LANDSCAPE IRRIGATION WITH EVAPOTRANSPIRATION CONTROLLERS IN A HUMID CLIMATE

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ABSTRACT. *The objective of this article is to present summary findings of multiple research studies concerning evapotranspiration (ET) controllers. Each study provided unique information concerning the performance and implementation techniques necessary to ensure successful integration with irrigation systems to optimize scheduling for water conservation. Based on these studies, ET controllers have the potential for irrigation savings of as much as 63%, without sacrificing landscape quality, when implemented in moderate to high water use scenarios and programmed correctly. Only homes that irrigated more than 450 mm per year had irrigation savings with an ET controller in southwest Florida. The ET controllers that underwent Irrigation Association Smart Water Application Technologies (SWAT) testing experienced oscillations in irrigation adequacy and scheduling efficiency dependent on rainfall. Assuming acceptable levels for irrigation adequacy and scheduling efficiency of 80% and 95%, respectively, there were only a few periods during the Florida SWAT test when both scores were above these thresholds. A maximum of 10% of scores were passing in any of the three evaluation periods with frequent rainfall, indicating that properly accounting for rainfall is a challenge for many of these controllers. The SWAT scores are indicators of water savings only if there is a potential for savings due to excess irrigation prior to implementation of the ET controller.*

Keywords. *ET controller, Irrigation, Scheduling, Soil water balance, SWAT, Turfgrass.*

The need for new methods of outdoor water conservation continues to grow as a result of increasing competition for existing water resources. Over half of total fresh water resources in the U.S. is used for irrigation (Hutson et al., 2004). Mayer et al. (1999) found that, on average, 58% of annual water use is for outdoor purposes, with a majority of outdoor water use assumed to be irrigation. Another study found that 64% of residential water use in central Florida was used for irrigation (Haley et al., 2007). As a result, new methods to reduce water use in irrigated urban landscapes can have a substantial impact on overall water conservation.

An evapotranspiration-based (ET) controller is one technology proposed for managing residential irrigation so that landscapes are irrigated based on plant needs, thereby eliminating excess water loss due to over-irrigation. The Irrigation Association has developed a Smart Water Application Technologies (SWAT) testing protocol that describes a procedure for testing ET controllers (Irrigation Association, 2008).

Most ET controller studies have been conducted in the western U.S. for utility companies or water districts typically under arid or semi-arid conditions. A 2002 study by the Los Angeles Department of Water and Power found 17.4% actual water savings and 78% potential water savings from a WeatherTRAK-enabled controller (Bamezai, 2004). Actual water savings were measured by comparing water use prior to the ET controller retrofit to water use post-retrofit, while potential water savings were measured by comparing the difference in post-retrofit water use and irrigation demand to the difference in pre-retrofit water use and irrigation demand. Aquacraft, Inc., performed an ET controller study in Colorado to determine reductions in water use compared to ET_o in which six sites were already irrigating below historical ET_o. First-year results showed an average water application of 94% of ET_o with ±20% error between sites, capturing 88% of the potential savings, while second-year average water applications were 71% of ET_o replacement and captured 92% of potential savings (Aquacraft, 2002, 2003). A more recent study by Aquacraft, Inc., in California evaluated the water use of 2,294 sites with ET controllers to determine the effectiveness of smart controller rebate programs. This study showed that maximum water savings were achieved by targeting homeowners with historically high application rates and who continually applied more than the gross irrigation requirement (GIR). Homeowners who generally irrigated below GIR experienced increases in irrigation application by installing an ET controller (Mayer et al., 2009). Testing in North Carolina consisted of WeatherTRAK-enabled Toro Intelli-sense con-

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trollers on tall fescue turfgrass using three irrigation frequency settings: 1, 2, and 7 d week^{-1}. The 2 and 7 d week^{-1} settings applied the most irrigation, totaling 623 mm and 652 mm, respectively, while the 1 d week^{-1} treatment applied 37% less (413 mm) than the 7 d week^{-1} treatment. All three irrigation schedules maintained very good turfgrass quality, indicating that they followed weather trends, although these controllers required more adjustments specific to the study location to achieve better efficiency (Vasanth et al., 2007).

In addition to field studies, bench testing has been conducted in the western U.S. Bench testing consists of monitoring the signal output (which would normally energize a solenoid valve) of ET controllers for hypothetical landscapes. The ET controllers are connected to dataloggers instead of actual irrigation systems, and the virtual water application is compared to a GIR. The Metropolitan Water District of Southern California conducted a year-long bench test in 2002 to compare the ability of ET controllers to irrigate according to 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° slope. The WeatherTRAK-enabled controller always applied less water than crop evapotranspiration, resulting in no over-irrigation, but deficit conditions occurred in the summer months. Percent soil water depletion for all scenarios except the sloped, in which over-irrigation occurred, fell within a 30% to 70% range, where typical management allowable depletion is 50% (MWD, 2004). A bench test conducted in 2003, also using WeatherTRAK-enabled controllers, was designed to determine the functionality and ease of implementation of the controllers. Irrigation equaled the turfgrass requirements only in April and October. Over-irrigation occurred during the rest of the year: >40% in November; 21% to 40% in March, June, and July; and 11% to 20% for the other months in which over-irrigation occurred. It was concluded that the poor results were due to very general controller settings, including using default uniformity and precipitation rates (Pittenger et al., 2004).

The University of Florida has performed various research studies to determine if several commercially available ET controllers could effectively and efficiently apply irrigation compared to both a University of Florida Institute of Food and Agricultural Sciences (UF-IFAS) recommended time-based irrigation schedule and theoretical plant water needs. The objective of this article is to present and discuss summary findings of multiple research studies, including two field studies, one cooperator study, and a bench test. Each study provided unique information concerning how an ET controller performs as well as implementation techniques necessary to ensure successful integration of ET controllers.

