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Irrigation scheduling performance by evapotranspiration-based controllers

S.L. Davis, M.D. Dukes*

Agricultural and Biological Engineering Department, University of Florida, P.O. Box 110570, Gainesville, FL 32611-0570, United States

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ABSTRACT

Evapotranspiration-based irrigation controllers, also known as ET controllers, use ET information or estimation to schedule irrigation. Previous research has shown that ET controllers could reduce irrigation as much as 42% when compared to a time-based irrigation schedule. The objective of this study was to determine the capability of three brands of ET-based irrigation controllers to schedule irrigation compared to a theoretically derived soil water balance model based on the Irrigation Association Smart Water Application Technologies (SWAT) protocol to determine the effectiveness of irrigation scheduling. Five treatments were established, T1–T5, replicated four times for a total of twenty field plots in a completely randomized block design. The irrigation treatments were as follows: T1, Weathermatic SL1600 with SLW15 weather monitor; T2, Toro Intelli-sense; T3, ETwater Smart Controller 100; T4, a time-based treatment determined by local recommendations; and T5, a reduced time-based treatment 60% of T4. All treatments utilized rain sensors set at a 6 mm threshold. A daily soil water balance model was used to calculate the theoretical irrigation requirements for comparison with actual irrigation water applied. Calculated in 30-day running totals, irrigation adequacy and scheduling efficiency were used to quantify under- and over-irrigation, respectively. The study period, 25 May 2006 through 27 November 2007, was drier than the historical average with a total of 1326 mm of rainfall compared to 1979 mm for the same historical period. It was found that all treatments applied less irrigation than required for all seasons. Additionally, the ET controllers applied only half of the irrigation calculated for the theoretical requirement for each irrigation event, on average. Irrigation adequacy decreased when the ET controllers were allowed to irrigate any day of the week. All treatments had decreased scheduling efficiency averages in the rainy season with the largest decrease of 29 percentile points with a timer and rain sensor (T4) and an average decrease of 20 percentile points for the ET controllers, indicating that site specific rainfall has a significant effect on scheduling efficiency results. Rainfall did not drastically impact the average irrigation adequacy results. For this study, there were two controller program settings that impacted the results. The first setting was the crop coefficients where specific values were chosen for the location of the study when calculating the theoretical requirement whereas the controllers used default values. The second setting was the soil type that defines the soil water holding capacity of the soil. The ET controllers were able to regularly adjust to real-time weather, unlike the conventional irrigation timers. However, the incorporation of site specific rainfall measurements is extremely important to their success at managing landscape water needs and at a minimum a rain sensor should be used.

1. Introduction

Florida continues to grow rapidly and traditional sources of water are limited. In recent years, Florida has had the largest net gain in population with an inflow of approximately 1108 people per day and fourth in overall population (United States Census Bureau, 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 have been shown to increase outdoor water use by 47% (Mayer et al., 1999).

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 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).

* Corresponding author. Tel.: +1 352 392 1864x205; fax: +1 352 392 4092.
E-mail address: mddukes@ufl.edu (M.D. Dukes).

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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. Parameters that drive ET are solar radiation, temperature, relative humidity, and wind speed (ASCE-EWRI, 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 (ASCE-EWRI, 2005).

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 measure climatic variables from on-site sensors and then calculate ET_O. Even though the controllers might take readings every second or every 15 min, 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 not signal fees associated with broadcasts from the manufacturer (Riley, 2005).

Signal-based controllers receive ET_O data via wireless communication. 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 US$ 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 and then adjusted based on site specific weather measurements to better account for differences in current ET_O from historical trends.

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 (signal-based) 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 equaled 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 case, where over-irrigation occurred, fell within a 30–70% target range and minimized runoff (Metropolitan Water District of Southern California, 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). Davis et al. (2009) reported that ET controllers could potentially produce annual savings of 42% when compared to a time-based irrigation schedule that replaces the net irrigation requirement without considering real-time rainfall and still maintain good turfgrass quality.

Smart Water Application Technologies (SWAT) is an effort of the Irrigation Association that has 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 (Irrigation Association, 2008).

Proper irrigation management could result in as much as a two-fold reduction in water usage (Florida Department of Environmental Protection, 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). The objective of this study was to determine the capability of three brands of ET-based irrigation controllers to schedule irrigation compared to a theoretically derived soil water balance model.

2. Materials and methods

This study was conducted at the University of Florida Gulf Coast Research and Education Center (GCREC) in Wimauma, FL. There were a total of twenty 7.62 m × 12.2 m plots. Each plot consisted of 65% St. Augustinegrass (*Stenotaphrum secundatum* 'Floratam') and 35% mixed ornamentals to represent a typical residential landscape in Florida. Results focus on the turfgrass. 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 data were collected at 15 min intervals for the following variables: wind speed, solar radiation, temperature, relative humidity, and rainfall depth from a Florida Automated Weather Network (FAWN) weather station located onsite. This paper provides additional results from the field study presented by Davis et al. (2009).

