EVAPOTRANSPIRATION-BASED IRRIGATION CONTROLLERS UNDER DRY CONDITIONS IN FLORIDA

By

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To my parental units.

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LIST OF ABBREVIATIONS

AEMN	Automated Environmental Monitoring Network
ANOVA	Analysis of variance
ASCE	American Society of Civil Engineers
CIMIS	California Irrigation Management Information System
CIT	Center for Irrigation Technology
DU	Distribution uniformity
ET	Evapotranspiration
ET_c	Crop evapotranspiration
ET_o	Reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FAWN	Florida Automated Weather Network
FDEP	Florida Department of Environmental Protection
GCREC	Gulf Coast Research and Education Center
GLM	General linear model
IA	Irrigation Association
ICID	International Commission for Irrigation and Drainage
K_c	Crop coefficient
MWDSC	Metropolitan Water District of Southern California
NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resource Conservation Service
NTEP	National turfgrass evaluation procedures
SWAT	Smart water application technology
SWFWMD	Southwest Florida Water Management District
TDR	Time domain reflectometry

UF	University of Florida
UF-IFAS	University of Florida Institute of Food and Agricultural Sciences
USCB	United States Census Bureau
USDOI	United States Department of Interior
USEPA	United States Environmental Protection Agency
WORS	Without rain sensor

Abstract of Thesis Presented to the Graduate School
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Evapotranspiration-based controllers, or ET controllers, are irrigation controllers that use evapotranspiration (ET) to schedule irrigation. The goal was to determine whether ET controllers could conserve water in Florida. The primary objectives of this research were to evaluate three brands of ET controllers to A) produce savings compared to a time clock schedule intended to mimic homeowner irrigation schedules while maintaining acceptable turfgrass quality, B) estimate reference evapotranspiration (ET_o) compared to the ASCE Standardized ET_o methodology, and C) schedule irrigation compared to a theoretical soil water balance model. Secondary objectives included a) quantifying the variation between controller replications, b) compare the performance of ET controllers based on distance to a weather data source, and c) measure the ET controller performance scores similar to the SWAT testing protocol.

Five treatments replicated four times totaled twenty plots measuring 7.62 m x 12.2 m. The plots, located at the UF GCREC, were partitioned into 65% St. Augustinegrass (*Stenotaphrum secundatum* 'Floratam') and 35% mixed-ornamentals to represent a typical Florida landscape. The irrigation treatments were as follows: Weathermatic SL1600 controller (T1), Toro Intelli-sense (T2), ET Water Smart Controller 100 (T3), a time-based treatment determined by UF-IFAS recommendations (T4), and a time-based treatment that is 60% of T4 (T5).

The study period experienced dry conditions containing 69% dry days. It was found that using a rain sensor with a time-based irrigation schedule conserved 21% of water despite the unusual dry conditions. Average savings compared to the time-based schedule without rain sensor across all seasons ranged from 35% to 42% for the ET controllers. Reducing the time-based schedule by 40% and including a rain sensor resulted in 53% savings showing that updating the time clock settings throughout the year can result in substantial irrigation savings. Turfgrass quality remained above minimally acceptable over the study period for all treatments. The ET controllers under-irrigated compared to the calculated theoretical irrigation requirement, on average, but fell within results seen for the time-based schedules.

Nine ET controllers, three replications of each brand being tested, were installed in addition to the main project to determine if there was variability between controllers concerning irrigation scheduling, ET_o estimation, and proximity to weather data source. There were no differences between the replications of the controllers for both irrigation scheduling and ET_o estimation. The signal-based controllers were affected by the proximity to the weather data source when estimating ET_o.

These controllers over-estimated ET_o by 8% due to the combination of using Hargreaves equation for ET_o calculations and over-estimating maximum temperatures.The Toro controller estimated ET_o within 1% when the weather station was within 100 m whereas the ET Water controller under-estimated by 12% compared to ET_o calculated from the on-site weather station data.

CHAPTER 1
INTRODUCTION

Water Demand and Use

Water is a limited resource and at any given time are areas in the country experiencing water shortages. More specifically, Florida has the second largest withdrawal of groundwater in the United States that is used for public supply (Solley et al. 1998). Also, compared to other states Florida has the largest net gain in population with an inflow of approximately 1,108 people per day and fourth in overall population (United States Census Bureau [USCB] 2005). New home construction has increased to accommodate such a large influx of people. Florida ranked first in the construction of single family residential units totaling 209,162 in 2005 (USCB 2007) and most new homes include in-ground automatic irrigation systems. However, homes with in-ground systems utilizing automated irrigation timers increase outdoor water use by 47% (Mayer et al. 1999). The need for landscape irrigation will continually grow with increased population and home construction if there is no change in the demand for aesthetically pleasing urban landscapes. Water supplies for non-consumptive uses, however, are decreasing due to increased demand (Southwest Florida Water Management District [SWFWMD] 2006) and irrigation must become more efficient to maintain landscapes of acceptable quality.

Natural climatic cycles ensure periods of critical drought and improvement in water conservation along with efficient water use is necessary to protect from water shortages and crises (Florida Department of Environmental Protection [FDEP] 2002). Southwest Florida rainfall averages 1,400 mm per year and average yearly rainfall typically exceeds average yearly ET (National Oceanic and Atmospheric Association [NOAA] 2005; Carriker 2000). However, irrigation is still necessary in Florida due to sandy soils with little soil water holding capacity that can cause plant stress in just a few days with no rain (Natural Resource Conservation Service

[NRCS] 2006). Proper irrigation management could result in as much as a two-fold reduction in water use (FDEP 2002).

Research has shown that most of Florida single family residences over-irrigate in late fall and winter due to the inconvenience of changing the time clock to reflect actual water needs or a misunderstanding concerning the amount of water necessary during the seasons (Haley et al. 2007). Increased watering during the fall and winter months does not allow dormancy to occur, leading to the need for additional mowing, and increases the likelihood of diseases, insects, weeds, and stresses to the lawn (Harivandi 1984). On a larger scale, increased watering contributes to the depletion of water resources and the potential to leach soluble chemicals such as fertilizer into the groundwater. Therefore, better irrigation management could potentially lead to water conservation as reducing problems associated with excess watering. The water savings estimated due to the increased watering efficiency is 25-30% and the savings due to peak demand reduction is substantial (United States Environmental Protection Agency [USEPA] 2004).

Residential Irrigation System Components

Irrigation systems, sectioned into zones, are designed by grouping sprinklers in such a way to maximize efficiency and connect to a water supply through appropriately sized piping capable of handling the potential water flow rates (Haman et al. 1989). Water sources may include municipal supply, private well, or a stationary surface water body such as a lake or pond. The quantity and size of each zone is determined by the flow rate available, the application rate, and the run time (Haman et al. 1989).

Irrigation Timers

Time clocks (i.e., timers) are installed when irrigation systems are installed to aid the user in operating the system. Irrigation timers range in complexity from a simple on/off switch with some type of timing mechanism operating only one valve, to a computer that will operate many zones with different programs (Haman et al. 1989). More complex timers can be programmed with an irrigation schedule for each valve (Haman et al. 1989), but it is believed that many homeowners leave the original settings programmed by the installation contractor.

Solenoid Valves

The timer controls water application by operating the valves. There are two types for residential irrigation: electrical or hydraulic (Haman et al. 1989). Most residential irrigation systems use electrical valves that must be matched to the power output of the controller, usually 24 volts AC. The power is connected through wires for electrical valves or control tubing for hydraulic valves (Haman et al. 1989).

Sprinkler Types

Water is dispersed from the conveyance system to the landscape through sprinklers or other types of emitters. Residential sprinklers are of three basic types: spray heads, rotary sprinklers, and impact sprinklers (Haman et al. 1989). A spray head has a fixed nozzle that can spray any variety of patterns such as 90 degrees to 360 degrees. Generally, they require 100 kPa to 250 kPa of water pressure and have a maximum watering radius no more than 5.5 m (Hunter Industries, Inc. 2006; Rain Bird 2007). Rotary sprinklers are sprinklers that rotate, resulting in the commonly used term "rotor" to describe them, so that a circular area is covered and require 172 kPa to 450 kPa supply pressures. They are used for irrigation of larger areas, greater than 4.6 m (Hunter Industries, Inc. 2006; Rain Bird 2007). Impact sprinklers can also be used for residential irrigation, though it is less common. Impact sprinklers are similar to rotors because they require 172 kPa to 414 kPa for a radius of 6.7 m to 13.7 m.

A relatively new type of spray head nozzle combines the flexibility of a spray head with a rotating distribution pattern and is known as a rotary nozzle. These nozzles have shown average water conservation potential of 31% due to an increased distribution uniformity compared to fixed spray heads (Solomon et al. 2006).

Rain Shutoff Devices

As of May 1991, Florida requires that any new irrigation system must maintain and operate a rain sensor (Florida Statutes, Chapter 373.62 n.d.; Florida Statutes 2001). Some counties mandate the use of a sensor regardless of the age of the system (Dukes and Haman 2002b). These sensors act as a switch that turns off irrigation due to a given threshold of rainfall. They are relatively inexpensive devices that should be mounted in an open area, free from cover and debris. One type of rain sensor is made from expanding disks. Expanding disk are hygroscopic porous disks that expand when wet and open the circuit to cease irrigation and remains in this state until the disks dry out (Hunter Industries, Inc. 2006).

Irrigation Scheduling

There are two methods to schedule irrigation: quantitative or qualitative. The quantitative method measures plant needs from the soil moisture or evapotranspiration (ET) loss directly using instruments such as tensiometers or dielectric probes. The other method commonly used by homeowners, qualitative, involves observing the lawn and irrigating when it looks stressed (Wade and Waltz 2004). Typical signs of stress include footprints remaining for a long time, a bluish-gray cast to the turfgrass, or a majority of leaf blades folded length-wise in half. A common rule of thumb irrigation recommendation is to irrigate when 30% of the lawn is at the point of wilting to encourage roots to grow deeper and become healthier and more drought tolerant (Tichenor et al. 2003).

Irrigation System Performance Analyses

Improper irrigation, whether it is under-irrigation or over-irrigation, can negatively impact landscapes as well as waste water resources. There are several ways to numerically evaluate the ability of an irrigation system to properly distribute water as well as the quality of the landscape.

Irrigation efficiency is the measure of the effectiveness of an irrigation system to supply water to a given landscape area. Methods to appropriately determine irrigation efficiency are difficult to determine quickly since the data are difficult to obtain (Burt et al. 1997). Therefore, distribution uniformity (DU) testing is used to get an idea of irrigation system performance. High efficiency can only be achieved with high DU values; however, DU does not represent efficiency. Thus, to distinguish DU from efficiency, Burt et al. (1997) recommended expressing as a ratio rather than percentage. DU is essentially a measure of variability from the mean application amount (i.e., depth in sprinkler irrigation). Commonly, the lowest quarter is used to produce the ratio (American Society of Civil Engineers [ASCE] 1978). It is represented by the following equation where DU_{lq} (mm/mm) is the low quarter distribution uniformity, d_{lq} (mm) is the average of the lowest 25% of depths, and d_{avg} (mm) is the average of all depths (Burt et al. 1997).

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

Volume can be used to calculate the ratio when identically sized catch cans are used to perform the test.

The Irrigation Association (IA; 2005) suggested that DU_{lq} overestimates the effect of non-uniform landscapes. Therefore, the low half distribution uniformity (DU_{lh}) should be used for irrigation scheduling purposes and can be estimated from DU_{lq} as a percentage by using a simple conversion equation.

$$DU_{lh} = 38.6 + 0.614 * DU_{lq} \quad (1\text{-}2)$$

Turfgrass quality must remain at acceptable levels when trying to conserve water. The National Turfgrass Evaluation Procedures (NTEP) created standards used to measure quality based on aspects such as color, density, uniformity, texture, and disease or environmental stress (Shearman and Morris 1998). NTEP developed a subjective rating system where turfgrass is rated on a scale from 1 to 9 where 1 represents dead turfgrass or bare ground, 9 represents an ideal turfgrass without weeds or disease, and 5 is considered to be the minimum acceptable quality for a residential setting.

Evapotranspiration

Evapotranspiration (ET) is defined as the evaporation from the soil surface and the transpiration through plant material (Allen et al. 1998). It is part of a balanced energy budget that exchanges energy for outgoing water at the surface of the plant. The components of ET are solar radiation, temperature, relative humidity, and wind speed (Allen et al. 2005). Reference ET (ET_o) is ET found using a hypothetical reference crop assumed to be similar to an actively growing, well-watered, dense green grass of uniform height (Allen et al. 2005).

There are various ways to estimate ET_o. Common field measurement methods include lysimeter experiments, soil water studies, and a long-term inflow-outflow water budget for large areas (Fangmeier et al. 2006). Computer simulated models can be used to predict ET_o and guide irrigation. Research has shown that influences such as turfgrass species, mowing height, and nitrogen fertility can affect models. Also, they are relative to an area in that a model could be accurate for a certain part of the country but inaccurate for the rest (Wade and Waltz 2004).

Typically, climatic data is collected and used as inputs to equations to calculate ET_o. There are three types of equations: mass transfer, energy balance, and empirical methods

(Fangmeier et al. 2006). Most of the current methods employ a combination of the three. The appropriate ET equation is chosen depending on many factors including geographical location, types of crops, and weather availability (Fangmeier et al. 2006). Two ET_o equations are pertinent to this study.

The Penman-Monteith equation is a standardized equation 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 (Allen et al. 2005). It is also considered the ASCE standardized reference evapotranspiration equation and is given here as:

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{C_n}{T + 273} \cdot (e_s - e_a) \cdot u_2}{\Delta + \gamma \cdot (1 + C_d u_2)} \tag{1-3}$$

Variables are defined as follows:

$$\Delta = \frac{2503 \cdot \exp\left(\frac{17.27T}{T + 237.3}\right)}{(T + 237.3)^2} \tag{1-4}$$

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \tag{1-5}$$

$$e^o T = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \tag{1-6}$$

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2} \tag{1-7}$$

$$R_n = R_{ns} - R_{nl} \tag{1-8}$$

$$R_{ns} = (1 - \alpha) \cdot R_s \tag{1-9}$$

$$R_{nl} = \sigma \cdot f_{cd} \cdot \left(0.34 - 0.14\sqrt{e_a}\right) \cdot \left[\frac{T_{K\,max}^4 + T_{K\,min}^4}{2}\right] \tag{1-10}$$

$$f_{cd} = 1.35 \frac{R_s}{R_{so}} - 0.35 \tag{1-11}$$

$$R_{so} = \left(0.75 + 2 \times 10^{-5} z\right) \cdot R_a \tag{1-12}$$

$$R_a = \frac{24}{\pi} G_{sc} \cdot d_r \cdot [\omega_s \cdot \sin(\varphi) \cdot \sin(\delta) + \cos(\varphi) \cdot \cos(\delta) \cdot \sin(\omega_s)] \quad (1\text{-}13)$$

$$d_r = 1 + 0.033 \cdot \cos\left(\frac{2\pi}{365} J\right) \quad (1\text{-}14)$$

$$\delta = 0.409 \cdot \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (1\text{-}15)$$

$$\omega_s = \arccos[-\tan(\varphi) \cdot \tan(\delta)] \quad (1\text{-}16)$$

$$u_2 = u_z \frac{4.87}{\ln(67.8 z_w - 5.42)} \quad (1\text{-}17)$$

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/day); heat flux, G (MJ/m^2/day); vapor pressure, Δ (kPa/°C), e_s (kPa), e_a (kPa); temperature, T (°C); and wind speed, u_2 (m/s). γ is the psychrometric constant and can be obtained from the measured mean atmospheric pressure (Allen et al. 2005). A grass reference crop rather than alfalfa is typically used in Florida since alfalfa is not produced on a large scale (Irmak and Haman 2003). For a grass reference, the constants C_n and C_d are 900 and 0.34, respectively (Allen et al. 2005).

The other important ET equation relevant to this study is the Hargreaves equation which is given as:

$$ET_0 = 0.0023 R_a TD^{1/2}(T + 17.8) \tag{1-18}$$

R_A (MJ/m^2/day) represents the extraterrestrial radiation, TD (°C) is the difference between the mean daily maximum temperature and the mean daily minimum temperature, and T (°C) is the mean ambient air temperature (Jenson et al. 1990). This equation only requires temperature as the weather input. Extraterrestrial radiation can be calculated from solar radiation using equations or can be found in a table by using the latitude for the location of interest. This equation is generally utilized in the western part of the United States because it was derived from Alta fescue grass (*Festuca arundinacea*) lysimeter data over an eight-year period in Davis, California (Jenson et al. 1990). Since temperature data are required to calculate ET_o with this equation, data collection is simplified and much less expensive compared to the Penman-Monteith equation. The disadvantage to the Hargreaves equation is that it has been found to overestimate ET_o in humid conditions compared to the Penman-Monteith approach (Trajkovic 2007).

Once the ET_o is calculated from an equation, crop water use can be estimated by using a crop coefficient. The relationship between ET_o and crop-evapotranspiration (ET_c) is as follows:

$$ET_C = K_C * ET_0 \tag{1-19}$$

K_c is the crop coefficient that adjusts ET_o to account for differences in ground cover, canopy characteristics, and aerodynamic resistance from the reference crop to calculate crop-specific ET loss (Jenson et al. 1990). Because ET_o is calculated using grass as the reference crop, crop coefficients must be chosen from empirical values derived from grass and not alfalfa. The crop specific K_c values can be found using curves or tables (Jenson et al. 1990; Allen et al. 1998).

Weather Data Quality Control

Weather station data should be subjected to quality control assessments (Allen et al. 2005) before using for other purposes. Comparisons should be made by comparing solar radiation (R_s), relative humidity (RH), temperature (T), and wind speed (u_2) data against relevant physical extremes.

Solar radiation and clear-sky solar radiation (R_{so}) are equal on cloud-free days. Quality control of R_s can be performed by plotting R_s and R_{so} over time. R_{so} may be calculated using the equation defined for the ASCE ET_o method (Equation 1-12) as well as a more detailed procedure described below (Allen et al. 2005).

$$R_{so} = (K_B + K_D) \cdot R_a \tag{1-20}$$

$$K_B = 0.98 \exp\left[\frac{-0.00146P}{K_t \sin\beta} - 0.075\left(\frac{W}{\sin\beta}\right)^{0.4}\right] \tag{1-21}$$

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{1-22}$$

$$W = 0.14 \cdot e_a \cdot P + 2.1 \tag{1-23}$$

$$\sin\beta = \sin\left[0.85 + 0.3\varphi \sin\left(\frac{2\pi}{365}J - 1.39\right) - 0.42\varphi^2\right] \tag{1-24}$$

$$K_D = 0.35 - 0.36 \cdot K_B \quad \text{for } K_B \geq 0.15 \tag{1-25}$$

$$K_D = 0.18 + 0.82 \cdot K_B \quad \text{for } K_B < 0.15 \tag{1-26}$$

K_B = clearness index for direct beam radiation
K_D = transmissivity index for diffuse radiation
P = atmospheric pressure at the site elevation, kPa
K_t = turbidity coefficient, $0 < K_t \leq 1.0$
W = precipitable water in the atmosphere, mm
β = angle of sun above the horizon, rad

Measured relative humidity should be in the range of 30% to 100% for humid climates. Relative humidity values less than this range are possible, but it is unreasonable to maintain values less than 30%. It is not possible to have relative humidity values greater than 100% in the physical environment. Daily maximum and minimum values of relative humidity were plotted to verify that the data falls in the acceptable range for a majority of the study period.

Another way to verify that the relative humidity data was collected correctly is to calculate daily dew point temperature and compare to the daily minimum temperature. Dew point temperature is calculated with the following equation (Allen et al. 2005):

$$T_{dew} = \frac{116.91 + 237.3 \cdot \ln(e_a)}{16.78 - \ln(e_a)} \tag{1-27}$$

T_{dew} = dew point temperature, °C

Dew point temperature and minimum temperature should be approximately the same a majority of the time in humid climates with the exceptions of days with changes in air mass, high winds, or cloudiness at night (Allen et al. 2005).

Air temperature data is most likely to be consistent and of the best quality data. Temperature data can be checked for quality by plotting the daily average calculated from the 24-hour time period and the average of the maximum and minimum temperatures of the same day over time. These averages should be within 3°C unless caused by rainfall events, unusually high wind speeds, or changes in air mass (Allen et al. 2005).

The quality of wind speed data is difficult to assess when duplicate instruments are not used. Ways to determine if the correct data is being reported include plotting daily average wind speed, daily maximum wind speed, and the gust factor. The gust factor is calculated as a ratio of maximum wind speed to average wind speed. If any of these figures exhibit consistently low values (< 1.0 m/s) or gust factor values of 1.0, there is some type of problem with the data (Allen et al. 2005).

Evapotranspiration-based Irrigation Controllers

Evapotranspiration-based controllers, also known as ET controllers or “smart” controllers, are irrigation controllers that use estimated ET to schedule irrigation. Each controller works differently depending on manufacturer but typically can be programmed with site specific conditions such as soil type, plant type, sprinkler type, sun and shade, etc. The controllers are designed to either replace the typical timer or act as an amendment to the timer. Also, controllers can have accessories that make them more accurate while others come as a complete package and need no additions (Riley 2005).

ET controllers receive ET_o information in three general ways, consequently dividing ET controllers into three main types: 1) historical-based controllers, 2) standalone controllers, and 3) signal-based controllers.

Historical-based Controllers

This type of controller relies on historical ET_o information for the area. Typically, monthly historical ET_o is programmed into the controller by the manufacturer or installing contractor. This is not as efficient as other methods because it does not take into account actual changes in the weather. For example, if there is an unusually rainy or dry month, the controller will not adjust for that difference from historical values. There are a few controllers on the market that use historical ET_o only, however, there are attachments such as temperature sensors to adjust monthly ET_o to daily ET_o. Examples of historical-based ET controllers are AquaConserve, Calsense, Rain Bird, and Rain Master.

Standalone Controllers

Standalone controllers typically receive climatic data from on-site measurement sensors and calculations to determine ET_o are performed by the controller. Even though the controllers might take readings every second or every fifteen minutes, the ET_o used for irrigation purposes is cumulative daily. On-site sensors could include: temperature, solar radiation, an ET gauge, or even a full weather station (Riley 2005). Controllers that use just temperature or solar radiation based sensors do not use the Penman-Monteith equation to calculate ET_o, instead another method of ET_o calculation would have to be used such as Hargreaves equation. Benefits of using standalone controllers are that they use real weather conditions but are not limited to the use of a full weather station and there are no signal fees associated with broadcasts from the manufacturer (Riley 2005). Examples of manufacturers with this type of controller are Weathermatic and Weatherset.

Signal-based Controllers

The majority of ET controllers on the market are signal-based. These controllers receive ET_o information from a company that collects climatic data from weather stations located near the irrigation site using satellite or internet technology. Depending on the manufacturer, the ET_o data can be from an average of multiple weather stations in the area or from a single weather station. Generally, with this type of controller the K_C value is programmed by the user or contractor so that it can calculate the ET_c of the various irrigation zones. There is typically signal fee (i.e., subscription) for this controller set by the manufacturer that normally ranges from $4 to $15 per month (Riley 2005). AccuWater, Aquasave, ET Water, Hydropoint, Irrisoft, Rainbird, and Water2Save are examples of companies that sell this type of controller.

General Features

ET controllers can be purchased as an add-on to the existing timer; its function is to obtain ET_o data and communicate with the timer. It can either allow the timer to bypass scheduled events or schedule run times depending on the amount of ET_c in a day. The timer would still be required to turn the irrigation system on or off. Irrigation could be scheduled as frequently as once a day which might be more than local restrictions allow. In response to locally specific watering restrictions, ET controllers can be set to irrigate during certain windows such as twice a week during 4pm to 10am. The ET controller will track the amount of ET_o lost since the last irrigation event and allow the system to irrigate the summed amount at the appropriate time.

ET controllers can also be purchased as a single unit to replace the typical timer. This controller does everything an add-on does as well as controls the irrigation system. The benefit to replacing the timer is the guarantee of no problems with integrating technologies. This type of controller would be ideal for new or replacement irrigation systems.

Studies have shown that there are perceptional barriers for ET controllers entering the market. Typical perceptions are: water savings not justified by the cost, possible decrease in landscape appearance, possibility that technologies will not integrate properly, possible loss of reliability and control, and no awareness of problems (USEPA 2004). However, commercially available residential ET controllers are generally inexpensive and the savings are seen within the first few years. Many municipalities and water management districts are providing incentives and starting programs that provide rebates for using water conserving technology such as ET controllers (Dewey 2003). The other listed perceptional barriers are related to lack of maintenance and malfunctioning of the controller.

Summary of ET Controller Technologies

There are many ET controllers on the market that vary based on design by the manufacturer. For this reason, three popular controllers will be summarized including specifications, advantages, and disadvantages (Table 1-1).

ET Water Systems LLC is a relatively new company that specializes in the manufacturing of a signal-based ET controller called the Smart Controller. They began marketing the Smart Controller 100 for residential use in California, Nevada, and Colorado in July 2004 (United States Department of Interior [USDOI] 2004). ET Water uses public weather stations where possible, and will adapt to situations where it is not possible by using private stations or installing their own. The ET Water controller can receive ET_o data through any phone line or cellular signal. All inputs specific to the landscape are entered onto the ET Water internet site using a personal computer. Internet connection at the controller is not necessary (ET Water Systems LLC 2005). There is also a manual scheduling option in case of problems with communications to the controller (USDOI 2004).

Hydropoint Data Systems, Inc. develops software to schedule irrigation called WeatherTRAK and provides a signal-based ET_o information service called WeatherTRAK ET Everywhere. This signal-based system is marketed under the WeatherTRAK trade name as the WeatherTRAK ET Plus and also by Toro as the Intelli-Sense and by Irritrol Systems as the Smart Dial Series. Hydropoint has access to over 14,000 weather stations via National Oceanic and Atmospheric Administration (NOAA), California Irrigation Management Information System (CIMIS), Denver's ET network, and Georgia's Automated Environmental Monitoring Network (AEMN). MM5 modeling developed by Penn State University is used to create virtual weather stations by interpolating between data collected between several weather station locations (Hydropoint Data Systems, Inc. 2003). ET_o calculations are accurate to one square kilometer for 90% of the country with a standard deviation of 0.254 mm for daily ET_o. Because the data collected is from a full scale weather station, the Penman-Monteith equation is used to calculate ET_o (Hydropoint Data Systems, Inc. 2003).

Weathermatic manufactures a standalone ET controller that relies on a weather monitor for temperature measurements and ZIP code for solar radiation to use as inputs to calculate ET_o with the Hargreaves equation (Hargreaves and Samani 1982). Even though Hargreaves equation tends to overestimate ET_o, it is impractical for homeowners to install full scale weather stations in their backyards (Trajkovic 2007; Weathermatic 2005). There is no historical data preinstalled or manually entered into the controller (USDOI 2004).

SWAT Testing

Smart Water Application Technologies (SWAT) is a subset of the Irrigation Association that developed a protocol for determining the effectiveness of irrigation scheduling by ET controllers. The protocol was designed to measure the ability of ET controllers to schedule irrigation that is adequate and efficient while minimizing run-off. Irrigation adequacy is measured by under-irrigation and scheduling efficiency is measured by over-irrigation determined from a soil water balance model. Testing must meet the requirements of 30 consecutive days of testing with 10.2 mm of total rainfall and 63.5 mm of ET_o (IA 2006c).

Previous Research

ET controllers have been studied frequently in the last five years in the western part of the United States. Savings were usually reported in terms of actual or potential. Potential savings is defined by Hunt et al. (2001) as the "difference between actual outdoor water applied and what should have been applied taking weather into account." Actual savings is determined by comparing current use to some reference use which is usually historically-based.

A study was conducted in 2002 in west San Fernando Valley, California by Los Angeles Department of Water and Power to assess the performance of weather-based technologies and customer acceptance. WeatherTRAK and Water2Save LLC controllers were installed professionally and given an initial schedule based on landscape and irrigation system characteristics, adjusting the schedule when systems showed signs of poor uniformity or tinkering by the landscaper. Twenty five sites were chosen, 18 of which were WeatherTRAK enabled controllers. Data collection occurred for two years before installation as well as one year after installation. The WeatherTRAK enabled controller showed 17.4% of actual savings relative to a normalized weather year found through statistical modeling from the pre-retrofit time period and both controllers, combined, exhibited 78% of potential savings. When homeowners were questioned about the use of the controller, they responded positively but recommended outreach education programs for landscapers as well as homeowners (Bamezai 2004).

The Metropolitan Water District of Southern California (MWDSC) conducted a year-long bench test in 2002 designed to compare the ability of ET controllers to determine theoretical water needs for three types of landscapes: cool season turf on loam with full sun, shaded annuals on sandy soils, and low water using ground cover on a sunny, 20 degree slope. AquaConserve, WeatherTRAK, and Weatherset controllers were compared by soil moisture depletion analyses. Irrigation run times were recorded by a data logger and actual quality of the landscape could not be assessed since this project was a bench test. Comparisons were made using the methods of maximum allowable water allowance, water balance, and percent soil moisture depletion. The WeatherTRAK enabled controller always applied less water than the maximum allowable water allowance resulting in no overwatering. This controller performed the water balance sufficiently so that water received equals water required except for the summer months where the controller showed a deficit in irrigation. Percent soil moisture depletion for all scenarios except for the sloped one, where over-irrigation occurred, fell within a 30%-70% target range as well as minimized runoff (Metropolitan Water District of Southern California [MWDSC] 2004).

A virtual study was conducted in 2003 using Aqua Conserve, WeatherSet, WeatherTRAK, and Calsense controllers. The study was designed to determine the data used by the controllers, ease of setup and operation, and how accurate they were at matching irrigation needs to five types of landscapes consisting of turfgrass, trees/shrubs, annuals, mixed high water use plants, and mixed low water use plants. A real-time reference landscape was used to calculate ETc for the turfgrass directly and was adapted for the trees/shrubs and annuals using a combination of real-time information, plant factors, and previous research. Irrigation equaled the turfgrass reference requirements in April and October only for the WeatherTRAK controller; over-irrigation was 21-40% in March, June, and July, over 40% in November, and 11-20% for the rest of the year. Trees/shrubs were over-irrigated by more than 40% for the entire study period. Annuals were over-irrigated by 21-40% in all months except January, March, April, and June; in those months irrigation was well over-estimated by more than 40%. The mixed high water use scenario was irrigated correctly from April through August, but was over-irrigated 21-40% in September and December, and under-irrigated by more than 40% in April. The mixed low water use plants received 15-60% less irrigation than ET_o during the study period. It is suspected that these results were due to very general controller settings. For instance, the uniformity and sprinkler precipitation rates remained as default values based on inputted generic sprinkler type (Pittenger et al. 2004).

A residential runoff reduction (R3) study was conducted using standard Sterling controllers modified for this study to accept a broadcast signal in Irvine California over an 18 month period. The objectives were to: 1) develop and expand the use of signal-based technology, 2) determine the effectiveness of an educational program for homeowners, 3) determine the connection between landscape water use and quantities and qualities of dry weather runoff, and 4) to gauge the acceptance of ET controller water management. Five similar neighborhoods, each with a single-point storm drain separate from other communities, participated in the study. Three neighborhoods were control groups and unaware of the study, one group received educational materials, and one was an ET controller group also with educational materials. The educational materials consisted of postcards sent with change in weather conditions suggesting days of week and minutes per day of irrigation. The ET controller group was mixed of single unit homes, condos, homeowner associations and public properties, totaling 129 sites. This group potentially saved 49% dry weather runoff and saved 71% compared to the control groups. The educational materials group totaled 223 homes and increased dry weather runoff directly by 36% and 72% compared to the control groups. Out of the ET controller group, 72% reported that their landscapes maintained or improved since installation and enjoyed using them (Diamond 2003).

Aquacraft, Inc. performed a three year study in Boulder, Greeley, and Longmont, Colorado from 2000 to 2002 to determine the reliability and effectiveness of a WeatherTRAK enabled ET controller. There were nine residences and one commercial property committed to the study in 2001, totaling ten sites. All savings were determined from comparisons to ET_o for the area instead of ETc that is specific to the plant and six sites were already irrigating below historical ET_o. By the end of the irrigation season, 94% of ET_o was replaced by irrigation with ±20% error between sites and 88% of the potential savings was captured. Due to various reasons, only seven sites remained through the 2002 season and five of the seven participants were historical under irrigators due to voluntary participation in the study. On average, 71% of ET_o was applied over the 2002 irrigation season and 92% of potential savings were captured. The historical under irrigators, though did not see actual water savings by using the system, maintained their historical average. The controllers applied the correct ET_o reliably and responded well to three different sets of drought restrictions with no replacements necessary during the study period (Aquacraft, Inc. 2002; Aquacraft, Inc. 2003).

Table 1-1. Summary of the Weathermatic, Toro, and ET Water controllers

Manufacturer	Weathermatic	Toro	ET Water
Controller	SL1600	Intelli-Sense	Smart Controller 100
Initial Cost	$359.95	$480[1]	$589
Service Cost	None	$48/yr	$199/yr
Number of Zones	4	6	12
Programmable Inputs	• Sprinkler Type • Plant Type • Soil Type • Percentage Adjustment	• Sprinkler Type • Plant Type • Soil Type • Slope • Sun and Shade • Efficiency	• Sprinkler Type • Plant Type • Soil Type • Slope • Sun and Shade • Efficiency
Replace Typical Timer?	Yes	Yes	Yes
Connectivity for ET Transmissions	None	Satellite/Paging Technology	Cellular Wireless
Accessories	SLW15 Weather Monitor	Bow Tie Antenna	None
Warranty	2-year	5-year	3-year
Advantages	• No signal service • Full weather station not required • Less expensive • Rain sensor included on monitor	• Uses standard ET_o calculations • Most researched	• Uses standard ET_o calculations • Internet scheduling could fit busy lifestyle
Disadvantages	• Method overestimates ET_o • Must have appropriate location for weather monitor • Limited research	• Ongoing service costs • Rain sensor extra • More expensive	• Ongoing service costs • Limited research • Rain sensor extra • More expensive

[1]Initial cost includes two years of signal service to the controller automatically.

CHAPTER 2
EVALUATION OF IRRIGATION APPLICATION BY EVAPOTRANSPIRATION-BASED IRRIGATION CONTROLLERS

Introduction

Water is a limited resource and there are areas all over the country experiencing water shortages. More specifically, Florida has the second largest withdrawal of groundwater in the United States that is used for public supply (Solley et al. 1998). Also, compared to other states Florida has the largest net gain in population with an inflow of approximately 1,108 people per day and fourth in overall population (Unite`d States Census Bureau [USCB] 2005). New home construction has increased to accommodate such a large influx of people and most new homes include in-ground automated irrigation systems. However, homes with in-ground systems utilizing automated irrigation timers alone increase outdoor water use by 47% (Mayer et al. 1999). The need for landscape irrigation will continually grow with increased population and home construction if there is no change in the demand for aesthetically pleasing urban landscapes.

Florida rainfall averages 1,400 mm per year and average yearly rainfall typically exceeds average yearly evapotranspiration (ET) (Carriker 2000). However, irrigation is still necessary in Florida due to sandy soils with little soil water holding capacities that can cause drought conditions in just a few days with no rain (Haley et al 2007; Haman et al. 1989). Thus, water stress in plants such as turfgrass and ornamentals can occur even during a rainy season (NRCS 2006). Water is a limited resource and irrigation must become more efficient to maintain landscapes of acceptable quality (Southwest Florida Water Management District [SWFWMD] 2005).

Evapotranspiration (ET) is defined as the evaporation from the soil surface and the transpiration through plant canopies (Allen et al. 1998). It is part of a balanced energy budget that exchanges energy for outgoing water at the surface of the plant. The components of ET are solar radiation, temperature, relative humidity, and wind speed (Allen et al. 2005). Reference ET (ET_o) is ET found using a hypothetical reference crop assumed to be similar to an actively growing, well-watered, dense green grass of uniform height (Allen et al. 2005).

Evapotranspiration-based controllers, also known as ET controllers, are irrigation controllers that use an estimation of ET to schedule irrigation. Each controller works differently depending on manufacturer, but typically can be programmed with various conditions specific to the landscape making them more efficient (Riley 2005). ET controllers receive ET_o information in three general ways, consequently dividing ET controllers into three main types: 1) standalone controllers, 2) signal-based controllers, and 3) historical-based controllers.

Standalone controllers typically receive climatic data from on-site measurement sensors and calculations to determine ET_o are performed by the controller. Even though the controllers might take readings every second or every fifteen minutes, the ETo used for irrigation purposes is cumulative daily. On-site sensors could include: temperature, solar radiation, an ET gauge, or even a full weather station (Riley 2005). Benefits of standalone controllers are that they are not limited by requiring the use of a full weather station and there are no signal fees associated with broadcasts from the manufacturer (Riley 2005).

Signal-based controllers receive ET_o information from a company that collects climatic data from weather stations located near the irrigation site using satellite or internet technology. Depending on the manufacturer, the ET_o data can be from an average of multiple weather stations in the area or from a single weather station. There is typically a signal fee (i.e., subscription) for this controller set by the manufacturer that normally ranges from $4 to $15 per month (Riley 2005).

Historical-based controllers rely on historical ET_o information for the area. Typically, monthly historical ETo is programmed into the controller by the manufacturer or installing contractor. This is not as efficient as other methods because it does not take into account actual changes in the weather.

ET controllers have been studied frequently in the last five years in the western part of the United States. Savings were usually reported in terms of actual or potential. Potential savings is defined by Hunt et al. (2001) as the "difference between actual outdoor water applied and what should have been applied taking weather into account." Actual savings is determined by comparing current use to some reference use which is usually historically-based.

A study conducted in 2002 in west San Fernando Valley, California by Los Angeles Department of Water and Power showed 17.4% of actual savings by a WeatherTRAK enabled controller relative to a normalized weather year found through statistical modeling from the pre-retrofit time period and 78% of potential savings (Bamezai 2004). A residential runoff reduction study was conducted using a modified Sterling irrigation controller to accept a broadcast signal from the WeatherTRAK ET Everywhere service in Irvine California; the ET controller group potentially saved 49% dry weather runoff and saved 71% compared to the control groups (Diamond 2003). Aquacraft, Inc. performed an ET controller study in Colorado to determine savings compared to ET_o for the area and six sites were already irrigating below historical ET_o. The first year resulted in 94% of ET_o replacement by irrigation with ±20% error between sites and 88% of the captured potential savings while the second year resulted in 71% of ET_o replacement and 92% of captured potential savings (Aquacraft, Inc. 2002; Aquacraft, Inc. 2003).

The objective of this study was to evaluate the ability of three brands of ET-based controllers to schedule irrigation by comparing irrigation application to a time clock schedule intended to mimic homeowner irrigation schedules, while maintaining acceptable turfgrass quality.

Materials and Methods

This study was conducted at the University of Florida Gulf Coast Research and Education Center (GCREC) in Wimauma, Florida and at the University of Florida Agricultural and Biological Engineering Department turfgrass plots in Gainesville, Florida (Figure 2-1; Figure 2-2). There were a total of twenty plots at the GCREC that measured 7.62 m x 12.2 m, bordered by a 15.2 cm tall black metal barrier, with 3.05 m buffer zones between adjacent plots (Figure 2-3). The buffer zones were covered with a white material that acted as a weed barrier. Each plot consisted of 65% St. Augustinegrass (*Stenotaphrum secundatum* 'Floratam') and 35% mixed ornamentals to represent a typical residential landscape in Florida. The ornamentals were as follows: Crape Myrtle (*Lagerstroemia indica* 'Natchez') (Figure 2-4A), Gold Mound Lantana (*Lantana camara* 'Gold Mound') (Figure 2-4B), Indian Hawthorne (*Raphiolepis indica*) (Fig 2-4C), Cape Plumbago (*Plumbago auriculata)* (Figure 2-4D), and Big Blue Liriope (*Liriope muscari* 'Big Blue') (Figure 2-4E). Landscapes were maintained through mowing, pruning, edging, mulching, fertilization, and pest and weed control according to current UF-IFAS recommendations (Black and Ruppert 1998; Sartain 1991). The treatments set up at the Gainesville turfgrass plots were tested virtually to study the variability in water application between ET controllers of the same brand.

Five treatments were established at the GCREC, T1 through T5, replicated four times for a total of twenty plots in a completely randomized block design. The irrigation treatments are as follows: T1, SL1600 controller with SLW15 weather monitor (Weathermatic, Inc., Dallas, TX); T2, Intelli-sense (Toro Company, Inc., Riverside, CA) utilizing the WeatherTRAK ET Everywhere service (Hydropoint Datasystems, Inc., Petaluma, CA); T3, Smart Controller 100

(ET Water Systems LCC, Corte Madera, CA); T4, a time-based treatment determined by UF-IFAS recommendations (Dukes and Haman 2002a); and T5, a time-based treatment that is 60% of T4 (Figure 2-5). All treatments utilized rain sensors set at a 6 mm threshold.

A metal shed housed the controllers on-site and a manifold table supported forty solenoid valve and flow meter combinations to supply and monitor irrigation to each zone of each plot (Fig 2-6). The flow meters (11.4 cm V100 w/ Pulse Output, AMCO Water Metering Systems, Ocala, FL) used to monitor irrigation water application were connected to five SDM-SW8A switch closure input modules (Campbell Scientific, Logan, UT) that in turn connected to a CR-10X data logger (Campbell Scientific, Logan, UT) (Fig 2-7). The CR-10X data logger monitored switch closures every 18.9 liters from the water meters. The data was also collected manually on a weekly basis at minimum. Each plot contained an irrigation zone for turfgrass and mixed ornamentals.

Irrigation sprinklers specified for the turfgrass portions of the plots consisted of Rain Bird (Glendora, CA) 1806 15 cm pop up spray bodies and Rain Bird R13-18 black rotary nozzles (Figure 2-8). In each plot, there were four sprinklers with a 180 degree arc (R13-18H) and a center sprinkler with a 360 degree arc (R13-18F). Microsprays (Maxijet, Dundee, FL) were installed to irrigate the mixed ornamental plants. A pressure regulator was installed at the plot to maintain a constant pressure of 6 kPa on the microsprays during irrigation.

Thirty year historical rainfall averages were calculated from monthly rainfall data collected by the National Oceanic and Atmospheric Administration (NOAA 2005) from 1975 through 2005. The closest NOAA weather station from the project site with available rainfall data was located approximately 28 km away, in Parrish, FL.

There were five seasons of data collection: 13 August, 2006 through 30 November, 2006 as fall 2006; 1 December, 2006 through 26 February, 2007 as winter 2006-2007; 27 February, 2007 through 31 May, 2007 as spring 2007; 1 June, 2007 through 31 August, 2007 as summer 2007; and 1 September, 2007 through 30 November, 2007 as fall 2007. All five treatments observed local watering restrictions during fall 2006 and winter 2006-2007 which included irrigation windows two days per week, Wednesday and Saturday, and no watering between 10 am and 4 pm. Also, the ET controller treatments were established based on the site location without accounting for system efficiency (Table 2-1). T1, the Weathermatic controller, was set to apply 100% of the calculated water requirement while T2 and T3, the Toro and ET Water controllers, were set to the maximum efficiency of 95%. The monthly irrigation depth for T4, the time-based treatment, was 60% of the net irrigation requirement derived from historical ET and effective rainfall specific to south Florida (Dukes and Haman 2002a) and T5 was a reduced treatment, applying 60% of the irrigation depth calculated from T4 (Table 2-2). Spring, summer, and fall 2007 differed from the previous three seasons in that the ET controller treatments allowed irrigation windows seven days per week and were updated with a system efficiency of 80% determined from irrigation uniformity testing (Table 2-3). The time-based treatment, T4, was increased to apply irrigation to replace 100% of the net irrigation requirement instead of 60% used during the first three seasons (Table 2-4). Once again, T5 applied 60% of T4 resulting in the reduced treatment applying 60% of the net irrigation requirement.

Results were quantified by comparing all treatments to a time-based treatment without a rain sensor (time WORS). The time-based treatment without a rain sensor was derived from T4 by including water application from irrigation events that were bypassed due to rain and was not an actual treatment. Irrigation runtimes for this treatment were adjusted monthly based on historical ET and effective rainfall. Data collection included: rainfall data at fifteen minute intervals from a Florida Automated Weather Network (FAWN) weather station located on-site; irrigation water applied per plot from totalizing flow meters; and turfgrass quality measurements.

Turfgrass quality was measured monthly using the National Turfgrass Evaluation Program (NTEP) standards (Shearman and Morris 2006). The turfgrass was rated on a scale from 1 to 9 where 1 represented dead turfgrass or bare ground, 9 represented an ideal turfgrass, and 5 was considered minimally acceptable quality for a residential setting. Each rating was determined by examining aspects of color, density, uniformity, texture, and disease or environmental stress.

Evaluations were made monthly by the same graduate research assistant using the NTEP standards (Appendix B). Volunteers belonging to the Master Gardeners Association were asked to evaluate the turfgrass quality various times of the year in addition to the ratings completed once per month as a quality control method (Appendix B). Approximately six Master Gardeners rated the study plots during the months of December 2006, January 2007, March 2007, May 2007, July 2007, and October 2007. The monthly ratings taken by the graduate research assistant were used in the statistical analysis of turfgrass quality for all seasons.

Water application was summed into weekly totals for statistical comparisons between treatments using weeks as repeated measures. Water application per plot was summed for 14 days prior to turfgrass rating days for statistical comparisons to turfgrass quality. Two-week water application was used for turfgrass quality comparisons because ratings were taken at irregular intervals throughout the season and the water applied over the two weeks prior to the rating date would have the most effect on the rating.

SAS statistical software (SAS Institute, Inc., Cary, NC) was used for all statistical analysis, utilizing the General Linear Model (GLM) procedure and the mixed procedure. The confidence interval was assumed to be 95%. Means separation was conducted using Duncan's multiple range test and least squares means separation was conducted using the Tukey-Kramer test for pairwise comparisons.

Results and Discussion

All months received less rain than historical average except for the following three months: July 2006, 97% higher than average; April 2007, 53% higher than average; October 2007 104% higher than average (Figure 2-9). Overall, both years were drier than the historical average with a total of 1326 mm of rainfall for the approximate 16-month study period occurring from August 2006 through November 2007. This was 33% less than the historical total from the local NOAA weather station and 29% less when compared to the Florida average of 1400 mm/year. There were 145 rain events over 472 days; 69% of the study period contained dry days.

Irrigation water application data was collected from the three replications of each brand of ET controller at the Gainesville turfgrass plots (Table 2-5). It was determined through an ANOVA that there were no differences between the Weathermatic replications (P=0.9263), the Toro replications (P=0.9998), or the ET Water replications (P= 0.9989). Therefore, the results found at the Gainesville turfgrass plots for each brand of controller increased the validity of the results from the controllers located at the GCREC.

Fall 2006

This season suffered from an infestation of chinch bugs (*Blissus insularis* 'Barber') and a fungal disease known as Curvularia. Chinch bugs are small pests that inhabit areas of thatch in St. Augustinegrass and live off of plant fluids causing the turfgrass to die (Buss 1993). Curvularia is a pathogen that typically attacks stressed plant material (Wong et al. 2005). The chinch bug problem was treated by Talstar with an active ingredient of Bifenthrin (7.9%) at a rate of 30 ml per 93 m^2 on 14 Sep, 2006. Scott's Lawn Fungus Control was applied to all turf areas on 19 September, 2006 with an active ingredient of Thiophanate-methyl at 2.3% to control the fungal problem. Damaged turfgrass was replaced with new sod during the week following 26 September, 2006; no more than 25% of any plot was resodded and most of the damage was located along the edges of the plots.

The time-based treatment, T4, irrigated the most by applying 230 mm, whereas the reduced time-based treatment, T5, irrigated the least, applying 144 mm (Figure 2-10). Cumulatively, the Weathermatic (T1) and Toro (T2) applied similar depths over the season totaling 197 mm and 193 mm, respectively. The ET Water controller, T3, did not function during this season; results could not be reported. All treatments irrigated less than the time WORS treatment, cumulatively totaling 317 mm.

The ET controller treatments applied less irrigation than the time WORS treatment except for the month of October as can be seen in the steeper slopes of the lines (Figure 2-10). October 2006 experienced less time-based irrigation because the schedule derived from Dukes and Haman (2002) contained an error for October in south Florida. Irrigation application for the time-based treatments should have resembled September since October had less rainfall and no more than a 4% difference in ET, totaling 119 mm in September and 115 mm in October.

Rainfall events occurred within 24 hours of a scheduled irrigation event, causing many of the scheduled events to be bypassed by all treatments. The Weathermatic controller, T1, bypassed more events due to the mandatory 48-hour bypass period initiated for each rainfall event greater than 6 mm in the early part of the season. Since the controller was only allowed to irrigate two days per week to follow watering restrictions, there were limited opportunities for this controller to allow irrigation to occur. However, the Weathermatic controller, T1, usually calculated larger irrigation depths per event when allowed to irrigate in the latter part of the season resulting in similar cumulative irrigation as the Toro controller, T2.

There were differences among treatments ($P<0.0001$), but not replications ($P=0.8073$) for fall water application (Table 2-6). The time-based treatments, T4 and T5, averaged 15 mm/wk and 9 mm/wk and were different from each other ($P=0.0002$). The ET controller treatments, T1 and T2, were not different from each other ($P=0.9995$), both averaging 12 mm/wk. There were also not differences between the time-based treatment, T4, and the Weathermatic controller, T1 ($P=0.4152$), or Toro controller, T2 ($P=0.2945$). The Weathermatic, T1, and Toro, T2, controllers were not different (T1: $P=0.0626$; T2: $P=0.1063$) compared to the reduced time-based treatment, T5. All treatments were different compared to the time WORS where this treatment applied an average of 20 mm/wk ($P\leq0.0002$).

Average turfgrass quality ratings were below the minimally acceptable value of 5.0 for all treatments due to pest problems, fungal disease, and the reduced October time schedule for the time-based treatments, T4 and T5, as described above (Table 2-7). Two-week water application was different across treatments ($P<0.0269$) whereas turfgrass quality ratings were not ($P=0.7279$). More specifically, the Weathermatic controller, T1, applied more weekly irrigation than the reduced time-based treatment, T5, causing differences ($P=0.0064$). Toro controller (T2) and the reduced time-based treatment (T5), however, were not different ($P=0.2506$) despite the Toro controller applying more per week. Water application was not correlated with turfgrass quality ($P=0.4503$).

All treatments showed savings compared to the time WORS treatment (Table 2-6). The reduced time-based treatment, T5, showed the most savings at 55% due to the extremely low water application in October. The time-based treatment, T4, showed 28% savings by also experiencing the low watering schedule in October. Savings from the ET controller treatments, the Weathermatic (T1) and Toro (T2), fell between the other treatments by saving 38% and 39%, respectively.

Winter 2006-2007

Winter water application was less than any other season due to the reduced climatic demand. Irrigation application ranged from 84 mm by T2, the Toro controller, to 169 mm by T4, the time-based treatment (Figure 2-11). The ET Water controller, T3, did not function during this season and results were not reported. Rainfall totaled 167 mm over the 88 day period. Irrigation events were less frequent for the ET controllers; the Toro (T2) irrigated 12 times and the Weathermatic (T1) irrigated 16 times out of a possible 25 irrigation days compared to 20 events by the time-based treatments, T4 and T5. Water savings were experienced by all treatments compared to the time WORS treatment ranging from 20% to 60%.

There were differences among treatments ($P<0.0001$), but not plot replications ($P=0.9484$) for weekly water application (Table 2-8). The Weathermatic controller, T1, and Toro controller, T2, were not different to each other ($P=0.1877$) by averaging 7 mm/wk and 6 mm/wk, respectively, but were different to T5, the reduced time-based treatment, (T1: $P=0.9663$; T2: $P=0.5401$) for this season averaging 7 mm/wk. However, these three treatments were different from T4, the time-based treatment ($P<0.0001$), by applying 11 mm/wk. Also, all treatments were different from the time WORS treatment ($P\leq0.0004$); water application averaged 14 mm/wk for this season.

Significant differences were observed between treatments ($P<0.0001$), but not plot replications ($P=0.9846$) for two-week water application (Table 2-9). Water application by all treatments were different with 95% confidence compared to the reduced time-based treatment, T5, except for T1, the Weathermatic controller ($P=0.8543$), and T2, the Toro controller

(P=0.1915). Turfgrass quality ratings ranged from 5.7 to 6.0 and were not different across treatments (P=0.4055). Also, there was not a correlation between two-week water application and turfgrass quality (P=0.0818).

Both ET controller treatments, T1 and T2, applied less water than the reduced time-based treatment, T5, unlike any other time of year. The ET controller treatments show potential to save over 50% of water applied in subsequent winter seasons.

Spring 2007

Irrigation application ranged from 244 mm by T5, the reduced time-based treatment, to 445 mm by T1, the Weathermatic controller (Figure 2-12). The time-based treatments, T4 and T5, bypassed three irrigation events in April that were attributed to the rain sensor, but no rainfall occurred during that time. These events were superimposed in the cumulative irrigation figure (Figure 2-12), but were not included in the weekly irrigation application averages (Table 2-10).

