 0.900 (Ritter and Muñoz-Carpena 2013), the probability distribution of NSE for the first and second layers had results falling within the “good” range of 0.800 to 0.899, totaling 5.2% and 36.7% for respective layers. The fifth and sixth layers had similar results with 0.3% and 7.4% of results falling into the “good” range. A majority of calculated NSE values were within the “very good” category for all six layers.

The model results for the daily SWAT were 0.019 mm^3 mm^{-3} for RMSE and 0.331 for NSE. Both of these performance measures were slightly worse than the results for the hourly SWB for the surface layer. Based on the performance thresholds proposed by Ritter and Muñoz-Carpena (2013), the daily SWAT was not an adequate model for estimating VWC.

In this study, HYDRUS-1D was successful at predicting VWC during the calibration period, but failed to have the same agreement during the validation period (Table 4-12). According to soil testing conducted in 2007 at the site, the saturated hydraulic conductivity averaged 317 mm h^{-1} at the 15 cm depth, 774 mm h^{-1} at the 30 cm depth, and 1,298 mm h^{-1} at the 45 cm depth. However, the inverse solution feature within HYDRUS-1D calibrated the saturated hydraulic conductivities to 5 mm h^{-1}, 5 mm h^{-1}, and 6.2 mm h^{-1} for the respective layers. Similar inaccuracies occurred for θ_r and θ_s with averages of 0.06 mm^3 mm^{-3} and 0.33 mm^3 mm^{-3}, respectively. Though the θ_r estimated using the inverse solution (0.055 mm^3 mm^{-3}) was appropriate for the first layer, estimations of 0.09 mm^3 mm^{-3} for each of the second and third layers were likely too high. Also, θ_s was estimated as 0.22 mm^3 mm^{-3} using the inverse solution, which was likely too low. The inverse solution function in HYDRUS-1D was only able to use the information given during the calibration period where measured VWC had a minimum of 0.12 mm^3 mm^{-3} and a maximum of 0.21 mm^3 mm^{-3}. Approximating the soil hydraulic parameters using a dataset that ranges from θ_r to θ_s during the calibration period was extremely important to the prediction of VWC by HYDRUS-1D during the validation period, but was unavailable for this study. However, using the same calibrated parameters in the hourly SWB had less effect on predicting VWC.

GCREC

Over the 10,968 hours processed for this dataset, there were 447 h with rainfall and 85 h where rainfall was greater than 2.54 mm. The maximum rainfall intensity observed was 64 mm/h with a maximum daily rainfall of 125 mm. According to an analysis completed by Davis et al. (2009), rainfall was significantly less frequent and lower in magnitude for this study period resulting in 33% less cumulative rainfall compared to the historical average.

There were 102 (RTIME) to 233 (Weathermatic) irrigation events logged by timestamp for all four treatments evaluated in this study. The ET controller treatments tended to irrigate more than twice per week when water restrictions were removed in the middle of the study period, beginning on Feb. 26, 2007. Due to the differences in the ways that the Weathermatic and Toro controllers schedule irrigation, the Weathermatic had 65 more irrigation events than the Toro. The TIME treatment had one additional event compared to the RTIME treatment due to rainfall occurring between the treatment runtimes that triggered the rain sensor to bypass mode.

The data set was separated into two periods for calibration and validation purposes resulting in a calibration period of Aug. 25, 2007 through Nov. 12, 2007 and validation period of Aug. 13, 2006 through Aug. 24, 2007. There were 112 rainfall events and 54 irrigation events during the 1,920 h calibration period with one rainfall event lasting 10 h that totaled 85 mm on Oct. 5, 2007. The remaining rainfall (335 h) and irrigation (84-179) events occurred during the validation period. Additionally, two 1-month periods within the validation period were selected as having frequent rainfall (Sep. 1, 2006 – Oct. 1, 2006) and infrequent rainfall (Apr. 1, 2007 – May 1, 2007) for further graphical evaluation of the models.

Calibration period

Results from the calibration period indicate acceptable agreement with measured VWC for all four treatments using all three models. The RMSE ranged from 0.020 mm^3 mm^{-3} (RTIME) to 0.024 mm^3 mm^{-3} (Toro, TIME) for the daily SWAT model, 0.017 mm^3 mm^{-3} (Weathermatic) to 0.022 mm^3 mm^{-3} (TIME) for the hourly SWB model, and 0.015

$mm^3\ mm^{-3}$ (Weathermatic) to 0.019 $mm^3\ mm^{-3}$ (TIME) using HYDRUS-1D (Table 4-13). The NSE ranged from 0.124 (TIME) to 0.413 (RTIME) for the daily SWAT model, 0.182 (TIME) to 0.310 (Toro) for the hourly SWB model, and 0.384 (Weathermatic) to 0.537 (RTIME) for HYDRUS-1D. With few exceptions, results improved by using the hourly SWB over the daily SWAT model, but the best results were achieved by HYDRUS-1D.

Taking into account measurement error of the sensors, average NSE increased for all three models. In general, the daily SWAT model had a lower average, ranging from 0.965 (TIME) to 0.978 (Weathermatic, RTIME), than the hourly SWB model, ranging from 0.971 (TIME) to 0.986 (Weathermatic). The highest scores within each treatment occurred by the HYDRUS-1D model, ranging from 0.979 (TIME) to 0.989 (Weathermatic). Maximum and minimum scores were obtained by the same treatments for each model, indicating that there was better calibration of the Weathermatic treatment than the TIME treatment likely due to soil profile characteristics that were not accurately represented in the models.

The results showed that the hourly SWB and HYDRUS-1D generally followed the fluctuations in VWC over time while the daily SWAT model maintained the average of the VWC curve without responding to sub-daily fluctuations (Figure 4-13, Figure 4-14, Figure 4-15, Figure 4-16). Additionally, the best agreement by the hourly SWB and HYDRUS-1D occurred when there were small increases in VWC. Large rainfall and irrigation events drained slower than predicted by both models with more error in the hourly SWB than HYDRUS-1D, which was true for all four treatments and clearly observed in the rainfall event on Oct. 5. The VWC frequently exceeded field capacity resulting in increased error for the daily SWAT model compared to the sub-daily models.

Validation period

The RMSE for all four treatments ranged from 0.017 $mm^3\ mm^{-3}$ (Weathermatic, RTIME) to 0.021 $mm^3\ mm^{-3}$ (Toro) for the daily SWAT model, 0.016 $mm^3\ mm^{-3}$ (TIME) to 0.022 $mm^3\ mm^{-3}$ (Toro) for the hourly SWAT model, and 0.013 $mm^3\ mm^{-3}$ (Weathermatic) to 0.018 $mm^3\ mm^{-3}$ (Toro) for HYDRUS-1D (Table 4-13). The NSE ranged from 0.011 (Weathermatic) to 0.490 (RTIME) for the daily SWAT model, 0.224 (Weathermatic) to 0.569 (TIME) for the hourly SWB model, and 0.504 (Toro) to 0.655 (TIME) for HYDRUS-1D. The NSE within each treatment improved with the increasing complexity of the model with lowest scores obtained by the daily SWAT model and highest scores obtained by HYDRUS-1D. However, the only treatments with acceptable performance occurred for HYDRUS-1D with the TIME and RTIME treatments only, barely exceeding the threshold of 0.65.

The average NSE increased for all treatments and models when the measurement error was taken into account (Table 4-13). The NSE ranged from 0.971 (Toro) to 0.982 (Weathermatic) for the daily SWAT model, 0.964 (RTIME) to 0.984 (Weathermatic, TIME) for the hourly SWB, and 0.981 (Toro) to 0.991 (Weathermatic) for HYDRUS-1D. The probability distribution of generated scores using the block bootstrapping technique fell within the “very good” category for all three models, indicating that the performance was stable and not bias.

During the month selected as the frequent rainfall period, there were a total of 15 rainfall events with two large rainfall events occurring on Sep. 3, totaling 34 mm, and Sep. 20, totaling 26 mm. In general, good approximation of the VWC draw down curve occurred by the hourly SWB for the first large rainfall event for all four treatments, but there was significantly more error in the second rainfall event (Figure 4-17A, Figure 4-18A, Figure 4-19A, Figure 4-20A). An exception occurred for the TIME treatment where the drawdown occurred more quickly in the model compared to the measured VWC during the first rainfall event with general underestimation of VWC over the month. The HYDRUS-1D model also underestimated measured VWC over the month, including both large rainfall events, for the TIME treatment. Overestimation of measured VWC occurred for the Weathermatic by both sub-daily models with the best approximations occurring for the Toro and RTIME treatments. The daily SWAT model responded to the frequent rainfall events, but failed to increase above field capacity resulting in a moving average of measured VWC.

Irrigation was the primary water input to the soil profile during the infrequent rainfall period. The Weathermatic was designed to accumulate deficits until the next allowable watering day, which was set to every day, thus resulting in daily irrigation events for this controller (Figure 4-17B). Due to daily irrigation, runtimes were short resulting in small increases in measured VWC. The daily SWAT model rarely fluctuated at all except during periods of drawdown occurring after a rainfall event whereas the hourly SWB and HYDRUS-1D models better approximated the sub-daily fluctuations in VWC. The Toro also irrigated frequently with shorter runtimes, but irrigated every other day (Figure 4-18B). Irrigation was best approximated by the HYDRUS-1D model due to periods of large underestimations by the hourly SWB.

The time-based treatments, TIME (Figure 4-19B) and RTIME (Figure 4-20B), applied the net irrigation requirement based on historical ET_C and rainfall in twice per week irrigation events to represent local water restrictions. The rain sensor associated with the TIME and RTIME treatments stopped working on Apr. 19, 2007 causing all irrigation to be bypassed despite many days without rainfall. During this time, measured VWC decreased significantly for both treatments, almost approximating θ_{PWP}. The hourly SWB model also declined with lower predictions than were measured by a maximum difference of 2.3% (RTIME) whereas HYDRUS-1D over-predicted VWC by a difference of 2.9% (TIME). This indicates that the stress coefficient added to the ET_C term when below θ_{MAD} was an appropriate estimation of the increasing difficulty of removing water from the soil system as VWC decreases. The daily SWAT model failed to account for VWC below θ_{MAD} that occurred between irrigation events.

The hourly SWB showed promising modeling outcomes compared to the daily SWAT model, but there were sources of error where VWC was either under- or over-predicted in all evaluated treatments resulting in neither model meeting acceptable performance standards. This indicates that some of the soil water interactions were not fully accounted for in the hourly SWB model. Some interactions could include lateral water movement, hysteresis, or a shallow water table. The HYDRUS-1D model also did not account for all soil water interactions, but had better results during the GCREC field study due to better approximations of water movement throughout the soil profile.

By design, the daily SWAT model was unable to simulate changes in VWC at the sub-daily scale or account for VWC above θ_{FC} and below θ_{PWP}. These assumptions may be acceptable for current ET controller testing because ET controllers apply irrigation in short, frequent irrigation events to maintain well-watered conditions. However, maintaining well-watered conditions is unnecessary for residential landscapes where maximum growth is not required. Thus, moving to a similar, more accurate model for ET controller testing that can account for the full range of water movement in the soil profile may encourage ET controller designs to allow less than well-watered conditions that promotes water conservation.

The NSE results during the calibration periods were higher for HYDRUS-1D compared to the hourly SWB for both studies. The major drawback to the soil water balance approach included significantly increased errors in layers that were deeper than 37.5 cm due to inaccurate estimations of infiltration causing compounded error in runoff and deep percolation estimates. Richards equation (used by HYDRUS-1D) or modified Green-Ampt with redistribution would have been more appropriate models that have more accurate estimations of VWC (Gowdish and Muñoz-Carpena 2009, Smith et al. 1993, Šimůnek and Hopmans 2009, Ogden and Saghafian 1997). However, the benefits to the hourly SWB such as less parameterization, shorter processing times, and stable, well-known software combined with NSE from the hourly SWB that was better than the current model outweigh the drawbacks to NSE that was lower than HYDRUS-1D. Additionally, the model's purpose is to evaluate performance over a minimum of thirty days thus VWC estimations over longer time periods were more important to this analysis than VWC at specific points in time. Thus, the hourly SWB would be preferable to HYDRUS-1D in association with longer time periods of relative soil moisture whereas HYDRUS-1D would be more appropriate for short time periods when absolute soil moisture is important.

The purpose of the SWAT test was to generate performance scores based on scheduling efficiency and irrigation adequacy where 100% scores are achieved when there is no over- and under-irrigation, respectively. The performance scores achieved when using the daily SWAT test fail to translate to real world performance due to the inability to represent the real system. The results from the analyses for the hourly SWB model indicate that the performance scores would likely be more accurate in the translation of performance scores to water savings. This relationship will be evaluated in Chapter 5.

Conclusions

The hourly soil water balance had better agreement with the deterministic soil water model compared to a daily soil water balance. This was shown in the first layer of the PSREU study during the calibration period where the NSE was 0.659 for the hourly SWB but only 0.514 for the daily SWAT, falling below the acceptable threshold for hydrological models of 0.65. Both models failed to meet the threshold during the validation period or during either period of the GCREC study. The hourly SWB had higher NSE results for the ET controller treatments, ranging from 0.224 to 0.266, during the validation period of the GCREC study compared to the daily SWAT, ranging from 0.011 to 0.181. Based on the results, the hourly SWB improved estimates of volumetric water content in a shallow root zone compared to the current testing standard.

The deterministic model required extensive parameterization of soil water characteristics that did not always translate to outside of the calibration period whereas the hourly soil water balance was more consistent in estimating volumetric water content using the same estimated parameters. This was clearly shown in the PSREU study where NSE results dropped for both models from the calibration period to the validation period, but NSE fell from 0.659 to 0.383 for the first layer whereas NSE fell from 0.756 to -0.452 for HYDRUS-1D in the same layer. Though the hourly SWB was not acceptable as a hydrological model, there was bias in using HYDRUS-1D during the validation period resulting in extremely poor agreement with field measured VWC.

The hourly soil water balance had its best agreement with field measured data within the top 37.5 cm of the soil profile, but results declined after the second layer due to accumulating errors as the layer depth increased. This was clear in the PSREU study during the calibration period where acceptable NSE results were 0.659 (layer 1) and 0.663 (layer 2), but increasingly declined in the remaining four layers. The same trend occurred during the validation period where the NSE was 0.383 (layer 1) and 0.358 (layer 2), but was negative for layers 3-5 and was only slightly above zero for layer 6. Thus, using the hourly SWB in layered scenarios greater than two layers is unadvisable without improvements to the model.

Though the daily soil water balance is an accepted method for estimating irrigation requirements, it does not accurately reflect the actual water movement in the soil profile that occurs on a sub-daily basis. Based on these results, there is confidence in implementing the hourly soil water balance as an alternative method for testing ET controllers that will more accurately reflect true soil-water relationships thus allowing for the estimation of water conservation potential.

Table 4-1. Crop coefficients used for each study location adapted from Jia et al. (2009).

Month	North Florida Crop Coefficient	Southwest Florida Crop Coefficient
January	0.35	0.45
February	0.35	0.45
March	0.55	0.55
April	0.80	0.80
May	0.90	0.90
June	0.75	0.75
July	0.70	0.70
August	0.70	0.70
September	0.75	0.75
October	0.70	0.70
November	0.60	0.60
December	0.45	0.45

Table 4-2. Hydraulic parameters required by the hourly SWB and HYDRUS-1D models for Layer 1 (0 – 22.5 cm) at the PSREU location.

Characteristic	Abbreviation (units)	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} ($mm^3\ mm^{-3}$)	0.055	0.055
Field Capacity	θ_{FC} ($mm^3\ mm^{-3}$)	0.15	NA
Saturation	θ_S ($mm^3\ mm^{-3}$)	0.22	0.22
Root depth	RZ (mm)	225	220
Allowable Surface Accumulation	ASA (mm)	0	0
Decay Time	t (h)	48	NA
Van Genuchten parameter	n	NA	1.93
Van Genuchten parameter	α (mm^{-1})	NA	0.0014
Saturated Hydraulic Conductivity	K_s ($mm\ h^{-1}$)	NA	5

Note: NA indicates that the parameter was not applicable to the model.

Table 4-3. Hydraulic parameters required by the hourly SWB and HYDRUS-1D models for Layer 2 (22.5 – 37.5 cm) at the PSREU location.

Characteristic	Abbreviation (units)	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} (mm^3 mm^{-3})	0.09	0.09
Field Capacity	θ_{FC} (mm^3 mm^{-3})	0.15	NA
Saturation	θ_S (mm^3 mm^{-3})	0.22	0.22
Root depth	RZ (mm)	150	150
Allowable Surface Accumulation	ASA (mm)	0	0
Decay Time	t (h)	48	NA
Van Genuchten parameter	n	NA	2.99
Van Genuchten parameter	α (mm^{-1})	NA	0.0011
Saturated Hydraulic Conductivity	K_s (mm h^{-1})	NA	5

Note: NA indicates that the parameter was not applicable to the model.

Table 4-4. Hydraulic parameters required by the hourly SWB and HYDRUS-1D models for Layer 3 (37.5 – 52.5 cm) at the PSREU location.

Characteristic	Abbreviation (units)	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} (mm^3 mm^{-3})	0.09	0.09
Field Capacity	θ_{FC} (mm^3 mm^{-3})	0.12	NA
Saturation	θ_S (mm^3 mm^{-3})	0.21	0.21
Root depth	RZ (mm)	150	150
Allowable Surface Accumulation	ASA (mm)	0	0
Decay Time	t (h)	48	NA
Van Genuchten parameter	n	NA	3.67
Van Genuchten parameter	α (mm^{-1})	NA	0.0016
Saturated Hydraulic Conductivity	K_s (mm h^{-1})	NA	6.2

Note: NA indicates that the parameter was not applicable to the model.

Table 4-5. Hydraulic parameters required by the hourly SWB and HYDRUS-1D models for Layer 4 (52.5 – 67.5 cm) at the PSREU location.

Characteristic	Abbreviation (units)	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} (mm^3 mm^{-3})	0.078	0.078
Field Capacity	θ_{FC} (mm^3 mm^{-3})	0.16	NA
Saturation	θ_S (mm^3 mm^{-3})	0.24	0.24
Root depth	RZ (mm)	150	150
Allowable Surface Accumulation	ASA (mm)	0	0
Decay Time	t (h)	48	NA
Van Genuchten parameter	n	NA	1.58
Van Genuchten parameter	α (mm^{-1})	NA	0.0021
Saturated Hydraulic Conductivity	K_s (mm h^{-1})	NA	11.2

Note: NA indicates that the parameter was not applicable to the model.

Table 4-6. Hydraulic parameters required by the hourly SWB and HYDRUS-1D models for Layer 5 (67.5 – 82.5 cm) at the PSREU location.

Characteristic	Abbreviation (units)	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} (mm^3 mm^{-3})	0.09	0.09
Field Capacity	θ_{FC} (mm^3 mm^{-3})	0.20	NA
Saturation	θ_S (mm^3 mm^{-3})	0.23	0.23
Root depth	RZ (mm)	150	150
Allowable Surface Accumulation	ASA (mm)	0	0
Decay Time	t (h)	48	NA
Van Genuchten parameter	n	NA	2.48
Van Genuchten parameter	α (mm^{-1})	NA	0.0013
Saturated Hydraulic Conductivity	K_s (mm h^{-1})	NA	16

Note: NA indicates that the parameter was not applicable to the model

Table 4-7. Hydraulic parameters required by the hourly SWB and HYDRUS-1D models for Layer 6 (82.5 – 97.5 cm) at the PSREU location.

Characteristic	Abbreviation (units)	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} (mm^3 mm^{-3})	0.09	0.09
Field Capacity	θ_{FC} (mm^3 mm^{-3})	0.20	NA
Saturation	θ_S (mm^3 mm^{-3})	0.22	0.22
Root depth	RZ (mm)	150	150
Allowable Surface Accumulation	ASA (mm)	0	0
Decay Time	t (h)	48	NA
Van Genuchten parameter	n	NA	2.56
Van Genuchten parameter	α (mm^{-1})	NA	0.001
Saturated Hydraulic Conductivity	K_s (mm h^{-1})	NA	17.8

Note: NA indicates that the parameter was not applicable to the model.

Table 4-8. Hydraulic parameters required for each model for the Weathermatic at the GCREC location.

Characteristic	Abbreviation (units)	Daily SWAT	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} ($mm^3\ mm^{-3}$)	NA	0.0665	0.0665
Field Capacity	θ_{FC} ($mm^3\ mm^{-3}$)	0.17	0.165	NA
Saturation	θ_S ($mm^3\ mm^{-3}$)	NA	0.480	0.480
Root depth	RZ (mm)	305	305	305
Allowable Surface Accumulation	ASA (mm)	0	0	0
Decay Time	t (h)	NA	48	NA
Van Genuchten parameter	n	NA	NA	1.925
Van Genuchten parameter	α (mm^{-1})	NA	NA	0.0192
Saturated Hydraulic Conductivity	K_s ($mm\ h^{-1}$)	NA	NA	91.2

Note: NA indicates that the parameter was not applicable to the model.

Table 4-9. Hydraulic parameters required for each model for the Toro at the GCREC location.

Characteristic	Abbreviation (units)	Daily SWAT	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} ($mm^3\ mm^{-3}$)	NA	0.0414	0.0414
Field Capacity	θ_{FC} ($mm^3\ mm^{-3}$)	0.17	0.164	NA
Saturation	θ_S ($mm^3\ mm^{-3}$)	NA	0.443	0.443
Root depth	RZ (mm)	305	305	305
Allowable Surface Accumulation	ASA (mm)	0	0	0
Decay Time	t (h)	NA	48	NA
Van Genuchten parameter	n	NA	NA	2.161
Van Genuchten parameter	α (mm^{-1})	NA	NA	0.0105
Saturated Hydraulic Conductivity	K_s ($mm\ h^{-1}$)	NA	NA	12.9

Note: NA indicates that the parameter was not applicable to the model.

Table 4-10. Hydraulic parameters required for each model for TIME at the GCREC location.

Characteristic	Abbreviation (units)	Daily SWAT	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} (mm^3 mm^{-3})	NA	0.0613	0.0613
Field Capacity	θ_{FC} (mm^3 mm^{-3})	0.17	0.161	NA
Saturation	θ_S (mm^3 mm^{-3})	NA	0.376	0.376
Root depth	RZ (mm)	305	305	305
Allowable Surface Accumulation	ASA (mm)	0	0	0
Decay Time	t (h)	NA	48	NA
Van Genuchten parameter	n	NA	NA	1.776
Van Genuchten parameter	α (mm^{-1})	NA	NA	0.0101
Saturated Hydraulic Conductivity	K_s (mm h^{-1})	NA	NA	70.4

Note: NA indicates that the parameter was not applicable to the model.

Table 4-11. Hydraulic parameters required for each model for RTIME at the GCREC location

Characteristic	Abbreviation (units)	Daily SWAT	Hourly SWB	HYDRUS-1D
Permanent Wilting Point	θ_{PWP} (mm^3 mm^{-3})	NA	0.0491	0.0491
Field Capacity	θ_{FC} (mm^3 mm^{-3})	0.17	0.167	NA
Saturation	θ_S (mm^3 mm^{-3})	NA	0.493	0. 493
Root depth	RZ (mm)	305	305	305
Allowable Surface Accumulation	ASA (mm)	0	0	0
Decay Time	t (h)	NA	48	NA
Van Genuchten parameter	n	NA	NA	2.319
Van Genuchten parameter	α (mm^{-1})	NA	NA	0.0100
Saturated Hydraulic Conductivity	K_s (mm h^{-1})	NA	NA	17.6

Note: NA indicates that the parameter was not applicable to the model.

Table 4-12. Evaluation measures of RMSE and NSE used to evaluate the model results during the calibration and validation periods for each layer in the PSREU study.

Layer Depth (cm)	Sensor Depth (cm)	Daily SWAT[a]	Hourly SWB	HYDRUS-1D
		Calibration Period RMSE ($mm^3\ mm^{-3}$)		
0 – 22.5	15	0.008	0.007	0.006
22.5 – 37.5	30	NA	0.009	0.009
37.5 – 52.5	45	NA	0.007	0.004
52.5 – 67.5	60	NA	0.011	0.006
67.5 – 82.5	75	NA	0.009	0.005
82.5 – 97.5	90	NA	0.010	0.004
		Calibration Period NSE[b]		
0 – 22.5	15	0.514 (0.995)	0.659 (0.996)	0.756 (0.997)
22.5 – 37.5	30	NA	0.663 (0.995)	0.629 (0.994)
37.5 – 52.5	45	NA	0.454 (0.994)	0.855 (0.998)
52.5 – 67.5	60	NA	0.224 (0.992)	0.811 (0.998)
67.5 – 82.5	75	NA	0.171 (0.993)	0.743 (0.998)
82.5 – 97.5	90	NA	-0.229 (0.989)	0.849 (0.999)
		Validation Period RMSE ($mm^3\ mm^{-3}$)		
0 – 22.5	15	0.019	0.018	0.027
22.5 – 37.5	30	NA	0.018	0.035
37.5 – 52.5	45	NA	0.012	0.020
52.5 – 67.5	60	NA	0.018	0.025
67.5 – 82.5	75	NA	0.017	0.020
82.5 – 97.5	90	NA	0.012	0.024
		Validation Period NSE		
0 – 22.5	15	0.331 (0.969)	0.383 (0.972)	-0.452 (0.933)
22.5 – 37.5	30	NA	0.358 (0.975)	-1.377 (0.907)
37.5 – 52.5	45	NA	-0.040 (0.981)	-2.108 (0.944)
52.5 – 67.5	60	NA	-0.369 (0.977)	-1.730 (0.954)
67.5 – 82.5	75	NA	-0.729 (0.967)	-1.509 (0.952)
82.5 – 97.5	90	NA	0.051 (0.983)	-2.703 (0.933)

[a]The daily SWAT is not capable of calculating layers thus all layers after the initial layer were not applicable (NA).
[b]Values in parentheses were averages determined using FITEVAL software that calculated the probability distribution of scores while incorporating the +/- 2% measurement error inherent in the soil moisture sensors.

Table 4-13. Evaluation measures of RMSE and NSE used to evaluate the model results during the calibration and validation periods for each treatment in the GCREC field study.

Treatment	Daily SWAT	Hourly SWB	HYDRUS-1D
	Calibration Period RMSE (mm^3 mm^{-3})		
Weathermatic	0.021	0.017	0.015
Toro	0.024	0.021	0.017
TIME	0.024	0.022	0.019
RTIME	0.020	0.020	0.016
	Calibration Period NSE		
Weathermatic	0.165 (0.978)	0.221 (0.986)	0.384 (0.989)
Toro	0.294 (0.967)	0.310 (0.976)	0.520 (0.984)
TIME	0.124 (0.965)	0.182 (0.971)	0.403 (0.979)
RTIME	0.413 (0.978)	0.299 (0.978)	0.537 (0.986)
	Validation Period RMSE (mm^3 mm^{-3})		
Weathermatic	0.017	0.017	0.013
Toro	0.021	0.022	0.018
TIME	0.018	0.016	0.014
RTIME	0.017	0.023	0.014
	Validation Period NSE		
Weathermatic	0.011 (0.982)	0.224 (0.984)	0.553 (0.991)
Toro	0.181 (0.971)	0.266 (0.972)	0.504 (0.981)
TIME	0.361 (0.978)	0.569 (0.984)	0.655 (0.987)
RTIME	0.490 (0.981)	0.077 (0.964)	0.651 (0.986)

Note: Values in parentheses were averages determined using FITEVAL software that calculated the probability distribution of scores while incorporating the +/- 2% measurement error inherent in the soil moisture sensors.

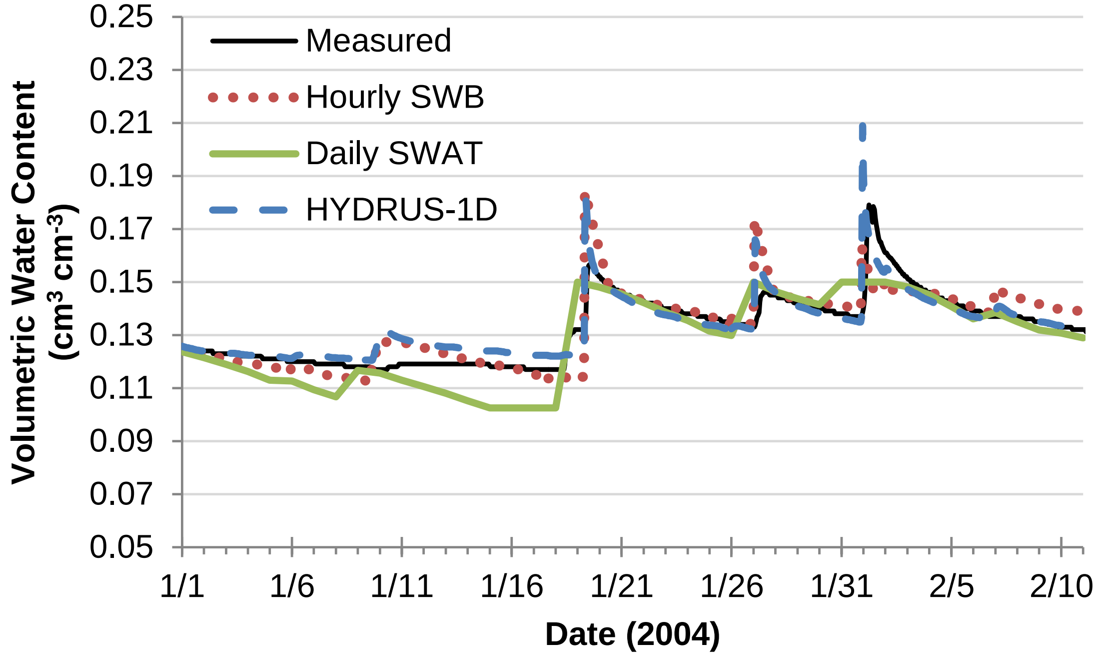

Figure 4-1. Time series comparison of volumetric water content measured at the 15 cm depth to three models in Citra, FL during the calibration period.

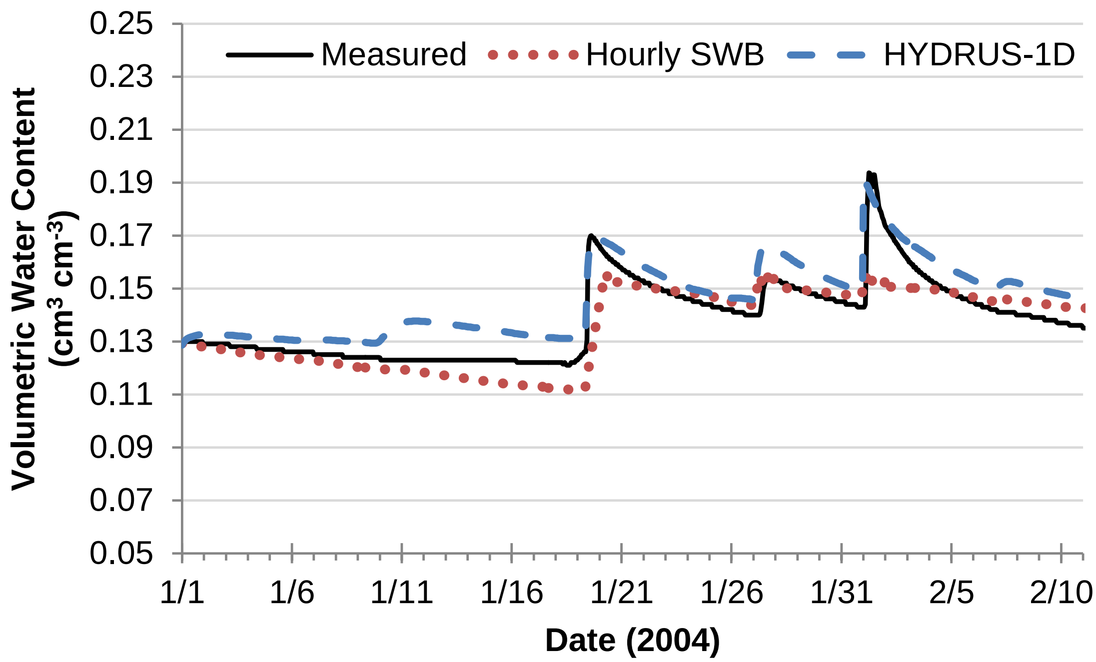

Figure 4-2. Time series comparison of volumetric water content measured at the 30 cm depth to two models in Citra, FL during the calibration period.

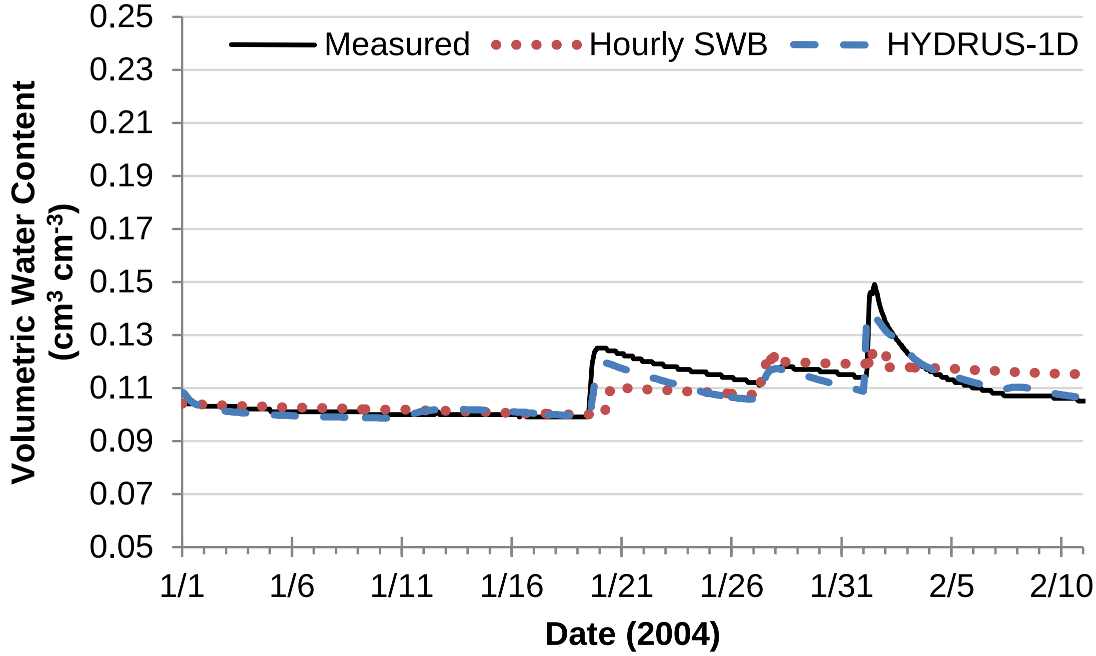

Figure 4-3. Time series comparison of volumetric water content measured at the 45 cm depth to two models in Citra, FL during the calibration period.

