Received: 2 October 2020 | Revised: 22 December 2020 | Accepted: 7 January 2021
DOI: 10.1002/aws2.1218

ORIGINAL RESEARCH

AWWA WATER SCIENCE

Long-term performance of smart irrigation controllers on single-family homes with excess irrigation

Bernardo Cardenas[1] | **Michael D. Dukes**[1,2] | **Eliza Breder**[1] | **Jacqueline W. Torbert**[3]

[1]Agricultural and Biological Engineering Department, University of Florida, Gainesville, Florida

[2]Center for Land Use Efficiency, University of Florida, Gainesville, Florida

[3]Orange County Utilities Water Division, Orlando, Florida

Correspondence
Michael D. Dukes, Center for Land Use Efficiency, University of Florida, Institute of Food & Agricultural Sciences, 2140 NE Waldo Rd., PO Box 110675 Gainesville, FL 32609 352-294-6720.
Email: mddukes@ufl.edu

Associate Editor: Peter Mayer

Abstract

The main objective of this study was to evaluate the long-term water conservation potential of two smart irrigation controllers when implemented in single-family homes with excess irrigation. Treatments were established in Orange County, Florida, across two types of soils and included homes monitored only (MO), homes that received an evapotranspiration (ET) controller or a soil moisture sensor (SMS) controller, and homes that received an ET or SMS plus an onsite specific programing and tutorial given to the homeowner (ETPgm or SMSPgm, respectively). All treatments resulted in significant water savings compared with the MO group, without negatively affecting the turf quality. Average irrigation reductions in sandy and flatwoods soils for ET were 21% and 17% and 26% and 31%, respectively, in the ETPgm group. The SMS group reduced irrigation by 18% and 42% in flatwoods and sandy soils, respectively, while the SMSPgm treatment applied 41% and 35% less water, respectively.

KEYWORDS

ET controller, landscape irrigation, smart irrigation controllers, soil moisture sensor

1 | INTRODUCTION

In 2010, the Orange County Utilities Water Division (OCU) primarily served unincorporated areas of Orange County and had more than 140,000 single-family home accounts, serving a population of approximately 490,000. Orange County is located in Central Florida, within an area of limited water resources and rapid population growth and where three water management districts converge: South Florida Water Management District, St. Johns River Water Management District, and Southwest Florida Water Management District. In the past, the districts worked independently to resolve water resource issues; however, in 2006, the Central Florida Coordination Area (CFCA) was created to estimate, regulate, and coordinate future water demands, including potable water. A report by the CFCA (2010) determined that groundwater resources were not suitable at the existing rate of growth, which was more than 28% between 2000 and 2010 (USCB, 2010). Key rule provisions of the CFCA limited the withdrawal of additional groundwater to no more than that needed to meet year 2013 demands unless supplemental water supplies were committed to meet demands after 2013.

To address water supply concerns, OCU embarked on residential water conservation programs. Among those, OCU wanted to evaluate, in real-world residential settings, smart irrigation controllers that had shown potential to conserve water, including soil moisture sensor (SMS) controllers and weather-based or evapotranspiration (ET) controllers. The SMS controllers save water, bypassing irrigation cycles when the soil is wet enough to maintain good plant growth and quality, while the most common water-saving mechanism for ET controllers is adjusting the runtimes to replace the estimated ET lost between irrigation cycles. In a climate in which rain can meet a significant amount of plant water needs (such as in the Southeast), SMS controllers have an advantage over most commercially available ET controllers because they capture onsite rainfall. Most ET controllers use expanding-disk rain sensors to measure rain. These types of rain sensors, however, have shown variable accuracy between different rain events and between different units (Cardenas-Lailhacar & Dukes, 2008; Meeks, Dukes, Migliaccio, & Cardenas-Lailhacar, 2012a), and their consistency of operation decreases over time (Meeks, Dukes, Migliaccio, & Cardenas-Lailhacar, 2012b). Most studies involving smart irrigation controllers in Florida were previously conducted on research plots.