All ET controller treatments irrigated a smaller amount per event, but more frequently than the time-based treatments (Figure 2-12). However, weekly water applications were not necessarily less by the ET controllers. Average weekly water application by T3, the ET Water controller, was 24 mm/wk (Table 2-10) and was found to be different from all other treatments: the Weathermatic controller, T1, averaged 32 mm/wk (P<0.0001); the Toro controller, T2, averaged 30 mm/wk (P=0.0002); T4, the time-based treatment averaged 29 mm/wk (P=0.0053); and T5, the reduced time-based treatment averaged 17 mm/wk (P<0.0001). All treatments except the reduced time-based treatment, T5, applied more weekly irrigation than the ET Water controller, T3. The other two ET controller treatments, the Weathermatic (T1) and Toro (T2) controllers, were not different from each other (P=0.5553); however, they were different from the reduced time-based treatment, T5 (P<0.0001). The Weathermatic controller, T1, and Toro controller, T2, were not different from T4, the time-based treatment (T1: P=0.1317; T2: P=0.9638).

Irrigation events occurred every day by the Weathermatic, T1, and ET Water, T3, treatments (Figure 2-12). The Weathermatic controller, T1, irrigated every allowable watering day regardless if a sufficient amount of water was calculated to have left the root zone. The ET Water treatment, T3, irrigated everyday because it was programmed with a 25% allowable depletion instead of 50% originally programmed causing the controller to irrigate when 25% of the water was calculated to have left the root zone. This controller also would not recognize a rain sensor despite repeated attempts with ET Water customer service to repair.

The ET Water controller, T3, frequently had poor signal strength and the irrigation schedule was not updated from April 9, 2007 through May 23, 2007. When signal problems occur, this controller uses the last schedule until communication can be re-established. Thus, the water application rate stayed constant throughout the spring season while the other treatments increased the irrigation rate (i.e., frequency) based on increased climatic demand and little rainfall. The 30% irrigation savings attributed to this controller (Table 2-10) was an over-estimate due to the constant irrigation rate in the spring.

The average two-week water application ranged from 31 mm by the 60% time-based treatment, T5, to 74 mm by the Weathermatic controller, T1 (Table 2-11). Differences were observed between treatments ($P<0.0001$), but not replications (P=0.9845) for two-week water application. Differences were not found between the Weathermatic, T1, and Toro, T2, controllers (P=0.9293), averaging 74 mm and 70 mm, as well as the ET Water controller, T3, and time-based treatment, T4 (P=1.000), both averaging 51 mm. However, T1 ($P\leq0.0006$) and T2 ($P\leq0.0060$) were different from T3 and T4. Also, all treatments were different from T5, the reduced time-based treatment (T1, T2: $P<0.0001$; T3, T4: $P=0.0025$). All treatments maintained similar turfgrass quality ratings well above the minimally acceptable level, averages ranging from 6.1 to 6.4, and were not different from each other ($P=0.9636$). Turfgrass quality was not correlated with two-week water application ($P=0.7451$). Despite the reduced watering by T5, the reduced time-based schedule still had an above average turfgrass quality rating.

Rainfall totaled 109 mm over this season. The time-based schedules, T4 and T5, applied irrigation during every scheduled event for the months of March and May (Figure 2-12). Each rain event occurring in March was not substantial enough to trigger the rain sensor to bypass irrigation and as mentioned earlier there was no rainfall in May. Irrigation savings by the ET controller treatments were based purely on their ability to match irrigation application with environmental demand and not affected by the variability of the rain sensor during these two months.

Water savings by all treatments compared to the time WORS treatment ranged from 9% by the Weathermatic controller, T1, to 50% by the reduced time-based treatment, T5 (Table 2-10). Average weekly water application for the time WORS treatment was different from the Toro controller, T2 ($P=0.0009$), but was not different from the Weathermatic controller, T1 ($P=0.1646$). The time-based treatments, T4 and T5, and ET Water controller, T3, were different ($P<0.0001$) to the time WORS treatment, also.

Summer 2007

Compared to the spring, rainfall was more frequent during the summer of 2007, totaling 446 mm. Irrigation ranged from 228 mm by T5, the reduced time-based treatment, to 425 mm by T4, the time-based treatment (Figure 2-13). The ET Water controller, T3, continued to apply irrigation every day without a functional rain sensor.

A power outage occurring on 8 June, 2007 caused the pump connected to the well, the source for irrigation water, to stop functioning as well as the Weathermatic weather monitor to discontinue taking measurements to calculate ET_o. The water source was switched to the pressurized system provided by the farm that could not supply a constant specified pressure until the pump could be replaced. The depth of irrigation applied per event for the time-based treatments, T4 and T5, were not constant throughout the season due to the changing pressure of the water source. All treatments were subject to same pressure issues. Since the Weathermatic controller, T1, did not operate based on an ET schedule, data for this controller was removed for this season. This controller continued to supply irrigation daily where total weekly irrigation applied equaled T4, the time-based treatment.

The ET controllers, T2 and T3, irrigated less depth per event, but applied irrigation more frequently than the time-based treatments (Figure 2-13); however, average weekly irrigation applied by the ET controllers, 26 mm/wk by the Toro controller (T2) and 24 mm/wk by the ET Water controller (T3), was greater than T5, the reduced time-based treatment (16 mm/wk; Table 2-12). The ET controller treatments, Toro (T2) and ET Water (T3), were not different from each other ($P=0.8021$), but were different from T5, the reduced time-based treatment ($P<0.0001$). The time-based treatment, T4, was different from the reduced time schedule, T5 ($P<0.0001$), the ET Water controller, T3 ($P=0.0012$), and the Toro controller, T2 ($P=0.0460$).

Turfgrass quality ratings were not different across treatments ($P=0.9329$) and remained above the minimally acceptable levels (Table 2-13). Differences were observed between treatments ($P<0.0001$), but not plot replications ($P=0.9606$) for two-week water application. The Toro controller, T2, was not different compared to the ET Water controller, T3 ($P=0.3126$) or the time-based treatment, T4 ($P=0.1812$). However, the ET Water controller, T3, was found to be different compared to T4 (P=0.0030). Both ET controller treatments, T2 and T3, were different compared to T5, the reduced time-based treatment (P<0.0001). The time-based treatments, T4 and T5, were also different from each other (P<0.0001). Turfgrass quality was not correlated with two-week water application (P=0.5910).

Water savings by all treatments compared to the time WORS treatment (Table 2-12) ranged from 31% by T4, the time-based treatment, to 63% by T5, the reduced time-based treatment. Savings from the ET controller treatments, the Toro (T2) and ET Water (T3) controllers, fell between the other treatments by saving 41% and 45%, respectively. The average weekly water application by the time WORS treatment was 44 mm/wk and was different from all treatments (P<0.0001).

Fall 2007

Water application ranged from 209 mm by T2, the Toro controller, to 427 mm by T4, the time-based treatment in the Fall 2007 (Figure 2-14). Rainfall during this period totaled 264 mm. There were differences between treatments (P<0.0001), but not plot replications (P=0.7412). Average weekly water application (Table 2-14) for the ET Water controller, T3, was 18 mm/wk and was not different compared to the other ET controller treatments, Weathermatic, T1 (20 mm/wk; P=0.5516) and Toro, T2 (15 mm/wk; P=0.1492), as well as the reduced time-based treatment, T5 (18 mm/wk; P=1.000). The Weathermatic controller, T1, and Toro, T2, controller were different compared to the time WORS treatment (P<0.0001) and were different from each other (P=0.0007). All treatments were different compared to the time-based treatment, T4 (P<0.0001).

The water source was switched back to the well after the pump was replaced on 31 August, 2007; water application by the time-based treatments was more constant per event (Figure 2-14). The ET Water controller, T3, was updated to a 50% allowable depletion before scheduling an irrigation event on 29 October, 2007 resulting in less frequent events with larger depths applied per event.

The weather monitor used to gather weather information for the Weathermatic controller, T1, was knocked off of its mount on 9 October, 2007. It was uncertain the length of time prior to this date that the monitor was not at a proper height or in the vertical direction. Irrigation occurred despite rain events due to the misalignment of the rain sensor and runtimes calculated by this controller during this period were possibly skewed.

There were no differences between any of the ET controller treatments in two-week water application. The ET Water controller, T3, was not different compared to the Weathermatic controller, T1 ($P=0.9985$) and the Toro controller, T2 ($P=0.3805$) totaling 39 mm. Also, the Weathermatic, T1 (40 mm) was not different ($P=0.2409$) compared to the Toro controller, T2 (33 mm). The Weathermatic controller, T1, and ET Water controller, T3, were not different compared to T5, the reduced time-based treatment (T1: $P=0.4097$; T3: $P=0.2634$) whereas the Toro controller, T2, was different ($P=0.0035$). All treatments were different compared to the time-based treatment, T4 ($P<0.0001$). Turfgrass quality was similar across all treatments and higher than the minimally acceptable value of 5, ranging from 6.4 to 7.1; quality was not different between treatments ($P=0.1699$). Turfgrass quality was not correlated with two-week irrigation depth ($P=0.1777$).

The Weathermatic controller, T1, saved 43% compared to time-based irrigation without a rain sensor while the Toro, T2, and ET Water, T3, controllers saved 59% and 50%, respectively. Both time-based treatments, T4 and T5, also showed water savings from 15% to 50%. The time WORS treatment was different compared to all treatments ($P\leq0.0006$).

Summary and Conclusions

The ET controller treatments consistently applied less than the time-based treatment utilizing a rain sensor (T4) for the first two seasons with only the exception of the incorrect irrigation schedule in October. The ET controller treatments always applied less than T4 over the last three seasons except for the following three months: 44% for April (Weathermatic, T1), 7% for May (Weathermatic, T1), and 5% for July (Toro, T2).

Some excess watering could be attributed to controller installation; the ET Water, T3, applied initial irrigation based on the assumption that the soil was dry, 0% volumetric moisture content, to account for the worst case scenario. Upon activation, the controller applied more water than necessary to ensure that the soil was filled to field capacity despite being well watered during the establishment period.

All treatments applied less water compared to cumulative irrigation for the theoretically-derived time-based treatment without a rain sensor (Time WORS). Average potential water savings by using a rain sensor at a 6 mm threshold was 21% over the entire study period. Rainfall was much less than the historical average resulting in dry conditions. These savings occurred despite dry conditions due to scheduling only two irrigation events per week. There was a high probability of rainfall events greater than 6 mm occurring within each season to cause at least one of the irrigation events to bypass, creating water savings. The reduced time-based treatment, T5, averaged 53% savings for the study period.

When operating properly, all ET controller treatments exhibited considerable savings according to statistical differences compared to time WORS for every season except spring 2007. This occurred because the time-based treatments were developed considering historical effective rainfall. However, the spring 2007 season experienced very little rainfall and an increase in the demand for irrigation. Even though more irrigation occurred compared to the time-based treatments, the ET controllers were reacting to the plant water needs based on real-time conditions and not historical needs.

The Weathermatic controller, T1, averaged 35% savings for the entire study period compared to the time WORS treatment. Average savings during watering restrictions, fall 2006 and winter 2006-2007, were 44%. This could be attributed to less cumulative irrigation application over the winter months due to more accurate estimation of water need for the season. Savings for 2007 seasons averaged 26% by this treatment. Savings were less because spring water requirements were higher than historical needs. Also, irrigation application was higher for the fall due to less rainfall bypassing caused by the orientation of the weather monitor.

The Toro controller, T2, showed considerable savings during both years averaging 50% for the fall 2006 and winter 2006-2007 seasons and 38% for the 2007 seasons, averaging 43% for the year. Average savings were less for the 2007 seasons due to increased water demand for spring. The ET Water controller, T3, resulted in 42% savings for the last three seasons. All treatments maintained acceptable turfgrass quality.

The Weathermatic and Toro treatments had more water savings for fall 2007 compared to fall 2006. It was likely that water savings were experienced by the ET controller treatments because watering restrictions were removed. The ET controllers were able to apply irrigation when calculated as necessary and not accumulating over many days before irrigation can occur. More savings were also possible for fall 2007 due to increasing the net irrigation requirement replacement for the time-based schedules from 60% to 100% after winter 2006-2007.

Haley et al. (2007) found that homes in Central Florida used an average of 149 mm/month when their time clocks were not adjusted over the year. Compared to this benchmark, fall 2006 and winter 2006-2007 savings for the ET controller treatments were 60% and 71% while the time-based treatments, T4, T5, and time WORS, saved 47%, 63%, and 29%, respectively. During the last three seasons, all treatments irrigated less than the average homeowner except for time WORS (29% increase). Savings ranged from 6% by the time-based treatment, T4, to 46% by the reduced time-based treatment, T5. ET controller savings were 20%, 26%, and 30% for the Weathermatic, Toro, and ET Water, respectively.

The time-based treatment, T4, developed from 100% replacement of the net irrigation requirement, consistently applied more cumulative irrigation compared to the ET controller treatments. Also, the reduced time-based schedule, T5, applied the least amount of water in all seasons except winter 2006-2007 and fall 2007. However, turfgrass quality remained above the minimally acceptable level for both treatments and there were no statistical differences between the ratings. As a result, 60% replacement of net irrigation requirements is appropriate for effective water application assuming good uniformity.

The reduced time-based schedule, T5, resulted in similar savings as ET controllers. Thus, as has been shown in previous research in Florida, changing time clock settings throughout the year can result in substantial irrigation savings. Fall 2006 and winter 2006-2007 were scheduled for only 36% replacement (60% reduction of 60% of the net irrigation requirement) of net irrigation requirement for the reduced time-based treatment, but still irrigated more in the winter compared to the ET controller treatments. Time-based treatments were developed from the net irrigation requirement for the area resulting in less water applied than if scheduled without using historical ET and effective rainfall. However, time-based schedules do not fluctuate with changing weather conditions and typical homeowners will not manually adjust on a regular basis. Thus, the ET controllers are necessary for consistent water savings.

Table 2-1. Program settings for each brand of ET controller for summer 2006, fall 2006, and winter 2006-2007

Setting	Weathermatic	Toro	ET Water
Sprinkler type[1]	15.2 mm/hr	15.5 mm/hr	15.5 mm/hr
Plant type[2]	Warm season turfgrass	Warm season turfgrass	Warm season turfgrass
Root depth	NA	152 mm	152 mm
Soil type[3]	Sandy	Sandy	Sandy
Slope	0°	0°	0°
Efficiency[4]	100%	100%	100%
Zip code[5]	33598	NA	NA
Microclimate	NA	Full Sun	Full Sun
Days allowed[6]	Wed, Sat	Wed, Sat	Wed, Sat

[1]Application rate or precipitation rate is termed sprinkler type for some ET controllers. [2]The plant type setting is used to choose crop coefficients to calculate plant evapotranspiration. [3]The soil type setting is used to determine the depth of available water for the root zone. [4]Scheduling efficiency is used to calculate gross irrigation once net irrigation is determined. [5]Zip code is used to find the latitude to determine the monthly solar radiation for ET calculations. [6]Days Allowed refers to the days irrigation was allowed to occur per week.

Table 2-2. Runtimes and application amounts per irrigation event[1] for the time-based treatment (T4) operating on a twice weekly schedule for fall 2006 and winter 2006-2007 seasons

Month	Mixed-ornamentals[2]		Turfgrass	
	Time[3] (min)	Depth (mm)	Time (min)	Depth (mm)
January	19	6	23	6
February	20	6	24	6
March	28	9	35	9
April	30	10	37	10
May	28	9	34	9
June	25	8	31	8
July	39	12	48	12
August	43	14	53	14
September	26	8	31	8
October	27	8	32	8
November	27	8	33	8
December	24	7	29	7
Total[4]	672	210	820	210

[1]Assumed 60% system efficiency and estimated effective rainfall for south Florida with 60% ET replacement. [2]Application rate of 0.61 in/hr for turfgrass and 0.75 in/hr for mixed-ornamentals. [3]Two irrigation events per week. [4]Total was calculated for the year including both irrigation events.

Table 2-3. Program settings for each brand of ET controller for spring 2007, summer 2007, and fall 2007

Setting	Weathermatic	Toro	ET Water
Sprinkler type[1]	15.2 mm/hr	15.5 mm/hr	15.5 mm/hr
Plant type[2]	Warm season turfgrass	Warm season turfgrass	Warm season turfgrass
Root depth	NA	152 mm	152 mm
Soil type[3]	Sandy	Sandy	Sandy
Slope	0°	0°	0°
Scheduling efficiency[4]	80%	80%	80%
Zip code[5]	33598	NA	NA
Microclimate	NA	Full sun	Full sun
Days allowed[6]	Everyday	Everyday	Everyday

[1]Application rate or precipitation rate is termed sprinkler type for some ET controllers. [2]The plant type setting is used to choose crop coefficients to ultimately calculate plant evapotranspiration. [3]The soil type setting is used to determine the depth of available water for the root zone. [4]Scheduling efficiency is used to calculate gross irrigation once net irrigation is determined. [5]Zip code is used to find the latitude to determine the monthly solar radiation for ET calculations. [6]Days Allowed refers to the days irrigation was allowed to occur per week.

Table 2-4. Runtimes and application amounts per irrigation event[1] for the time-based treatment (T4) operating on a twice weekly schedule for spring, summer, and fall 2007 seasons

Month	Mixed-ornamentals[2]		Turfgrass	
	Time[3] (min)	Depth (mm)	Time (min)	Depth (mm)
January	31	10	39	10
February	33	11	41	11
March	47	15	58	15
April	50	16	62	16
May	46	15	56	15
June	42	13	51	13
July	65	21	80	21
August	72	23	88	23
September	43	14	52	14
October	43	14	53	14
November	44	14	55	14
December	39	12	48	12
Total[4]	1110	356	1366	356

[1]Assumed 60% system efficiency and estimated effective rainfall for south Florida with 60% ET replacement. [2]Application rate of 0.61 in/hr for turfgrass and 0.75 in/hr for mixed-ornamentals. [3]Two irrigation events per week. [4]Total was calculated for the year including both irrigation events.

Table 2-5. Average daily irrigation water application for the three replications of ET controllers located at the Gainesville turfgrass plots from May 22, 2007 through November 30, 2007

Replication	Weathermatic	Toro	ET Water
A	1.1 *a*	1.5 *a*	1.2 *a*
B	1.2 *a*	1.5 *a*	1.2 *a*
C	1.1 *a*	1.5 *a*	1.2 *a*
Average**	1.1 *B*	1.5 *A*	1.2 *B*

*Numbers with different letters indicated differences at the 95% confidence level using Duncan's Multiple Range Test. **Statistical analysis was performed on controller brands and results are shown with different letters for average values.

Table 2-6. Fall 2006 weekly water application (August 13 through November 30) and savings compared to the time-WORS treatment[1] using cumulative season totals

Treatment	Controller	Average water application (mm/wk)	Savings compared to time WORS
1	Weathermatic	12 *bc*	38%
2	Toro	12 *bc*	39%
3	ET Water	NA[2]	NA
4	Time	15 *b*	28%
5	0.6*Time	9 *c*	55%
Time WORS		20 *a*	--

[*]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test. [1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4. [2]NA is an abbreviation for Not Applicable and was used for treatments that were not working.

Table 2-7. Fall 2006 two-week water application and turf quality summary (August 13 through November 30)

Treatment	Controller	Two-week water applied (mm)	Turfgrass quality[1]
1	Weathermatic	30 *a*	4.8 *a*
2	Toro	23 *ab*	4.9 *a*
3	ET Water	NA[2]	NA
4	Time	20 *ab*	4.7 *a*
5	0.6*Time	14 b	4.8 *a*

[*]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test. [1]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable. [2]NA is an abbreviation for Not Applicable and was used for treatments that were not working.

Table 2-8. Winter 2006-2007 weekly water application (December 1 through February 26) and savings compared to the time WORS treatment[1] using cumulative season totals

Treatment	Controller	Average water application (mm/wk)	Savings compared to time WORS
1	Weathermatic	7 *c*	50%
2	Toro	6 *c*	60%
3	ET Water	NA[2]	NA
4	Time	11 *b*	20%
5	0.6*Time	7 *c*	49%
Time WORS		14 *a*	--

[*]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test. [1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4. [2]NA is an abbreviation for Not Applicable and was used for treatments that were not working.

Table 2-9. Winter 2006-2007 two-week water application and turf quality summary (December 1 through February 26)

Treatment	Controller	Two-week water applied (mm)	Turfgrass quality[1]
1	Weathermatic	18 *b*	5.7 *a*
2	Toro	11 *c*	5.9 *a*
3	ET Water	NA[2]	NA
4	Time	26 *a*	6.0 *a*
5	0.6*Time	16 *bc*	5.7 *a*

[*]Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. [1]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable. [2]NA is an abbreviation for Not Applicable and was used for treatments that were not working.

Table 2-10. Spring 2007 weekly water application (February 27 through May 31) and savings compared to the time WORS treatment[1] using cumulative season totals

Treatment	Controller	Average water application (mm/wk)	Savings compared to time WORS
1	Weathermatic	32 *ab*	9%
2	Toro	30 *b*	15%
3	ET Water	24 *c*	30%
4	Time	29 *b*	18%
5	0.6*Time	17 *d*	50%
Time WORS		35 *a*	--

*Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. [1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4.

Table 2-11. Spring 2007 two-week water application and turf quality summary (February 27 through May 31)

Treatment	Controller	Two-week water applied (mm)	Turfgrass quality[1]
1	Weathermatic	74 *a*	6.2 *a*
2	Toro	70 *a*	6.4 *a*
3	ET Water	51 *b*	6.3 *a*
4	Time	51 *b*	6.2 *a*
5	0.6*Time	31 *c*	6.1 *a*

*Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. [1]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable.

Table 2-12. Summer 2007 weekly water application (June 1 through August 31) and savings compared to the time WORS treatment[1] using cumulative season totals

Treatment	Controller	Average water application (mm/wk)	Savings compared to time WORS
1	Weathermatic	NA[2]	NA
2	Toro	26 *bc*	41%
3	ET Water	24 *c*	45%
4	Time	30 *b*	31%
5	0.6*Time	16 *d*	63%
Time WORS		44 *a*	--

[*]Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. [1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4. [2]NA is an abbreviation for Not Applicable and was used for treatments that were not working.

Table 2-13. Summer 2007 two-week water application and turf quality summary (Jun 1 through Aug 31)

Treatment	Controller	Two-week water applied (mm)	Turfgrass quality[1]
1	Weathermatic	NA[2]	NA
2	Toro	57 *ab*	6.1 *a*
3	ET Water	52 *b*	6.1 *a*
4	Time	64 *a*	6.1 *a*
5	0.6*Time	32 *c*	5.8 *a*

[*]Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. [1]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable. [2]NA is an abbreviation for Not Applicable and was used for treatments that were not working.

Table 2-14. Fall 2007 weekly water application (September 1 through November 30) and savings compared to the time WORS treatment[1] using cumulative season totals

Treatment	Controller	Average water application (mm/wk)	Savings compared to time WORS
1	Weathermatic	20 *c*	43%
2	Toro	15 *d*	59%
3	ET Water	18 *cd*	50%
4	Time	31 *b*	15%
5	0.6*Time	18 *cd*	50%
Time WORS		36 *a*	--

[*]Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. [1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4.

Table 2-15. Fall 2007 water application and turf quality summary (September 1 through November 30)

Treatment	Controller	Two-week water applied (mm)	Turfgrass quality
1	Weathermatic	40 *bc*	6.4 *a*
2	Toro	33 *c*	7.1 *a*
3	ET Water	39 *bc*	7.0 *a*
4	Time	77 *a*	6.6 *a*
5	0.6*Time	45 *b*	6.5 *a*

[*]Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. [1]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable.

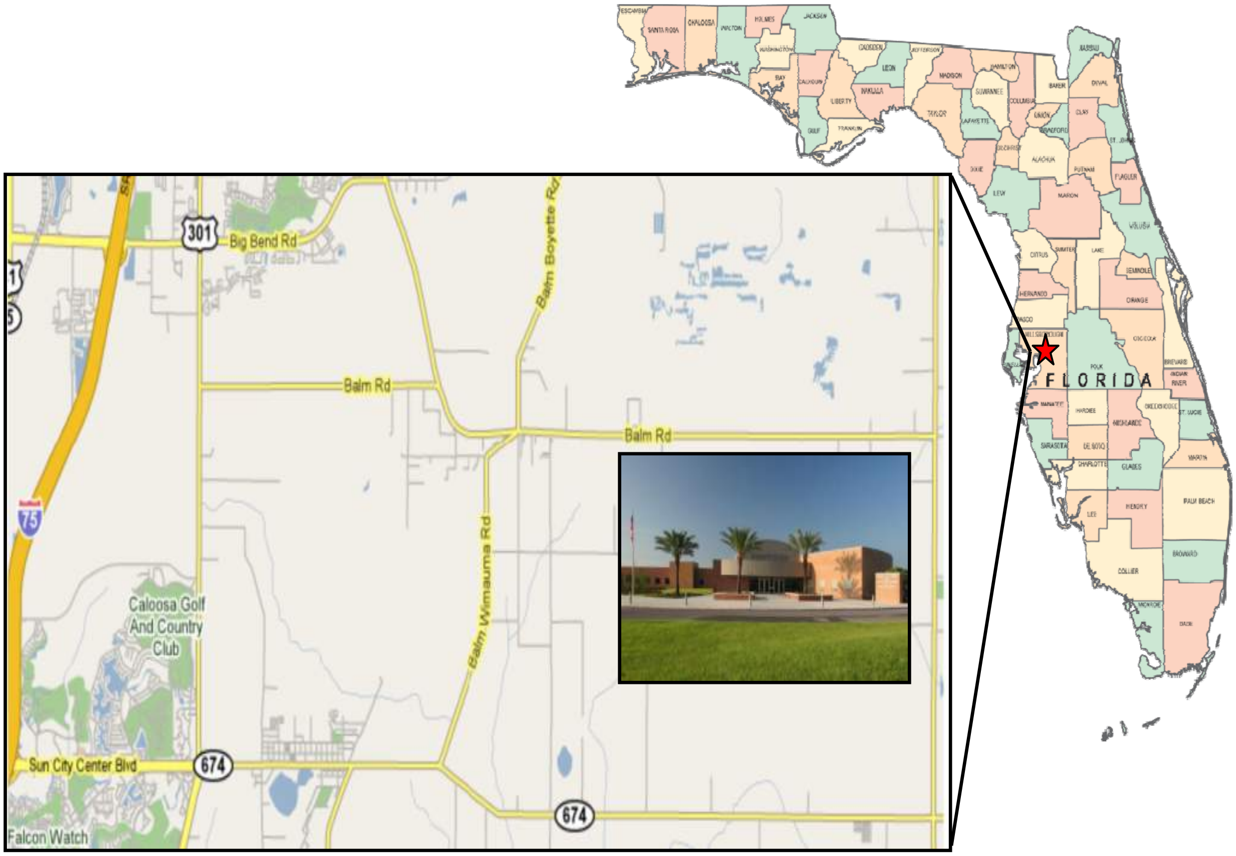

Figure 2-1. Three brands of ET controllers were tested on twenty landscaped plots at the University of Florida Gulf Coast Research and Education Center.

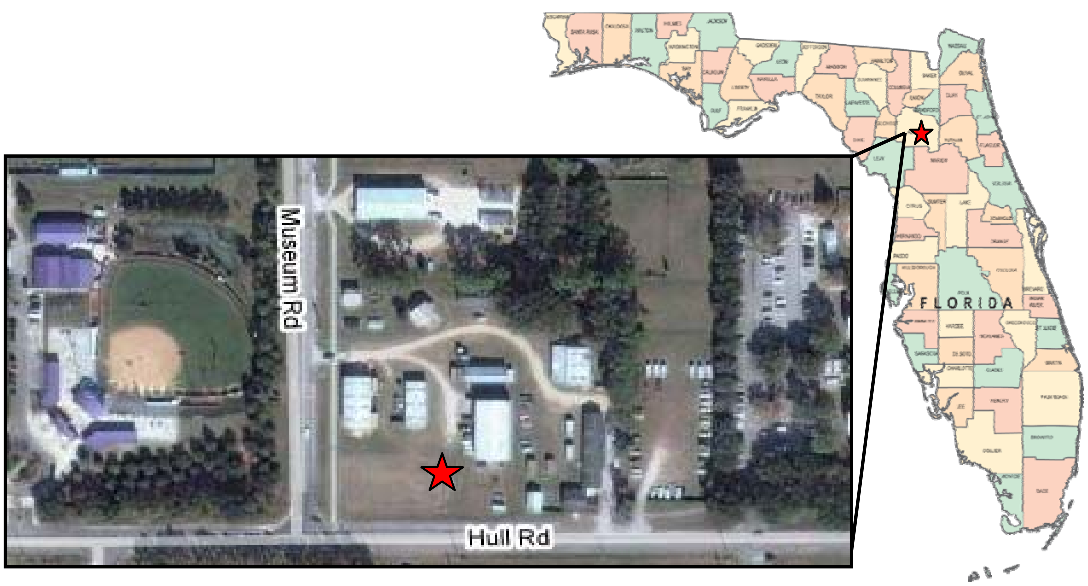

Figure 2-2. Nine additional ET controllers, three of each brand, are installed at the University of Florida Gainesville turfgrass plots (Aerial photo from Google Maps).

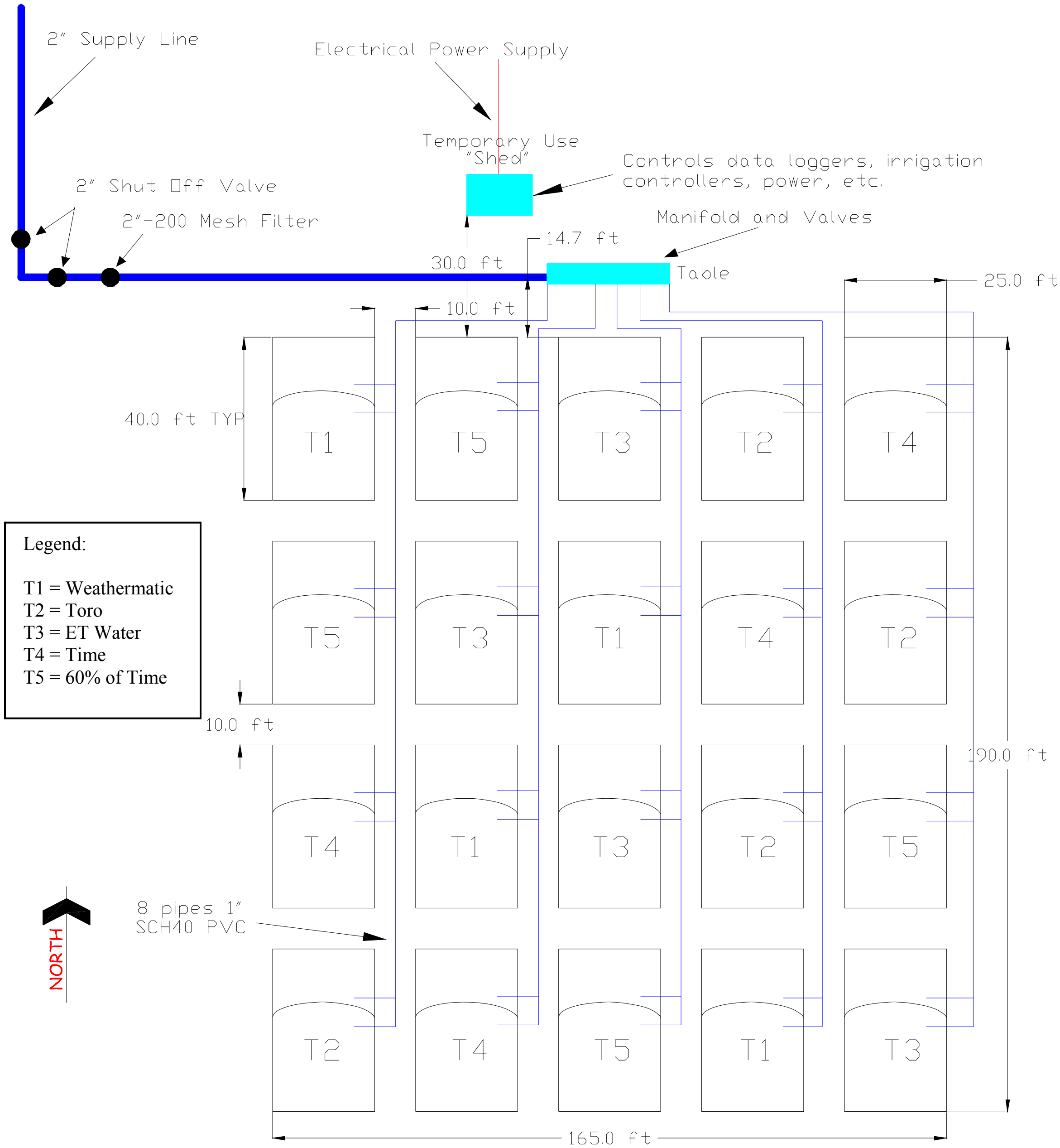

Figure 2-3. Research plot layout and controller treatments at the University of Florida Gulf Coast Research and Education Center in Wimauma, FL.

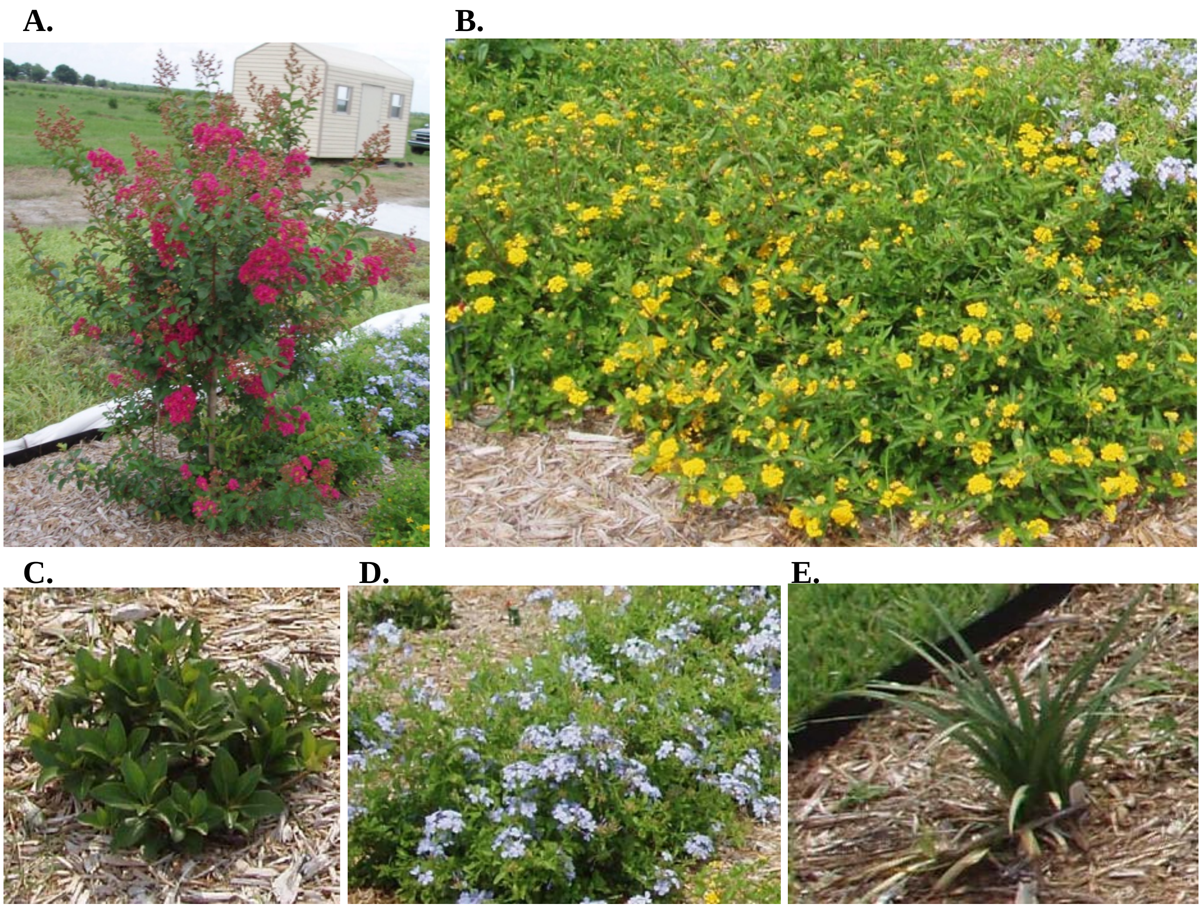

Figure 2-4. The ornamental plants chosen are: (A) Crape Myrtle (*Lagerstroemia indica* 'Natchez') (B) Gold Mound Lantana (*Lantana camara* 'Gold Mound') (C) Indian Hawthorne (*Raphiolepis indica*) (D) Cape Plumbago (*Plumbago auriculata)* (E) Big Blue Liriope (*Liriope muscari* 'Big Blue').

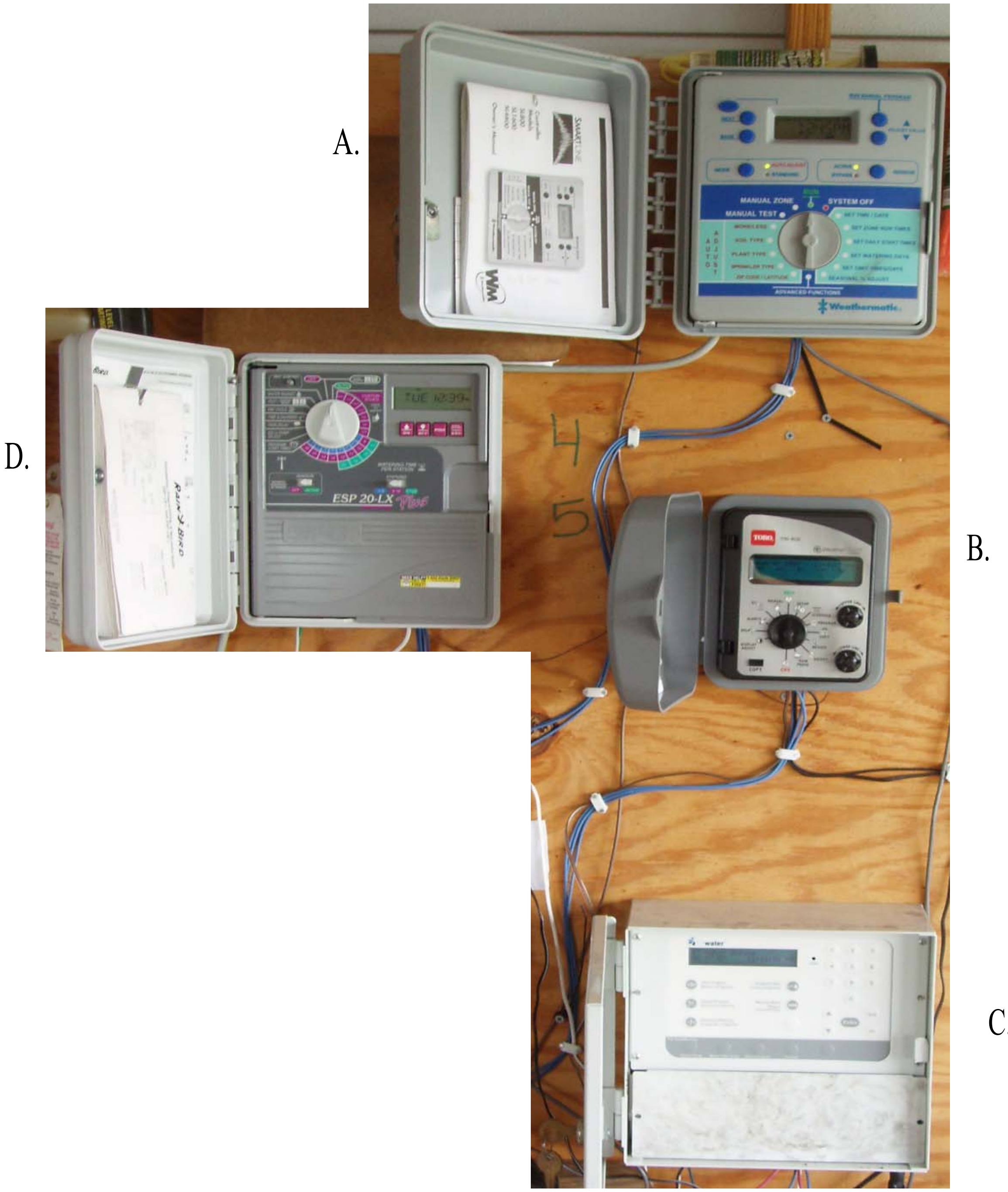

Figure 2-5. The ET Controllers chosen for the study located at the University of Florida Gulf Coast Research and Education Center in Wimauma, FL A) Weathermatic SL1600 B) Toro Intelli-sense C) ET Water Smart Controller 100 and irrigation timer D) Rain Bird.

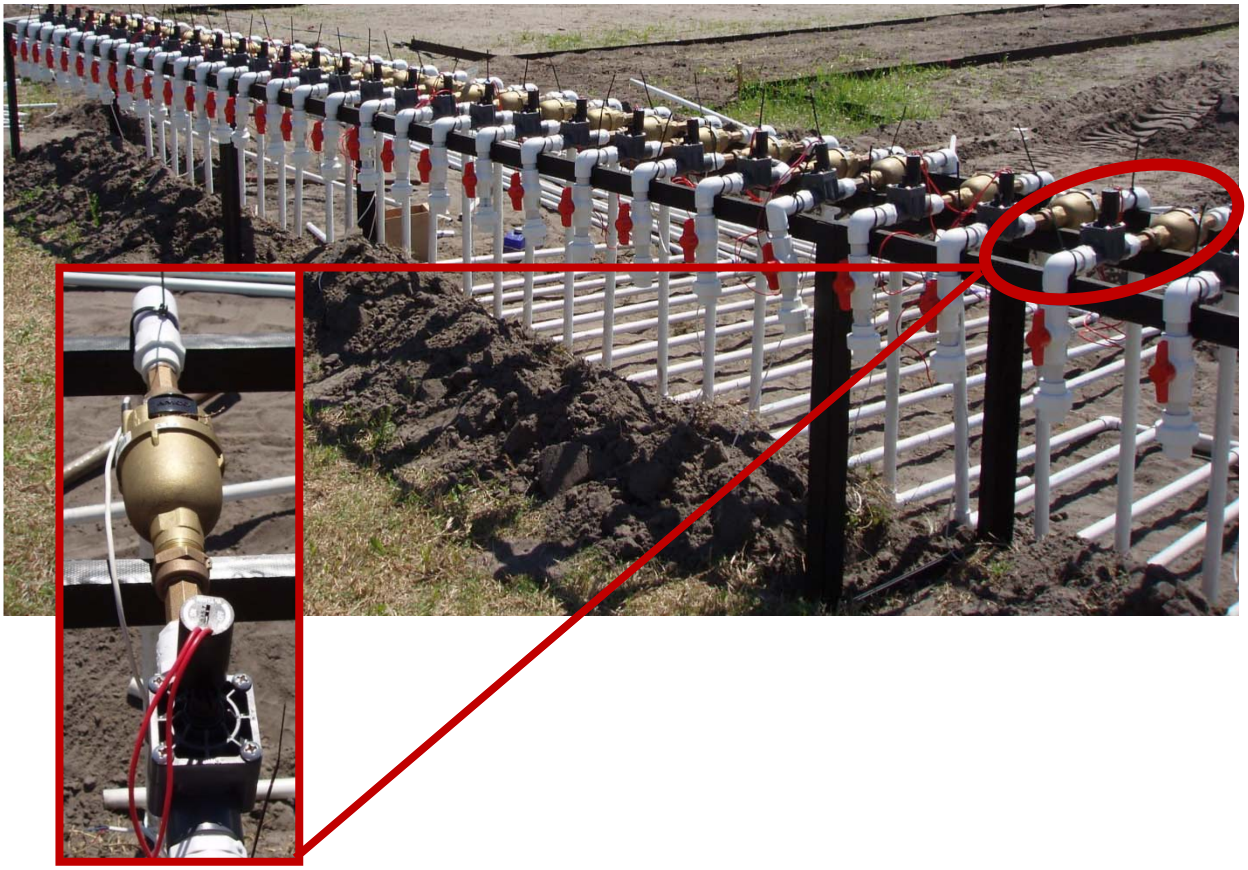

Figure 2-6. Irrigation water application to each plot was monitored by 11.4 cm V100 w/ pulse output flow meters manufactured by AMCO Water Metering Systems (Ocala, FL).

B.

A.

A.

A.

A.

A.

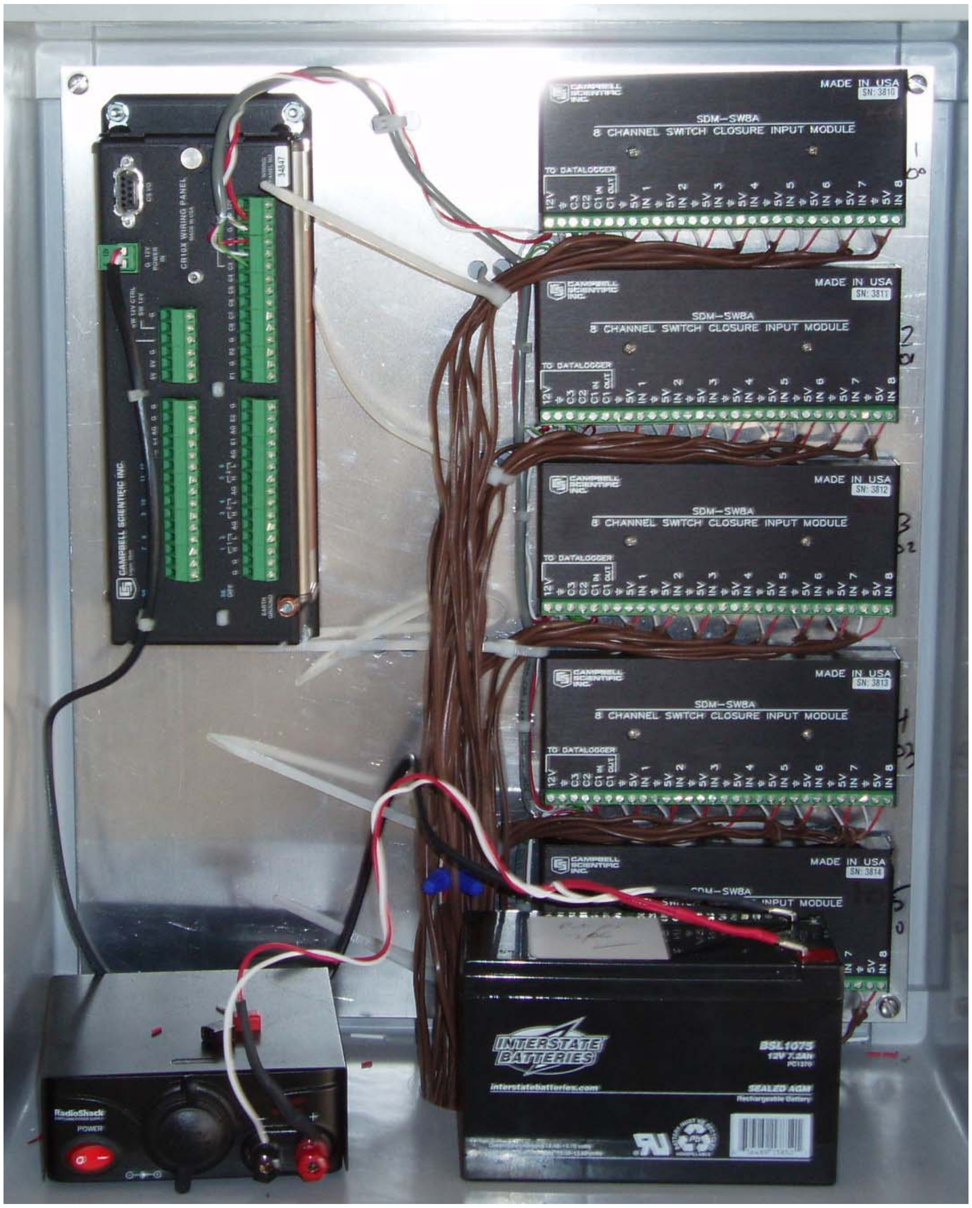

Figure 2-7. Flow meters are wired to (A) five SDM-SW8A switch closure input modules that in turn connect to a (B) CR-10X data logger. Water applied is recorded by switch closures every 18.9 liters.

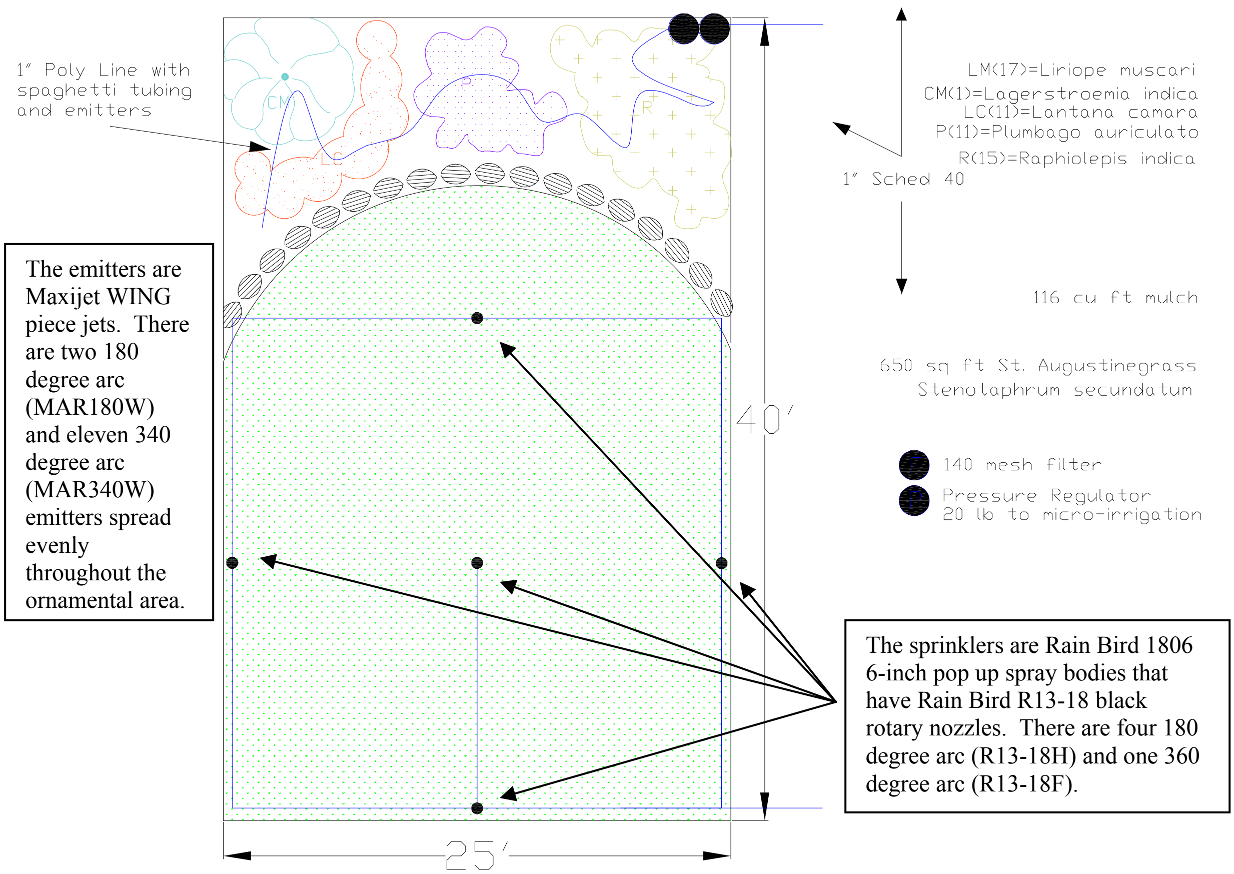

Figure 2-8. Individual plot design of the twenty research plots located at the University of Florida Gulf Coast Research and Education Center in Wimauma, FL.

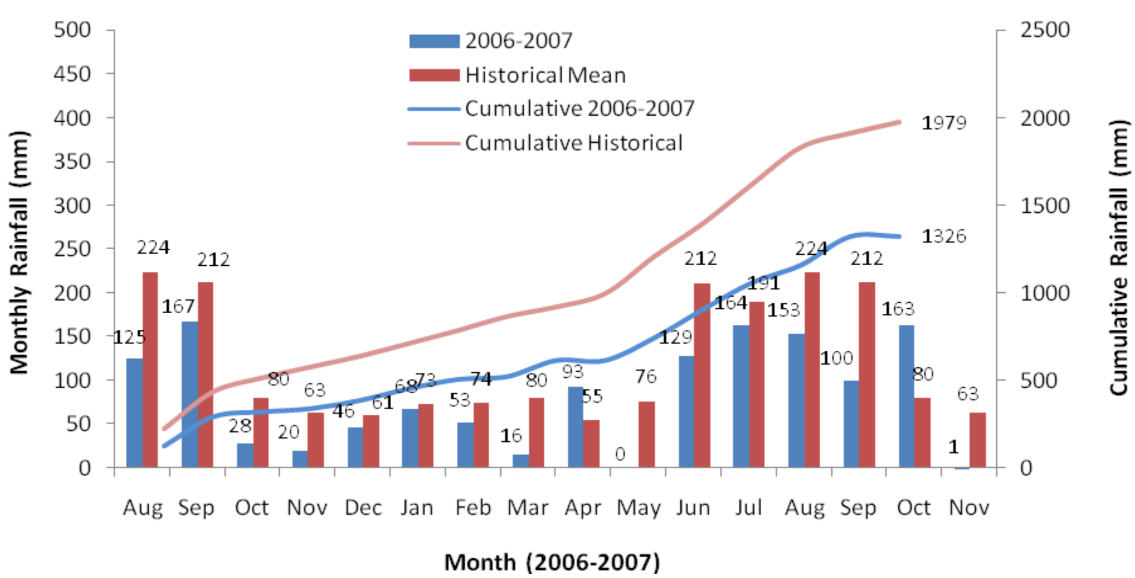

Figure 2-9. Comparison of rainfall for the 2006-2007 study period and average historical rainfall on a monthly and cumulative basis for southwest Florida.