MATERIALS AND METHODS

SOIL WATER BALANCE

A daily soil water balance model was used to calculate GIR for comparison with actual irrigation water applied. The daily soil water balance was calculated using (Irrigation Association, 2005):

$$\mathrm{SWB}_i = \mathrm{SWB}_{i-1} - \mathrm{PWR} + R_e + \mathrm{IWR}_{\mathrm{net}} \tag{1}$$

where SWB is the soil water balance level (mm) on day i or i-1, PWR is the plant water requirement (mm) on day i, R_e is effective rainfall (mm) on day i, and $\mathrm{IWR}_{\mathrm{net}}$ is the net irrigation water requirement (mm) on day i.

The soil water balance level can fluctuate from permanent wilting point (PWP) to field capacity (FC). The PWP is the minimum water level below which the plant material can become permanently damaged, and FC is the maximum water level that can be stored before gravitational drainage (Irrigation Association, 2005). Both PWP and FC are expressed as depth of water (mm) per depth of soil (mm), where the depth of soil was chosen to be the same as the depth of the root zone programmed into the controllers (152 mm).

The PWR equals the amount of water necessary to maintain healthy plant material (Irrigation Association, 2005). The PWR is calculated as the plant-specific evapotranspiration (ET_c) for any given plant material by applying a crop coefficient (K_c) using the following equation (Allen et al., 1998):

$$\mathrm{ET}_c = K_c \times \mathrm{ET}_o \tag{2}$$

where the K_c values for turfgrass were selected, based on the location of the field study, from Jia et al. (2009) or were specified by plant type and exposure expressed in the SWAT protocol (Irrigation Association, 2008) for the bench test.

Effective rainfall was limited to the portion of total daily rainfall as the depth that would cause the SWB to reach FC after PWR was taken into account. Rainfall that exceeded the soil storage capacity was considered lost due to surface runoff or deep percolation.

The $\mathrm{IWR}_{\mathrm{net}}$ is the amount of irrigation required to increase soil water storage to field capacity, thus satisfying PWR (Irrigation Association, 2005). The $\mathrm{IWR}_{\mathrm{net}}$ was calculated only on days when the SWB fell below management allowable depletion (MAD), calculated as 50% of the difference between FC and PWP. When calculating $\mathrm{IWR}_{\mathrm{net}}$, deep percolation and surface runoff were considered negligible. To compare actual irrigation applied by the treatments to $\mathrm{IWR}_{\mathrm{net}}$, GIR was calculated from $\mathrm{IWR}_{\mathrm{net}}$ using a runtime multiplier (RTM) ultimately determined from the lower quarter distribution uniformity (DU_{lq}) of the system (Irrigation Association, 2005). The field and cooperator studies used on-site catch-can testing to determine DU_{lq}. The lower half distribution uniformity (DU_{lh}) was calculated using DU_{lq} in percentage form, as follows (Irrigation Association, 2005):

$$\mathrm{DU}_{lh} = 38.6 + 0.614 \times \mathrm{DU}_{lq} \tag{3}$$

which, in turn, was used to calculate the RTM using the following equation (Irrigation Association, 2005):

$$\mathrm{RTM} = \frac{100}{\mathrm{DU}_{lh}} \tag{4}$$

The GIR was calculated by multiplying IWR_{net} by RTM (Irrigation Association, 2005). Bench testing based on the SWAT protocol used RTM values described in the protocol. In all field studies, the RTM used for GIR was the same as the RTM of the controllers. The SWAT protocol compares irrigation application by ET controllers to the soil water balance to determine if the controllers over- or under-irrigate. The SWAT test is valid if reference evapotranspiration (ET_o) and rainfall total at least 63.5 and 10.2 mm, respectively, summed over a minimum 30 d period. The treatments were evaluated using the SWB developed to calculate GIR. Detailed descriptions of the calculation methodology using SWAT terminology can be found in Davis and Dukes (2009, 2010).

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 d running totals with the following equation:

$$E = \frac{I_N - SL}{I_N} \times 100 \tag{5}$$

where I_N (mm) is the sum of IWR_{net} applied over the 30 days, and SL (mm) is the sum of the scheduling losses. These losses include the summed depth of water above field capacity as well as runoff caused by excess cycle times or inadequate soak times based on infiltration rates. Runoff caused by cycle/soak scheduling was not considered for the field and cooperator studies, but it was taken into account for the bench tests based on infiltration rates provided by the SWAT protocol (Irrigation Association, 2008).

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 d running totals using the following equation:

$$A = \frac{(\text{ET}_c - \text{Deficit})}{\text{ET}_c} \times 100 \tag{6}$$

where ET_c (mm) represents the plant-specific evapotranspiration calculated from ET_o using crop coefficients (K_c), and Deficit (mm) represents the sum of the depth of water below MAD over the 30 d period.

CONTROLLERS

Three controller brands were evaluated in most of the research projects discussed here: the Weathermatic SL1600 controller with SLW15 weather monitor (Dallas, Tex.), the Toro Intelli-sense (Riverside, Cal.) using WeatherTRAK ET Everywhere service (Hydropoint Datasystems, Inc., Petaluma, Cal.), and the ETwater Smart Controller 100 (Corte Madera, Cal.). Additionally, the Rain Bird ET Manager (Glendora, Cal.) was tested in one field study.

The Weathermatic controller is a stand-alone controller because it uses a supplemental weather monitor to measure temperature to calculate ET_o on-site. The controller uses the Hargreaves equation due to the equation's reliance on only temperature and solar radiation to calculate ET_o (Hargreaves and Samani, 1982). The weather monitor determines maximum and minimum daily air temperatures. Solar radiation values are latitude-based and thus not measured directly.

The Toro and ETwater controllers receive ET_o and rain information through a satellite signal, instead of calculating those parameters as the Weathermatic does. According to the manufacturers, daily ET_o and rainfall information are derived from weather stations located in proximity to the controller, and the ASCE-EWRI equation is used for calculating ET_o (ASCE-EWRI, 2005). The use of the ASCE-EWRI equation requires more weather parameters (e.g., temperature, relative humidity, solar radiation, and wind speed) than are required for the Hargreaves equation, thus allowing for the use of a more robust ET equation. Although these controllers are similar, they differ in key ways. For example, the ETwater controller was designed so that all programming must be completed using a website, while the Toro controller is programmed via the controller interface. Additionally, the ETwater controller receives ET_o based on weather data from a single weather station located off-site, while the Toro controller receives ET_o based on weather data interpolated using a model that triangulates between multiple off-site weather stations.