Since 2004, in North Central Florida, different SMS models designed for landscape irrigation have been investigated under different weather conditions, probe burial depths, threshold settings, irrigation frequencies, and soil salinities and temperatures. Even under those different variables, most of the studied SMS controllers resulted in significant water savings compared with an automated irrigation system without sensor feedback from the irrigated area. During normal to wet weather conditions, Cardenas-Lailhacar, Dukes, and Miller (2008) reported that the SMS controllers tested reduced irrigation by 69%–92%, with an average of 72%, relative to homeowner irrigation schedules with a timer, without adversely affecting turf quality. During dry periods, in the same study site, Cardenas-Lailhacar, Dukes, and Miller (2010) reported average savings of between 34% and 54% depending on different scheduling settings, with turf quality ratings sometimes falling below the minimum acceptable level. McCready, Dukes, and Miller (2009) reported that when SMS controllers were optimized in terms of setting thresholds, irrigation reduction was as high as 60% and 90% under dry conditions and normal rainfall, respectively. These savings were obtained even when the different SMS models operated with diverse precision (Cardenas-Lailhacar & Dukes, 2010).

Before this study, few but promising results were reported for ET controllers in Florida. In a study conducted in Southwest Florida, Davis, Dukes, and Miller (2009) tested three models and reported maximum savings of 60% during the winter period and minimum savings of 9% when persistent dry conditions occurred during the spring, with water savings that averaged 43% over the 15-month study period and with no reduction in turf quality. Moreover, that study found that ET controllers were about twice as effective at reducing irrigation compared with a rain sensor. In Central Florida, in a 13-month study period, McCready et al. (2009) reported that two ET controller models resulted in water savings ranging from 25% to 63% compared with a typical homeowner irrigation schedule.

Dukes (2012) summarized and reviewed 11 ET controller research studies performed outside of Florida, published before the implementation of this study, and that were carried out under residential, commercial, and public site conditions. Most of these studies typically compared preinstallation water use with postinstallation use, and only two studies included more than 35 homes. Reported water savings ranged between 3% and 21% for residential landscapes, but no statistical analysis considering random error was performed for the comparisons, and results were published without a peer-review process.

Article Impact Statement

Water entities and utilities planning to create a rebate program using smart irrigation controllers can benefit from this long-term study.

Only two studies had previously evaluated ET controller performance for larger numbers of homes, both carried out in California. Kennedy/Jenks Consultants (2008) reported results for 1,222 residential and commercial sites, with only 33% of the residential sites demonstrating a significant decrease in water consumption; 18% had an increase in water consumption, and 50% had no change. Mayer et al. (2009) evaluated pre- and postinstallation water use in 2,294 residential landscapes and reported an overall irrigation reduction of 6.1%. However, they found that 41.8% of the homes had a significant increase in irrigation water consumption after implementation, corresponding to sites that historically irrigated less than the theoretical landscape irrigation requirement. Therefore, ET controllers should be installed preferably in homes that overirrigate their landscape; otherwise, irrigation water use could increase after installation.

Accordingly, implementing an ET controller rebate program across an entire utility area might result in high costs, with a modest or no desired outcome. Therefore, OCU decided to target only excess irrigators to evaluate a possible rebate program. Consequently, the main objective of this study was to evaluate the water conservation potential of two smart irrigation controllers when implemented in single-family homes with excess irrigation in Orange County, Florida.

2 | MATERIALS AND METHODS

2.1 | Cooperator selection

For this study, irrigation applied versus irrigation required was compared in single-family homes in the OCU service area. Homes with overirrigation trends were identified as customers with potential irrigation savings.

2.1.1 | Estimated irrigation applied

The initial irrigation applied by each home was estimated because less than 3% of the potable customers had dedicated irrigation meters. Monthly water billing records, from January 2003 through December 2008, were provided by OCU to the University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS). This database consisted of more than 7.5 million monthly records from residential homes with no irrigation meters. Additional home parameters such as year built, subdivision, parcel area, and built area were also supplied. The irrigable area was calculated as the total parcel area minus the footprint of the built area.