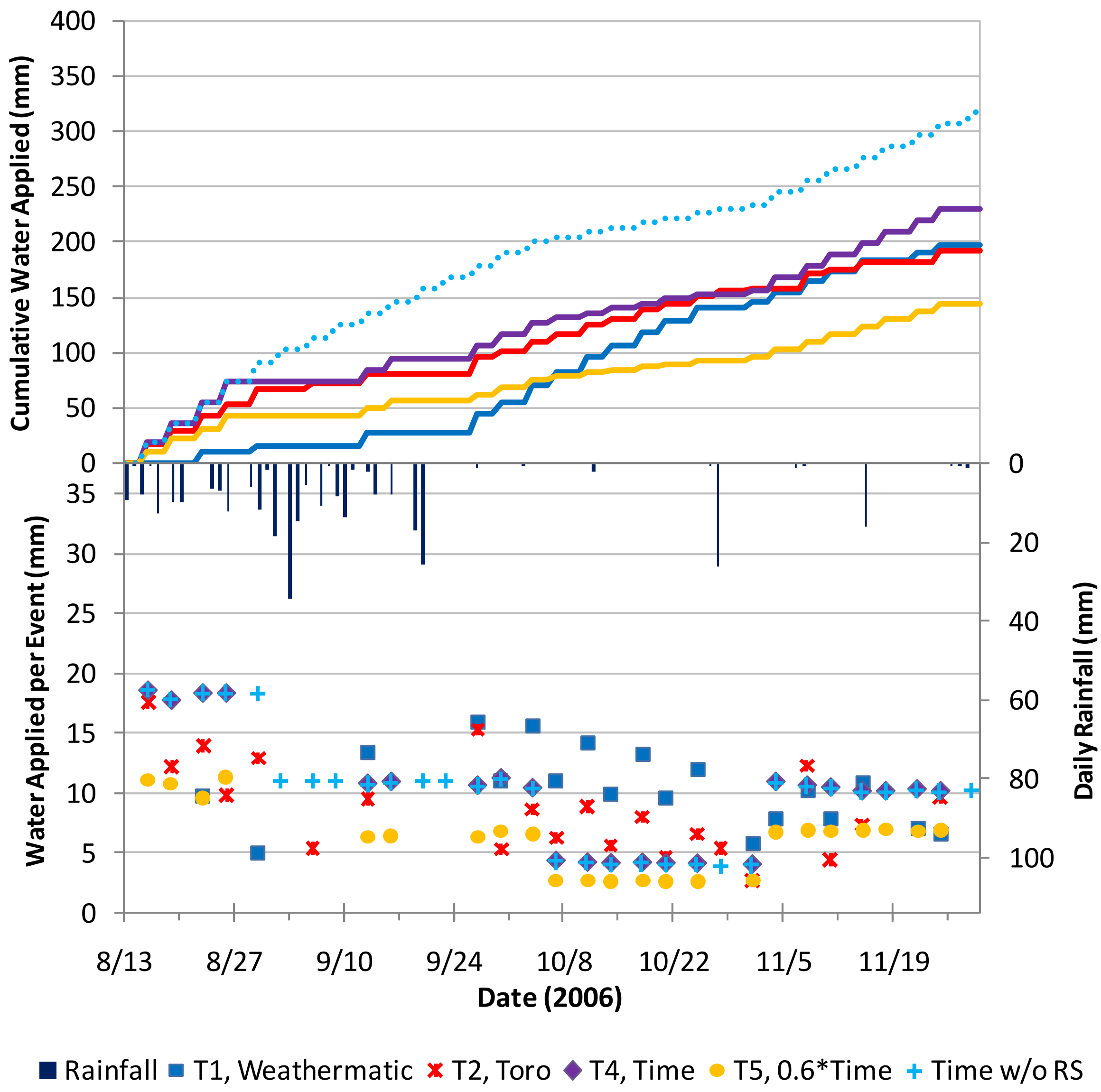

Figure 2-10. Fall 2006 cumulative and daily water application and daily rainfall (August 13 – November 30).

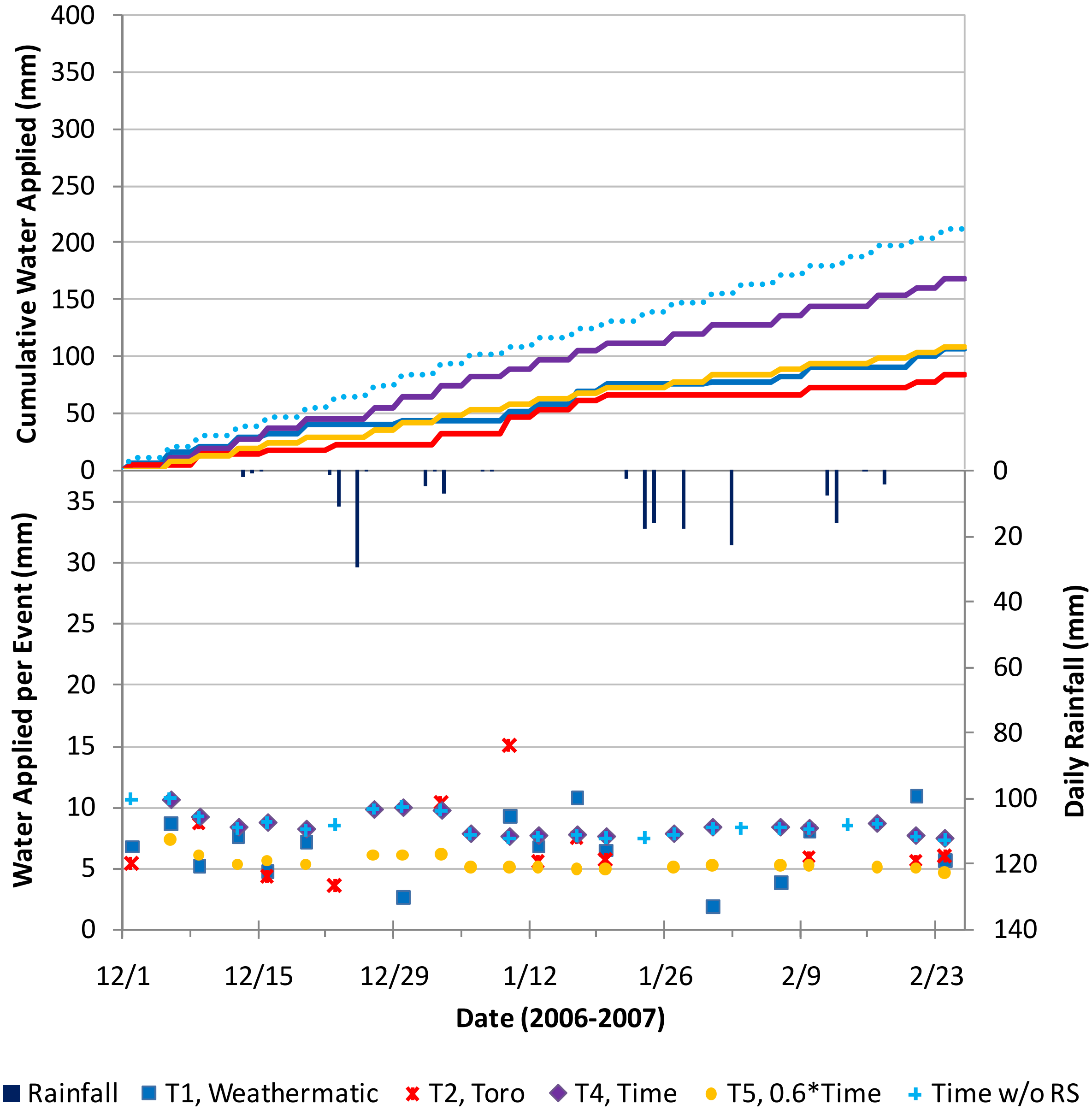

Figure 2-11. Winter 2006-2007 cumulative and daily water applied and daily rainfall (December 1 – February 26).

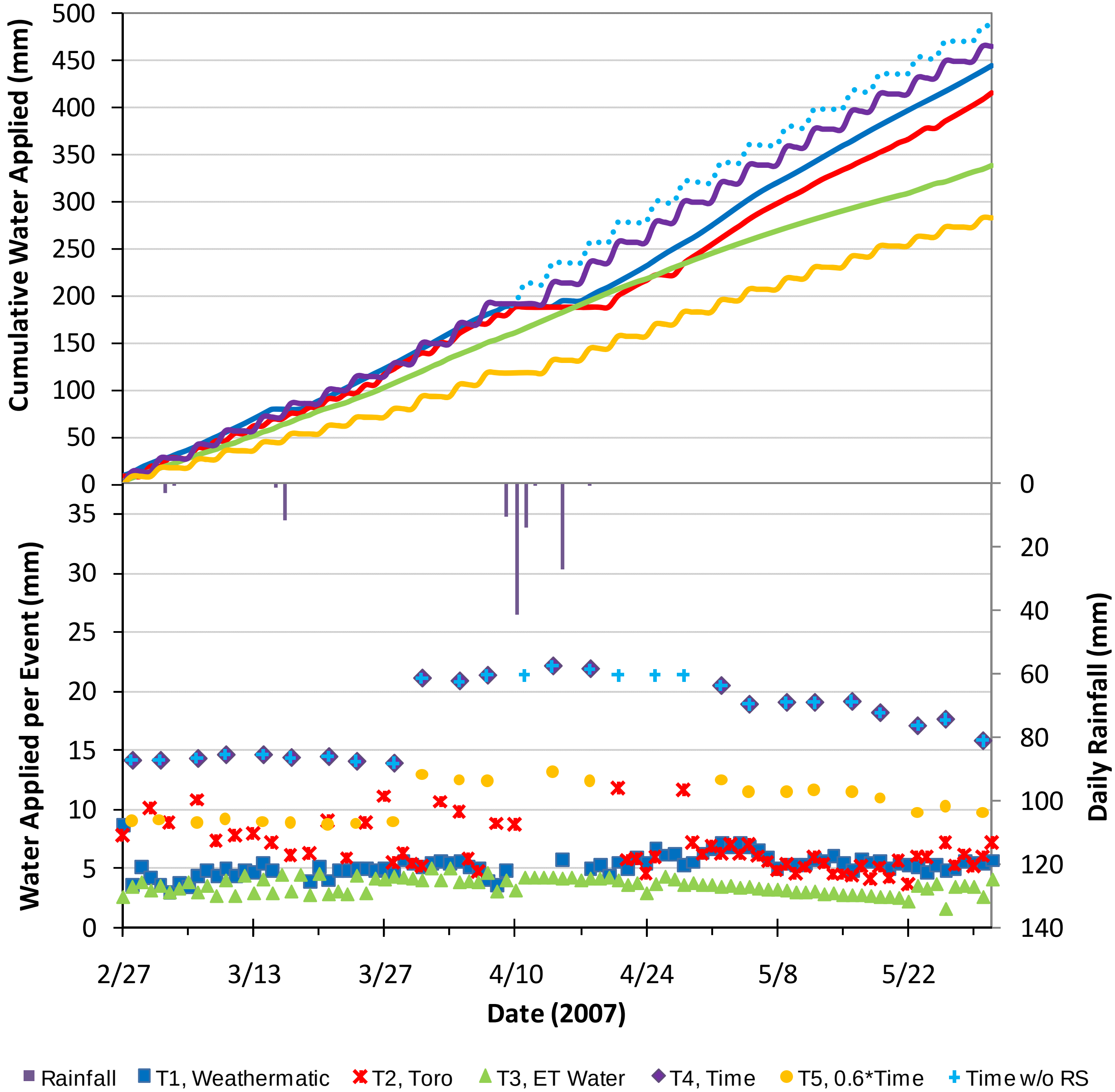

Figure 2-12. Spring 2007 cumulative and daily water applied and daily rainfall (February 27 – May 31).

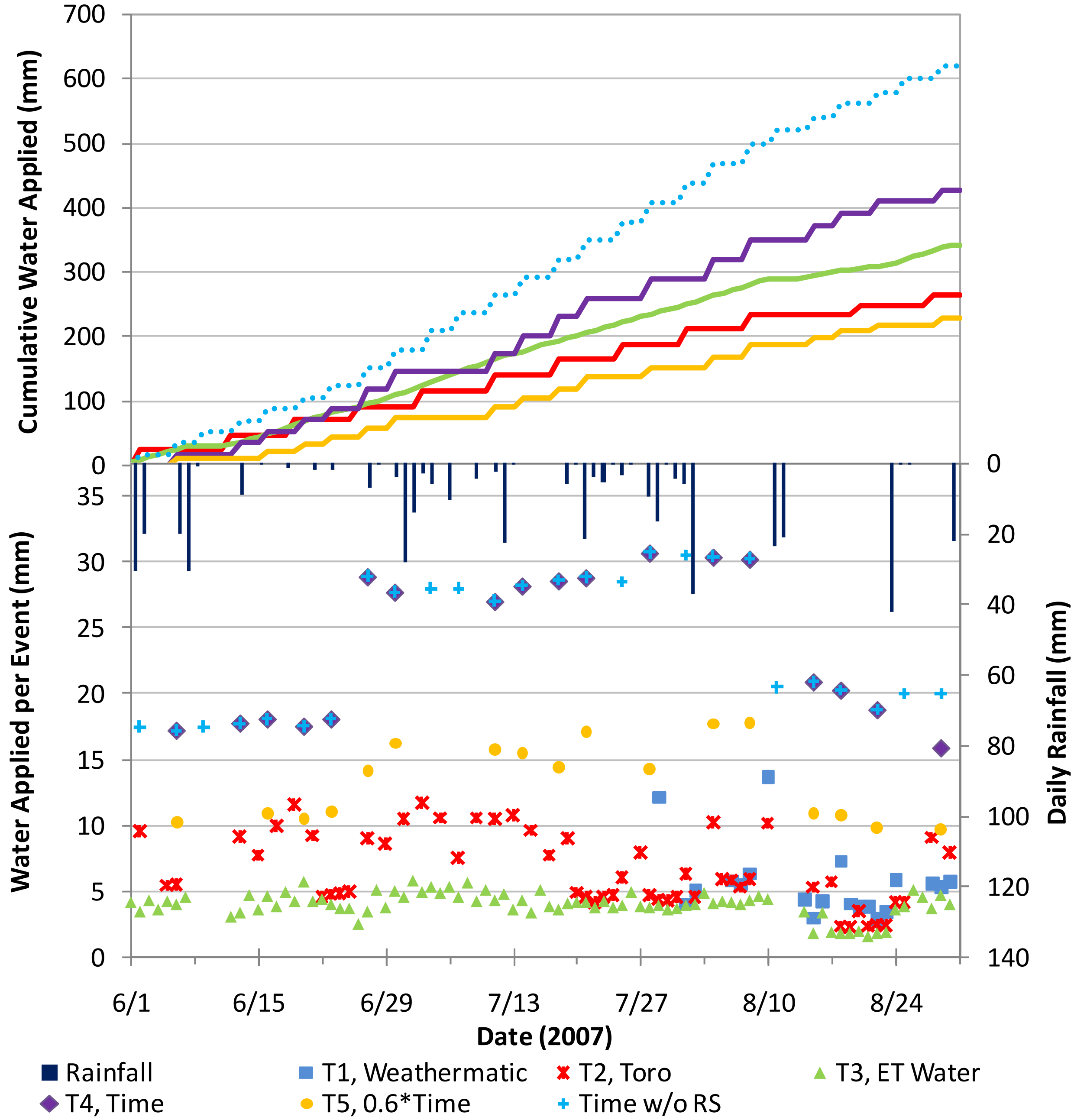

Figure 2-13. Summer 2007 cumulative and daily water applied and daily rainfall (June 1 – August 31).

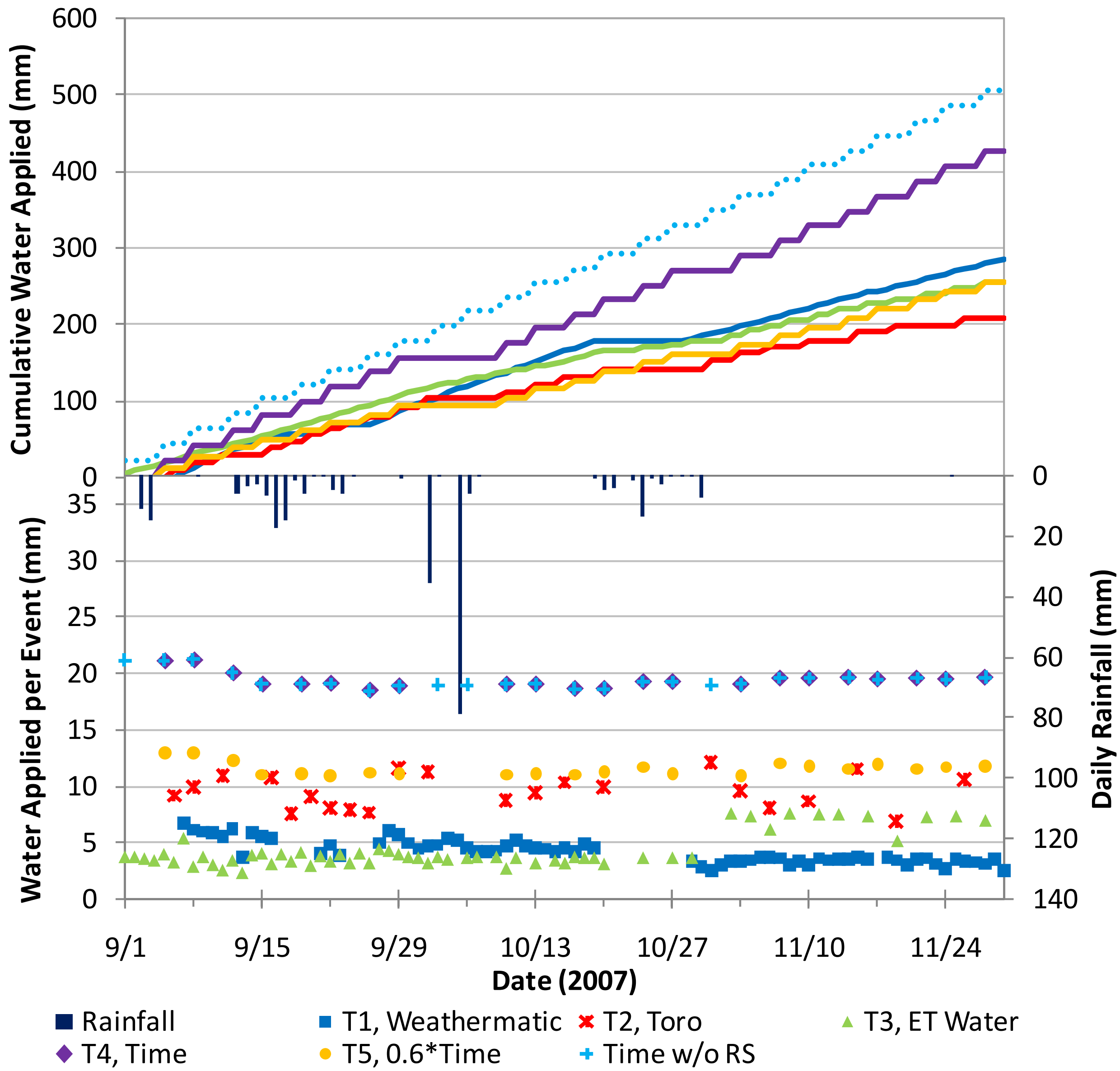

Figure 2-14. Fall 2007 cumulative and daily water applied and daily rainfall (September 1 – November 30).

CHAPTER 3
REFERENCE EVAPOTRANSPIRATION ESTIMATION BY EVAPOTRANSPIRATION-BASED IRRIGATION CONTROLLERS

Introduction

Water is a limited resource and many areas in the world are experiencing water shortages. More specifically, Florida has the second largest withdrawal of groundwater in the U.S. that is used for public supply (Solley et al. 1998). Also, compared to other states Florida has the largest net gain in population with an inflow of approximately 1,108 people per day and fourth in overall population (United States Census Bureau [USCB] 2005). New home construction has increased to accommodate such a large influx of people. Florida ranked first in the construction of single family residential units totaling 209,162 in 2005 (USCB 2007). Most new homes include in-ground automated irrigation systems. However, homes with in-ground systems utilizing automated irrigation timers alone increase outdoor water use by 47% (Mayer et al. 1999). The need for landscape irrigation will continually grow with increased population and home construction if there is no change in the demand for aesthetically pleasing urban landscapes.

Research has shown that Florida single family residences over-irrigate in late fall and winter because time clock schedules are not adjusted to match changing environmental demand (Haley et al. 2007). Increased watering during the fall and winter months can delay dormancy, leading to the need for additional mowing, and increases the likelihood of diseases, insects, weeds, and stresses to the lawn (Harivandi 1984). On a larger scale, the increased watering contributes to the depletion of water resources and can result in leaching of soluble chemicals into shallow groundwater. Therefore, better irrigation management could potentially lead to water conservation, landscape problems, and less groundwater pollution.

Evapotranspiration (ET) is defined as the evaporation from a soil surface and the transpiration from plant material (Allen et al. 1998). ET is part of a balanced energy budget that exchanges energy for outgoing water at the surface of the plant. The components of ET are solar radiation, temperature, relative humidity, and wind speed (Allen et al. 2005). Reference ET (ET_o) is defined as the ET from a hypothetical reference crop with the characteristics of an actively growing, well-watered, dense green cool season grass of uniform height (Allen et al. 2005).

Typically, climatic data is used as inputs to equations to estimate ET_o. There are three types of equations: mass transfer, energy balance, and empirical methods (Fangmeier et al. 2006). Most of the current methods employ a combination of the three. The appropriate ET equation is chosen depending on many factors including geographical location, types of crops, and weather data availability (Fangmeier et al. 2006).

Evapotranspiration-based controllers, also known as ET controllers, are irrigation controllers that use an ET value to schedule irrigation. Each controller works differently depending on manufacturer, but typically can be programmed with various conditions specific to the landscape making them more efficient (Riley 2005). ET controllers receive ET_o information in three general ways, consequently dividing ET controllers into three main types: 1) standalone controllers, 2) signal-based controllers, and 3) historical-based controllers.

Standalone controllers typically receive climatic data from on-site sensors and calculations to determine ET_o are performed by the controller. Even though the controllers might take readings every second or every fifteen minutes, cumulative daily ET_o is used for irrigation scheduling. On-site sensors could include: temperature, solar radiation, an ET gauge, or even a full weather station (Riley 2005). Benefits of standalone controllers are that they are not limited by requiring the use of a full weather station and there are no signal fees associated with broadcasts from the manufacturer (Riley 2005).

Signal-based controllers receive ET_o information from a company that collects climatic data from weather stations located near the irrigation site using satellite or internet technology. Depending on the manufacturer, the ET_o data can be from an average of multiple weather stations in the area or from a single weather station. There is typically a signal fee (i.e., subscription) for this controller set by the manufacturer that normally ranges from $4 to $15 per month (Riley 2005).

Historical-based controllers rely on historical ET_o information for the area. Typically, monthly historical ET_o is programmed into the controller by the manufacturer or installing contractor. Theoretically, this method does not result in as accurate an ET_o estimate because site specific weather variability is not considered.

Irrigation application by ET controllers has been studied frequently in the last five years in the western U.S. Studies were conducted by the Los Angeles Department of Water and Power (Bamezai 2004), Irvine Ranch Water District (Diamond 2003), Aquacraft, Inc. (Aquacraft, Inc. 2002; Aquacraft, Inc. 2003), Metropolitan Water District of Southern California MWDSC 2004), and University of California Cooperative Extension (Pittenger et al. 2004) and results are detailed in Chapter 1 and summarized in Chapter 2. However, comparisons of ET_o estimations have yet to be documented.

The objectives of this experiment were the following: A.) compare the ET_o estimation by three brands of ET-based irrigation controllers to the ASCE-EWRI Standardized ET methodology, B.) quantify the variation between controllers of the same brand, and C.) compare the performance of the controllers based on approximate distance to a publicly available weather data source.

Materials and Methods

This study was conducted at the University of Florida Gulf Coast Research and Education Center (GCREC) in Wimauma, Florida and at the University of Florida Agricultural and Biological Engineering Department turfgrass plots in Gainesville, Florida (see Chapter, Figure 2-1; Figure 2-2). Three ET controller brands were installed at GCREC as follows: SL1600 controller with SLW15 weather monitor (Weathermatic, Inc., Dallas, TX), Intelli-sense (Toro Company, Inc., Riverside, CA) utilizing the WeatherTRAK ET Everywhere service (Hydropoint Datasystems, Inc., Petaluma, CA), and Smart Controller 100 (ET Water Systems LCC, Corte Madera, CA). These three brands were also installed at the Gainesville turfgrass plots in three replications. The replications at the Gainesville site allowed the study of variability between controllers of the same brand. In addition, the Gainesville site was approximately 11 km from the closest public weather station located at the Gainesville Regional Airport whereas the site at GCREC had a Florida Automated Weather Network (FAWN) station within 100 m of the research site with weather data available via the internet.

Data collection from the GCREC location included: climate data at fifteen minute intervals such as wind speed, solar radiation, temperature, relative humidity, and rainfall depth from a Florida Automated Weather Network (FAWN) weather station located on-site. Maximum and minimum temperature data from the Weathermatic SL1600, daily and weekly summed ET_o data from the Toro Intelli-sense controller, and weekly summed average ET_o from the ET Water Smart Controller 100 were recorded manually. Data collection from the Gainesville location was identical to collection at GCREC with the exception of the weather stations being installed and maintained as part of the research.

SAS statistical software (SAS Institute, Inc., Cary, NC) was used for all statistical analysis, utilizing the General Linear Model (GLM) procedure and the mixed procedure with a 95% confidence level. Time was used as a replication. Means separation was conducted using Duncan's Multiple Range test and least squares means was conducted using the Tukey-Kramer test for pairwise comparisons.

Reference Evapotranspiration Calculations

The ASCE standardized reference evapotranspiration equation (Allen et al. 2005) was used to calculate ET_o as seen below.

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \dfrac{C_n}{T + 273} \cdot (e_s - e_a) \cdot u_2}{\Delta + \gamma \cdot (1 + C_d u_2)} \tag{3-1}$$

Variables are defined as follows:

$$\Delta = \frac{2503 \cdot \exp\left(\dfrac{17.27T}{T + 237.3}\right)}{(T + 237.3)^2} \tag{3-2}$$

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

$$e^o T = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \tag{3-4}$$

$$e_a = \frac{e^o(T_{min})\dfrac{RH_{max}}{100} + e^o(T_{max})\dfrac{RH_{min}}{100}}{2} \tag{3-5}$$

$$R_n = R_{ns} - R_{nl} \tag{3-6}$$

$$R_{ns} = (1 - \alpha) \cdot R_s \tag{3-7}$$

$$R_{nl} = \sigma \cdot f_{cd} \cdot \left(0.34 - 0.14\sqrt{e_a}\right) \cdot \left[\frac{T^4_{K\,max} + T^4_{K\,min}}{2}\right] \tag{3-8}$$

$$f_{cd} = 1.35 \frac{R_s}{R_{so}} - 0.35 \tag{3-9}$$

$$R_{so} = \left(0.75 + 2 \times 10^{-5} z\right) \cdot R_a \tag{3-10}$$

$$R_a = \frac{24}{\pi} G_{sc} \cdot d_r \cdot \left[\omega_s \cdot \sin(\varphi) \cdot \sin(\delta) + \cos(\varphi) \cdot \cos(\delta) \cdot \sin(\omega_s)\right] \tag{3-11}$$

$$d_r = 1 + 0.033 \cdot \cos\left(\frac{2\pi}{365} J\right) \qquad 3\text{-}12$$

$$\delta = 0.409 \cdot \sin\left(\frac{2\pi}{365} J - 1.39\right) \qquad 3\text{-}13$$

$$\omega_s = \arccos[-\tan(\varphi) \cdot \tan(\delta)] \qquad 3\text{-}14$$

$$u_2 = u_z \frac{4.87}{\ln(67.8 z_w - 5.42)} \qquad 3\text{-}15$$

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, 4.901×10^{-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

The standard reference crop is grass for Florida (Irmak and Haman 2003) resulting in constants C_n and C_d as 900 and 0.34, respectively (Allen et al. 2005).

Controllers that use only a portion of the climatic parameters listed above do not use the ASCE standardized ET_o equation to calculate ET. Another ET_o estimation method is the Hargreaves equation (Hargreaves and Samani 1982). The equation is as follows:

$$ET_0 = 0.0023 \cdot R_a \cdot TD^{1/2} \cdot (T + 17.8) \quad 3\text{-}16$$

TD = difference between the daily maximum and daily minimum temperature, °C

This equation relies on solar radiation calculated from extraterrestrial radiation and temperature measurements.

Controller Descriptions

The Weathermatic controller, T1, is a standalone controller because it utilizes an on-site weather monitor to collect ambient air temperature used to calculate ET_o by the Hargreaves method (Equation 3-16). This controller stores the maximum and minimum daily temperature used to calculate ET_o, allowing an independent manual calculation of ET_o using the Hargreaves method.

The Toro and ET Water controllers are signal-based. According to the manufacturers, climate parameters such as temperature, relative humidity, wind speed, and solar radiation are collected from publicly available weather stations and ET_o was calculated using the ASCE method (Equation 3-1). The ET_o values were sent to the Toro controllers using paging technology based on the microzone, or designated area of similar ET_o, determined by Hydropoint Data Systems (Newport Beach, CA). ET_o data for the GCREC controller was made available through e-mail by Hydropoint for comparison to calculated ET_o. The ET Water controller used a public weather station to calculate ET_o and broadcasted the value to the controller daily using cellular technology. This data was also sent by e-mail from ET Water Systems LCC for the controller at the GCREC. ET_o data provided by the manufacturers were compared against values read directly on the controller in the case of the Toro and against values gathered from the ET Water website.

ET_o data collection at the GCREC occurred 25 May, 2007 through 30 November, 2007, for the Weathermatic controller. ET_o values sent to the Toro controller were provided by the manufacturer from 13 August, 2006 through 30 November, 2007. ET_o values sent to the ET Water controller were provided by the manufacturer from 4 August, 2006 through 30 November, 2007. As a result, ET_o comparisons between all controllers at the GCREC must begin on 13 August, 2007. ET_o comparisons for the controllers at the Gainesville turfgrass plots began on 22 May, 2007.

Periods of unavailable data for any controller were removed for all controllers when comparing directly. Data for the GCREC controllers was unavailable from ET Water from 17 August, 2006 through 28 August, 2006 as well as 18 September, 2006 through 22 September, 2006. The Toro controller also had missing ET_o data on 12 August, 2006 and 4 September, 2006. Missing data for the controllers at the Gainesville turfgrass plots occurred throughout the period by a few days or less at a time.

Site Descriptions

Nine ET controllers, three replicates of each treatment brand, were installed on May 22, 2007 (Figure 3-1). Each Weathermatic controller utilized an individual on-site weather monitor; each monitor was located at the same height above the ground, 1.83 m, and they were staggered 0.81 m apart (Figure 3-2). The other six controllers were connected to Mini-clik rain sensors (Hunter Industries, Inc., San Marcos, CA). These controllers were virtually tested as they were not connected to actual irrigation systems. ET_o data was collected directly from the controllers without manufacturer assistance.

Five treatments were established at GCREC, T1 through T5, replicated four times for a total of twenty plots in a completely randomized block design (see Chapter, Figure 2-3). From those five treatments, T1 through T3 were ET controllers: T1, Weathermatic SL1600 controller with SLW15 weather monitor; T2, Toro Intelli-sense utilizing the WeatherTRAK ET Everywhere service; and T3, ET Water Smart Controller 100. These treatments controlled irrigation to plots at this location.

The twenty plots measured 7.62 m x 12.2 m, bordered by a 15.2 cm tall black metal barrier, with 3.05 m buffer zones between adjacent plots. Each plot consisted of 65% St. Augustinegrass (*Stenotaphrum secundatum* 'Floratam') and 35% mixed ornamentals to represent a typical residential landscape in Florida. The ornamentals were as follows: Crape Myrtle (*Lagerstroemia indica* 'Natchez') (see Chapter, Figure 2-3A), Gold Mound Lantana (*Lantana camara* 'Gold Mound') (see Chapter, Figure 2-3B), Indian Hawthorne (*Raphiolepis indica*) (see Chapter, Figure 2-3C), Cape Plumbago (*Plumbago auriculata)* (see Chapter, Figure 2-3D), and Big Blue Liriope (*Liriope muscari* 'Big Blue') (see Chapter, Figure 2-3E). Landscapes were maintained through mowing, pruning, edging, mulching, fertilization, and pest and weed control according to current UF-IFAS recommendations (Black and Ruppert 1998; Sartain 1991).

Weather Stations

On-site weather stations were used to collect weather data for comparison purposes using the ASCE method (Equation 3-1) or Hargreaves method (Equation 3-16), where appropriate. The weather station located on-site at the Gainesville turfgrass plots was installed and managed by our team on a regular basis. The weather station located at GCREC was managed by FAWN personnel. Sensor heights for the FAWN station were similar to the Gainesville weather station except for the anemometer that was mounted at a 10 m height; wind speed data was corrected to 2 m (Equation 3-15). Data was collected from a third weather station located at the Gainesville Regional Airport. This station, operated by the National Oceanic and Atmospheric Administration (NOAA), was the closest weather station with publically available weather data to the Gainesville turfgrass plots.

Climatic data was collected at 15-minute intervals for the on-site weather stations and daily intervals for the NOAA weather station at the Gainesville Regional Airport. All stations were subjected to quality control assessments (Allen et al. 2005) by comparing solar radiation (R_s), relative humidity (RH), temperature (T), and wind speed (u_2) data against relevant physical extremes.

Solar radiation and clear-sky solar radiation are equal on cloud-free days. Quality control of R_s was performed by plotting R_s and R_{so} over time. R_{so} was calculated using the ASCE methodology (Equation 3-10) as well as a more detailed procedure described below (Allen et al. 2005).

$$R_{so} = (K_B + K_D) \cdot R_a \tag{3-17}$$

$$K_B = 0.98 \exp\left[\frac{-0.00146P}{K_t \sin\beta} - 0.075\left(\frac{W}{\sin\beta}\right)^{0.4}\right] \tag{3-18}$$

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{3-19}$$

$$W = 0.14 \cdot e_a \cdot P + 2.1 \tag{3-20}$$

$$\sin\beta = \sin\left[0.85 + 0.3\varphi \sin\left(\frac{2\pi}{365}J - 1.39\right) - 0.42\varphi^2\right] \tag{3-21}$$

$$K_D = 0.35 - 0.36 \cdot K_B \quad \text{for } K_B \geq 0.15 \tag{3-22}$$

$$K_D = 0.18 + 0.82 \cdot K_B \quad \text{for } K_B < 0.15 \tag{3-23}$$

K_B = clearness index for direct beam radiation
K_D = transmissivity index for diffuse radiation
P = atmospheric pressure at the site elevation, kPa
K_t = turbidity coefficient, $0 < K_t \leq 1.0$
W = precipitable water in the atmosphere, mm
β = angle of sun above the horizon, rad

Measured relative humidity should be in the range of 30% to 100% for humid climates (Allen et al. 2005). Relative humidity values less than this range are possible, but it is unreasonable to maintain values less than 30%. It is not possible to have relative humidity values greater than 100% in the physical environment. Daily maximum and minimum values of relative humidity were plotted to verify that the data falls in the acceptable range for a majority of the study period.

Another way to verify that the relative humidity data was collected correctly is to calculate daily dew point temperature and compare to the daily minimum temperature. Dew point temperature is calculated with the following equation (Allen et al. 2005):

$$T_{dew} = \frac{116.91 + 237.3 \cdot \ln(e_a)}{16.78 - \ln(e_a)} \qquad 3\text{-}24$$

T_{dew} = dew point temperature, °C

Dew point temperature and minimum temperature should be approximately the same a majority of the time in humid climates with the exceptions of days with changes in air mass, high winds, or cloudiness at night (Allen et al. 2005).

Air temperature data is most likely to be consistent and of the best quality data. Temperature data can be checked for quality by plotting the daily average calculated from the 24-hour time period and the average of the maximum and minimum temperatures of the same day over time. These averages should be within 3°C unless caused by rainfall events, unusually high wind speeds, or changes in air mass (Allen et al. 2005).

The quality of wind speed data is difficult to assess when duplicate instruments are not used. Ways to determine if the correct data is being reported include plotting daily average wind speed, daily maximum wind speed, and the gust factor. The gust factor is calculated as a ratio of maximum wind speed to average wind speed. If any of these figures exhibit consistently low values (< 1.0 m/s) or gust factor values of 1.0, there is some type of problem with the data (Allen et al. 2005).

Results and Discussion

The nine controllers located at the Gainesville turfgrass plots were installed to determine the variability between controllers of the same brand. These controllers were labeled as replications A, B, and C for each brand of controller. The three controllers located at GCREC were labeled as T1, T2, and T3 for each brand. Table 3-1 contains the treatment codes for each controller and a summary of pertinent information concerning the controller such as location, installation date, and method for obtaining ET_o.

Climatic Data Quality Control

Solar radiation and clear-sky solar radiation should be equal on cloud-free days. Quality control of R_s was performed by plotting R_s and R_{so} against daily timesteps where R_{so} was calculated using the Equation 3-10 as well as Equation 3-17. Both the GCREC and Gainesville locations showed that Equation 3-10 predicted R_{so} fairly well compared to the more detailed calculations of Equation 3-17 (Figure 3-3; Figure 3-4; Figure 3-5).

Both years of FAWN data showed R_s fitting the R_{so} curve in late fall, winter, and spring months (Figure 3-3). The summer and early fall months rarely fit the curve for both years, due to cloudy conditions common in the summer and early fall. The NOAA data from the Gainesville Regional Airport (Figure 3-4) as well as the R_s data from the Gainesville turfgrass plots (Figure 3-5) showed the same trend as the data collected at GCREC in Hillsborough County in that R_s rarely fit the R_{so} curve until late in the fall season.

Daily maximum and minimum values of relative humidity were plotted to verify that the data fell in the acceptable range (30% to 100%) for a majority of the study period. None of the weather stations logged relative humidity values greater than 100%. The GCREC weather station measured minimum values above 30% most of the time except from mid-January through May for both years (Figure 3-6). These months are considered part of the dry season in Florida;

arid conditions could result in lower values of relative humidity as long as it never falls below the range of 5% to 10%. The minimum relative humidity at this location was 15% and values dropped below 20% only 9 times in 23 months showing that the quality of the data is appropriate. Minimum relative humidity data collected from the NOAA station only fell below 30% by 12% over seven years of data and fell below 20% by 2% of the time (Figure 3-7). The Gainesville turfgrass plots weather station also measured minimum relative humidity above 30% for 94% of the time, with only 11 days having minimum RH values below 30% (Figure 3-8).

Dew point temperature was calculated and compared to minimum temperature as another way to verify the relative humidity data. Dew point temperature and minimum temperature should be approximately the same on any particular day for a majority of the time in humid climates. Dew point temperature and minimum temperature were very similar to each other at any of the weather station locations. Data from the FAWN station at the GCREC (Figure 3-9), Gainesville NOAA station (Figure 3-10), and the Gainesville turfgrass plots location (Figure 3-11) fit to a one to one scale best with higher temperatures. Minimum temperatures were slightly higher than dew point temperatures in cooler temperatures for all weather data.

The temperature data was checked for quality by plotting the daily mean calculated from the 24-hour time period and the average of the maximum and minimum temperatures of the same day against each other (Figure 3-12; Figure 3-13). There was very little variation between the two averages for both the GCREC and Gainesville turfgrass plots locations when looking at the figures. These averages should be within 3°C unless caused by rainfall events, unusually high wind speeds, or changes in air mass. Both locations had differences less than 3°C for 100% of the time period. Only maximum and minimum temperature data was available for the

Gainesville Regional Airport weather station. As a result, mean temperature and average temperature could not be compared for this location.

Daily average wind speed, daily maximum wind speed, and the gust factor were plotted to assess wind speed data quality for both locations. The FAWN weather station did not show wind speeds that were consistently low; the average wind speed for the GCREC location was 2.4 m/s (Figure 3-14). The wind speed at the Gainesville location averaged 1.1 m/s (Figure 3-15), much lower than the GCREC location, but wind speeds varied daily and data collection was over a much shorter length of time than the GCREC location. The gust factor, calculated as a ratio of maximum to average wind speed, was not less than 1.0 at either site (Figure 3-16; Figure 3-17). Daily average wind speed data was plotted for the NOAA weather station averaging 1.9 m/s (Figure 3-18).

Standalone Controller

Data collected from the three replicated Weathermatic controllers installed at the Gainesville turfgrass plots was used to calculate ET_o using the Hargreaves equation and the on-site weather station data was used to calculate ET_o using the ASCE standardized ET_o equation and Hargreaves equation. The cumulative ET_o calculated for WM-A, WM-B, and WM-C was 1023 mm, 1021 mm, and 995 mm, respectively (Figure 3-19). These controllers overestimated ET_o by 26% to 29% compared to the ASCE method (791 mm) and by 18% to 22% compared to the Hargreaves method (842 mm). The daily ET_o estimation by the three Weathermatic controllers, averaging 5.4 mm, were not found to be different from each other ($P=0.5674$). However, these controllers were different ($P<0.0001$) from the ASCE method and the Hargreaves method, averaging 4.2 mm and 4.5 mm, respectively (Table 3-2).

The Weathermatic controllers calculated ET_o by the Hargreaves method (Equation 3-16) and was based on two parameters: 1.) R_a determined from manufacturer programmed tables (Ra-

WM) and 2.) daily minimum and maximum temperatures from an on-site weather monitor (T-WM). Both parameters had the potential to create variability in the ET_o estimation. Comparisons made of ET_o calculated from the Hargreaves Method (Equation 3-16) included: temperature reported by the Weathermatic controller and R_a estimated from a table (T-WM, Ra-WM); temperature reported by the Weathermatic controller and R_a determined from on-site weather station data (T-WM, Ra-WS); temperature determined from on-site weather station data and R_a estimated from a table (T-WS, Ra-WM); and temperature and R_a determined from the on-site weather station data (Hargreaves Method). These comparisons showed which of the two parameters, temperature (Table 3-3) or R_a (Table 3-4), caused variability among ET_o estimation. It was determined that there was a difference between ET_o calculated using temperatures from different sources ($P<0.0001$) whereas there was no difference between ET_o calculated using R_a from a table vs. calculated ($P = 0.6007$). Temperature estimation was the critical parameter influencing ET_o estimation by the Hargreaves method.

Cumulative ET_o from the Weathermatic controller (T1) located at the GCREC was compared to ET_o calculated by the ASCE method and Hargreaves method using the FAWN weather station data (Figure 3-20) using the comparisons described above for the Gainesville location. Daily ET_o estimations by the Weathermatic controller averaged 4.7 mm compared to the ASCE method averaging 4.4 mm and were found to be different ($P<0.0001$; Table 3-5). Cumulative ET_o calculated using the ASCE method totaled 2095 mm. ET_o calculated using FAWN data for daily maximum and minimum temperatures (T-FAWN) but different R_a methods were similar to each other, totaling 1986 mm and 2002 mm, an average 5% decrease compared to the ASCE method. Temperature collected by the on-site weather monitor (T-WM) estimated the highest cumulative ET_o, 2239 mm to 2256 mm, overestimating by 7% on average compared to the ASCE method. As was in the Gainesville experiment, daily ET_o calculated using Hargreaves method at the GCREC location was influenced by temperature (P<0.0001; Table 3-6) and not alternative methods of obtaining R_a (P=0.5908; Table 3-7).

Maximum and minimum temperatures collected by the three controllers at the Gainesville turfgrass plots were compared to the on-site weather station (Figs. 3-21; 3-22). According to the figures, maximum temperatures varied from the on-site weather station temperatures while minimum temperatures did not. It was found that the daily maximum temperatures were higher than the weather station data (P<0.0001) whereas the daily minimums were not different (P=0.7798). Also, the three controllers resulted in daily T_{max} and T_{min} values that were not different from each other (Table 3-8).

As was seen at the Gainesville location, temperature impacted the variability of ET_o calculations using Hargreaves method. The daily maximum temperature was typically higher when measured from the Weathermatic on-site weather monitor compared to the FAWN station (Figure 3-23). The maximum temperature measured by the Weathermatic controller was found to be different (P<0.0001) than the FAWN weather data (Table 3-5). The daily minimum temperature data did not show the same variability as the daily maximum temperature data (Figure 3-24). Minimum temperatures were not statistically different (P=0.1425) when comparing the FAWN weather data and the Weathermatic measurements (Table 3-5).

It was shown by Trajkovic (2007) that the Hargreaves equation overpredicts ET_o compared to the ASCE method under humid conditions. Hargreaves equation did cumulatively over-estimate ET_o compared to the ASCE method at the Gainesville turfgrass plots (Figure 3-19). However, this was not the case for the GCREC location. As was described in Chapter 4, there were only two short periods of rainfall in the late summer and early fall months resulting in relatively dry years and unusual arid conditions in Florida. The ET_o was possibly under-estimated from the on-site weather station at the Gainesville turfgrass plots due to lower wind speeds possibly caused from its urban location.

Signal-based Controllers

Cumulative ET_o totaled 713 mm for the replicated Toro controllers at the Gainesville turfgrass plots (Figure 3-25). These controllers overestimated ET_o by 15% compared to 618 mm from the ASCE method using the weather data from the on-site weather station. However, these controllers estimated ET_o at 662 mm or within 4% of the cumulative ET_o calculated from the NOAA weather station, totaling 639 mm, which was a similar value (P=0.8890; Table 3-2). The average daily ET_o estimation by the Toro controllers, 5.2 mm, was different compared to the ASCE method averaging 4.2 mm (P<0.0001), but was not different compared to the NOAA weather station (P=0.9999).

According to Hydropoint Data Systems, Inc., the chosen location for these controllers set by their company was different from the actual location, putting the controllers in a different microzone. The microzone error was corrected on November 28, 2007; hence the entire treatment period was affected by this error. As a result, the ET_o estimation by these controllers could have affected the data. However, Hydropoint Data Systems representatives indicated that the change in microzones would result in a minor influence on the ET_o data.

The FAWN weather station located at the GCREC is on-site and the data are publically available. Cumulative ET_o for the Toro controller at this location, totaling 2017 mm, was within 1% of the FAWN data using the ASCE method (Table 3-9). Daily ET_o estimations averaged 4.3 mm for the Toro controller and 4.4 mm for the ASCE method and were not different (P=0.1555; Table 3-2).

There were no variations between the three replications of the ET Water controllers at the Gainesville turfgrass plots, so the mean ET_o of the three controllers was equal to the ET_o used by all three controllers. ET Water provided a seven day summed ET_o value via their website. ET_o calculated from the on-site weather station data as well as the NOAA weather station was also summed into seven day totals for comparison purposes.

The ET Water controllers at the Gainesville turfgrass plots resulted in 733 mm of cumulative weekly ET_o (Figure 3-26), over-estimating by 6% compared to the ET_o calculated from the on-site weather station (693 mm). The average weekly ET_o (Table 3-10) for the ET Water controllers was not different ($P<0.1470$) compared to the average weekly ET_o calculated from the on-site weather station data. However, the average weekly ET_o for the ET Water controllers was different compared to the NOAA weather station data ($P<0.0001$). The ET Water controller located at the GCREC underestimated ET_o by 12%, calculating 1664 mm compared to 1900 mm of the ASCE method (Table 3-9).

The ET Water controller at the GCREC under-estimated average daily ET_o compared to the FAWN weather station (Table 3-2). When compared directly, there were differences between the estimations ($P<0.0001$).

Overall Comparisons

Since the Weathermatic and Toro replications located at the Gainesville turfgrass plots were not statistically different, the replicates of both brands were averaged and expressed as one value for comparison between types of controllers. Both the Weathermatic and the Toro overestimated ET_o compared to the ASCE method by 24% and 16%, respectively. Also, the Weathermatic overestimated ET_o by 7% compared to the Toro controller (Figure 3-27). Also, the daily ET_o (Table 3-2) calculated for the Weathermatic (5.4 mm) and Toro (5.2 mm) controllers were considered different ($P<0.0001$) compared to the ASCE method (4.2 mm) as well as each other ($P<0.0001$).

Daily ET_o values for the Weathermatic and Toro controllers were summed into rolling seven day totals for comparison with the ET Water controller as well as the ASCE method (Figure 3-28). When one day of data was not recorded, the rolling seven day totals for the Weathermatic and Toro controllers could not be calculated for seven days. This caused many gaps in the data; only approximately eight cumulative ET_o data points could be calculated for all treatments. The Weathermatic controller consistently calculated higher estimated ET_o. The Toro controller calculated similar cumulative weekly ET_o compared to the NOAA weather station. Also, the ET Water controller calculated cumulative weekly ET_o similarly to the on-site data using the ASCE method.

Direct comparisons of cumulative ET_o were made between the three brands of controllers at the GCREC location when compared during time periods of available data from every controller (Figure 3-29). The Weathermatic controller, T1, overestimated cumulative ET_o by 3% (1601 mm) compared to the estimation of 1548 mm using the ASCE method and FAWN weather data for this time period. ET_o calculated by T2, the Toro controller, totaled 1545 mm; there was no cumulative difference in ET_o when compared to the ASCE method over the study period. The ET Water controller, T3, calculated 1334 mm of ET_o, 14% less than the ASCE method.

Daily ET_o calculated by each treatment was found to be different from each other (Table 3-5). ET Water was different from all other treatments ($P<0.0001$) and the Weathermatic was statistically different from the Toro ($P=0.0001$) and the ASCE method ($P=0.0001$).

Summary and Conclusions

Weather data collected from all three locations (the GCREC FAWN weather station, the NOAA weather station, and the Gainesville turfgrass plots) were quality checked according to standardized recommendations. It was determined that solar radiation, temperature, relative humidity, and wind speed data met acceptable quality standards. The data was used to calculate ET_o using either the ASCE method (Equation 3-1) or Hargreaves method (Equation 3-16).

When analyzing daily ET_o estimations using different temperature and Ra sources, it was determined that temperature was a driving factor in the Hargreaves method whereas the method was not affected by the source of R_a. Statistical analysis of the temperatures collected from the Weathermatic compared to the local weather station (FAWN for GCREC and on-site for Gainesville turfgrass plots) showed that there are differences in maximum temperature measurements where the Weathermatic values were higher and not minimum temperature measurements. However, maximum and minimum temperatures were not significantly different among the replicated Weathermatic controllers. Thus the temperature sensor performance of the Weathermatic controller had a substantial impact on ET_o estimation.

Within the replications, controllers of all brands did not result in different daily ET_o estimations. Also, the trends observed by the controllers at both locations were similar. Therefore, the replications installed at the Gainesville turfgrass plots for each brand of controller increased the validity of the results from the controllers located at the GCREC. The Toro controller at the GCREC estimated cumulative ET_o approximately equal to the cumulative ETo calculated using the on-site FAWN weather station data over a 16-month period. The ET Water controller, on the other hand, underestimated ET_o by 12% compared to the same weather station and time period. This trend was also seen at the Gainesville turfgrass plots. The NOAA weather station located at the Gainesville Regional Airport was the closest public weather station to the

Gainesville project site. The Toro controller was within 4% of the cumulative ET_o calculated from the NOAA weather station data; whereas, the ET Water controller under-estimated cumulative ET_o by 8%. Data collection period for these controllers occurred over 7 months.

Despite being able to accurately estimate ET_o at the closest weather station, the Toro controller over-estimated ET_o compared to the ET_o calculated from the Gainesville turfgrass plots weather station by 15%. The proximity of the weather station to the controller location is an important factor in determining the representativeness of ET_o at the controller location. The ET Water controller resulted in similar ET_o estimates as the Gainesville Airport, the closest publically available weather data to the research site.

The Toro controllers at the Gainesville location were receiving ET_o calculated for a location that was 1 km North and 1 km East away from the actual location of the controllers. It is highly probable that the publically available weather data used to calculate ET_o was still from the Gainesville Regional Airport weather station because the Airport is also northeast from the Gainesville turfgrass plots.

When comparing ET_o estimated by all brands, it was determined that they were all different from each other. The Weathermatic and ET Water controllers over-estimated and under-estimated ET_o, respectively, compared to the ASCE method whereas the Toro controller was not statistically different from the ET_o estimated from public weather stations at all locations. The trend in ETo when looking at daily and cumulative estimations was the same for the GCREC location (Table 3-7; 3-9). The Weathermatic controller consistently over-estimated ET_o while the ET Water controller consistently under-estimated ET_o. The Toro controller was not different in daily ET_o estimations and was within 1% for cumulative comparisons.