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 were 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 (ETwater Systems LCC, Corte Madera, CA); T4, a time-based treatment determined by UF-IFAS recommendations (Dukes and Haman, 2002); and T5, a reduced time-based treatment that is 60% of T4. The ET controllers were purchased as commercially-available equipment and were programmed using the manuals provided by the manufacturers according to site specific conditions. Technical support was contacted only when necessary throughout the course of the study. All treatments except the Weathermatic utilized Mini-Clik rain sensors (Hunter Industries, Inc., San Marcos, CA) set at a 6 mm threshold. The Weathermatic weather monitor included an expanding disk rain sensor that was set at a 6 mm treshold. Water meters (11.4 cm V100 w/Pulse Output, AMCO Water Metering Systems, Ocala, FL) were used to monitor irrigation water application on St. Augustinegrass with automated data acquisition as described by Davis et al. (2009).

The amount of water held by the root zone available to the plant is available water, AW (mm) and is calculated as follows:

$$AW = \frac{(FC - PWP) \times RZ}{100} \tag{1}$$

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 leave the root zone before irrigation is required is readily available water, RAW (mm), and is calculated using the following equation (Irrigation Association, 2005):

$$\mathrm{RAW} = \mathrm{AW} \times \mathrm{MAD} \quad (2)$$

The soil type at the project site was mapped as Zolfo fine sand (Natural Resources Conservation Service, 1989). According to the soil survey, the Zolfo series is a somewhat poorly drained soil composed of sandy, siliceous, hyperthermic Grossarenic Entic Haplohumods. From the literature, the field capacity and permanent wilting point for Zolfo fine sand was given as 13% and 3% (all soil moisture values are presented on a volumetric basis), respectively (Carlisle et al., 1985).

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:

$$D_i = D_{i-1} - (P - \mathrm{RO})_i - I_{N,i} - \mathrm{CR}_i + \mathrm{ET}_{\mathrm{C},i} + \mathrm{DP}_i \quad (3)$$

where D (mm) is the soil water depletion assuming i is the current day and $i-1$ is the previous day, P (mm) is the daily precipitation, RO (mm) is the runoff, I_{NET} (mm) is the net irrigation depth, CR (mm) is the capillary rise, $\mathrm{ET_C}$ (mm) is the crop evapotranspiration, and DP (mm) is the deep percolation (Allen et al., 1998). This equation was simplified since the water table for the research site is deeper than 1 m, thus CR was estimated as zero. For the purposes of estimating an ideal irrigation schedule, DP was estimated as zero because the soil moisture content of the root zone was not allowed to exceed field capacity.

Precipitation in southwest Florida is exclusively rainfall. The amount of rainfall able to be held by the root zone, shown in Eq. (3) as $(P - \mathrm{RO})_i$, can also be represented as effective rainfall, R_E (mm). Rainfall causing the soil water content to exceed field capacity in the soil water balance model was considered lost due to runoff or drainage.

Net irrigation was calculated for the theoretical requirement so that irrigation occurred when the readily available water was depleted and the depth of irrigation applied was the difference between field capacity and the soil water level. In this case, I_N equals the amount of water the soil can effectively hold. For the purposes of evaluating irrigation controllers, the depth of irrigation able to be held by the root zone at the time of a controller irrigation event is the effective irrigation, I_E (mm). Any irrigation application causing the soil water level to exceed field capacity was considered surplus.

By taking into account the assumptions used for this study, equation 3 can be simplified to:

$$D_i = D_{i-1} - R_{E,i} - I_{E,i} + \mathrm{ET}_{\mathrm{C},i} \quad (4)$$

According to the manufacturers (Hydropoint Data Systems Inc., 2003; ETwater Systems, 2005), $\mathrm{ET_O}$ was calculated by the Toro and ETwater controllers using the ASCE standardized $\mathrm{ET_O}$ equation (ASCE-EWRI, 2005). The Weathermatic controller utilized the Hargreaves equation to estimate $\mathrm{ET_O}$ (Hargreaves and Samani, 1982). The ASCE-EWRI standardized $\mathrm{ET_O}$ 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:

$$\mathrm{ET_C} = K_c \times \mathrm{ET_O} \quad (5)$$

The K_c values chosen for the theoretical soil water balance model were interpolated between north-central and south Florida warm season turfgrass values from Jia et al. (2009) (Table 1) since the study location is in between these two regions. The Weathermatic controller used a fixed K_c value of 0.60 for each month. The K_c values for the Toro and ETwater controllers were considered proprietary information and were not made available.