The irrigation water use for each household was calculated by subtracting estimated indoor water use from monthly total meter record. Indoor water use was estimated using the per capita methodology (Mayer et al., 1999), which has also been used in other studies (Boyer, Dukes, Duerr, & Bliznyuk, 2018; Friedman, Heaney, Morales, & Palenchar, 2013; Romero & Dukes, 2014). The reported average indoor water use per capita for the nearby location of Tampa was assumed, which was 66 gpd (Mayer et al., 1999), and was multiplied by the average number of inhabitants in each house, which was 2.25 for Orlando (USCB, 2006). The resulting estimated average indoor use per home was 4,462 gal/month. This estimated indoor water use was then subtracted from the monthly water use bill, and the difference was considered to be the irrigation water use since most of the outdoor water is estimated to be used for irrigation (Mayer et al., 1999). By dividing volume of irrigation water by irrigable area, the irrigation depth applied was obtained.

2.1.2 | Theoretical irrigation requirement

Agroclimatic conditions define the net irrigation requirement (NIR), which is the theoretical amount of water required for adequate plant growth and quality. According to the Soil Survey of Orange County (USDA, 1989), the dominant soil types in the study area are flatwoods and sandy, both with high infiltration rates. In sandy soils, the water table is deep, and the organic matter, nutrients, and colloids are carried rapidly downward, while in the flatwoods soils, the water table is near or at the surface, and the organic matter is translocated a short distance, forming a humus-rich spodic horizon.

The NIR of these two soils was estimated using a soil–water balance equation, calculated on a daily basis for 6 years and then averaged monthly. The soil–water balance equation is as follows:

$$\mathrm{SW}_t = \mathrm{SW}_{t-1} - \mathrm{ETc}_{t-1} + R_{t-1} + I_{t-1} - D_{t-1} - \mathrm{Roff}_{t-1} \quad (1)$$

where SW_t is the soil water content on a given day, SW_{t-1} is the soil water content on the previous day, ETc_{t-1} is the crop ET on the previous day, R_{t-1} is the rainfall on the previous day, I_{t-1} is net irrigation on the previous day, D_{t-1} is drainage on the previous day, and Roff_{t-1} is runoff on the previous day, with all components having units of depth (in.).

Additional inputs to the soil–water balance included field capacity (FC), permanent wilting point (PWP), and available water-holding capacity (AWHC). FC is the maximum water content that can be stored in the soil before gravitational drainage, PWP is the water level at which plants can no longer extract water from the root zone, and AWHC is the amount of water held by the soil between FC and PWP (Irrigation Association, 2005). The characteristics of these soils were used to determine the range of AWHC of the soil profile. Assuming an 8-in. root depth, frequently found in warm-season turfgrasses (Huang, Duncan, & Carrow, 1997; Shedd, Dukes, & Miller, 2008), the resultant AWHC was 1.12 in. for flatwoods soils and 0.50 in. for sandy soils.

Irrigation was simulated once the soil water content reached the maximum allowable depletion, which was defined as 50% of AWHC. The irrigation refilled the soil up to FC, and therefore, drainage (D) was negligible in the soil–water balance equation. In addition, runoff (Roff) was neglected during irrigation because of the coarse texture of the soils at the study sites, where infiltration rates of 6–20 in./h have been reported (USDA, 1989). Finally, the amount of daily rain that exceeded the FC level was considered lost as a result of surface runoff and/or deep percolation.

The daily $\mathrm{ET_c}$ value was calculated as follows:

$$\mathrm{ET_c} = \mathrm{ET_o} \times K_c \quad (2)$$

where $\mathrm{ET_o}$ is the reference ET, and K_c is a crop coefficient. The $\mathrm{ET_o}$ was calculated through the american society of civil engineers–environmental water & resources institute (ASCE-EWRI) standardized equation (ASCE-EWRI, 2005), with weather data such as solar radiation, air temperature, relative humidity, and wind speed. Daily weather data, including rainfall, were available from two county weather stations. One weather station represented the east and south parts of the county, and the other represented the west part of the county. The K_c values are ratios of average crop-specific ET to average $\mathrm{ET_o}$. Monthly K_c values for warm-season turfgrasses, used at this stage, were obtained from a South Florida study by Stewart and Mills (1967).