Table 3-1. ET controller codes and experimental information

Code	Controller	Rep[1]	Location	Installation Date	ET_o Equation	Method to Obtain ET_o
WM-A	Weathermatic	1	Gainesville	May 2007	3-16[2]	Standalone
WM-B	Weathermatic	2	Gainesville	May 2007	3-16	Standalone
WM-C	Weathermatic	3	Gainesville	May 2007	3-16	Standalone
T-A	Toro	1	Gainesville	May 2007	3-1[3]	Signal-based
T-B	Toro	2	Gainesville	May 2007	3-1	Signal-based
T-C	Toro	3	Gainesville	May 2007	3-1	Signal-based
ETW-A	ET Water	1	Gainesville	May 2007	3-1	Signal-based
ETW-B	ET Water	2	Gainesville	May 2007	3-1	Signal-based
ETW-C	ET Water	3	Gainesville	May 2007	3-1	Signal-based
T1	Weathermatic	NA[4]	GCREC	May 2006	3-16	Standalone
T2	Toro	NA	GCREC	Aug 2006	3-1	Signal-based
T3	ET Water	NA	GCREC	Aug 2006	3-1	Signal-based

[1]Rep refers to replication defined as multiple controllers at the same location. [2]Equation 3-16 was used to calculate ET_o using Hargreaves Equation (Hargreaves and Samani 1982). [3]Equation 3-1was used to calculate ET_o using the ASCE standardized equation (Allen et al. 2005). [4]NA indicates that there are no replications of controllers at that location.

Table 3-2. Daily ET_o between treatments at the Gainesville turfgrass plots

Treatment	n	ET_o (mm)
Weathermatic	558	5.4 *a*
Toro	414	5.2 *b*
NOAA ASCE Method	162	5.2 *b*
Hargreaves Method	192	4.5 *c*
On-site ASCE Method	192	4.2 *d*

* Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. **Time was used as a replication in the statistical analysis.

Table 3-3. Dependency on temperature using mean daily ET_o values for the Weathermatic controller replications at the Gainesville turfgrass plots

Treatment	Data Origination	ET_o (mm)
WM-A	Weather Monitor	5.44 *a*
WM-B	Weather Monitor	5.43 *a*
WM-C	Weather Monitor	5.30 *a*
Hargreaves Method	Weather Station	4.53 *b*

*Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. **Time was used as a replication in the statistical analysis.

Table 3-4. Dependency on R_a using mean daily ET_o values for the Weathermatic controller replications at the Gainesville turfgrass plots

Treatment	Data Origination	ET_o (mm)
WM-A	Weather Monitor	5.01 *a*
WM-B	Weather Monitor	5.01 *a*
WM-C	Weather Monitor	4.94 *a*
Hargreaves Method	Weather Station	4.96 *a*

*Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. **Time was used as a replication in the statistical analysis.

Table 3-5. Average daily ET_o, maximum temperature, and minimum temperature between treatments at the GCREC location

Treatment	N	ET_o (mm)	T_{max} (°C)	T_{min} (°C)
T1	487	4.7 *a*	29.7 *a*	16.2 *a*
T2	467	4.3 *b*	NA	NA
T3	439	3.7 *c*	NA	NA
ASCE Method	552	4.4 *b*	28.1 *b*	17.0 *a*

* NA indicates that data collection of this parameter was not applicable for the controller. ** Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. ***Time was used as a replication in the statistical analysis.

Table 3-6. Dependency on temperature using mean daily ET_o values for the Weathermatic controller replications at the GCREC

Treatment	Data Origination	ET_o (mm)
T1	Weather Monitor	4.64 *a*
Hargreaves Method	Weather Station	4.12 *b*

*Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. **Time was used as a replication in the statistical analysis.

Table 3-7. Dependency on R_a using mean daily ET_o values for the Weathermatic controller replications at the GCREC

Treatment	Data Origination	ET_o (mm)
T1	Weather Monitor	4.40 *a*
Hargreaves Method	Weather Station	4.36 *a*

*Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. **Time was used as a replication in the statistical analysis.

Table 3-8. Minimum and maximum temperatures between the Weathermatic controllers and the on-site weather station at the Gainesville turfgrass plots

Treatment	n	T_{max} (°C)	T_{min} (°C)
WM-A	186	33.7 *a*	19.5 *a*
WM-B	187	33.8 *a*	19.9 *a*
WM-C	187	33.2 *a*	19.7 *a*
Measured Temperature	192	30.2 *b*	19.6 *a*

* Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. **Time was used as a replication in the statistical analysis.

Table 3-9. Totals and percentage differences of average cumulative ET_o between treatments at the GCREC location and the measured ET_o from the FAWN weather station

Treatment	TMT ET_o (mm)	ASCE Method (mm)	Difference (%)
T1	2256	2095	8
T2	2017	1990	1
T3	1664	1900	-12

* ASCE Method totals vary due to start and end dates of data collection as well as random days of unavailable data within each dataset.

Table 3-10. Weekly ET_o between the ET Water controllers and local weather stations for the Gainesville turfgrass plots location

Treatment	N	ET_o (mm)
ET Water	129	30.5 *a*
On-site Measured	192	29.8 *a*
NOAA Measured	162	36.5 *b*

*Numbers with different letters in columns indicate differences at the 95% confidence level using Duncan's Multiple Range Test. **Time was used as a replication in the statistical analysis.

Figure 3-1. The ET controllers installed on the University of Florida Gainesville Campus. They are A) Toro A, B) Toro B, C) Toro C, D) Weathermatic A, E) Weathermatic B, F) Weathermatic C, G) ET Water A, H) ET Water B, and I) ET Water C.

Figure 3-2. Weathermatic SLW10 weather monitors were installed 1.83 m above ground level and 0.81 m apart for A.) Weathermatic A, B.) Weathermatic B, and C.) Weathermatic C.

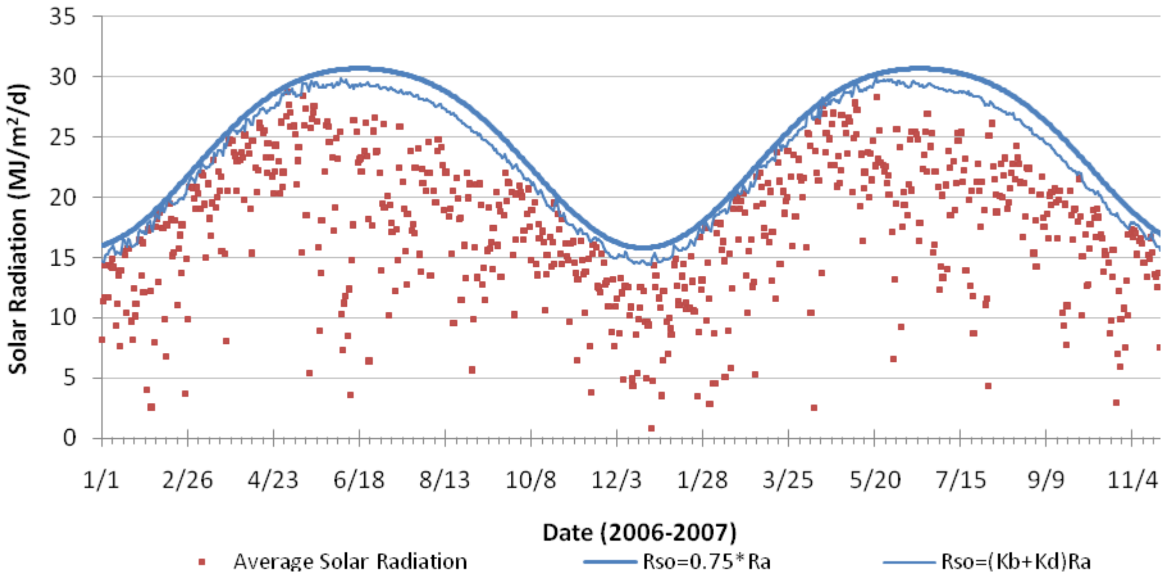

Figure 3-3. The FAWN measured solar radiation (R_s) and clear-sky solar radiation (R_{so}) for 2006 and 2007 using the weather station in Balm, FL.

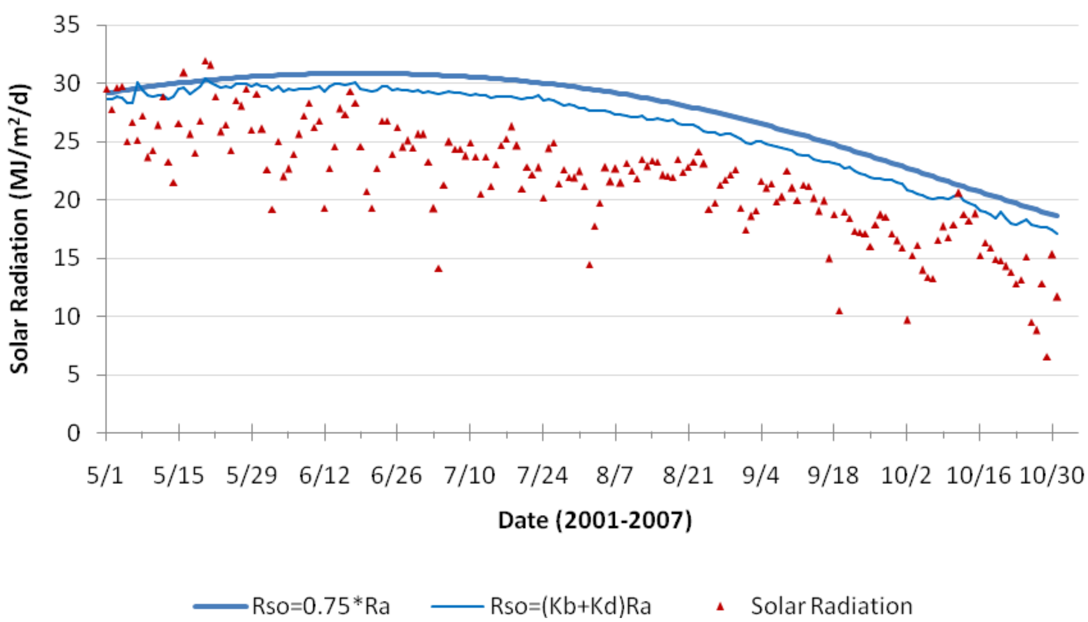

Figure 3-4. Data from the NOAA weather station in Gainesville, FL was used to calculate solar radiation ($R_s = K_{rs} \cdot R_a \sqrt{T_{max} - T_{min}}$) and clear-sky solar radiation (R_{so}) from May through October 2007.

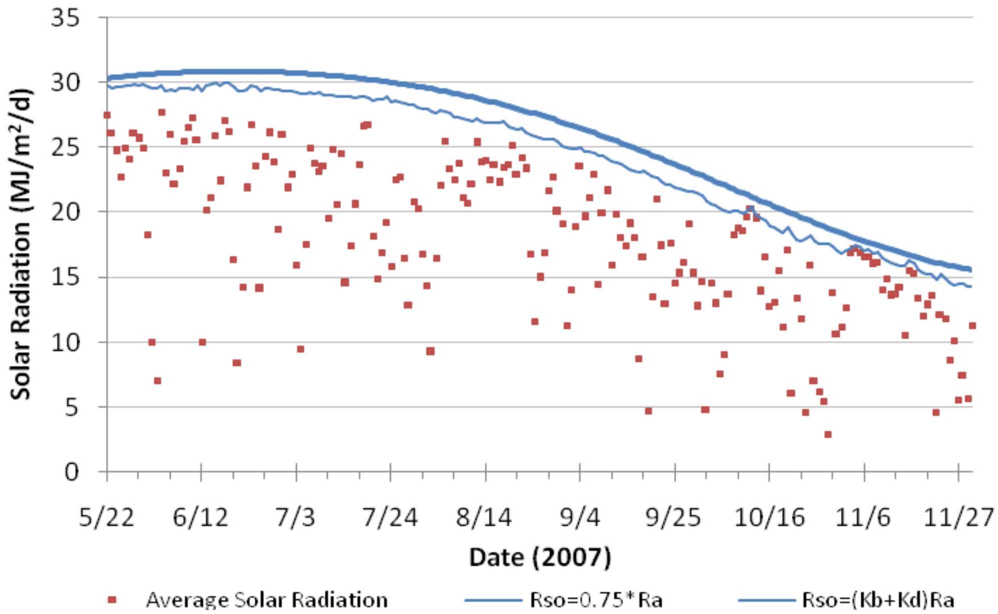

Figure 3-5. Measured solar radiation and clear-sky solar radiation from May 22 to November 30, 2007 for the on-site weather station in Gainesville, FL.

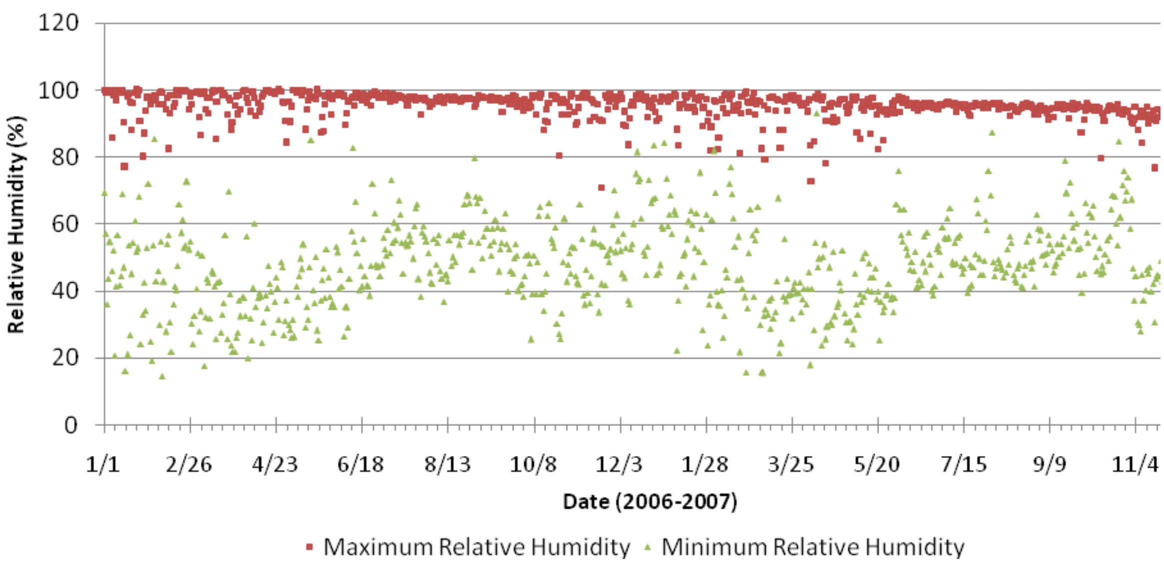

Figure 3-6. The FAWN daily maximum and minimum relative humidity for 2006 and 2007 using the weather station located in Balm, FL.

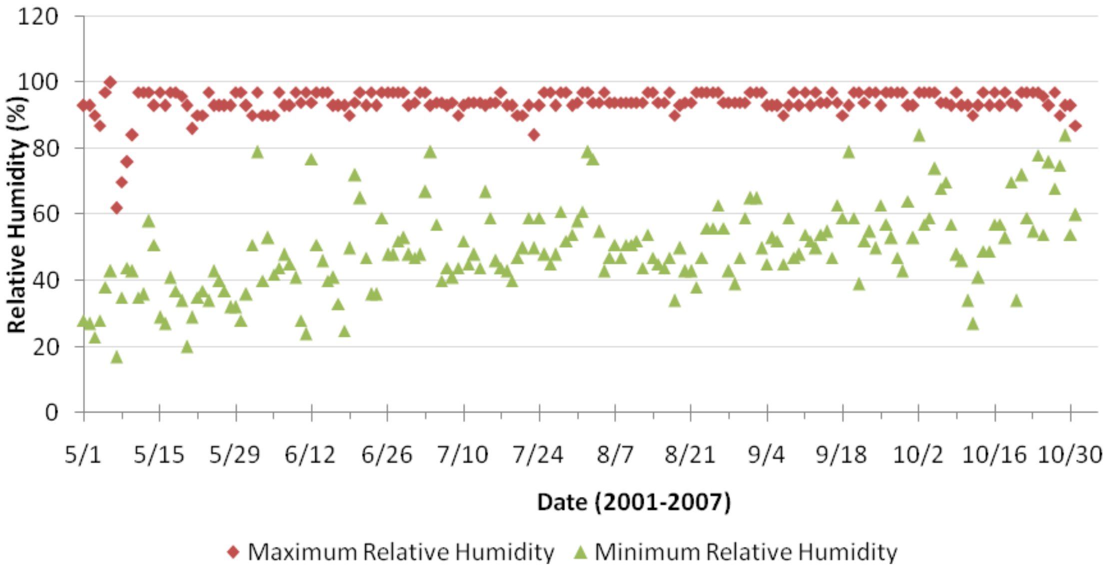

Figure 3-7. The data from the NOAA weather station located in Gainesville, FL was used for daily maximum and minimum relative humidity from May through October 2007.

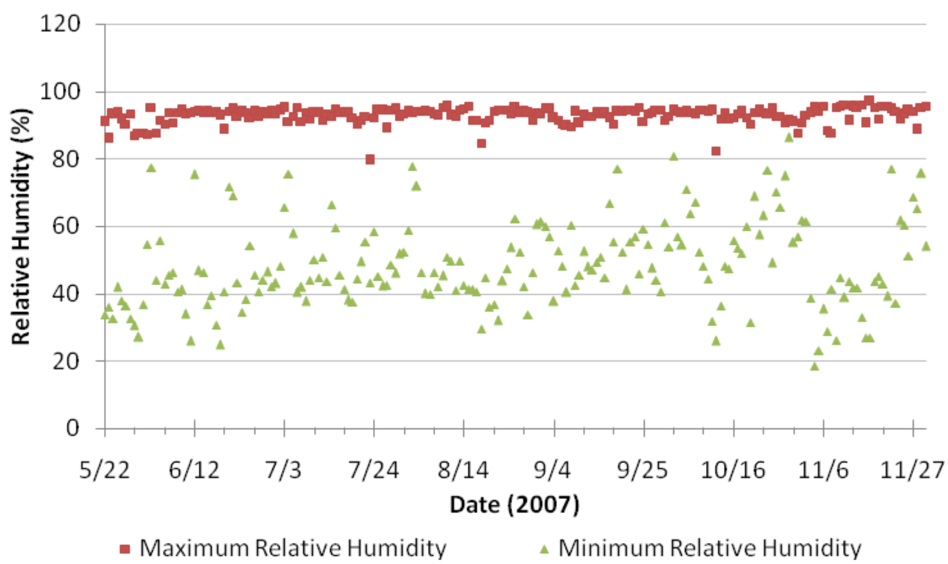

Figure 3-8. Daily maximum and minimum relative humidity for the on-site weather station located in Gainesville, FL from May 22 through November 30, 2007.

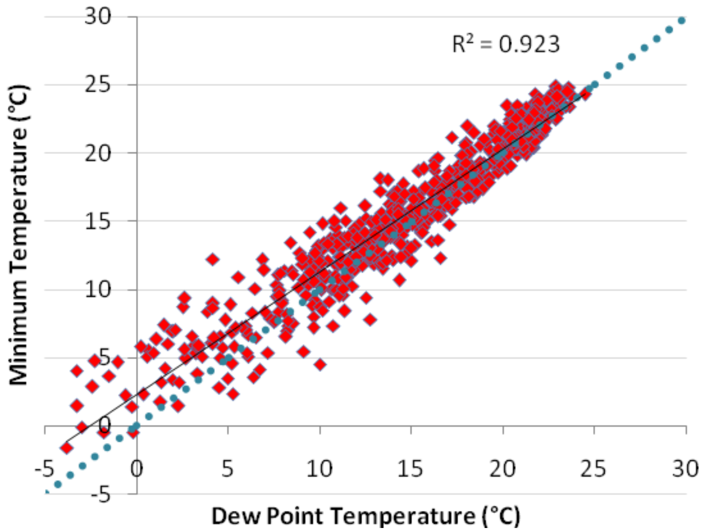

Figure 3-9. The FAWN daily minimum temperature and calculated dew point temperature for 2006 and 2007 using the weather station located in Balm, FL.

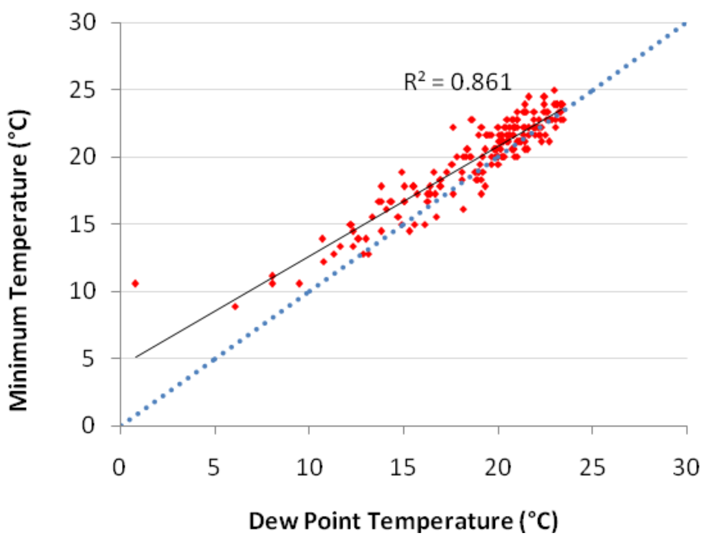

Figure 3-10. The NOAA weather station located in Gainesville, FL was used to obtain daily minimum temperature and calculated dewpoint temperature from May through October 2007.

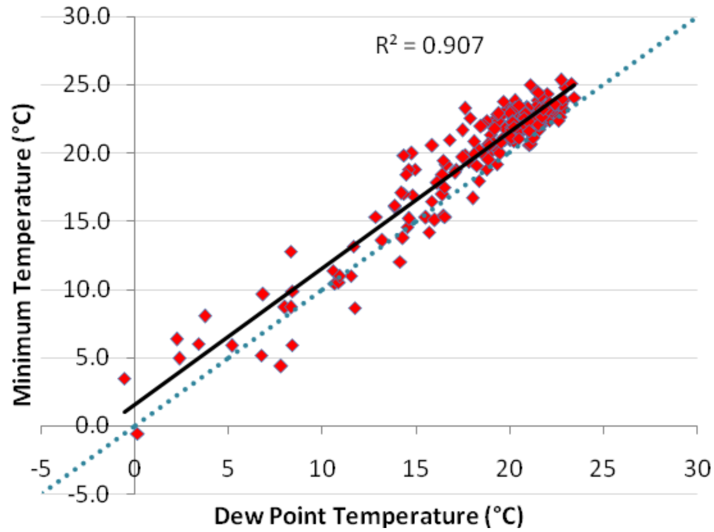

Figure 3-11. Daily minimum temperature and calculated dewpoint temperature for the on-site weather station located in Gainesville, FL from May 22 through November 30, 2007.

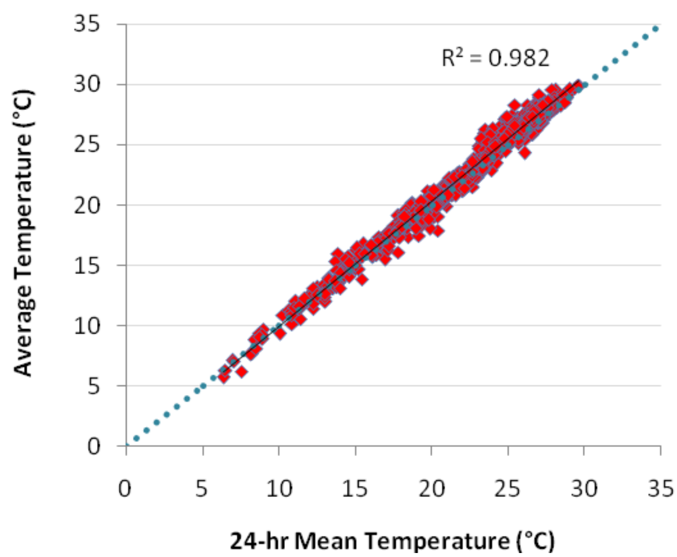

Figure 3-12. The FAWN daily mean temperatures calculated using 24 hours of temperature data plotted against the average of the maximum and minimum temperatures of that day for 2006 and 2007 using the weather station located at Balm, FL.

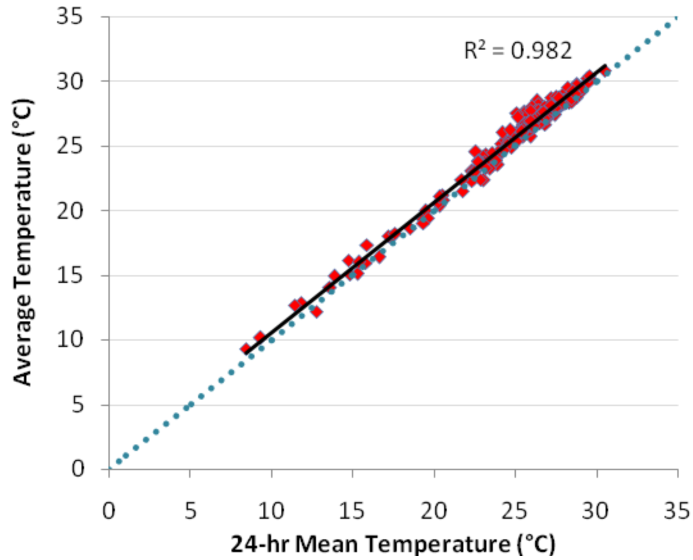

Figure 3-13. Daily mean temperatures calculated using 24 hours of temperature data plotted against the average of the maximum and minimum temperatures of that day for the on-site weather station located in Gainesville, FL from May 22 through November 30, 2007.

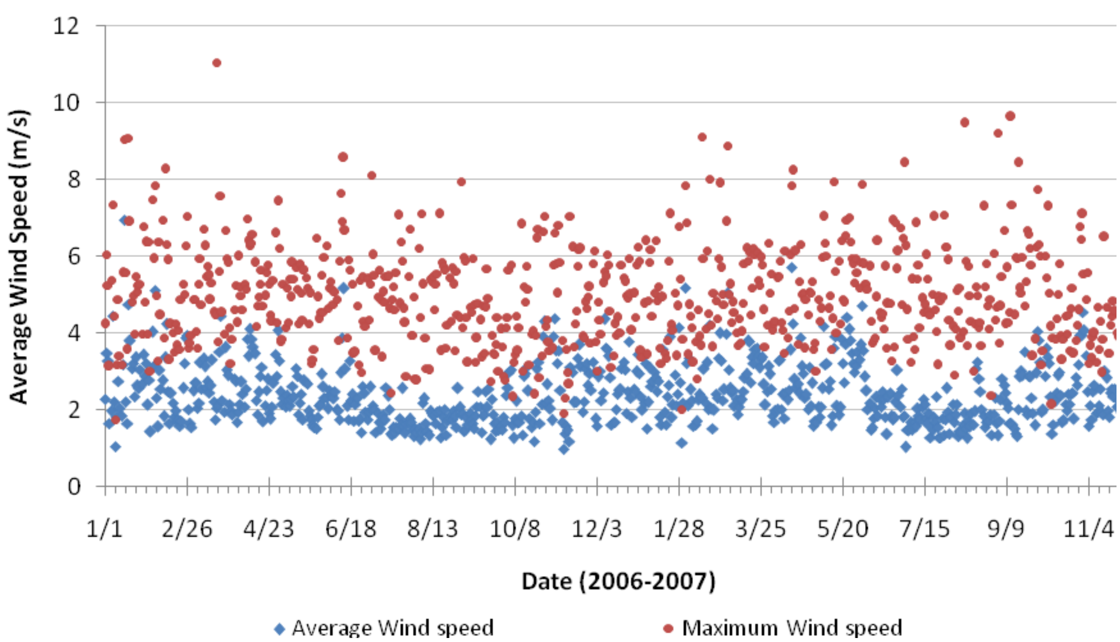

Figure 3-14. The FAWN daily maximum and average wind speed (at 2 m) for 2006 and 2007 using the weather station located at Balm, FL.

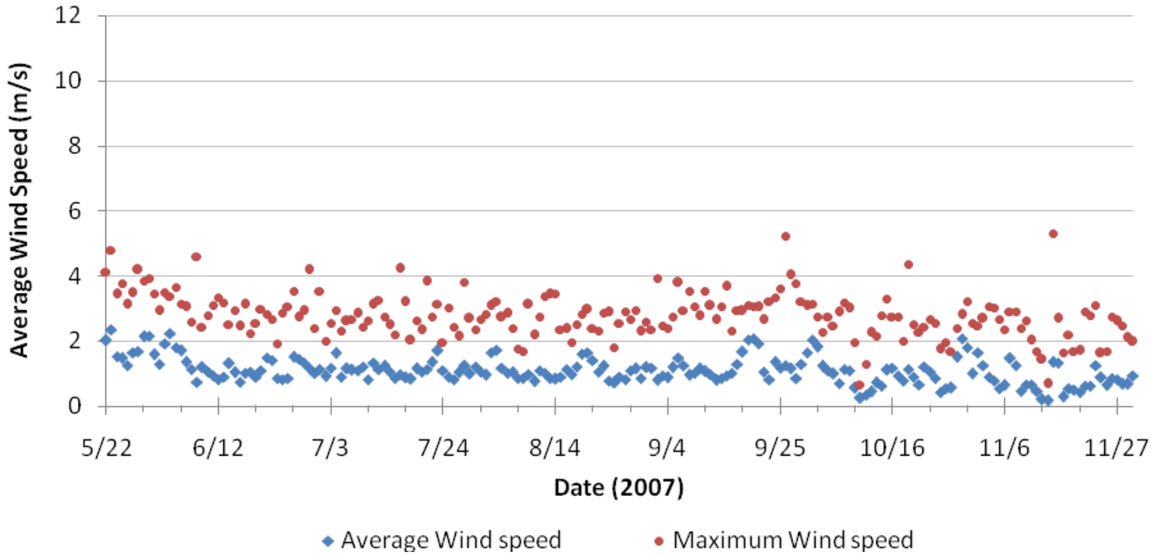

Figure 3-15. Daily maximum and average wind speed (at 2 m) for the on-site weather station located in Gainesville, FL from May 22 through November 30, 2007.

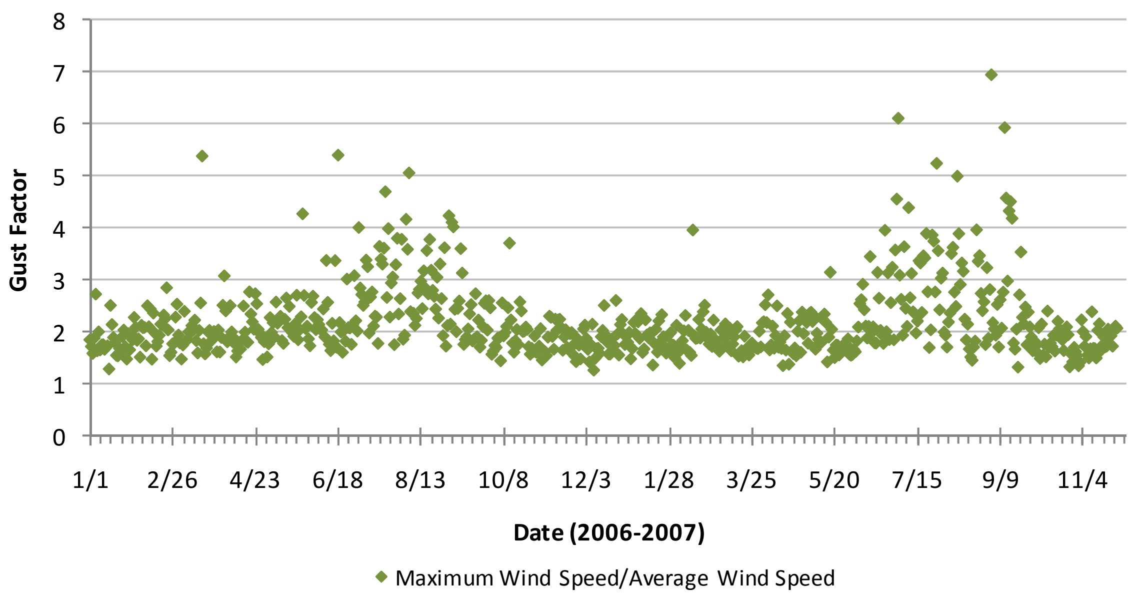

Figure 3-16. The FAWN daily gust factor calculated as the maximum wind speed divided by the average wind speed for 2006 using the weather station located at Balm, FL.

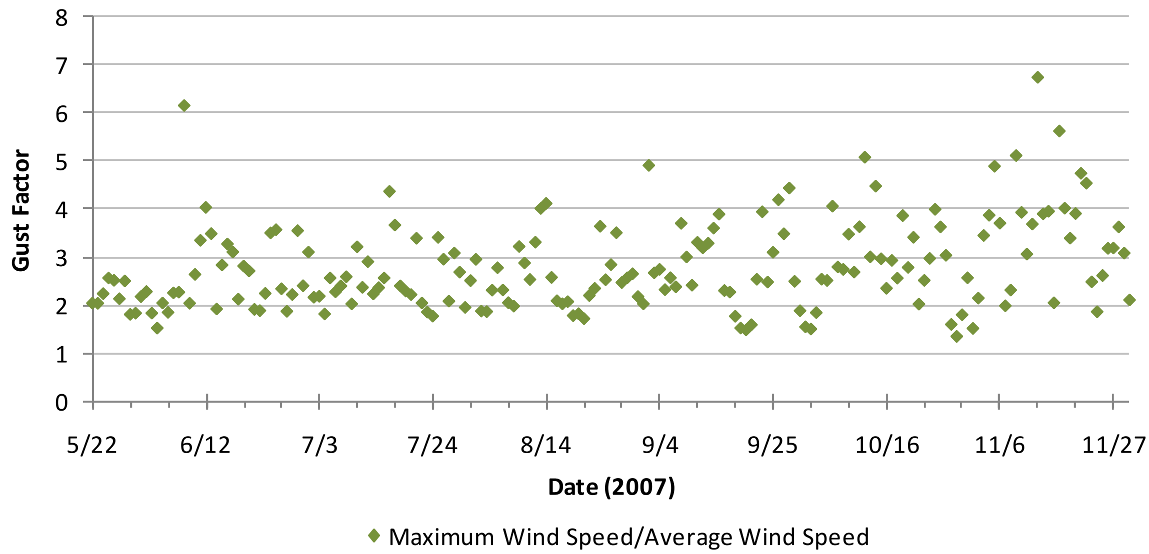

Figure 3-17. Daily gust factor calculated as the maximum wind speed divided by the average wind speed for the on-site weather station located in Gainesville, FL from May 22 through November 30, 2007.

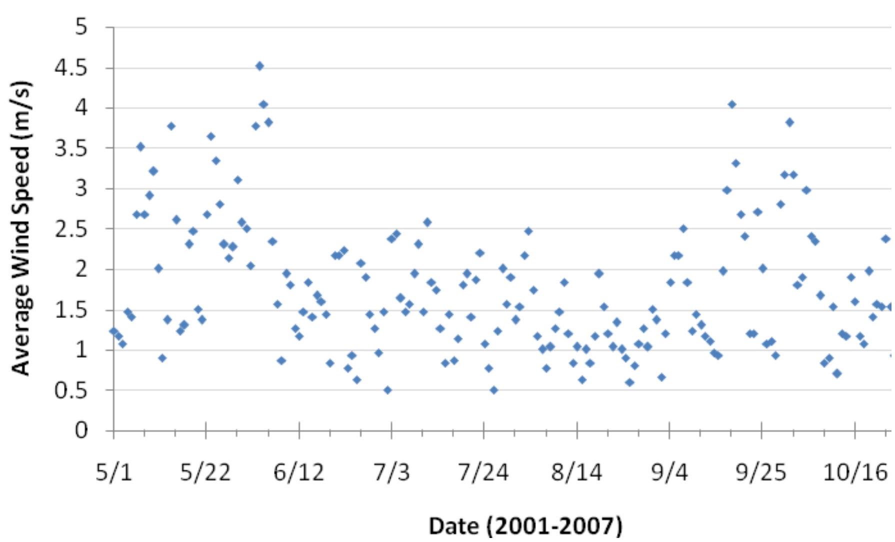

Figure 3-18. The NOAA weather station located in Gainesville, FL was used to obtain daily average wind speed (at 2 m) from May through October 2007.

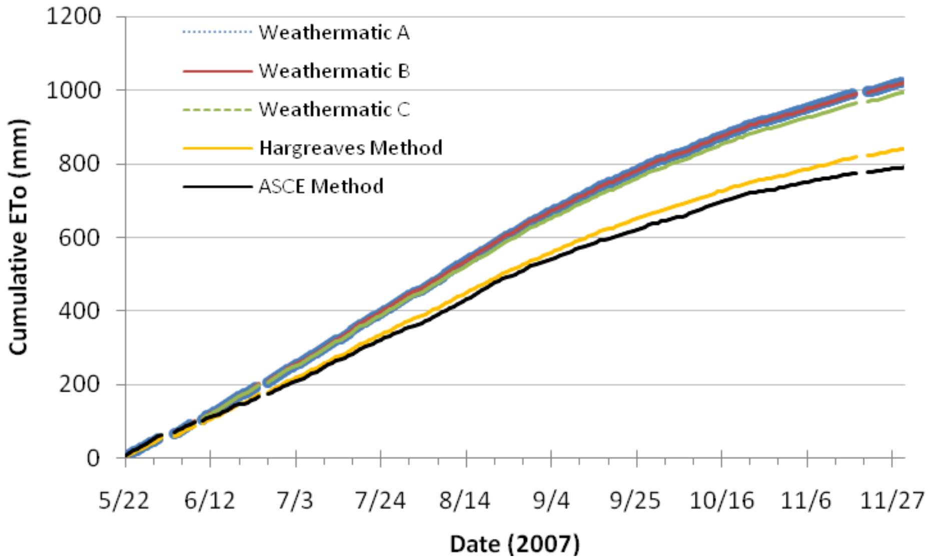

Figure 3-19. Cumulative ET_o for three replications of Weathermatic controllers compared to Hargreaves equation and the ASCE standardized equation using data collected from an on-site weather station in Gainesville, FL.

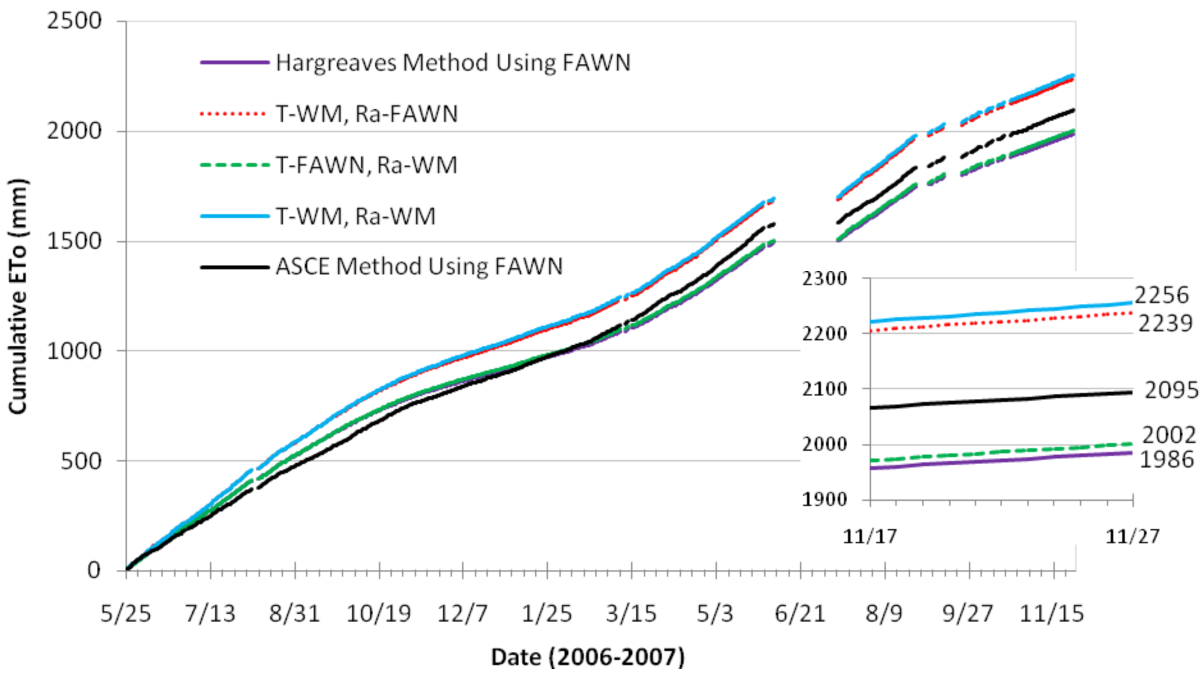

Figure 3-20. Cumulative ET_o calculated from weather data collected by the Weathermatic controller or FAWN weather station. T-WM and R-WM represent values used by the Weathermatic controller, and T-FAWN and Ra-FAWN represent values measured by the FAWN weather station. All ET_o calculations were performed using Hargreaves equation except for ASCE Method using FAWN.

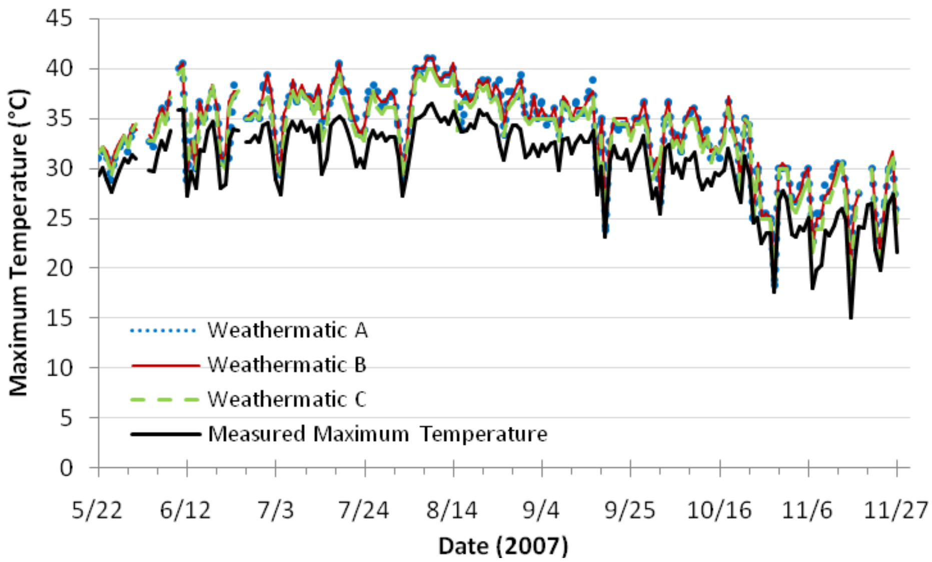

Figure 3-21. Daily maximum temperature comparisons between the three Weathermatic controllers and an on-site weather station in Gainesville, FL.

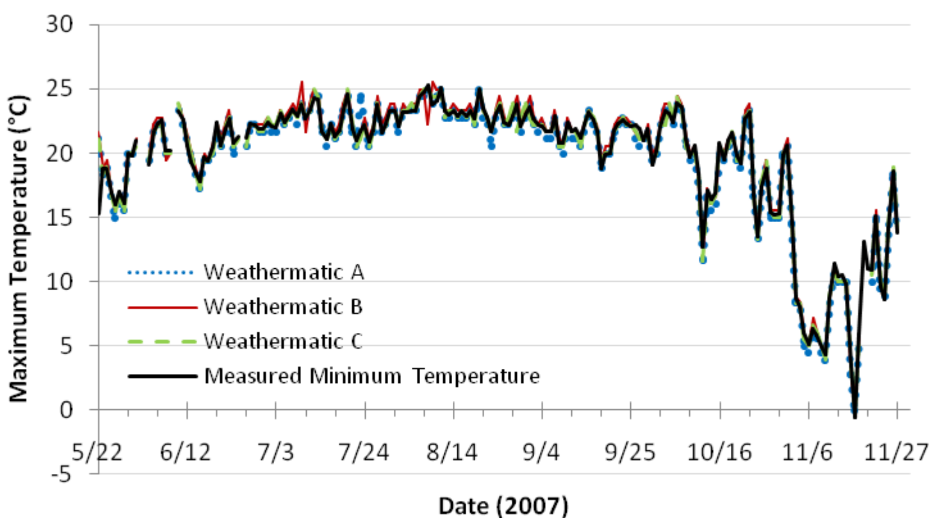

Figure 3-22. Daily minimum temperature comparisons between the three Weathermatic controllers and an on-site weather station in Gainesville, FL.

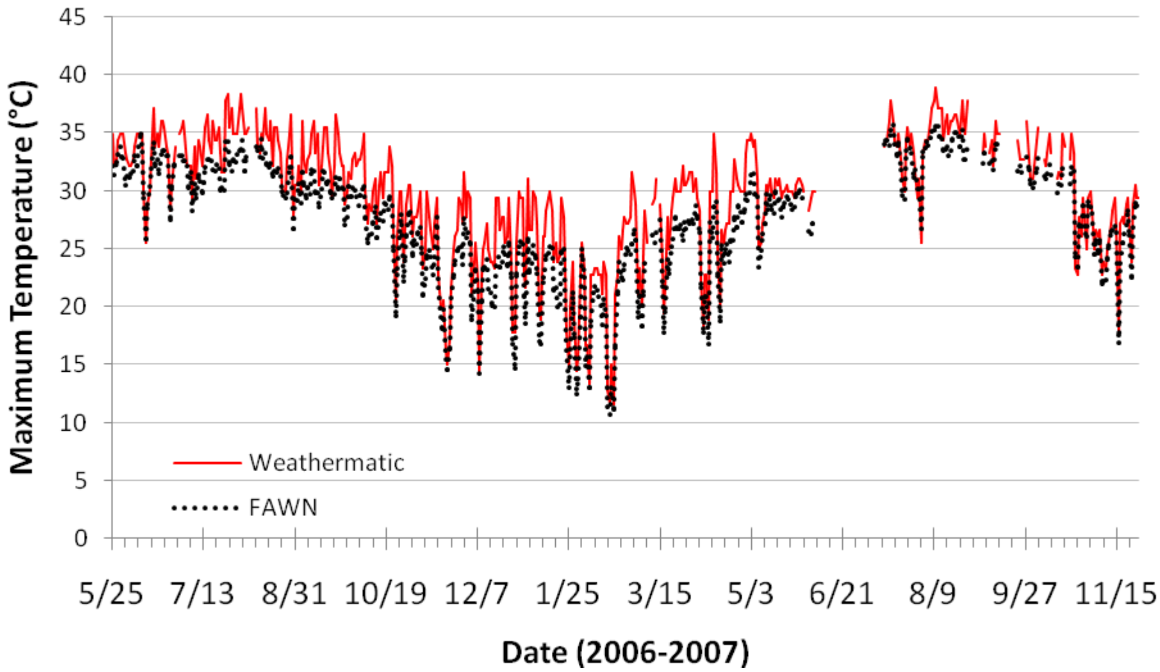

Figure 3-23. Daily maximum temperature comparison from the Weathermatic controller and the FAWN on-site weather station.

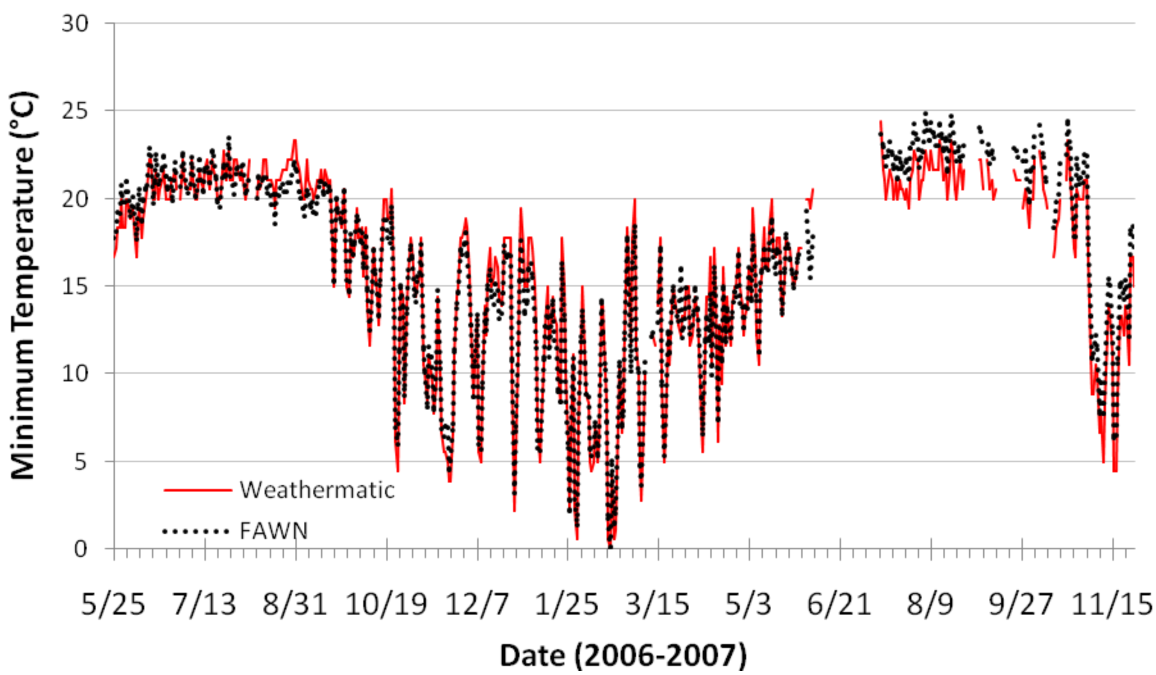

Figure 3-24. Daily minimum temperature comparison from the Weathermatic controller and the FAWN on-site weather station.

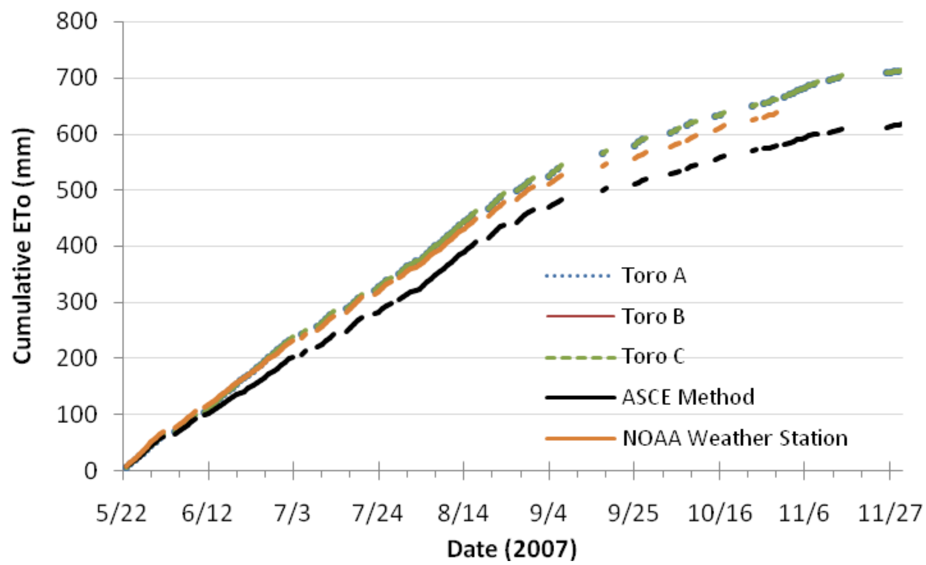

Figure 3-25. Cumulative ET_o for three replications of Toro controllers compared to the ASCE standard using data collected from an on-site weather station and the ASCE standard using the NOAA weather station data in Gainesville, FL.

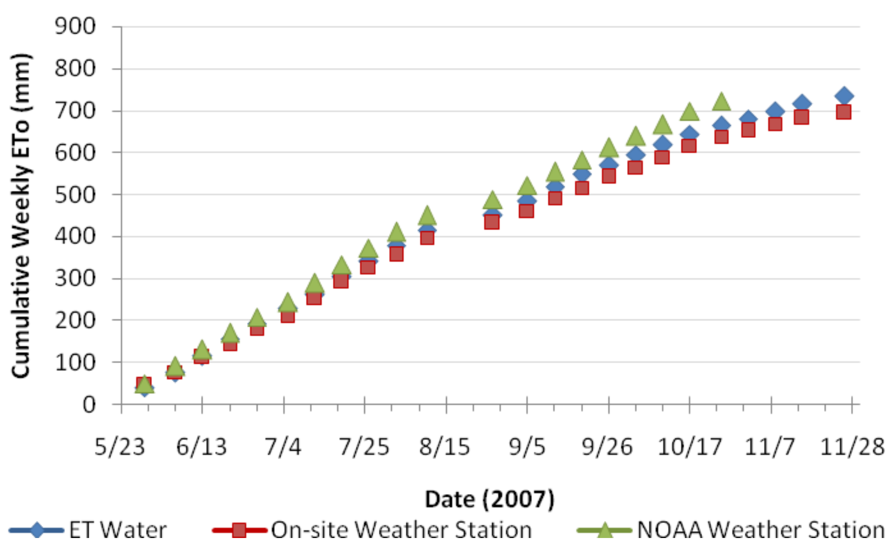

Figure 3-26. Cumulative ET_o for the ET Water controller, calculated using the ASCE method from on-site weather station data, and calculated using the ASCE method from the NOAA weather station data in Gainesville, FL.