The ET Manager also uses ET_o calculated using the ASCE-EWRI equation (ASCE-EWRI, 2005). This controller receives hourly weather data through the Weather Reach service and calculates ET_o at the controller. However, this controller was designed as an add-on device to a time clock. Although this controller maintains a soil water balance similar to the other controllers, the add-on attribute limits the controller to only bypassing unnecessary irrigation events scheduled by the user. Unnecessary events are determined by the soil water balance using daily ET, rainfall, irrigation application depth based on default or user-input application rates and other inputs.

Each controller handles rainfall differently. The Weathermatic controller uses an expanding-disk rain sensor located on the weather monitor to pause irrigation for a preset number of hours or days. The Toro controller utilizes a rain pause feature whereby the controller pauses for a certain number of days based on proprietary algorithms. The ETwater controller incorporates the depth of rainfall measured at the weather station associated with the controller into the soil water balance to directly determine the amount of irrigation required. The ET Manager uses a tipping-bucket rain gauge mounted on-site to measure rainfall. The Toro and ETwater controllers were outfitted with Mini-Clik rain sensors set at a 6 mm threshold (Hunter Industries, Inc., San Marcos, Cal.) for every study except when specified.

SUMMARY DESCRIPTION OF PROJECTS

A field study was performed in southwest Florida (SWF field study) to determine how the ET controllers would perform compared to various time-based irrigation schedules on real landscapes. Two brands of ET controllers (Toro Intelli-Sense and Weathermatic SL1600) controlled irrigation on 72 m^2 St. Augustine turfgrass plots. In addition, two time-based irrigation schedules based on UF-IFAS recommendations were used as comparisons. The first schedule was intended to replace 100% of the net irrigation requirement (TIME), and the second treatment replaced 60% of the net irrigation requirement (RTIME). All treatments were compared to a TIME WOS (without sensor) schedule that was created by including the irrigation events bypassed by the rain sensor of the TIME treatment. A more detailed description can be found in Davis et al. (2009).

Another field study involving ET controllers was conducted in central Florida (CF field study) on St. Augustine grass plots measuring 18.2 m^2. Two brands of ET controllers (Toro Intelli-Sense and Rain Bird ET Manager) were installed to schedule irrigation at an irrigation frequency of 2 d $week^{-1}$. Similarly to the SWF field study, a time-based treatment developed from UF-IFAS recommendations was implemented to replace 100% of the net irrigation requirement without using a rain sensor (WOS). A more detailed description can be found at McCready et al. (2009).

A cooperator study involved testing one brand of ET controller, chosen based on favorable results from the SWF field study, in a residential setting to determine if potential water savings could also be achieved under real-world conditions. Thirty-six cooperators were selected for this study located throughout southwest Florida, specifically the Apollo Beach, Riverview, and Valrico areas. Cooperators were separated into two treatment groups: 21 cooperators were outfitted with Toro Intelli-sense ET controllers (ET controller group), and the remaining 15 were asked to maintain their current irrigation practices (comparison group). Automatic meter reading devices (AMRs) were installed on the household water meters in January 2009 and collected sub-hourly water meter data through January 2010.

Irrigation water use for each cooperator was determined from the total household water use by removing any water accumulated for a single sub-hourly time period that was less than the minimum volume capable of the irrigation system based on the calculated application rates determined during the initial irrigation system evaluation. The average per capita indoor water use for the cooperators ranged from 57 to 590 L d^{-1}, averaging 261 L d^{-1}, which is the same average that was found in a U.S. study covering twelve cities (Mayer et al., 1999).

The ET controller bench test was designed so that irrigation was calculated from recorded timestamps of zone initiation and termination. The bench test was not connected to an actual irrigation system; relays were substituted for solenoid valves. A CR-10X datalogger (Campbell Scientific, Logan, Utah) was connected to each relay, through a switch input multiplexer as necessary, to record when the circuit closed (recorded as a 1, indicating irrigation is on) and when the circuit opened (recorded as a 0, indicating irrigation is off).

To date, the SWAT test has been performed in California as a bench test under generally semi-arid conditions. It was previously unknown if the results reported from California were transferable to different climates, such as Florida, which is typically humid with unpredictable rainfall patterns. Additionally, the EPA WaterSense program required that the SWAT test be reproducible so that the EPA could adopt it directly as a part of the testing procedures for labeling ET controllers as water-saving devices. The tested ET controllers, comprising the Toro Intelli-Sense, Weathermatic SL1600, and ETwater Smart Controller 100, were randomly renamed for the Florida SWAT test by request of the EPA WaterSense program. The ET controllers that do not include on-site rain bypass devices as a standard addition were duplicated so that one controller received a Mini-Clik rain sensor and one did not. A total of five controllers were evaluated in this study and labeled ET-A WOS (without rain sensor), ET-A WRS (with rain sensor), ET-B WOS, ET-B WRS, and ET-C. Additional information concerning the study description and results can be found in Davis and Dukes (2009, 2011).

DATA COLLECTION

Weather data were collected from various weather stations for all of the ET controller projects. All weather stations were at least equipped to provide temperature, relative humidity, solar radiation, and wind speed at 15 min intervals to calculate ET_o using the ASCE-EWRI method. Weather data were continually verified for quality throughout the study periods. The weather station used for the SWF field study was located 100 m from the project site and was managed by the Florida Automated Weather Network (FAWN). The remaining weather stations were managed by research personnel. The CF field study used weather data from a station located within 900 m of the experimental site. Weather station distances from the cooperating homes varied but were not greater than 4 km. Two additional rain gauges were added to ensure rainfall measurement within 500 m of some cooperating homes. One weather station was associated with the bench tests and was 17 m from the mounting location.

For all tests except the bench tests, turfgrass quality ratings were taken seasonally at minimum using National Turfgrass Evaluation Program (NTEP) procedures (Shearman and Morris, 1998). The rating scale ranges from 1 to 9, where 1 represents dead turfgrass or bare ground, and 9 represents the highest possible quality, primarily based on color and density. A rating of 5 was chosen as minimally acceptable.