Table 1
Monthly crop coefficients for the Tampa area were interpolated from coefficients measured in north-central (Citra, FL) and south Florida and were used for the theoretical irrigation requirement.

Month	North-central Florida	South Florida	Interpolated Values
January	0.35	0.70	0.45
February	0.35	0.78	0.45
March	0.55	0.77	0.65
April	0.80	0.85	0.80
May	0.90	1.0	0.90
June	0.75	0.85	0.75
July	0.70	0.85	0.70
August	0.70	0.90	0.70
September	0.75	0.85	0.75
October	0.70	0.84	0.70
November	0.60	0.82	0.60
December	0.45	0.70	0.45

Gross irrigation (I_G) was calculated to compare to the measured amount of water applied by the treatments. The gross irrigation depth is calculated from net irrigation using an efficiency factor ultimately determined from the low quarter distribution uniformity ($\mathrm{DU_{lq}}$) of the system (Irrigation Association, 2005). Originally, the uniformity was not known and the controllers were programmed with near perfect efficiency values (Davis et al., 2009). As the field study progressed, on-site catch-can testing was performed to determine that the $\mathrm{DU_{lq}}$ averaged for the field site was 0.70. The low half distribution uniformity ($\mathrm{DU_{lh}}$) was calculated using $\mathrm{DU_{lq}}$ in percentage form as follows:

$$\mathrm{DU_{lh}} = 38.6 + 0.614 \times \mathrm{DU_{lq}} \quad (5)$$

which, in turn, was used to calculate the application efficiency factor (AE) using the equation:

$$\mathrm{AE} = \frac{100}{\mathrm{DU_{lh}}} \quad (6)$$

The gross irrigation was calculated by multiplying the net irrigation depth by the efficiency factor, determined from Eqs. (5) and (6) to be 1.25 (Irrigation Association, 2005). The controllers were updated with the efficiency factor beginning spring 2007 (Davis et al., 2009). The efficiency factor used for the theoretical irrigation requirement reflected the controller settings.

The current method for evaluating irrigation scheduling techniques by ET controllers uses the SWAT protocol developed by the Irrigation Association (Irrigation Association, 2008). The SWAT protocol describes the comparison of irrigation application by ET controllers to the soil water balance to determine if the controllers over- or under-irrigate. The controller performance under the SWAT test is valid if $\mathrm{ET_O}$ and rainfall total 63.5 mm and 10.2 mm, respectively, summed over a 30-day period. The treatments of this study were evaluated using the soil water balance developed to calculate the theoretical irrigation requirement.

Scheduling efficiency (%) was defined as the ability of a controller to schedule irrigation without applying excess irrigation that results in drainage or runoff (Irrigation Association, 2008). It was calculated in 30-day running totals with the following equation:

$$E = \frac{I_N - \mathrm{Surplus}}{I_N} \times 100 \quad (7)$$

where I_N (mm) is the sum of net irrigation applied over the 30 days and Surplus (mm) is the summed depth of water above the field capacity.

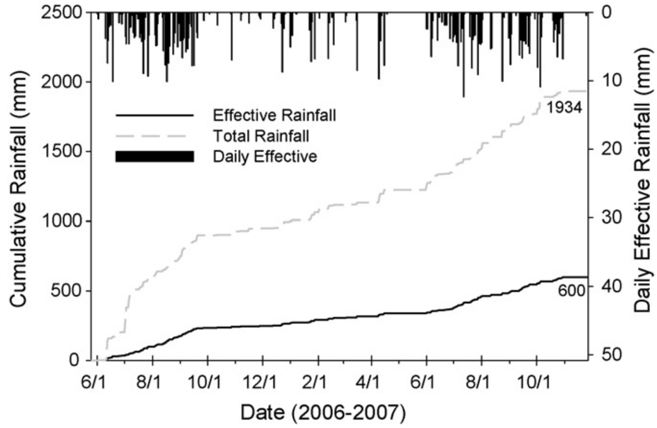

Fig. 1. Measured total rainfall and effective rainfall determined from the soil water balance model for the study period using the weather station in Balm, FL.

Irrigation adequacy (%), on the other hand, quantifies the ability of the controller to supply sufficient irrigation to meet plant demand (Irrigation Association, 2008). It was also calculated in 30-day running totals using the following equation:

$$A = \frac{ET_C - \text{Deficit}}{ET_C} \times 100 \quad (8)$$

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

This study began on 13 August 2006 and ended on 27 November 2007. Though there were five seasons of data collection, only three distinct seasons are discussed here: 1 December 2006 through 26 February 2007 as winter 2006–2007; 27 February 2007–31 May 2007 as spring 2007; and 1 June 2007–31 August 2007 as summer 2007. Applied irrigation depths were compared to a theoretical requirement calculated using a daily soil water balance with inputs similar to user-defined inputs programmed into the controllers for all seasons (Davis et al., 2009).