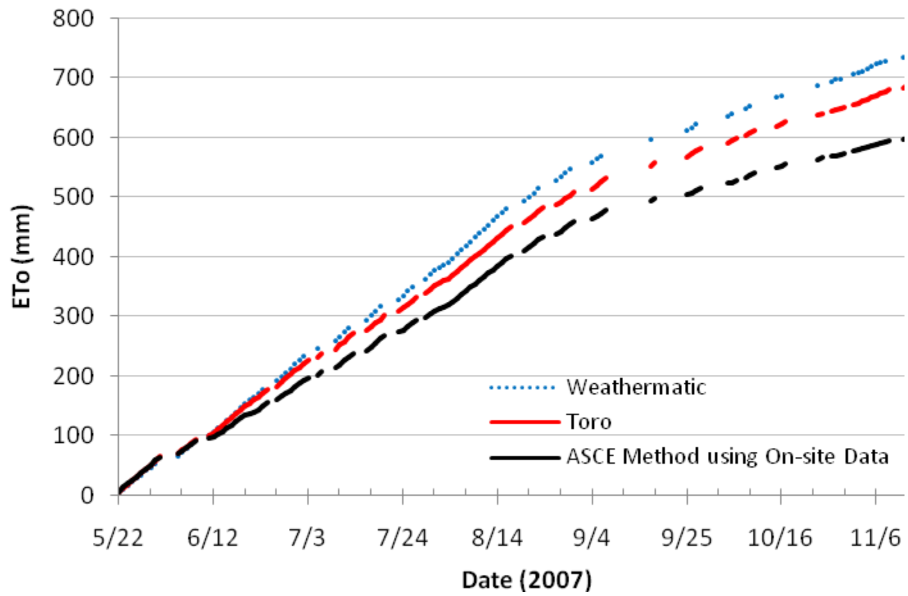

Figure 3-27. Average cumulative daily ET_o for the Weathermatic and Toro controllers compared to the ASCE standard using data collected from an on-site weather station in Gainesville, FL.

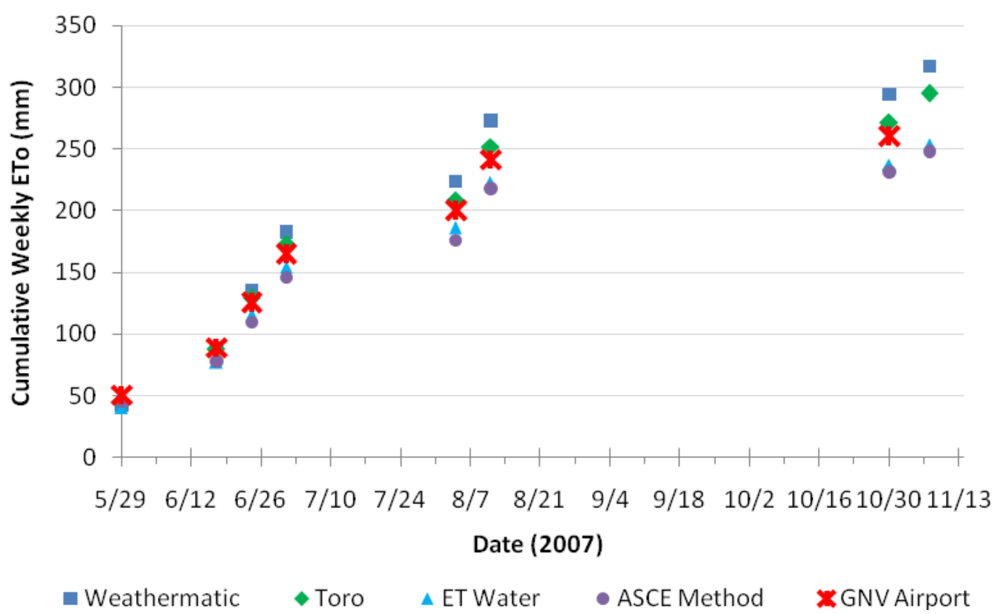

Figure 3-28. Seven day total ET_o shown cumulatively for all three brands of controllers (Weathermatic, Toro, and ET Water) compared to the ASCE method using data from the on-site weather station in Gainesville.

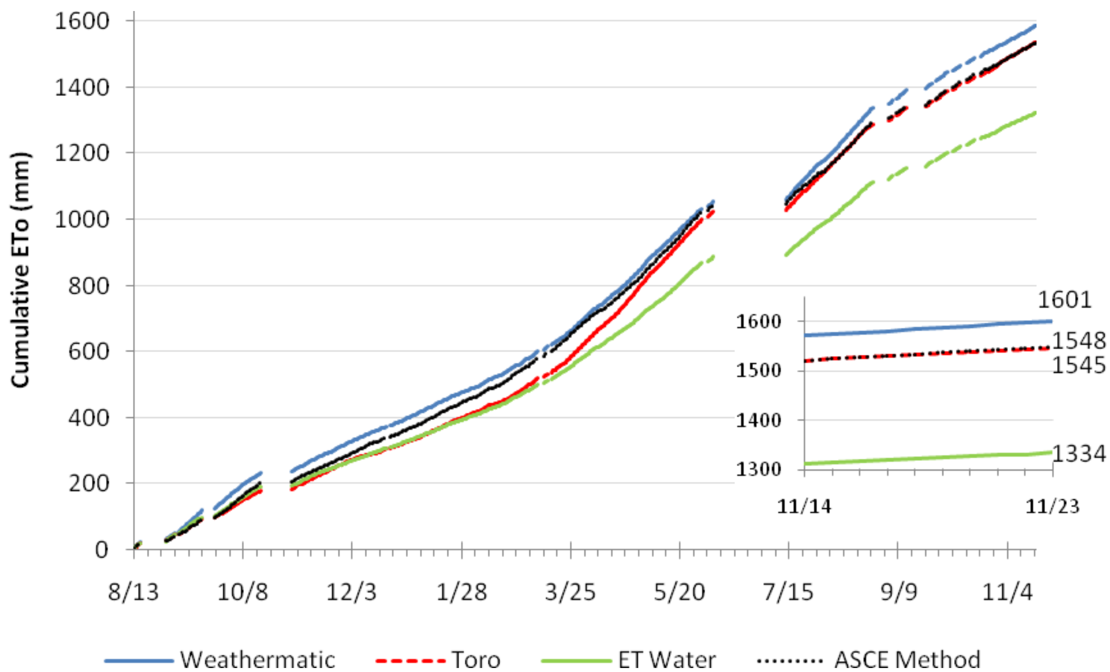

Figure 3-29. Cumulative ET_o for the Weathermatic, Toro, and ET Water controllers at GCREC and calculated using FAWN data and the ASCE method.

CHAPTER 4
IRRIGATION SCHEDULING BY EVAPOTRANSPIRATION-BASED IRRIGATION CONTROLLERS

Introduction

Natural climatic cycles ensure periods of critical drought and improvement in water conservation is necessary since drought is not the criteria for efficient water use (Florida Department of Environmental Protection [FDEP] 2002). Florida continues to grow rapidly and traditional sources of water are limited. Florida has the largest net gain in population with an inflow of approximately 1,108 people per day and fourth in overall population (United States Census Bureau [USCB] 2005). New home construction has increased to accommodate such a large influx of people and most new homes include in-ground automated irrigation systems. However, homes with in-ground systems utilizing automated irrigation timers increase outdoor water use by 47% (Mayer et al. 1999). Proper irrigation management could result in as much as a two-fold reduction in water usage (FDEP 2002). Also, improper irrigation, whether it is under-irrigation or over-irrigation, can negatively impact landscapes as well as waste water resources (Burt et al. 1997).

Irrigation scheduling can be done using quantitative or qualitative methods. The method commonly used by homeowners involves observing the lawn and irrigating when it looks stressed (Wade and Waltz 2004). However, research has shown that single families in Florida over-irrigate their landscapes due to the misunderstanding of seasonal water needs or the inconvenience of updating the irrigation time clock to reflect the actual water needs of the landscape (Haley et al. 2007). Alternatively, the quantitative method measures plant needs from soil moisture levels using instruments such as tensiometers or dielectric probes or evapotranspiration loss (Wade and Waltz 2004).

Evapotranspiration (ET) is defined as the evaporation from a soil surface and the transpiration from plant material (Allen et al. 1998). ET is part of a balanced energy budget that exchanges energy for outgoing water at the surface of the plant. The components of ET are solar radiation, temperature, relative humidity, and wind speed (Allen et al. 2005). Reference ET (ET_o) is defined as the ET from a hypothetical reference crop with the characteristics of an actively growing, well-watered, dense green cool season grass of uniform height (Allen et al. 2005).

Typically, climatic data is used as inputs to equations to estimate ET_o. There are three types of equations: mass transfer, energy balance, and empirical methods (Fangmeier et al. 2006). Most of the current methods employ a combination of the three. The appropriate ET equation is chosen depending on many factors including geographical location, types of crops, and weather data availability (Fangmeier et al. 2006).

Evapotranspiration-based controllers, also known as ET controllers, are irrigation controllers that use ET_o to schedule irrigation. Depending on manufacturer, ET controllers can be programmed with various conditions specific to the landscape making them more efficient (Riley 2005). ET controllers receive ET_o information in three general ways, consequently dividing ET controllers into three main types: 1) standalone controllers, 2) signal-based controllers, and 3) historical-based controllers.

Standalone controllers typically receive climatic data from on-site sensors and calculations to determine ET_o are performed by the controller. Even though the controllers might take readings every second or every fifteen minutes, cumulative daily ET_o is used for irrigation scheduling. On-site sensors could include: temperature, solar radiation, an ET gauge, or even a full weather station (Riley 2005). Benefits of standalone controllers are that they are not limited by requiring the use of a full weather station and there are no signal fees associated with broadcasts from the manufacturer (Riley 2005).

Signal-based controllers receive ET_o information from a company that collects climatic data from weather stations located near the irrigation site using satellite or internet technology. Depending on the manufacturer, the ET_o data can be from an average of multiple weather stations in the area or from a single weather station. There is typically a signal fee (i.e., subscription) for this controller set by the manufacturer that normally ranges from \$4 to \$15 per month (Riley 2005).

Historical-based controllers rely on historical ET_o information for the area. Typically, monthly historical ET_o is programmed into the controller by the manufacturer or installing contractor. Theoretically, this method does not result in as accurate an ET_o estimate because site specific weather variability is not considered.

Bench testing or virtual studies have been conducted where results were determined from whether the controllers would have accurately irrigated based on scheduling and ET_o estimation. The Metropolitan Water District of Southern California conducted a year-long bench test in 2002 designed to compare the ability of ET controllers to determine theoretical water needs for three types of landscapes: cool season turf on loam with full sun, shaded annuals on sandy soils, and low water using ground cover on a sunny, 20 degree slope. The WeatherTRAK enabled controller always applied less water than the maximum allowable water allowance resulting in no overwatering. This controller performed the water balance sufficiently so that water received equals water required except for the summer months where the controller showed a deficit in irrigation. Percent soil moisture depletion for all scenarios except for the sloped one, where over-irrigation occurred, fell within a 30%-70% target range and minimized runoff (Metropolitan

Water District of Southern California [MWDSC] 2004). A virtual study was conducted in 2003, also using a WeatherTRAK enabled controller, designed to determine the data used by the controllers, ease of setup and operation, and how accurate they were at matching irrigation needs to five types of landscapes consisting of turfgrass, trees/shrubs, annuals, mixed high water use plants, and mixed low water use plants. Irrigation equaled the turfgrass requirements in April and October only; over-irrigation was 21-40% in March, June, and July, over 40% in November, and 11-20% for the rest of the year. It was concluded that poor results were due to very general controller settings including using default uniformity and precipitation rates (Pittenger et al. 2004).

Smart Water Application Technologies (SWAT) is a subset of the Irrigation Association that developed a protocol for determining the effectiveness of irrigation scheduling by ET controllers. The protocol was designed to measure the ability of ET controllers to schedule irrigation that is adequate and efficient while minimizing run-off. Adequacy is a measure of under-irrigation and scheduling efficiency is a measure of over-irrigation determined from a soil water balance model. Testing must meet the requirements of 30 consecutive days of testing with 10.2 mm of total rainfall and 63.5 mm of ET_o (Irrigation Association [IA] 2006c).

The objective is to determine the capability of three brands of ET-based irrigation controllers to schedule irrigation compared to a theoretically derived soil water balance model.

Materials and Methods

This study was conducted at the University of Florida Gulf Coast Research and Education Center (GCREC) in Wimauma, Florida (see Chapter, Figure 2-1). There were a total of twenty plots that measured 7.62 m x 12.2 m, bordered by a 15.2 cm tall black metal barrier, with 3.05 m buffer zones between adjacent plots (see Chapter, Figure 2-3). The buffer zones were covered with a white material that acted as a weed barrier. Each plot consisted of 65% St.

Augustinegrass (*Stenotaphrum secundatum* 'Floratam') and 35% mixed ornamentals to represent a typical residential landscape in Florida. The ornamentals were as follows: Crape Myrtle (*Lagerstroemia indica* 'Natchez') (see Chapter, Figure 2-4A), Gold Mound Lantana (*Lantana camara* 'Gold Mound') (see Chapter, Figure 2-4B), Indian Hawthorne (*Raphiolepis indica*) (see Chapter, Fig 2-4C), Cape Plumbago (*Plumbago auriculata)* (see Chapter, Figure 2-4D), and Big Blue Liriope (*Liriope muscari* 'Big Blue') (see Chapter, Figure 2-4E). Landscapes were maintained through mowing, pruning, edging, mulching, fertilization, and pest and weed control according to current UF-IFAS recommendations (Black and Ruppert 1998; Sartain 1991).

Five treatments were established, T1 through T5, replicated four times for a total of twenty plots in a completely randomized block design. The irrigation treatments are as follows: T1, SL1600 controller with SLW15 weather monitor (Weathermatic, Inc., Dallas, TX); T2, Intelli-sense (Toro Company, Inc., Riverside, CA) utilizing the WeatherTRAK ET Everywhere service (Hydropoint Datasystems, Inc., Petaluma, CA); T3, Smart Controller 100 (ET Water Systems LCC, Corte Madera, CA); T4, a time-based treatment determined by UF-IFAS recommendations (Dukes and Haman 2002a); and T5, a time-based treatment that is 60% of T4 (see Chapter, Figure 2-5). All treatments utilized Mini-clik rain sensors (Hunter Industries, Inc., San Marcos, CA) set at a 6 mm threshold.

A metal shed housed the controllers on-site and a manifold table supported forty solenoid valve and flow meter combinations to supply and monitor irrigation to each zone of each plot (see Chapter, Fig 2-6). The flow meters (11.4 cm V100 w/ Pulse Output, AMCO Water Metering Systems, Ocala, FL) used to monitor irrigation water application were connected to five SDM-SW8A switch closure input modules (Campbell Scientific, Logan, UT) that in turn connected to a CR-10X data logger (Campbell Scientific, Logan, UT) (see Chapter, Fig 2-7).

The CR-10X data logger monitored switch closures every 18.9 liters from the water meters. The data was also collected manually on a weekly basis at minimum. Each plot contained an irrigation zone for turfgrass and mixed ornamentals.

Irrigation sprinklers specified for the turfgrass portions of the plots consisted of Rain Bird (Glendora, CA) 1806 15 cm pop up spray bodies and Rain Bird R13-18 black rotary nozzles (see Chapter, Figure 2-8). In each plot, there were four sprinklers with a 180 degree arc (R13-18H) and a center sprinkler with a 360 degree arc (R13-18F). Microsprays (Maxijet, Dundee, FL) were installed to irrigate the mixed ornamental plants. A pressure regulator was installed at the plot to maintain a constant pressure of 6 kPa on the microsprays during irrigation.

It was determined that the application rate specified by the manufacturer for the turfgrass plots of 15.5 mm/hr was not the actual rate during the entire treatment period. The application rate was determined to be 20.3 mm/hr on average. As a result, all treatments over-applied irrigation due to calculating a larger runtime for the same theoretical depth to be applied. The measured water application for each treatment was corrected for this error by calculating the runtime specified for each treatment determined from the measured water application totals and then calculating a corrected depth using the new average application rate.

The type of soil located at the project site was mapped as Zolfo fine sand (NRCS 1989). According to the soil survey, the Zolfo series is a somewhat poorly drained soil composed of sandy, siliceous, hyperthermic Grossarenic Entic Haplohumods. The field capacity and permanent wilting point for Zolfo fine sand was determined from laboratory samples to be 13% and 3% (all soil moisture values are presented on a volumetric basis), respectively (Carlisle et al. 1985). Time domain reflectometry (TDR) probes (Campbell Scientific, Inc., Logan, UT) were buried in turfgrass and mixed-ornamental areas of each plot to monitor soil moisture in the root zone represented as 10 cm to 18 cm for St. Augustinegrass and the upper root zone of the mixed ornamentals.

According to the manufacturers (Hydropoint Data Systems, Inc. 2003; ET Water 2005), ET_o was calculated by the Toro and ET Water controllers using the ASCE standardized ET_o equation (Allen et al. 2005). The Weathermatic controller utilized the Hargreaves equation to estimate ET_o (Hargreaves and Samani 1982). The ASCE standardized ET_o equation was used in the soil water balance model for comparison purposes.

Plant-specific ET can be calculated for a plant material by applying a crop coefficient (K_c), using the following equation:

$$ET_c = K_c * ET_o \tag{4-1}$$

K_c values chosen for the theoretical soil water balance model were developed from warm season turfgrass in central Florida (Jia et al. 2007) and were adjusted during the winter months to reflect common weather conditions for southwest Florida (Table 4-1). The Weathermatic controller used a fixed K_c value of 0.60 for each month. K_c values for the Toro and ET Water controllers were considered proprietary information and were not made available.

A daily soil water balance model was used to calculate the theoretical irrigation requirements for comparison with actual irrigation water applied. The balance is defined as:

$$\Delta S = Pe + I - ET_C - D - RO = 0 \tag{4-2}$$

where ΔS (mm) is the change in soil water storage within the root zone, Pe (mm) is the effective rainfall, I (mm) is the irrigation depth, ET_c (mm) is the crop evapotranspiration, D (mm) is drainage, and RO (mm) is surface runoff (Fangmeier et al. 2006). Due to the flat topography and relatively high permeability on site (NRCS 1989), it was assumed that there is negligible surface runoff and irrigation is scheduled so that, ideally, there is negligible drainage. These assumptions reduce equation 4-2 to the equation used to calculate the irrigation depth required:

$$I = ET_c - Pe \qquad \text{4-3}$$

Effective rainfall is the amount of rainfall that is stored in the root zone. The remainder of rainfall is considered runoff or drainage below the root zone. Rainfall causing the soil water content to exceed field capacity in the soil water balance model was assumed to be lost due to runoff or drainage.

The amount of water able to be held by the root zone and is available to the plant is called available water, AW (mm). Available water is calculated from soil parameters using the equation:

$$AW = \frac{(FC - PWP) * RZ}{100} \qquad \text{4-4}$$

where FC (cm^3 of water/cm^3 of soil) is the field capacity, PWP (cm^3 of water/cm^3 of soil) is the permanent wilting point, and RZ (mm) is the root zone depth (Irrigation Association 2005). To prevent plant stress, available water should not be allowed to reach the PWP before irrigation is scheduled; irrigation should be applied when the water level drops by a percentage known as the maximum allowable depletion (MAD), chosen as 50% for warm season turfgrass (Allen et al. 1998). The amount of water allowed to be used before irrigation is required is called readily available water, RAW (mm), and is calculated using the following equation (IA 2005):

$$RAW = AW * MAD \qquad \text{4-5}$$

The net irrigation depth to be applied is determined from the change in soil water level occurring due to ET_C loss and effective rainfall. However, the theoretical gross irrigation depth is necessary to compare to the amount of water applied by the treatments. The gross irrigation depth is calculated from an efficiency factor ultimately determined from the low quarter distribution uniformity (DU_{lq}) of the system (IA 2005). The DU_{lq} was determined to be 0.70 from on-site catch-can testing. The low half distribution uniformity (DU_{lh}) was calculated using DU_{lq} in percentage form as follows:

$$DU_{lh} = 38.6 + 0.614 * DU_{lq} \tag{4-6}$$

which, in turn, is used to calculate the efficiency factor (E) using the equation:

$$E = \frac{100}{DU_{lh}} \tag{4-7}$$

The gross irrigation is calculated by multiplying the net irrigation depth by the efficiency factor, determined from Equation 4-6 and Equation 4-7 to be 1.25 (IA 2005).

Scheduling efficiency was defined as the ability of a controller to schedule irrigation without applying excess irrigation that results in drainage or runoff (IA 2006c). It was calculated in 30-day running totals with the following equation:

$$E = \frac{(I_{net} - \text{Surplus})}{I_{net}} \cdot 100 \tag{4-8}$$

where I_{net} (mm) refers to the sum of net irrigation applied over the 30 days and Surplus (mm) refers to the summed depth of water above the field capacity.

Irrigation adequacy, on the other hand, quantified the ability of the controller to supply sufficient irrigation so that it met the demand for water (IA 2006c). It was also calculated in 30-day running totals using the following equation:

$$A = \frac{(ET_C - \text{Deficit})}{ET_C} \cdot 100 \tag{4-9}$$

where Deficit represents the sum of the depth of water below the maximum allowable depletion over the 30-day period in mm.

Ranges of irrigation adequacy and scheduling efficiency were large when considered over a long period of time. As a result, performance ranges were designated to determine the frequency of certain scores. Designations were as follows: 90% to 100%, 70% to 90%, 50% to 70%, and below 50%.

There were six seasons of data collection: May 25, 2006 through August 12, 2006 as summer 2006; August 13, 2006 through November 30, 2006 as fall 2006; December 1, 2006 through February 26, 2007 as winter 2006-2007; February 27, 2007 through May 31, 2007 as spring 2007; June 1, 2007 through August 31, 2007 as summer 2007; and September 1, 2007 through November 30, 2007 as fall 2007. Applied irrigation depths were compared to depths calculated using a daily soil water balance with inputs similar to user-defined inputs programmed into the controllers for the first three seasons (see Chapter, Table 2-2) and the last three seasons (see Chapter, Table 2-3).

All five treatments observed 2 d/wk watering restrictions during summer 2006, fall 2006, and winter 2006-2007, Wednesday and Saturday, and no watering between 10 am and 4 pm. Also, the ET controller treatments were established based on the site location without accounting for system efficiency. T1, the Weathermatic controller, was set to apply 100% of the calculated water requirement while T2 and T3, the Toro and ET Water controllers, were set to the maximum efficiency of 95%. The monthly irrigation depth for T4, the time-based treatment, was 60% of the net irrigation requirement derived from historical ET and effective rainfall specific to south Florida (Dukes and Haman 2002a) and T5 was a reduced treatment, applying 60% of the irrigation depth calculated from T4 (see Chapter 2, Table 2-1).

Spring, summer, and fall 2007 differed from the previous three seasons in that the ET controller treatments allowed irrigation windows seven days per week and were updated with a system efficiency of 80% determined from uniformity testing discussed in Chapter 5. The time-based treatment, T4, was increased to apply irrigation to replace 100% of the net irrigation requirement instead of 60% used during the first three seasons. Once again, T5 applied 60% of T4 resulting in the reduced treatment applying 60% of the net irrigation requirement.

Data collection included: climate data at fifteen minute intervals such as wind speed, solar radiation, temperature, relative humidity, and rainfall depth from a Florida Automated Weather Network (FAWN) weather station located onsite and soil moisture content from TDR probes.

Results

Thirty year historical rainfall averages were calculated from monthly rainfall data collected by the National Oceanic and Atmospheric Administration (NOAA 2005) from 1975 through 2005 approximately 28 km away, in Parrish, FL. All months received less rain than historical average except for the following three months: July 2006, 97% higher than average; April 2007, 53% higher than average; October 2007 104% higher than average (Figure 4-1). Overall, both years were drier than the historical average with a total of 1,971 mm of rainfall for the approximate 19-month study period, May 2006 through November 2007, compared to 2,458 mm for the same historical period.

High intensity and large rainfall events can lead to runoff or drainage below the root zone. The portion of rainfall stored in the root zone is considered effective in that this precipitation can contribute to plant water needs. The cumulative depth of effective rainfall from the daily soil water balance, 514 mm, was 73% less than the total cumulative rainfall, 1,934 mm, over the treatment period (Figure 4-2). Only a fraction of each event was able to be stored in the root zone on a regular basis due to the limited turfgrass root zone of 15 cm and the low soil water holding capacity of 10% by volume. There were two distinct wet periods occurring approximately from June through September for 2006 and June through October for 2007. The wetter period in 2007 lasted a month longer than in 2006, but had at least three distinct dry periods within the wet period resulting in similar cumulative rainfall depths for both years, 204 mm for 2006 and 228 mm for 2007.

In the soil water balance model, measured rainfall depth was used as an input and effective rainfall was calculated based on the depth required to fill the root zone to field capacity. However, ET controllers use a variety of methods to handle rainfall depending on the manufacturer.

The Weathermatic controller incorporated rainfall by using an expanding disk rain sensor. This controller bypassed irrigation for 48 hours when the rain sensor sensed rainfall based on a 6 mm set threshold; whereas, the rain sensors on the remaining controllers have been shown to dry out between 68% to 85% of the time 24-30 hours after rainfall (Cardenas-Lailhacar and Dukes 2008). This controller maintained an accumulating deficit total based on ET_C losses and irrigates to refill the deficit total regardless of soil water holding capacity. The controller was designed to operate in areas with mandatory watering restrictions. When enough rain fell to trigger the rain sensor (6 mm setting), the deficit was reduced by 25.4 mm/hr until reset to zero (Weathermatic 2005).

The Toro controller was connected to a rain sensor, similar to all of the treatments, but the controller treats the rain sensor bypass mode as a non-watering day. When the rain sensor bypasses irrigation, the controller keeps track of the number of days and then applies irrigation as if rain never occurred. This results in more irrigation applied than required since irrigation supplements rainfall. This controller, however, is sent a rainfall signal by the WeatherTRAK ET Everywhere system to incorporate rainfall into the determination of irrigation applied. This is done by setting certain rainfall depths to the number of days the controller should wait until irrigation should be resumed. Rainfall depths are collected from the public weather station that the manufacturer uses to calculate ET_o and may or may not reflect the rainfall amount at the controller location.

During the entire treatment period, the ET Water controller did not recognize the rain sensor and did not bypass irrigation according to localized rainfall events. Rainfall was taken into account with the soil water balance when scheduling irrigation, but the weather station used was over 10 miles away from the project site (ET Water Website 2006). Rainfall can vary substantially over short distances in Florida.

The Weathermatic and ET Water controllers began treatments on May 25, 2006; however, hardware issues with the ET Water controller arose late in the summer season causing the controller to be nonfunctional. As a result, the ET Water controller did not control irrigation during the fall 2006 and winter 2006-2007 seasons. Once the controller was repaired, the programmed settings were updated to reflect settings described for spring 2007. However, maximum allowable depletion was set to 25% instead of 50% for unknown reasons and remained that way for the spring, summer, and fall 2007 seasons. The Toro controller was not installed until August 13, 2006.

The time-based treatments applied irrigation twice per week for every season unless bypassing occurred due to rainfall or time-clock malfunction. The irrigation schedule was developed from the net irrigation requirement determined from historical ET and effective rainfall and was adjusted monthly. T4 was set for 60% replacement for summer 2006, fall 2006, and winter 2006-2007 and 100% replacement for spring, summer, and fall 2007. The irrigation schedule for T5, the reduced time-based treatment, was set for 36% replacement for summer 2006, fall 2006, and winter 2006-2007 and 60% replacement for spring, summer, and fall 2007.

As a result, T4 functioned similarly to a historical ET controller with a crop coefficent the same as the Weathermatic controller for the first three seasons while T5 did so for the last three seasons. The first three seasons for T5 could possibly be considered a deficit treatment due to 36% being approximately half of any of the average crop coefficients.

Summer 2006

The summer 2006 season varies from other seasons because it was during the setup of the treatments resulting in different settings throughout the season (Table 4-2). The soil water balance model used to determine the theoretical irrigation requirement incorporates these differences.

Summer was relatively wet with rainfall occuring every few days. Irrigation application for the Weathermatic controller was 159 mm resulting in 24% under-irrigation compared 208 mm calculated as the theoretical irrigation requirement (Figure 4-3). The Weathermatic scheduled larger irrigation depth per application, averaging 23% greater than the theoretical requirement, but had fewer irrigation events in the season. Rainfall was frequent enough during this season to limit the number of events to 13 out of 23 possible.

The Weathermatic controller calculated irrigation adequacy averaging 59% (Table 4-3). Adequacy scores were higher when rainfall filled the root zone to field capacity and irrigation did not occur. This was because rainfall occurred often during this season so that deficits could not accumulate from lack of water. However when irrigation was necessary, the controller scheduled irrigation on the next available watering day causing a deficit to develop before the watering could occur. This controller averaged -57% in scheduling efficiency (Table 4-3). Scheduling efficiency was lower when the depth applied per irrigation event exceeded field capacity according to the soil water balance model or irrigation occurred on a morning where rainfall occurred later the same day. The 13 irrigation events applied more water than the root zone could theoretically hold due to the combination of no soil water holding capacity concepts of the controller and watering restrictions causing very low scheduling efficiency scores.

The ET Water controller applied 203 mm of irrigation compared to 186 mm of the theoretical irrigation requirement, only over-irrigating by 9% on a cumulative basis (Figure 4-4). Depth applied per event averaged 3% greater than the theoretical requirement and had one additional irrigation event. Irrigation adequacy scores averaged 50%, while scheduling efficiency averaged 82% (Table 4-4). Adequacy suffered from following watering restrictions; deficits accumulated between watering days when rainfall did not occur. Scheduling efficiency scores were less than 100% due to slightly larger irrigation depths per event resulting in over-irrigation.

The T4 irrigation schedule resulted in 13% over-irrigation, totaling 236 mm compared to 208 mm by the theoretical irrigation requirement (Figure 4-5) whereas T5 under-irrigated by 27%, totaling 152 mm (Figure 4-6). The rain sensor failed during the last week of June causing irrigation to occur when not necessary throughout the rest of the rainy season. Under-irrigation would have occurred if the rain sensor would have functioned appropriately. Compared to the theoretical amount, irrigation applied per event was 19% greater by T4 and 23% less by T5. Irrigation was applied for the same number of events by T4, T5, and the theoretical requirement due to a combination of the faulty rain sensor for T4 and T5 and no watering restrictions for the theoretical requirement.

The time-based treatment, T4, averaged 64% in scheduling efficiency and 65% in irrigation adequacy (Table 4-5). Initially, this treatment bypassed irrigation events due to rainfall causing some deficit conditions and lower irrigation adequacy due to watering restrictions. Once the rain sensor ceased to function, irrigation and rainfall kept the water level above the maximum allowable depletion level. However, this combination caused the scheduling efficiency to decrease over time. The scheduling efficiency percentage never reached 100% like the ET controllers sometimes did. This effect was due to consistently applying more irrigation than required on watering days.

The reduced time-based treatment, T5, performed similarly to T4; scheduling efficiency and irrigation adequacy averaged 78% and 54%, respectively (Table 4-6). The irrigation adequacy increased when the rain sensor malfunctioned and the scheduling efficiency trend slightly decreased. Scheduling efficiency was higher than T4 for this treatment because less water was applied per event; however, scheduling efficiency suffered because irrigation depth applied was sometimes greater than required to fill the root zone to field capacity.

Cumulative season irrigation application was the lowest by T5, the reduced time-based treatment. The soil moisture content for this treatment, however, rarely fell below field capacity and never fell below the maximum allowable depletion (Figure 4-7). Thus, this treatment was well-watered for the summer 2006 season. Since the other treatments applied more irrigation than T5, it can be assumed that all treatments remained well-watered for the summer 2006 season.

Fall 2006

September of the fall 2006 season experienced most of the rainfall whereas the rest of the season only had 8 rainfall events. The Weathermatic controller under-irrigated by 13%, applying 150 mm compared to the theoretical requirement of 172 mm (Figure 4-8). This treatment averaged 13% less than the theoretical irrigation depth for each event.

Scheduling efficiency and irrigation adequacy averaged -62% and 85%, respectively, for the Weathermatic controller (Table 4-3). Scheduling efficiency was low during the rainy portion of the season because the controller only bypassed some irrigation events even though rainfall filled the root zone to field capacity. It was shown by Cardenas-Lailhacar and Dukes (2008) that the sensivity in rain sensor bypassing was variable, especially for sensors set for less than 13 mm. Scheduling efficiency increased once irrigation became the primary water supply and rainfall was infrequent. Irrigation adequacy was generally good with scores decreasing in the middle of the season. This was due to one irrigation event skipped compared to the soil water balance requirements causing the controller to accumulate a small deficit until rainfall filled the root zone to capacity. Because the irrigation adequacy and scheduling efficiency results were determined from 30 day totals, one day of deficit or surplus affected 30 scores.

Irrigation applied by the Toro controller for fall 2006 was 147 mm, under-irrigating by 15% compared to the theoretical irrigation requirement, calculated as 172 mm (Figure 4-9). Over-irrigation occurred at the beginning of the season when it was generally wet causing the rain sensor to frequently bypass events due to rainfall. However, inefficiency in the rain sensor or inconsistency in the rainfall data collected by the controller caused the controller to schedule more events than the theoretical requirement. The Toro applied irrigation in 7 events compared to the 2 events calculated as the theoretical requirement. Also, this controller will schedule irrigation as if there is no water in the root zone when first installed as a precaution to protect poorly-managed landscapes despite this treatment being well-watered prior to treatment commencement. The controller applied 13.5 mm of irrigation during its first irrigation event when the overall average application per event was 6.7 mm. Once frequent rainfall events stopped on September 22, the slope of the cumulative irrigation application for the Toro controller was much less than the slope of the theoretical requirement resulting in overall savings. The average application per event by the Toro controller was 26% less than the depth per event by the theoretical irrigation requirement.

Irrigation adequacy averaged -69% for the Toro controller (Table 4-7). Deficits were not an issue in the early part of the fall season due to frequent rainfall as well as continued irrigation. Once irrigation became the primary source for water in the root zone, water levels decreased regularly below the maximum allowable depletion causing a severe decline in irrigation adequacy attributable to watering restrictions. Scheduling efficiency showed opposite trends, averaging 84% (Table 4-7). The depth of irrigation applied during the rainy period of the season was greater than the root zone could hold causing a surplus and decreasing scheduling efficiency according to the daily soil water balance. Irrigation occurring in early morning could not account for rainfall occurring later in the day, an inherent error in daily timesteps of the model. When adequacy declined, scheduling efficiency was nearly 100% most of the time because over-irrigation did not occur often.

The time-based irrigation schedules for October in fall 2006 were incorrect based on an error in the document used to develop the schedule. The irrigation schedule should have been similar to both September and November. Thus, the theoretical application for October was calculated by averaging application per event for September and November, and substituting that average depth for events that actually occurred in October. As a result, T4 and T5 would have applied 22% (210 mm) more than the theoretical requirement (Figure 4-10) and 25% (130 mm) less than the theoretical requirement of 172 mm (Figure 4-11), respectively. Irrigation application per event was only 1% greater than the theoretical requirement for T4 and 38% less than the theoretical requirement for T5. Both time-based treatments applied irrigation for just 4 more events than the theoretical requirement, totaling 23 events.

The time-based treatment, T4, irrigated adequately during the first half of the season but did not perform as well during the latter half, averaging -57% (Table 4-5). Irrigation supplemented rainfall so that deficits never occurred. The irrigation schedule for this treatment averaged 75% in scheduling efficiency (Table 4-5), suffering during the first half of the season, but not during the latter half. Reduced irrigation in October allowed the irrigation events to not exceed field capacity causing this treatment to consistently score 100% for all of the 30-day periods including most of this month. However, the rest of the irrigation events applied more water than necessary to fill the root zone to field capacity resulting in lower scheduling efficiency scores.

The reduced time-based treatment (T5) generally resulted in a higher scheduling efficiency than T4, averaging 86% (Table 4-6). This was due to the smaller irrigation depth per event resulting in less cumulative surplus and a longer time period of 100% scores. Irrigation adequacy for T5 averaged -101% (Table 4-6). Irrigation was fairly adequate for the majority of the first half of the season due to frequent rainfall. However, adequacy suffered because the reduced time schedule did not regularly apply enough irrigation to keep the water level above the maximum allowable depletion due to the incorrect irrigation schedule in October and little to no rainfall.

The reduced time-based treatment cumulatively under-irrigated the most for the fall 2006 season. Water levels were maintained near field capacity for most of the season except for October where the incorrect irrigation schedule caused soil moisture to decline (Figure 4-12). Despite October, this treatment was well-watered for the fall season.

Winter 2006-2007

Rainfall during the winter 2006-2007 season occurred occasionally throughout the season, totaling 17 events over 88 days (Figure 4-13). The Weathermatic controller over-irrigated by 8% compared to the theoretical irrigation requirement, applying 82 mm and 76 mm, respectively. The controller averaged 39% less than the theoretical requirement for irrigation depth per event, but scheduled irrigation 16 events compared to 9 events for the theoretical requirement.

Scheduling efficiency averaged -98% and irrigation adequacy averaged 100% for the Weathermatic controller (Table 4-3). This treatment had perfect irrigation adequacy during all of the winter season. This controller never under-irrigated. However, the controller was generally less efficient at applying irrigation. This excess was a result of applying irrigation before the water level dropped below the maximum allowable depletion since the irrigation depth per event averaged less than the theoretical requirement.

The Toro controller applied 15% less than the theoretical requirement during the winter 2006-2007 season, totaling 64 mm and 76 mm, respectively (Figure 4-14). The Toro controller applied 36% less per event on average compared to the theoretical requirement resulting in less cumulative application.

The smaller irrigation depth per event allowed the Toro treatment to apply irrrigation without over-irrigating during the first half of the season, scoring 100% in scheduling efficiency (Table 4-7). The remainder of the season varied in scheduling efficiency, from 42% back to 100% by the end of the season; average scheduling efficiency was 71%. Irrigation adequacy scores averaged from 22%. Irrigation did not adequately supplement rainfall during the first half of the season resulting in constant cumulative deficit and lower adequacy. However, irrigation was adequate when supplementing rainfall over the last portion of the season resulting in very little cumulative deficit.

The rain sensor for the time-based treatments was less sensitive than some because it did not bypass many events during the winter 2006-2007 season. The irrigation applied by the theoretical irrigation requirement was 76 mm; T4 over-irrigated by 70%, applying 129 mm (Figure 4-15), and T5 over-irrigated by 8%, applying 82 mm (Figure 4-16). The reduced time-based treatment applied irrigation similarly to the theoretical requirement due to the crop coefficient of the theoretical requirement being similar to the reduction percentage of the treatment. Cumulative over-irrigation occurred because additional events took place that were not bypassed by the rain sensor. There was twice the total number of events for the time-based treatments while applying 23% and 51% less irrigation per event compared to the theoretical requirement.

The time-based treatment, T4, resulted in irrigation adequacy of 98% on average (Table 4-5). This treatment applied adequate irrigation over the winter season due to applying irrigation consistently and not allowing a deficit to accrue. However, scheduling efficiency averaged 55%; this treatment cumulatively over-irrigated causing the scheduling efficiency to remain lower.

The reduced time-based treatment scored 95% for irrigation adequacy and 83% for scheduling efficiency (Table 4-6). Adequacy and scheduling efficiency were so high for the latter half of the season due to small and frequent irrigation events. Adequacy increased to 100% once enough rain fell to bring the water level above maximum allowable depletion so that irrigation became supplemental again.

The Toro controller treatment, T2, cumulatively irrigated the least for this season. However, soil moisture levels were maintained near field capacity and above the maximum allowable depletion (Figure 4-17). This treatment, despite applying less than other treatments, was well-watered for the winter 2006-2007 season.

Spring 2007

Rainfall was infrequent during the spring 2007 season, totaling 22 mm of effective rainfall from 9 events over 94 days; there was no rainfall in May. The Weathermatic controller under-irrigated by 25%, applying 339 mm of irrigation compared to 453 mm of irrigation calculated by the theoretical requirement (Figure 4-18). Irrigation occurred everyday by the Weathermatic controller unless in bypass mode due to the rain sensor. The controller averaged 67% less irrigation depth per event, but applied irrigation for 48 additional events compared to the soil water balance totaling 84 events.

Irrigation adequacy and scheduling efficiency averaged 69% and 70%, respectively, for the Weathermatic controller treatment (Table 4-3). Adequacy decreased when the turfgrass water requirements changed, creating deficit accumulation. Irrigation application was slightly greater than required initially, causing lower scheduling efficiencies until the deficit accumulated enough so that irrigation depths per event were not greater than field capacity.

The Toro controller applied 317 mm of irrigation, under-irrigating by 30%, compared to 453 mm calculated for the theoretical irrigation requirement (Figure 4-19). Irrigation application per event was half for the Toro controller, averaging 7 mm/event, compared to the theoretical requirement, but there were approximately twice as many events applied by the Toro than the theoretical requirement, totaling 62 events. Overall, the Toro controller applied 59% less per event than was scheduled by the theoretical irrigation requirement.

The Toro controller adequately applied irrigation at the beginning of the season, achieving 100% until rainfall and change in seasonal water needs caused under-irrigation to occur, ending at an irrigation adequacy of -98%, averaging 6% (Table 4-7). Irrigation was scheduled efficiently with scores ranging from 77% to 100%, averaging 90%. Similarly to the Weathermatic, scheduling efficiency increased to 100% in the latter part of the season due to the accumulated deficit reflected in the irrigation adequacy score.

Irrigation occuring over the season for the ET Water controller totaled 259 mm, under-irrigating by 43% compared to the theoretical irrigation requirement which totaled 451 mm (Figure 4-20). The theoretical irrigation requirement increased application per event to match perceived seasonal need whereas the ET Water controller did not update its schedule for an extended period of time. The controller failed to update its irrigation schedule due to signal issues from April 9, 2007 until May 23, 2007. It is likely that the controller would have updated crop coefficients and fluctuated with weather conditions if updated daily.

The ET Water controller scored 28% in irrigation adequacy where the deficit accumulated from the lack of change with seasonal water requirements (Table 4-4). Scheduling efficiency, however, averaged 97%. This controller was generally able to schedule irrigation without applying more than the root zone could hold on a regular basis.

The spring 2007 season experienced very little rainfall; however, the rain sensor caused irrigation to stop for an extended period of time resulting in less irrigation than representative of the treatments. The additional irrigation events were added into the treatments as theoretically would have been applied if the malfunction had not occurred. The application per event for the theoretical treatment was derived from the average of similar irrigation applications in the same month. The time-based treatments, T4 and T5, applied 21% (356 mm) and 52% (215 mm) less than the theoretical irrigation requirement, calculated as 453 mm (Figure 4-21; Fig 4-22). The irrigation applied per event by T4 was 9% greater than the theoretical requirement and T5 was

34% less than the requirement; both treatments applied irrigation for a less number of events, totaling 26 events compared to 36 by the theoretical irrigation requirement. Under-irrigation by both treatments can be attributed to less number of events as well as higher crop coefficients compared to the reductions from historical of the time-based treatments.

Irrigation adequacy for the time-based treatment, T4, and the reduced time-based treatment, T5, averaged 30% and -13%; adequacy dropped in the latter part of the season due to the high theoretical requirement (Table 4-5; Table 4-6). Scheduling efficiency averaged 77% for T4 and 97% for T5. Scheduling efficiency was lower in the beginning of the season because the depth applied per event filled the root zone past field capacity. However, scheduling efficiency increased as the deficit increased and adequacy decreased.

Spring 2007 resulted in the most under-irrigation compared to the theoretical requirement by T5. According to the soil moisture data, the volumetric water content only fell below the maximum allowable depletion during the period where the rain sensor did not allow irrigation to occur even though there was no rainfall (Figure 4-23). Otherwise, the treatment remained well-watered indicating that all treatments were well-watered for this season.

Summer 2007

The summer 2007 season was rainy, bringing lightning into the area. On June 8, 2007, a lightning storm affected the irrigation equipment including the pump for the irrigation well. The GCREC maintenance crew immediately transferred the water source of the project to the farm system. However, pressure problems were apparent in August. The pump was replaced at the end of August and the water source transferred back to the irrigation well, fixing the pressure problems.

The Weathermatic controller defaulted to a time-based schedule during this season. The weather monitor used to gather data to calculate ET_o was inoperable after being affected by the power outage; the weather monitor was replaced for the fall 2007 season.

Rainfall was much more frequent, beginning the wet period in the summer 2007 season. However, the rain sensor connected to the Toro controller became much less sensitive to rainfall causing the rain sensor to bypass irrigation for intense rainfall events. Irrigation application per event was 58% less for the Toro controller than the theoretical irrigation requirement, but applied irrigation for 55 events compared to 24 events for the theoretical requirement (Figure 4-24). This summer season resulted in 3% under-irrigation by applying 278 mm compared to the theoretical requirement that applied 287 mm. However, under-irrigation was only possible due to the lack of pressure supply during the month of August.

Irrigation adequacy for the Toro controller scored 18% to 98%, averaging 71% (Table 4-7). This controller applied irrigation consistently to climb out of the deficit created from under-irrigation in the previous season. However, once August's reduced irrigation application from the lack of pressure occurred, adequacy dropped again due to accumulating deficit. Scheduling efficiency for the Toro controller ranged from 79% to 100%, averaging 85%, as a result of smaller, more frequent irrigation events. This controller only over-irrigated minimally throughout the entire season to cause the scheduling efficiency score to be less than 100%.

Cumulative irrigation over summer 2007 was 260 mm, 18% less than the theoretical requirement that totaled 319 mm (Figure 4-25). Application depth per event for the ET Water controller was 54% less than irrigation depth per event for the theoretical requirement. However, the ET Water controller scheduled twice as many events as the theoretical requirement. Similar to the Toro controller, under-irrigation was only possible due to the lack of pressure supply resulting in reduced irrrigation in August.

Also similar to the Toro controller were its irrigation adequacy and scheduling efficiency scores. Irrigation adequacy for the ET Water controller scored 66%, applying irrigation consistently to reduce the deficit created last season (Table 4-4). However, once irrigation decreased from the lack of pressure, adequacy scores fell again due to accumulating deficit. Scheduling efficiency for this controller averaged 93% as a result of smaller, more frequent irrigation events. This controller also over-irrigated minimally throughout the entire season to cause the scheduling efficiency score to be less than 100%.

Irrigation application for the rainy summer 2007 season by T4 and T5 was 324 mm and 174 mm, respectively (Figure 4-26; Figure 4-27). These treatments applied 13% greater than the theoretical irrigation requirement and 40% less than the theoretical irrigation requirement, calculated to apply 287 mm. Application per event by T4 was 51% greater than the theoretical requirement while T4 applied 15% less than the theoretical requirement on average. Over-irrigation and under-irrigation occurred because the time-based treatments applied irrigation for less number of events in combination with the difference in average irrigation depth per event. Also, the time-based treatments were affected by the lack of pressure in August just as the other treatments.

Irrigation adequacy averaged 72% over the summer season for T4, the time-based treatment (Table 4-5). Initially, the irrigation adequacy score suffered from the deficit accumulated over the latter part of the spring season. However, rainfall was frequent over the season to increase the water level so that less accumulation below the maximum allowable depletion occurred. Scheduling efficiency, however, suffered from the increased water level causing irrigation depths to be greater than field capacity and decreasing scheduling efficiency scores, averaging 48%.

The reduced-time-based treatment, T5, applied less irrigation per event than T4. This affected the irrigation adequacy and scheduling efficiency scores appropriately by accumulating more deficit totals before irrigation became supplemental to rainfall as well as increasing scheduling efficiency ranges by not applying more than field capacity as much as T4 did. Irrigation adequacy and scheduling efficiency averaged 34% and 78%, respectively (Table 4-6).

The reduced time-based treatment, T5, was well watered during the summer 2007 season. The volumetric soil moisture content remained above the maximum allowable depletion level for the entire season and water levels frequently exceeded field capacity (Figure 4-28). This treatment cumulatively applied the least amount of irrigation for the season.

Fall 2007

Results from the Weathermatic controller for this season were not necessarily representative of the treatment because the weather monitor was damaged and left in an undesirable position (Figure 4-29). The weather monitor was not able to detect rainfall in this position resulting in excess irrigation. It is unknown the length of time this controller was affected by the situation and whether the height and orientation affected the temperature measurements; the weather monitor was replaced to the proper position on October 9, 2007.

Fall 2007 experienced much more rainfall during most of the season since it was included in the wet period. Rainfall events mostly occurred prior to November; only 1 event out of 32 occurred in November. The Weathermatic controller applied 220 mm of irrigation compared to 167 mm calculated as the theoretical irrigation requirement, over-irrigating by 32% (Figure 4-30). The controller did not bypass irrigation from September 27 through October 20, applying irrigation during 5 rainfall events. Irrigation adequacy was high for this season, averaging 99% (Table 4-3), due to frequent rainfall and excess irrigation during the rainy period; the root zone of this treatment experienced very little under-irrigation. However, irrigation occurring when not necessary severely affected the scheduling efficiency, averaging 23%.

Cumulatively, the Toro controller applied the same amount of irrigation as the theoretical irrigation requirement, totaling 166 mm (Figure 4-31). Once again, the Toro controller applied less irrigation per event by 32%, but applied irrigation more often totaling 23 events compared to 16 events calculated for the theoretical requirement. Periods of frequent irrigation events resulted in high irrigation adequacy scores where scores averaging 55% (Table 4-7). Irrigation still occurred when there were frequent rainfall events at the beginning of the season. Scheduling efficiency suffered due to the excess irrigation, but recovered later in the season when rainfall bypassing resumed. Scheduling efficiency averaged 79% over the fall season.

Irrigation application by the ET Water controller in the fall 2007 season was cumulatively equal to the calculated theoretical irrigation requirement, totaling 199 mm (Figure 4-32). Over-irrigation occurred during the first half of the season due to the rainy conditions and not recognizing a rain sensor. The latter half of the season applied less irrigation per event compared to the theoretical irrigation requirement, apparent in the steeper slope of the theoretical requirement.

Irrigation adequacy for the ET Water controller averaged 79% (Table 4-4). Adequacy scores were affected by the reduced irrigation over the rainy period in late October. Rainfall depths used by the manufacturer to incorporate into the controller's soil water balance were from a different weather station than the one used for the soil water balance model. The irrigation depths were calculated using the alternate rainfall data causing the irrigation depths to vary in adequacy over that time period. Irrigation scheduling efficiency averaged 92% over the fall season. Irrigation depths per event were small enough to over-irrigate cumulatively by a small amount keeping the scores generally high.

Irrigation occurred despite significant rainfall events during the first portion of the fall 2007 season by the time-based treatments. T4 and T5 over-irrigated by 95% (326 mm) and 17% (194 mm), respectively, compared to 166 mm by the theoretical irrigation requirement (Figure 4-33; Figure 4-34). Compared to the theoretical requirement, more irrigation per event was applied for T4 by 40% and less irrigation per event was applied for T5 by 17%. There were more irrigation events scheduled by the time-based treatments than the theoretical irrigation requirement due to the less sensitive rain sensor bypassing less events as well as the theoretical irrigation requirement taking rainfall into account when calculating the depth to be applied.

The time-based treatment, T4, and the reduced time-based treatment, T5, only had small amounts of under-irrigation due to watering day restrictions resulting in irrigation adequacy averaging 94% and 89%, respectively (Table 4-5, 4-9). Irrigation adequacy was sometimes not as high for T5 compared to T4 due to the reduced irrigation depth per event. Scheduling efficiency suffered, however, because the irrigation applied over the 30 day periods was in excess of water requirements causing consistent over-irrigation; scheduling efficiency averaged 36% for T4 and 61% for T5. Scheduling efficiency was so low in the first part of the season due to irrigation application despite frequent rainfall for both treatments.

The Toro controller, T2, applied the least amount of irrigation for the fall 2007 season compared to the other treatments. The treatment maintained volumetric soil water content above field capacity most of the time resulting in well-watered conditions (Figure 4-35).

Discussion

It was determined in Chapter 3 that the Weathermatic controller over-estimated ETo used for scheduling irrigation. However, cumulative irrigation applied was less than the theoretical requirement during summer 2006, fall 2006, and spring 2007. This was due to the combination of using a lower crop coefficient (0.6 fixed over time) than was representative of the actual site and the 48-hour rain sensor bypass period which accumulated irrigation deficits. The 48 hour bypass is longer than recent research has indicated where expanding disk rain sensors dry out with 24 hrs most of the time. The crop coefficient used by the controller during winter 2006-2007, when over-irrigation occurred, was greater than the one used by the soil water balance model. Fall 2007 most likely over-irrigated due to the position of the weather monitor during the rainy period.

The Weathermatic controller regularly over-irrigated as proven by the generally low scheduling efficiency scores, 65% of the scores were less than 50%, and irrigated frequently enough to keep adequacy scores above 50% for 88% of the time (Figure 4-36). Watering restrictions cut irrigation days to two per week for the first three seasons. Scheduling efficiency scores were much lower for these seasons, averaging -72%, because irrigation occurred to refill the entire deficit each time despite what the root zone could actually hold. This was because the Weathermatic controller did not use a traditional soil water balance with a root zone. Adequacy scores were high because irrigation occurred everyday since watering restrictions were lifted and the controller replaced the water loss from the previous day without depleting to a certain maximum allowable depletion. The most under-irrigation compared to the theoretical requirement for this controller occurred during the spring 2007 season when average scheduling efficiency and adequacy were both high values and the controller was allowed to irrigate seven days per week.

Chapter 3 showed that the cumulative ETo estimation by the Toro controller compared to the ASCE method using on-site weather data were nearly identical, estimating within 1% of each other. Settings used to calculate the theoretical irrigation requirement were identical to the Toro controller settings except for crop coefficient and method for rainfall estimation. The calculated theoretical requirement likely used crop coefficients that were much larger than the coefficients used by the Toro controller since they were developed for California and not Florida, resulting in the under-estimation of the actual requirement of the study site. Also, the Toro controller translated rainfall depths into number of days to pause irrigation without including rainfall into irrigation scheduling by the controller. The rain pause feature for the Toro controller sometimes caused the controller to bypass irrigation for up to 5 days due to a considerable amount of rainfall. However, sandy soils in Florida have small soil water holding capacities and most rainfall was lost to drainage. The soil water balance model only considers effective rainfall and irrigation bypassing never occurred for more than 3 days. This difference also caused the Toro to under-irrigate compared to the theoretical requirement.