Statistical analyses were performed using SAS (SAS Institute, Inc., Cary, N.C.) software across all projects. Water application and turfgrass quality for both field studies were analyzed using the general linear model procedure and the mixed procedure with means separation conducted using Duncan's multiple range test. The cooperator study was analyzed using the glimmix procedure in which irrigation application required a log transformation, and comparisons were made using the least mean square differences by treatment and location. Significance was determined at a 95% confidence level.

RESULTS AND DISCUSSION

SWF FIELD STUDY

The ET controllers averaged 43% annual water savings compared to TIME WOS and were about twice as effective at reducing irrigation compared to a rain sensor alone.

Table 1. Average weekly irrigation application, cumulative seasonal water savings, and turfgrass quality for the SWF field study (data from Davis et al., 2009).[a]

	Winter 2006			Spring 2007		
Treatment	Irrigation (mm week^{-1})	Savings[b] (%)	Turfgrass Quality[c]	Irrigation (mm week^{-1})	Savings[b] (%)	Turfgrass Quality[c]
Weathermatic	7 c	50	5.7 a	32 ab	9	6.2 a
Toro	6 c	60	5.9 a	30 b	15	6.4 a
TIME	11 b	20	6.0 a	29 b	18	6.2 a
RTIME	7 c	49	5.7 a	17 d	50	6.1 a
TIME WOS	14 a	0	NA[d]	35 a	0	NA

[a] Within a column, values followed by different letters are different at the 95% confidence level using Duncan's multiple range test.

[b] Savings compared to TIME WOS, where TIME WOS is a time-based treatment without bypassed rain events in TIME. Savings were calculated using cumulative period totals.

[c] Turfgrass quality ratings use a 1 to 9 scale, where 1 is lowest quality, 9 is highest quality, and 5 is minimally acceptable.

[d] NA indicates that the treatment was derived from a different treatment, and there were no results possible in this category.

Turfgrass quality remained above minimally acceptable despite significant irrigation reduction and the dry conditions (table 1). The controllers adjusted irrigation schedules to the climatic demand effectively, with maximum savings of 60% during the winter 2006-2007 period and minimum savings of 9% during spring 2007, when demand was highest.

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, averaging 74% for the ET controllers, compared to the other drier season of spring 2007, when scheduling efficiency averaged 94%, indicating inaccuracy in accounting for site-specific rainfall (Davis and Dukes, 2010). The Weathermatic and Toro controllers both used a rain pause feature that did not handle rainfall as accurately as on-site measurement. Additionally, the Toro and ETwater controllers both used rainfall from a weather station that may not be representative of the depth of rain at the controller location.

In a humid climate, accurate measurements of effective rainfall are important for maintaining high scheduling efficiencies. Using weather stations that are many kilometers away or using forecasting models to estimate rainfall are typically not accurate enough to determine site-specific irrigation requirements in Florida. Localized rainfall events are common and occur frequently during the rainy season. Including a way to measure rainfall on-site may be the only way to maximize water savings from ET controllers where rainfall is substantial and unpredictable. Another smart controller field study conducted in a humid climate found that irrigation application by a Toro Intelli-Sense controller was in excess of the amount of irrigation required, possibly due in part to inaccurate rainfall estimation (Vasanth et al., 2007). It was suggested that using more representative weather stations to better account for site conditions would improve scheduling efficiency, thus increasing water conservation.

Inputs to the ET controllers, both manufacturer- and user-programmed, are important for proper irrigation scheduling. The crop coefficients used by the ET controllers were either averages for the entire year, as in the Weathermatic, or unknown, but they 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 instead of the California-derived crop coefficients used by the SWAT protocol and possibly by the signal-based controllers, and this could explain some of the lower scheduling efficiency and adequacy scores.

Although estimates of ET_o are generally standardized and fairly accurate between controller brands, the crop coefficients used by ET controllers have not been as consistent. Using an annual crop coefficient does not adequately adjust ET_o for seasonal variations, which should be a requirement for a smart technology such as an ET controller. Additionally, using crop coefficients for a specific location, such as central California, does not adequately represent the seasonal fluctuations in Florida or other regions. Default crop coefficients for cool-season turfgrass were used in a North Carolina study (Vasanth et al., 2007). Although the controllers followed the weather trends, the failure to produce significant water savings could be attributed to program settings, such as the crop coefficients. Having an option to customize monthly crop coefficients instead of using default values would be of value to an experienced irrigation professional but would not help a novice user, such as a homeowner or landscaper.

The inputs to the controllers that were known were used to calculate GIR; however, it is possible that the landscape characteristics were different from the program settings used by the controllers. For example, the ET controllers likely used different values for readily available water than the value used in the soil water balance based on site conditions. As a result, it would be considerably difficult for these controllers to maintain both high irrigation adequacy and scheduling efficiency scores.

The RTIME treatment resulted in similar savings as the ET controllers in winter and performed better than the ET controllers in spring (table 1). Thus, as has been shown in previous research in Florida, changing time clock settings throughout the year can result in substantial irrigation savings (Haley et al., 2007). Winter 2006-2007 was scheduled for only 36% replacement of net irrigation requirement for the reduced time-based treatment but was still irrigated the same as the ET controller treatments in the winter. This result indicates that the ET controllers were effective at reducing irrigation application during low climatic demand. 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 many homeowners do not adjust time clock irrigation schedules on a regular

Table 2. Average weekly irrigation application, cumulative seasonal water savings, and turfgrass quality for the CF field study (data from McCready et al., 2009).[a]

	Fall 2006			Spring 2007		
Treatment	Irrigation (mm week^{-1})	Savings[b] (%)	Turfgrass Quality[c]	Irrigation (mm week^{-1})	Savings[b] (%)	Turfgrass Quality[c]
Toro	9 c	63	6.5 ab	29 b	25	6.1 a
ET Manager	14 b	40	7.1 a	15 c	59	4.5 b
WOS	24 a	0	6.1 b	39 a	0	6.5 a

[a] Within a column, values followed by different letters are different at the 95% confidence level using Duncan's multiple range test.