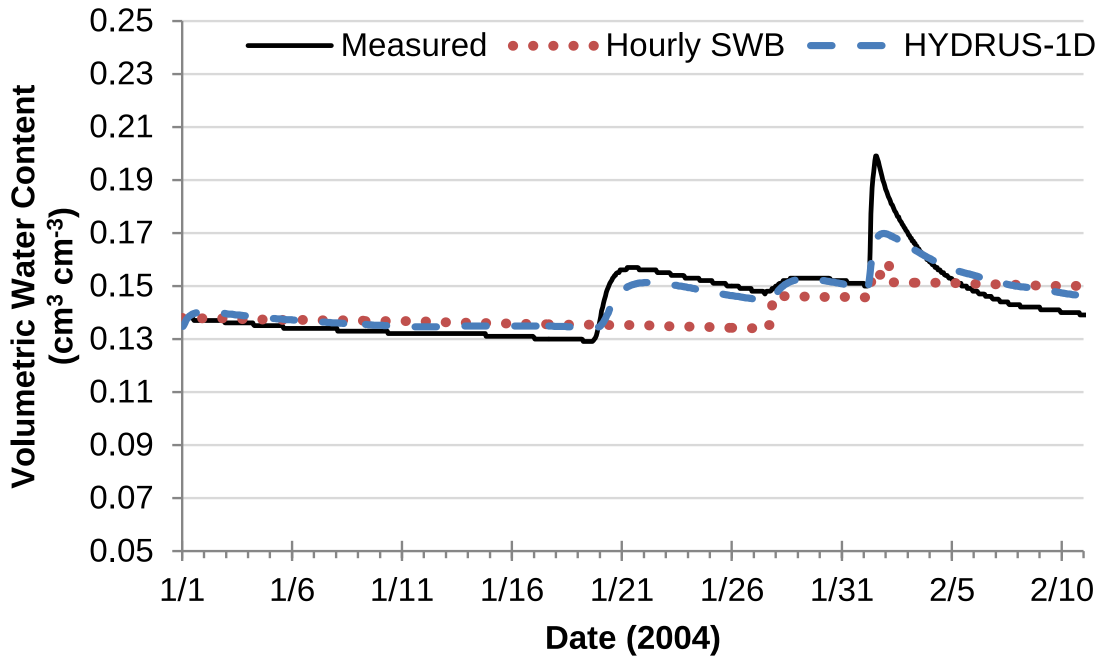

Figure 4-4. Time series comparison of volumetric water content measured at the 60 cm depth to two models in Citra, FL during the calibration period.

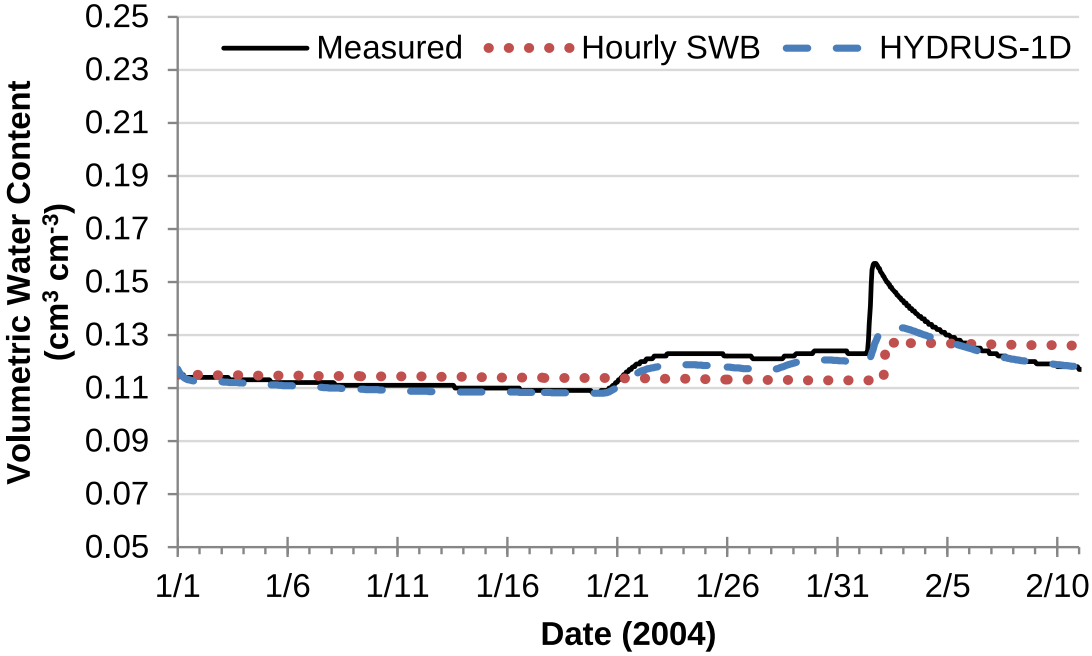

Figure 4-5. Time series comparison of volumetric water content measured at the 75 cm depth to two models in Citra, FL during the calibration period.

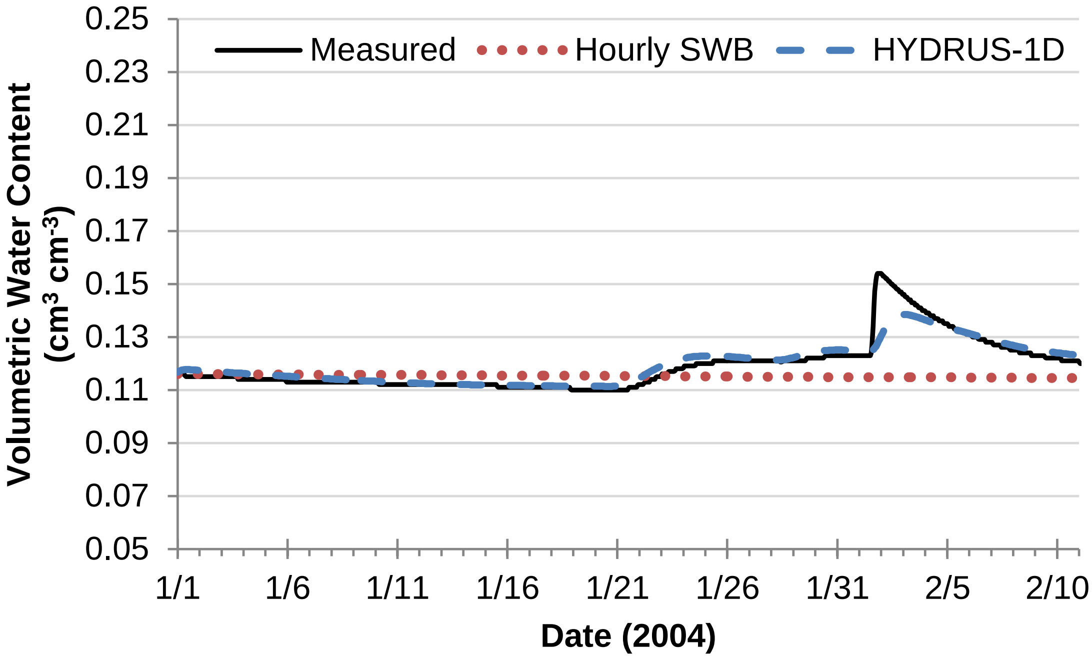

Figure 4-6. Time series comparison of volumetric water content measured at the 90 cm depth to two models in Citra, FL during the calibration period.

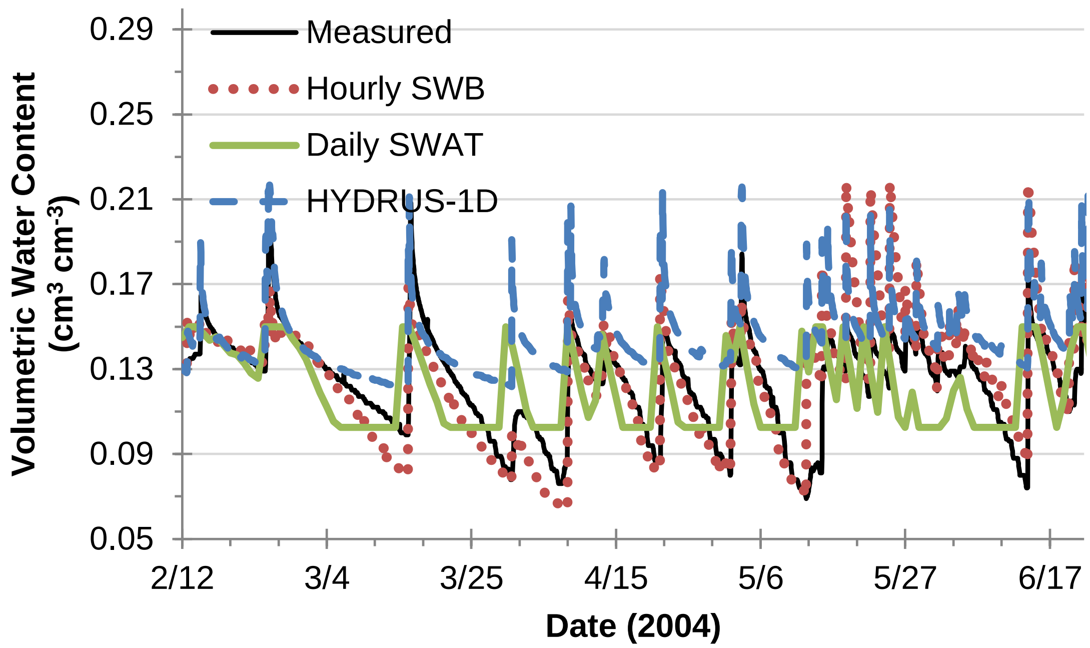

Figure 4-7. Time series comparison of volumetric water content measured at the 15 cm depth to the three models in Citra, FL during the validation period.

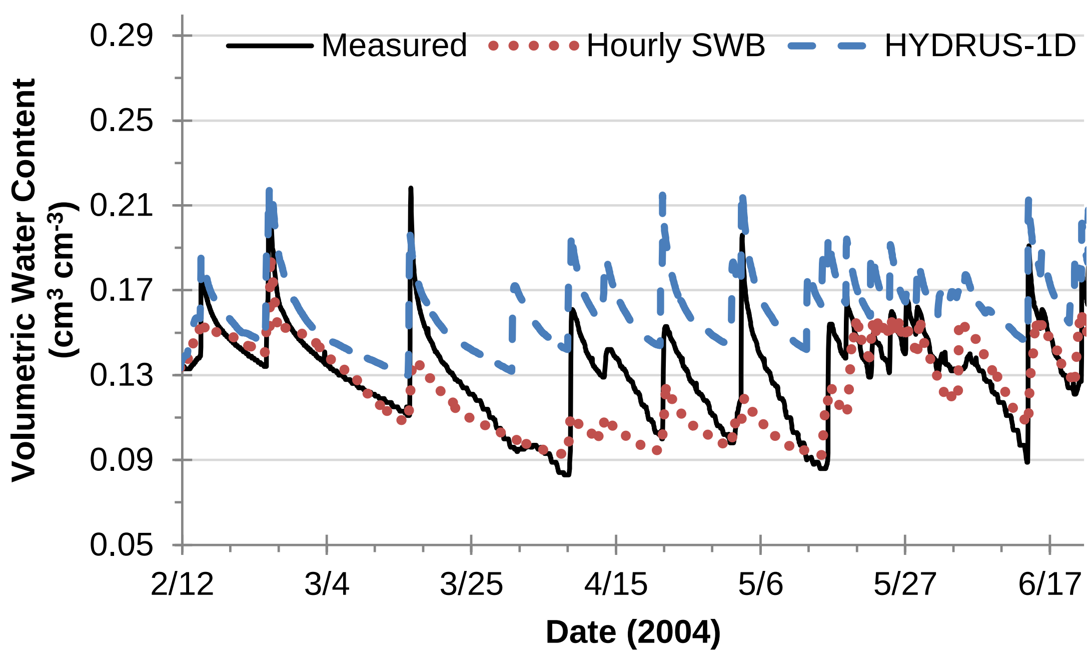

Figure 4-8. Time series comparison of volumetric water content measured at the 30 cm depth to the two models in Citra, FL during the validation period.

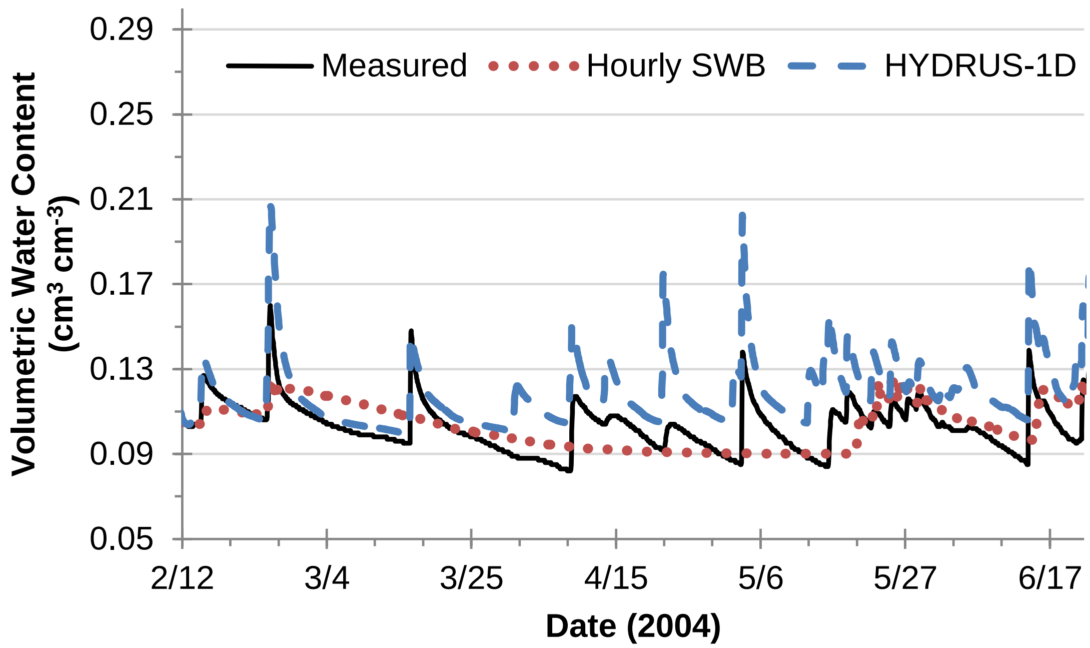

Figure 4-9. Time series comparison of volumetric water content measured at the 45 cm depth to the two models in Citra, FL during the validation period.

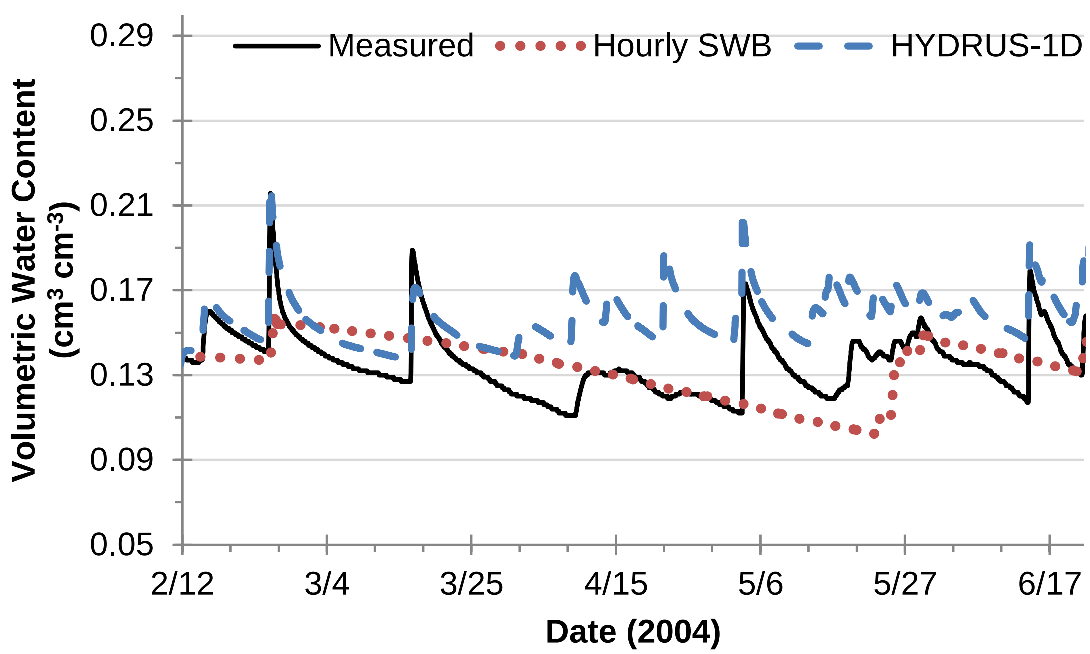

Figure 4-10. Time series comparison of volumetric water content measured at the 60 cm depth to the two models in Citra, FL during the validation period.

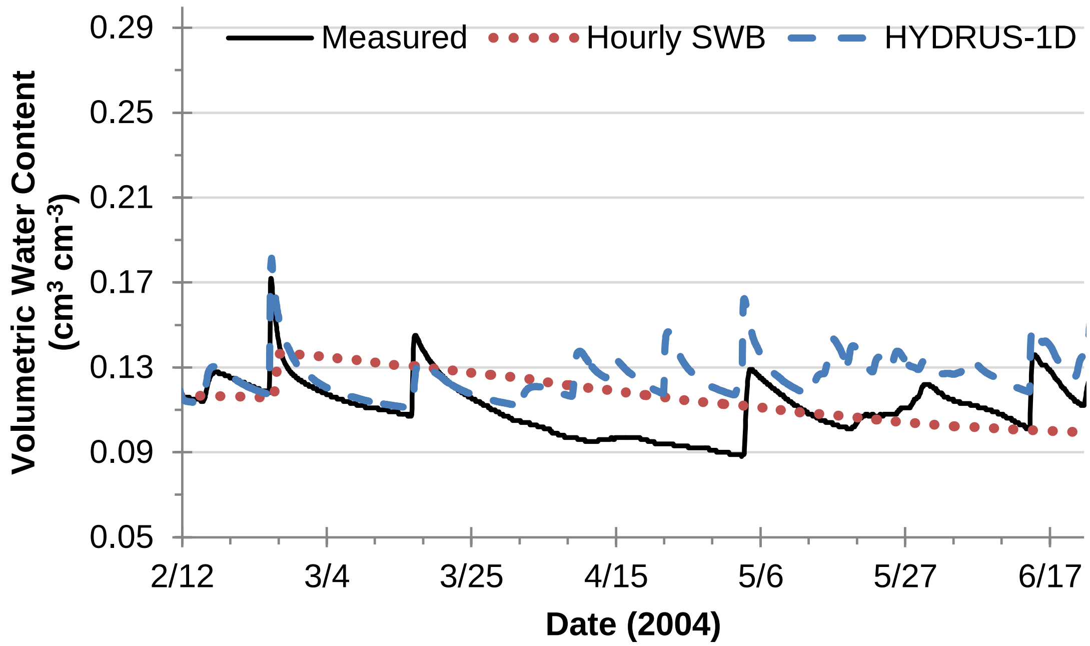

Figure 4-11. Time series comparison of volumetric water content measured at the 75 cm depth to the two models in Citra, FL during the validation period.

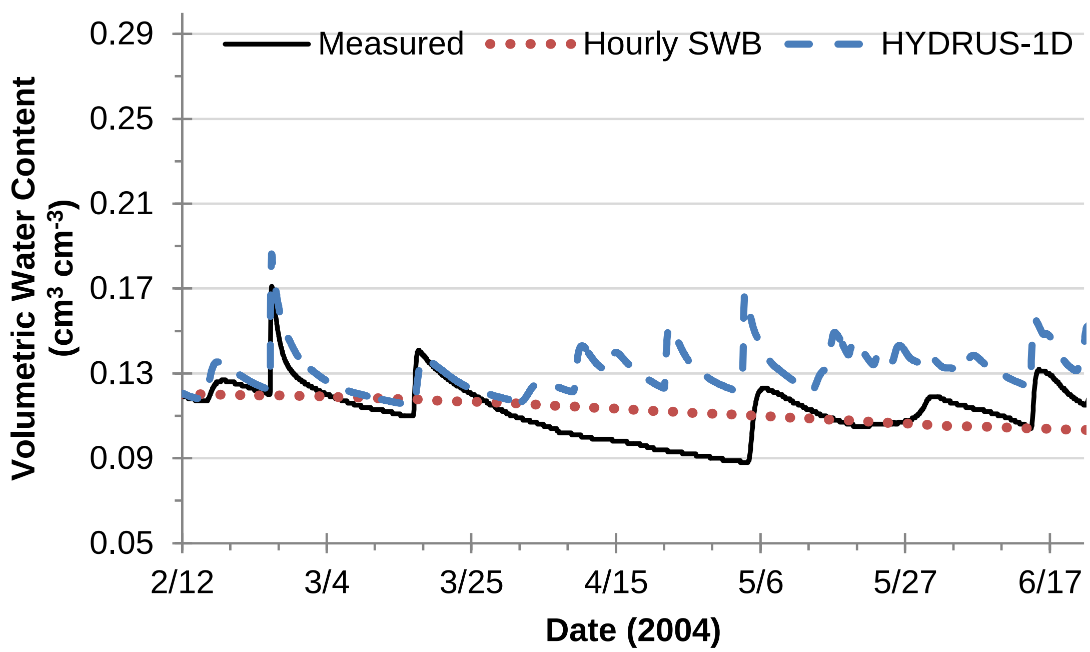

Figure 4-12. Time series comparison of volumetric water content measured at the 90 cm depth to the two models in Citra, FL during the validation period.

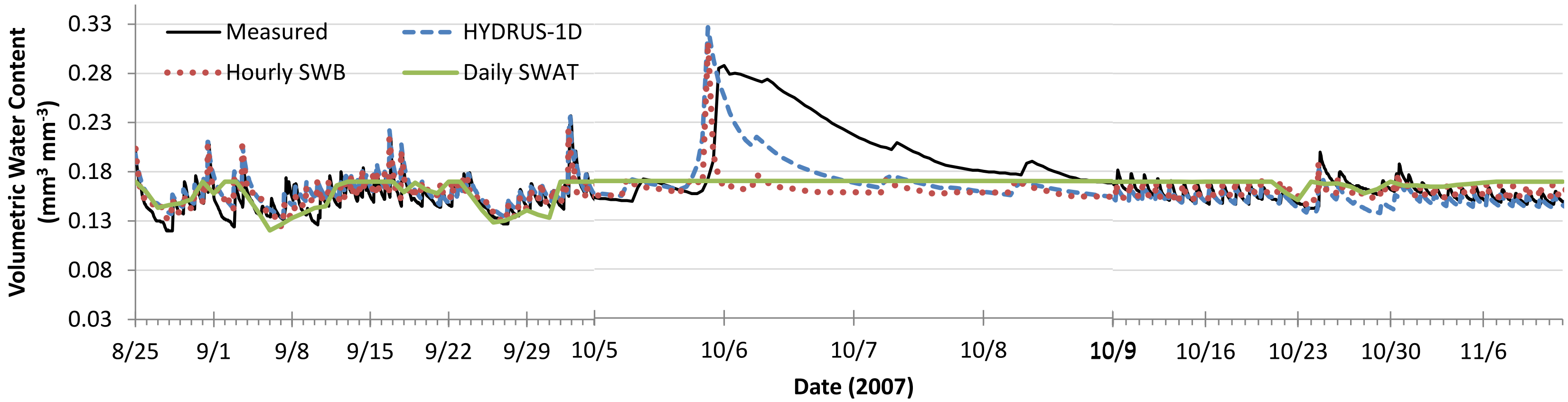

Figure 4-13. Time series results using the hourly SWB, daily SWAT, and HYDRUS 1-D models for the Weathermatic during the calibration period.

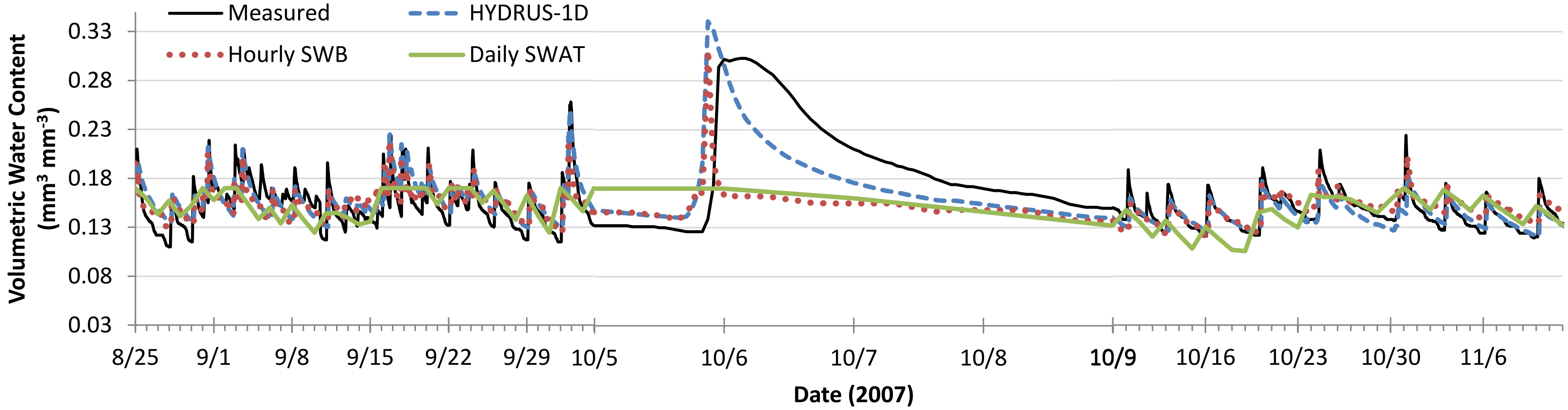

Figure 4-14. Time series results using the hourly SWB, daily SWAT, and HYDRUS 1-D models for the Toro during the calibration period.

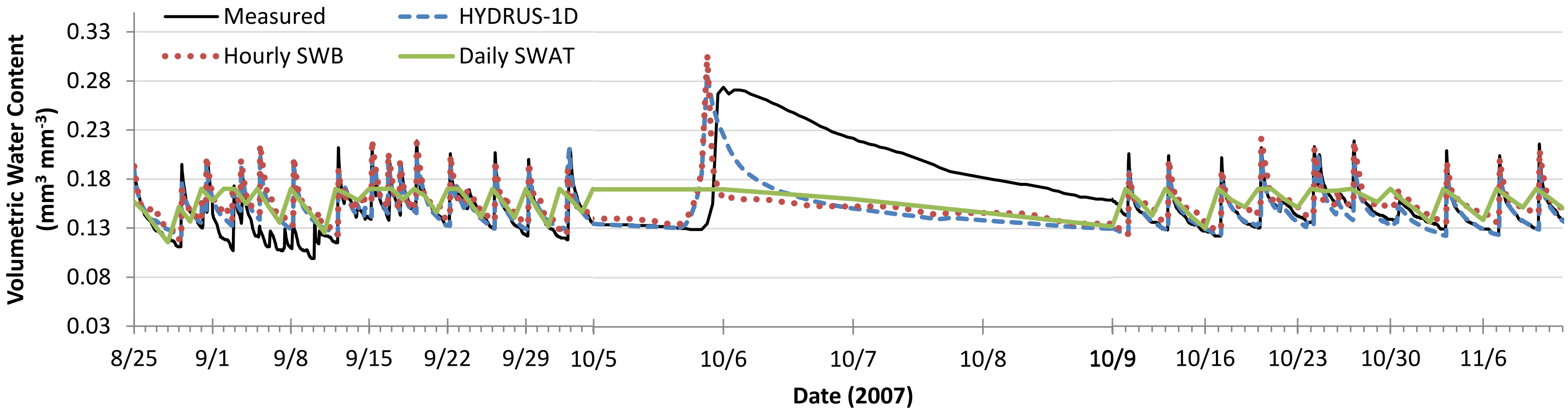

Figure 4-15. Time series results using the hourly SWB, daily SWAT, and HYDRUS 1-D models for TIME during the calibration period.

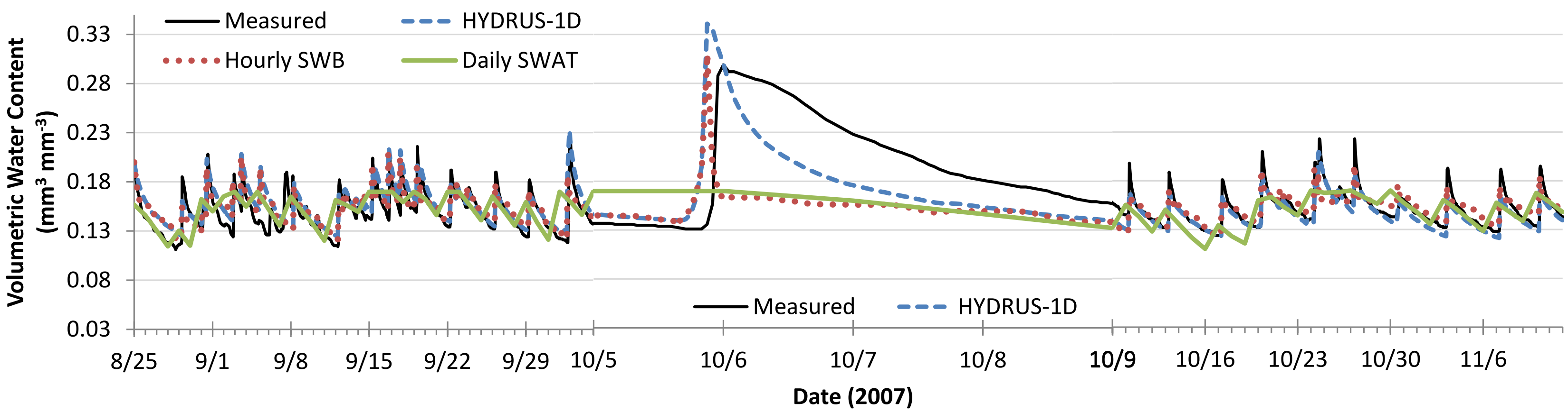

Figure 4-16. Time series results using the hourly SWB, daily SWAT, and HYDRUS 1-D models for RTIME during the calibration period.

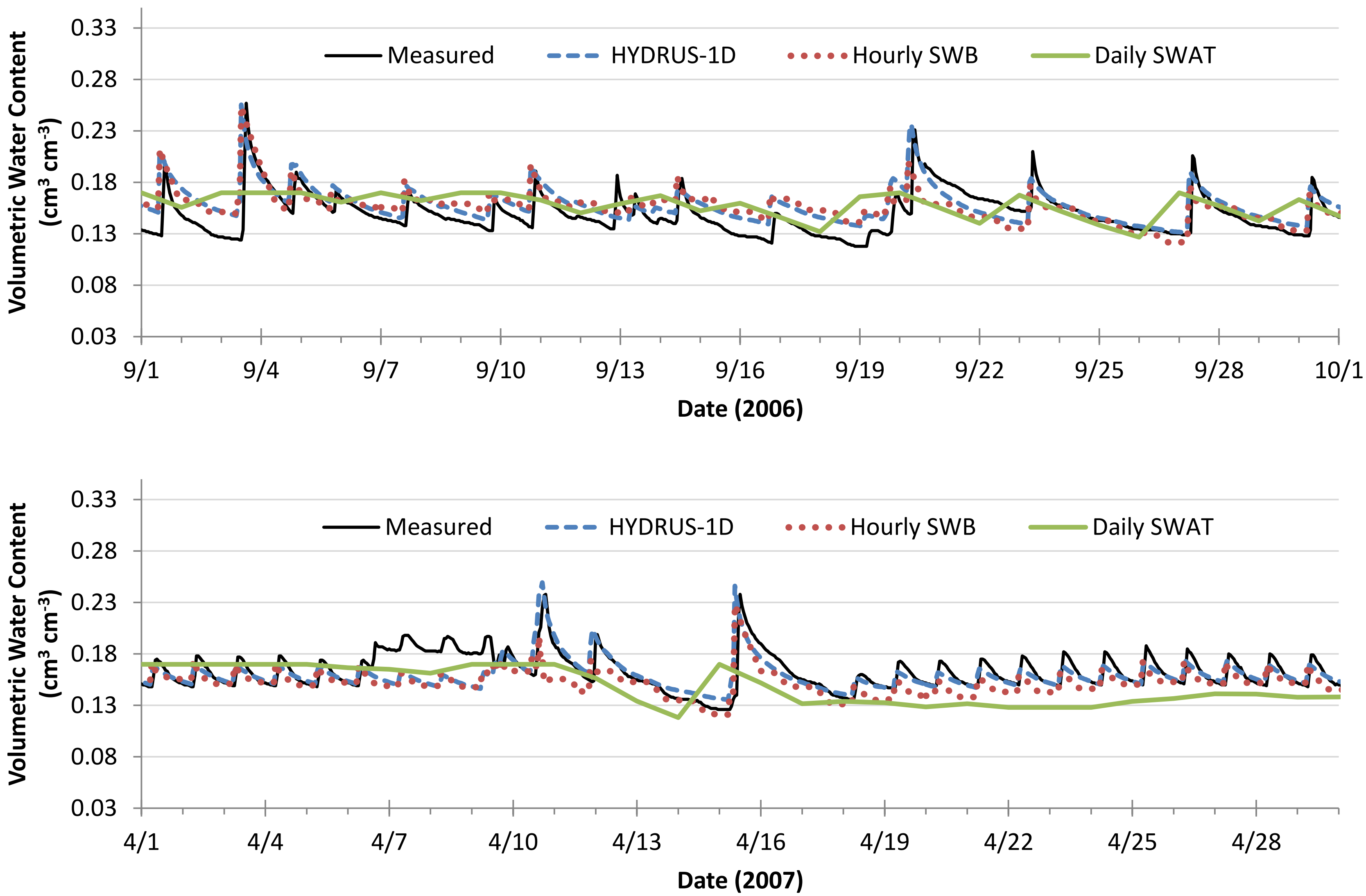

Figure 4-17. The volumetric water content was estimated using all three models for the Weathermatic during the validation period at the GCREC during a month with A) frequent rainfall and B) infrequent rainfall.