Scheduling efficiency values were relatively high for every season where 79% of the scores were above 70% for the study period, showing that the Toro controller was able to accurately judge the depth of irrigation required to fill the root zone to field capacity (Figure 4-37). Only 4% of the scores were below 50%. Average irrigation adequacy scores were negatively impacted over the first half of the study period due to day of week watering restrictions. Irrigation adequacy increased to positive values, but was still low for the last half of the study period; 51% of the scores were below 50%. Under-irrigation was also seen in the cumulative totals of irrigation application for the seasons. However, it was determined in Chapter 2 that turfgrass quality remained above acceptable quality standards despite low average adequacy scores for every season. Under-irrigation for short periods of time will not negatively affect the quality of the landscape.

Chapter 3 showed that that ETo estimation by the ET Water controller was 8% less than the ETo calculated using weather data from the onsite weather station. As a result, this controller under-irrigated compared to the theoretical requirement during the dry periods. The spring 2007 season resulted in the most savings, including using an early April schedule to irrigate throughout late April and May. Irrigation was over-applied during wet periods because the controller failed to utilize the rain sensor.

Scheduling efficiency scores were above 90% for 85% of the time for all seasons showing that the ET Water controller was also able to accurately judge the depth of irrigation required to fill the root zone to field capacity (Figure 4-38). Irrigation adequacy scores were frequently lower than the scheduling efficiency, but were also relatively high where performance was greater than 50% for 67% of the study period. Under-irrigation was apparent in the under-irrigation compared to the theoretical requirement for spring and summer 2007, calculated as -43% and -18%, respectively, where adequacy averaged the lower values of 28% and 66%. Similarly to the Toro controller, turfgrass quality maintained acceptable levels for the entire study period as was determined in Chapter 2.

The time-based treatments, T4 and T5, followed the theoretical requirement trends when water needs reflected the historical net irrigation requirement. However, these treatments were not able to adjust for real weather conditions especially during periods of irregular weather changes from historical averages. These treatments maintained watering restrictions throughout the entire study period ensuring average irrigation adequacy measurements less than 100%; scores were greater than 50% for 68% of the time for T4 and 96% of the time for T5 (Figure 4-

39, 4-40). Scheduling efficiency scores were greater than 50% for 67% of the time and 56% of the time for T4 and T5, respectively. As would be expected, irrigation adequacy scores were greater for T4 than T5 while scheduling efficiency scores were greater for T5 than T4.

The theoretical irrigation requirement did not always result in irrigation adequacy and scheduling efficiency scores of 100% (Figure 4-41). The irrigation adequacy performance never reached 100% because the readily available water was allowed to deplete below the maximum allowable depletion before irrigation occurred. Scheduling efficiency suffered from rainfall where irrigation events scheduled from the water needs of the previous day occur on the same day as rainfall. Despite the performance results of the theoretical requirement, the published SWAT scores for these controllers were within 5% of 100% for both irrigation adequacy and scheduling efficiency.

Conclusions

Rainfall in Florida is localized and important in determining how well these controllers schedule irrigation. The Weathermatic and Toro controllers both utilize a rain pause feature where the controller pauses irrigation for a certain number of days determined by the manufacturer. The Weathermatic controller tested here (newer controller models have an adjustable rain pause from 1 to 7 days) always pauses for 48 hours despite whether there was enough rainfall to maintain adequate soil moisture levels. The Toro controller uses a predetermined scale to choose the number of days based on depth of rainfall, whether or not that depth was effective. Though it is unclear exactly how it is done, rainfall is factored into the scheduling of the ET Water. However, they use rainfall at a weather station that may not be representative of the depth of rain at the site location.

Inputs to the ET controllers, both manufacturer and user programmed, are extremely important to proper irrigation scheduling. Crop coefficients used by the ET controllers were either average for the entire year as in the Weathermatic or unknown, but were not necessarily representative of the values measured in Florida. The crop coefficients developed for Florida by Jia et al. (2007) were used in the soil water balance model and could explain some of the lower scheduling efficiency and adequacy scores. Crop coefficients for the signal-based controllers were developed for California and not specific to Florida. For example, all ET controllers irrigated much less than the theoretical requirement for May where the crop coefficient was 0.90.

The known inputs to the controllers were used to calculate the theoretical irrigation requirement; however, most of the time, the irrigation treatments maintained well-watered conditions according to the soil moisture content data even when the theoretical comparison showed under-irrigation and cumulative deficits through low adequacy scores.

The depth of the readily available water for the soil water balance model was 7.6 mm. This depth was most likely much smaller than what was used by the ET controllers to schedule irrigation. The smallest value for this depth is 14 mm for the SWAT testing protocol. As a result, it would be considerably harder for these controllers to maintain high irrigation adequacy and scheduling efficiency scores at the same time by not irrigating too much or too little.

The SWAT testing protocol is the only accepted way to test whether these controllers adequately schedule irrigation. The landscape scenario was published and the manufacturers could program the controllers before the test began so that their maximum allowable depletion depth was within the published values to ensure nearly perfect adequacy and scheduling efficiency scores. There are also no differences between the controller weather data and the weather data used for the soil water balance model due to the close proximity of the weather station to the test site; however, measurement of the ability of the controller to properly schedule irrigation depends on how well site appropriate whether data used to estimate ETo are collected.

SWAT currently allows manufacturers to continually test their controllers until they score what the manufacturer finds acceptable, tweaking between 30-day periods; they also allow the manufacturer to decide whether to publish the results. It is likely that some controllers will be tested for six months to a year before achieving scores that are acceptable and the scores usually end as being within 5% of 100%. However, as was shown above in 30-day moving totals, controllers will schedule differently in a short period of time depending on weather conditions, rainfall, and time of year.

As was seen in the scheduling efficiency and irrigation adequacy results for the theoretical requirement, rainfall was an important factor for determining the irrigation adequacy and scheduling efficiency results. Currently, only 10.2 mm of rainfall was required to complete the test with publishable results. However, such a small amount of rainfall does not allow the controller to show how it will perform in wet periods distinctive to Florida's historical climate.

A properly managed time-based schedule with rain sensor could provide the same water savings as an ET controller while maintaining adequacy and scheduling efficiency; however, it must be regularly adjusted to match climatic demand. A properly programmed ET controller could work better than manual irrigation scheduling so that irrigation would consistently be supplemental to rainfall and to minimize extraneous watering. However, the results show that ET controllers perform irrigation scheduling as well as the program settings and how they measure and incorporate rainfall.

Table 4-1. Monthly crop coefficients for warm season turfgrass used to calculate crop evapotranspiration for the determination of the theoretical irrigation requirement

Month	Theoretical[1]	SWAT[2]
January	0.46	0.52
February	0.46	0.64
March	0.57	0.70
April	0.83	0.73
May	0.90	0.73
June	0.77	0.71
July	0.73	0.69
August	0.72	0.67
September	0.69	0.64
October	0.65	0.60
November	0.60	0.57
December	0.46	0.53
Average	0.65	0.64

[1]Theoretical refers to the crop coefficients used in the soil water balance model to determine the theoretical irrigation requirement (Jia et al. 2007). [2]SWAT refers to the crop coefficients used for ET controller testing by the Smart Water Application Technology group under the Irrigation Association (IA 2006c) developed in California.

Table 4-2. Program setting differences[1] from Table 2-2 for the summer 2006 season

Start Date	End Date	Setting	Treatment	Difference from Table 2-2
May 25	Jul 10	Sprinkler Type[2]	Weathermatic	25.4 mm/hr
May 25	Jul 10	Sprinkler Type	ET Water	18.0 mm/hr
May 25	Jun 8	Scheduling efficiency	ET Water	45%
May 25	Jun 8	Root Depth	ET Water	305 mm
May 25	Aug 10	Sprinkler Type	Time-based[4]	19.1 mm/hr
Jun 20	Jun 29	MAD[3]	ET Water	35%

[1]Settings outside of these dates are the same as listed in Table 2-2. [2]Application rate or precipitation rate is termed sprinkler type for some ET controllers. [3]MAD refers to the maximum allowable depletion. [4]Time-based treatment refers to both the time-based treatment, T4, and the reduced time-based treatment, T5.

Table 4-3. Weathermatic controller, T1, results for average scheduling efficiency and irrigation adequacy calculated using 30-day moving totals, percentage difference in irrigation application from the theoretical requirement, cumulative rainfall, and number of rainfall events for each season

Season	Scheduling Efficiency (%)		Irrigation Adequacy (%)		Difference from Theoretical[1] (%)	Rainfall	
	Avg[2]	CV[3]	Avg	CV		Cum[4] (mm)	Events[5]
Sum 06	-57	-234	59	42	-24	641	32
Fall 06	-62	-342	85	16	-13	308	33
Win 06-07	-98	-114	100	0	8	167	16
Spr 07	70	32	69	58	-25	109	9
Sum 07	NA[6]	NA	NA	NA	NA	446	37
Fall 07	23	24	99	2	32	264	32
Average	-25	-278	82	22	-4		

[1]Difference from theoretical is the difference between cumulative water application for the season compared to the theoretical irrigation requirement. [2]Avg is the average value calculated from all 30-day moving totals for the season. [3]CV is the coefficient of variation calculated from all 30-day moving totals for the season. [4]Cum is the cumulative total rainfall for the season. [5]Events is the number of rainfall events that occurred over the season. [6]NA is an abbreviation for Not Applicable and indicates seasons where the treatment was not working.

Table 4-4. The ET Water controller, T3, results for average scheduling efficiency and irrigation adequacy calculated using 30-day moving totals, percentage difference in irrigation application from the theoretical requirement, cumulative rainfall, and number of rainfall events for each season

Season	Scheduling Efficiency (%)		Irrigation Adequacy (%)		Difference from Theoretical[1] (%)	Rainfall	
	Avg[2]	CV[3]	Avg	CV		Cum[4] (mm)	Events[5]
Sum 06	82	21	50	56	9	641	32
Fall 06	NA[6]	NA	NA	NA	NA	308	33
Win 06-07	NA	NA	NA	NA	NA	167	16
Spr 07	97	2	28	290	-43	109	9
Sum 07	93	1	66	43	-18	446	37
Fall 07	92	3	79	25	0	264	32
Average	91	7	56	39	-13		

[1]Difference from theoretical is the difference between cumulative water application for the season compared to the theoretical irrigation requirement. [2]Avg is the average value calculated from all 30-day moving totals for the season. [3]CV is the coefficient of variation calculated from all 30-day moving totals for the season. [4]Cum is the cumulative total rainfall for the season. [5]Events is the number of rainfall events that occurred over the season. [6]NA is an abbreviation for Not Applicable and indicates seasons where the treatment was not working.

Table 4-5. Time-based treatment, T4, results for average scheduling efficiency and irrigation adequacy calculated using 30-day moving totals, percentage difference in irrigation application from the theoretical requirement, cumulative rainfall, and number of rainfall events for each season

Season	Scheduling Efficiency (%)		Irrigation Adequacy (%)		Difference from Theoretical[1] (%)	Rainfall	
	Avg[2]	CV[3]	Avg	CV		Cum[4] (mm)	Events[5]
Sum 06	64	12	65	36	13	641	32
Fall 06	75	34	-57	-211	2 (22)[7]	308	33
Win 06-07	55	20	98	8	70	167	16
Spr 07	77	21	30	176	-32 (-21)	109	9
Sum 07	48	20	72	10	13	446	37
Fall 07	36	24	94	3	95	264	32
Average	59	27	50	115	27 (32)		

[1]Difference from theoretical is the difference between cumulative water application for the season compared to the theoretical irrigation requirement. [2]Avg is the average value calculated from all 30-day moving totals for the season. [3]CV is the coefficient of variation calculated from all 30-day moving totals for the season. [4]Cum is the cumulative total rainfall for the season. [5]Events is the number of rainfall events that occurred over the season. [6]NA is an abbreviation for Not Applicable and indicates seasons where the treatment was not working. [7]Parentheses represent what the treatment would have applied if the rain sensor had not malfunctioned.

Table 4-6. Reduced time-based treatment, T5, results for average scheduling efficiency and irrigation adequacy calculated using 30-day moving totals, percentage difference in irrigation application from the theoretical requirement, cumulative rainfall, and number of rainfall events for each season

Season	Scheduling Efficiency (%)		Irrigation Adequacy (%)		Difference from Theoretical[1] (%)	Rainfall	
	Avg[2]	CV[3]	Avg	CV		Cum[4] (mm)	Events[5]
Sum 06	78	10	54	41	-27	641	32
Fall 06	86	23	-101	-135	-36 (-25)	308	33
Win 06-07	83	14	95	13	8	167	16
Spr 07	97	5	-13	-497	-59 (-52)	109	9
Sum 07	78	12	34	136	-40	446	37
Fall 07	61	16	89	8	17	264	32
Average	80	15	26	282	-23		

[1]Difference from theoretical is the difference between cumulative water application for the season compared to the theoretical irrigation requirement. [2]Avg is the average value calculated from all 30-day moving totals for the season. [3]CV is the coefficient of variation calculated from all 30-day moving totals for the season. [4]Cum is the cumulative total rainfall for the season. [5]Events is the number of rainfall events that occurred over the season. [6]NA is an abbreviation for Not Applicable and indicates seasons where the treatment was not working.

Table 4-7. Toro controller, T2, results for average scheduling efficiency and irrigation adequacy calculated using 30-day moving totals, percentage difference in irrigation application from the theoretical requirement, cumulative rainfall, and number of rainfall events for each season

Season	Scheduling Efficiency (%)		Irrigation Adequacy (%)		Difference from Theoretical[1] (%)	Rainfall	
	Avg[2]	CV[3]	Avg	CV		Cum[4] (mm)	Events[5]
Sum 06	NA[6]	NA	NA	NA	NA	641	32
Fall 06	84	25	-69	-156	-15	308	33
Win 06-07	71	25	22	509	-15	167	16
Spr 07	90	9	6	1386	-30	109	9
Sum 07	85	4	71	41	-3	446	37
Fall 07	79	11	55	62	0	264	32
Average	82	9	17	324	-13		

[1]Difference from theoretical is the difference between cumulative water application for the season compared to the theoretical irrigation requirement. [2]Avg is the average value calculated from all 30-day moving totals for the season. [3]CV is the coefficient of variation calculated from all 30-day moving totals for the season. [4]Cum is the cumulative total rainfall for the season. [5]Events is the number of rainfall events that occurred over the season. [6]NA is an abbreviation for Not Applicable and indicates seasons where the treatment was not working.

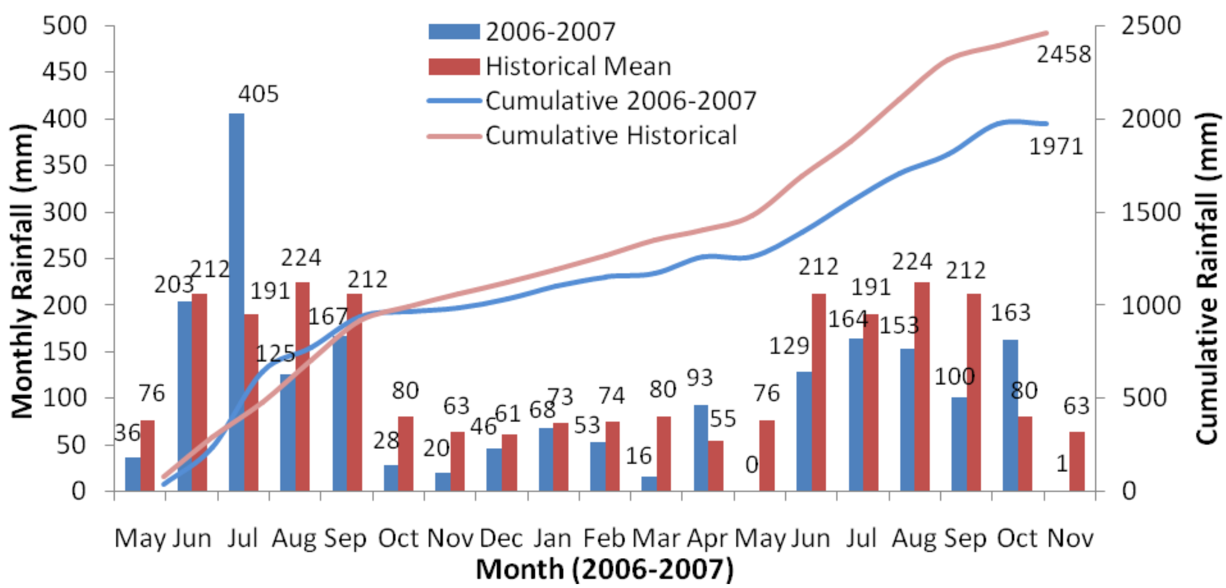

Figure 4-1. Comparison of rainfall for the 2006-2007 study period and average historical rainfall on a monthly and cumulative basis.

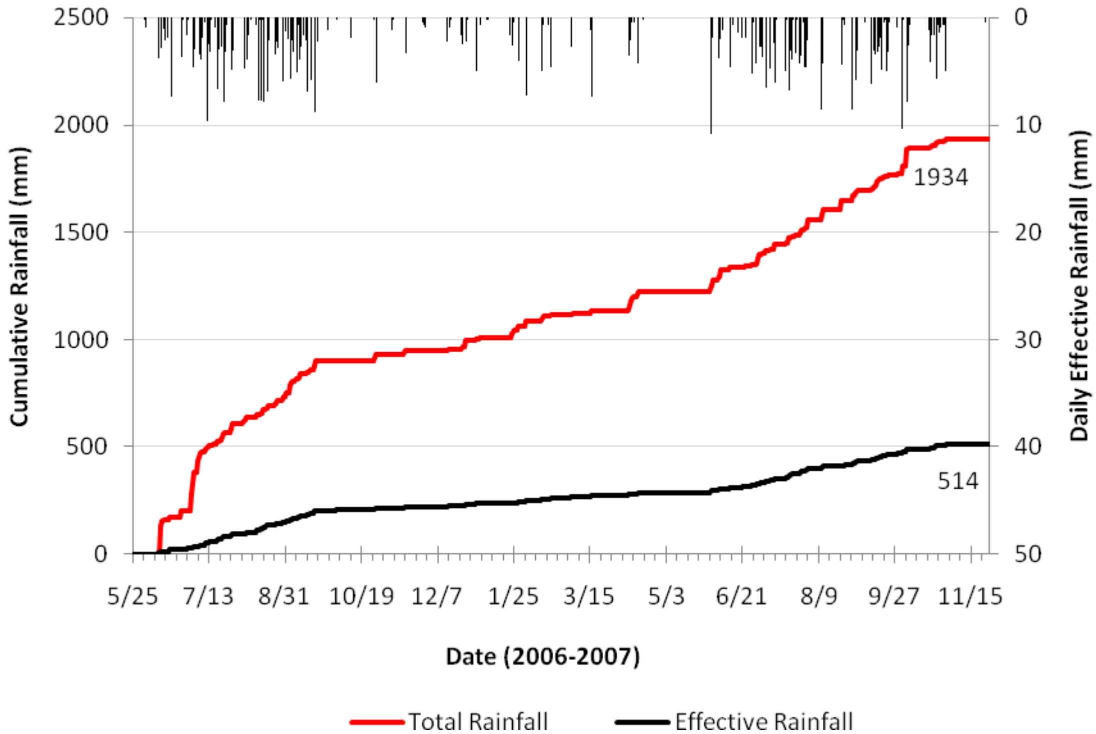

Figure 4-2. The FAWN measured total rainfall and effective rainfall determined from the soil water balance model for the study period using the weather station in Balm, FL.

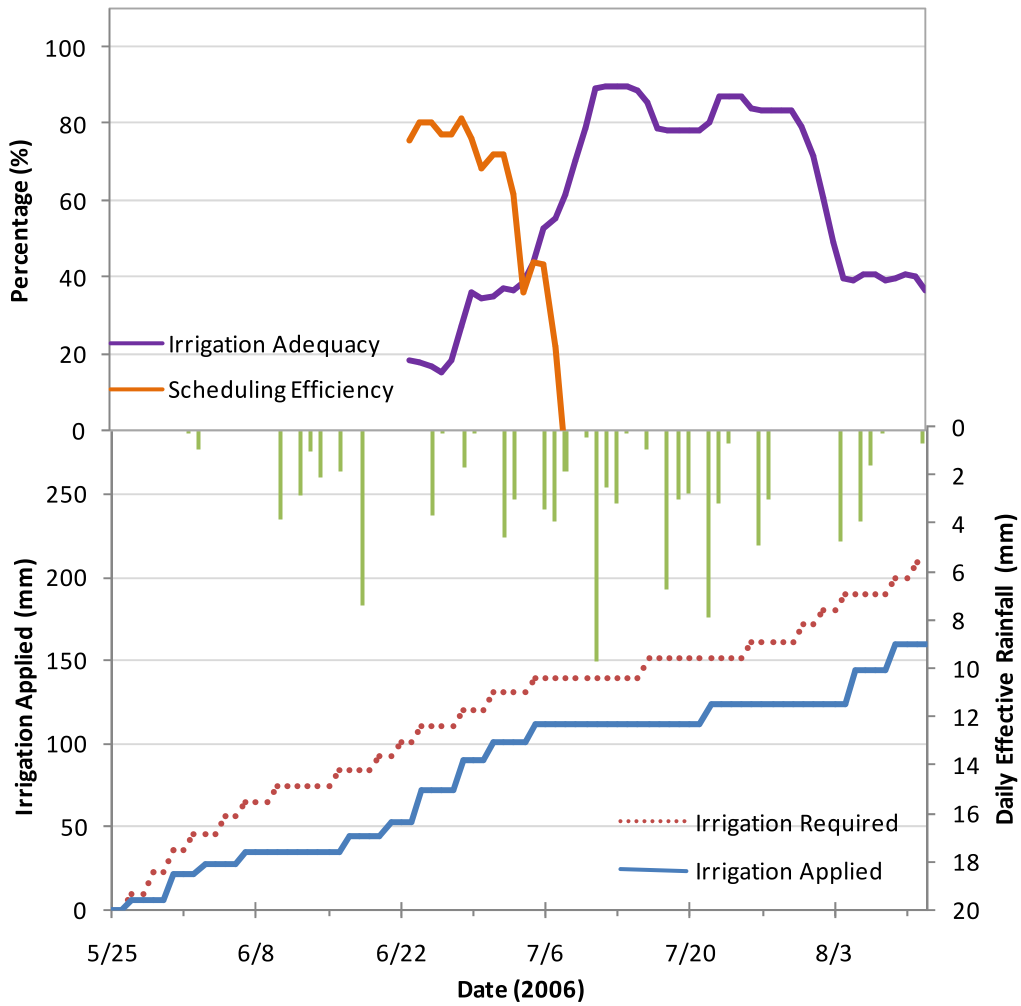

Figure 4-3. Weathermatic controller (T1) results over the summer 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

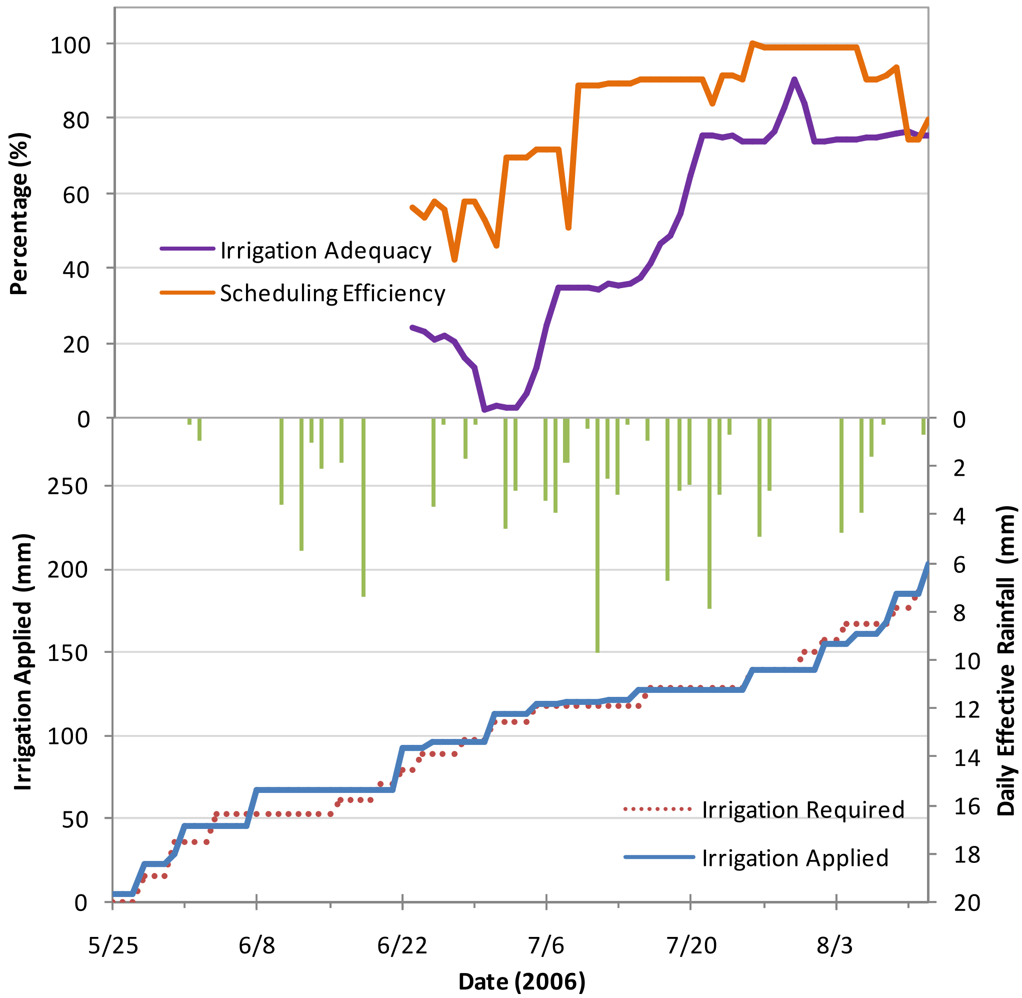

Figure 4-4. ET Water controller (T3) results over the summer 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

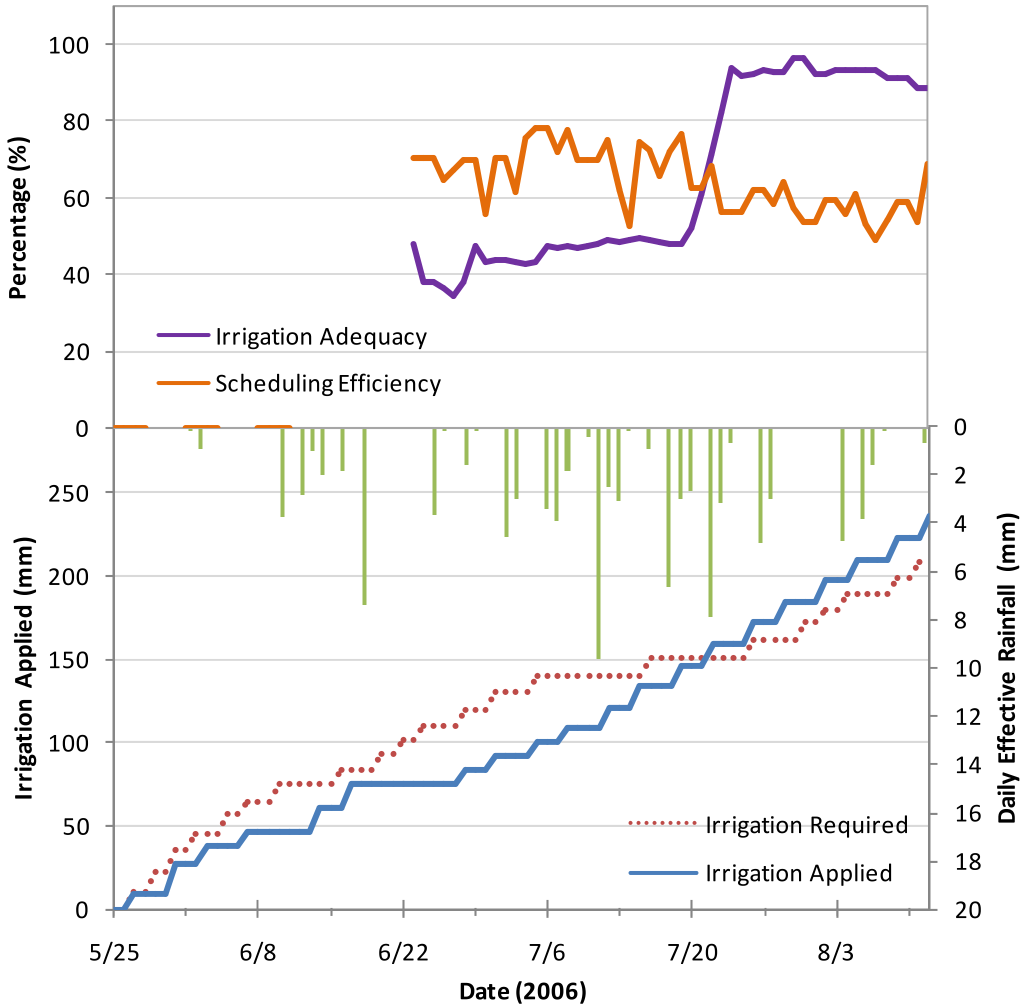

Figure 4-5. Time-based treatment (T4) results over the summer 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

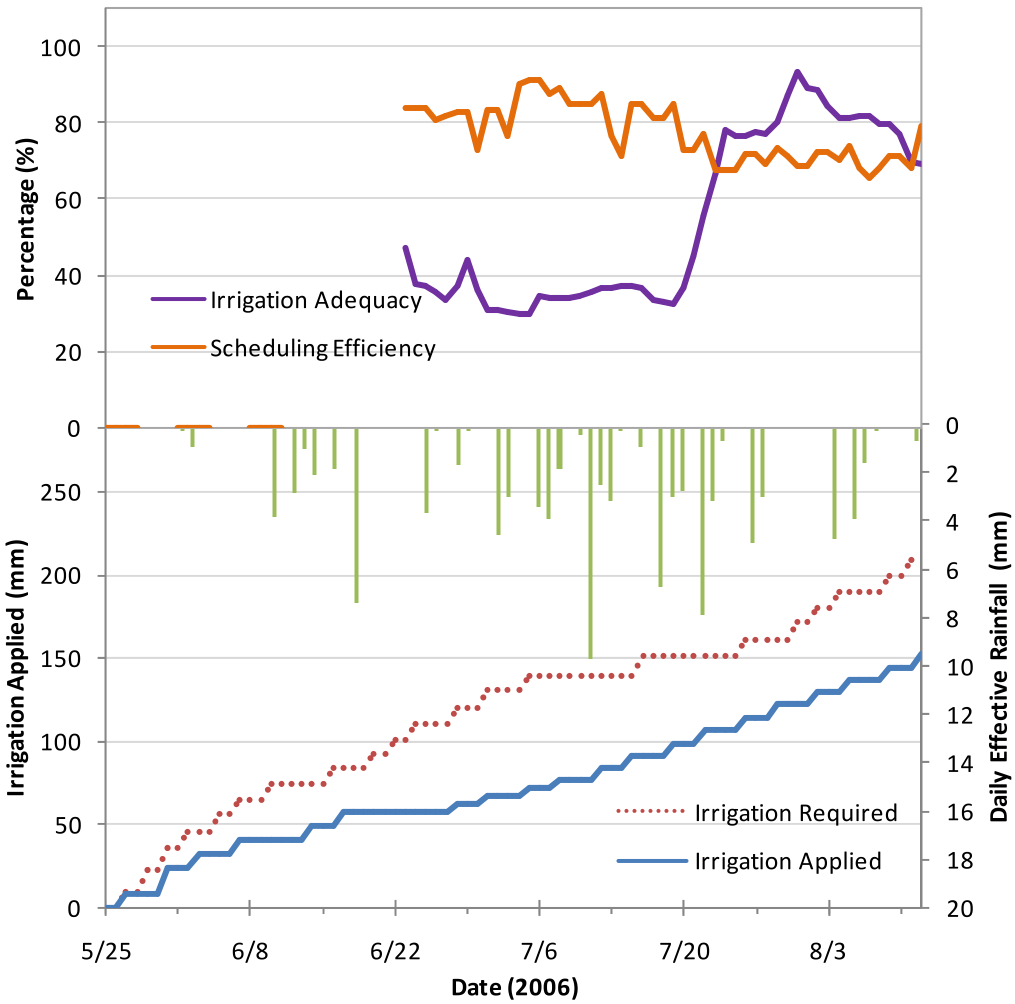

Figure 4-6. Reduced time-based treatment (T5) results over the summer 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

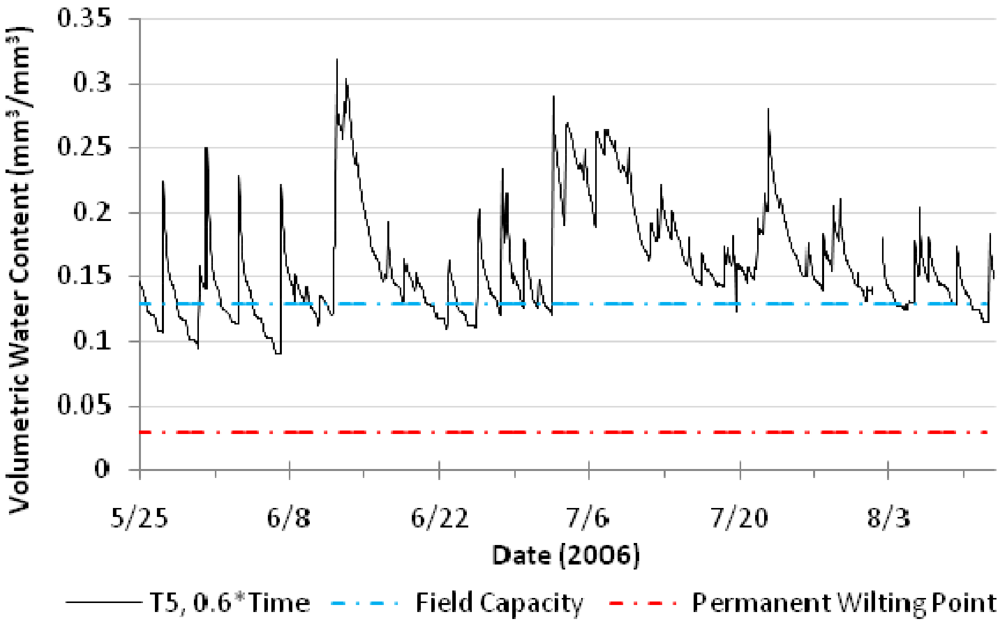

Figure 4-7. Measured volumetric soil moisture content over the summer 2006 season for T5, the reduced time-based treatment.

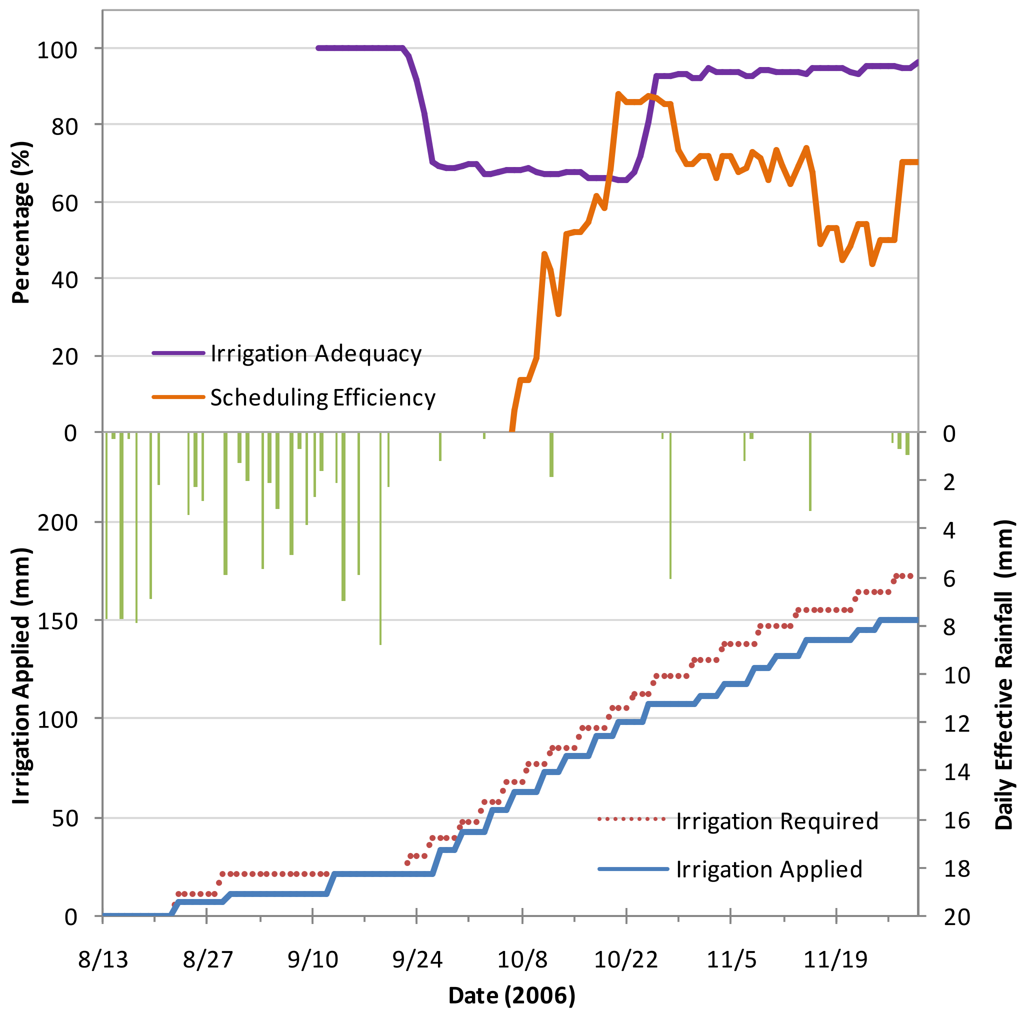

Figure 4-8. Weathermatic controller (T1) results over the fall 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

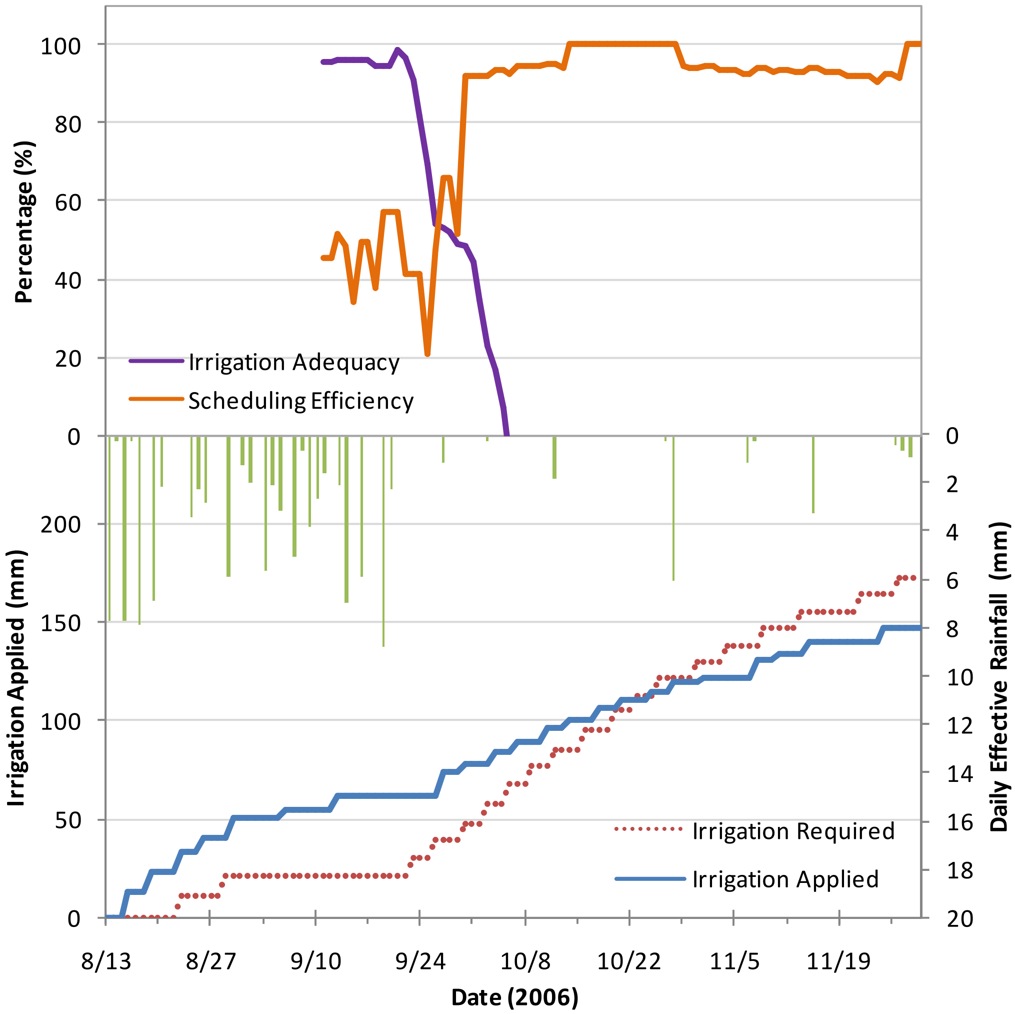

Figure 4-9. Toro controller (T2) results over the fall 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

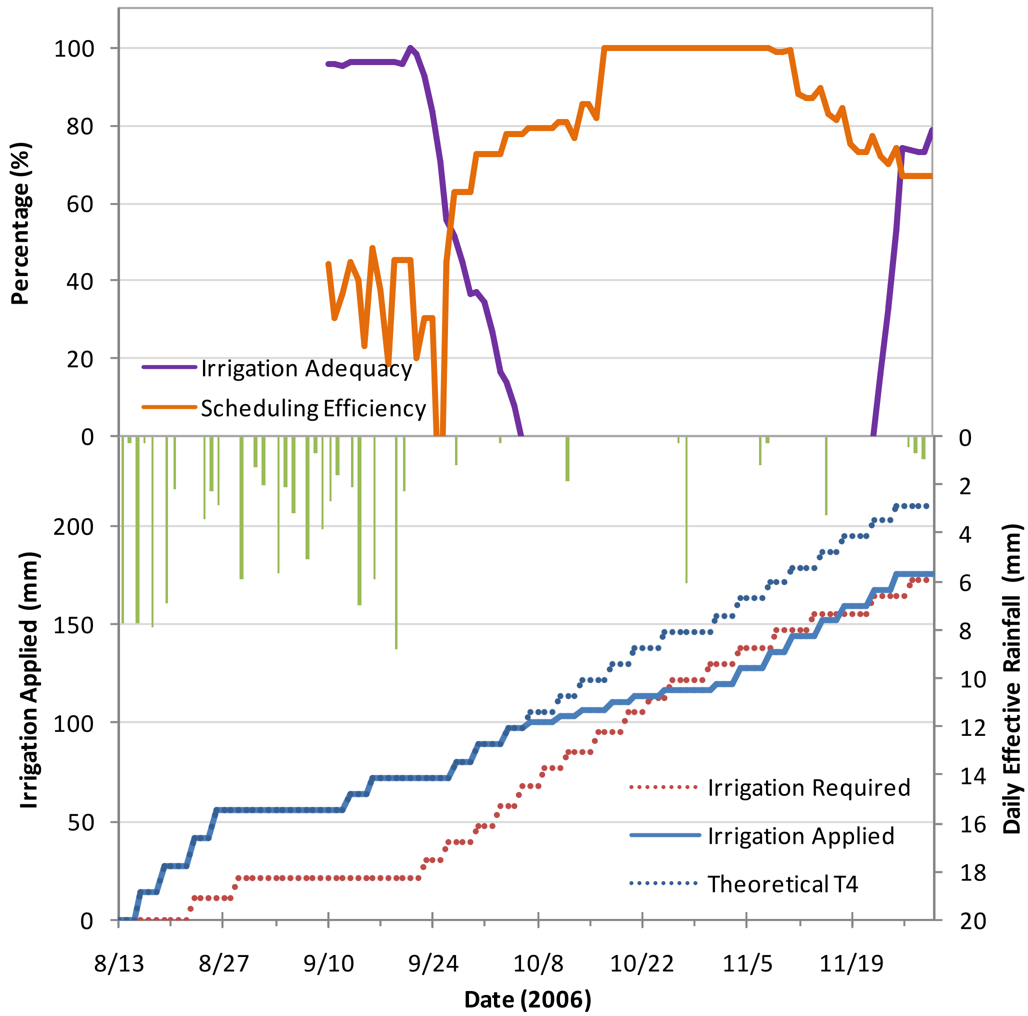

Figure 4-10. Time-based treatment (T4) results over the fall 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency. Actual water application was used in the calculations of irrigation adequacy and irrigation scheduling efficiency.

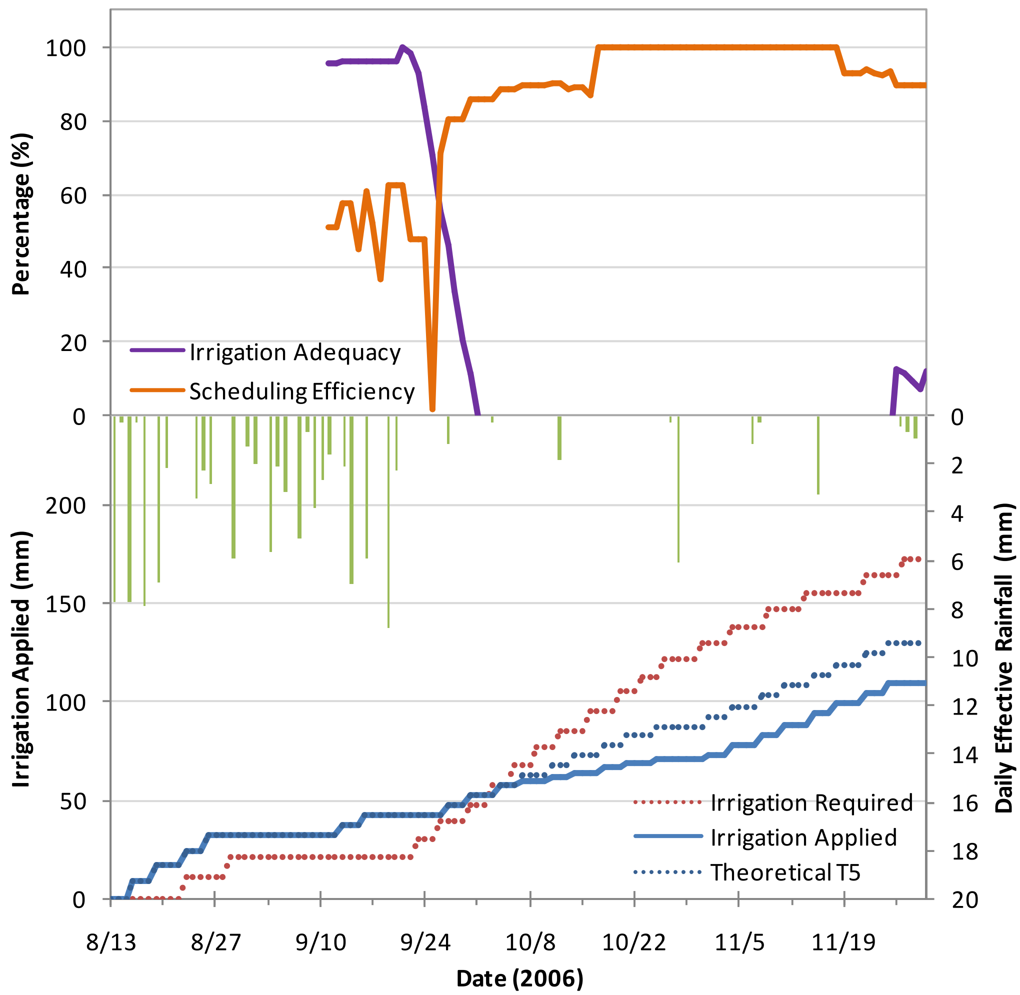

Figure 4-11. Reduced time-based treatment (T5) results over the fall 2006 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency. Actual water application was used in the calculations of irrigation adequacy and irrigation scheduling efficiency.

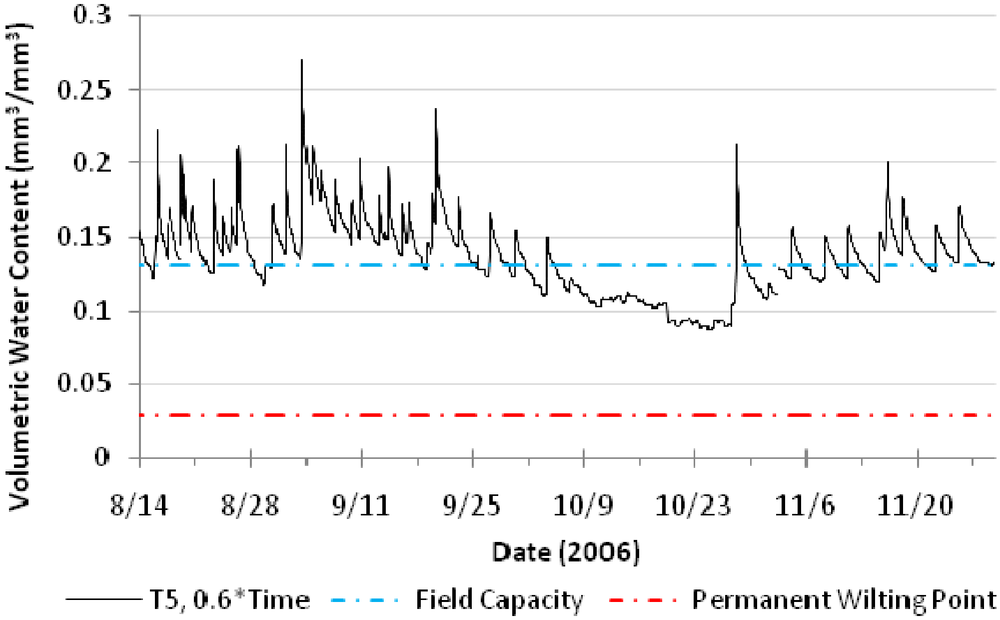

Figure 4-12. Volumetric soil moisture content over the fall 2006 season for T5, the reduced time-based treatment.