3. Results and discussion

Thirty year historical rainfall averages were calculated from monthly rainfall data collected by the National Oceanic and Atmospheric Administration (2005) from 1975 through 2005 approximately 28 km away, in Parrish, FL. All months received less rain than historical average except for April 2007, 69% higher than average, and October 2007, 104% higher than average (Davis et al., 2009). Overall, both years were drier than the historical average with a total of 1326 mm of rainfall for the approximate 16-month study period, August 2006 through November 2007, compared to 1979 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, 600 mm, was 69% less than the total cumulative rainfall, 1934 mm, over the treatment period (Fig. 1). Only a fraction of each event, averaging 38% when daily rainfall totaled more than 6 mm, 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 (Carlisle et al., 1985).

Similar to the overall rainfall conditions, most of the seasons experienced less than adequate rainfall. Winter 2006–2007 had 167 mm of rainfall occurring from 16 events over 88 days (Table 2). Even more severe conditions occurred during spring 2007 where 109 mm of rainfall occurred in only 9 events with no rainfall occurring in May. However, there were some periods of frequent rainfall despite the overall trend. A distinct wet period occurred during summer 2007 where 446 mm fell in 37 events.

Table 2
Cumulative rainfall and number of rainfall events for each season.

Season	Rainfall	
	Total (mm)	Events (#)
Winter 06-07	167	16
Spring 07	109	9
Summer 07	446	37

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 h 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 85% of the time within 30 h after rainfall (Cardenas-Lailhacar and Dukes, 2008). This controller maintains 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 falls to trigger the rain sensor (6 mm setting), the deficit is reduced by 25.4 mm/h 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 ETwater 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 (ETwater Website, 2006). Rainfall can vary substantially over short distances in Florida.

The Weathermatic and ETwater controllers began treatments on May 25, 2006; however, hardware issues with the ETwater controller arose late in the summer season causing the controller to be nonfunctional. As a result, the ETwater 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 bypass 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

Table 3
Treatment results for cumulative net irrigation application, average irrigation application per event, and the percentage difference theoretical net irrigation requirement across experiment seasons.

Treatment	Cumulative Gross Irrigation (mm)		Difference from Theoretical[a] (%)	Average Irrigation Per Event (mm)		Difference from Theoretical[b] (%)
	Applied	Theoretical		Applied	Theoretical	
Winter 2006–2007						
Weathermatic	80	82	−3	5.1	8.1	−41
Toro	60	82	−27	5.1	8.1	−41
ETwater	NA	NA	NA	NA	NA	NA
Time	127	82	54	6.4	8.1	−26
Reduced Time	81	82	−2	4.1	8.1	−53
Spring 2007						
Weathermatic	267	361	−26	3.3	10.4	−69
Toro	249	361	−31	4.1	10.4	−62
ETwater	204	375	−46	2.3	5.8	−61
Time	280	361	−22	10.7	10.4	−2
Reduced Time	169	361	−53	6.6	10.4	−40
Summer 2007						
Weathermatic	NA[c]	NA	NA	NA	NA	NA
Toro	229	220	4	4.1	9.1	−56
ETwater	213	237	−10	2.5	5.1	−50
Time	277	220	26	15.5	9.1	69
Reduced Time	148	220	−33	8.6	9.1	−6

[a] Difference from theoretical is the difference between actual cumulative water application for the season compared to the soil water balance determined irrigation requirement.
[b] Difference from theoretical is the difference between the actual average irrigation application per event for the season compared to the soil water balance determined application per event.
[c] NA indicates seasons where the treatment was not working.

for winter 2006–2007 and 100% replacement for spring and summer 2007. The irrigation schedule for T5, the reduced time-based treatment, was set for 36% replacement for winter 2006–2007 and 60% replacement for spring and summer 2007. As a result, T4 functioned similarly to a historical ET controller with a crop coefficient 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.

3.1. Weathermatic

The Weathermatic controller under-irrigated by 3% compared to the theoretical irrigation requirement, applying 80 mm and 82 mm, respectively, for the winter 2006–2007 season (Table 3). This controller also under-irrigated during the spring 2007 season by 26%, applying 267 and 361 mm, respectively. Irrigation application varied between these seasons due to the removal of day-of-the-week water restrictions. As a result, 84 irrigation events occurred out of a possible 94 events during the spring season (irrigation could occur any day) compared to only 16 irrigation events out of a possible 25 events in the winter season (irrigation restricted to 2 d/wk) (Table 4). Consequently, average irrigation applied per event was greater for the winter season than the spring season, but the controller irrigated less than the theoretical requirement for both seasons, averaging 41% less for the winter season and 69% less for the spring season. Irrigation occurred on every allowable watering day by the Weathermatic controller unless in bypass mode due to the rain sensor.