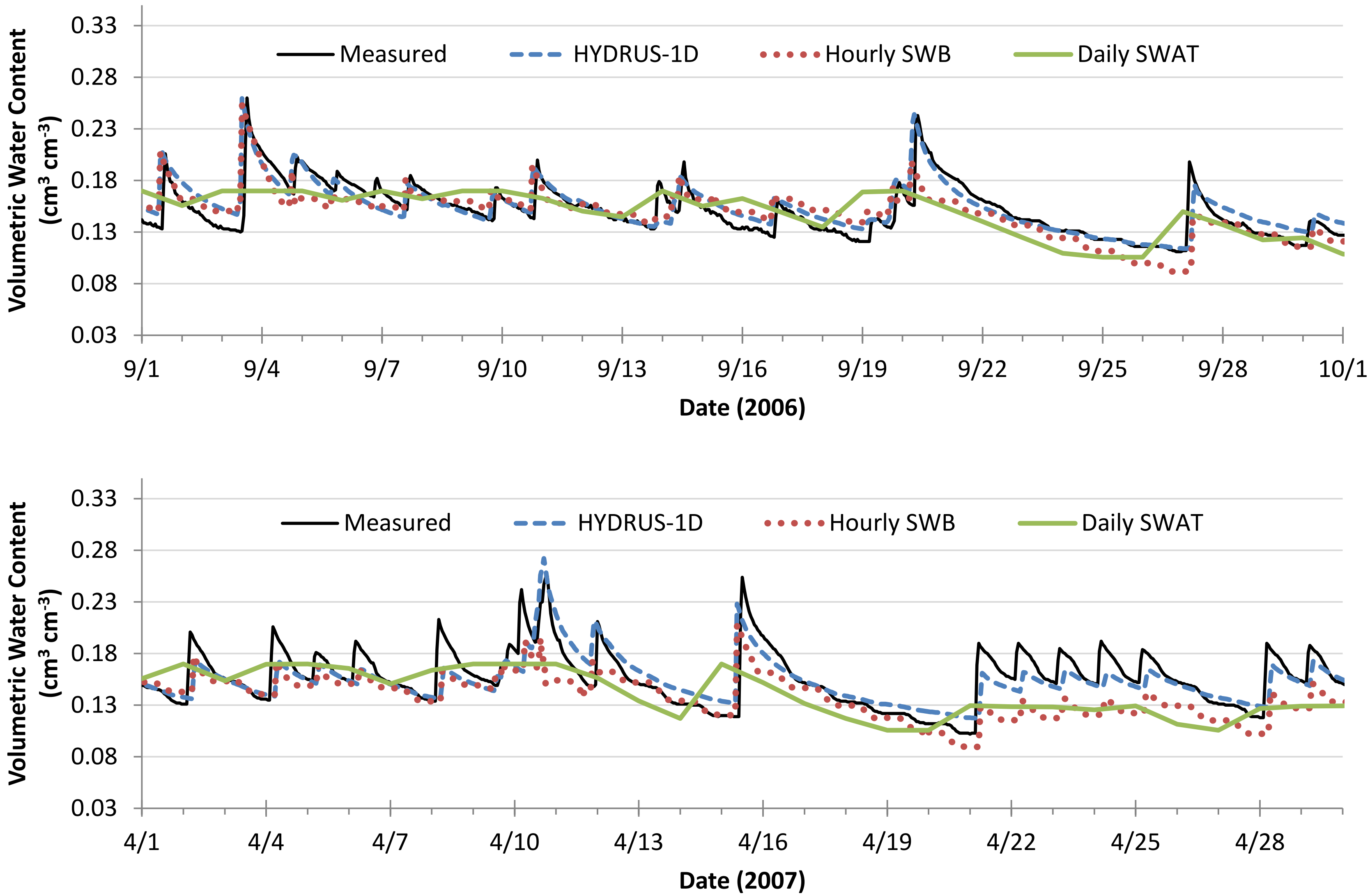

Figure 4-18. The volumetric water content was estimated using all three models for the Toro during the validation period at the GCREC during a month with A) frequent rainfall and B) infrequent rainfall.

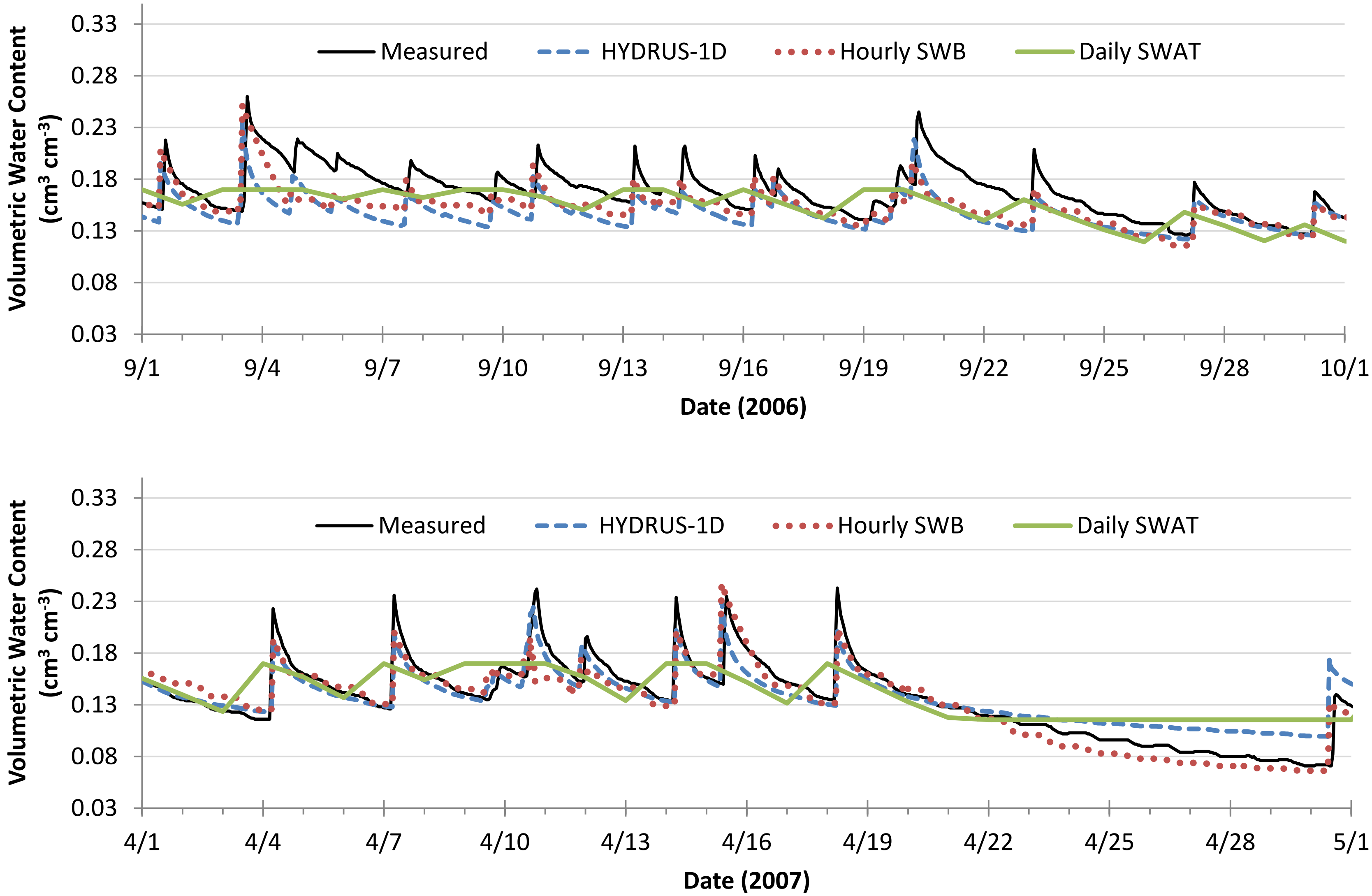

Figure 4-19. The volumetric water content was estimated using all three models for TIME during the validation period at the GCREC during a month with A) frequent rainfall and B) infrequent rainfall

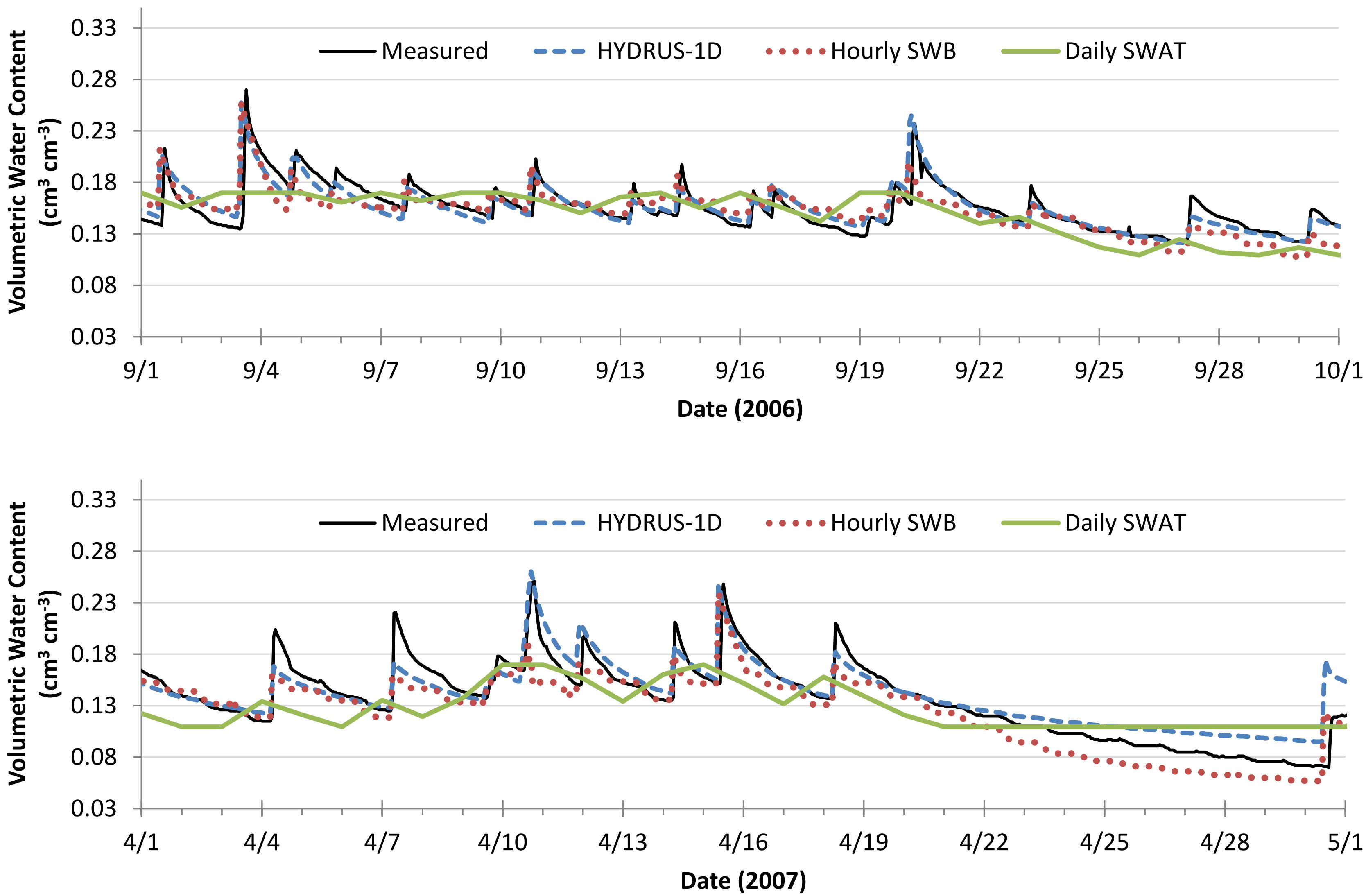

Figure 4-20. The volumetric water content was estimated using all three models for RTIME during the validation period at the GCREC during a month with A) frequent rainfall and B) infrequent rainfall.

CHAPTER 5
SIMULATED PERFORMANCE OF EVAPOTRANSPIRATION BASED IRRIGATION CONTROLLERS USING SOIL WATER BALANCE MODELS

Introduction

Models are used to solve problems in the real world when actual data cannot be collected. In soil water modeling, mathematical representations are used to simulate hydrological processes in the variably saturated shallow soil profile. Models can be described in a number of ways such as physically based vs. empirically based, temporal vs. spatial, or static vs. dynamic. The appropriate model should be created or selected based on the purpose of the model while factoring the types of available input data and ability to produce meaningful outcomes. Complex models require extensive input data provided by the user, numerical approximation techniques, and intense computations compared to simple models that are generally easier to use (Jeong et al. 2010). However, simple models sometimes lack key biological and hydrological processes making the model less realistic (Ranatunga et al. 2008). Thus, it is important to find a good balance between simplistic models that lack computational intensity and complex models that better approximate the real system.

One modern technology currently promoted for water conservation is the weather-based irrigation controller that uses reference evapotranspiration (ET_O) to estimate plant water needs. For this reason, weather-based irrigation controllers are commonly called ET controllers. Though they vary in functionality by brand and model, most ET controllers use a soil water balance to determine when and how much irrigation is needed. Research has shown that ET controllers have the potential to produce water savings when implemented in scenarios with frequent excessive irrigation (Mayer et al. 2009; Davis and Dukes, in review). They have also been shown to increase irrigation at homes that historically irrigate at or below the theoretical irrigation requirement (Mayer et al. 2009; Davis and Dukes 2014).

The Irrigation Association developed the Smart Water Application Technologies (SWAT) Testing Protocol for Weather-Based Irrigation Controllers as a method to evaluate the ability of ET controllers to adequately and efficiently schedule irrigation (IA 2008). This testing protocol, established in 2002 and in its 8th draft, specifies a 30-day test with baseline totals of 63.5 mm of ET_O and 10.2 mm of rainfall to determine if ET controllers irrigate efficiently. Publishing SWAT test results are at the discretion of the manufacturer and can be continually tested until achieving acceptable scores during a valid testing period.

In June 2006, the United States Environmental Protection Agency (USEPA) started the WaterSense program to certify products as water-saving devices by incorporating a WaterSense label on product packaging. By Jan. 2007, the first device labeled as part of this program was the high efficiency toilet that used less than 4.9 L per flush with other products following such as faucets, showerheads, and urinals. The first outdoor product eligible for the WaterSense label was the ET controller with the final specification released on Nov. 3, 2011 and the first device officially labeled in May 2012 (USEPA 2012). This specification was developed by adopting the Irrigation Association's SWAT testing protocol with minor modifications. Instead of publishing test scores as the Irrigation Association does, the USEPA chose minimums of 80% for irrigation adequacy and 95% for scheduling efficiency as the score requirements for WaterSense labeling and publishes the controller information when they meet or exceed these scores.

In 2009 and 2010, the SWAT test was evaluated for transferability, or applicability of scores to different areas of the country, and reproducibility, or the ability to obtain identical results using the same input information by various testing labs (Davis and Dukes 2010). It was determined that the results of the SWAT test were not transferrable across the United States due to decreasing scheduling efficiency scores during periods of increased rainfall frequency (Davis and Dukes 2012). Other significant deficiencies included the low rainfall and ET_O requirements for a valid test, penalized scores due to the mandate that rainfall must be taken into account before irrigation despite when irrigation occurred prior to rainfall on the same day, and inconsistencies in controller programming compared to theoretical landscape characteristics to achieve high scores.

Based on these deficiencies, it was hypothesized that an hourly soil water balance would better match actual soil water content than the daily soil water balance specified by the SWAT test thus translating efficacy results into better predictions of real world performance. The objective of this research was to compare the performance results of ET controllers, quantified as irrigation adequacy and scheduling efficiency, using an hourly soil water balance and the SWAT test.

Materials and Methods

Soil Water Balance

The soil water content (θ) is calculated as the ratio between the volume of water to total volume (water, air, and soil particles) of the root zone. In a natural landscape system, θ can range from residual water content (θ_r), where additional energy is required to remove water from the profile, to saturation (θ_s), where all pore spaces are filled with water. Field capacity (θ_{FC}) is achieved when gravitational forces equal surface tension forces (cohesive and adhesive) between water molecules and soil particles resulting in no drainage due to gravity (Richards 1931). Water storage at water contents between θ_{FC} and θ_s is temporary and drains to θ_{FC} over time based on soil hydraulic properties. To reduce water stress on the plant material, the water content should be maintained above θ_r at a maximum allowable depletion (θ_{MAD}) typically selected as 50% between θ_r and θ_{FC} (IA 2013).

The soil water balance is a simple model that uses a tipping bucket approach to soil water movement in a homogeneous soil profile (i.e. depth per unit area of root zone) over a specified timestep (Ranatunga et al. 2008). The model is based on the principle that soil water at the current depth (Z) and timestep (i) was affected by the soil water at the previous timestep (i-1) and inputs and outputs of crop evapotranspiration (ET_C), rainfall (R), irrigation (I), runoff (RO), and deep percolation (D) occurring at i (Equation 4-1).

The ET_C (Equation 1-28) was calculated from ET_O (Equation 1-13) determined from local microclimate variables and crop coefficients specific to the studies (Table 5-1). Rainfall and irrigation were utilized similarly in the model where the depth equals the total that fell (R) or was applied (I) over the unit area during the timestep of interest. Events that cause θ to exceed an upper limit, typically θ_{FC} or θ_s, result in separating total depth into effective depth, which is considered available for plant use, and a combination of runoff and deep percolation losses. When total depth results in θ that is less than the upper limit, total depth equals effective depth. Runoff and deep percolation are two different physical processes that both potentially occur when θ exceeds θ_{FC} resulting in water losses from the soil profile. Generally, runoff occurs due to improper cycle/soak scheduling of irrigation and landscape inclines whereas deep percolation occurs due to excess rainfall or irrigation. It is difficult and unnecessary to separate these losses because they are quantified outside of the soil profile and the variable of interest is the change in depth of water within the soil profile.

Daily SWAT Model

The SWAT test (IA 2008) uses a modified daily soil water balance to simulate the soil water dynamics of a landscape plant system. It was developed as an industry tool to evaluate the irrigation scheduling capabilities of ET controllers. Test results are considered valid if meeting the 30-day baseline totals of 63.5 mm and 10.2 mm for ET_O and R, respectively. Publishing SWAT test results to the public are at the discretion of the manufacturer and can be continually tested until achieving acceptable scores during a valid testing period. The SWAT protocol specifies six diverse virtual landscapes that are primarily described by plant material, sprinkler type, soil type, and slope (IA 2008).

The soil water balance specified by the SWAT test was modified to restrict water movement to between θ_{MAD} to θ_{FC}. The range is referred to as the root zone working water storage (RZWWS) (IA 2008). In addition to new terminology, water level fluctuations were limited to zero and RZWWS, or the maximum value able to be stored depending on the tested zone. A water level of zero does not equate to the absence of water in the soil column. Therefore, the soil water balance used for the SWAT test does not represent the actual water level in the soil profile, but the level under which the plant material will no longer be considered well-watered. An additional modification included reducing total daily rainfall by 20% citing losses to non-uniformity and runoff (IA 2008).

In the SWAT test, runoff and deep percolation were defined as scheduling losses consisting of direct runoff when irrigation cycles exceed maximum runtimes based on infiltration rates, soak runoff when irrigation cycles occur prior to minimum soak times based on infiltration rates, and surplus that occurred when the irrigation cycle causes θ to exceed θ_{FC}.

The performance results of ET controllers evaluated by the SWAT test are presented as scheduling efficiency (E) and irrigation adequacy (A). Scheduling efficiency is a measure of over-irrigation quantified by estimating scheduling losses over a 30-day period combined from three sources: soil moisture rising above field capacity, too long cycle times, and too short soak times (Equation 1-52). The I_N (mm) is net irrigation and SL (mm) is scheduling losses, both summed over thirty days, resulting in a single E (%) for each 30-day period. Similarly, irrigation adequacy is a measure of under-irrigation and can be quantified by depths when conditions were not considered well-watered over the 30-day period (Equation 1-53). The ET_C (mm) and D (mm) as the amount of deficit were summed over thirty days, resulting in a single A (%) for each 30-day period. Deficit is calculated as the cumulative depth below well-watered conditions, or depth below θ_{MAD}. Results of 100% for either score would indicate that the irrigation scheduling performance by the ET controller was effectively perfect.

In addition to evaluating irrigation schedules, the model can be used to predict the gross irrigation requirement (GIR) by implementing a minor change in the irrigation reference. Instead of inputting I_N into the model directly, it is calculated as the depth of water required to achieve θ_{FC} when θ_{MAD} is reached.

Hourly SWB Model

An hourly soil water balance was developed in efforts to address some deficiencies in the SWAT test such as lack of transferability and penalized scores due to mandating that rainfall occurred before irrigation despite actual order of events. All calculations specified in the daily version were maintained so that soil water movement within the RZWWS occurred in the same way. However, the soil water balance was updated to incorporate soil water movement above θ_{FC} and below θ_{MAD}. These simplifications may benefit the controllers during the test by not continually penalizing for deficit or surplus conditions. However, soil water levels in real systems can frequently exceed θ_{FC} until reaching saturation with deep percolation naturally occurring during each timestep until returning to equilibrium at θ_{FC}. Additionally, water levels falling below θ_{MAD} resulting in deficit conditions can occur in real systems and should be observed in the model.

To account for soil water levels higher than field capacity, an exponential decay function (Equation 4-2) was incorporated into each timestep used to represent drainage to equilibrium. When deficit conditions occur and soil moisture falls below θ_{MAD}, the ability for ET_C to be removed from the soil profile by the plant material becomes more difficult. To account for this phenomenon, a stress coefficient (Equation 4-4) was introduced to the ET_C calculation.

Data Description

Bench testing study

The Weathermatic SL1600 (Garland, TX), Toro Intelli-Sense (Riverside, CA), and ET Water Smart Controller 100 (Novato, CA) were installed at the University of Florida Agricultural and Biological Engineering turfgrass research facility in Gainesville, FL. The Toro and ET Water controllers were signal-based where they received daily ET_O information through cellular technology. These two controllers were duplicated so that one controller of each brand utilized an additional Mini-Clik rain sensor (Hunter Industries, Inc., San Marcos, CA) set at a 6 mm threshold, denoted as with rain sensor, while the remaining controllers relied on product abilities alone, denoted as without rain sensor. The Weathermatic was a standalone controller that calculated ET_O using temperature information collected on-site.

These controller models were selected based on their previous SWAT testing by the Center for Irrigation Technology (CIT) in Fresno, California as well as previous testing conducted by our research group (Davis et al. 2009; Davis and Dukes 2010). Results from the 2010 Florida SWAT Test using three controllers of each brand showed that there was little variability between replications (Davis et al. 2009). Thus, performance results of these brands are likely to be similar to controllers of the same brand being utilized in the real world but may not be representative of all controller brands.

Based on results from Davis and Dukes (2011), the duplicate controllers performed almost identically despite the addition of a rain sensor. The three controllers with rain sensors were selected for evaluation in this study. The treatments with rain sensors were chosen over the treatments without rain sensors based on results by Rutland and Dukes (2013) that suggested the addition of a rain sensor was beneficial to the functionality of an ET controller in Florida.

Each controller was connected to a CR-10X datalogger (Campbell Scientific, Logan, UT) via a set of relays to record time and date at the beginning and end of each irrigation event for all active zones. Weather data were collected from a weather station located on-site and managed by research personnel. Weather parameters included temperature, relative humidity, solar radiation, and wind speed collected at 15 minute intervals. Values for reference evapotranspiration (ET_O) were calculated using Equation 1-13 as specified in the SWAT protocol (IA 2008).

Each controller was programmed by the manufacturer, or with the manufacturer's supervision. It was intended that the settings would duplicate the original SWAT test performed by CIT. However, since controller settings are not reported in the current SWAT protocol, we were unable to verify identical settings to the original SWAT test for the controllers. The official test began when the manufacturer determined that the controller(s) were programmed correctly.

Four 60-day datasets were selected to represent a variety of weather conditions specified as frequent rainfall, infrequent rainfall, high ET_O, and low ET_O (Table 5-2). Each period was selected by comparing the rainfall and ET_O amount over the 60-day period with the historical averages over the same sixty days determined from 37 years of Gainesville Regional Airport weather data from 1970 through 2006 (NCDC 2007).

Field plot study

Sixteen St. Augustinegrass plots measuring 7.6 m by 7.9 m were established at the University of Florida Gulf Coast Research and Education Center (GCREC) in Balm, FL. These plots were created to evaluate the ability of ET controllers to apply irrigation efficiently in southwest Florida. The treatments, replicated four times, were: A) Weathermatic SL1600, B) Toro Intelli-Sense, C) TIME treatment based on 100% replacement of the net irrigation requirement, and D) RTIME treatment that was 60% of the TIME treatment. The variable of interest for these treatments was irrigation application only; thus, all plot maintenance and nutrient management remained constant across all treatments based on University of Florida – Institute of Food and Agricultural Sciences recommendations (Sartain 1991; Black and Ruppert 1998).

Detailed methods and results concerning these treatments can be found in Davis et al. (2009), Davis and Dukes (2010), and Davis and Dukes (2012). Each plot was maintained using an irrigation system with dedicated flow meter to measure volumes of irrigation application per plot. The flow meters were connected to a data logger that recorded sub-daily irrigation to easily separate irrigation system maintenance activities and treatment-related irrigation.

Weather data during the study period, ranging from Aug. 13, 2006 to Nov. 27, 2007, was collected from the Florida Automated Weather Network (FAWN) weather station located at the GCREC. Weather parameters included temperature, relative humidity, solar radiation, and wind speed collected at 15 minute intervals. The ET_O was calculated using the ASCE ET equation (ASCE 2005). Rainfall was also collected from this weather station.

Statistical analysis

Statistical trends in performance results of irrigation adequacy and scheduling efficiency were analyzed using Statistical Analytical Systems (SAS) software (Cary, NC). The general linear model procedure was used to determine significant differences in means of performance scores based on controller brand, model type, and weather conditions. Significance was determined at a 95% confidence level.

The correlation procedure was used to determine if there was a significant dependence between irrigation application and performance results. Correlation coefficients can range from -1 (strong negative correlation) to 1 (strong positive correlation) where 0 indicates no correlation between the variables. Irrigation adequacy and scheduling efficiency scores are measures of under- and over-irrigation, respectively, and should not be affected by the opposite circumstance. As a result, correlations were limited to 30-day scores when irrigation was less than GIR for irrigation adequacy and greater than GIR for scheduling efficiency.

Results

Bench Testing Study

Frequent rainfall period

The cumulative rainfall during the frequent rainfall period totaled 269 mm occurring over 60 days (Table 5-2). This amount of rainfall was less than the historical average by 17%; however, the number of rain events during the period was similar with 28 events compared to an average of 27 events. The 30-day ET_O values calculated on a daily basis ranged from 105 mm to 133 mm and on an hourly basis ranged from 102 mm to 115 mm (Figure 5-1). The ET_O totals were above the minimum requirement of 63.5 mm for all 30-day periods. Rainfall was also above the minimum of 10.2 mm, ranging from 123 mm to 183 mm.

Using the GIR, 107 mm and 142 mm of irrigation were required according to the daily SWAT model and hourly SWAT model, respectively (Table 5-3), despite frequent rainfall over this period due to the small soil water holding capacity. Irrigation application over the 60-day period ranged from 74 mm by Weathermatic, 31% savings from daily GIR and 48% savings from hourly GIR, to 150 mm by Toro, 40% more than daily GIR and 6% more than hourly GIR. Irrigation application by the ET Water fell within this range, applying 132 mm. This controller increased irrigation by 23% more than daily GIR, but had water savings of 7% compared to the hourly GIR.

In general, irrigation adequacy results reflected irrigation application by the controllers compared to the GIR. Irrigation adequacy for the ET Water were 100% for all thirty scores using the daily SWAT model where irrigation application was higher than GIR, but were slightly lower and declined over time using the hourly SWB where irrigation was slightly less than GIR, ranging from 73% to 93% (Figure 5-2). The Toro controller maintained scores of 100% using the daily SWAT model and above 96% using the hourly SWB while consistently irrigating more than GIR using both models (Figure 5-3). The Weathermatic applied less than the GIR for both models resulting in scores ranging from 85% to 100% for the daily SWAT model and 59% to 71% for the hourly SWB model (Figure 5-4).

Scheduling efficiency results were maintained at 100% for both models by the Weathermatic only. Results ranged from 92% to 97% for ET Water and 97% to 100% for Toro using the hourly SWB. Decreased scores for ET Water and Toro occurred when using the daily SWAT model, reaching a minimum of 87% and 92%, respectively. A decline in scheduling efficiency scores by the ET Water and Toro controllers occurred due to over-irrigation of 23% and 40%, respectively, compared to GIR.

Mean irrigation adequacy and scheduling efficiency scores were significantly different between the daily SWAT and hourly SWB models for each controller if the controller had scores less than 100% (Table 5-3). Irrigation adequacy scores decreased from 100% to 91% for the ET Water and from 88% to 65% for the Weathermatic. The opposite effect occurred for scheduling efficiency scores, showing increases from 90% to 94% for ET Water and 95% to 98% for the Toro. As a result, there were differences in performance results attributed to the model.

Infrequent rainfall period

The rainfall over the infrequent rainfall period totaled 46 mm in 10 events resulting in 64% less rainfall than the historical average (Table 5-2). There were three 30-day periods at the end of the season that did not meet the minimum ET_O

requirement of 63.5 mm when using the daily values, ranging from 58 mm to 100 mm (Figure 5-5). However, the 30-day ET_O using the hourly calculations met the minimum requirement during all 30-day periods ranging from 64 mm to 90 mm. Additionally, all 30-day periods met the minimum rainfall requirement of 10.2 mm, ranging from 14 mm to 27 mm.

Irrigation application by the treatments ranged from 94 mm to 137 mm by the ET Water and Toro controllers, respectively (Table 5-4). The ET Water had reduced irrigation application compared to GIR using both models, resulting in 3% reduction from daily SWAT and 33% reduction from hourly SWB. The Toro and Weathermatic controllers had reductions in irrigation application compared to hourly GIR by 3% and 10%, but increased irrigation compared to daily GIR by 41% and 31%, respectively.

Irrigation adequacy for ET Water ranged from 84% to 96%, averaging 89%, for the daily SWAT model and 34% to 79%, averaging 64%, for the hourly SWB model (Table 5-4; Figure 5-6). Though cumulative irrigation by this controller was similar to GIR calculated using the daily SWAT model, there were many times where deficit conditions occurred resulting in lower irrigation adequacy scores across 30-day periods within the 60-day period. Irrigation adequacy results for the Toro and Weathermatic controllers scored 100% for all 30-day periods using both models due to frequent irrigation (Figure 5-7; Figure 5-8).

Mean scheduling efficiency scores were not different across controller brands for the daily SWAT model, but scores from the hourly SWB model were different for the ET Water and Toro controllers, averaging 92% and 94%, respectively. The ET Water controller had perfect scores using the daily SWAT model, but scores began at 87%

and steadily increased to 100% by the end of the period using the hourly SWB model. Results for the Toro ranged from 91% to 100% whereas the Weathermatic had repeatedly perfect scores. Short and frequent irrigation events resulted in relatively little over-irrigation.

Low ET_O period

During the low ET_O period, ET_O totaled 163 mm with a daily average of 3 mm, 22% below the historical average (Table 5-2). Thirty-day ET_O increased over the period from 72 mm to 96 mm using the daily values and 57 mm to 81 mm for the hourly values (Figure 5-9). Due to the lower values using the hourly ET_O, there were seven 30-day periods that were below the minimum ET_O requirement of 63.5 mm. Rainfall was consistently greater than the minimum requirement of 10.2 mm for this period with a total of 63 mm and a range of 63 mm to 115 mm.

It was estimated that 76 mm and 94 mm of irrigation were required according to the daily GIR and hourly GIR, respectively, over this 60-day period to supplement rainfall (Table 5-5). The ET Water irrigated 11% more than daily GIR and 11% less than hourly GIR, totaling 84 mm. The Toro irrigated less than the GIR by 9% on a daily basis and 27% on an hourly basis by applying 69 mm. Results were not reported for the Weathermatic due to equipment malfunction.

Irrigation adequacy results for the daily SWAT model ranged from 93% to 100% for the ET Water (Figure 5-10) and 90% to 98% for the Toro (Figure 5-11). There was no difference in scores using the daily SWAT model for these two controllers (Table 5-5). Scores decreased when using the hourly SWB model with ranges of 48% to 94% for ET Water and 12% to 72% for Toro. Mean scores using the hourly SWB were different from daily SWAT model, decreasing to 75% for ET Water and 43% for Toro.

Scheduling efficiency results for both controllers using the hourly SWB model were 100% across all 30-day periods. This was also true for Toro when using the daily SWAT model. However, ET Water had mostly less than perfect scheduling efficiency scores using the daily SWAT model with results ranging from 70% to 100% and averaging 82%, which was different from the hourly SWB model.

High ET_O period

The highest 60-day ET_O, totaling 287 mm, occurred during the high ET_O period with a 5 mm daily average (Table 5-2). The total ET_O was 14% less than the historical average and rainfall was also less than its historical average by 22%, totaling 124 mm. The 30-day ET_O values ranged from 122 mm to 170 mm for the daily calculations and 124 mm to 143 mm for the hourly calculations (Figure 5-12). The 30-day rainfall values ranged from 55 mm to 100 mm for this time period. Minimum requirements for the SWAT test were met for all time periods using both methods.

There was a high demand for irrigation during this time period due to the combination of high ET_O and less than normal rainfall totals. As with all other periods, the GIR was higher for the hourly SWB model than the daily SWAT model with a total irrigation requirement of 231 mm for the daily GIR and 283 mm for the hourly GIR (Table 5-6). The ET Water applied more than daily GIR by 13% and less than hourly GIR by 7%, applying 262 mm. The Toro applied the most similar amount of irrigation to daily GIR, totaling 236 mm, but was 17% less than the hourly GIR. The Weathermatic controller applied less than what was required for both models, totaling 185 mm, with results of 20% to 35% less than the daily and hourly GIR, respectively.