[b] Savings compared to WOS, where WOS is a time-based treatment developed from the net irrigation requirement without a rain sensor. Savings were calculated using cumulative period totals.

[c] Turfgrass quality ratings used a 1 to 9 scale, where 1 is lowest quality, 9 is highest quality, and 5 is minimally acceptable.

basis. Thus, the ET controllers tested here have shown that they can adjust irrigation in response to real-time or near-real-time climatic demand. The actual water conservation potential of these controllers in landscapes will depend on irrigator habits and preferences.

CF FIELD STUDY

The Toro and ET Manager controllers resulted in water savings ranging from 25% to 63%; however, in the spring season, the ET Manager treatment produced less than acceptable turfgrass quality due to an inappropriate input parameter setting related to effective rainfall (table 2). This input affected the controller-calculated water holding capacity of the soil and caused bypassed irrigation opportunities 57% of the time, compared to bypassing 9% of the opportunities by the Toro. During the fall 2006 season, both controllers produced similar acceptable turfgrass quality ratings despite reduced water application.

Selection of program settings for ET controllers is extremely important for maximizing water savings without sacrificing landscape quality. Program selections should be made by considering the time periods when irrigation is most required. For example, irrigation savings were at the expense of landscape quality for the ET Manager controller in spring 2007. This controller used a unique effective rainfall setting that maintained a certain deficit from field capacity to minimize runoff from future rainfall. High ET demand, averaging 26 mm week^{-1}, combined with low rainfall created increasing deficit conditions from which the controller could not recover. However, in fall 2006, this setting did not negatively impact turfgrass quality due to lower ET demand, which averaged 11 mm week^{-1}.

The settings used for ET controllers should be able to satisfy irrigation requirements during periods of high climatic demand. Some ET controllers even specify that settings should reflect climatic conditions in July, since this is the period of highest ET in most of the U.S. However, the highest ET in Florida is in May. This phenomenon was apparent in the central Florida field study, where the Rain Bird ET Manager failed to sufficiently account for very little rainfall during the spring season and severely affected the turfgrass quality. Program settings should be chosen to ensure good landscape health during high climatic demand periods with the reliance that the smart technology can adjust to account for periods of less intense irrigation needs.

The ET controllers were programmed with 95% efficiency factors for all three seasons. However, the WOS treatment was determined assuming 60% efficiency, which equaled the DU_{lq} results from the site. If the Toro controller had been programmed with an efficiency factor equal to the DU_{lq}, then more irrigation would have been applied, which would have resulted in over-irrigation occurring in the spring season compared to WOS. However, additional irrigation was not necessary because the turfgrass quality ratings were above the acceptable threshold. Efficiency adjustments based on DU_{lq} cause an overestimation in irrigation application and would not be necessary for systems with good irrigation coverage and in good working condition.

It is likely that default settings programmed into an ET controller cannot be broadly applied throughout the country or even throughout the same state. Water pressures, system designs, and other irrigation system characteristics as well as weather patterns cannot be expected to be the same in Colorado as they would be in Florida. Vasanth et al. (2007) found that general programming of an ET controller resulted in gross over-irrigation compared to both a time-based schedule and a soil moisture sensor. Initial programming should be completed by a qualified professional who understands the parameters being programmed and can make adjustments based on site specifications. Individual settings programmed into the ET controller can dramatically affect the amount of irrigation applied. Determining the correct application rate and efficiency of the system can be one of the highest water saving techniques that is completely controlled by the user and not the technology. Although default settings for application rate and efficiency are usually provided, many factors can affect these parameters that are unique to each irrigation system. Even if the required depth of irrigation is accurately calculated by the ET controller, over- or under-irrigation could occur by incorrectly calculating the runtime using an unrepresentative application rate, or irrigation could be artificially increased due to a low efficiency value. Poorly programmed application rates can double or even triple irrigation application and negate any positive outcomes from choosing a smart technology. The time and effort required to calculate application rates for each irrigation system should be considered part of the installation methodology, rather than relying on default programming information.

COOPERATOR STUDY

Over the study period, there was high ET and less than normal rainfall, creating higher than normal irrigation demand. An ET controller would produce significant savings if used by a homeowner who historically irrigated at or higher than GIR. However, most of the cooperators in both treatment groups only irrigated a fraction of GIR and simi-

Table 3. Average monthly irrigation application from February 2009 through January 2010 as compared to average monthly historical irrigation and average gross irrigation determined using the soil water balance. Turfgrass quality ratings were used to determine if decreases in irrigation application were at the expense of the landscape.[a]

Location	Treatment	No. of Homes	Irrigation (mm month^{-1})	Historical Irrigation (mm month^{-1})	Gross Irrigation Requirement (mm month^{-1})	Turfgrass Quality[b]
Apollo Beach	Comparison	6	50 cd	67 abc	68 abc	5.7 BC
	ET	7	38 d	55 bcd	66 bc	5.6 BC
Riverview	Comparison	3	11 f	45 d	73 abc	6.0 ABC
	ET	5	32 de	48 cd	76 ab	6.7 AB
Valrico	Comparison	6	30 e	67 abc	69 abc	5.1 C
	ET	9	42 d	55 bcd	87 a	7.4 A

[a] Values followed by different lowercase letters in the same column or row are different at the 95% confidence level.

[b] In the Turfgrass Quality column, values followed by different uppercase letters are different at the 95% confidence level.

larly to or less than their historical average, likely due to temporary extreme irrigation restrictions (4 hours only, 1 d week^{-1}) that were in place from 3 April 2009 through 30 June 2009. It is possible that the perception of the drought and increased watering restrictions during spring 2009 could have promoted deficit irrigation practices and a shift in priorities from high landscape quality to reducing water use. ET controller homes were exempt from day of the week restrictions but were asked to change their irrigation start times to midnight.