Cumulative irrigation applied by the Weathermatic controller was less than the theoretical requirement during winter 2006–2007 and spring 2007. This was due to the combination of using a lower crop coefficient (0.6 fixed) than was representative of the actual site and the 48-h rain sensor bypass period which accumulated irrigation deficits. The 48-h bypass is longer than the average dry out period of 24 h for expanding disk rain sensors as indicated in recent research by Cardenas-Lailhacar and Dukes (2008).

Scheduling efficiency results for this controller were generally high, averaging 91% for winter 2006–2007 and 94% for spring 2007 (Table 5). Efficiency results were high due to irrigation application per event being approximately half of the irrigation simulated by the soil water balance, resulting in little over-irrigation due to excessive run times. Irrigation adequacy averaged 100% with only a few instances of less than perfect results occurring in the winter season. This was not surprising due to the similar cumulative irrigation application between the Weathermatic and the theoretical

Table 4
The number of days irrigation occurred and the total number of irrigation events possible for each season.

Season	Winter 2006–2007		Spring 2007		Summer 2007	
	Applied	Theoretical	Applied	Theoretical	Applied	Theoretical
Weathermatic	16	10	84	35	NA[a]	NA
Toro	12	10	62	35	55	24
ETwater	NA	NA	94	64	84	47
Time	20	10	26	35	18	24
Reduced Time	20	10	26	35	17	24
Possible Events	25	94[b]/27[c]	92/26			

[a] NA indicates seasons where the treatment was not working.
[b] Total number of possible irrigation events for the ET controllers, Weathermatic, Toro, and ETwater.
[c] Total number of possible irrigation events for the time-based treatments, Time and Reduced Time.

Table 5
Treatment results for average scheduling efficiency and irrigation adequacy calculated using 30-day moving totals and percentage difference in irrigation application from the theoretical requirement for experiment seasons.

Treatment	Scheduling Efficiency (%)				Irrigation Adequacy (%)			
	Avg[a]	Min[b]	Max[c]	CV[d]	Avg	Min	Max	CV
Winter 2006–2007								
Weathermatic	91	85	100	3	100	95	100	1
Toro	76	24	100	29	93	72	100	8
ETwater	NA[e]	NA	NA	NA	NA	NA	NA	NA
Time	64	41	83	19	99	85	100	3
Reduced Time	85	68	100	13	99	82	100	4
Spring 2007								
Weathermatic	94	88	100	3	90	73	100	9
Toro	97	91	100	4	85	66	97	11
ETwater	90	86	96	4	71	49	78	11
Time	87	79	93	4	86	72	100	8
Reduced Time	99	96	100	2	70	49	95	16
Summer 2007								
Weathermatic	NA	NA	NA	NA	NA	NA	NA	NA
Toro	74	54	100	14	83	57	96	15
ETwater	73	54	96	14	73	33	92	24
Time	58	36	100	30	79	56	92	14
Reduced Time	78	61	100	14	70	33	92	26

[a] Avg is the average value calculated from all 30-day moving totals for the season.
[b] Min is the minimum value calculated from all 30-day moving totals for the season.
[c] Max is the maximum value calculated from all 30-day moving totals for the season.
[d] CV is the coefficient of variation calculated from all 30-day moving totals for the season.
[e] NA indicates seasons where a controller was not working.

requirement. However, irrigation adequacy results were less than perfect due to the combination of water savings for the season as well as less irrigation application per event, averaging 90% for the spring season.

Turfgrass quality was evaluated for every season using methods described in the National Turfgrass Evaluation Program (NTEP) handbook (Shearman and Morris, 1998). Ratings were chosen based mostly on density and color using a scale from 1 to 9 where 1 represents dead turf and 9 represents perfection. Acceptable turfgrass quality was considered a 5 rating. As indicated by the good irrigation adequacy and scheduling efficiency scores, the Weathermatic controller applied enough water to maintain a healthy landscape as was evidenced by turfgrass quality results of 5.7 and 6.2 for winter 2006–2007 and spring 2007, respectively (Davis et al., 2009). Despite the reduction in water application compared to the theoretical irrigation requirement in the spring 2007 season, the turfgrass quality remained above minimum acceptability.

The main difference between winter and spring seasons was the elimination of day-of-the-week water restrictions for the spring season. These seasons are otherwise comparable due to less rainy conditions with a significant amount of irrigation required. Ideally, removing water restrictions would benefit an ET controller's irrigation scheduling capabilities by allowing the controller to determine when irrigation is necessary. Contrary to intuition, both scheduling efficiency and irrigation adequacy results declined from the winter season to the spring season. This was most likely due to the simplicity of the controller in that it kept a running total of ET loss for replacement and did not maintain a soil water balance. Removing water restrictions caused the controller to irrigate every day unless bypassing due to rainfall for 48 h.