2.2 | Irrigation ratio

To preselect homes with overirrigation trends, an irrigation ratio (IR) was calculated as follows:

$$\text{Irrigation ratio (IR)} = \frac{\text{Estimated irrigation applied}}{\text{Net irrigation requirement (NIR)}} \quad (3)$$

If a home resulted in IR > 1, the resident was considered an overirrigator, and if a home resulted in IR < 1, the resident was estimated to be underirrigating. Customers with an IR > 1.5 were considered excess irrigators and were selected as potential cooperators for the study. Homes with IR > 4 were not preselected since the ratio could have reflected major irrigation system issues.

2.3 | Questionnaire

On the basis of the IR results, 7,408 accounts met the criteria for an excess irrigator (5% of the population). A letter was mailed by UF/IFAS to customers who were invited to participate in an irrigation water conservation program. If selected, they would receive a free irrigation system evaluation, a free installed irrigation water meter, and the possibility of a free installed smart irrigation controller. Interested customers were asked to respond to an online questionnaire to determine their baseline irrigation knowledge and to include their contact information. There were 843 survey responses (11.4%) from 795 residents (10.7%) that included valid contact information. Selection criteria required that all potential cooperators have an in-ground automated irrigation system, that the residents could not be renters, and it was necessary that they intended to live in the home for the next two or more years. Those who did not respond to all parts of these selection criteria or had account issues, such as late payment, were not selected for the study.

2.4 | Irrigation system evaluation

Once the potential cooperators were filtered according to the previous criteria, onsite evaluations were scheduled to characterize their irrigation systems and to check for any potential issues that could interfere with the project. These evaluations were performed only in locations with a high density of respondents to meet the statistical requirements for treatment replications while minimizing spatial variability.

Some homes were not completely evaluated and were disqualified from the study because of poor landscape quality or major irrigation system problems, such as broken pipes, broken solenoid valves, or broken sprinkler heads. For homes that were given a complete site evaluation, information such as timer location, number of irrigation zones, existing meter type, and irrigable area was collected.

After evaluation, the irrigation applied at those homes was recalculated using the water bill records coupled with the irrigable area measured on site. In addition, IR was recalculated.

2.5 | Locations and treatments

A total of 167 residential homes were ultimately selected within the OCU service area. The selected cooperators signed an agreement with UF/IFAS and OCU, which included requirements such as consenting that the devices installed in their home for the study would become the homeowner's responsibility once the research project was completed, having a properly functioning backflow preventer, and allowing UF/IFAS personnel to collect irrigation data.

Five experimental treatments were designated for this study across the two dominant soil types and clustered in nine areas throughout the OCU service area (Table 1). Four treatments included the addition of either an ET controller or an SMS controller to the already existing irrigation system. The ET controller groups received ESP-SMT controllers (Rain Bird Corporation, Azusa, CA), and the SMS-based groups received WaterTec S100 systems (Baseline, Boise, ID). Two treatments, identified as ET and SMS (Table 2), were installed using methods determined solely by the installing contractor, without UF/IFAS intervention. The remaining two treatments, named ETPgm and SMSPgm, were paired with an educational program that included UF/IFAS training the contractor prior to installations, brief educational training of the cooperators receiving an ET (ETPgm) or an SMS (SMSPgm), and UF/IFAS site-specific programming of the smart irrigation controller. All cooperators who received a smart irrigation controller also received a variance from day-of-the-week water restrictions. The fifth treatment did not receive interventions with irrigation practices, was monitored only (MO), and was used as the comparison treatment.

The five treatments were distributed within each location cluster so that there were at least three cooperators per treatment group and so that homes were spread across the two soil types in the county, except for three locations where securing 20 cooperators was not a viable option (Table 1). Some treatments were not included in the north and north–northeast areas because of a lack of cooperators.