The irrigation adequacy results for the ET Water and Toro controllers using the daily SWAT ranged from 91% to 99% (Figure 5-13) and 87% to 100% (Figure 5-14), respectively, with no difference between mean scores (Table 5-6). Results were much lower for these controllers using the hourly SWB with ranges of 18% to 36% for ET Water and 15% to 32% for Toro. These results were significantly different from their respective daily SWAT scores, but were not different from each other. Irrigation adequacy for the Weathermatic using the daily model had a decreasing trend in scores from 100% to 75% (Figure 5-15). However, irrigation adequacy results for the hourly SWB ranged from 19% to 80% with a general upward trend. Mean scores were different for this controller, averaging 82% using the daily SWAT model and 47% using the hourly SWB model.

Scheduling efficiency results were consistently 100% for ET Water and Toro using the hourly SWB, but had respective minimums of 87% and 95% at the beginning of the period for the daily SWAT model. The mean scores for the ET Water were different due to lower scores at the beginning of the period. The Weathermatic had the opposite trend where daily SWAT scores were 100% whereas the hourly SWB scores decreased after the fourth 30-day period to 70%, also resulting in significant differences between model types.

Correlation coefficients

Correlation coefficients for irrigation adequacy scores ranged from -0.280 (Weathermatic) to 0.125 (ET Water) for the daily SWAT model and from -0.324 (Weathermatic) to -0.783 (ET Water) for the hourly SWB model (Table 5-7). For the daily SWAT model, the coefficient for the Weathermatic was significant (P-value = 0.0250) indicating that irrigation adequacy scores were slightly dependent on irrigation application. Also, correlation coefficients for the hourly SWB were significant for all three controllers thus also having dependence. However, coefficients were not significant for the ET Water (P-value = 0.4185) and Toro (P-value = 0.3351) controllers using the daily SWAT model. These results indicate that there was a stronger relationship between irrigation application and irrigation adequacy scores for the hourly SWB model than for the daily SWAT model.

For scheduling efficiency scores associated with the daily SWAT model, correlation coefficients ranged from -0.304 (Weathermatic) to 0.224 (ET Water), but none of the coefficients were significant thus there was not enough information to show a correlation. However, correlation coefficients were significant (P-value < 0.0001) for the ET Water and Toro, equaling 0.518 and 0.483, respectively. These coefficients indicate that there was a relationship between irrigation application and scheduling efficiency scores for the hourly SWB model, but not the daily SWAT model. Since the Weathermatic did not irrigate more than the GIR, there was a lack of data to calculate a coefficient for this controller.

Field Plot Study

This study was conducted during a drought period (Davis et al. 2009) resulting in high ET_O (2,475 mm) and low rainfall (1,293 mm) compared to historical averages of 1,845 mm and 1,738 mm, respectively (Table 5-2). There were similar numbers of rainfall events with 145 events occurring during the study period and 153 events as the historical average. The 30-day ET_O ranged from 91 mm to 222 mm when calculated using daily climatological data and from 63 mm to 184 mm when calculated using hourly data (Figure 5-16). The 30-day rainfall totals ranged from 0 mm to 210 mm.

The irrigation adequacy scores for the Weathermatic showed that the daily SWAT model predicted very little periods of deficit with two instances where the scores reached lows of 93% (mid-December 2006) and 84% (mid-June 2007) (Figure 5-17).

Perfect irrigation adequacy scores were achieved by the hourly SWB model. Scheduling efficiency scores began as 100% values during the beginning of the study with fluctuating scores occurring during beginning periods of frequent rainfall occurring over winter 2006, minimum score of 81%, and summer 2007, minimum score of 48%, for the daily SWAT model. The same trends occurred for the hourly SWB model with declining scores during initial periods of frequent rainfall. However, the hourly SWB had lower scores overall with minimums of 60% in mid-December 2006 and 28% in mid-June 2007.

For the Toro controller, irrigation adequacy fluctuated with short periods of scores just greater than 80% according to the daily SWAT model whereas the scores for the hourly SWB approximated 100% for most of the study period (Figure 5-18). There was a period in the fall 2006 season where irrigation adequacy declined for both models, reaching a minimum score of 57% for daily SWAT and 30% for hourly SWB. Scheduling efficiency was near perfect for both models during the period when irrigation adequacy scores were low, however, there were fluctuating results during the rest of the study period with minimums of 73% and 46% for the daily SWAT and hourly SWB, respectively. These periods of low values correspond to periods of frequent rainfall.

The TIME and RTIME treatments were developed to replace the historical net irrigation requirement at rates of 100% and 60%. There was a calculation error resulting in an irrigation runtime that was much lower than the net irrigation requirement during the month of Oct. 2006. Additionally, there was a period of a few weeks were irrigation was shut off to these treatments resulting in no irrigation application despite the schedule in Apr. 2007.

The irrigation adequacy results remained above 95% for both models and both time-based treatments during most of the study period with the only exceptions occurring during Oct. 2006 and Apr. 2007 corresponding to errors in the irrigation schedule previously described (Figure 5-19; Figure 5-20). The declines in irrigation adequacy scores were much more apparent in RTIME, reaching a score of 0% at one point, compared to TIME where the minimum score was 49%. Though the actual values of the irrigation adequacy scores varied between models, the differences were small during a majority of the 30-day periods.

Scheduling efficiency scores mirrored the irrigation adequacy results with high scores occurring during the periods of reduced runtimes/no irrigation and lower scores occurring the rest of the study period. The daily SWAT model had higher scores than the hourly SWB model for both time-based treatments. Additionally, there were higher scores by the RTIME compared to TIME due to the shorter runtimes since only 60% of the net irrigation requirement was replaced. Despite the reduced schedule, over-irrigation still occurred by RTIME indicating that it was not a deficit treatment.

Discussion

The GIR was 23% to 45% larger when calculated using the hourly SWB compared to the daily SWAT model using the seasonal periods despite the general trend of lower cumulative ET_O when calculated hourly. This may have occurred due to the lack of irrigation restrictions on the hourly SWB where irrigation was allowed to occur during any hour that MB dropped below maximum allowable depletion regardless of time of day or day of week. Due to the mechanics of a daily model, irrigation frequency must be in 24 h timesteps thus resulting in fewer opportunities for irrigation and more opportunities to take advantage of rainfall. For example, there were four irrigation events for the daily GIR and six events for the hourly GIR during the frequent rainfall period, resulting in 35 mm of additional irrigation. With gross irrigation events averaging 23 mm, a few additional irrigation events would impact the GIR. Including an allowable watering window in the hourly SWB may reduce the GIR, but would introduce sub-daily periods of deficit conditions.

The results for the bench testing study showed general trends of declining irrigation adequacy scores and high scheduling efficiency scores for the controllers indicating that the controllers erred on the side of deficit conditions. However, the results for the field study showed the opposite trend of high irrigation adequacy and fluctuating scheduling efficiency indicating over-irrigation. Additionally, there were few instances of correlation between irrigation application and SWAT performance scores for the daily SWAT model used during the bench testing study. The settings programmed into the controllers for these testing periods were selected by the manufacturers as representative of the landscapes described in the SWAT protocol. However, the settings used were not always identical to the landscape descriptions despite having the option available. The controllers in the field study were programmed with settings that described the landscape such as sand for soil type and warm season turfgrass for plant type (Davis et al. 2009). As a result, predictions of conservative water use based on SWAT test results were not observed in the field study where over-irrigation occurred. Based on the settings discrepancy, the results from daily SWAT tests are not representative of actual ET controller performance when implemented in an actual landscape setting.

The USEPA chose minimums of 80% for irrigation adequacy and 95% for scheduling efficiency as the score requirements for WaterSense labeling. In most cases of the bench testing study, the scores fell much lower than 80% when using the hourly SWB model in situations where the irrigation adequacy was less than perfect but above 80% using the daily SWAT model. In these instances, scheduling efficiency scores remained above 95% resulting in no change in outcome based on this requirement. Though it would be undesirable to penalize a controller for a small error that dramatically drops the score, such large discrepancies with the model are most likely connected to the programming issue previously discussed. As was found in Chapter 4, the hourly SWB more accurately reflects actual soil water movement in a soil profile and scores may benefit from more realistic program settings. This was seen in the field study where non-passing scores for irrigation adequacy and scheduling efficiency occurred with both models for mostly the same time periods despite differences in score magnitude.

Previously published results from the field study showed that the ET controllers averaged 43% annual water savings with maximum savings of 60% occurring in the fall/winter months and some over-irrigation during the hot and dry spring season (Davis et al. 2009). These savings were calculated based on the TIME treatment that replaced 100% of the net irrigation requirement. However, TIME also showed gross over-watering during most of the study (Davis and Dukes 2010), which was evidenced by low scheduling efficiency scores using both models. Additionally, RTIME was just as beneficial in water savings as the ET controllers by replacing 60% of the net irrigation requirement (Davis et al. 2009). Though TIME may reflect actual homeowner practices in Florida and an ET controller would be beneficial for excessive irrigators, it was not accurate as the sole measure of water conservation performance by ET controllers.

Conclusion

The hourly SWB was preferential to the daily SWAT due to the realistic representation of soil water movement by hourly SWB resulting in a correlation of SWAT scores to irrigation application. An additional benefit to hourly SWB was that higher performance scores were achieved when using accurate landscape programming instead of manufacturer selected settings that forced short, frequent irrigation events.

In many cases, the performance scores declined when using the hourly SWB in the bench testing study where program settings were not realistic for the described landscape resulting in frequent under-irrigation. As a result, there was an increased failure rate of achieving the WaterSense label using the hourly SWB. The irrigation adequacy results were most affected with scores declining as much as 80 percentile points. Thus, the failure rate of irrigation adequacy results frequently went from 0% with the daily SWAT to 100% with the hourly SWB, with the change in the failing rate ranging from 13 percentile points to 100 percentile points. The decline in scheduling efficiency results were less drastic, falling no more than 30 percentile points and typically falling less than 10 percentile points at any one 30-day period.

When program settings were related to the landscape characteristics, as in the field plot study, all treatments tended to have over-irrigation. As a result, scheduling efficiency was the primary performance measure affected by the chosen model. However, the WaterSense threshold of 95% for scheduling efficiency is already so high that both models frequently resulted in failing scores, with failure rates of 47% to 88%

for the daily SWAT and 75% to 94% for the hourly SWB. Due to more irrigation being considered over-irrigation with the hourly SWB model, there was an increase in passing irrigation adequacy results at the 80% threshold with a minimum passing rate of 74% for the daily SWAT and 80% for the hourly SWB.

The time-based treatments selected to represent actual homeowner practices in Florida resulted in excessive irrigation during the field plot study. Though the ET controllers were able to decrease irrigation compared to 100% replacement of the net irrigation requirement, there were no additional water savings compared to 60% replacement. Additionally, the performance scores using either model for the ET controllers, scheduling efficiency averaging 75-77%, were not very different from the irrigation treatment scheduled for 60% replacement, scheduling efficiency averaging 81%, with all treatments experiencing over-irrigation. Based on the results of the field study, ET controllers reduced irrigation application compared to excessive irrigators, but still over-irrigated during the study period thus the ET controllers failed to meet true irrigation efficiency standards.

Table 5-1. Crop coefficients for each study.

Month	Bench Test Study[a]	Field Plot Study[b]
Jan.	0.52	0.45
Feb.	0.64	0.45
Mar.	0.70	0.55
Apr.	0.73	0.80
May	0.73	0.90
Jun.	0.71	0.75
Jul.	0.69	0.70
Aug.	0.67	0.70
Sep.	0.64	0.75
Oct.	0.60	0.70
Nov.	0.57	0.60
Dec.	0.53	0.45

[a]Specified for zone 2 of the SWAT protocol (IA 2008)
[b]Specified for southwest Florida (Jia et al. 2009)

Table 5-2. Summary of treatment periods evaluated by the models.

Data Period	Start Date	End Date	Cumulative Daily ET_O (mm)		Cumulative Rainfall (mm)		Rainfall Events (#)	
			Observed	Historical	Observed	Historical	Observed	Historical
Frequent. Rain	Jul. 28, 2009	Sep. 25, 2009	239	269	269	323	28	27
Infrequent. Rain	Sep. 26, 2009	Nov. 24, 2009	157	203	46	127	10	12
Low ET_O	Jan. 27, 2010	Mar. 26, 2010	163	208	198	185	17	14
High ET_O	Apr. 7, 2010	Jun. 5, 2010	287	333	124	160	16	13
Field Plots	Aug. 13, 2006	Nov. 27, 2007	2,475	1,845	1,293	1,738	145	153

Table 5-3. Cumulative irrigation, water savings compared to GIR, and performance scores during the frequent rainfall period, lasting sixty days, for each controller.

Controller	Irrigation (mm)	Water Savings (%)	Irrigation Adequacy (%)	Scheduling Efficiency (%)
		Daily SWAT		
ET Water	132	-23	100 a	90 E
Toro	150	-40	100 a	95 C
Weathermatic	74	31	88 c	100 A
GIR	107	0	100	100
		Hourly SWB		
ET Water	132	7	91 b	94 D
Toro	150	-6	100 a	98 B
Weathermatic	74	48	65 d	100 A
GIR	142	0	100	100

Note: Different letters within the same case indicate significant differences between treatments.

Table 5-4. Cumulative irrigation, water savings, and performance scores during the infrequent rainfall period, lasting sixty days, for each controller.

Controller	Irrigation (mm)	Water Savings (%)	Irrigation Adequacy (%)	Scheduling Efficiency (%)
		Daily SWAT		
ET Water	94	3	89 b	100 A
Toro	137	-41	100 a	99 A
Weathermatic	127	-31	100 a	99 A
GIR	97	0	100	100
		Hourly SWB		
ET Water	94	33	64 c	92 C
Toro	137	3	100 a	94 B
Weathermatic	127	10	100 a	100 A
GIR	141	0	100	100

Note: Different letters within the same case indicate significant differences between treatments.

Table 5-5. Cumulative irrigation, water savings, and performance scores during the low ET_O period, lasting sixty days, for each controller.

Controller	Irrigation (mm)	Water Savings (%)	Irrigation Adequacy (%)	Scheduling Efficiency (%)
		Daily SWAT		
ET Water	84	-11	95 a	82 B
Toro	69	9	92 a	100 A
Weathermatic	NA	NA	NA	NA
GIR	76	0	100	100
		Hourly SWB		
ET Water	84	11	75 b	100 A
Toro	69	27	43 c	100 A
Weathermatic	NA	NA	NA	NA
GIR	94	0	100	100

Note: Different letters within the same case indicate significant differences between treatments.

Table 5-6. Cumulative irrigation, water savings, and performance scores during the high ET_O period, lasting sixty days, for each controller.

Controller	Irrigation (mm)	Water Savings (%)	Irrigation Adequacy (%)	Scheduling Efficiency (%)
		Daily SWAT		
ET Water	262	-13	94 a	92 B
Toro	236	-2	93 a	98 A
Weathermatic	185	20	82 b	100 A
GIR	231	0	100	100
		Hourly SWB		
ET Water	262	7	23 d	100 A
Toro	236	17	19 d	100 A
Weathermatic	185	35	47 c	74 C
GIR	283	0	100	100

Note: Different letters within the same case indicate significant differences between treatments.

Table 5-7. Correlation coefficients were used to determine dependence between the performance results and irrigation application for each treatment and model.

	Daily SWAT		Hourly SWB	
Controller	Correlation Coefficient	P-Value	Correlation Coefficient	P-Value
Irrigation Adequacy				
ET Water	0.125	0.4185	-0.783	<0.0001
Toro	-0.142	0.3351	-0.585	<0.0001
Weathermatic	-0.280	0.0250	-0.324	0.0090
Scheduling Efficiency				
ET Water	0.224	0.0598	0.518	<0.0001
Toro	-0.074	0.5330	0.483	<0.0001
Weathermatic	-0.304	0.1306	NR	NR

Note: The Weathermatic had too few instances of over-irrigation for statistical analysis thus results related to scheduling efficiency could not be reported.

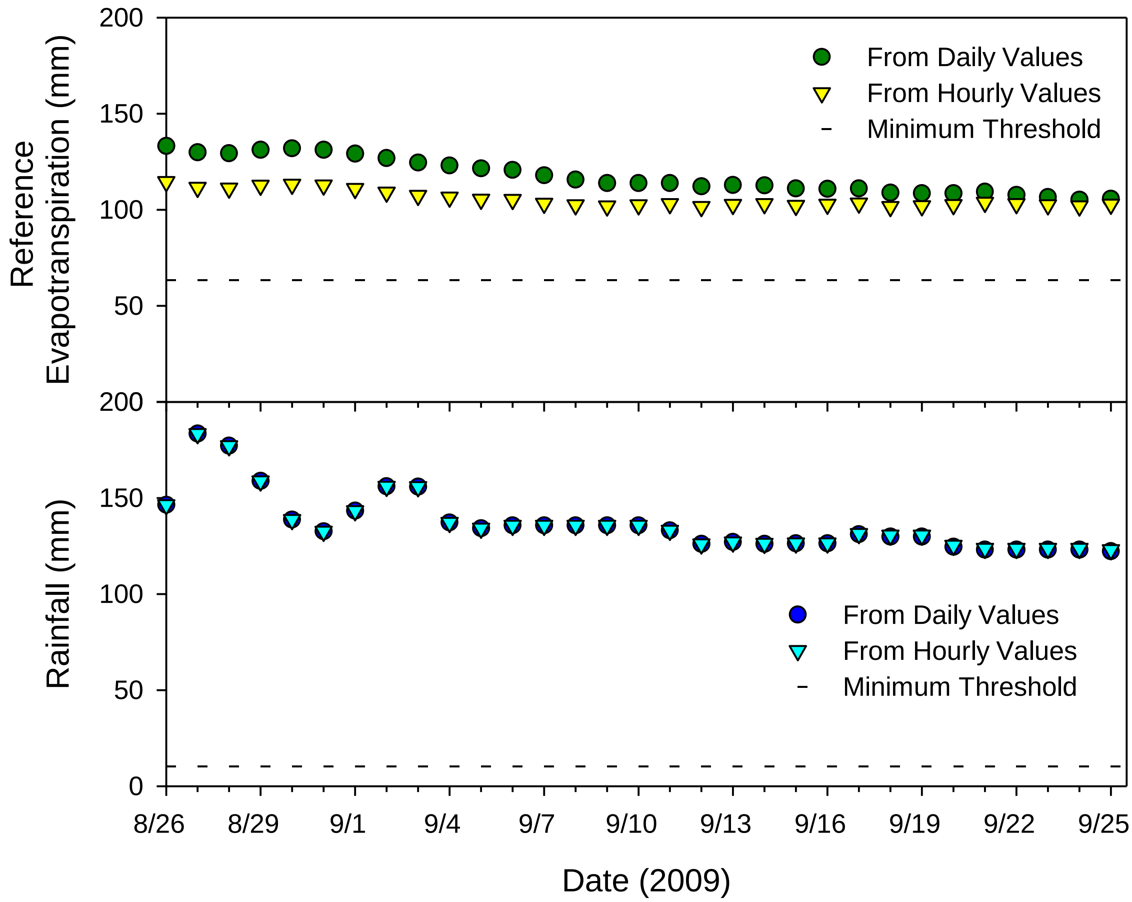

Figure 5-1. Thirty-day totals of ET_O and rainfall for the frequent rainfall period that must meet or exceed the thresholds for a valid testing period.

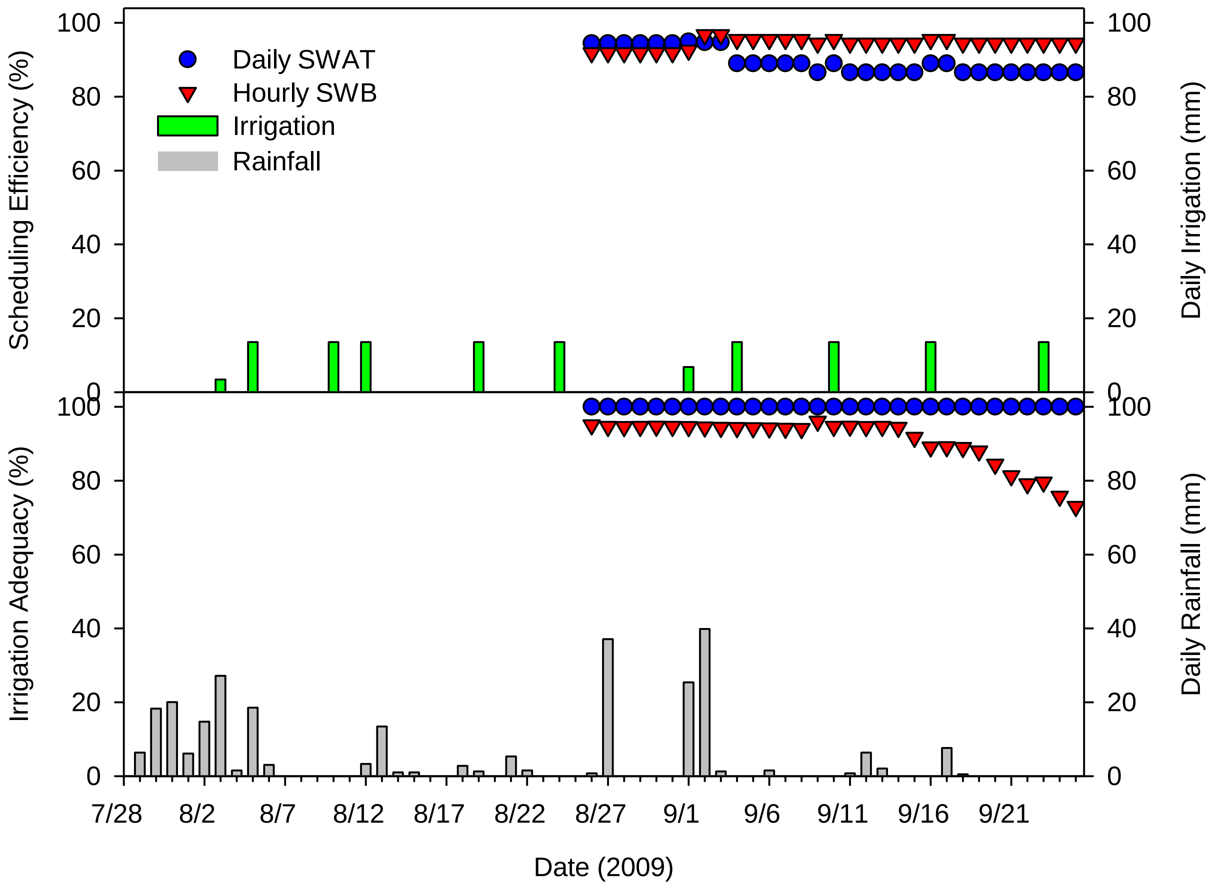

Figure 5-2. Thirty-day performance scores for the frequent rainfall period by the ET Water.

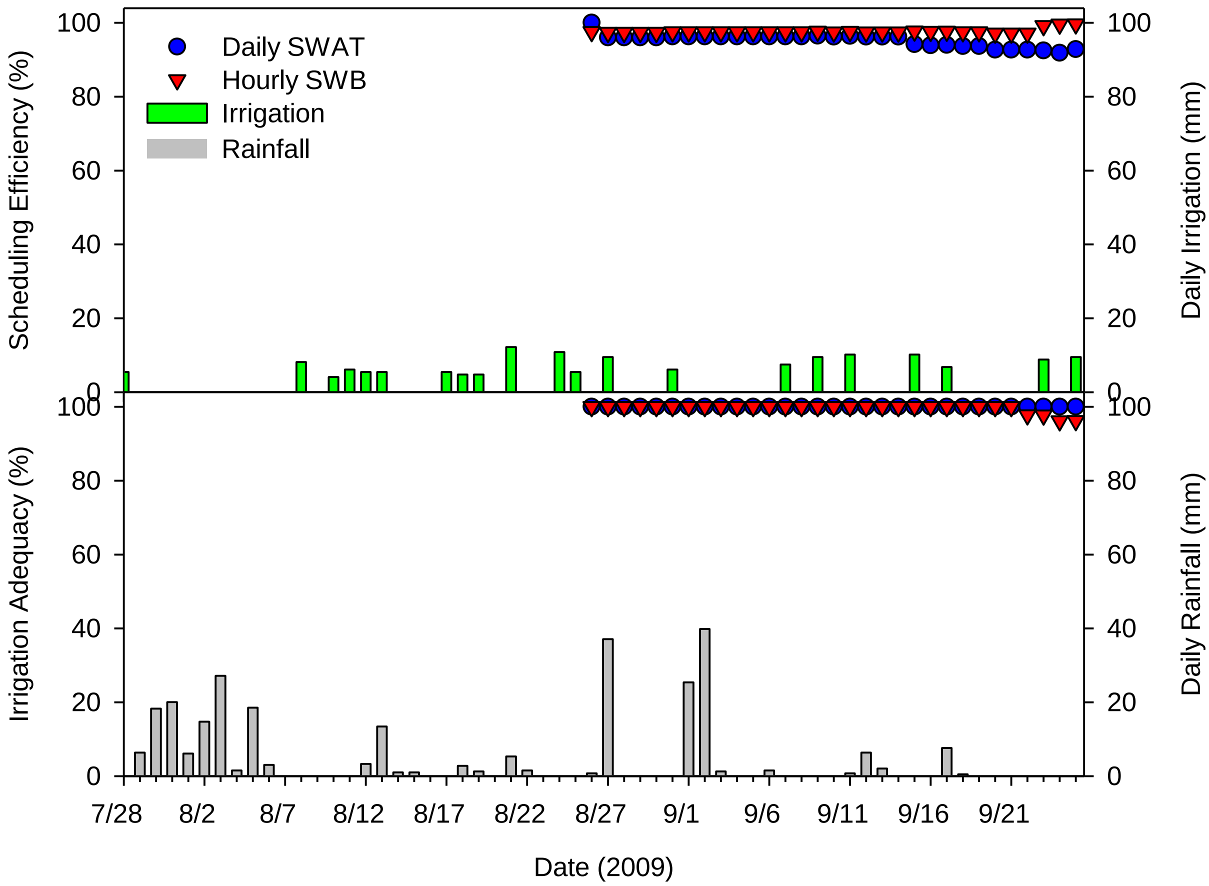

Figure 5-3. Thirty-day performance scores for the frequent rainfall period by the Toro.

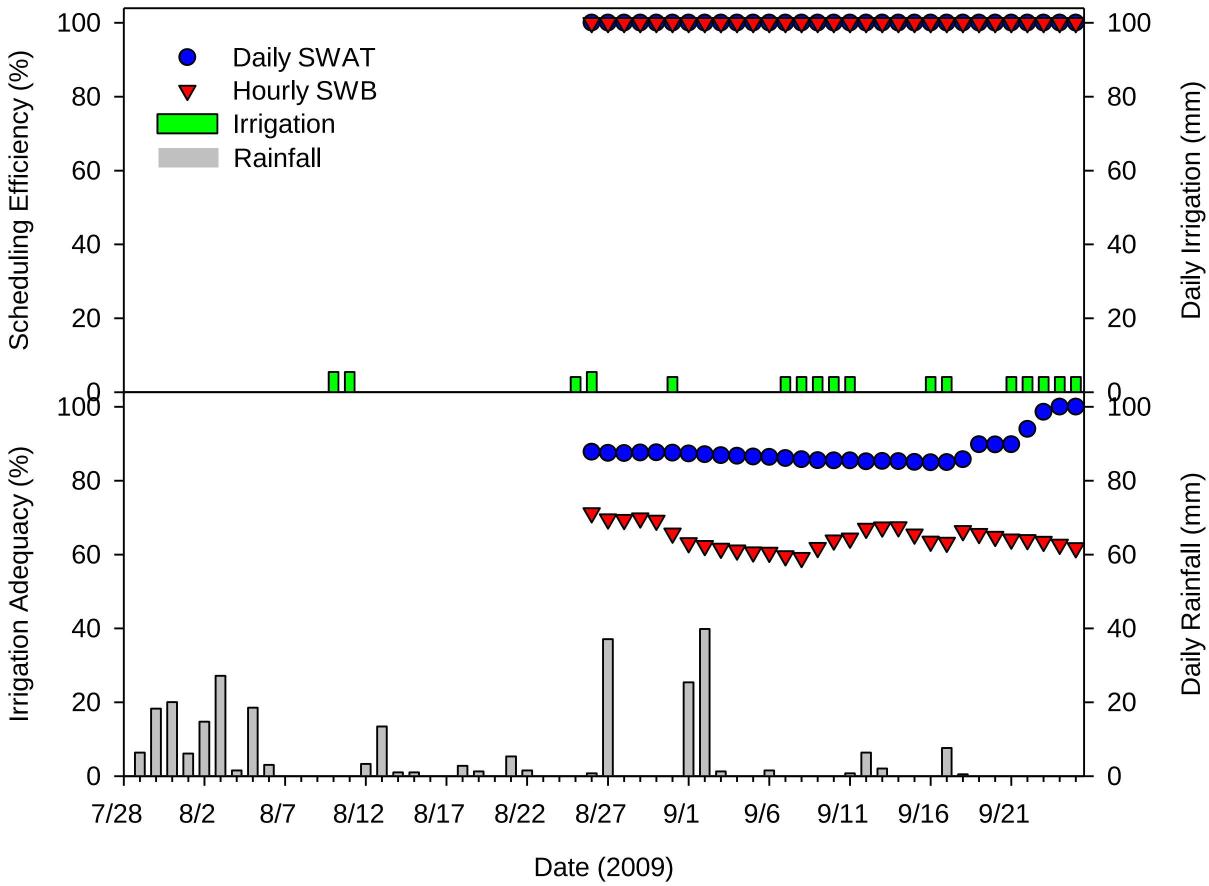

Figure 5-4. Thirty-day performance scores for the frequent rainfall period by the Weathermatic.

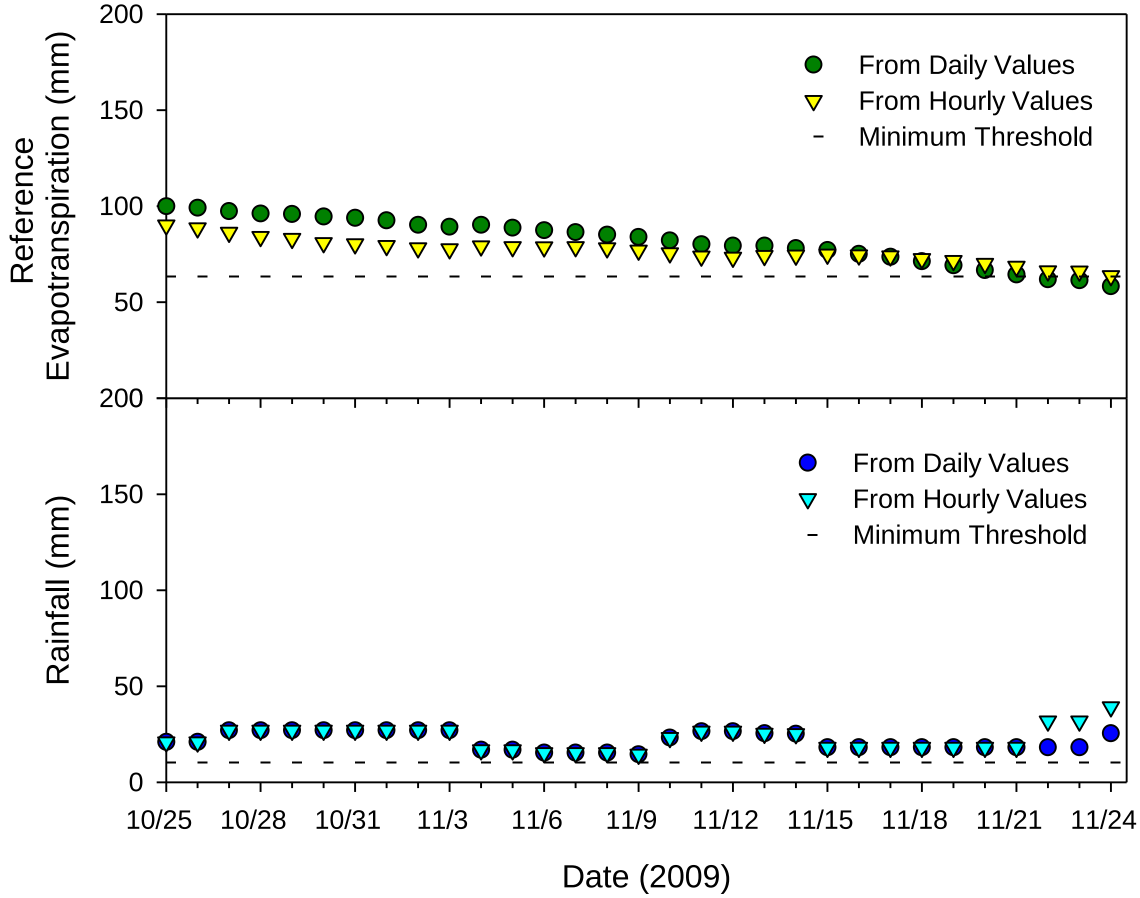

Figure 5-5. Thirty-day totals of ET_O and rainfall for the infrequent rainfall period that must meet or exceed the thresholds for a valid testing period.