The Weathermatic controller was damaged by a lightning storm during summer 2007. This controller defaulted to a time-based schedule for this season to minimize damage to the landscape; therefore, results are not reported for this season. The backup time-based schedule was updated monthly with the same weekly irrigation as T4, but applied it over seven days instead of two days due to lifted watering restrictions for this season.

3.2. Toro

The Toro controller applied 60 mm of irrigation during the winter 2006–2007 season and 249 mm of irrigation during the spring 2007 season (Table 3). This controller applied 27% and 31% less than the theoretical requirement for each season, totaling 82 mm and 361 mm, respectively. The controller applied significantly less than the theoretical requirement despite rainfall totals that were less than the historical average.

The Toro controller applied 41% less per event on average compared to the theoretical requirement resulting in less cumulative application for the winter season. Irrigation occurred 12 times out of a possible 25 watering days (Table 4). Irrigation application per event was 62% less than the theoretical requirement for the spring season, averaging 4.1 mm/event. There were approximately twice as many events applied by the Toro (62) than the theoretical requirement (35).

Rainfall was much more frequent, beginning in the summer 2007 season. However, the rain sensor connected to the Toro controller only bypassed irrigation for intense rainfall events. According to Cardenas-Lailhacar and Dukes (2008), this behavior is typical of expanding disk rain sensors similar to the sensors used in this study. Irrigation application per event was 56% less for the Toro controller than the theoretical irrigation requirement, but applied irrigation for 55 events compared to 24 events for the theoretical requirement. This summer season resulted in 4% over-irrigation by applying 229 mm compared to the theoretical requirement that applied 220 mm.

The smaller irrigation depth per event allowed the Toro treatment to apply irrigation without over-irrigating during the first part of the winter season, scoring 100% in scheduling efficiency (Table 5). The remainder of the season varied in scheduling efficiency, from 24% back to 100% by the end of the season; average scheduling efficiency was 76%. Irrigation adequacy scores averaged 93%. Irrigation did not adequately supplement rainfall during the first half of the season resulting in constant cumulative deficit and adequacy scores as low as 72%. However, irrigation was adequate when supplementing rainfall over the last portion of the winter season resulting in less cumulative deficit.

The Toro controller did not always adequately apply irrigation during the spring season, but the results did reach a maximum irrigation adequacy score of 97%. Rainfall and a change in seasonal water needs caused under-irrigation to occur, ending at an irrigation adequacy of 66%, averaging 85%. Irrigation was scheduled efficiently with scores ranging from 91% to 100%, averaging 97%. 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.

Similar to the other seasons, irrigation adequacy for the summer season ranged from 57% to 96%, averaging 83%. This controller applied irrigation consistently to climb out of the deficit created from under-irrigation in the previous season. Scheduling efficiency for the Toro controller ranged from 54% to 100%, averaging 74%, as a result of smaller, more frequent irrigation events. This controller over-irrigated minimally throughout the entire season to cause the scheduling efficiency score to be less than 100%.The 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 higher than the coefficients used by the Toro controller since the controller used coefficients 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.

Turfgrass quality ratings for the winter 2006–2007, spring 2007, and summer 2007 seasons averaged 5.9, 6.4, and 6.1, respectively (Davis et al., 2009). A reduction in water application for the winter and spring seasons did not affect the turfgrass quality negatively. There was a slight over-application during the summer season, but could be considered negligible considering the difference was only 9 mm over 3 months and the turfgrass quality did not vary significantly. Despite sometimes low irrigation adequacy and scheduling efficiency scores, the overall quality of the landscape did not suffer as a result.

Similarly to the Weathermatic controller, the irrigation adequacy results decreased slightly by removing day-of-the-week water restrictions. However, scheduling efficiency results increased as would be expected when allowing the controller to perform as designed. Increased scores could also be due to smaller irrigation applications per event from increasing the number of allowable watering days.

Scheduling efficiency results decreased, without change in irrigation adequacy results, for the rainy summer season compared to the drier spring season. The combination of using a rain sensor that was not sensitive and the rain pause feature, where the controller pauses irrigation for a certain number of days dependent on rainfall volume, did not directly correspond to the soil water balance.

3.3. ETwater

The ETwater controller was not operational for the winter 2006–2007 season, but was functional during the other two seasons. Irrigation occurring over the spring season totaled 204 mm, under-irrigating by 46% compared to the theoretical irrigation requirement which totaled 375 mm (Table 3). The theoretical irrigation requirement increased application per event to match seasonal need whereas the ETwater 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. Average irrigation application per event was only 2.3 mm, 61% less than the average application by the theoretical requirement.