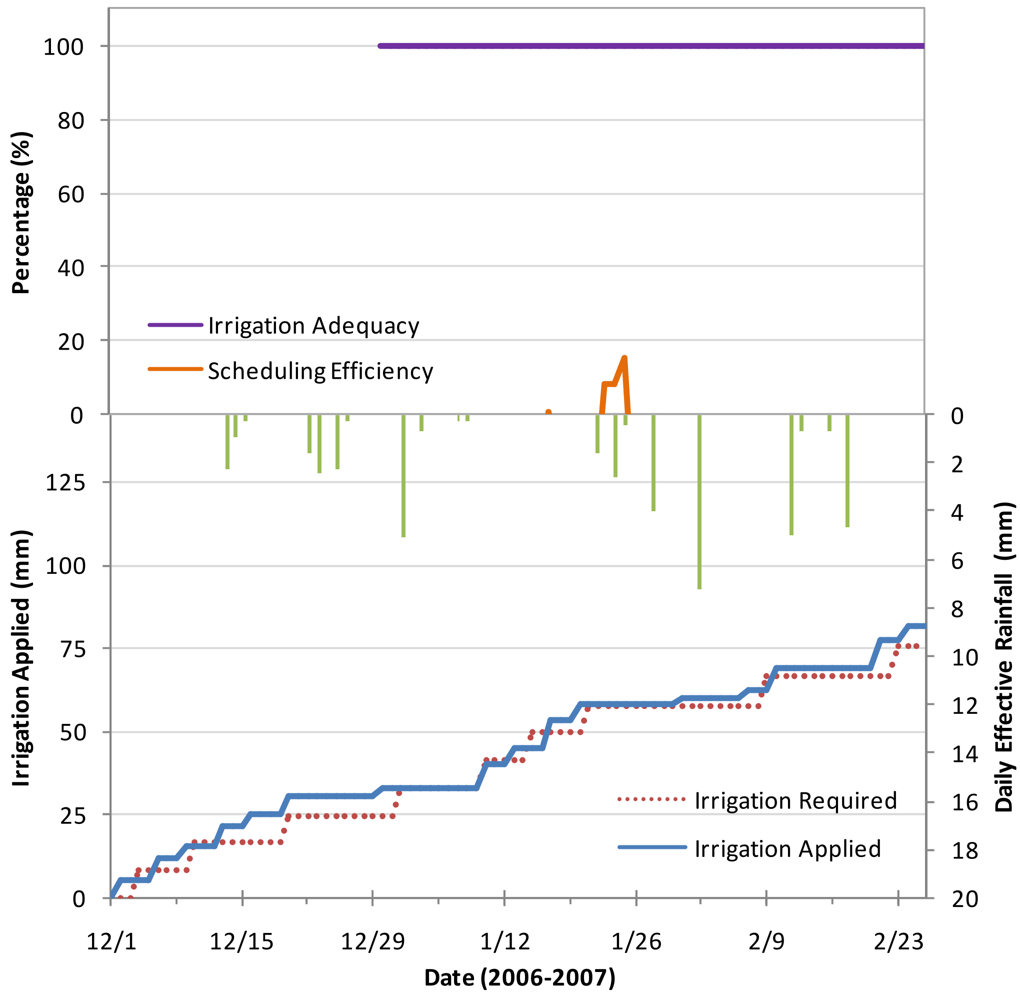

Figure 4-13. Weathermatic controller (T1) results over the winter 2006-2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

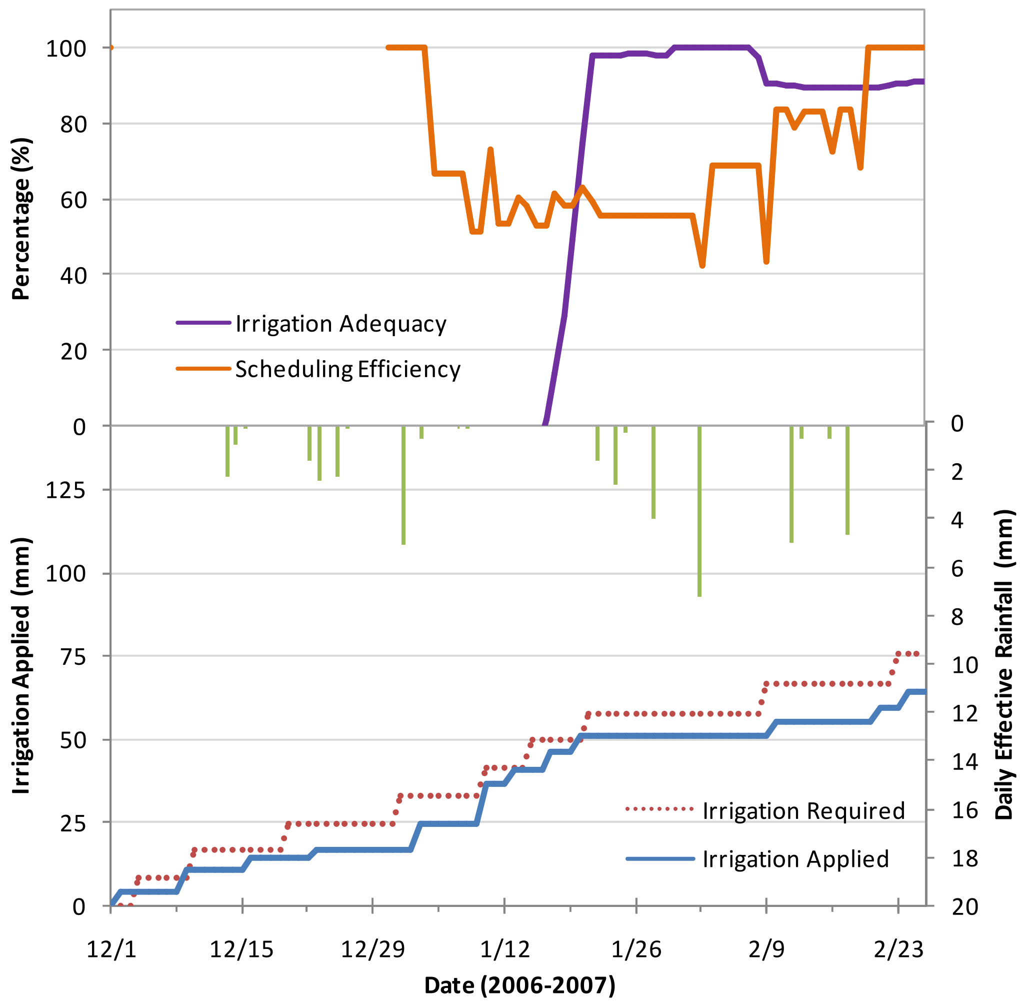

Figure 4-14. Toro controller (T2) results over the winter 2006-2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

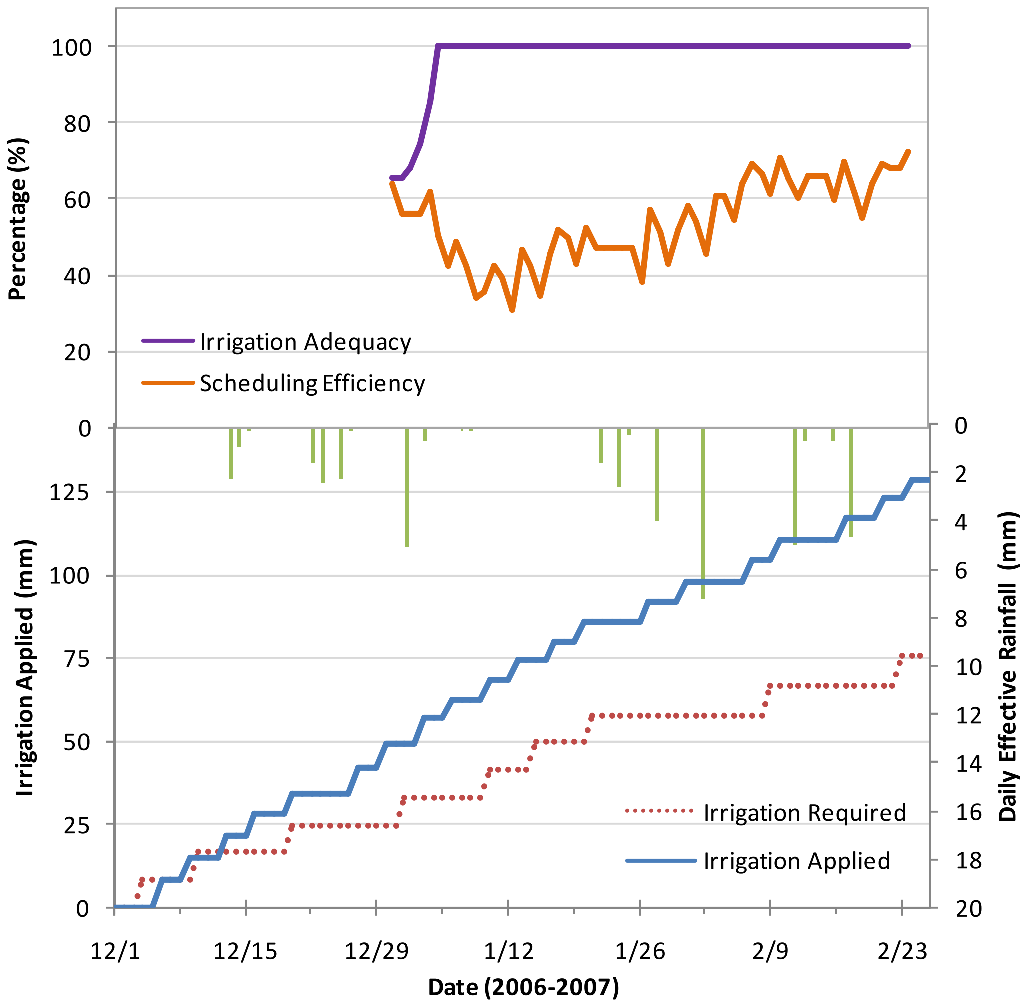

Figure 4-15. Time-based treatment (T4) results over the winter 2006-2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

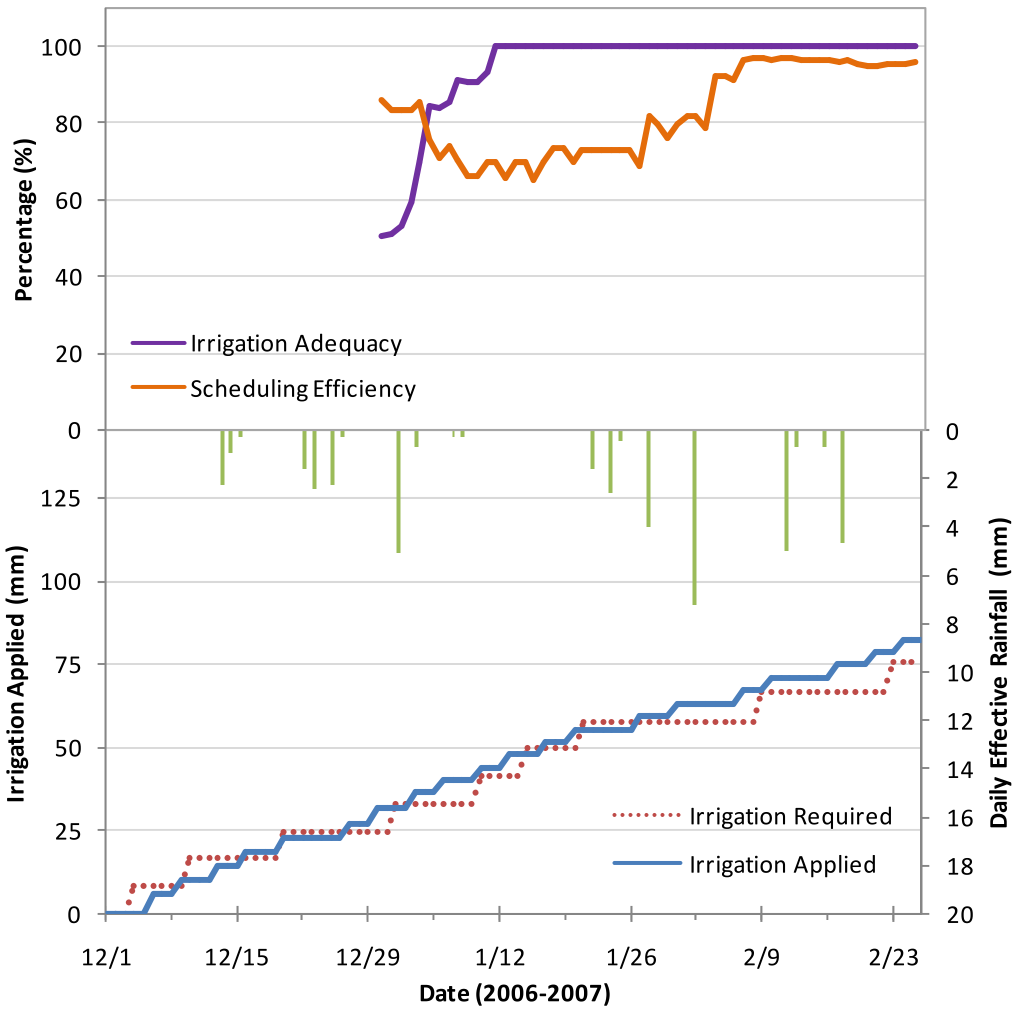

Figure 4-16. Reduced time-based treatment (T5) results over the winter 2006-2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

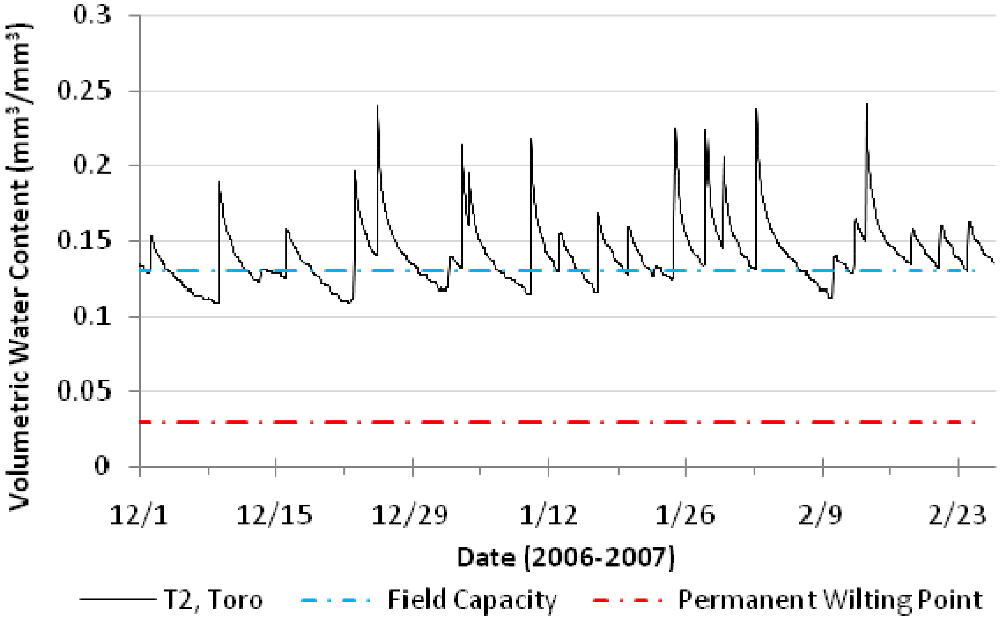

Figure 4-17. Volumetric soil moisture content over the winter 2006-2007 season for T2, the Toro controller.

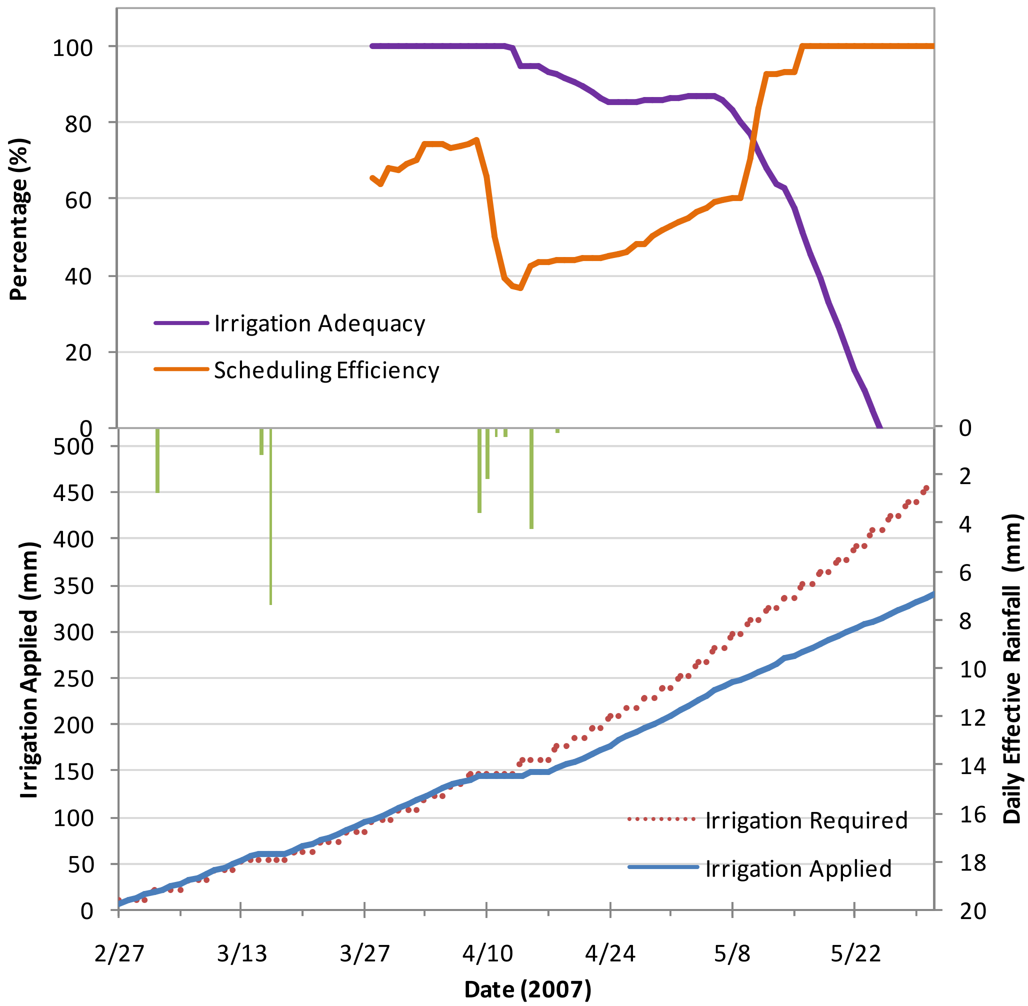

Figure 4-18. Weathermatic controller (T1) results over the spring 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

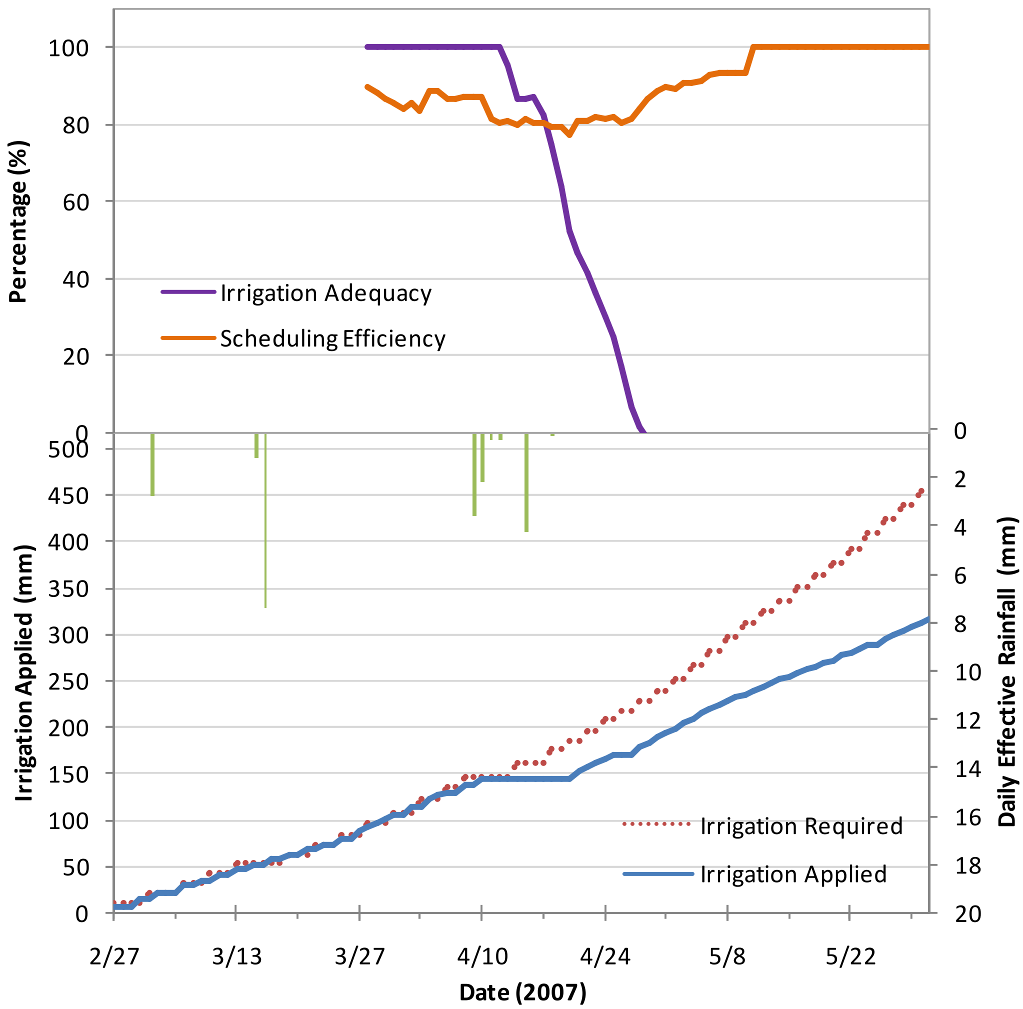

Figure 4-19. Toro controller (T2) results over the spring 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

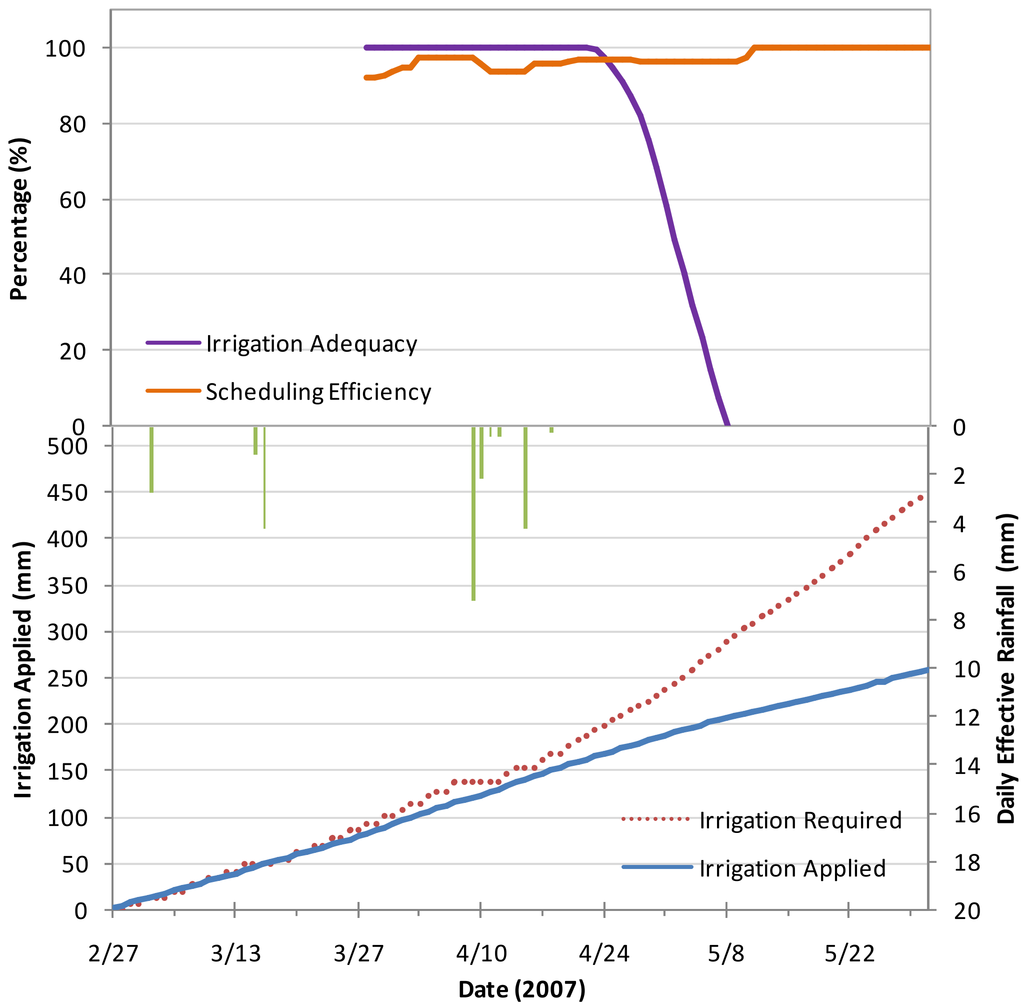

Figure 4-20. ET Water controller (T3) results over the spring 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

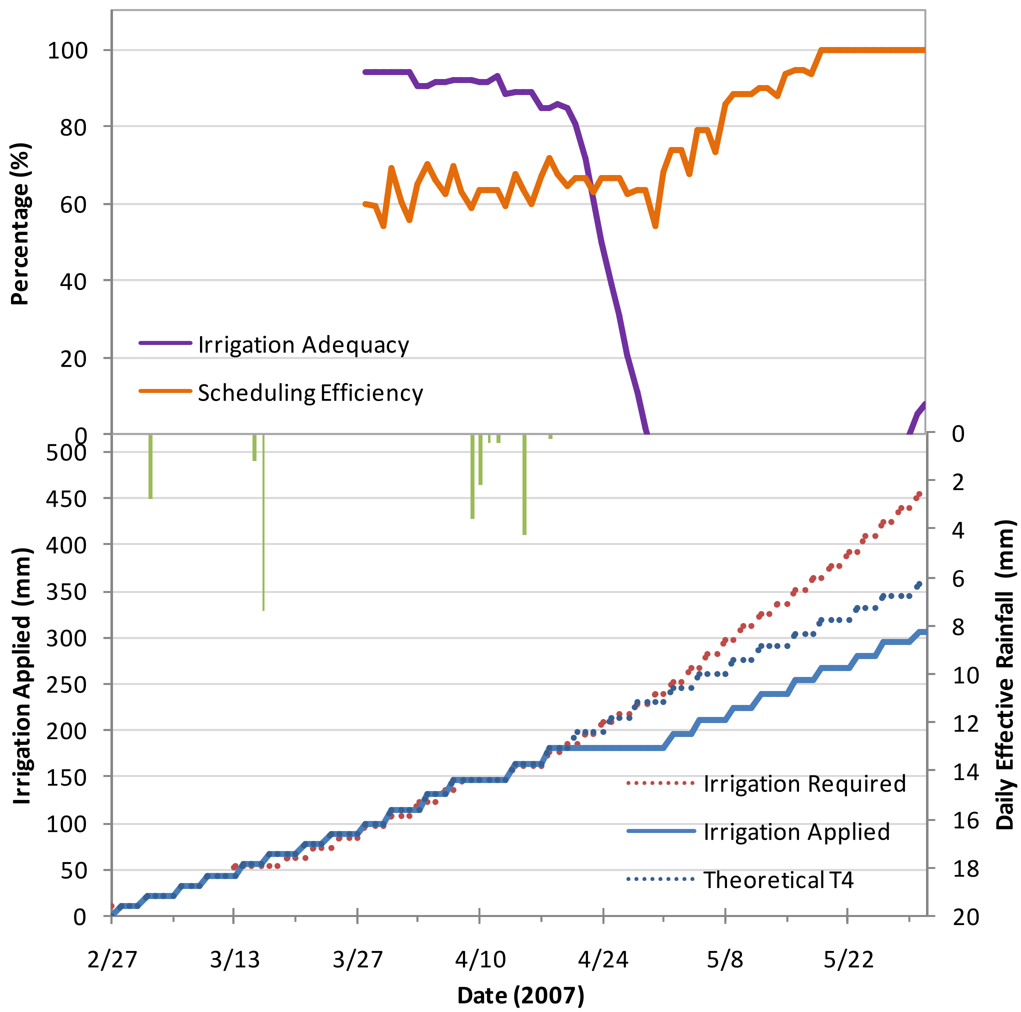

Figure 4-21. Time-based treatment (T4) results over the spring 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

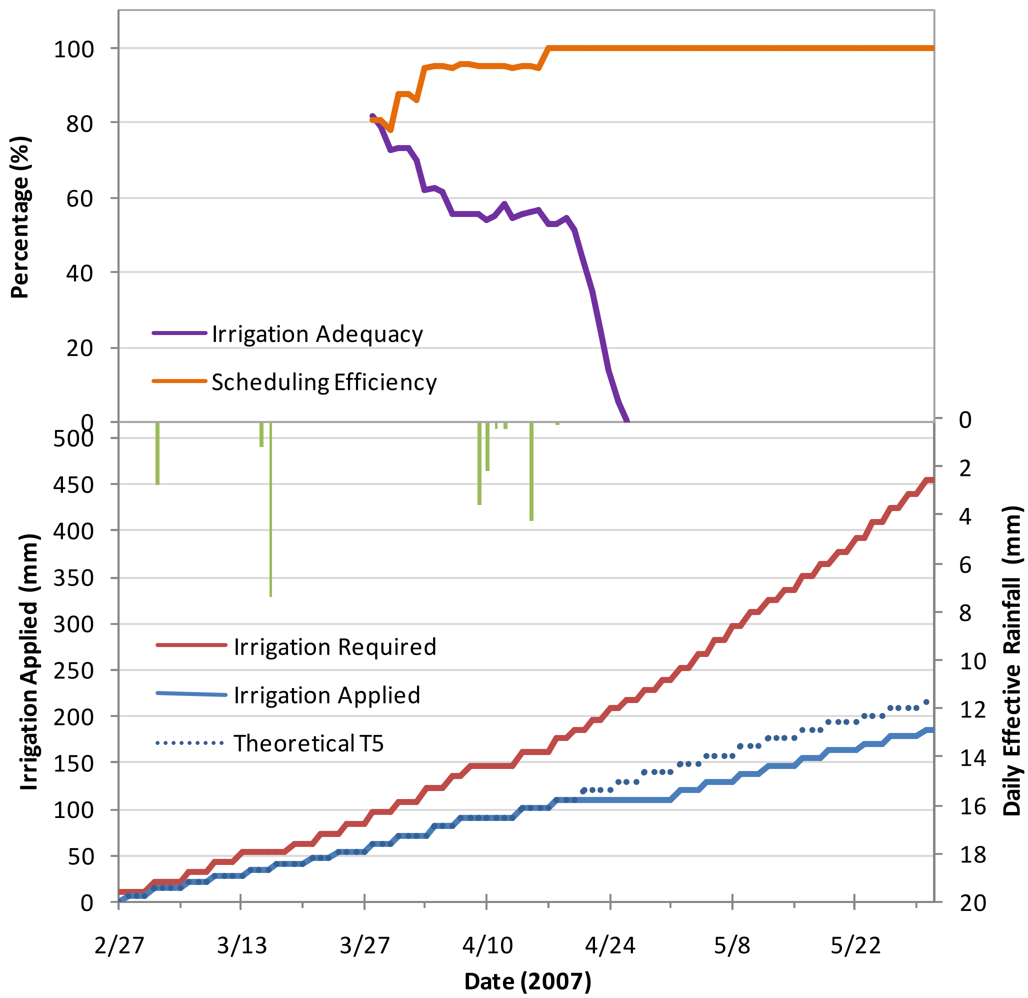

Figure 4-22. Reduced time-based treatment (T5) results over the spring 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

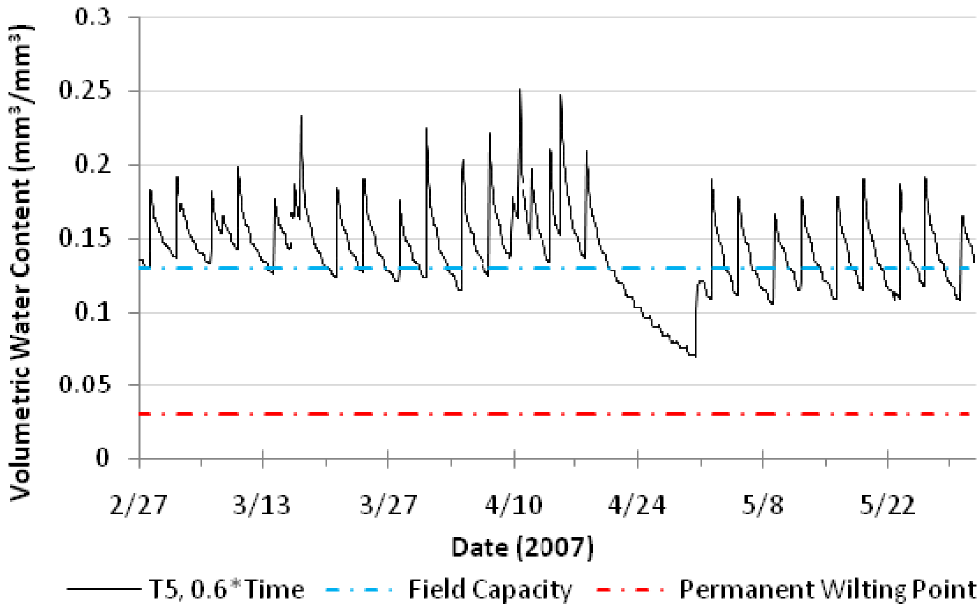

Figure 4-23. Volumetric soil moisture content over the spring 2007 season for T5, the reduced time-based treatment.

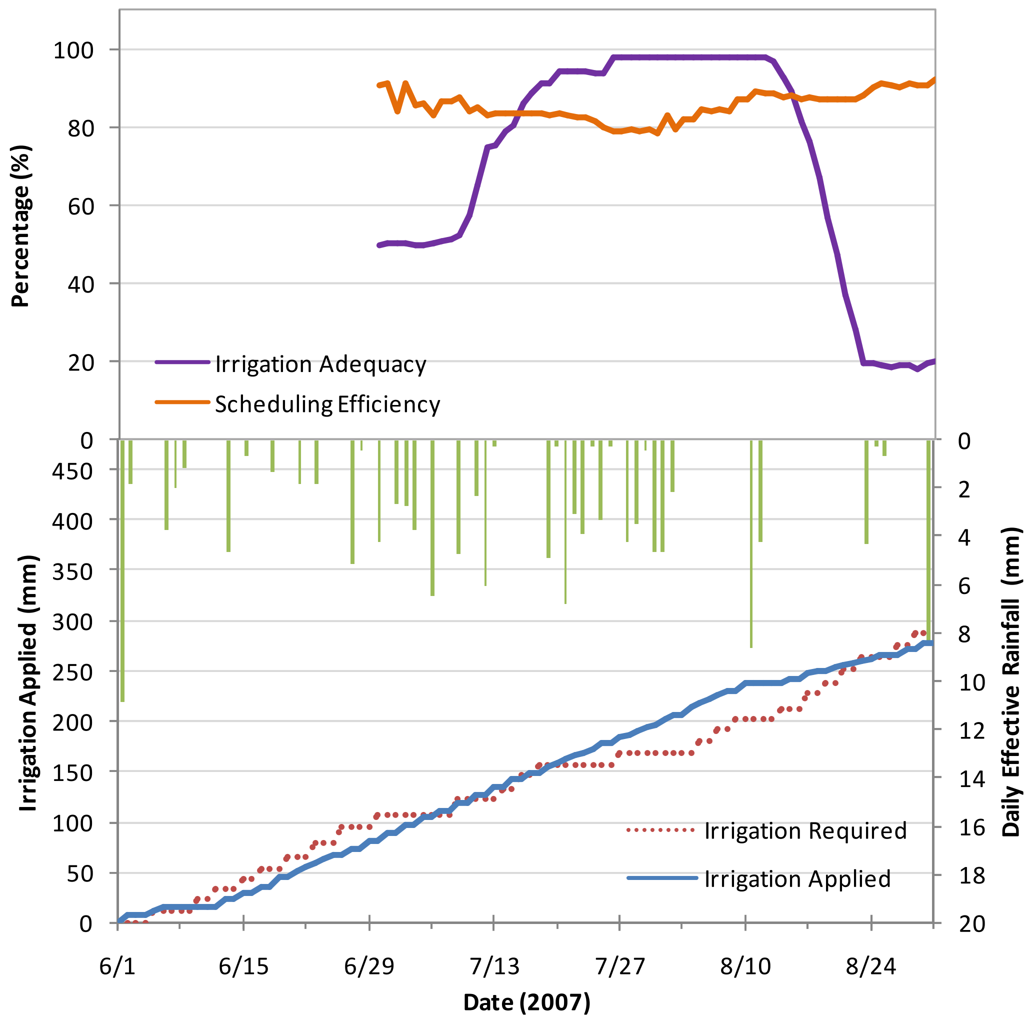

Figure 4-24. Toro controller (T2) results over the summer 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

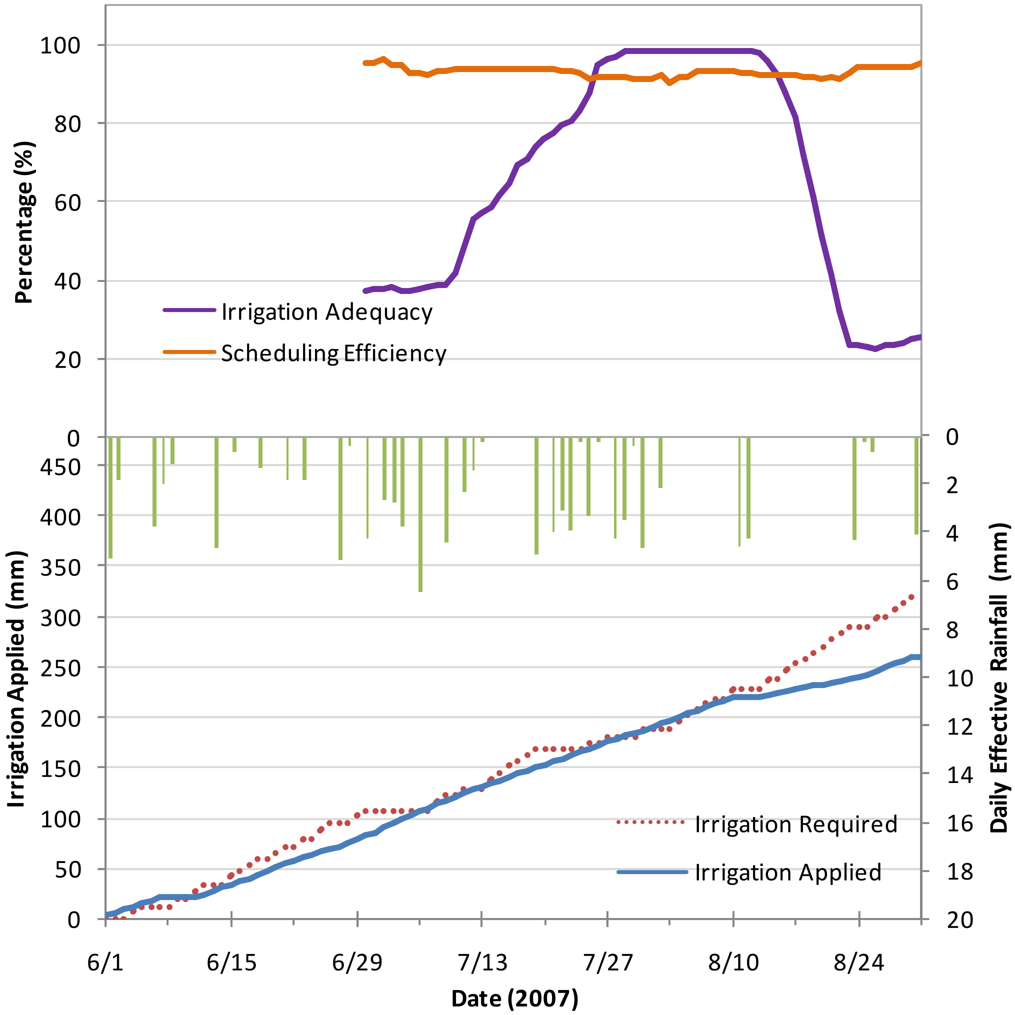

Figure 4-25. ET Water controller (T3) results over the summer 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

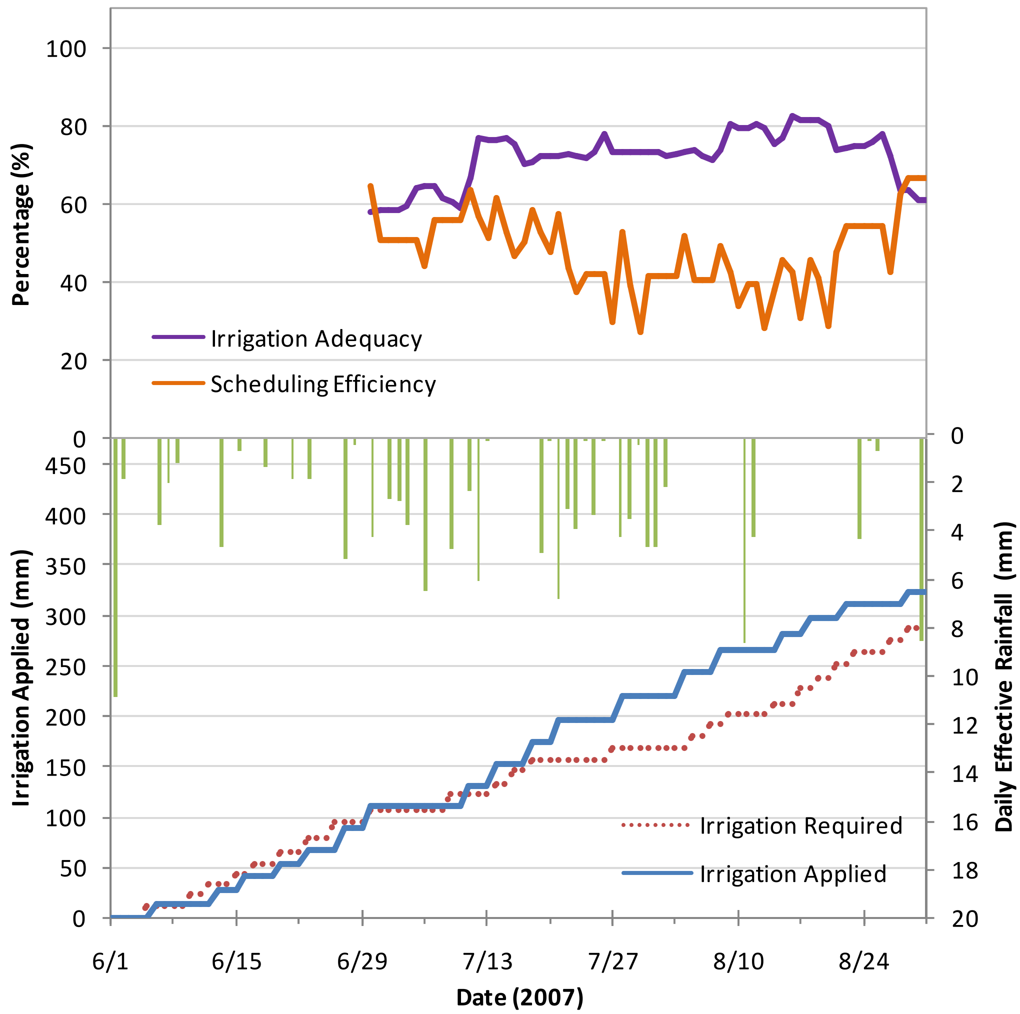

Figure 4-26. Time-based treatment (T4) results over the summer 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

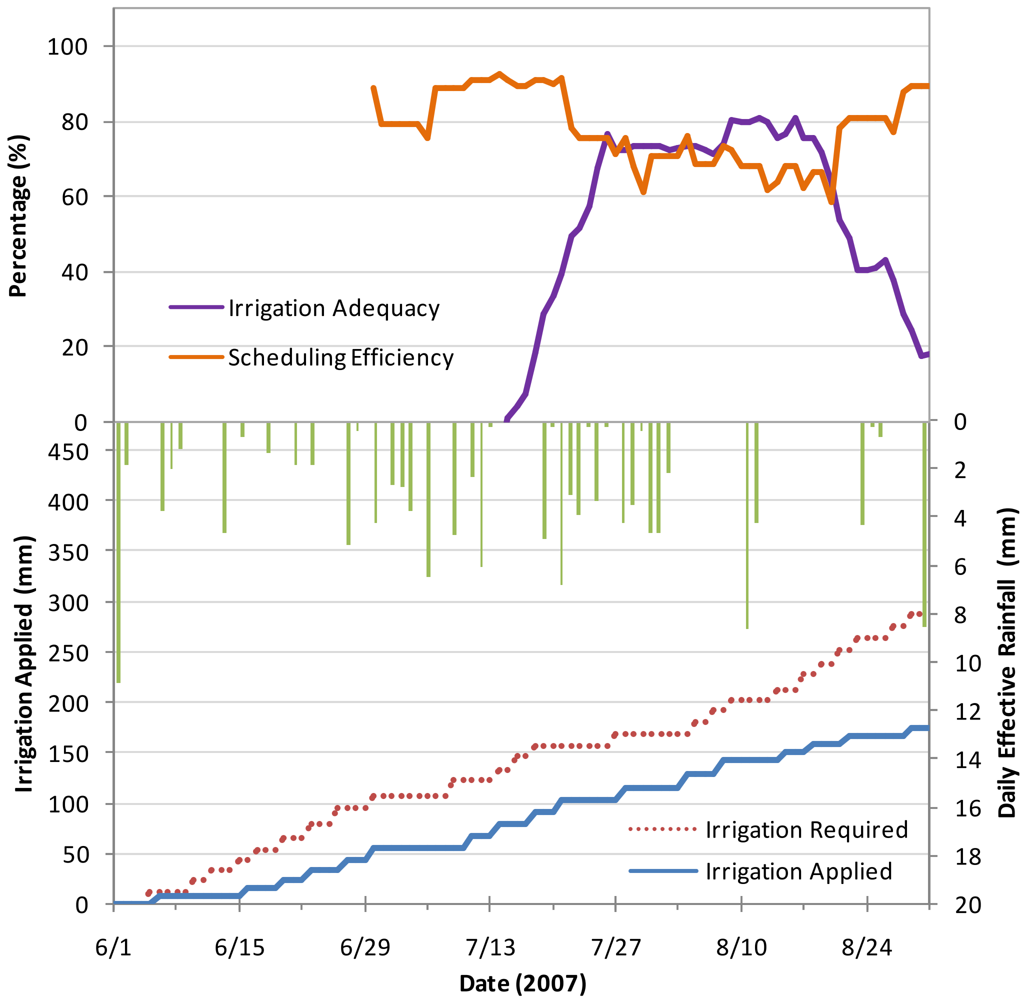

Figure 4-27. Reduced time-based treatment (T5) results over the summer 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

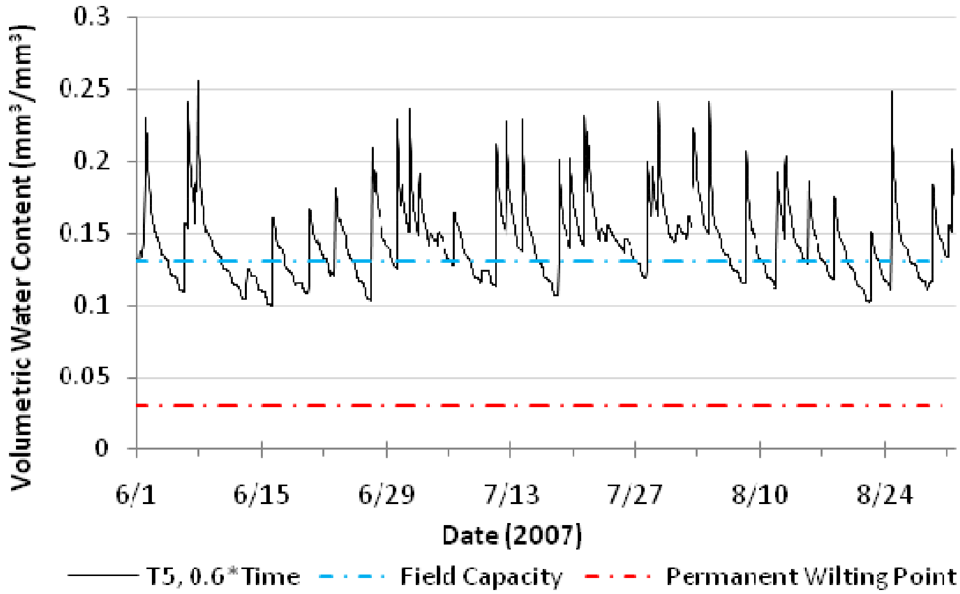

Figure 4-28. Volumetric soil moisture content for the Summer 2007 season for T5, the reduced time-based treatment.

Figure 4-29. The position of the Weathermatic weather monitor when it was damaged.