For all three treatment locations, both the comparison and ET controller groups irrigated similarly to or less than their historical average calculated using their previous five years of water use records from 2001 to 2006 (table 3). In both Valrico and Riverview, the comparison group had significantly less monthly irrigation application, averaging 30 and 11 mm, respectively, than their historical averages of 67 and 45 mm. This indicates that the cooperators in these areas changed their irrigation habits to become low water users between 2006 and 2009 when the study began. While the true cause of the change is unknown, irrigation habits could likely have been affected by the stricter watering restrictions, as described previously, or may have been subject to influence due to the research project, although we have not seen this extreme a response in other homeowner cooperative studies (Haley et al., 2007; Haley and Dukes, 2011).

Cooperators within both treatments in Riverview and the ET controller treatment in Valrico applied less water historically than what was calculated as GIR using the soil water balance. The treatments in Riverview historically averaged 45 and 48 mm for the comparison and ET controller treatments, respectively, compared to 73 and 76 mm calculated as necessary for these treatments on a monthly basis. The ET controller group in Valrico also applied less irrigation historically (averaging 55 mm month^{-1}) than GIR. This indicates that many cooperators within these treatments were not actually high water users, as was the intention for this study. Potential cooperators were limited to the top 50% of all water users within Hillsborough County Water Resource Services area and were selected from areas where a large number of high water users were identified. However, it is possible that many potential participants who meet these criteria still under-irrigate compared to GIR determined for well-watered conditions.

Between the treatment groups, the ET controller group showed increased monthly irrigation applications in Riverview and Valrico, averaging 32 and 42 mm, respectively, compared to 11 and 30 mm applied by the comparison group. In Valrico, the decrease in irrigation by the comparison group significantly impacted the turfgrass quality of the landscapes, whereas the ET controller group was able to maintain a significantly better turfgrass quality rating. However, the decline in irrigation application in Riverview failed to negatively impact the turfgrass quality significantly, despite a drastic decrease in irrigation application by the comparison group. The comparison group in Riverview consisted of only three cooperators who did not have the full-sun landscapes common to many planned development communities in Florida. These homes had established tree-covered landscapes that would have contributed to the acceptable turfgrass quality ratings. High water tables could have been present at two of the homes; one home continually experienced periods of poor drainage, with standing water in the vegetated culvert, and another home was located along a creek. Conversely, the ET controller group applied less irrigation per month in the Apollo Beach area, averaging 38 mm for the ET controller group and 50 mm for the comparison group, although the means were not statistically different. Turfgrass quality was not negatively affected by the treatments in this location.

Change in behavior in the ET controller group ranged

Table 4. Cumulative irrigation application as compared to cumulative historical irrigation application and gross irrigation requirement.[a]

Location	Treatment	Irrigation (mm)	Historical Irrigation (mm)	Difference from Historical (%)	Gross Irrigation Requirement (mm)	Difference from Gross (%)
Apollo Beach	Comparison	598	721	-17.1	579	3.2
	ET	452	519	-12.9	592	-23.4
Riverview	Comparison	129	210	-38.5	651	-79.9
	ET	370	499	-25.8	741	-49.9
Valrico	Comparison	374	616	-39.2	776	-51.8
	ET	500	495	1.1	885	-43.6

[a] Gross irrigation was determined using the soil water balance as a gross irrigation requirement.

from no reduction (increase of 1.1%) to a 25.8% reduction compared to the historical average (table 4). These reductions were generally less than the water savings found in both field studies and suggest that implementing ET controllers in the real world may result in lower water savings than expected. Although these controllers were under the control of the homeowner and not in a strict research environment, these cooperators received complimentary site-specific adjustments from University of Florida researchers when requested and did not have to rely on irrigation contractors or other technical support options. If this service had not been provided, the reductions might have been even less substantial.

All groups applied less than GIR, ranging from 23.4% to 79.9% of GIR, except for the comparison group in Apollo Beach, which applied 3.2% more than GIR. The reductions for the comparison groups could correlate to their irrigation application compared to the historical period in which deficit irrigation occurred. The ET controller groups had a narrower range of reduction (based on GIR), from 23.4% in Apollo Beach to 51.8% in Valrico, indicating that the ET controllers were continually scheduling less than the gross irrigation required.

Overall, the ET controllers did not increase outdoor water use compared to the historical trends, even though most of the study period was non-rainy and the controllers are designed to maintain well-watered conditions. An ET controller should produce significant savings if used by a homeowner who historically irrigated more than 450 mm per year in this region. According to the results of this study, if the cooperators historically irrigated similarly to or more than GIR, which was estimated to be greater than 450 mm per year, then the irrigation savings would have been substantial. However, most of the cooperators in this study only irrigated a small fraction of the gross requirement on average.

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

FLORIDA SWAT TEST

This study was implemented in 2009 to evaluate three ET controller brands previously tested by SWAT and the University of Florida independently to determine the reproducibility and transferability of the SWAT test as a whole. Unfortunately, cumulative totals for rainfall and ET_o over the study period in Florida were lower than historic levels, averaging 56% and 40% less, respectively. Consequently, the results found from the 2009 Florida SWAT test (Davis and Dukes, 2009) showed that the ET controllers generally scored well in SWAT scheduling efficiency and irrigation adequacy scores, with only slightly lower scores than published from the original SWAT test in California. Scheduling efficiency results were lower than the original published scores by 2.5 percentage points for the ET-A controllers, by 14 percentage points by the ET-B controllers, and by 4.6 percentage points by the ET-C. Given the uncharacteristically dry conditions, similar to the California testing conditions, it is likely that the Florida SWAT test scores were generally higher than would occur in a rainy period.

The Florida SWAT test was repeated in 2010 to re-evaluate the SWAT performance during four 60 d periods of different weather conditions that included frequent rainfall, infrequent rainfall, high ET_o, and low ET_o. For each ET controller, 30 d moving averages were assessed to obtain 30 results of irrigation adequacy and 30 results of scheduling efficiency per 60 d period for each of the six zones described by the SWAT testing protocol. The EPA WaterSense program has suggested thresholds for scheduling efficiency and irrigation adequacy of 95% and 80%, respectively, in their technical specifications. These thresholds were chosen to encourage controller results to err on the side of under-irrigation rather than over-irrigation. The percentage of scores above the thresholds was calculated as a rate of passing.