Cumulative irrigation over summer 2007 for the ETwater controller was 213 mm, 10% less than the theoretical requirement that totaled 237 mm. Application depth per event for the ETwater controller was 50% less than irrigation depth per event for the theoretical requirement. However, the ETwater controller scheduled twice as many events as the theoretical requirement (Table 4).

The ETwater controller under-irrigated compared to the theoretical requirement during every operational season. Most of these savings occurred during the dry periods of each season. 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 which we believe to have been an isolated hardware issue.

The ETwater controller scored a minimum of 49% in irrigation adequacy for the spring season where the deficit accumulated from the lack of change with seasonal water requirements, but averaged a 71% (Table 4). Scheduling efficiency, however, averaged 90% with a much smaller range of 86–96%. This controller was generally able to schedule irrigation without applying more than the root zone could hold on a regular basis in the spring.

Similar to the Toro controller results for the summer season were its irrigation adequacy and scheduling efficiency scores. Irrigation adequacy for the ETwater controller scored 73%, applying irrigation consistently to reduce the deficit created the previous season. However, adequacy scores fell to as low as 33% due to accumulating deficit occurring later in the season. Scheduling efficiency for this controller averaged 73% as a result of frequent irrigation events. This controller also over-irrigated minimally throughout the entire season to cause the scheduling efficiency score to reach a maximum of 96%.

Scheduling efficiency scores were below 96% over the majority of all seasons showing somewhat of a tendency for the ETwater controller to underestimate the depth of irrigation required to fill the root zone to field capacity. Irrigation adequacy scores were frequently lower than the scheduling efficiency scores. Less than perfect irrigation adequacy scores were apparent in the under-irrigation compared to the theoretical requirement for spring and summer 2007, calculated as −46% and −10%, respectively, where adequacy reached minimum values of 49% and 33% for these seasons. However, turfgrass quality did not suffer as a result, averaging a 6.1 rating for turfgrass quality (Davis et al., 2009).

3.4. Time-based treatments

The irrigation calculated by the theoretical irrigation requirement was 82 mm in the winter 2006–2007; T4 over-irrigated by 54%, applying 127 mm, and T5 under-irrigated by 2%, applying 81 mm (Table 3). The T5 reduced time 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. More under-irrigation did not occur for T5 because of additional events that were not bypassed by the rain sensor. There was twice the total number of events for the time-based treatments, each applying irrigation 20 times (Table 4), while applying 26% and 53% less irrigation per event compared to the theoretical requirement for T4 and T5, respectively (Table 3).

In the spring 2007, the T4 and T5 treatments applied 22% (280 mm) and 53% (169 mm) less than the theoretical requirement (361 mm). The irrigation applied per event by T4 was 2% less than the theoretical requirement and T5 was 40% less than the requirement; both treatments applied less irrigation events (26) compared to the theoretical irrigation requirement (35, Table 4). Under-irrigation by both treatments can be attributed to less number of events due to a combination of water restrictions and bypassing due to rainfall as well as higher crop coefficients compared to the reductions from historical of the time-based treatments.

Irrigation application for the rainy summer 2007 season by T4 and T5 was 277 mm and 148 mm, respectively. These treatments applied 26% more than the theoretical irrigation requirement and 33% less than the theoretical irrigation requirement, calculated to apply 220 mm. Application per event by T4 was 69% greater than the theoretical requirement while T5 applied 6% less than the theoretical requirement on average. 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 (Table 4).

The T4 treatment resulted in irrigation adequacy of 99% on average for the winter season (Table 5). This treatment generally applied adequate irrigation, ranging from 85% to 100%, due to consistent irrigation and not allowing a deficit to accrue. However, scheduling efficiency averaged 64% with a minimum of 41% indicating that this treatment over-irrigated causing the scheduling efficiency to become lower. The T5 treatment scored 99% for irrigation adequacy and 85% for scheduling efficiency. Adequacy and scheduling efficiency were high for the latter half of the season, with both scores reaching 100%, 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.

Irrigation adequacy for the T4 and T5 treatments averaged 86% and 70%, respectively, for the spring season. Irrigation adequacy fell in the latter part of the season due to the high theoretical requirement. Conversely, scheduling efficiency averaged 87% for T4 and 99% for T5. Scheduling efficiency was less than perfect 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.

Irrigation adequacy averaged 79% over the summer season for T4. 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 58%. The T5 treatment 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 70% and 78%, respectively.

Despite low irrigation adequacy scores occurring throughout each season, turfgrass quality ratings remained above the acceptable threshold of 5, averaging a 6 rating for both treatments (Davis et al., 2009). Quality ratings were not significantly different from each other suggesting that the landscape was not affected by irrigation application less than the theoretical requirement, with a maximum difference of 53% from the theoretical requirement by T5 in spring 2007 (Table 3).