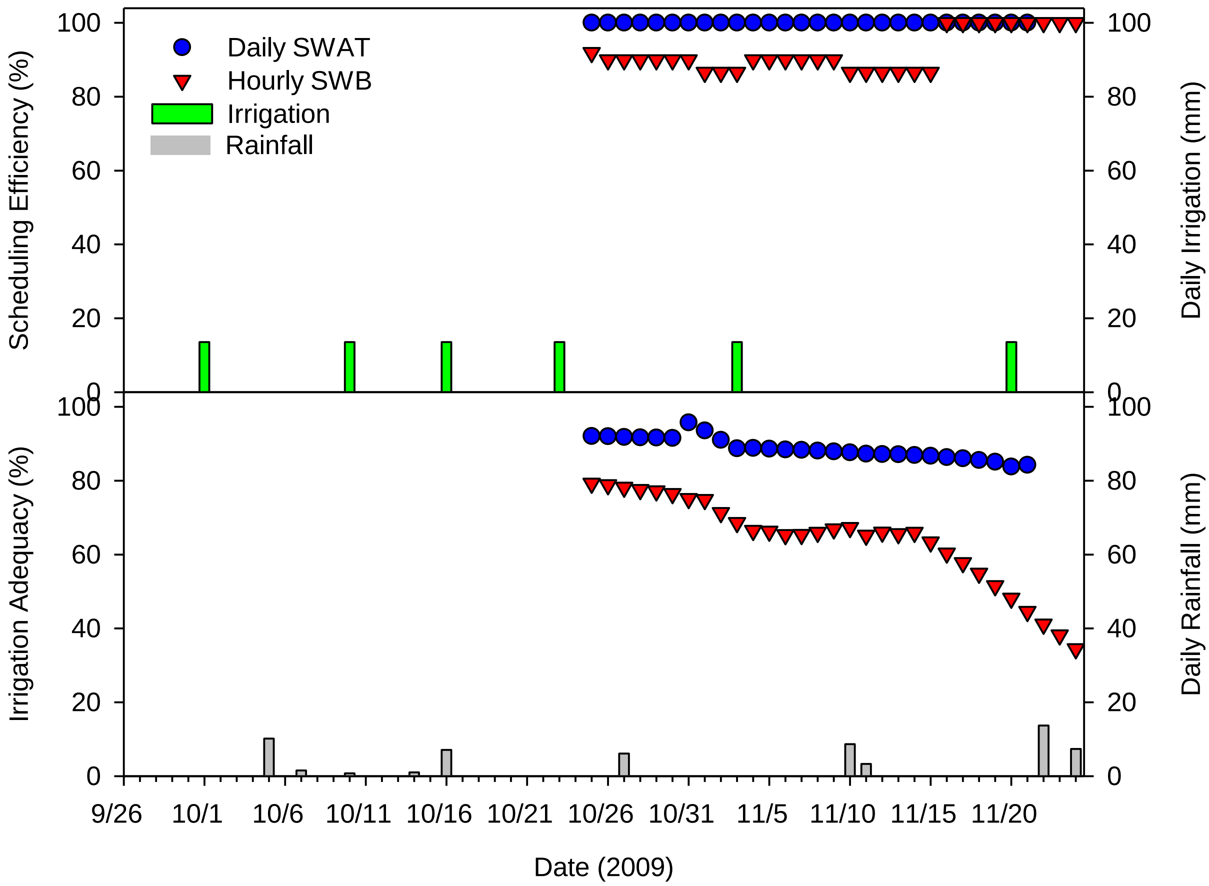

Figure 5-6. Thirty-day performance scores for the infrequent rainfall period by the ET Water.

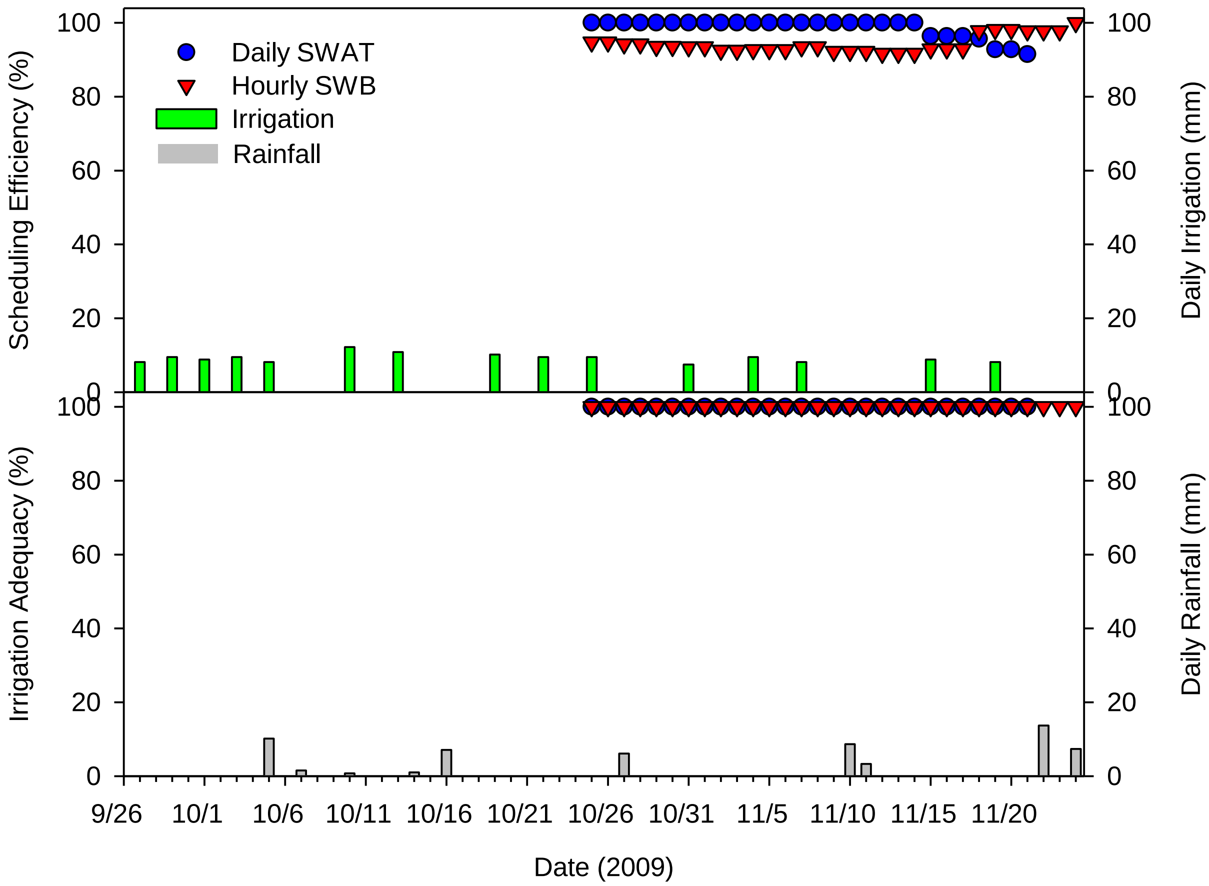

Figure 5-7. Thirty-day performance scores for the infrequent rainfall period by the Toro.

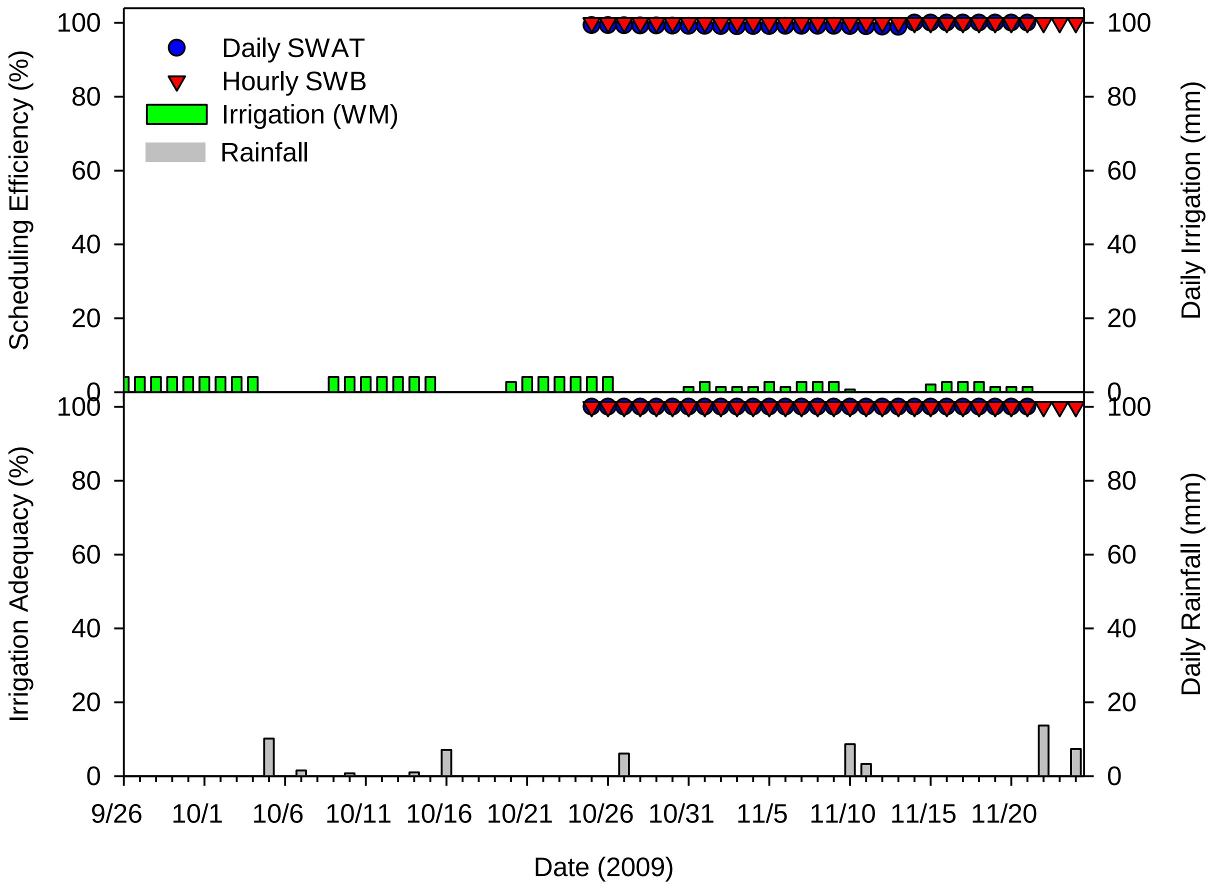

Figure 5-8. Thirty-day performance scores for the infrequent rainfall period by the Weathermatic.

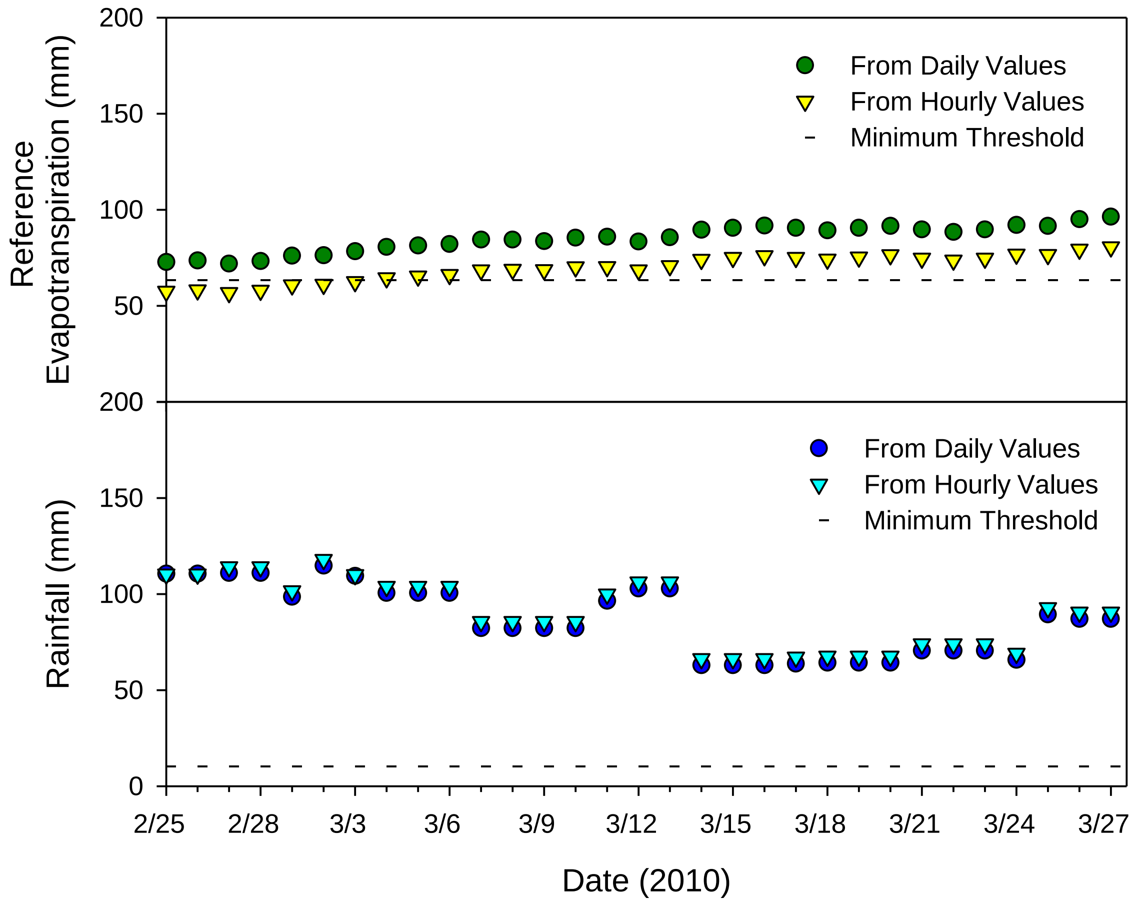

Figure 5-9. Thirty-day totals of ET_O and rainfall for the low ET_O period that must meet or exceed the thresholds for a valid testing period.

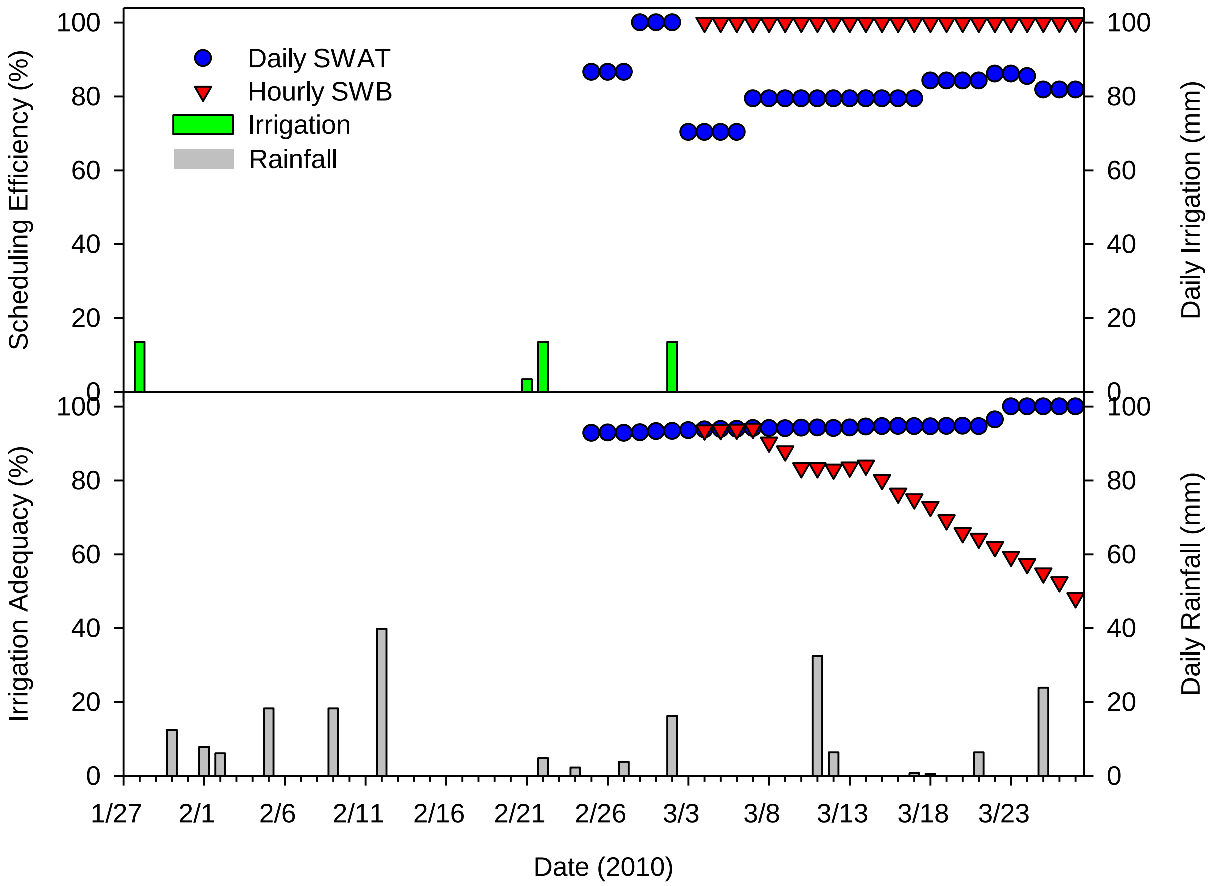

Figure 5-10. Thirty-day performance scores for the low ET_O period by the ET Water.

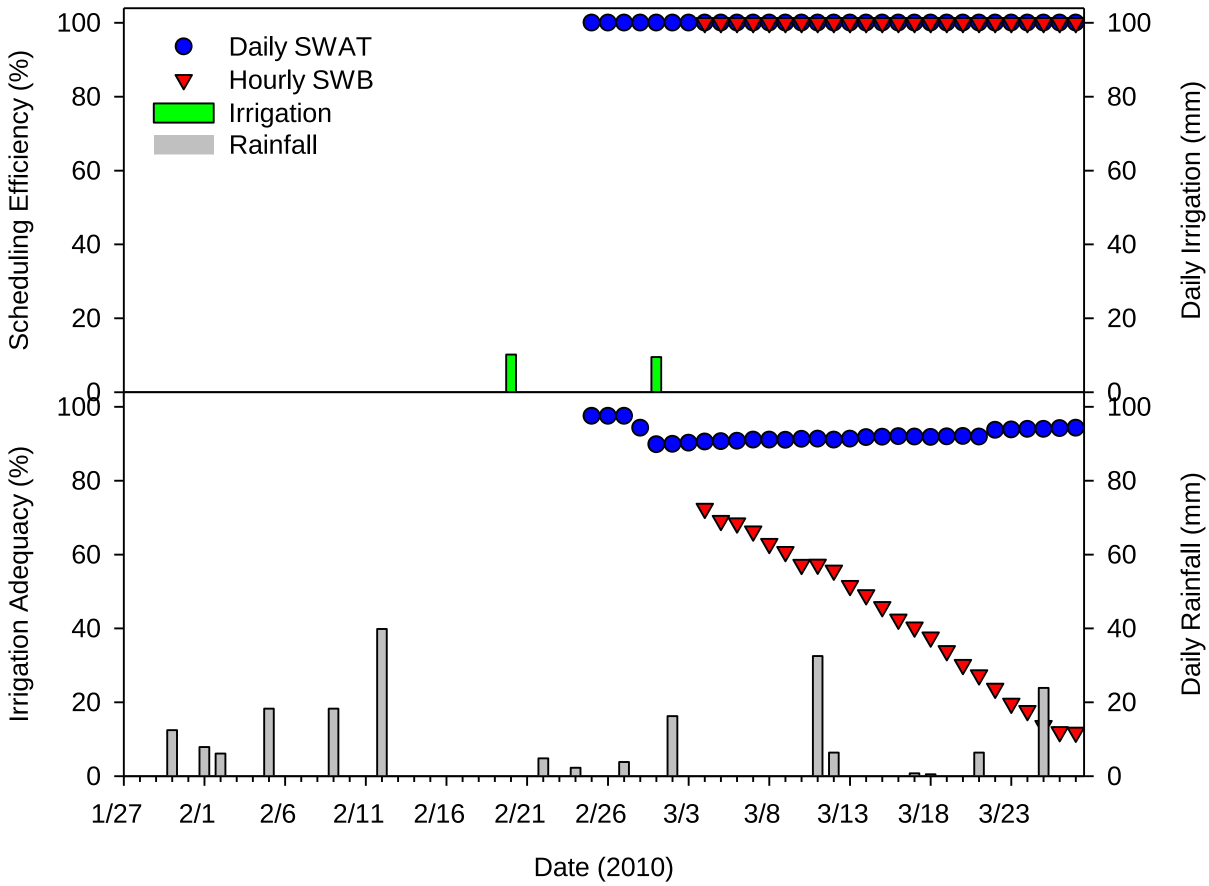

Figure 5-11. Thirty-day performance scores for the low ET_O period by the Toro.

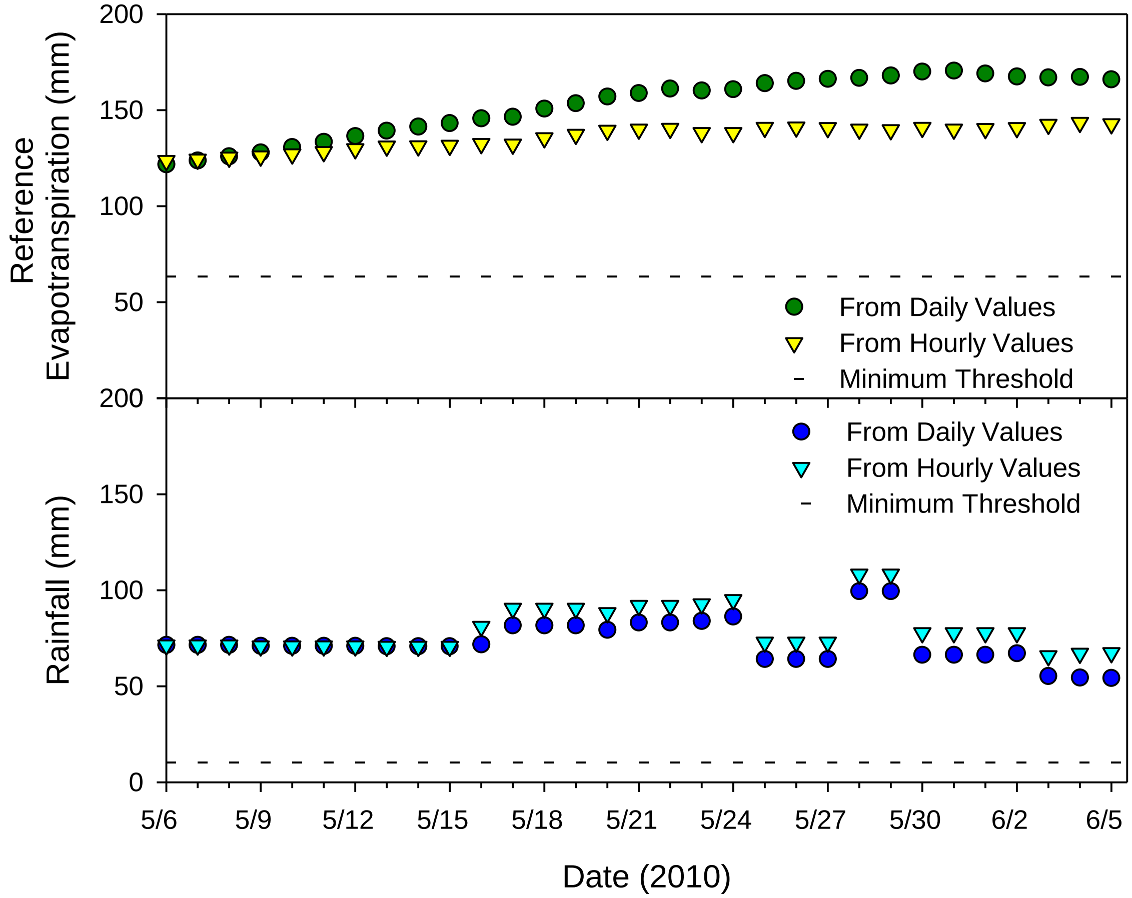

Figure 5-12. Thirty-day totals of ET_O and rainfall for the high ET_O period that must meet or exceed the thresholds for a valid testing period.

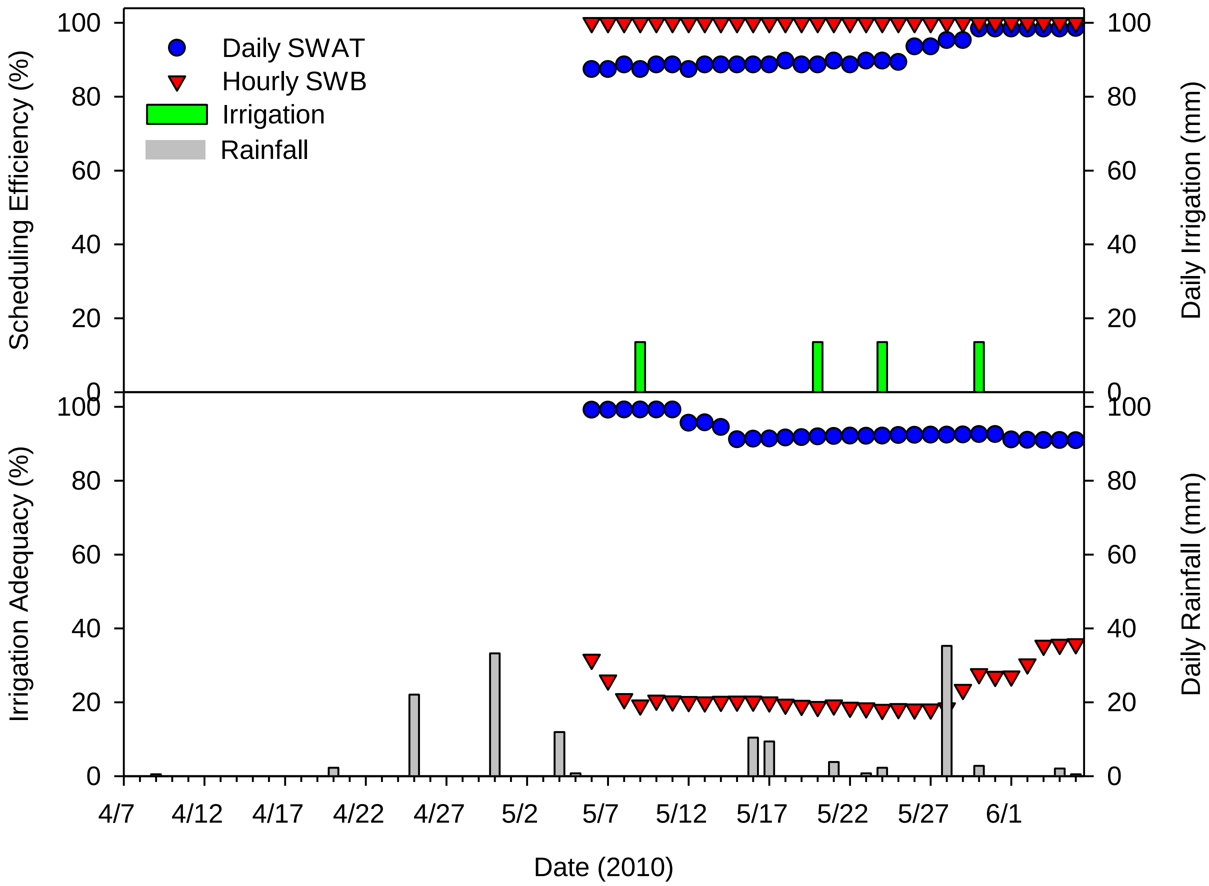

Figure 5-13. Thirty-day performance scores for the high ET_O period by the ET Water.

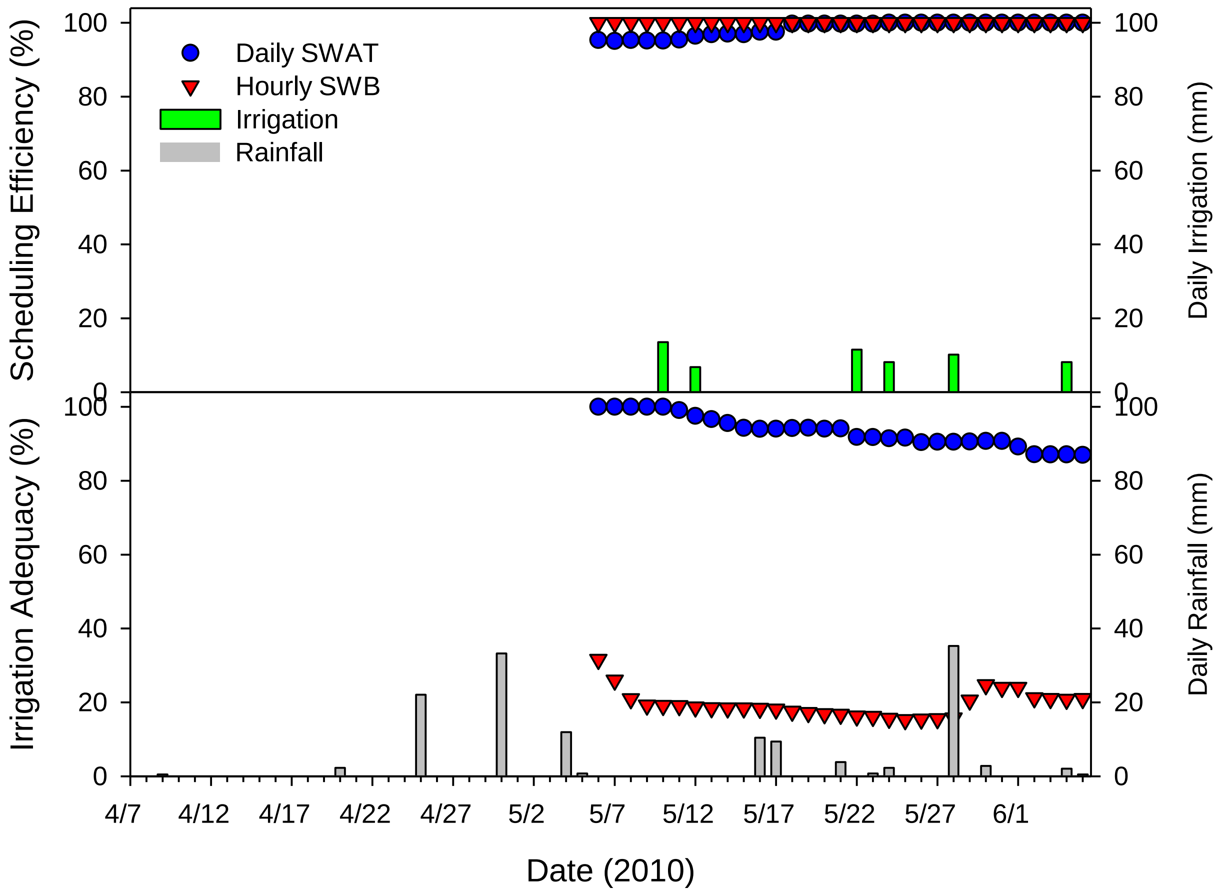

Figure 5-14. Thirty-day performance scores for the high ET_O period by the Toro.

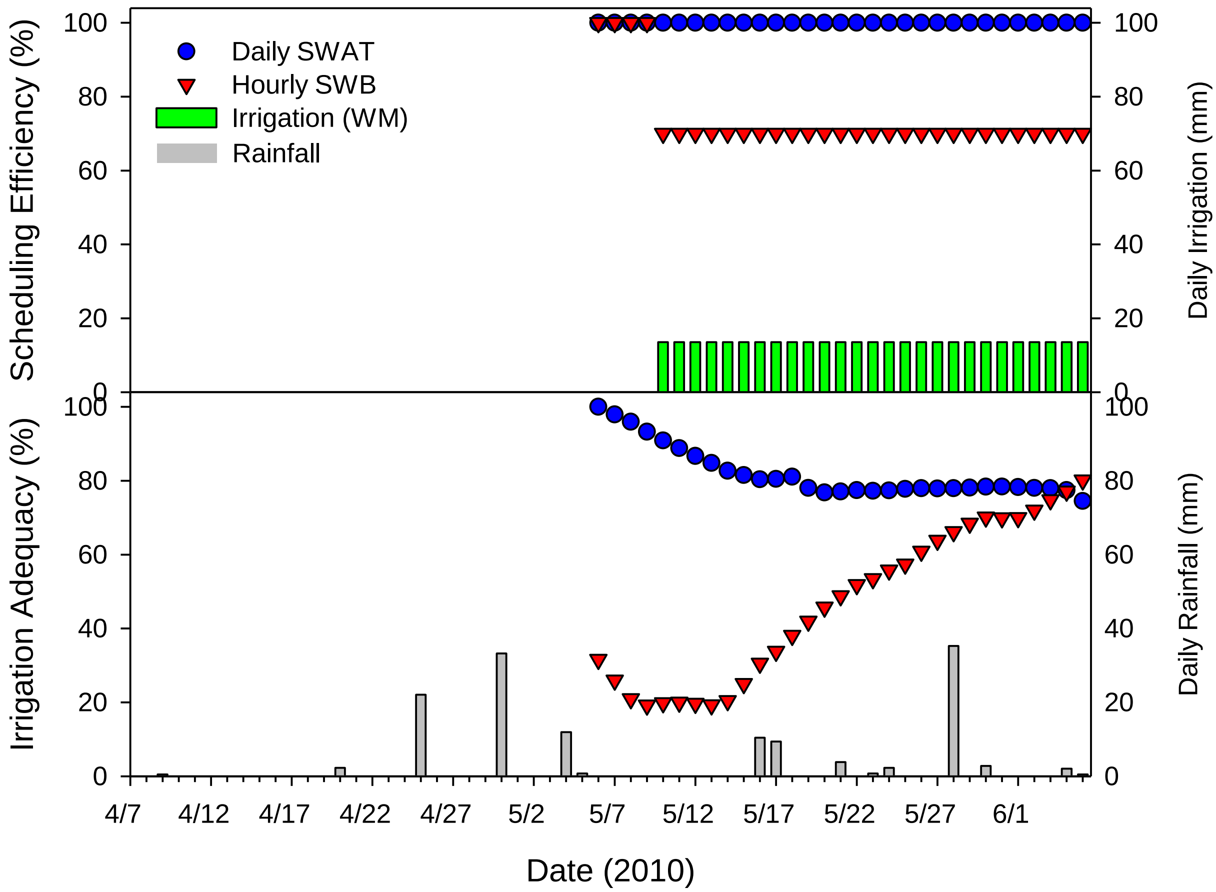

Figure 5-15. Thirty-day performance scores for the high ET_O period by the Weathermatic.