This analysis showed that the most influential weather conditions were during periods of frequent rainfall. A period was defined as having frequent rainfall when the number of rainfall events exceeded the average number of rainfall events over the same period using 30 years of rainfall data. The passing rate was not limited by irrigation adequacy, indicating that the controllers never allowed deficit conditions (i.e., if anything, they tended to over-irrigate). During this period, scheduling efficiency scores decreased well below the proposed threshold of 95%, thus severely decreasing the passing rate for most controllers (table 5). Average scheduling efficiency scores between the infrequent and frequent rainfall periods dropped by 15 to 20 percentage points for zone 2 and by 34 to 45 percentage points for zone 4. Overall, testing in periods of increased rainfall frequency caused a decrease in scheduling efficiency results, thus decreasing the overall rate of passing scores. This same trend was seen in the SWF field study, where scheduling efficiency dropped by 20 percentage points from a non-rainy season to a rainy season.

All controllers showed a decrease in passing scores due to low scheduling efficiency during the high and low ET_o periods, in addition to the frequent rainfall period, due to 125 to 198 mm of rainfall occurring over 16 to 17 events in each period. This amount of rainfall would be considered frequent when compared to the current SWAT testing location in central California, but it would be considered an average amount of rainfall in Florida compared to historical trends. The infrequent rainfall period had rainfall conditions more similar to those of central California, with only 46 mm of rainfall and increased scheduling efficiency scores over the 60 d period. Again, passing rates were not limited by irrigation adequacy scores during these three periods; thus, passing rates were higher because scheduling efficiency scores were higher.

The ET_o, rainfall, and test length minimum requirements

Table 5. Percentage of scores that were greater than the acceptable score thresholds of 80% for irrigation adequacy and 95% for scheduling efficiency using the minimum score received out of all six zones.

Controller	Irrigation Adequacy (%)	Scheduling Efficiency (%)	Both
Frequent rainfall			
ET-A WOS	100	0	0
ET-A WRS	100	0	0
ET-B WOS	100	0	0
ET-B WRS	100	3	3
ET-C	100	100	100
Infrequent rainfall			
ET-A WOS	100	58	58
ET-A WRS	100	100	100
ET-B WOS	100	10	10
ET-B WRS	100	10	10
ET-C	100	94	94
Low ET_o			
ET-A WOS	100	10	10
ET-A WRS	100	10	10
ET-B WOS	100	0	0
ET-B WRS	100	0	0
ET-C[a]	NA	NA	NA
High ET_o			
ET-A WOS	100	0	0
ET-A WRS	100	10	10
ET-B WOS	100	0	0
ET-B WRS	100	0	0
ET-C	42	0	0

[a] Scores not reported due to a malfunction in the controller equipment.

of 63.5 mm, 10.2 mm, and 30 d, respectively, were originally selected based on southern California's arid climate. However, these minimum requirements are considered low for humid climates such as Florida, where 10.2 mm of rainfall can be achieved in a day during the rainy season. Despite the current SWAT minimum ET_o and rainfall thresholds, these limits do not adequately show the ability of ET controllers to adjust to changing climatic conditions over time unless the test period includes a climatic transition period, e.g., spring to summer. For example, the Florida SWAT test showed that the transition from non-rainy to rainy conditions negatively impacted the SWAT scores. Each controller met the minimum requirements for ET_o and rainfall and had at least one 30 d period when both irrigation adequacy and scheduling efficiency were above 95%. As a result, moving 30 d total results over a longer period would provide results more reflective of controller performance over time. It is recommended that testing occur during conditions representative of the growing season, i.e., ET_o ranging from 381 to 508 mm for a minimum 90 d period and rainfall of 127 mm in a minimum of ten events would be reasonable limits for the eastern U.S.

Rainfall in humid climates can be unpredictable and localized, making it difficult to schedule irrigation in subhumid to humid regions. The ET controllers are penalized by irrigation occurring on the same day as rainfall according to the protocol, even if the irrigation occurs prior to the rainfall event. Additionally, the test results showed that using a rain sensor did not affect irrigation adequacy for any controller and increased scheduling efficiency for one controller brand. The study period was unusually dry, with rainfall depths less than half of the 30-year historical rainfall totaled for the same time period. Conducting the test under dry conditions and programming the controllers with small and frequent irrigation events virtually guarantees high SWAT scores of irrigation adequacy and scheduling efficiency. However, the results may not be representative of real-world performance because all controllers were set up with unrealistic programs not typically found in systems in the field. Unrealistic programs included runtimes of just 1 or 2 min or any combination of program settings adjusted to be different from the landscape descriptions described in the protocol.

In addition to revising and clarifying the protocol document, recommendations include increasing the length of the test to allow the controllers to adjust over time, disclosing program settings with test results, and increasing the rainfall threshold. It is imperative to observe the controller's ability to handle rainfall over a longer period of time, since it is more difficult to accurately schedule irrigation in rainy climates vs. arid climates.

CONCLUSION

Based on studies summarized here, ET controllers have the potential for up to 63% water savings compared to a calendar-based recommended schedule without sacrificing landscape quality when programmed correctly in moderate to high water use scenarios. Homeowners who already irrigate less than well-watered conditions and accept declines in landscape quality on a regular basis will not benefit from using an ET controller in terms of water savings. In fact, their irrigation use may increase with an ET controller. However, homeowners who set their time clocks to a peak irrigation schedule without updating the controller settings throughout the year may see significant reductions in irrigation, specifically during the fall and winter seasons. Additionally, proper controller programming is essential to maximize water savings while maintaining acceptable landscape quality.

The Florida SWAT test had results similar to the official testing results published by the Irrigation Association only during the single period that had infrequent rainfall. As a result, the scheduling efficiency scores suffered, resulting in low passing rates during most periods. There was a maximum of 10% of 30 d periods when scheduling efficiency results were above these thresholds during periods with frequent rainfall. Additionally, controller programming by the manufacturers' representatives sometimes differed from the landscapes described in the protocol. The differences were designed to create short and frequent irrigation runtimes that maximize the probability that the controller will not over- or under-irrigate. However, this technique diminishes the applicability of the SWAT test results to real-world performance for similar landscapes. Additionally, updating the reported results of the SWAT test to include moving 30 d scores over a representative growing season with minimum ET_o of 381 to 508 mm for a 90 d period and rainfall of 127 mm in a minimum of ten events would provide more realistic results of controller performance over time.