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 differences from historical averages. These treatments maintained water restrictions throughout the entire study period ensuring average irrigation adequacy measurements less than 100%. As would be expected, irrigation adequacy scores were greater for T4 than T5 while scheduling efficiency scores were greater for T5 than T4.

3.5. Overall results

The soil water holding capacity is low for this type of soil and was estimated at 15 mm for the 152 mm root zone used as the theoretical requirement. As a consequence, matching irrigation schedules to achieve perfect irrigation adequacy and scheduling efficiency using this type of analysis is unlikely. In combination with the high water needs of turfgrass, there were many opportunities to decrease irrigation adequacy and scheduling efficiency results without improper scheduling techniques by any of the treatments.

Twice weekly water restrictions were observed by all treatments for the winter 2006–2007 season, but were lifted for the ET controllers for the subsequent seasons. It can be assumed that the major difference between the winter season and the spring season were water restrictions due to less rainy conditions occurring for both time periods. It can be inferred that irrigation adequacy decreased when allowed to irrigate every day.

Typical to Florida weather patterns, summer 2007 was much more rainy than spring 2007. All treatments had decreased scheduling efficiency averages in the summer season with the largest decrease of 29 percentile points by the T4 treatment. This is an important indication that rainfall has a significant effect on scheduling efficiency results. Rainfall did not dramatically impact (<7 percentile point change) the average irrigation adequacy results. However, the range of results for both irrigation adequacy and scheduling efficiency increased from spring to summer likely due to a short period of little rainfall at the beginning of the season before frequent rainfall began. All controllers utilized rain sensors as a way to cost effectively account for rainfall on-site that the controllers may not otherwise take into account. However, Cardenas-Lailhacar and Dukes (2008) found that expanding disk rain sensors tend to have high variability in accuracy in regards to the threshold, sometimes not pausing for events that are five times greater than their threshold or discontinuing the bypass mode after only a few hours. Thus, ET controllers must use more accurate ways to incorporate rainfall to schedule irrigation appropriately.

Irrigation adequacy and scheduling efficiency results determined through SWAT testing for the ET controllers were published by the Irrigation Association. Published results showed that these controllers scheduled irrigation nearly perfectly when tested, with 100% irrigation adequacy and a minimum score of 98.5% scheduling efficiency across the controllers tested for this study. However, these controllers were tested with considerably less rainfall, totaling 100 mm for the controller with the lowest scheduling efficiency score and less than 21 mm for the remaining controllers. The test is valid for publication with only 10 mm of rainfall. Our results describe fluctuations in scores over time depending on weather conditions, specifically rainfall, and water restrictions. As a result, it is important to test these controllers over a range of conditions to determine the overall performance of the controller and not a static 30-day period.

Generally, it is apparent by the behavior of the adequacy and efficiency results when the controller applies more or less irrigation per event than determined necessary by the storage characteristics. For this type of analysis, extreme differences in scores can indicate mismatched water levels between the soil water balance and the treatment's water level. This would be a temporary issue that could be rectified with one rainfall event larger than field capacity. Otherwise, it is an indication of improper scheduling of irrigation application per event according to the soil water balance inputs used to determine irrigation required.

According to turfgrass quality results for all seasons, all treatments maintained minimum acceptability on average with no statistical differences between turfgrass quality and irrigation application (Davis et al., 2009). As a result, it can be assumed that all treatments received a sufficient amount of water over the study period despite large ranges in irrigation adequacy and scheduling efficiency results. Under-irrigation for short periods of time will not negatively affect the overall quality of the landscape.

4. Conclusions

Rainfall in Florida is localized and important in determining how well ET controllers schedule irrigation. Scheduling efficiency was much lower for all treatments during the rainy summer season compared to the other drier seasons indicating inaccuracy in determining site specific rainfall. 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 paused for 48 h 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. Rainfall is also factored into the scheduling of the ETwater. However, both the Toro and ETwater controllers use rainfall from a weather station that may not be representative of the depth of rain at the controller 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. (2009) 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, it is possible that the landscape characteristics were different than the program settings used by the controllers. For example, field capacity and permanent wilting point were chosen for the theoretical irrigation requirement based on a soil survey. However, a controller program setting of "sand" and could mean different depths for individual controllers. The ET controllers likely used different values for readily available water than was used in the soil water balance based on site conditions. 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.

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 SWAT 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 a rainy climate.

Removing watering restrictions and allowing the controllers to schedule irrigation on any day resulted in decreased irrigation adequacy results. This was the opposite of the expected outcome. However, irrigation adequacy may not be an accurate measure of performance due to all treatments maintaining acceptable turfgrass quality. Consequently, thresholds of acceptability for both irrigation adequacy and scheduling efficiency should be defined based on quantifiable measures such as plant response.

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 has the potential to be more efficient than manual irrigation scheduling so that irrigation would consistently supplement rainfall and minimize over watering.

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