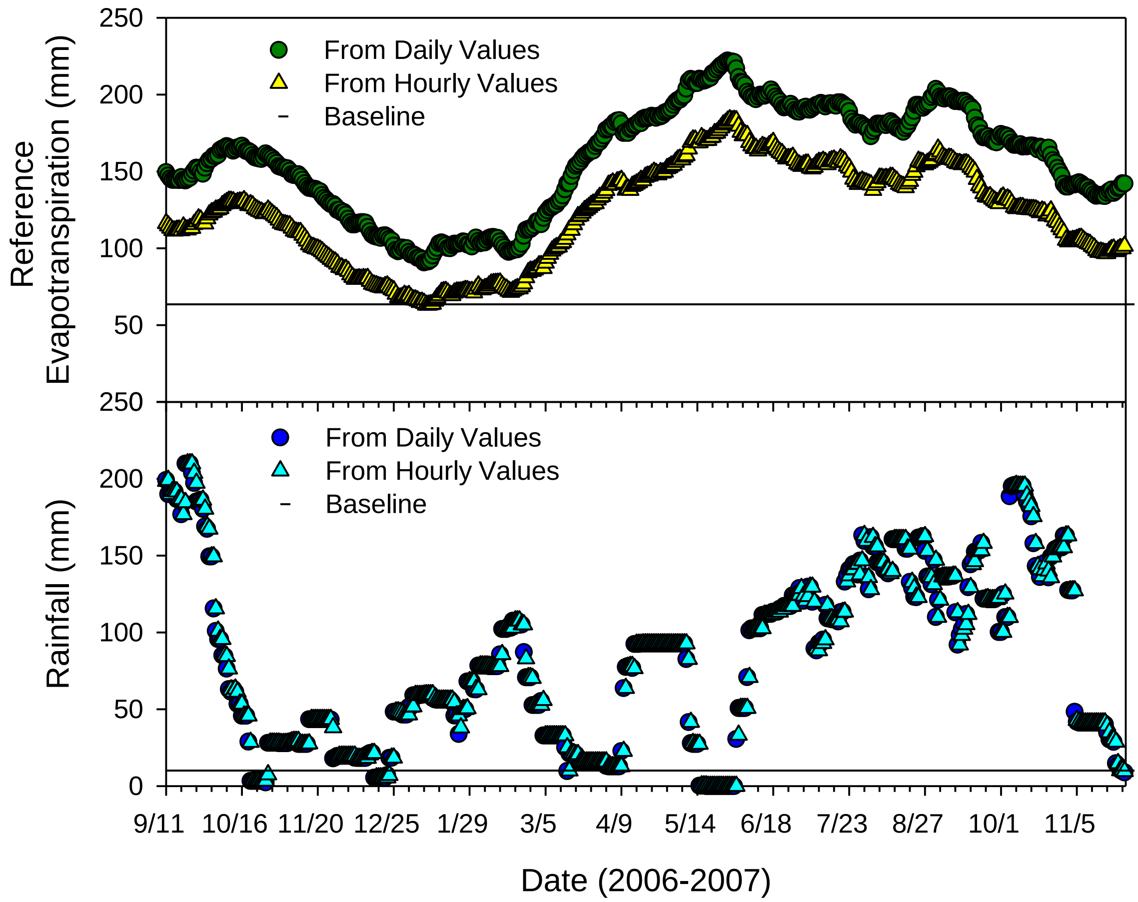

Figure 5-16. Thirty-day totals of ET_O and rainfall for the field plot study at the GCREC that must meet or exceed the thresholds for a valid testing period.

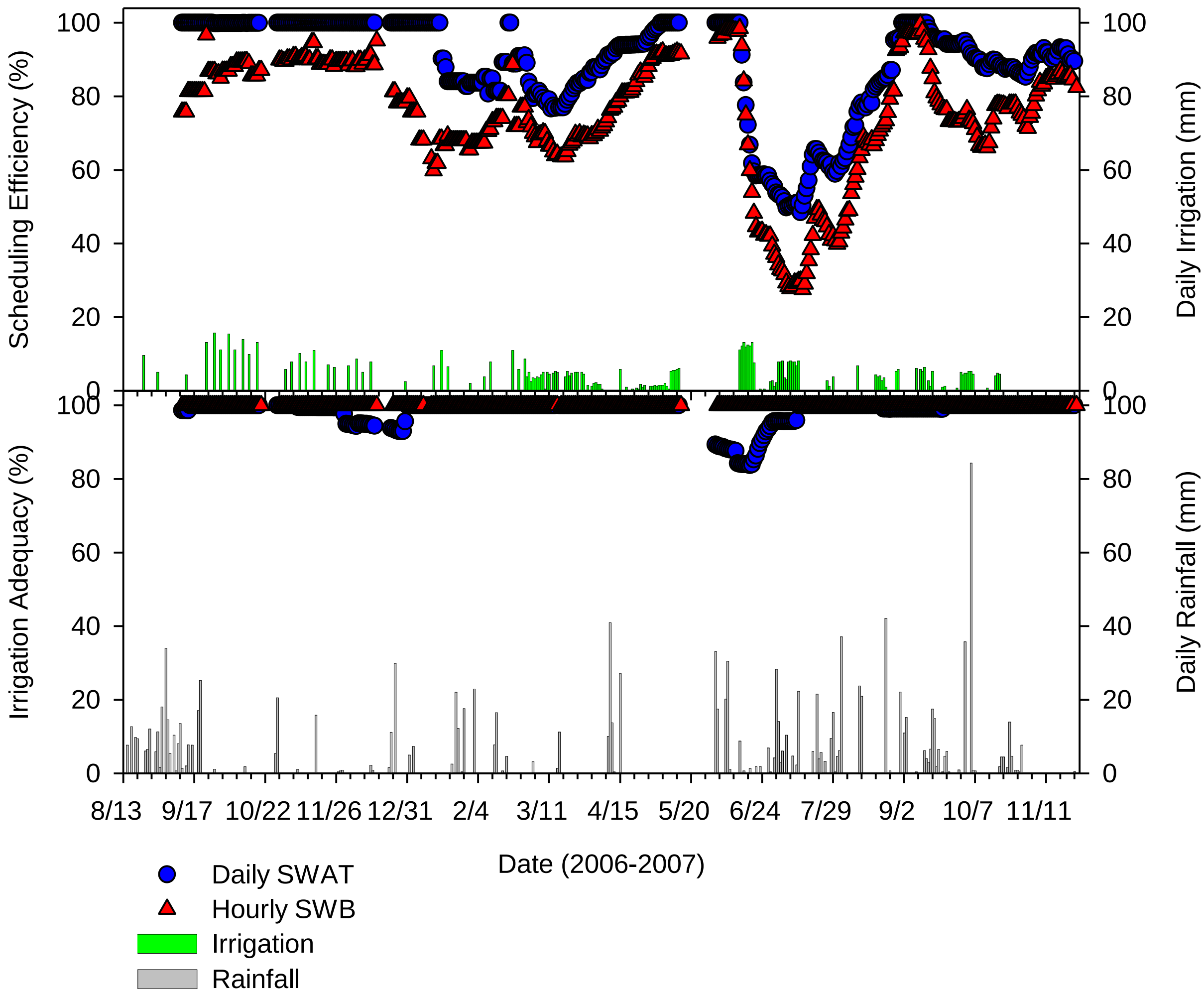

Figure 5-17. Thirty-day performance scores for the Weathermatic evaluated during the field plot study at the GCREC.

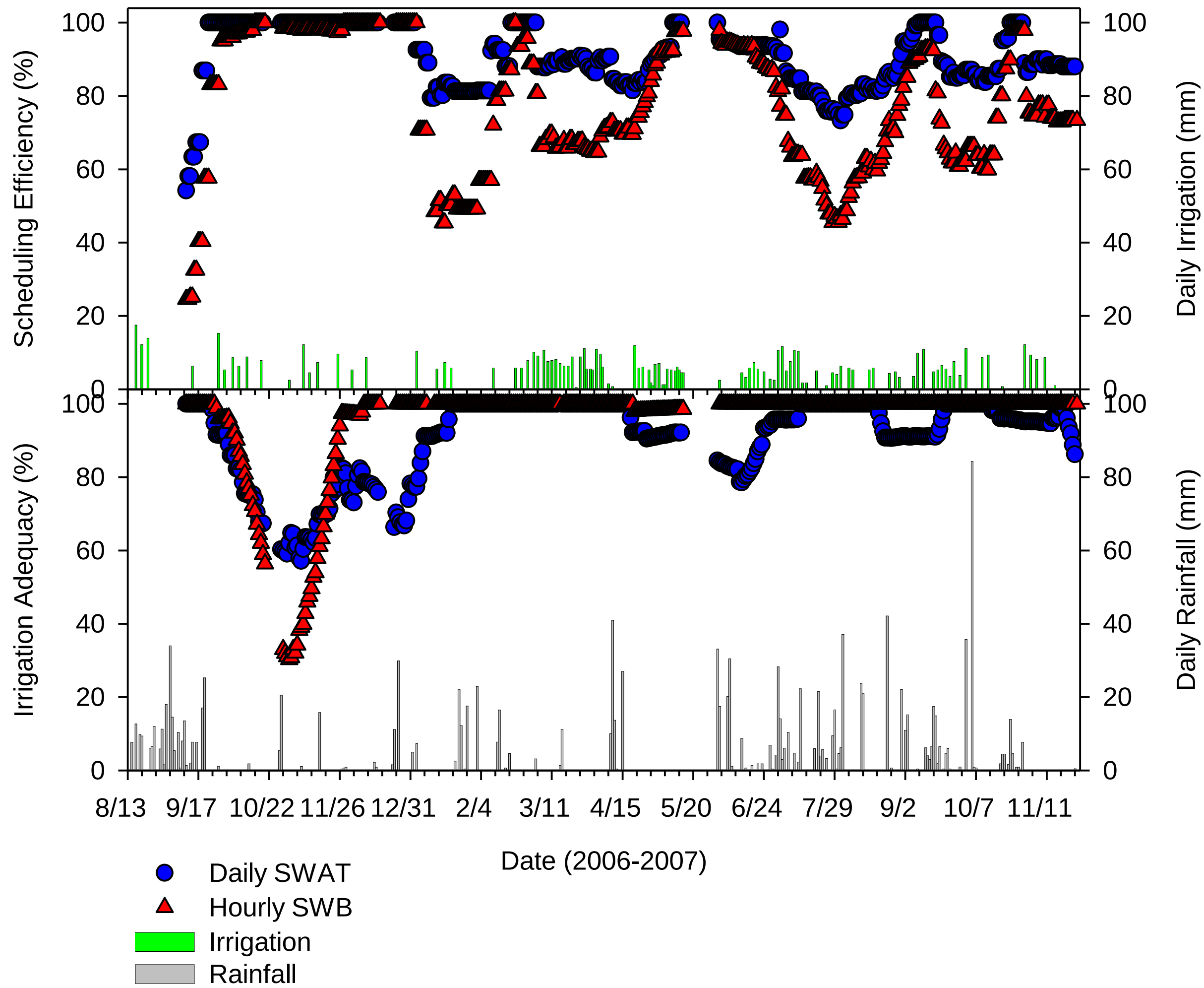

Figure 5-18. Thirty-day performance scores for the Toro evaluated during the field plot study at the GCREC.

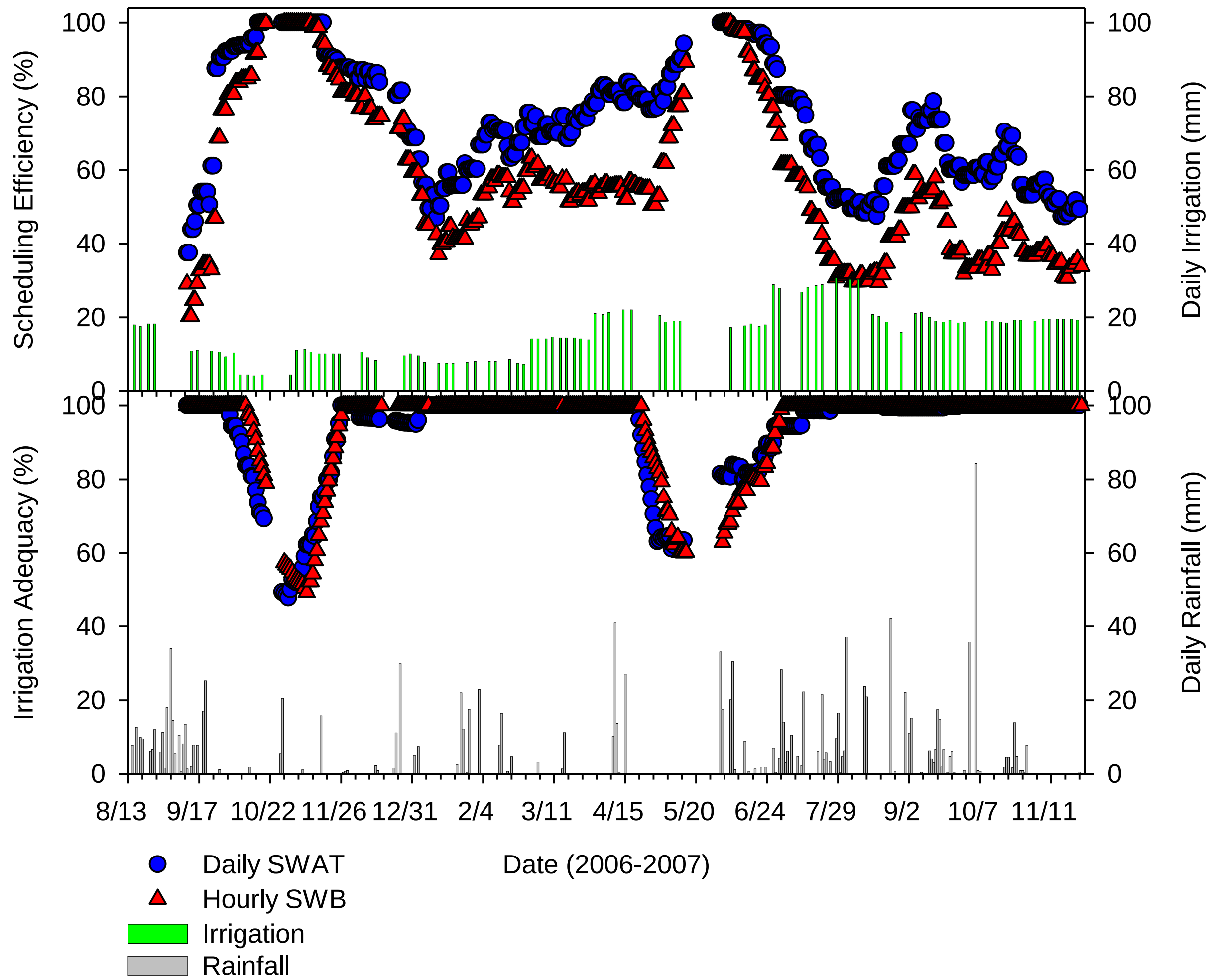

Figure 5-19. Thirty-day performance scores for the TIME treatment evaluated during the field plot study at the GCREC.

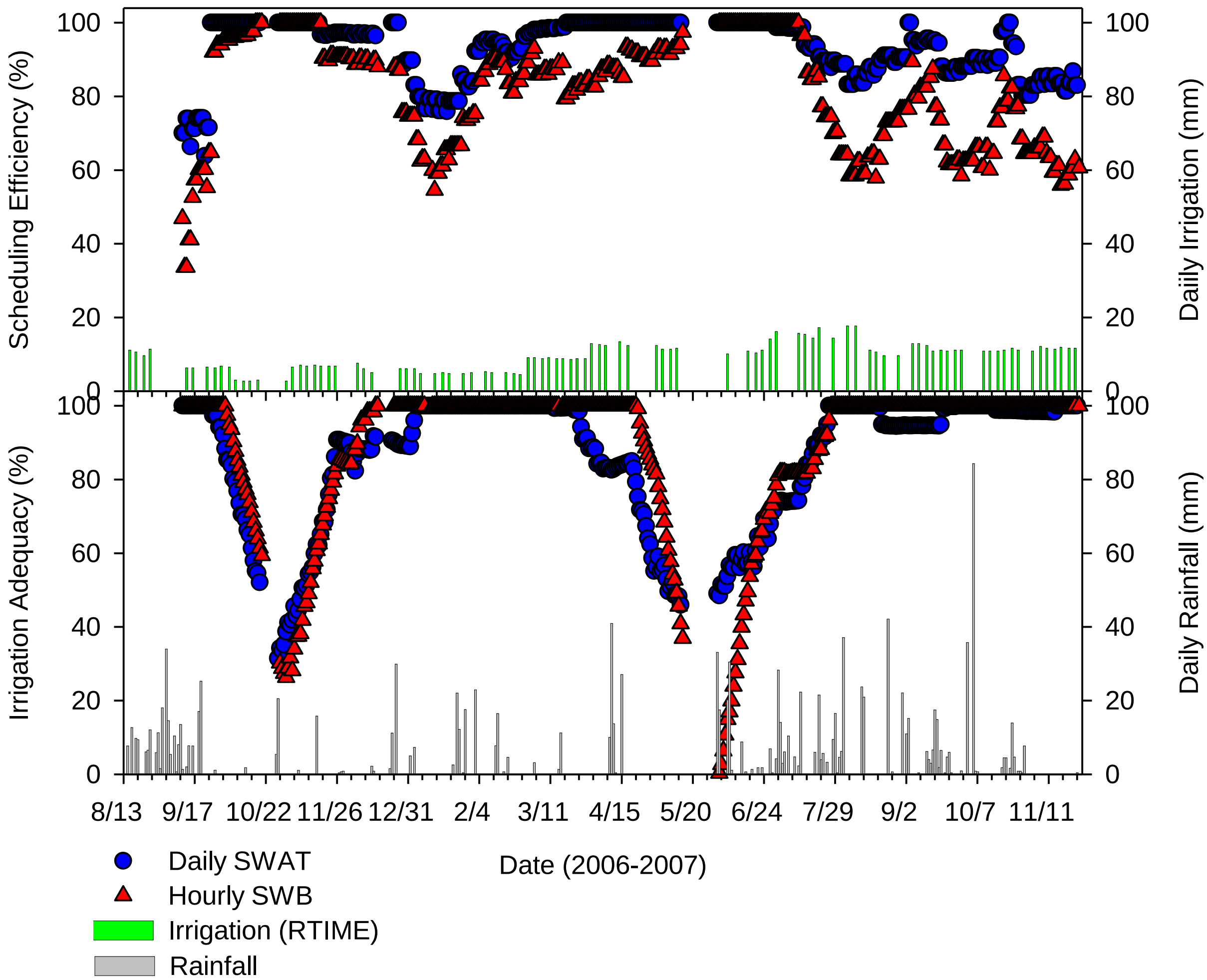

Figure 5-20. Thirty-day performance scores for the RTIME treatment evaluated during the field plot study at the GCREC.

CHAPTER 6
REGRESSION ANALYSIS FOR SENSITIVITY OF AN HOURLY SOIL WATER BALANCE MODEL

Introduction

In efforts to conserve our limited fresh water resources, smart controller technologies were developed as devices designed to improve the efficiency of residential irrigation application. One smart technology is the weather-based irrigation controller that uses reference evapotranspiration (ET_O) to estimate plant water needs, commonly referred to as the ET controller. Though they vary in functionality by brand and model, some ET controllers use a soil water balance (SWB) to determine how much irrigation is necessary and when to apply it. Research has shown that ET controllers have the potential to produce water savings when implemented in scenarios with frequent excessive irrigation (Mayer et al. 2009; Davis and Dukes, in review). They have also been shown to increase irrigation at homes that historically irrigate at or below the theoretical irrigation requirement (Mayer et al. 2009; Davis and Dukes 2014).

The Irrigation Association developed the Smart Water Application Technologies (SWAT) Testing Protocol for Weather-Based Irrigation Controllers as a method to evaluate the irrigation scheduling capabilities of ET controllers (IA 2008). This testing protocol, established in 2002 and now in its 8th draft, specifies a daily soil water balance occurring over a 30-day period to determine if ET controllers can maintain theoretical soil moisture. Results are quantified as irrigation adequacy, a measure of under-irrigation, and scheduling efficiency, a measure of over-irrigation. The protocol specifies that testing results are valid when 30-day totals of rainfall and ET_O meet or exceed 10.2 mm and 63.5 mm, respectively. Publishing SWAT test results are at the discretion of the manufacturer and can be continually tested until achieving acceptable scores during a valid testing period.

The United States Environmental Protection Agency (USEPA) adopted the daily SWAT test as part of their specification for certifying weather-based irrigation controllers as water-saving devices. Instead of publishing performance results as the Irrigation Association does, the USEPA chose minimums of 80% for irrigation adequacy and 95% for scheduling efficiency as the minimum requirements to achieve certification. The results after the first valid 30-day period are compared to the thresholds to determine pass/fail status. Only the controller models and not the quantitative results are published if meeting the minimum requirements.

In chapter 4, an hourly SWB was developed to address the deficiencies in the daily SWAT test that were apparent when evaluated against measured soil moisture data and negatively impacted the transferability of the performance results. The primary deficiencies include inability to store water above field capacity, inability to allow deficit conditions, and the adaptation of transpiration rates based on water storage. The hourly SWB better represented the sub-daily fluctuations in soil moisture resulting in a more accurate estimation of soil water content. The results of chapter 5 indicated that controllers tested using settings meant to pass the daily SWAT test resulted in under-irrigation using the hourly SWB, thus compromising whether the controller achieved passing performance scores for WaterSense certification. As a result, water use efficiency did not translate to controllers implemented in field plot studies that tended to over-irrigate when programmed with parameters specific to landscape descriptions.

Though the results from these chapters were positive, the limitations to the application of the hourly SWB model are unknown. The method for determining the value of the model and appropriateness in future applications is a sensitivity and uncertainty analysis (Beven 2006). A sensitivity analysis evaluates the contribution of uncertainty in the input factors, such as hydraulic parameters in a hydrological model, to the outcomes of the model and an uncertainty analysis quantifies the uncertainty due to the input factors (Helton 1993). Typically, the testing required in quantifying uncertainty is extensive and costly making it unfeasible for some modeling efforts, but determining the sensitivity of each input factor can be completed without additional testing. The objective of this study was to evaluate the uncertainty of the input factors on the performance results obtained using the hourly SWB by performing a regression-based sensitivity analysis.

Materials and Methods

Hourly SWB

Soil water content (θ) in a soil profile is calculated as the ratio between the volume of water to total volume (water, air, and soil particles). In a natural landscape system, θ can range from permanent wilting point (θ_{PWP}), where additional energy is required to remove water from the profile, to saturation (θ_s), where all pore spaces are filled with water. Field capacity (θ_{FC}) is achieved when gravitational forces equal surface tension forces (cohesive and adhesive) between water molecules and soil particles resulting in no drainage due to gravity (Richards 1931). Water storage at water contents between θ_{FC} and θ_s is temporary and drains to θ_{FC} over time based on soil hydraulic properties. To reduce water stress on the plant material, the water content should be maintained above θ_{PWP} at a maximum allowable depletion (θ_{MAD}) selected as a fraction between θ_{PWP} and θ_{FC} (IA 2013).

The soil water balance is a simple model that uses a tipping bucket approach to soil water movement in a homogeneous soil profile (i.e. depth per unit area of root zone) over a specified timestep (Ranatunga et al. 2008). The model is based on the principle that soil water at the current depth (Z) and timestep (i) was affected by the soil water at the previous timestep (i-1) and inputs and outputs of crop evapotranspiration (ET_C), rainfall (R), irrigation (I), runoff (RO), and deep percolation (D) occurring at i (Equation 4-1).

The ET_C was calculated using Equation 4-2 from ET_O determined from local microclimate variables and crop coefficients specific to the studies (Table 5-1). Rainfall and irrigation were utilized similarly in the model where the depth equals the total that fell (R) or was applied (I) over the unit area during the timestep of interest. Events that cause θ to exceed an upper limit of θ_s resulted in separating total depth into effective depth, which is considered available for plant use, and a combination of runoff and deep percolation losses. When total depth results in θ that is less than the upper limit, total depth equals effective depth. Runoff and deep percolation are two different physical processes that both potentially occur when θ exceeds θ_{FC} resulting in water losses from the soil profile. Generally, runoff occurs due to improper cycle/soak scheduling of irrigation and landscape inclines whereas deep percolation occurs due to excess rainfall or irrigation. It is difficult and unnecessary to separate these losses because they are quantified outside of the soil profile and the variable of interest is the change in depth of water within the soil profile.

To account for soil water levels higher than field capacity, an exponential decay function (Equation 4-3) was incorporated into each timestep used to represent drainage to equilibrium. When deficit conditions occur and soil moisture falls below θ_{MAD}, the ability for ET_C to be removed from the soil profile by the plant material becomes more difficult. To account for this phenomenon, a stress coefficient (Equation 4-5) was introduced to the ET_C calculation. Additional details on these changes can be found in Chapter 4.

The performance results of ET controllers determined from the soil water balance are presented as scheduling efficiency (E) and irrigation adequacy (A). Scheduling efficiency is a measure of over-irrigation quantified by estimating scheduling losses over a 30-day period combined from three sources: soil moisture rising above field capacity, too long cycle times, and too short soak times (Equation 5-1). Similarly, irrigation adequacy is a measure of under-irrigation and can be quantified by depths when conditions were not considered well-watered over the 30-day period (Equation 5-2). Results of 100% for either score would indicate that the irrigation scheduling performance by the ET controller was effectively perfect.

Case Studies

Bench test study

The Weathermatic SL1600 (Garland, TX), Toro Intelli-Sense (Riverside, CA), and ET Water Smart Controller 100 (Novato, CA) were installed at the University of Florida Agricultural and Biological Engineering turfgrass research facility in Gainesville, FL. Results from the 2010 Florida SWAT Test using three controllers of each brand showed that there was little variability between replications (Davis et al. 2009). Thus, performance results for these brands are likely to be similar to controllers of the same brand being utilized in the real world, but may not be representative of all controller brands. Additionally, the Toro and ET Water were provided rain sensors and the Weathermatic was equipped with a rain sensor, all set at a 6 mm threshold.

Each controller was connected to a CR-10X datalogger (Campbell Scientific, Logan, UT) via a set of relays to record time and date at the beginning and end of each irrigation event for all active zones. Weather data were collected from a weather station located on-site and managed by research personnel. Weather parameters included temperature, relative humidity, solar radiation, and wind speed collected at fifteen minute intervals. Values for ET_O were calculated using the American Society of Civil Engineers standardized ET_O equation (ASCE 2005) as specified in the SWAT protocol (IA 2008).

Each controller was programmed by the manufacturer, or with the manufacturer's supervision, with all six zones specified in the SWAT test. For this analysis, only zone 2 was considered due to its previous analysis in Chapter 5 and the similarity of this zone's description to landscapes in Florida. In Chapter 5, four 60-day datasets were selected to represent a variety of weather conditions specified as frequent rainfall, infrequent rainfall, high ET_O, and low ET_O (Table 5-2). Each period was selected by comparing the rainfall and ET_O amount over the 60-day period with the historical averages over the same sixty days determined from 37 years of Gainesville Regional Airport weather data from 1970 through 2006 (NCDC 2007). The high ET_O period was chosen as a representative period for this analysis due to the occurrence of high ET_O, frequent rainfall, and disparity between performance results using the hourly SWB compared to the daily SWAT test (IA 2008) found in Chapter 5.

GCREC field plot study

Sixteen St. Augustinegrass plots measuring 7.6 m by 7.9 m were established at the University of Florida Gulf Coast Research and Education Center (GCREC) in Balm, FL. These plots were created to evaluate the ability of ET controllers to apply irrigation efficiently in southwest Florida. The treatments, replicated four times, were: A) Weathermatic SL1600, B) Toro Intelli-Sense, C) TIME treatment based on 100% replacement of the net irrigation requirement, and D) RTIME treatment that was 60% of the TIME treatment. The variable of interest for these treatments was irrigation application only; thus, all plot maintenance and nutrient management remained constant across all treatments based on University of Florida – Institute of Food and Agricultural Sciences recommendations (Sartain 1991; Black and Ruppert 1998).

Detailed methods and results concerning these treatments can be found in Davis et al. (2009), Davis and Dukes (2010), and Davis and Dukes (2012). Each plot was maintained using an irrigation system with dedicated flow meter to measure volumes of irrigation application per plot. The flow meters were connected to a data logger that recorded sub-daily irrigation to easily separate irrigation system maintenance activities and treatment-related irrigation.

Weather data during the study period, ranging from Aug. 13, 2006 to Nov. 12, 2007, was collected from the Florida Automated Weather Network (FAWN) weather station located at the GCREC. Weather parameters included temperature, relative humidity, solar radiation, and wind speed collected at fifteen minute intervals. The ET_O was calculated using the ASCE-EWRI ET equation (ASCE 2005). Rainfall was also collected from this weather station.

Sensitivity Analysis

Sensitivity analysis methods are used to determine the sensitivity of model results to input parameters (Saltelli et al. 2000). This helps to avoid over-parameterization and verify the representation of the physical system. In this study, the Monte Carlo simulation was used to perform a regression analysis to evaluate the effect of changing various input factors on the model output. This type of evaluation is a version of a one-at-a-time (OAT) sensitivity analysis. The simulation involves three important steps (Helton 1993).

- Select range and distribution of input factors
- Generate sample input factors based on the distributions
- Produce model results from each sample input sequence

The input factors selected as important to the hourly SWB were θ_{PWP}, θ_{FC}, θ_s, and the fraction (MAD) that determines θ_{MAD}. Because these factors were already determined using the inverse solution feature of HYDRUS-1D (Chapter 4), preference was given to the inverse solution value in the probability distribution functions. Thus, a triangular distribution was selected for all four parameters with the maximum and minimum limits of each range being less likely to occur in the real system. There were 1,000 randomly selected combinations of input factors chosen using a Microsoft Office Excel add-in called EasyFitXL (Mathwave Technologies, Spokane, WA) for the bench test study (Figure 6-1) and the field plot study (Figure 6-2). These combinations were chosen once and applied identically to all treatments.

The hourly SWB was performed for each combination of input factors resulting in 1,000 results for the response variables of irrigation adequacy and scheduling efficiency for each timestep evaluated. Only one 30-day period was evaluated for the high ET_O

period for the bench test study, with the 30-day period ending Jun. 5, 2010. In Chapter 5, irrigation adequacy and scheduling efficiency results for the GCREC field plot study were calculated for every 30-day period occurring in the study period resulting in rolling averages. For this analysis, only completely independent scores were evaluated thus only fifteen 30-day periods were applicable.

Statistical analyses were completed using Statistical Analytical Systems (SAS) software (Cary, NC). The correlation procedure was used to determine the Pearson correlation coefficient between model results of irrigation adequacy and scheduling efficiency to each of the input factors. The correlation coefficient ranges from -1 to 1 where more positive or more negative values indicate a stronger relationship between the two variables. For the purposes of this analysis, a weak correlation was considered between -0.2 and 0.2 when the coefficient was significant at a 95% confidence level. A moderate correlation was considered between 0.2 and 0.5 or between -0.5 to -0.2. A strong correlation was greater than 0.5 or less than -0.5.

Results

Irrigation Adequacy

Bench test study

The net irrigation requirement can be generalized as the difference between ET_O and rainfall and is usually an over-estimated benchmark. During the thirty days that represented the high ET_O period, the net irrigation requirement approximated 76 mm (Table 6-1). The Toro and ET Water controllers applied less irrigation than the net irrigation requirement, totaling 58 mm and 54 mm. The Weathermatic applied 366 mm, which was 382% more than the net irrigation requirement.

Across all 1,000 iterations of the Monte Carlo simulation for the ET Water, irrigation adequacy results averaged 37.8% with a CV of 0.108 (Table 6-2). This controller had only 2% of results that fell above the EPA WaterSense threshold of 80% indicating very little chance of passing the test. There was no correlation between irrigation adequacy results and the input factors of θ_{PWP}, θ_{FC}, or θ_{s}. However, there was a strong correlation for MAD with a correlation coefficient of 0.800. Thus, the irrigation adequacy results were highly influenced by θ_{MAD}.

The irrigation adequacy for the Toro averaged 24.7% with a CV of 0.262 indicating a large distribution of results (Table 6-2). The Toro had very few results that exceeded the EPA WaterSense threshold of 80%, totaling 1% of the 1,000 iterations. There was no correlation between results and θ_{s}, but there was a moderate correlation for θ_{PWP} and θ_{FC}, with a coefficients of -0.399 and 0.406, respectively. Similar to the results of the ET Water, there was a strong correlation with MAD, having a correlation coefficient of 0.738.

Due to the over-application of irrigation by the Weathermatic, irrigation adequacy averaged 82.8% across the 1,000 replications using the Monte Carlo simulation with a coefficient of variation (CV) of 0.035 (Table 6-2). Due to over-irrigation, the Weathermatic was the only controller with considerable number of scores above the WaterSense threshold of 80%, totaling 66%. There was a strong correlation between irrigation adequacy results and θ_{PWP}, with a coefficient of 0.537, θ_{FC}, with a coefficient of -0.582, and MAD, with a coefficient of 0.545. There was no correlation between irrigation adequacy and θ_{s}.

The MAD is the fraction of the available water holding capacity that is considered well-watered with higher values indicating a larger fraction of well-watered storage. Irrigation adequacy scores for ET Water (Figure 6-3A) and Toro (Figure 6-3B) had similar trends with a steadily increasing slope across the 0.3 to 0.7 range. Over-irrigation was the primary driving factor for the Weathermatic, which limits the range of irrigation adequacy scores, resulting in a less inclined slope across the range of MAD (Figure 6-3C).

GCREC field plot study

The net irrigation requirement ranged from no irrigation required due to enough rainfall to satisfy the plant water needs to 142 mm required for the 30-day period ending May 12, 2007 due to the combination of 170 mm of ET_O but only 28 mm of rainfall (Table 6-3). The previous 30-day period ending Apr. 12, 2007 had similar irrigation requirements, estimated as 129 mm, due to high ET_O and low rainfall. As would be expected, months with low or no irrigation requirement occurred during winter periods where ET_O was low. Periods where the irrigation application did not satisfy the net irrigation requirement occurred for all four treatments, occurring twice for the Weathermatic, five times for the Toro, twice for TIME, and seven times for RTIME.