The SWAT scores can indicate water savings only if there is a potential for savings from excess irrigation prior to implementation of the ET controller. If irrigation was conservative prior to ET controller implementation, then it is likely that the ET controller will increase irrigation application. In addition to seeing this trend in the cooperator study, this conclusion was also found by Mayer et al. (2009), in which the sites already irrigating less than the gross irrigation requirement did not experience water savings with an ET controller. Other smart irrigation technologies that do not increase existing irrigation, such as soil moisture sensors, would be more appropriate in that situation.

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REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop requirements. Irrigation and Drainage Paper No. 56. Rome, Italy: United Nations FAO.

ASCE-EWRI. 2005. The ASCE standardized reference evapotranspiration equation. Technical Committee report to the Environmental and Water Resources Institute of the American Society of Civil Engineers from the Task Committee on Standardization of Reference Evapotranspiration. Reston, Va.: ASCE-EWRI.

Aquacraft. 2002. Performance evaluation of WeatherTRAK irrigation controllers in Colorado. Boulder, Colo.: Aquacraft, Inc. Available at: www.aquacraft.com. Accessed 21 October 2005.

Aquacraft. 2003. Report on performance of ET-based irrigation controller: Analysis of operation of WeatherTRAK controller in field conditions during 2002. Boulder, Colo.: Aquacraft, Inc. Available at: www.aquacraft.com. Accessed 21 October 2005.

Bamezai, A. 2004. LADWP weather-based irrigation controller pilot study. Available at: www.cuwcc.org/WorkArea/showcontent.aspx?id=2544. Accessed 3 April 2012.

Davis, S. L., and M. D. Dukes. 2009. Examination of SWAT protocol utilizing a performance analysis of weather-based irrigation controllers. Available at: www.epa.gov/watersense/docs/university_of_florida_report.pdf. Accessed 3 April 2012.

Davis, S. L., and M. D. Dukes. 2010. Irrigation scheduling performance by evapotranspiration-based controllers. *Agric. Water Mgmt.* 98(1): 19-28.

Davis, S. L., and M. D. Dukes. 2011. Examination of SWAT protocol utilizing a performance analysis of weather-based irrigation controllers: Update with extended data. Available at: www.epa.gov/watersense/docs/controller_2010-epa-report.pdf. Accessed 1 August 2011.

Davis, S. L., M. D. Dukes, and G. L. Miller. 2009. Landscape irrigation by evapotranspiration-based irrigation controllers under dry conditions in southwest Florida. *Agric. Water Mgmt.* 96(12): 1828-1836.

Haley, M. B., and M. D. Dukes. 2011. Validation of landscape irrigation reduction with soil moisture sensor irrigation controllers. *J. Irrig. and Drainage Eng.* 138(2): doi:10.1061/(ASCE)IR.1943-4774.0000391.

Haley, M. B., M. D. Dukes, and G. L. Miller. 2007. Residential irrigation water use in central Florida. *J. Irrig. and Drainage Eng.* 133(5): 427-434.

Hargreaves, G. H., and Z. A. Samani. 1982. Estimating potential evapotranspiration. *J. Irrig. and Drainage Eng.* 108(3): 223-230.

Hutson, S. S., N. L. Barber, J. F. Kenny, K. S. Linsey, D. S. Lumia, and M. A. Maupin. 2004. Estimated use of water in the United States in 2000. USGS Circular 1268. Reston, Va.: U.S. Geological Survey.

Irrigation Association. 2005. Landscape irrigation scheduling and water management. Falls Church, Va.: Irrigation Association, Water Management Committee.

Irrigation Association. 2008. Smart water application technology (SWAT) turf and landscape irrigation equipment testing protocol for climatologically based controllers: 8th draft. Falls Church, Va.: Irrigation Association. Available at: www.irrigation.org. Accessed 15 October 2008.

Jia, X., M. D. Dukes, and J. M. Jacobs. 2009. Bahiagrass crop coefficients from eddy correlation measurements in central Florida. *Irrig. Sci.* 28(1): 5-15.

Mayer, P. W., W. B. DeOreo, E. M. Opitz, J. C. Kiefer, W. Y. Davis, B. Dziegielewski, and J. O. Nelson. 1999. Residential end uses of water. Denver, Colo.: American Water Works Association Research Foundation.

Mayer, P. W., W. B. DeOreo, M. Hayden, R. Davis, E. Caldwell, T. Miller, and P. J. Bickel. 2009. Evaluation of California weather-based "smart" irrigation controller programs. Boulder, Colo.: Aquacraft, Inc. Available at: www.aquacraft.com. Accessed 15 August 2009.

McCready, M. S., M. D. Dukes, and G. L. Miller. 2009. Water conservation potential of smart irrigation controllers on St. Augustinegrass. *Agric. Water Mgmt.* 96(11): 1623-1632.

MWD. 2004. Weather-based controller bench test report. Los Angeles, Cal.: Metropolitan Water District of Southern California. Available at: www.cuwcc.org/WorkArea/showcontent.aspx?id=2542. Accessed 3 April 2012.

Pittenger, D. R., D. A. Shaw, and W. E. Richie. 2004. Evaluation of weather-sensing landscape irrigation controllers. Riverside, Cal.: University of California Cooperative Extension.

Shearman. R. C., and K. N. Morris. 1998. *NTEP Turfgrass Evaluation Workbook*. Presented at the NTEP Turfgrass Evaluation Workshop, 17 October 1998. Beltsville, Md. National Turfgrass Evaluation Program.

Vasanth, A., G. L. Grabow, D. Bowman, R. L. Huffman, and G. L. Miller. 2007. Evaluation of evapotranspiration-based and soil-moisture-based irrigation control in turf. In *Proc. Irrig. Assoc. Conf.* Falls Church, Va.: Irrigation Association.