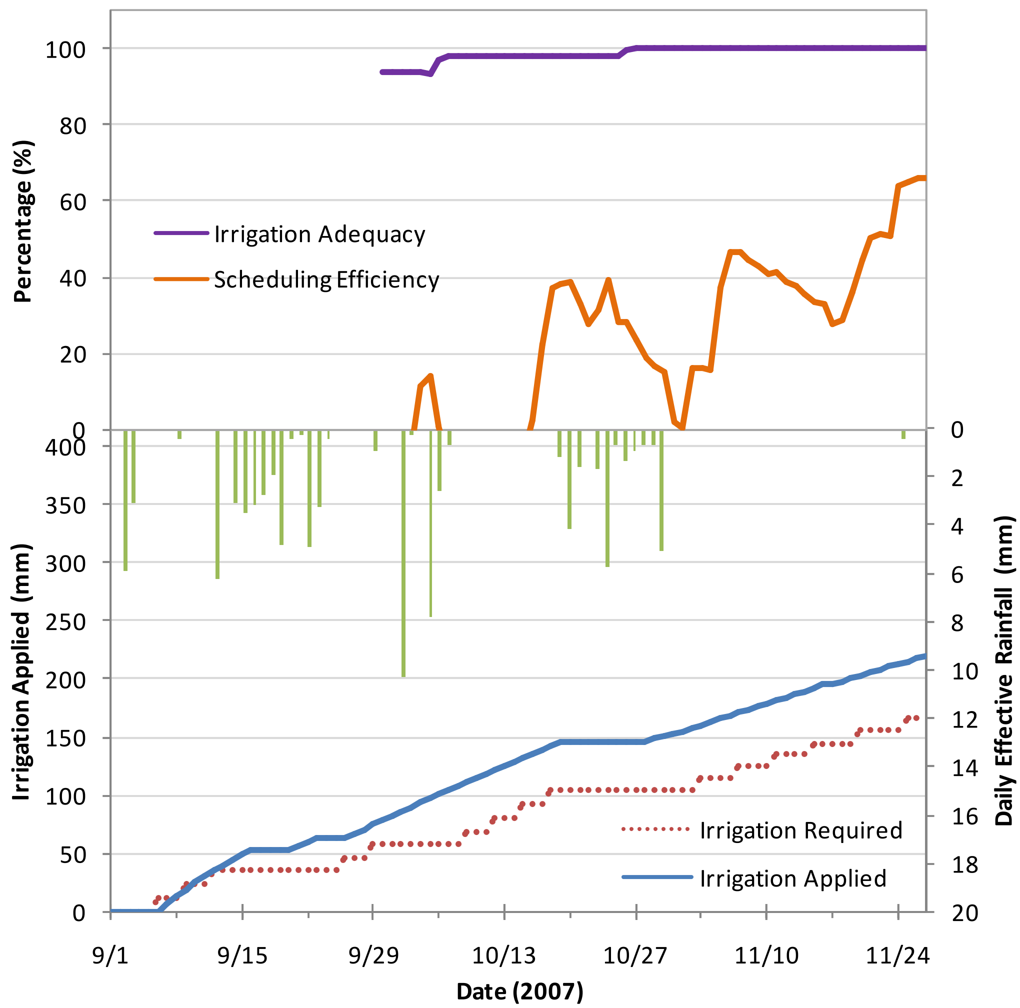

Figure 4-30. Weathermatic controller (T1) results over the fall 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

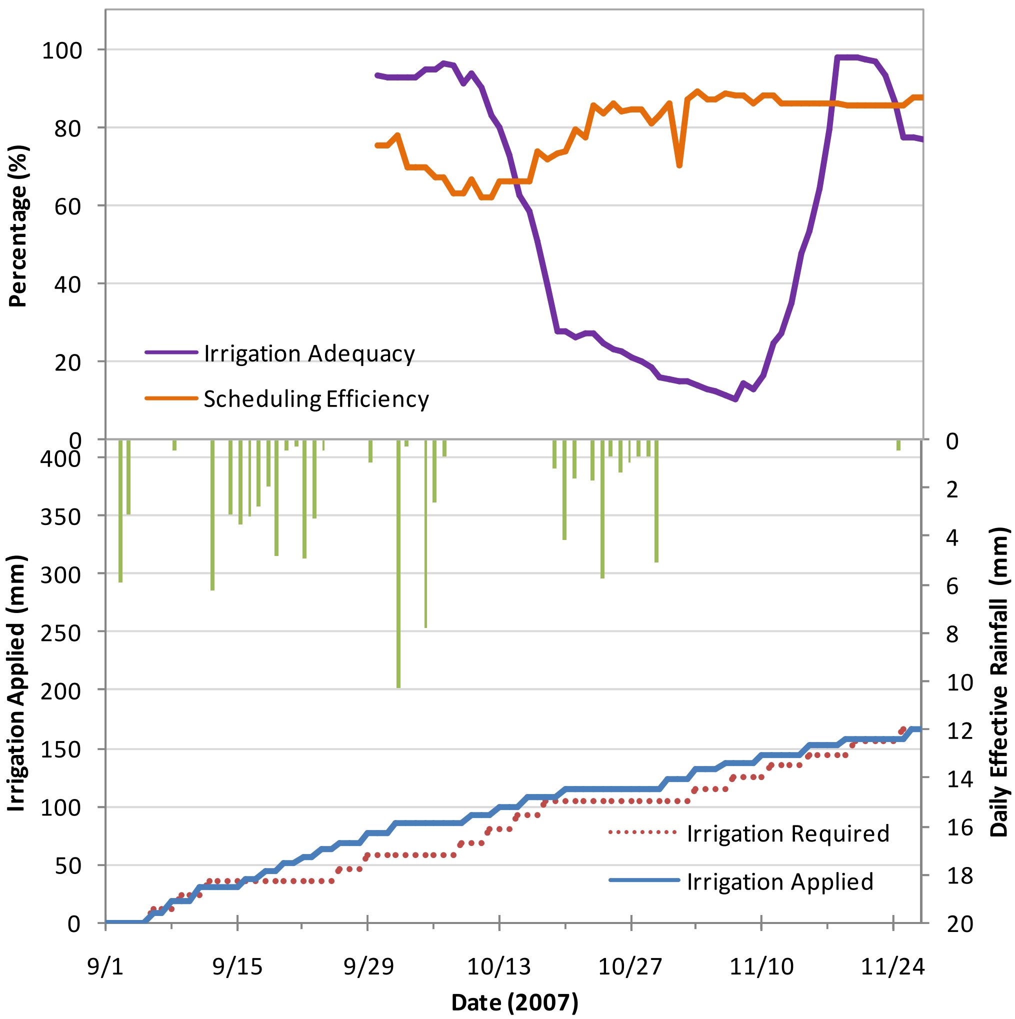

Figure 4-31. Toro controller (T2) results over the fall 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

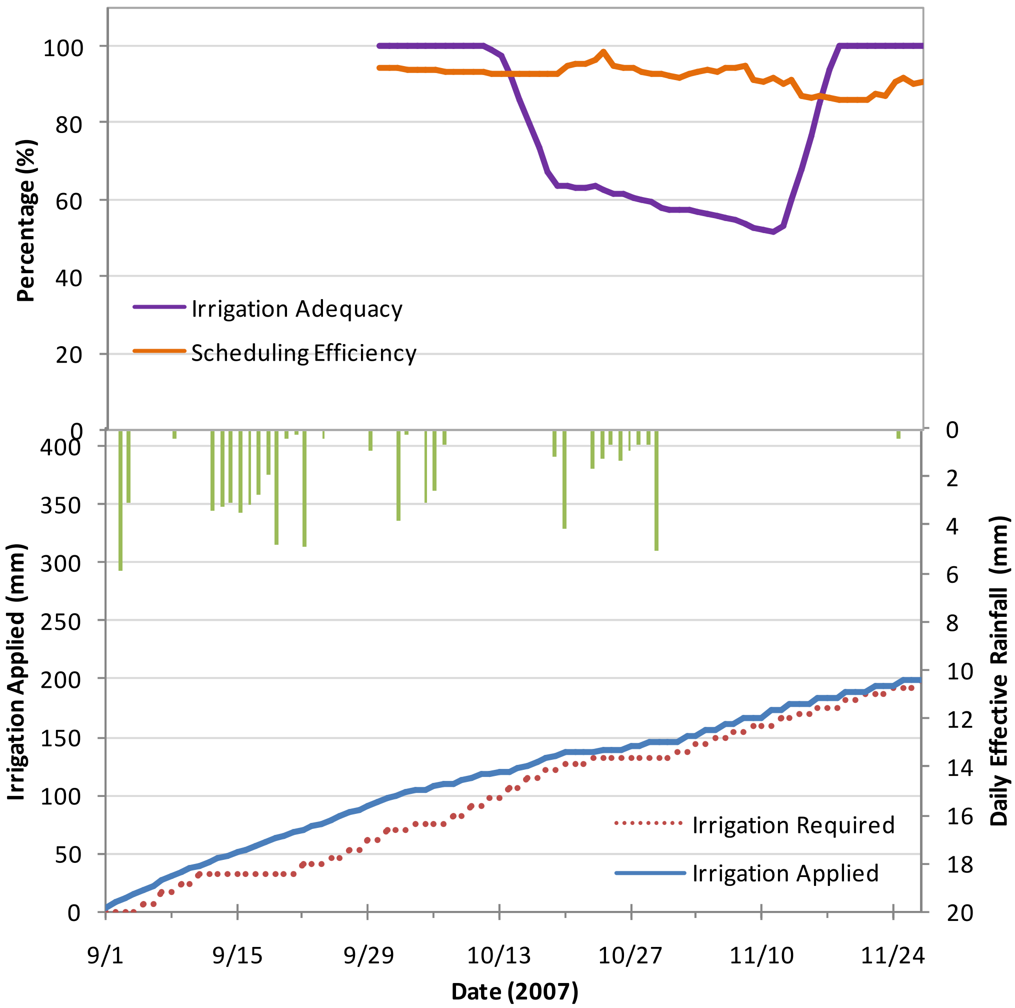

Figure 4-32. ET Water controller (T3) results over the fall 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

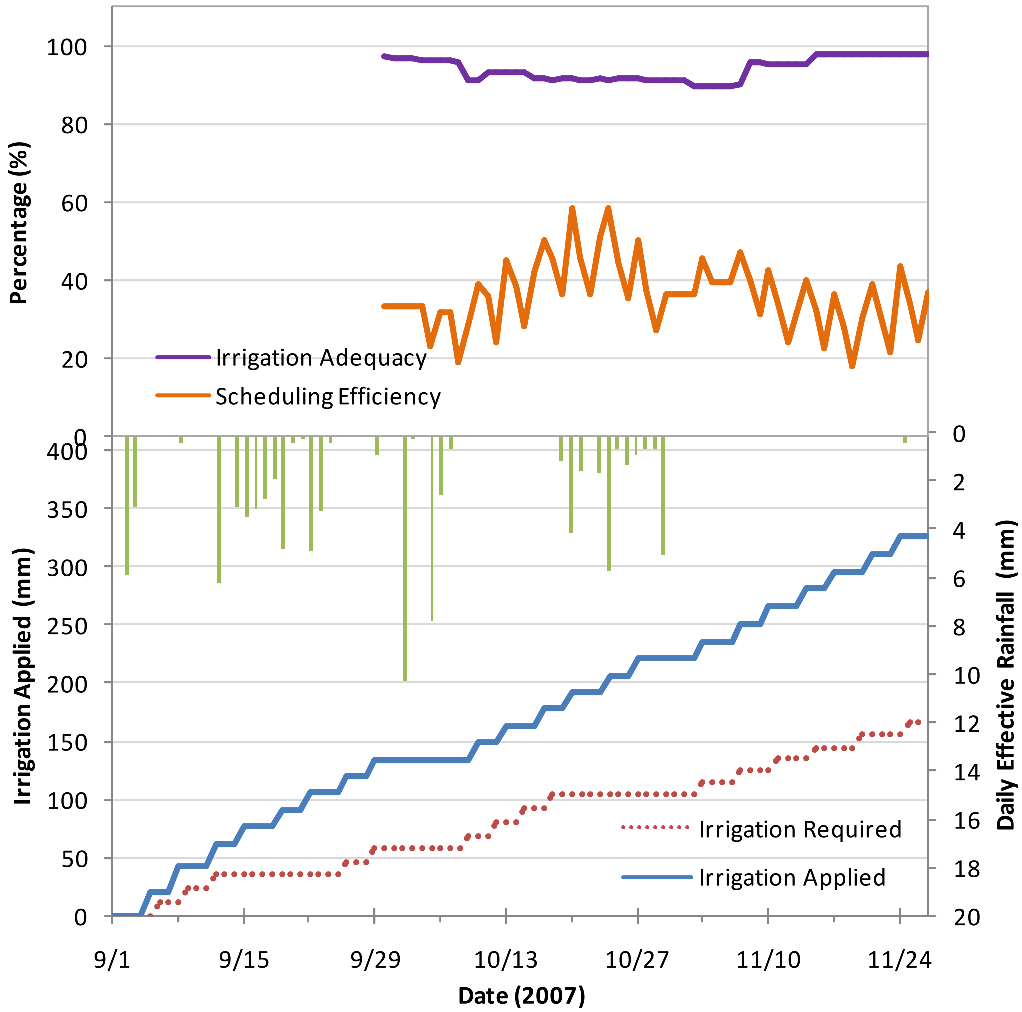

Figure 4-33. Time-based treatment (T4) results over the fall 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

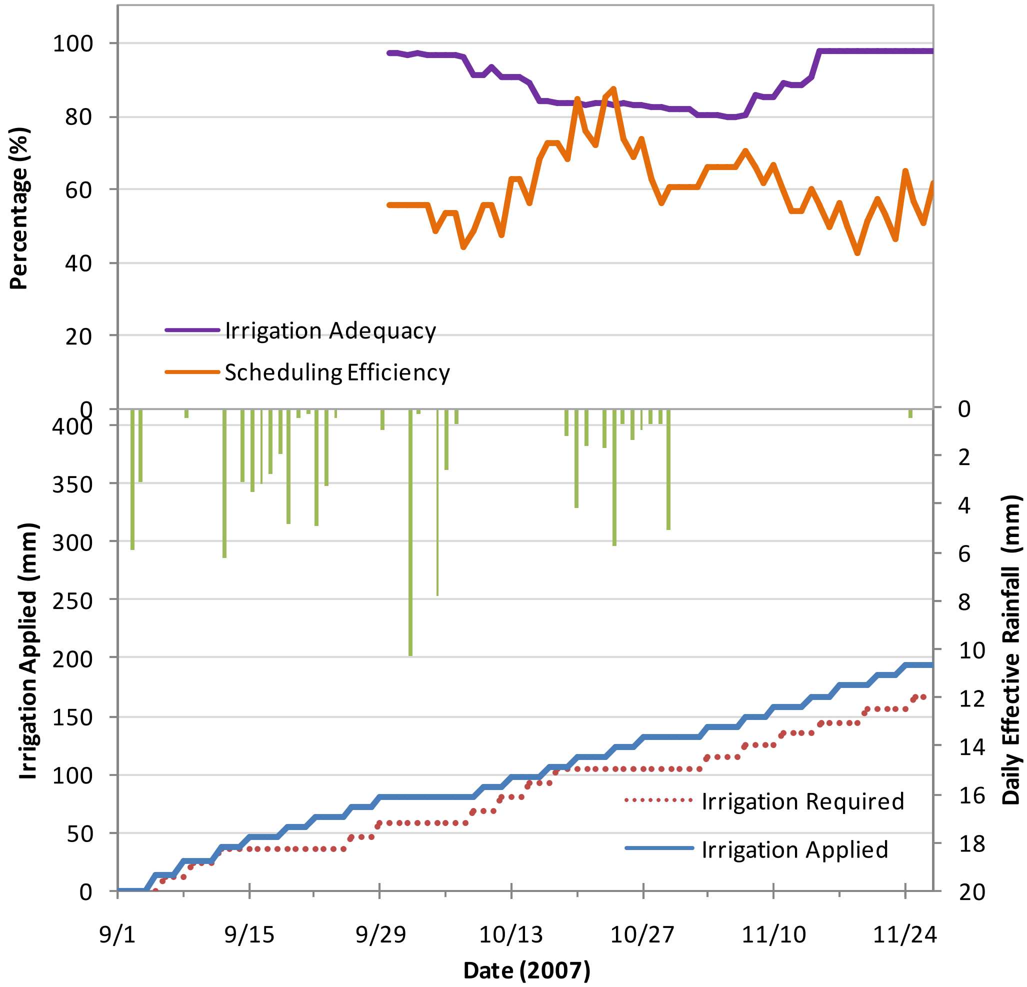

Figure 4-34. Reduced time-based treatment (T5) results over the fall 2007 season for cumulative theoretical irrigation depth applied, daily effective rainfall, and 30-day moving totals of irrigation adequacy and scheduling efficiency.

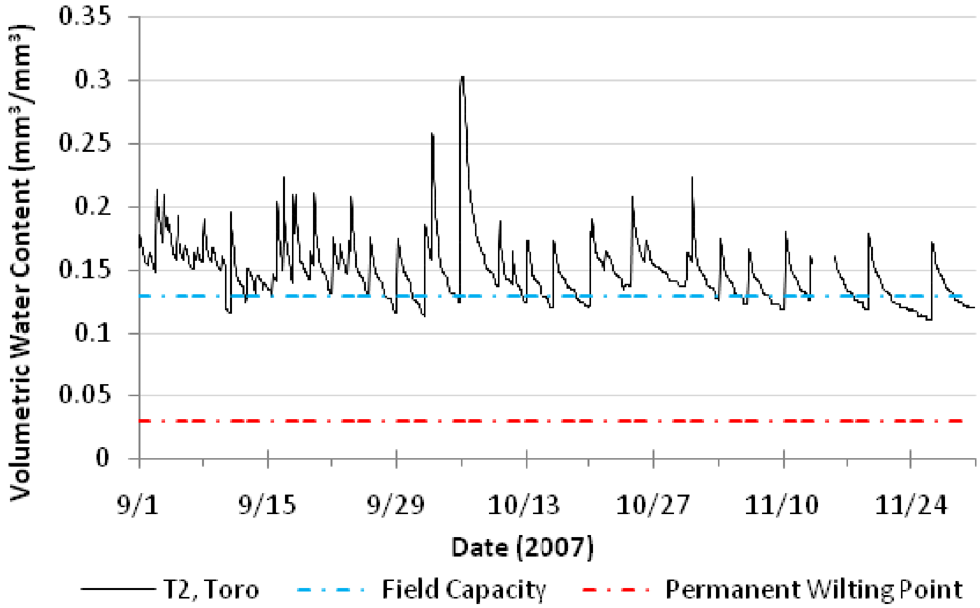

Figure 4-35. Volumetric soil moisture content for the fall 2007 season for T2, the Toro controller.

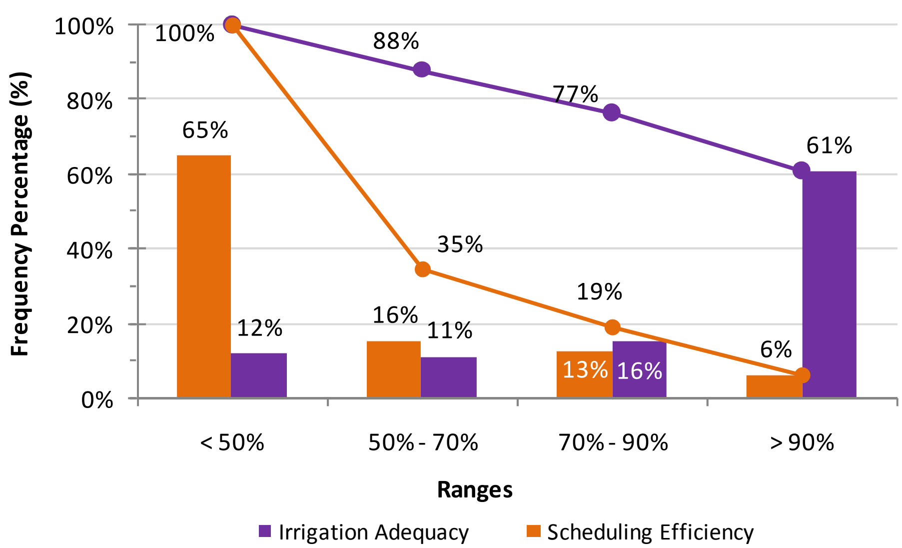

Figure 4-36. Weathermatic controller, T1, percent frequency of irrigation adequacy and scheduling efficiency scores for the following performance ranges: greater than 90%, 70% to 90%, 50% to 70%, and less than 50%.

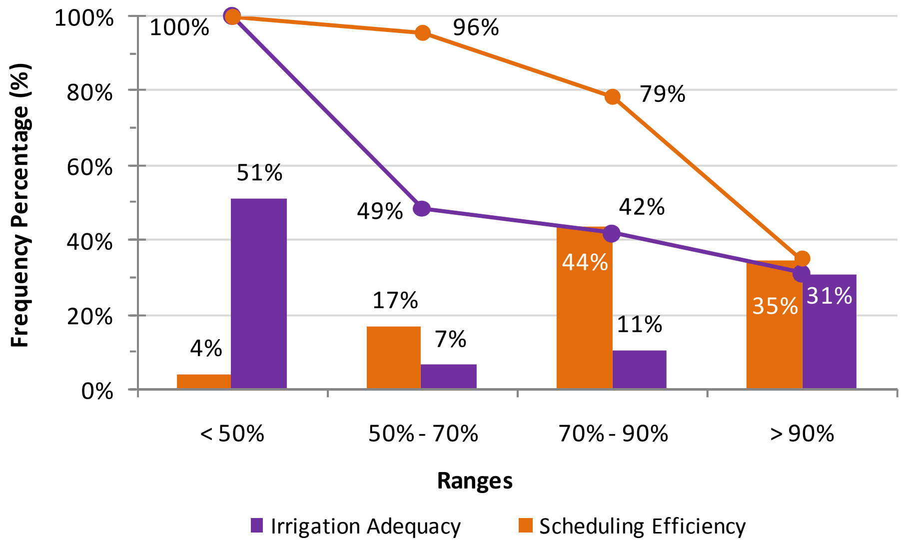

Figure 4-37. Toro controller, T2, percent frequency of irrigation adequacy and scheduling efficiency scores for the following performance ranges: greater than 90%, 70% to 90%, 50% to 70%, and less than 50%.

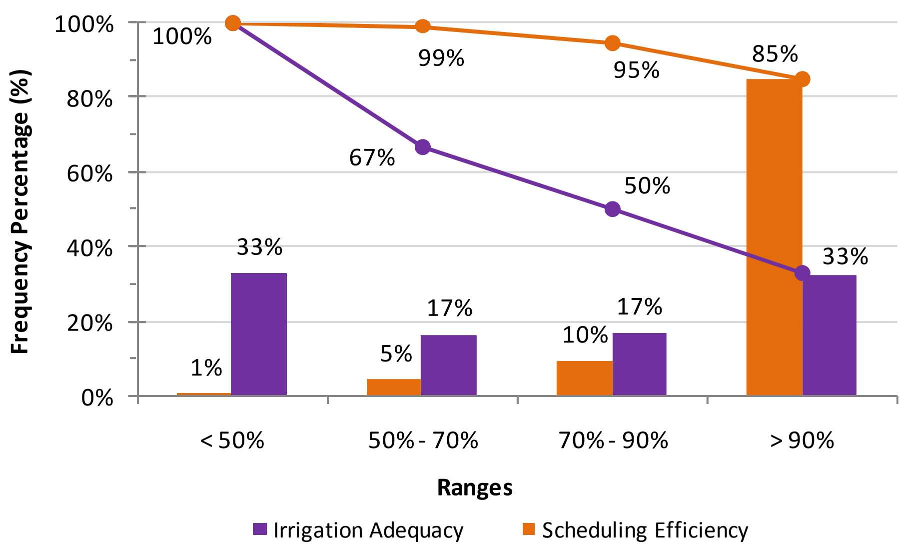

Figure 4-38. ET Water controller, T3, percent frequency of irrigation adequacy and scheduling efficiency scores for the following performance ranges: greater than 90%, 70% to 90%, 50% to 70%, and less than 50%.

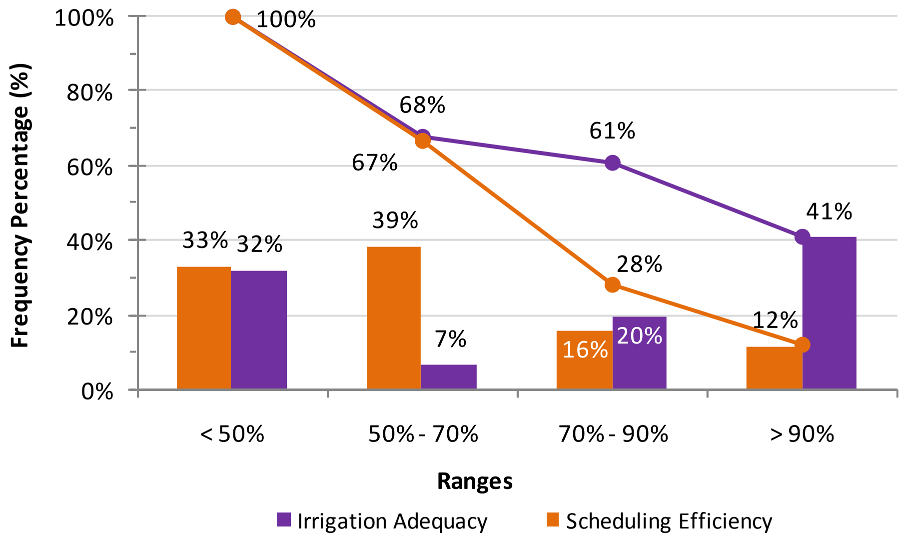

Figure 4-39. Time-based treatment, T4, percent frequency of irrigation adequacy and scheduling efficiency scores for the following performance ranges: greater than 90%, 70% to 90%, 50% to 70%, and less than 50%.

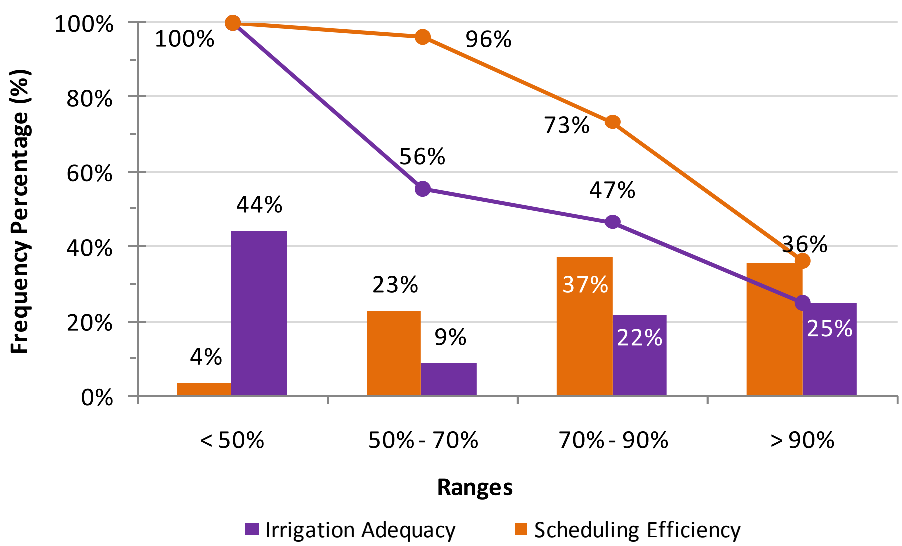

Figure 4-40. Reduced time-based treatment, T5, percent frequency of irrigation adequacy and scheduling efficiency scores for the following performance ranges: greater than 90%, 70% to 90%, 50% to 70%, and less than 50%.

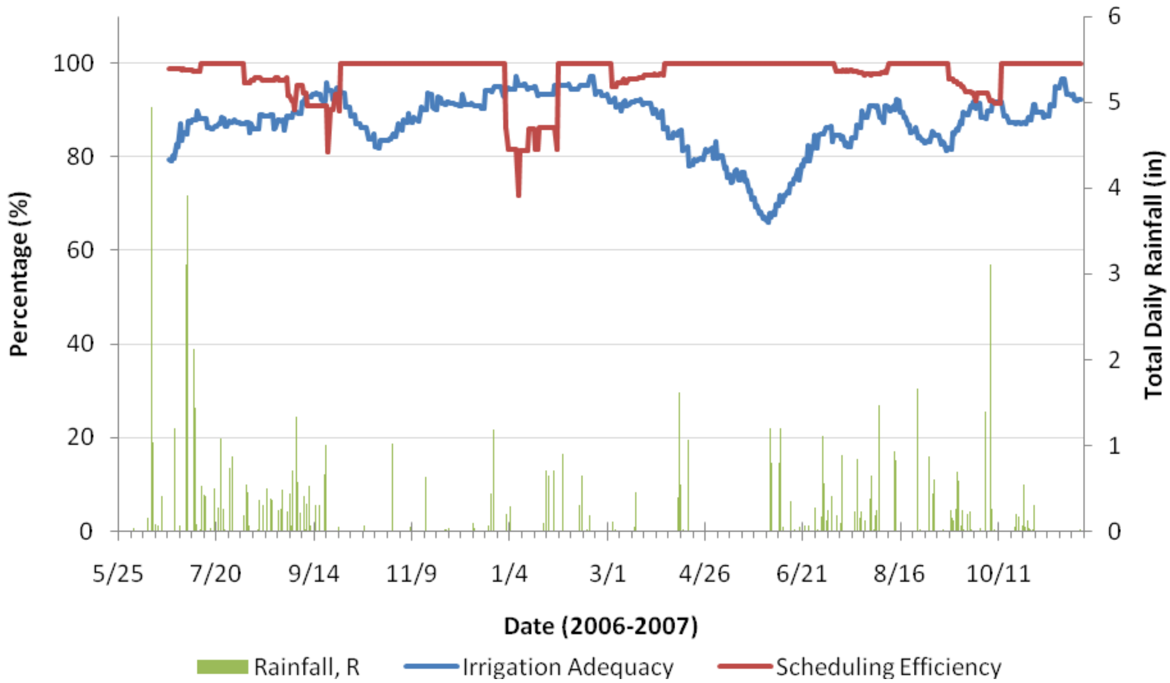

Figure 4-41. Total daily rainfall and 30-day moving totals of irrigation adequacy and scheduling efficiency for the theoretical irrigation requirement over the entire study period.

CHAPTER 5
CONCLUSIONS AND FUTURE WORK

Conclusions

The goal of this research was to determine whether ET-based irrigation controllers would be able to conserve water in Florida climate conditions. The primary objectives of this research were to evaluate the ability of three brands of ET-based controllers to A) schedule irrigation by comparing irrigation application to a time clock schedule intended to mimic homeowner irrigation schedules, while maintaining acceptable turfgrass quality, B) estimate reference evapotranspiration compared to the ASCE Standardized Reference Evapotranspiration methodology, and C) schedule irrigation compared to a theoretically derived soil water balance model. Secondary objectives included a) quantifying the variation between controllers of the same brand, b) compare the performance of the ET controllers based on approximate distance to a publically available weather data source, and c) measure the ET controller performance using the SWAT testing protocol.

Rainfall over the study period, May 25, 2006 through November 30, 2007, was less than the thirty year historical rainfall averages for the same time period. Although drier than normal, there were two distinct wet periods ranging from June through September for 2006 and June through October for 2007. The study period experienced dry conditions containing 69% dry days. It was found that using a rain sensor with a time-based irrigation schedule conserved 21% of water despite the unusual dry conditions.

The three brands of ET controllers studied were as follows: Weathermatic SL1600 controller with SLW15 weather monitor; Toro Intelli-sense utilizing the WeatherTRAK ET Everywhere service; and ET Water Smart Controller 100. There were three controllers, one of each brand, installed in southwest Florida at a project site where the controllers scheduled irrigation on mixed landscape plots. Controllers observed watering restrictions of 2d/wk and were programmed with a system efficiency of 100% or 95%for the first half of the study period. Watering restrictions were lifted to allow 7d/wk irrigation and included a system efficiency of 80% based on distribution uniformity testing for the last half of the study.

Nine ET controllers, three replications of each brand being tested, were installed in addition to the main project to determine if there was variability between controllers concerning irrigation scheduling, reference evapotranspiration (ET_o) estimation, and proximity to weather data source. There were no differences between the replications of the controllers for both irrigation scheduling and ET_o estimation.

The Weathermatic controllers were not affected by the proximity of a weather station as they used an on-site weather monitor for data collection. These controllers over-estimated ET_o by 8% due to the combination of using Hargreaves equation for ET_o calculations and over-estimating maximum temperatures. It was found using data collected from the Weathermatic controllers that Hargreaves equation was dependent on quality of temperature data and independent of the source for extraterrestrial radiation data. The Toro controllers estimated ET_o within 1% when the weather station was within 100 m of the controller, but had a 16% error when the nearest publically available weather station was 11 km away. The ET Water controllers over-estimated compared to the public weather station by 8% and under-estimated by 12% compared to ET_o calculated from the on-site weather station data. There was very little variability between controller replications for ET_o estimation or water application which increases the validity of the results found using the controllers at the main project site.

Water application by the ET controllers on mixed landscape plots was compared to a time-based schedule without a rain sensor. This treatment represented a conservative homeowner because the schedule was based on the historical net irrigation requirement and was updated monthly to reflect historical changes in weather conditions. Average savings compared to the time-based schedule without rain sensor across all seasons ranged from 35% to 42% for the ET controllers. Reducing the time-based schedule by 40% and including a rain sensor resulted in 53% savings showing that updating the time clock settings throughout the year can result in substantial irrigation savings. However, time-based schedules do not fluctuate with changing weather conditions and typical homeowners will not manually adjust on a regular basis. Thus, the ET controllers are necessary for consistent water savings.

Weekly water application showed that the ET controllers applied less irrigation per week than the time-based schedule without a rain sensor. Also, the ET controllers applied weekly irrigation similarly to the time-based schedule utilizing a rain sensor during seasons where water requirements were high such as spring and summer. Conversely, weekly water application was similar to the reduced time-based schedule during seasons when water requirements were low such as fall and winter. There were not treatment differences in turfgrass quality over the entire study period and ratings remained above the minimally acceptable level. Also, there was no correlation between turfgrass quality and amount of irrigation.

Water application by the ET controllers and the time-based schedules at the main project site was compared to a theoretical water requirement determined from a soil water balance model. The treatments were subjected to irrigation adequacy and scheduling efficiency testing using 30-day moving totals similar to the SWAT protocol testing. Controllers were evaluated on the frequency of scores within the following ranges: greater than 90%, 70% to 90%, 50% to 70%, and less than 50%.

It was determined that the Weathermatic controller averaged performed in the highest range 61% of the time in irrigation adequacy and the lowest range 65% in scheduling efficiency while under-irrigating by -4% compared to the theoretical irrigation requirement. This controller was designed to operate on watering restrictions and irrigated based only on accumulated water loss between allowable watering days. This controller scored high on irrigation adequacy during dry periods when irrigation was the primary plant water input. However, irrigation adequacy suffered when the rain sensor bypassed irrigation events when under watering restrictions due to a mandatory 48 hour rain delay. Scheduling efficiency performance was poor when under watering restrictions because irrigation occurred to refill the crop evapotranspiration (ET_c) loss without consideration to the soil water holding capacity. Once the watering restrictions were lifted, the Weathermatic controller applied irrigation everyday in small amounts resulting in higher scheduling efficiency results.

The Toro controller performed above the 70% to 90% range for 42% of the time and in the less than 50% range for 51% of the time for irrigation adequacy. Scheduling efficiency remained high with 79% in the 70% to 90% range or above and 4% in the less than 50% range. Under-irrigation averaged 13% compared to the theoretical irrigation requirement. This controller applied small amounts of irrigation per event resulting in high efficiency performance, but low irrigation adequacy when under 2 d/wk watering restrictions. The ET Water controller had the same amount of under-irrigation as the Toro compared to the theoretical irrigation requirement, but scored higher in irrigation adequacy and scheduling efficiency more frequently with 50% and 95% of the scores above 70%, respectively. Scheduling efficiency was high for this controller because it applied small amounts of irrigation every day. This controller did not update the irrigation schedule from April 9 through May 23, 2007 causing the controller to not account for increased plant water needs. Also, because irrigation occurred everyday and this controller did not recognize the rain sensor, the average irrigation adequacy was higher than the Toro controller.

Cumulative irrigation averaged 27% over and 23% less compared to the theoretical irrigation requirement for the time-based schedule and reduced time-based schedule, respectively; both treatments utilized a rain sensor. The time-based schedule resulted in scores of 61% above 70% for irrigation adequacy and 72% below 70% for scheduling efficiency. The reduced time-based schedule scored 47% and 73% of the time above 70% for irrigation adequacy and scheduling efficiency, respectively. These treatments were subject to 2 d/wk watering restrictions for the entire time period, resulting in lower adequacy scores, and irrigated more than the soil water holding capacity. The reduced time-based treatment applied less irrigation per event, resulting in higher efficiency scores than the time-based schedule, but suffered in adequacy due to less water in the root zone for depletion. The ET controllers under-irrigated compared to the theoretical, on average, but fell within results seen for the time-based schedules.

Future Work

These controllers were tested near public weather stations in a research setting and were shown to save water under these conditions. However, water savings for residential homeowners tend to be less than controlled research experiments. Therefore, these controllers should be tested in real homes with homeowner interaction to see if they are still important to water conservation efforts in Florida.

Only three brands of ET controllers were tested with this study, but there are approximately a dozen ET controllers currently commercially available for residential landscape use. Testing other controllers would be informative in understanding all of the options on the market and would help to determine the best type of ET controller for maximum water conservation in Florida's climate.

The results found from this study were for relatively dry conditions. Rainfall was shown to impact the ability of the ET controllers to schedule irrigation. Studies should continue through rainy years to fully determine average irrigation savings by using these controllers in Florida. Also, observing these controllers in wet years could assist in making a recommendation to manufacturers on how to better incorporate rainfall into ET-based scheduling so that they can fully penetrate the Florida market eventually leading to statewide water conservation.

The variability between controller replications was determined from only four months of data collection. Variability could increase with a longer time period. The replications should be monitored for an extended period of time to determine if and when the variability between controllers becomes significant.

It was determined from this research that the programmed settings for ET controllers are important in scheduling the correct amount of water application to ensure efficient irrigation. However, the average homeowner cannot program a VCR let alone a new technology such as this. Future work should include the development of recommendations for common ET controllers to aid in the process of integrating the controllers into Florida homes.

The results were compared to a theoretical irrigation requirement developed from a daily soil water balance. However, there are many assumptions made that increased the error in the calculations. It would be interesting to explore the possibility of scheduling irrigation based on a smaller timestep, such as an hourly soil water balance, to determine the effects of the daily timestep assumptions. Also, the inputs to the soil water balance model could be refined with measurements of site conditions such as field capacity and permanent wilting point.

APPENDIX A
STATISTICAL ANALYSIS AND RESULTS FOR CHAPTER 2

```
/* Statistics for Chapter 2 */

/*
  This section was created to analyze water applied (mm)
  for fall 2006 assuming weeks are reps within the season.
  Treatment 6 refers to the theoretical time-based treatment.
*/

options nodate nonumber center formdlim="*" linesize=88;

TITLE 'Fall 2006 Water Application';
data Ch2.fal06;
set Ch2.fall2006;

julian=juldate7(date);
week=week(date);

proc sort; by plot week;

data Ch2.fall06a;
set Ch2.fal06;
        by plot week;
        if First.week then week_sum = 0;
        week_sum + depth;
        if Last.week;
run;

proc sort data=Ch2.fall06a; by tmt;

proc glm data=Ch2.fall06a;
        class tmt;
        model week_sum = tmt rep tmt*rep;
        means tmt/duncan;
run;

proc mixed data=Ch2.fall06a;
        class tmt rep plot week;
        model week_sum = tmt;
        random rep plot week;
        lsmeans tmt/adjust=tukey pdiff;
run;

/*
  This section was created to analyze water applied (mm)
```

```
  for winter 2006-2007 assuming weeks are reps within the season.
*/

TITLE 'Winter 2006-2007 Water Application';

data Ch2.win06;
set Ch2.win2006;

julian=juldate7(date);
week=week(date);

proc sort; by plot week;

data Ch2.win06a;
set Ch2.win06;
        by plot week;
        if First.week then week_sum = 0;
        week_sum + depth;
        if Last.week;
run;

proc sort data=Ch2.win06a; by tmt;

proc glm data=Ch2.win06a;
        class tmt;
        model week_sum = tmt rep tmt*rep;
        means tmt/duncan;
run;

proc mixed data=Ch2.win06a;
        class tmt rep plot week;
        model week_sum = tmt;
        random rep plot week;
        lsmeans tmt/adjust=tukey pdiff;
run;

/*
  This section was created to analyze water applied (mm)
  for spring 2007 assuming weeks are reps within the season.
*/

TITLE 'Spring 2007 Water Application';

data Ch2.spr07;
set Ch2.spr2007;
```

```
julian=juldate7(date);
week=week(date);

proc sort; by plot week;

data Ch2.spr07a;
set Ch2.spr07;
	by plot week;
	if First.week then week_sum = 0;
	week_sum + depth;
	if Last.week;
run;

proc sort data=Ch2.spr07a; by tmt;

proc glm data=Ch2.spr07a;
	class tmt;
	model week_sum = tmt rep tmt*rep;
	means tmt/duncan;
run;

proc mixed data=Ch2.spr07a;
	class tmt rep plot week;
	model week_sum = tmt;
	random rep plot week;
	lsmeans tmt/adjust=tukey pdiff;
run;

/*
  This section was created to analyze water applied (mm)
  for summer2007 assuming weeks are reps within the season.
*/

TITLE 'Summer 2007 Water Application';

data Ch2.sum07;
set Ch2.sum2007;

julian=juldate7(date);
week=week(date);

proc sort; by plot week;

data Ch2.sum07a;
set Ch2.sum07;
	by plot week;
```

```
		if First.week then week_sum = 0;
		week_sum + depth;
		if Last.week;
run;

proc sort data=Ch2.sum07a; by tmt;

proc glm data=Ch2.sum07a;
		class tmt;
		model week_sum = tmt rep tmt*rep;
		means tmt/duncan;
run;

proc mixed data=Ch2.sum07a;
		class tmt rep plot week;
		model week_sum = tmt;
		random rep plot week;
		lsmeans tmt/adjust=tukey pdiff;
run;

/*
  This section was created to analyze water applied (mm)
  for fall 2007 assuming weeks are reps within the season.
*/

TITLE 'Fall 2007 Water Application';

data Ch2.fal07;
set Ch2.fall2007;

julian=juldate7(date);
week=week(date);

proc sort; by plot week;

data Ch2.fal07a;
set Ch2.fal07;
		by plot week;
		if First.week then week_sum = 0;
		week_sum + depth;
		if Last.week;
run;

proc sort data=Ch2.fal07a; by tmt;

proc glm data=Ch2.fal07a;
```

```
	class tmt;
	model week_sum = tmt rep tmt*rep;
	means tmt/duncan;
run;

proc mixed data=Ch2.fal07a;
	class tmt rep plot week;
	model week_sum = tmt;
	random rep plot week;
	lsmeans tmt/adjust=tukey pdiff;
run;

/*
 This section was created to analyze water applied (mm)
 and turfgrass quality ratings for every season assuming that
 the length of time affecting the quality rating would be for
 the two weeks prior to the rating day (2wk).
*/

TITLE 'Chapter 2 - Water Application and Turfgrass Quality';

data Ch2.new_water_qual;
set Ch2.water_qual;

proc sort data=Ch2.new_water_qual; by season;

proc corr; by season;
	var two_wk tq;
run;

proc glm data=Ch2.new_water_qual; by season;
	class tmt rep;
	model two_wk tq = tmt rep tmt*rep;
	means tmt/duncan;
run;

proc mixed data=Ch2.new_water_qual; by season;
	class season tmt rep plot;
	model two_wk = tmt;
	random season rep plot;
	lsmeans tmt/adjust=tukey pdiff;
run;
```

```
/* Chapter 2 Campus Plots Analysis */

options nodate nonumber center;

data Campus_water;

input date $ tmt $ rep $ depth;

cards;
REMOVED DUE TO LENGTH
;

proc sort; by tmt;

proc glm;
	by tmt;
	class rep;
	model depth = rep;
	means rep/duncan;
run;

proc glm;
	class tmt rep;
	model depth = tmt rep;
	means tmt/duncan;
run;

proc mixed;
	class tmt date rep;
	model depth = tmt;
	random date rep;
	lsmeans tmt/adjust=tukey pdiff;
run;
```

APPENDIX B
TURFGRASS QUALITY RATINGS

Table B-1. Turfgrass quality ratings by the graduate research assistant for the summer 2006 season.

Plot	July 10	August 10
1	7	6
2	7	6
3	6	6
4	6	6
5	6	6
6	6	6
7	5	6
8	7	6
9	5	6
10	5	5
11	5	5
12	5	5
13	5	5
14	7	6
15	6	5
16	6	5
17	5	5
18	5	5
19	7	5
20	6	5

Table B-2. Turfgrass quality ratings by the graduate research assistant for the fall 2006 season.

Plot	September 12	October 12	November 2	November 16
1	4	5	5	5
2	5	4	5	5
3	5	4	4	5
4	5	4	6	7
5	5	5	4	5
6	5	5	5	5
7	6	5	4	6
8	5	6	4	7
9	5	4	5	6
10	4	5	5	5
11	5	5	5	5
12	4	5	5	7
13	5	5	5	5
14	5	4	5	7
15	4	5	5	6
16	5	5	5	5
17	3	6	5	6
18	4	5	4	5
19	5	5	5	7
20	5	4	5	5

Table B-3. Turfgrass quality ratings by the graduate research assistant for the winter 2006-2007 season.

Plot	December 12	December 20	February 1
1	6	5	6
2	6	8	6
3	5	6	6
4	7	7	6
5	5	6	5
6	5	7	5
7	6	6	5
8	7	6	7
9	5	4	5
10	6	5	4
11	7	6	5
12	7	5	6
13	5	6	5
14	6	6	5
15	7	6	6
16	6	5	7
17	6	5	6
18	6	6	6
19	8	6	7
20	6	6	6

Table B-4. Turfgrass quality ratings by the graduate research assistant for the spring 2007 season.

Plot	April 2	May 2	May 29
1	7	8	5
2	7	7	5
3	6	5	5
4	7	8	6
5	6	8	5
6	6	7	5
7	7	8	5
8	7	8	5
9	7	7	5
10	6	7	5
11	6	7	5
12	8	8	5
13	7	7	5
14	6	8	6
15	7	7	6
16	7	7	5
17	6	7	5
18	7	7	5
19	8	8	5
20	7	7	5

Table B-5. Turfgrass quality ratings by the graduate research assistant for the summer 2007 season.

Plot	June 26	July 27	August 28
1	5	7	5
2	5	7	6
3	4	6	5
4	7	8	6
5	5	7	5
6	5	7	5
7	5	8	7
8	6	8	7
9	5	7	5
10	5	7	5
11	6	8	6
12	5	8	7
13	5	7	5
14	5	8	6
15	5	8	7
16	5	7	7
17	5	7	7
18	5	7	6
19	6	8	7
20	5	7	7

Table B-6. Turfgrass quality ratings by the graduate research assistant for the fall 2007 season.

Plot	September 27	October 30	December 4
1	5	7	8
2	8	7	8
3	5	6	8
4	8	7	6
5	6	6	5
6	7	7	6
7	6	7	7
8	8	7	7
9	6	6	4
10	6	8	8
11	6	7	8
12	8	8	8
13	5	7	4
14	6	7	8
15	6	6	6
16	8	7	8
17	6	8	5
18	6	7	8
19	8	8	8
20	7	8	8

Table B-7. Turfgrass quality ratings by Master Gardener 1 over the study period.

Plot	Dec 20, 2006	Feb 1, 2007	Apr 2, 2007	Jun 6, 2007	Aug 3, 2007	Oct 30, 2007
1	7	NA	6	6	7	7
2	6	NA	6	6	7	7
3	6	NA	6	6	7	7
4	7	NA	6	7	7	7
5	6	NA	5	7	7	7
6	5	NA	5	6	7	7
7	6	NA	6	7	7	7
8	6	NA	7	7	7	7
9	6	NA	6	7	7	7
10	7	NA	6	7	7	7
11	7	NA	6	7	7	7
12	6	NA	7	7	7	7
13	6	NA	7	7	7	7
14	6	NA	7	7	7	7
15	6	NA	7	7	7	7
16	6	NA	7	7	7	7
17	6	NA	7	7	7	7
18	6	NA	7	7	7	7
19	6	NA	7	7	7	7
20	6	NA	7	7	7	7

*NA occurred when rater was not available to evaluate turfgrass quality.

Table B-8. Turfgrass quality ratings by Master Gardener 2 over the study period.

Plot	Dec 20, 2006	Feb 1, 2007	Apr 2, 2007	Jun 6, 2007	Aug 3, 2007	Oct 30, 2007
1	5	6	NA	7	8	8
2	7	7	NA	7	8	7
3	7	6	NA	6	8	8
4	7	7	NA	8	8	8
5	6	6	NA	7	8	8
6	6	6	NA	7	8	8
7	7	7	NA	7	8	8
8	7	7	NA	7	8	8
9	6	6	NA	7	8	7
10	7	6	NA	7	8	7
11	7	7	NA	7	8	7
12	6	6	NA	7	8	8
13	7	6	NA	6	8	8
14	6	6	NA	7	8	8
15	7	7	NA	7	8	7
16	6	7	NA	8	8	7
17	6	7	NA	7	8	8
18	7	7	NA	7	8	7
19	7	7	NA	8	8	8
20	7	6	NA	7	8	8

*NA occurred when rater was not available to evaluate turfgrass quality.

Table B-9. Turfgrass quality ratings by Master Gardener 3 over the study period.

Plot	Dec 20, 2006	Feb 1, 2007	Apr 2, 2007	Jun 6, 2007	Aug 3, 2007	Oct 30, 2007
1	8	7	7	7	8	8
2	8	7	7	8	8	7
3	7	6	7	7	8	6
4	8	7	7	8	8	7
5	8	6	7	8	8	8
6	7	6	6	8	8	7
7	8	7	6	7	8	8
8	8	7	7	8	8	7
9	8	6	7	8	8	7
10	8	6	6	8	8	8
11	8	7	6	8	8	8
12	8	6	7	8	8	8
13	8	7	7	7	8	8
14	7	6	7	7	8	8
15	7	7	7	8	8	8
16	8	6	7	7	8	7
17	8	7	7	8	8	8
18	8	6	7	8	8	8
19	8	7	7	8	8	8
20	8	6	7	8	8	8

*NA occurred when rater was not available to evaluate turfgrass quality.

Table B-10. Turfgrass quality ratings by Master Gardener 4 over the study period.

Plot	Dec 20, 2006	Feb 1, 2007	Apr 2, 2007	Jun 6, 2007	Aug 3, 2007	Oct 30, 2007
1	6	NA	NA	NA	7	NA
2	7	NA	NA	NA	6	NA
3	6	NA	NA	NA	6	NA
4	8	NA	NA	NA	6	NA
5	7	NA	NA	NA	6	NA
6	7	NA	NA	NA	7	NA
7	7	NA	NA	NA	7	NA
8	8	NA	NA	NA	7	NA
9	5	NA	NA	NA	7	NA
10	6	NA	NA	NA	7	NA
11	7	NA	NA	NA	7	NA
12	8	NA	NA	NA	8	NA
13	7	NA	NA	NA	7	NA
14	7	NA	NA	NA	7	NA
15	7	NA	NA	NA	7	NA
16	8	NA	NA	NA	7	NA
17	8	NA	NA	NA	6	NA
18	7	NA	NA	NA	6	NA
19	8	NA	NA	NA	7	NA
20	6	NA	NA	NA	6	NA

*NA occurred when rater was not available to evaluate turfgrass quality.

Table B-11. Turfgrass quality ratings by Master Gardener 5 over the study period.

Plot	Dec 20, 2006	Feb 1, 2007	Apr 2, 2007	Jun 6, 2007	Aug 3, 2007	Oct 30, 2007
1	7	NA	7	7	8	8
2	7	NA	7	7	8	8
3	7	NA	7	7	7	8
4	8	NA	8	7	8	7
5	7	NA	6	7	8	8
6	7	NA	7	7	8	8
7	7	NA	7	7	8	8
8	8	NA	7	7	8	8
9	7	NA	7	6	8	8
10	7	NA	7	7	8	8
11	7	NA	7	7	8	8
12	7	NA	7	7	8	8
13	6	NA	7	7	8	8
14	7	NA	6	7	8	8
15	7	NA	7	7	8	7
16	8	NA	7	7	8	8
17	7	NA	7	7	8	8
18	7	NA	7	7	8	8
19	8	NA	7	7	8	8
20	7	NA	6	7	8	8

*NA occurred when rater was not available to evaluate turfgrass quality.

Table B-12. Turfgrass quality ratings by Master Gardener 6 over the study period.

Plot	Dec 20, 2006	Feb 1, 2007	Apr 2, 2007	Jun 6, 2007	Aug 3, 2007	Oct 30, 2007
1	NA	7	7	NA	NA	7
2	NA	8	7	NA	NA	7
3	NA	6	7	NA	NA	7
4	NA	7	7	NA	NA	7
5	NA	6	7	NA	NA	7
6	NA	7	7	NA	NA	7
7	NA	7	7	NA	NA	7
8	NA	7	7	NA	NA	7
9	NA	7	7	NA	NA	7
10	NA	7	6	NA	NA	7
11	NA	7	7	NA	NA	7
12	NA	7	7	NA	NA	7
13	NA	7	7	NA	NA	7
14	NA	7	7	NA	NA	7
15	NA	7	7	NA	NA	7
16	NA	7	7	NA	NA	7
17	NA	7	7	NA	NA	7
18	NA	7	7	NA	NA	7
19	NA	7	7	NA	NA	7
20	NA	6	6	NA	NA	7

*NA occurred when rater was not available to evaluate turfgrass quality.

APPENDIX C
STATISTICAL ANALYSIS AND RESULTS FOR CHAPTER 3

```
/* Statistics for Chapter 3 of ET Controller Thesis */

options nodate nonumber center formdlim="*" linesize=88;
/*
  This section compares temperature and extraterrestrial radiation
  methods through calculated ETo values using Hargreaves Equation
  for the Gainesville turfgrass plots. Temperature and extraterrestrial
  radiation values were from the Weathermatic controllers and the
  on-site weather station.
*/

data Ch3.gnv_tra_et;
set Ch3.gnv_tra;

Title 'Parameter sensitivity for Hargreaves Equation at GNV Turfgrass Plots';

proc sort data=Ch3.gnv_tra_et; by rep;

proc glm data=Ch3.gnv_tra_et; by rep;
        class T_meth Ra_meth;
        model ET =  Ra_meth T_meth T_meth*Ra_meth;
        means T_meth/duncan;
        means Ra_meth/duncan;
run;

/*
  This section compares temperature and extraterrestrial radiation
  methods through calculated ETo values using Hargreaves Equation
  for the GCREC.  Temperature and extraterrestrial radiation values
  were from the Weathermatic controller and the FAWN weather station.
*/

data Ch3.gcrec_tra_et;
set Ch3.gcrec_tra;

Title 'Parameter sensitivity for Hargreaves Equation at GCREC';

proc glm data=Ch3.gcrec_tra_et;
        class T_meth Ra_meth;
        model ET =  Ra_meth T_meth T_meth*Ra_meth;
        means T_meth/duncan;
        means Ra_meth/duncan;
run;
```

```
/*
  This section will analyze differences in maximum and minimum
  temperatures for the Weathermatic replications at the Gainesville
  turfgrass plots compared to the temperature measured from the
  on-site weather station.
*/

data Ch3.gnv_t;
set Ch3.gnv_temp;

TITLE 'Chapter 3 - Temperature comparisons for the GNV Weathermatic Replications';

proc glm data=Ch3.gnv_t;
        class season tmt;
        model tmax tmin = season tmt;
        means tmt/duncan;
run;

/*
  This section will analyze differences in maximum and minimum
  temperatures for the Weathermatic at the GCREC compared to
  the temperature measured from the on-site weather station.
*/

data Ch3.gcrec_t;
set Ch3.gcrec_temp;

TITLE 'Chapter 3 - Temperature comparisons for the GCREC Weathermatic';

proc glm data=Ch3.gcrec_t;
        class season tmt;
        model tmax tmin = season tmt;
        means tmt/duncan;
run;

/*
 This section was created to analyze ETo calculated/collected
 from the controller replications at the Gainesville turfgrass
 plots.
*/

data Ch3.campus_et;
set Ch3.campus;

TITLE 'Chapter 3 - ET for Campus Controllers';
```

```
proc sort data=Ch3.campus_et; by tmt;

proc glm data=Ch3.campus_et;
	by tmt;
	class rep;
	model et = rep;
	means rep/duncan;
run;

proc glm data=Ch3.campus_et;
	class season tmt rep;
	model et = season tmt rep;
	means tmt/duncan;
run;

proc mixed data=Ch3.campus_et;
	class tmt month year season rep;
	model et = tmt;
	random month year season rep;
	lsmeans tmt/adjust=tukey pdiff;
run;

/*
  This section was created to analyze ETo calculated/collected
  from the controllers at the GCREC.
*/

data Ch3.GCREC_et;
set Ch3.GCREC;

TITLE 'Chapter 3 - ET for GCREC Controllers';

proc glm data=Ch3.GCREC_et;
	class season tmt;
	model et = season tmt;
	means tmt/duncan;
run;

proc mixed data=Ch3.GCREC_et;
	class tmt month year season;
	model et = tmt;
	random month year season;
	lsmeans tmt/adjust=tukey pdiff;
run;

/*
```

```
  This section will analyze the ET Water rolling 7 day ETo totals compared
  to the on-site weather station and the GNV airport weather station for the
  ET Water replications at the Gainesville turfgrass plots.
*/

data Ch3.gnv_etw_wket;
set Ch3.gnv_etw;

TITLE 'Chapter 3 - ET Water 7 day rolling ETo for GNV Replications';

proc glm data=Ch3.gnv_etw_wket;
        class season tmt;
        model wk_et = season tmt;
        means tmt/duncan;
run;

proc mixed data=Ch3.gnv_etw_wket;
        class tmt season;
        model wk_et = tmt;
        random season;
        lsmeans tmt/adjust=tukey pdiff;
run;

/*
  This section will analyze the ET Water rolling 7 day ETo totals compared
  to the other ET controllers where data was available for the controllers
  at the Gainesville turfgrass plots.
*/

data Ch3.gnv_7day_wket;
set Ch3.gnv_7day;

TITLE 'Chapter 3 - 7 day rolling ETo for GNV Controllers';

proc glm data=Ch3.gnv_7day_wket;
        class tmt;
        model wk_et = tmt;
        means tmt/duncan;
run;

proc mixed data=Ch3.gnv_7day_wket;
        class tmt date;
        model wk_et = tmt;
        random date;
        lsmeans tmt/adjust=tukey pdiff;
      run;
```

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BIOGRAPHICAL SKETCH

Stacia L. Davis began her educational career at Colfax Elementary School in Fairmont, WV. Colfax Elementary was a modest school, serving approximately 60 children, first through sixth grade, in a split classroom structure where her education was personalized and creativity was high. She was uprooted from Colfax Elementary toward the end of sixth grade to attend Wendover Middle School in Greensburg, PA. This change sparked a need to define her strengths and abilities while choosing advanced courses in all subject areas. Hempfield Area Senior High School became an important stepping stone in determining her place in academia because Stacia chose to concentrate on the advanced math and sciences offered. It was clear to everyone, including Stacia, that engineering was her niche.

Ms. Davis chose to attend the University of Pittsburgh because of their diverse engineering program. Freshman engineering brought about many opportunities; some opportunities included presenting on wetlands at a sustainability conference and gaining tools still inadvertently used (such as HTML and C programming). Her next 3 years were used studying civil engineering with a concentration in environmental engineering while serving as president of Chi Epsilon and treasurer of the National Society of Collegiate Scholars. She also worked in the engineering field for companies such as CDM, Allegheny Energy, and Rhea Engineers and obtained her Engineer-In-Training status before completing her Bachelor of Science.

Ms. Davis narrowed her focus when leaving PITT and chose to pursue a higher degree in the land and water resources engineering section of the Agricultural and Biological Engineering department at the University of Florida. Here, she researched water conservation through residential irrigation focusing on ET-based irrigation controllers and turfgrass. She enjoyed her time spent in this department and will continue on with her academic goals by seeking a doctorate in the same area.