There was very little variation in irrigation adequacy across the 30-day periods for the Weathermatic, with means ranging from 94.2% to 100% and the maximum CV calculated as 0.094 (Table 6-4). During the period with the lowest mean, ending on Nov. 11, 2006, 76% of the scores were above the EPA WaterSense threshold of 80%. Likewise, the periods with the highest mean, occurring three times, had 98% of scores that met or exceeded the WaterSense threshold. Only one period had a strong correlation between θ_{PWP} and irrigation adequacy while the remaining 14 periods had a weak to moderate correlation. Similar results were also true for θ_{FC}. There were ten periods wehre irrigation adequacy and θ_s were not significantly correlated while the remaining periods were only weakly correlated. A wide range of correlations occurred for MAD, ranging from not significant (five periods) to 0.564. When evaluating one of the periods with a strong correlation, most of the results fell at 100% with a considerable amount of scatter (Figure 6-4).

Average irrigation adequacy ranged from 74.2% (Nov. 11, 2006), with the maximum CV of 0.160 occurring on Dec. 11, 2006, to 99.9% (Aug. 10, 2007), with the minimum CV of 0.010 for the Toro controller (Table 6-5). There were only 9% of the results exceeding the EPA WaterSense threshold of 80% during the Nov. 2006 period whereas there were 97% of results exceeding the WaterSense threshold for the period with the highest average. Moderate to no correlations occurred for θ_{PWP} and θ_s when evaluating irrigation adequacy with two periods of strong correlation for θ_{PWP}. There was a more consistent relationship for θ_{FC} where the coefficients ranged from 0.156 to 0.614 with six periods above 0.5. A majority of moderate to strong correlations occurred for MAD, ranging from 0.215 (Sep. 12, 2006) to 0.871 (Nov. 11, 2006). In the period with the strongest correlation, irrigation adequacy increased steadily as MAD increased (Figure 6-5).

Irrigation adequacy results for the TIME treatment ranged from 56.3% (Nov. 11, 2006) to 100% (Jan. 12, 2007) with the lowest CV of 0.001 (Table 6-6). As a result, only 6% of irrigation adequacy scores exceeded the 80% WaterSense threshold for the period with the lowest average compared to 99% of the scores exceeding the threshold for the period with the highest average. Similar to the other treatments, the input factor with the strongest correlations was MAD, ranging from 0.107 (Mar. 13, 2007) to 0.993 (May 12, 2007). The lower correlation coefficients occurred during the periods with the highest averages, indicating that there were too few deficit conditions to develop a full relationship between irrigation adequacy and MAD. During the period of strongest correlation between MAD and irrigation adequacy, irrigation adequacy increased as MAD increased (Figure 6-6).

Irrigation adequacy for RTIME ranged from 38.2% (Jun. 11, 2007) to 100% (Jan. 12, 2007) with respective CV values of 0.179 and 0.002 (Table 6-7). The period with the highest mean had 99% of scores that exceeded EPA WaterSense criteria whereas the period with the lowest mean had only 3% of passing scores. Similar to the other treatments, there was a weak to moderate correlation between irrigation adequacy and θ_{PWP} or θ_{FC} whereas there was little to no correlation with θ_s. Also, there was a weak to strong correlation with MAD, ranging from 0.147 (Mar. 13, 2007) to 0.833 (May 12, 2007). The periods with the correlation coefficients that were not significant for MAD coincided with the periods with the highest averages resulting in little variation in irrigation adequacy due to consistently high scores. The linear relationship increased as MAD increased across the period with the highest correlation coefficient (Figure 6-7), likely due to persistent deficit conditions by RTIME with an estimated 30-day deficit of 60 mm (Table 6-3).

Scheduling Efficiency

Bench test study

Scheduling efficiency is a measure of over-irrigation and will not fluctuate due during prolonged deficit conditions. Due to under-irrigation occurring by the ET Water and Toro controllers during the high ET_O period, scheduling efficiency results remained at 100% despite repetitive variations of all four input factors (Table 6-2).

The Weathermatic frequently had over-irrigation during this period resulting in an average of 51.7% for scheduling efficiency (Table 6-2). There was very little change in scheduling efficiency from varying the input factors resulting in a low CV of 0.024. All four input factors had significant correlation coefficients for this treatment. There was a moderate correlation for θ_{PWP} and MAD with coefficients of -0.274 and 0.256, respectively. Also, there was a weak correlation with θ_{FC}, having a coefficient of 0.102. A strong correlation existed for θ_s with a coefficient of 0.693. Though θ_s was strongly correlated, the magnitude of the change in scheduling efficiency results was small across the range of input factor values indicating that the varying inputs of θ_s had little impact on final score (Figure 6-8). Compared to the WaterSense threshold of 95% for scheduling efficiency, there were no passing scores for the Weathermatic.

GCREC field plot study

There were four out of fifteen periods that did not require irrigation according to the net irrigation requirement (Table 6-3). Irrigation was applied by all four treatments during all periods thus resulting in over-irrigation and declining scheduling efficiency scores. Over-irrigation was highest during the summer months with maximum excess totaling between 113 mm (RTIME, Aug. 10, 2007) and 209 mm (Weathermatic, Jul. 11, 2007) across treatments due to a lack of effective means for handling rainfall.

For the Weathermatic, scheduling efficiency ranged from 20% (Jul. 11, 2007) to 94.5% (Jun. 11, 2007) across the fifteen time periods (Table 6-4). In most cases, a high frequency of scores occurred around the mean resulting in low CV values, reaching a maximum of 0.181. A majority of periods would not have met the EPA WaterSense threshold for scheduling efficiency of 95% due to such precision around the mean score. There was a weak or no correlation between scheduling efficiency and θ_{PWP} or MAD. In a majority of periods, there were weak or no correlation with θ_{FC}. However, there was a moderate correlation to θ_{FC} for the period ending Nov. 11, 2006 and a strong correlation for the period ending Dec. 11, 2006. These were the only two periods where the Weathermatic did not apply more than the net irrigation requirement. The majority of moderate to strong correlations occurred between scheduling efficiency and θ_s, ranging from 0.197 (Dec. 11, 2006) to 0.919 (Aug. 10, 2007). The lowest correlation coefficient occurred during the period where the correlation coefficient for θ_{FC} was highest. The θ_s increased scheduling efficiency linearly beginning when θ_s was 0.26 $mm^3\ mm^{-3}$ (Figure 6-9).

Scheduling efficiency ranged from 17.0% (Sep. 12, 2006) to 99.9% (Dec. 11, 2006) for the Toro controller with the highest CV of 0.152 (Table 6-5). The period with the highest mean also had 99% of results above the EPA WaterSense threshold of 95%. Very few instances of moderate correlation occurred between scheduling efficiency and θ_{PWP}, θ_{FC}, and MAD. However, a majority of moderate to strong correlation occurred with θ_s with correlation coefficients ranging from 0.078 (Nov. 11, 2006) to 0.880 (Apr. 12, 2007). Similar to the Weathermatic, the period with the lowest correlation coefficient occurred during a period where θ_{FC} had the highest coefficient due to 36 mm of deficit. Also, the period with the strongest correlation had a linearly increasing trend beginning at 0.28 $mm^3\ mm^{-3}$ (Figure 6-10).

Scheduling efficiency for TIME resulted in a range of 16.1% (Sep. 12, 2006) to 89.7% (Jun. 11, 2007) with the largest CV calculated as 0.108 indicating very little change of scores due to variations in the input factors (Table 6-6). Only the period with the highest average had results that exceeded the EPA WaterSense criteria of 95%, totaling 84%. The periods ending May 12, 2007 and Jun. 11, 2007 had moderate correlations with θ_{PWP}, θ_{FC}, and MAD with weak correlation with θ_s due to deficit conditions occurring during parts of the periods. Otherwise, moderate to strong correlation exists between scheduling efficiency and θ_s with a maximum coefficient of 0.950 for the period ending Dec. 11, 2006. The linear, increasing trend of scheduling efficiency across θ_s occurred over the entire range with no limitations to the relationship (Figure 6-11).

Scheduling efficiency ranged from 27.8% (Sep. 12, 2006) to 99.9% (Jun. 11, 2007) for RTIME (Table 6-7), thus mirroring the results of the TIME treatment. There were more periods of deficit for this treatment due to having a reduced timer schedule resulting in a few periods with moderate to strong correlations between scheduling efficiency and θ_{FC} and moderate correlations with θ_{PWP} and MAD. However, a majority of moderate to strong correlations occurred for θ_s, with a maximum coefficient of 0.844 for the period ending Oct. 9, 2007. The linear, increasing trend of scheduling efficiency across θ_s occurred for RTIME in the same manner as the trend for the TIME treatment (Figure 6-12). The magnitude of scores were higher for RTIME due to less irrigation application than TIME, but the change in scores across θ_s was the same, 45% to 65% for TIME (Figure 6-11) and 75% to 95% for RTIME (Figure 6-12), totaling approximately twenty percentile points.

Discussion

Both SWAT test results of irrigation adequacy and scheduling efficiency were impacted by variations of the input factors of θ_{PWP}, θ_{FC}, θ_s, and MAD. In both studies, there was a strong correlation between irrigation adequacy and MAD whereas the relationship between scheduling efficiency was moderately correlated with θ_s during periods of over-irrigation and the other three input factors when under-irrigation occurredThe relationships between irrigation adequacy and MAD as well as scheduling efficiency and θ_s were a linear trend.

Despite the high correlation coefficients, there was still scatter in portions of the scatter plots, indicating that there may be other unexplored input factors affecting the model results. Root depth would be a likely factor to significantly impact the results. However, this parameter was not identified as an input factor in this analysis due to the correlation between root depth and all four input factors that would not be addressed. Helton (1993) explained that relationships between the input factors create complexities to a sensitivity analysis that are beyond the scope of this chapter.

Though there were strong correlations in both studies, irrigation adequacy and scheduling efficiency were largely unaffected by the variations in all input factors. The maximum difference was approximately thirty percentile points despite using extreme values. Consequently, the primary input that affected the irrigation adequacy and scheduling efficiency scores was irrigation. In 30-day periods where irrigation and rainfall exceeded ET_O, scheduling efficiency was low. Likewise, when irrigation and rainfall totaled less than ET_O there was the possibility of deficit conditions occurring during the 30-day period resulting in low irrigation adequacy. Considering its purpose was to judge irrigation scheduling performance, the model was stable across wide ranges of assumed hydraulic parameters. In most cases, the irrigation schedule was a better predictor of performance than the input factors.

The inputs of ET_O and rainfall were also extremely important to the irrigation adequacy and scheduling efficiency scores. The soil hydraulic parameters were the same for each 30-day period in the GCREC field plot study. Thus differences in average SWAT test results were primarily due to varying ET_O and rainfall and how the controller scheduled irrigation in reaction to these weather conditions. Chopart and Vauclin (1990) also found that water-related inputs were the most influential parameters to the results of the water balance model and not the soil properties. In general, improper estimation of the soil hydraulic parameters were not an important factor for meeting the EPA WaterSense criteria.

The selection of the input factors and their assumed probability distributions were based on educated guesses and may have introduced error into the analysis. However, the maximums and minimums of the ranges were selected to evaluate the stability of the model by using extreme but realistic values and defining the limits of the model through the regression analysis (Jones and Luyten 1998; Saltelli et al. 2000). The model consistently produced results that were reasonable given the inputs thus justifying the introduced error in assumptions.

Conclusion

Irrigation adequacy was most sensitive to the model inputs with the only clear relationship occurring between irrigation adequacy and MAD. The correlation between MAD and irrigation adequacy ranged from 0.545 to 0.800 for the bench test study and maximum correlations ranged from 0.564 to 0.933 for the field plot study. Despite such high correlation for all treatments, there was very little increase in irrigation adequacy results due to increasing values of MAD within a reasonable range.

Scheduling efficiency had a moderate to strong relationship to varying θ_s when over-irrigation was prominent, but also had a small effect on final scores. For the bench test study, the correlation coefficient was 0.693 for the one treatment that did not have a perfect score. Likewise, the maximum correlation coefficients ranged from 0.844 to 0.950 for the field plot study. When there were periods of deficit conditions, the model input of θ_{FC} had a strong correlation combined with a weak correlation to θ_s resulting in a minimum coefficient of 0.577 for θ_{FC}.

Both performance results were highly dependent on irrigation application thus satisfying the purpose of the model with good stability. There was also a seasonal dependence on irrigation adequacy and scheduling efficiency results that was primarily based on ET_O and rainfall that was directly inputted into the model. It would be beneficial to continue with the evaluation of the sensitivity and uncertainty of the model using global sensitivity techniques.

Table 6-1. Summary of data used for the soil water balance for the bench test study during the thirty days ending Jun. 5, 2010, representing the high ET_O period.

Description	Depth (mm)
30-day ET_O	143
30-day Rainfall	67
30-day Irrigation for Weathermatic	366
30-day Irrigation for Toro	58
30-day Irrigation for ET Water	54

Table 6-2. Statistical results[a] of irrigation adequacy and scheduling efficiency for each ET controller in the bench test study after performing the global sensitivity analysis using the Monte Carlo simulation.

Statistic	Weathermatic	Toro	ET Water
	Irrigation Adequacy		
Mean (%)	82.8	24.7	37.8
Coefficient of Variation	0.035	0.262	0.108
Correlation Coefficient for θ_{PWP}	0.537*	-0.399	-0.319
Correlation Coefficient for θ_{FC}	-0.582*	0.406	0.311
Correlation Coefficient for θ_s	NS	NS	NS
Correlation Coefficient for MAD	0.545*	0.738*	0.800*
	Scheduling Efficiency		
Mean	51.7	100	100
Coefficient of Variation	0.024	0	0
Correlation Coefficient for θ_{PWP}	-0.274	NA[c]	NA
Correlation Coefficient for θ_{FC}	0.102	NA	NA
Correlation Coefficient for θ_s	0.693*	NA	NA
Correlation Coefficient for MAD	0.256	NA	NA

[a]Asterisk denotes strong correlation selected as greater than 0.5 or less than -0.5.
[b]Correlation coefficients that were not significant at a 95% confidence level were indicated by NS.
[c]Correlation coefficients that could not be calculated are indicated by NA.

Table 6-3. Summary of data used for the soil water balance during each 30-day evaluation period for the GCREC field plot study.

End Date of Evaluation Period	30-day ET_O (mm)	30-day Rainfall (mm)	30-day Irrigation for Weathermatic (mm)	30-day Irrigation for Toro (mm)	30-day Irrigation for TIME (mm)	30-day Irrigation for RTIME (mm)
9/12/2006	115	199	15	64	72	43
10/12/2006	130	61	85	51	72	45
11/11/2006	110	29	69	45	43	28
12/11/2006	80	18	53	36	71	48
1/12/2007	64	59	31	34	70	44
2/11/2007	77	78	38	25	55	35
3/13/2007	104	33	81	65	81	51
4/12/2007	142	13	132	134	135	82
5/12/2007	170	28	148	125	123	82
6/11/2007	163	103	124	123	124	74
7/11/2007	157	93	273	136	128	63
8/10/2007	145	146	128	147	204	113
9/9/2007	157	137	87	81	118	67
10/9/2007	126	195	116	84	115	68
11/8/2007	105	41	83	68	153	90

Table 6-4. Statistical results[a] of irrigation adequacy and scheduling efficiency for the Weathermatic in the GCREC field plot study after performing the global sensitivity analysis using the Monte Carlo simulation.

Statistic	Mean (%)	CV	Correlation Coefficient for θ_{PWP}	Correlation Coefficient for θ_{FC}	Correlation Coefficient for θ_s	Correlation Coefficient for MAD
			Irrigation Adequacy			
9/12/2006	96.5	0.043	-0.486	-0.502*	NS	0.564*
10/12/2006	97.7	0.056	-0.426	0.465	-0.097	0.342
11/11/2006	94.2	0.094	-0.513*	-0.333	NS	0.545*
12/11/2006	98.5	0.050	-0.369	0.359	-0.129	0.293
1/12/2007	100.0	0.006	-0.145	0.142	NS	NS
2/11/2007	99.9	0.008	-0.127	0.129	NS	NS
3/13/2007	100.0	0.004	-0.115	0.125	NS	NS
4/12/2007	99.9	0.006	-0.172	0.183	NS	NS
5/12/2007	99.2	0.021	-0.396	0.436	-0.078	0.295
6/11/2007	95.2	0.084	-0.454	0.547*	-0.066	0.463
7/11/2007	97.5	0.021	-0.442	0.576*	NS	0.554*
8/10/2007	98.8	0.026	-0.426	0.488	NS	0.409
9/9/2007	99.2	0.026	-0.377	0.404	NS	0.289
10/9/2007	99.7	0.010	-0.350	0.350	-0.065	0.246
11/8/2007	100.0	0.002	-0.118	0.124	NS	NS
			Scheduling Efficiency			
9/12/2006	73.3	0.058	-0.139	NS	0.379	0.077
10/12/2006	78.8	0.081	-0.124	NS	0.633*	NS
11/11/2006	82.6	0.064	-0.098	0.454	0.547*	NS
12/11/2006	90.7	0.063	-0.111	0.870*	0.197	NS
1/12/2007	63.2	0.043	NS	-0.095	0.609*	NS
2/11/2007	62.2	0.052	NS	-0.172	0.799*	NS
3/13/2007	54.8	0.114	NS	-0.195	0.797*	NS
4/12/2007	63.9	0.148	NS	-0.202	0.750*	NS
5/12/2007	83.3	0.130	NS	-0.207	0.652*	NS
6/11/2007	94.5	0.097	NS	-0.167	0.413	NS
7/11/2007	20.0	0.125	-0.148	NS	0.870*	0.076
8/10/2007	42.3	0.181	NS	-0.166	0.919*	NS
9/9/2007	93.5	0.038	NS	0.145	0.361	NS
10/9/2007	54.8	0.097	NS	-0.183	0.827*	NS
11/8/2007	72.2	0.116	NS	-0.196	0.693*	NS

[a]Asterisk denotes strong correlation selected as greater than 0.5 or less than -0.5.
[b]Correlation coefficients that were not significant at a 95% confidence level were indicated by NS.

Table 6-5. Statistical results[a] of irrigation adequacy and scheduling efficiency for the Toro in the GCREC field plot study after performing the global sensitivity analysis using the Monte Carlo simulation.

Statistic	Mean (%)	CV	Correlation Coefficient for θ_{PWP}	Correlation Coefficient for θ_{FC}	Correlation Coefficient for θ_s	Correlation Coefficient for MAD
			Irrigation Adequacy			
9/12/2006	99.7	0.013	-0.337	0.340	NS	0.215
10/12/2006	74.2	0.146	-0.349	0.407	-0.106	0.706*
11/11/2006	53.3	0.114	-0.081	NS	-0.094	0.871*
12/11/2006	87.9	0.160	-0.484	0.556*	-0.208	0.542*
1/12/2007	97.2	0.041	-0.414	0.470	-0.196	0.554*
2/11/2007	99.6	0.021	-0.322	0.317	NS	0.180
3/13/2007	99.9	0.010	-0.157	0.156	NS	NS
4/12/2007	99.8	0.013	-0.253	0.240	-0.084	0.115
5/12/2007	94.3	0.046	-0.476	0.584*	-0.106	0.616*
6/11/2007	90.3	0.103	-0.479	0.589*	-0.062	0.597*
7/11/2007	97.1	0.030	-0.505*	0.593*	-0.064	0.526*
8/10/2007	99.7	0.013	-0.318	0.300	NS	0.184
9/9/2007	93.4	0.077	-0.511*	0.614*	NS	0.494
10/9/2007	99.0	0.032	-0.377	0.391	-0.087	0.264
11/8/2007	96.5	0.067	-0.404	0.518*	-0.065	0.417
			Scheduling Efficiency			
9/12/2006	17.0	0.080	NS	0.267	0.527*	NS
10/12/2006	97.5	0.021	-0.249	0.165	0.309	NS
11/11/2006	85.0	0.057	-0.424	0.696*	0.078	0.246
12/11/2006	99.9	0.008	-0.130	0.137	NS	NS
1/12/2007	45.3	0.087	-0.361	0.438	0.540*	0.245
2/11/2007	72.2	0.044	NS	-0.168	0.740*	NS
3/13/2007	56.2	0.067	NS	-0.172	0.876*	NS
4/12/2007	53.4	0.153	NS	-0.196	0.880*	NS
5/12/2007	93.6	0.063	-0.238	0.096	0.476	0.114
6/11/2007	92.4	0.055	NS	-0.104	0.358	NS
7/11/2007	56.2	0.076	-0.163	NS	0.798*	NS
8/10/2007	44.4	0.133	NS	-0.198	0.656*	NS
9/9/2007	85.4	0.044	NS	0.184	0.687*	NS
10/9/2007	46.9	0.075	-0.075	-0.098	0.870*	NS
11/8/2007	71.4	0.041	-0.253	0.122	0.509*	0.094

[a]Asterisk denotes strong correlation selected as greater than 0.5 or less than -0.5.
[b]Correlation coefficients that were not significant at a 95% confidence level were indicated by NS.

Table 6-6. Statistical results[a] of irrigation adequacy and scheduling efficiency for TIME in the GCREC field plot study after performing the global sensitivity analysis using the Monte Carlo simulation.

Statistic	Mean (%)	CV	Correlation Coefficient for θ_{PWP}	Correlation Coefficient for θ_{FC}	Correlation Coefficient for θ_s	Correlation Coefficient for MAD
			Irrigation Adequacy			
9/12/2006	99.7	0.012	-0.335	0.343	-0.062	0.205
10/12/2006	89.8	0.101	-0.475	0.596*	-0.117	0.534*
11/11/2006	56.3	0.072	-0.207	0.170	-0.102	0.635*
12/11/2006	98.6	0.032	-0.423	0.488	-0.098	0.352
1/12/2007	100.0	0.001	-0.064	0.074	NS	NS
2/11/2007	99.9	0.009	-0.125	0.127	-0.067	NS
3/13/2007	99.8	0.016	-0.242	0.226	NS	0.106
4/12/2007	99.0	0.036	-0.361	0.362	-0.073	0.247
5/12/2007	81.4	0.082	-0.197	0.181	-0.137	0.933*
6/11/2007	79.8	0.107	-0.409	0.523*	-0.207	0.730*
7/11/2007	95.0	0.066	-0.493	0.582*	-0.074	0.490
8/10/2007	98.8	0.028	-0.414	0.478	-0.117	0.345
9/9/2007	98.1	0.042	-0.443	0.467	-0.080	0.377
10/9/2007	99.0	0.033	-0.367	0.389	NS	0.261
11/8/2007	98.9	0.028	-0.403	0.467	NS	0.329
			Scheduling Efficiency			
9/12/2006	16.1	0.080	NS	NS	0.817*	NS
10/12/2006	78.4	0.029	-0.089	NS	0.490	NS
11/11/2006	68.7	0.083	NS	0.737*	0.332	NS
12/11/2006	58.1	0.075	-0.068	-0.065	0.950*	NS
1/12/2007	32.0	0.072	NS	-0.138	0.776*	NS
2/11/2007	54.0	0.083	NS	-0.139	0.907*	NS
3/13/2007	47.1	0.061	NS	-0.164	0.833*	NS
4/12/2007	45.5	0.067	-0.073	-0.112	0.853*	NS
5/12/2007	72.6	0.108	-0.558*	0.690*	0.079	0.132
6/11/2007	89.7	0.070	-0.529*	0.577*	0.096	0.227
7/11/2007	49.0	0.073	-0.391	0.324	0.525*	0.191
8/10/2007	27.8	0.087	-0.107	-0.103	0.799*	NS
9/9/2007	45.8	0.062	-0.151	0.331	0.579*	NS
10/9/2007	29.4	0.057	-0.084	-0.154	0.725*	NS
11/8/2007	34.1	0.045	-0.131	NS	0.317	NS

[a]Asterisk denotes strong correlation selected as greater than 0.5 or less than -0.5.
[b]Correlation coefficients that were not significant at a 95% confidence level were indicated by NS.

Table 6-7. Statistical results[a] of irrigation adequacy and scheduling efficiency for RTIME in the GCREC field plot study after performing the global sensitivity analysis using the Monte Carlo simulation.

Statistic	Mean (%)	CV	Correlation Coefficient for θ_{PWP}	Correlation Coefficient for θ_{FC}	Correlation Coefficient for θ_s	Correlation Coefficient for MAD
Irrigation Adequacy						
9/12/2006	99.7	0.012	-0.335	0.340	NS	0.209
10/12/2006	72.4	0.134	-0.409	0.516*	-0.091	0.612*
11/11/2006	63.5	0.063	NS	-0.274	NS	0.450
12/11/2006	98.0	0.044	-0.436	0.489	NS	0.379
1/12/2007	100.0	0.002	-0.078	0.087	NS	NS
2/11/2007	99.9	0.008	-0.152	0.151	NS	NS
3/13/2007	99.5	0.028	-0.279	0.261	NS	0.147
4/12/2007	96.8	0.074	-0.430	0.489	NS	0.375
5/12/2007	63.1	0.125	0.254	-0.409	-0.112	0.833*
6/11/2007	38.2	0.179	0.403	-0.571*	NS	0.604*
7/11/2007	73.0	0.127	-0.388	0.455	NS	0.768*
8/10/2007	98.6	0.030	-0.434	0.499	-0.065	0.386
9/9/2007	93.3	0.074	-0.506	0.594*	-0.105	0.532*
10/9/2007	98.3	0.044	-0.414	0.461	-0.069	0.335
11/8/2007	97.6	0.054	-0.410	0.499	NS	0.382
Scheduling Efficiency						
9/12/2006	27.8	0.103	NS	0.257	0.673*	NS
10/12/2006	90.8	0.017	NS	-0.183	0.766*	NS
11/11/2006	93.4	0.066	NS	0.881*	NS	NS
12/11/2006	89.1	0.035	NS	0.132	0.832*	NS
1/12/2007	52.5	0.059	NS	NS	0.803*	NS
2/11/2007	84.9	0.035	NS	-0.156	0.518*	NS
3/13/2007	81.0	0.026	NS	-0.086	0.635*	NS
4/12/2007	86.6	0.027	-0.239	0.133	0.433	0.068
5/12/2007	89.4	0.052	-0.406	0.347	0.360	NS
6/11/2007	99.9	0.015	-0.142	0.150	NS	NS
7/11/2007	94.0	0.063	-0.557*	0.702*	NS	0.275
8/10/2007	52.1	0.052	-0.196	NS	0.761*	0.074
9/9/2007	74.7	0.039	-0.075	-0.096	0.744*	NS
10/9/2007	54.0	0.053	-0.107	-0.078	0.844*	NS
11/8/2007	66.6	0.033	-0.248	0.136	0.145	0.079

[a]Asterisk denotes strong correlation selected as greater than 0.5 or less than -0.5.
[b]Correlation coefficients that were not significant at a 95% confidence level were indicated by NS.

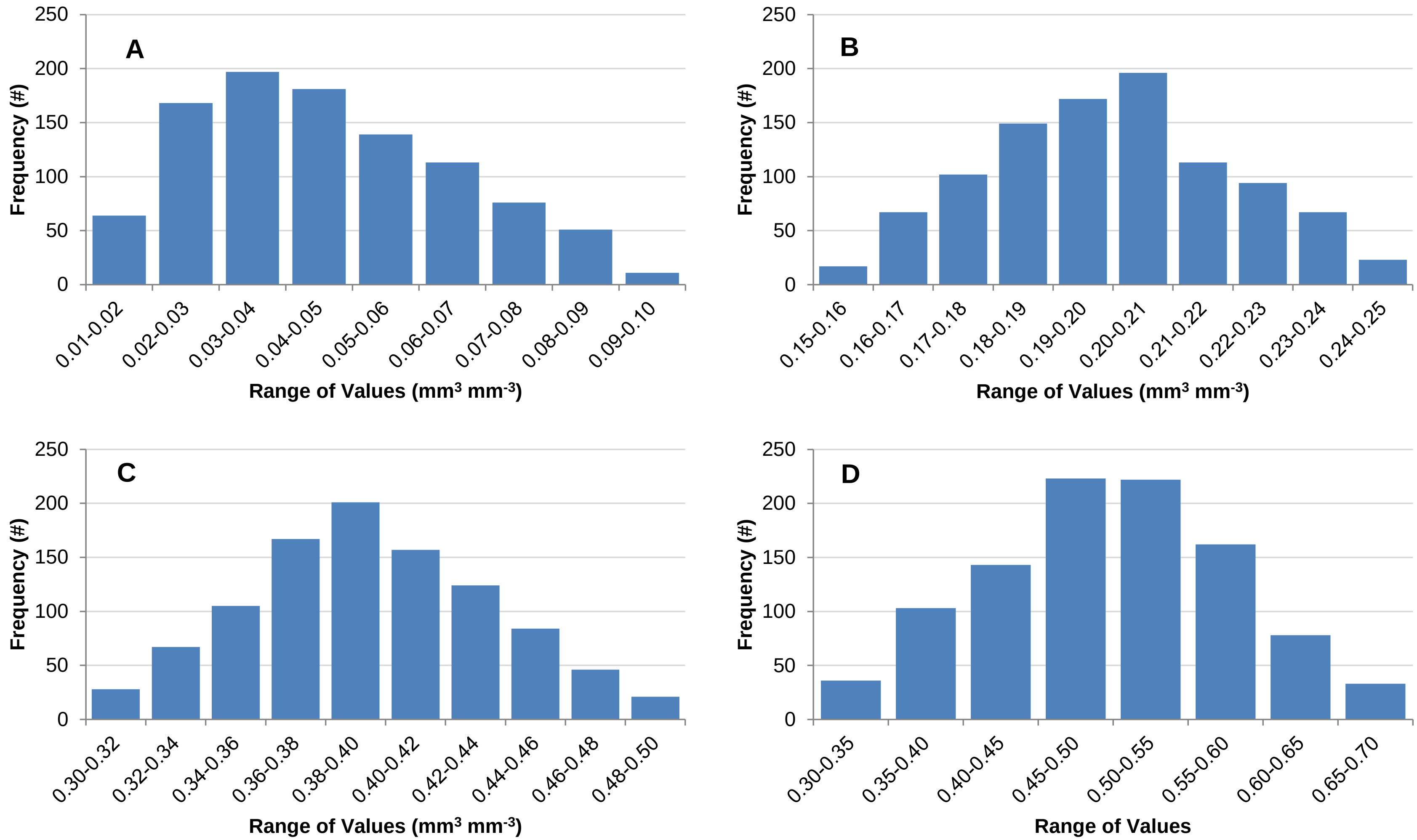

Figure 6-1. Probability densities used in the bench test study for A) permanent wilting point, B) field capacity, C) saturation, and D) maximum allowable depletion.

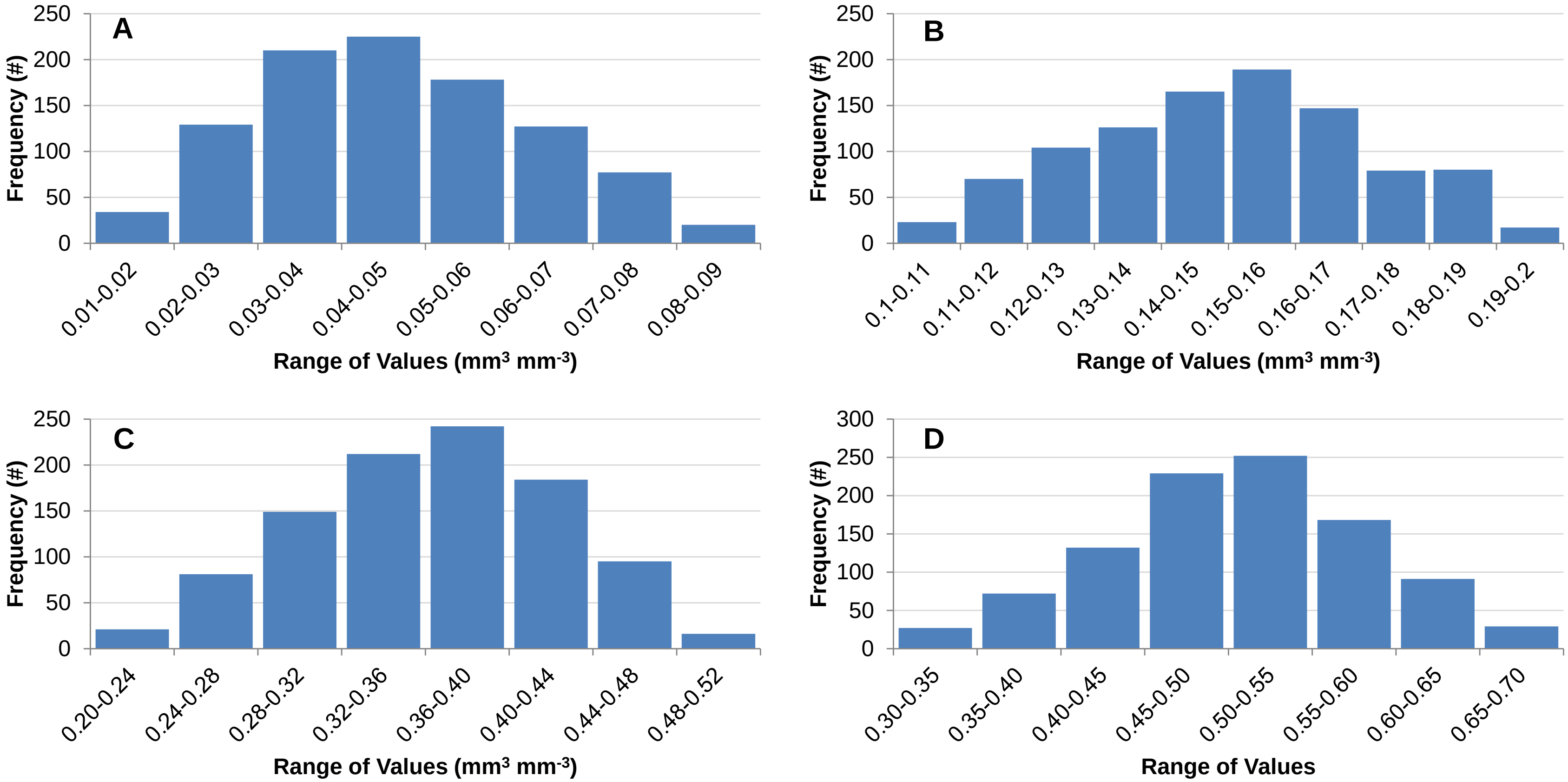

Figure 6-2. Probability densities used in the GCREC field plot study for A) permanent wilting point, B) field capacity, C) saturation, and D) maximum allowable depletion.

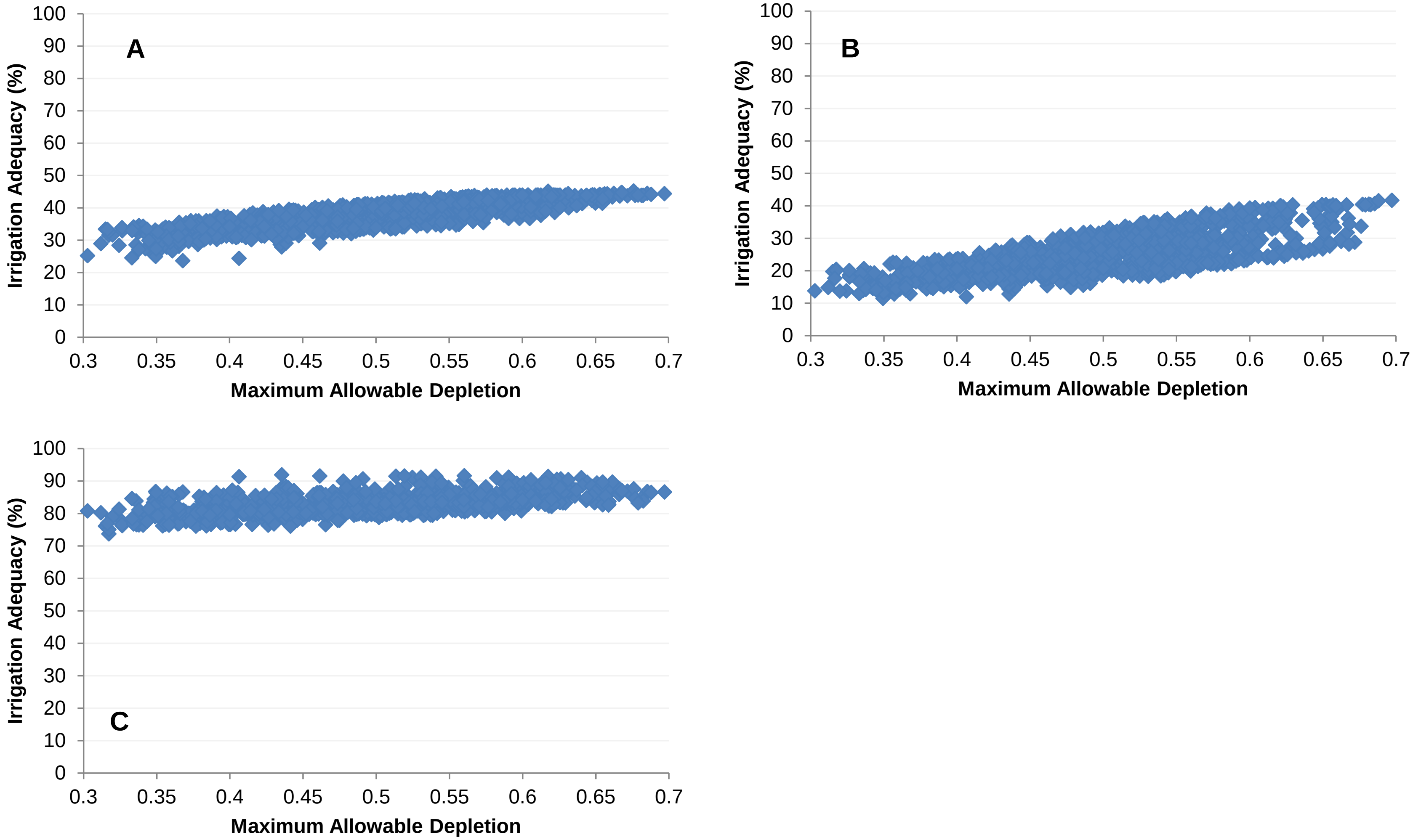

Figure 6-3. Response in irrigation adequacy to varying the input factor of maximum allowable depletion during the bench test study for the A) ET Water, B) Toro, and C) Weathermatic.

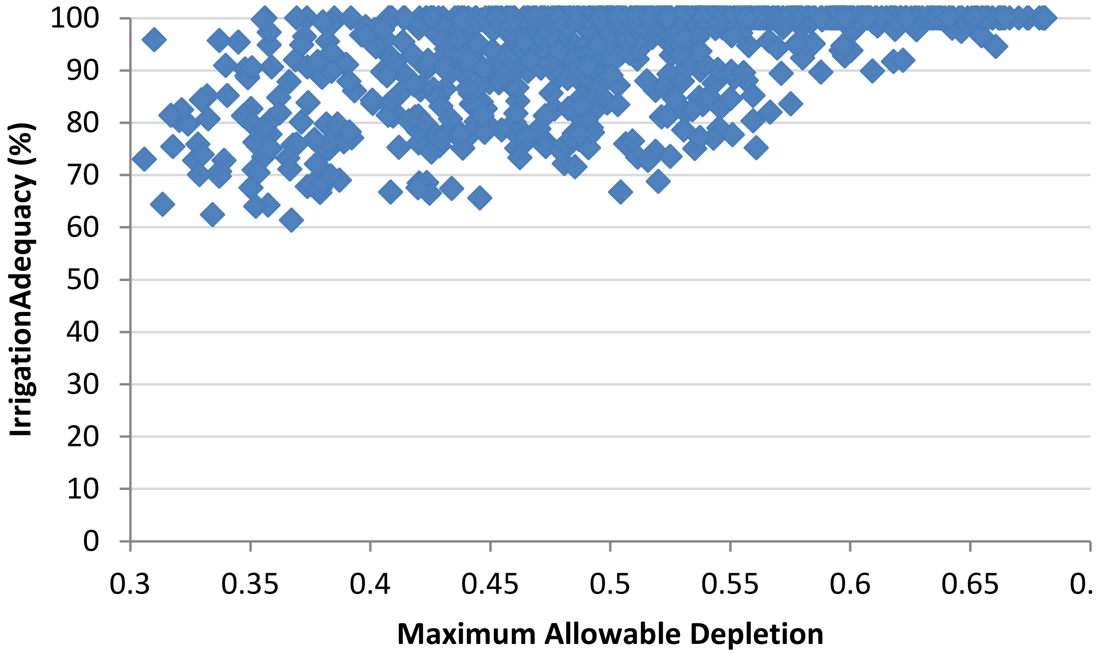

Figure 6-4. Response in irrigation adequacy due to varying the input factor of maximum allowable depletion for the Weathermatic for the period ending Nov. 11, 2006 in the GCREC field study where the correlation coefficient was 0.545.

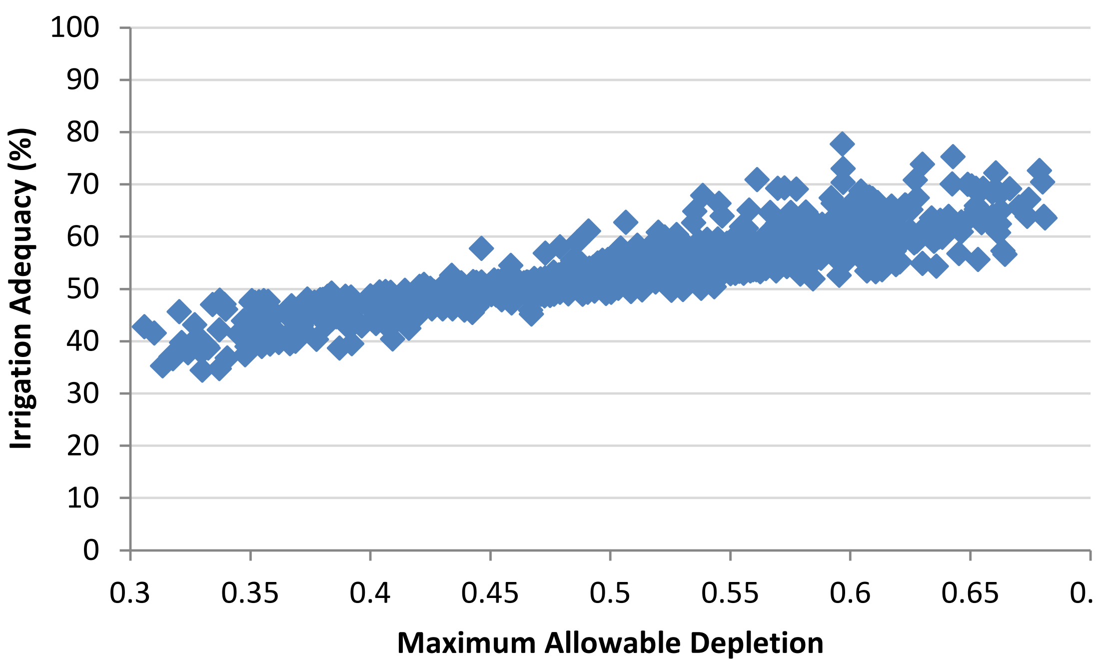

Figure 6-5. Response in irrigation adequacy due to varying the input factor of maximum allowable depletion for the Toro for the period ending Nov. 11, 2006 in the GCREC field study where the correlation coefficient was 0.871.

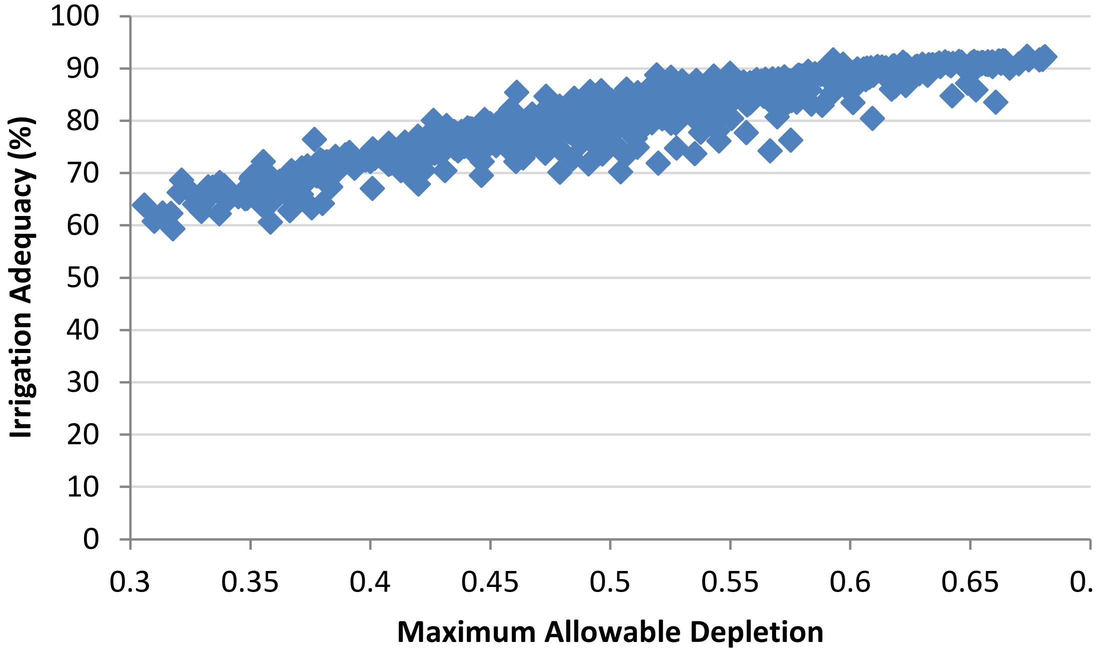

Figure 6-6. Response in irrigation adequacy due to varying the input factor of maximum allowable depletion for TIME for the period ending May 12, 2007 in the GCREC field study where the correlation coefficient was 0.933.

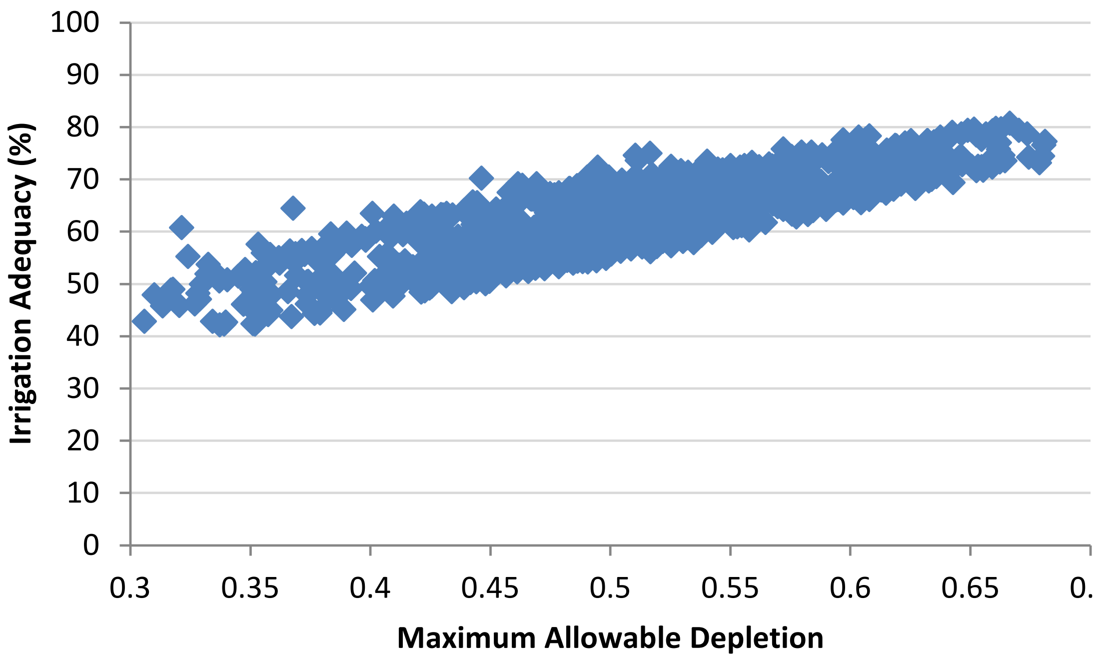

Figure 6-7. Response in irrigation adequacy due to varying the input factor of maximum allowable depletion for RTIME for the period ending May 12, 2007 in the GCREC field study where the correlation coefficient was 0.833.

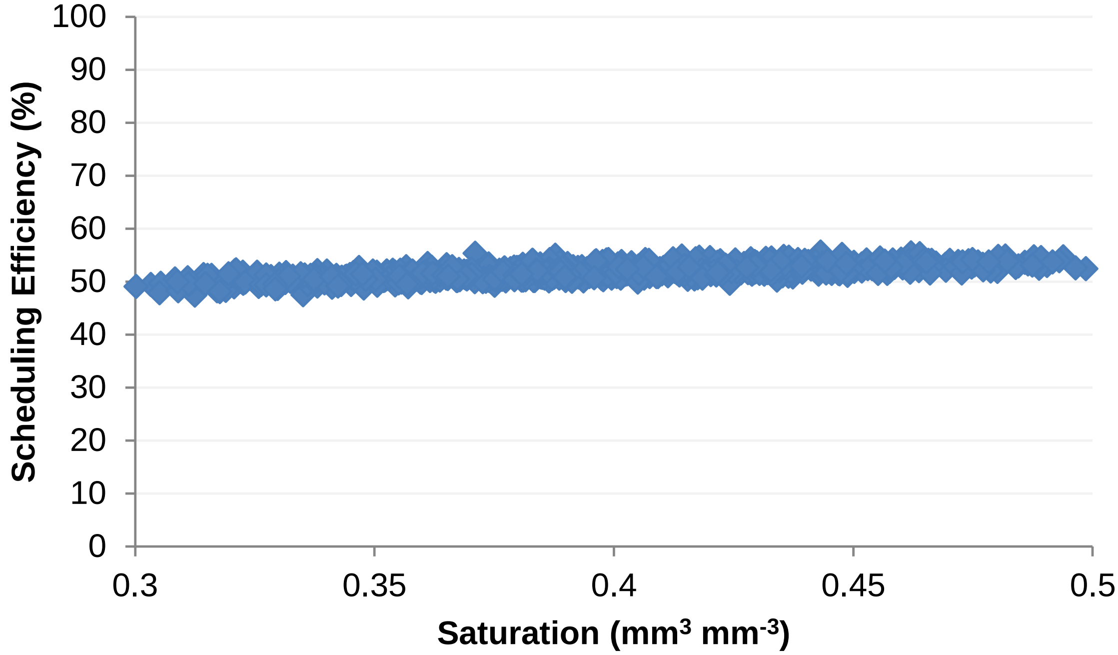

Figure 6-8. Response by the Weathermatic during the bench test study between scheduling efficiency and varying the input factors of θ_s.

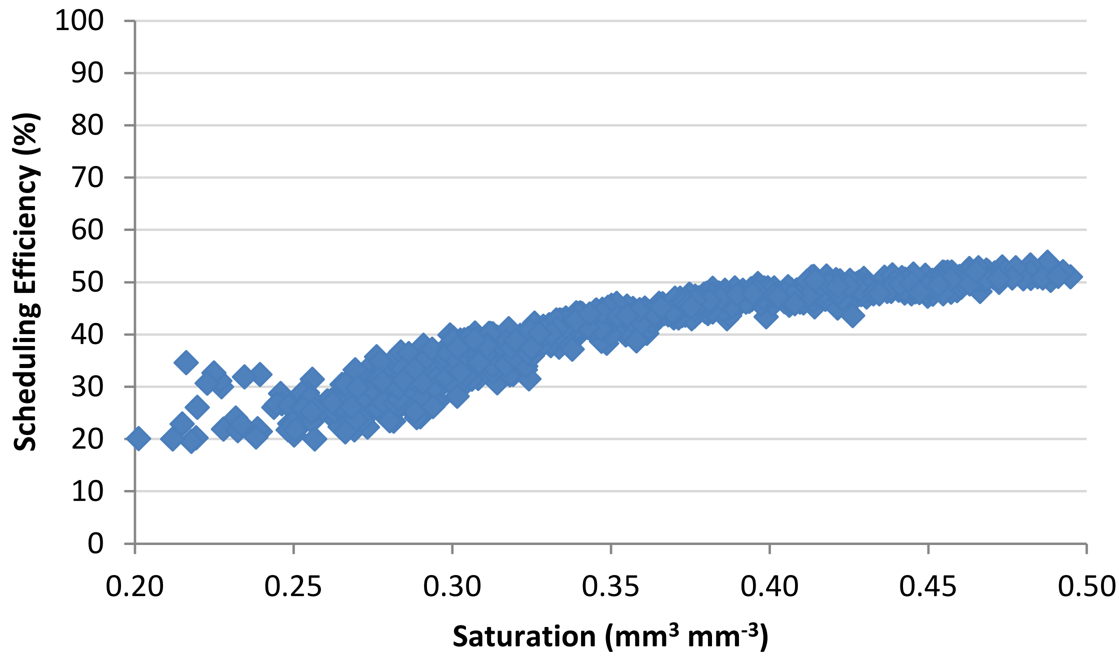

Figure 6-9. Response in scheduling efficiency due to varying the input factor of saturation for the Weathermatic for the period ending Aug. 10, 2007 in the GCREC field study where the correlation coefficient was 0.920.

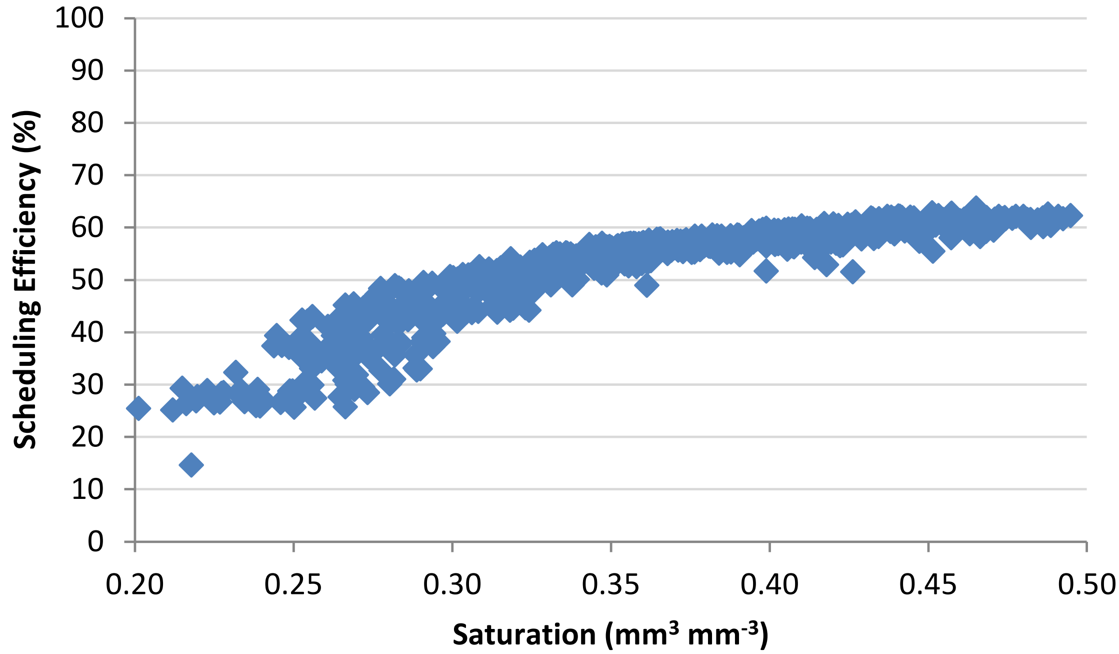

Figure 6-10. Response in scheduling efficiency due to varying the input factor of saturation for the Toro for the period ending Apr. 12, 2007 in the GCREC field study where the correlation coefficient was 0.877.

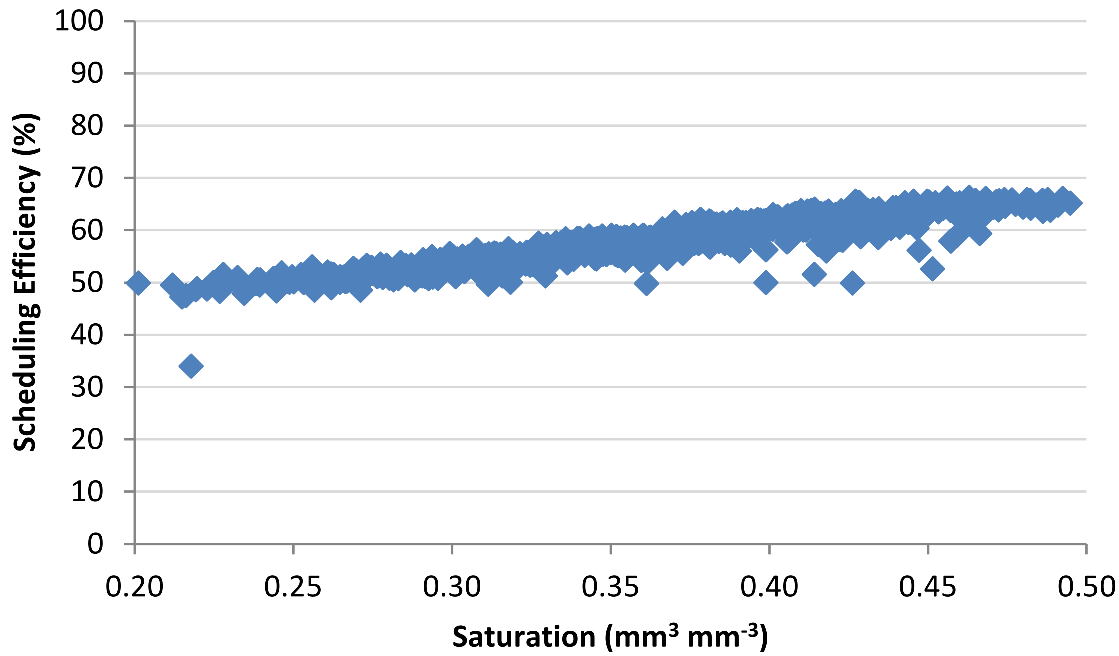

Figure 6-11. Response in scheduling efficiency due to varying the input factor of saturation for TIME for the period ending Dec. 11, 2006 in the GCREC field study where the correlation coefficient was 0.931.

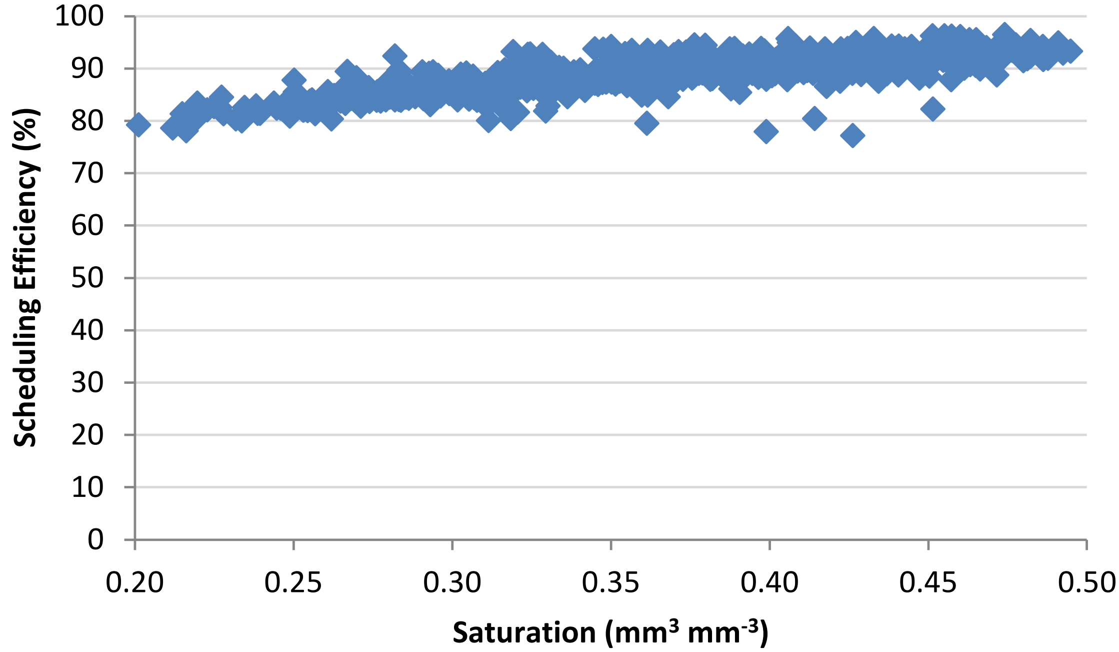

Figure 6-12. Response in scheduling efficiency due to varying the input factor of saturation for RTIME for the period ending Dec. 11, 2006 in the GCREC field study where the correlation coefficient was 0.800.

CHAPTER 7
CONCLUSIONS

The ET controller has the potential to produce water savings without sacrificing landscape quality in Florida when implemented at residences that habitually irrigate excessively and programmed with settings that are appropriate for the landscape. In Hillsborough County, where cooperators were already conservative in their irrigation habits, total irrigation reductions ranged from 23%-41% compared to the GIR and 23%-34% compared to their historical average irrigation. In Orange County, where cooperators regularly irrigated more than 1.5 times the GIR prior to the study, cooperators continued to irrigate at or above the GIR. However, due to the over-irrigation habits of the Orange County cooperators, the ET treatment generally reduced irrigation by -12% to 39% compared to the neighboring homes with no added technology. This treatment increased irrigation application during the wet seasons on both soil types. The education provided as part of the ET+Edu treatment was effective at reducing irrigation application by 1 to 49 percentile points in addition to water savings by ET treatment.

The time-based treatments selected to represent actual homeowner practices in Florida resulted in excessive irrigation during the field plot study. Though the ET controllers decreased irrigation compared to 100% replacement of the net irrigation requirement, there were no additional water savings compared to 60% replacement. Additionally, the performance scores of irrigation adequacy and scheduling efficiency for the ET controllers were not different from the 60% replacement with all treatments experiencing over-irrigation.

Homeowners who already irrigate less than well-watered conditions or accept declines in landscape quality on a regular basis will not benefit from using an ET controller in terms of water savings. This was seen in Riverview where cooperators with an ET controller had historically irrigated 23% less than GIR, but increased their irrigation application by 54% compared to their neighbors during the study. Homeowners who set their time clocks to a peak irrigation schedule without updating the controller settings throughout the year may see significant reductions in irrigation by implementing an ET controller, specifically during the fall and winter seasons. Proper controller programming was essential to achieving maximum water savings while maintaining acceptable landscape quality. This occurred in Orange County where the ET treatment frequently irrigated 2% to 68% more than the GIR assuming a 60% efficiency, which is an achievable standard, across all seasons. The ET+Edu, which included site-specific programming, reduced irrigation by 9 to 72 percentile points compared to ET. If the time and effort of proper programming is not achievable, other smart irrigation technologies that do not increase existing irrigation, such as soil moisture sensors, would be more appropriate.

Even though water savings are achievable when using ET controllers, controllers vary by brand and model thus requiring an adequate method for determining the efficacy of the controllers. The current industry standard for evaluating ET controllers, termed the Smart Water Application Technologies (SWAT) test (IA 2008), uses a daily soil water balance to determine whether the controller over- or under-irrigates during a 30-day period for a theoretical landscape. However, performance scores of irrigation adequacy (a measure of under-irrigation) and scheduling efficiency (a measure of over-irrigation) do not translate to real world performance. The EPA adopted the daily SWAT test as the testing methodology for the WaterSense program where ET controllers are considered water-saving devices if achieving thresholds of 80% for irrigation adequacy and 95% for scheduling efficiency.

A variety of deficiencies were identified in the daily SWAT test that hinders the application of the test results outside of the exact testing conditions. In response to some of these deficiencies, an hourly soil water balance (SWB) was developed as an alternative to the daily SWAT test and both models were evaluated against HYDRUS-1D that uses Richards' equation, a proven deterministic model. The hourly SWB better matched the deterministic soil water model compared to the daily SWAT test thus improving estimates of volumetric water content in a shallow root zone. This was shown in the first layer of the PSREU study during the calibration period where the NSE was 0.659 for the hourly SWB but only 0.514 for the daily SWAT, falling below the acceptable threshold for hydrological models of 0.65. Both models failed to meet the threshold during the validation period or during either period of the GCREC study. The hourly SWB had higher NSE for the ET controller treatments, ranging from 0.224 to 0.266, during the validation period of the GCREC study compared to the daily SWAT, ranging from 0.011 to 0.181. Based on the results, the hourly SWB improved estimates of volumetric water content in a shallow root zone compared to the current testing standard.

The hourly SWB was preferential to the daily SWAT based on the combination of more accurate landscape programming required to obtain high performance scores and the realistic representation of soil water movement by hourly SWB resulting in a more accurate translation of SWAT scores to controller performance in the landscape. The correlation between irrigation adequacy and under-irrigation when using the hourly SWB ranged from -0.324 to -0.783 for the bench test study. For the same study, the correlation was 0.483 to 0.518 for scheduling efficiency and over-irrigation. There was not a significant correlation for either performance measure for the daily SWAT model.

The ability of the controllers to surpass the WaterSense thresholds was affected by model type, with controllers unable to pass the test using the hourly SWB, when manufacturers used program settings that were not realistic for the described landscape. The irrigation adequacy results for the bench test study were most affected due to frequent under-irrigation with scores declining as much as 80 percentile points. Thus, the failure rate of irrigation adequacy results frequently went from 0% with the daily SWAT to 100% with the hourly SWB, with the change in the failing rate ranging from 13 percentile points to 100 percentile points. The decline in scheduling efficiency results were less drastic, falling no more than 30 percentile points and typically falling less than 10 percentile points.

The differences in scores by model type were rarely a factor for WaterSense labeling criteria in the field plot study when program settings were accurate for the landscape. There was frequent over-irrigation thus scheduling efficiency was the primary performance measure affected by the model choice. Failure rates were higher for the hourly SWB, ranging from 75% to 94% compared to failure rates of 47% to 88% for the daily SWAT. However, the WaterSense threshold for scheduling efficiency was already so high at 95% that both models failed to meet the criteria.

A regression analysis was used to evaluate the stability of the model results on selecting the soil hydraulic parameters of permanent wilting point, field capacity, saturation, and maximum allowable depletion fraction. These four parameters were varied using a Monte Carlo simulation across a wide range using a triangular distribution. Irrigation adequacy was most sensitive to the model inputs with a clear relationship with MAD, having correlation coefficients ranging from 0.545 to 0.800 for the bench test study and maximum correlations ranged from 0.564 to 0.933 for the field plot study. Scheduling efficiency had a strong relationship to θ_s with a correlation coefficient of 0.693 for the bench test study and maximum correlation coefficients ranging from 0.844 to 0.950 for the field plot study.

Despite such high correlation for all treatments, there was very little increase in the performance results of irrigation adequacy and scheduling efficiency due to increasing values of MAD and θ_s, respectively. Therefore, the variations in the performance results were highly dependent on the irrigation scheduling techniques of the ET controller and not the model input factors, thus satisfying the purpose of the model with good stability.

The hourly SWB can be used as an alternative method for testing ET controllers that will more accurately reflect true soil-water relationships thus allowing for the estimation of water conservation potential. The improved relationship between ET controller performance and the performance measures of irrigation adequacy and scheduling efficiency used by the EPA WaterSense program allows the possibility of translatable scores to scenarios beyond the conditions of the testing period.

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BIOGRAPHICAL SKETCH

Stacia L. Davis has always enjoyed learning while attending Colfax Elementary School in Fairmont, WV, Wendover Middle School in Greensburg, PA, and Hempfield Area Senior High School in Greensburg, PA. These schools were important stepping stones in determining her academic path as she concentrated on the advanced math and science classes offered. It was clear to everyone, including Stacia, that engineering was her niche.

Ms. Davis attended the University of Pittsburgh where she studied civil and environmental engineering. She also worked in the engineering field for companies such as CDM, Allegheny Energy, and Rhea Engineers. She passed the FE exam, adding the title of Engineer-In-Training before completing her Bachelor of Science, and fully intends on sitting for the professional engineering exam as well.

Ms. Davis narrowed her focus when leaving PITT and chose to pursue a Masters in Engineering degree in irrigation engineering in the Agricultural and Biological Engineering department at the University of Florida. Here, she researched water conservation in residential irrigation focusing on ET controllers and turfgrass. She continued her research in areas of water modeling and performance testing of ET controllers during her recently completed PhD program, also in irrigation engineering at the University of Florida.

Ms. Davis accepted a faculty position with Louisiana State University located at the Red River Research Station in Bossier City, LA. Her position is part of a water cluster that will address the water issues of the state of Louisiana with her focus on irrigation. She is excited to begin this new chapter of her life with exciting opportunities in research and extension.