TABLE 1 Number of cooperators by soil type, location, and treatment

		Treatments					
Soil type	Group name and location	Evapotranspiration	ETPgm	Soil moisture sensor controller	SMSPgm	Monitored only	Total
Flatwoods	SW 1	4	4	4	4	4	20
Flatwoods	SW 2	4	4	4	4	4	20
Flatwoods	E1	4	4	4	4	4	20
Flatwoods	E2	4	4	4	4	4	20
Flatwoods	E3	4	4	4	4	4	20
Sandy	W 1	4	4	4	4	3	19
Sandy	NNE	0	5	0	5	5	15
Sandy	N	0	5	0	5	3	13
Sandy	W 2	4	4	4	4	4	20
	Total	28	38	28	38	35	167

Abbreviations: E, east; N, north; NNE, north-northeast; SW, southwest; W, west.

TABLE 2 Irrigation treatments

			Irrigation	
Treatment code	Description or brand and model	Programed by	Frequency (day/week)	Cycles per day
MO	Monitored only	NA	NA	NA
ET	Rain Bird ESP-SMT	Contractor	7	1
SMS	Baseline WaterTec S100	Contractor	7	1
ETPgm	Rain Bird ESP-SMT	University of Florida, Institute of Food and Agricultural Sciences (UF/IFAS)	3	1
SMSPgm	Baseline WaterTec S100	UF/IFAS	3	2

In these two locations, the cooperators were concentrated in the ETPgm, SMSPgm, and MO treatments to provide adequate replication for statistical analysis.

2.6 | Equipment installation

An irrigation contractor familiar with smart irrigation controllers was selected by OCU to install the necessary equipment and provide service hours for minor repairs and issues. Equipment installed included smart irrigation technologies, new irrigation meters, and backflow preventers where necessary. At each participant home, including the MO group, a dedicated irrigation line and a flowmeter (E-Coder R900i, Neptune Technology Group, Tallassee, AL) were installed. The flowmeters had built-in automatic meter reading (AMR) capability, which recorded hourly irrigation volume, with a resolution of 0.1 gal. The volume applied at each home was converted to irrigation depth using the irrigated area measured during the initial onsite irrigation system evaluation.

At the 28 homes in the ET treatment group, the controller was installed and programmed by the irrigation contractor. The controllers were given typical default values for settings such as application rates, landscape coefficients, and AWHC. In addition, the contractor installed an SMS at each home of the SMS treatment group, for a total of 28 systems installed. The contractor installed each probe by burying it 6 in.deep and covering it with loosely packed soil. The SMS interface was programmed with a threshold set between 10% and 15% according to the contractor's evaluation of the soil type. The irrigation timers were reprogrammed to irrigate every day for 20 min if the zone contained primarily spray heads or 45 min for zones with primarily rotor heads.

2.7 | Programing and education

The ET controllers of the 39 homes in the ETPgm treatment group were also installed by the irrigation contractor, but UF/IFAS personnel gave each of these homes site-specific programming for the controller, including individual zone application rates. These application rates were calculated by running each zone for 2 min, totaling the output volume, and dividing it by the area of each zone. After site-specific program settings were updated, the residents were given a 5-min tutorial on the ET controller, a brochure on the controller features, and contact information in case they had questions or concerns. The cooperators that were not selected to participate in the educational training received the brochure via mail.

After the initial implementation of the 28 SMS technologies by the contractor, UF/IFAS set up the remaining 38 SMS systems for the SMSPgm treatment. Installation for the SMS and SMSPgm treatment groups was done at separate times to separate the specific installation methodology. For the SMSPgm group, the same contractor was instructed to dig a hole at a UF/IFAS-specified sunny location and insert the probe adjacent to the opening, horizontally, into an undisturbed soil column at a depth of 3 in. During the educational training session, the irrigation timer was reprogrammed to apply 0.25 in. of irrigation per zone, twice per day, 3 days per week. The runtimes associated with applying 0.25 in. were calculated using the zone-specific application rate following the same procedure described for ETPgm. The residents were then given a 5-min tutorial on the SMS technology. Functions such as how to bypass the sensor, recognize signs of nonfunctionality, and how to adjust the threshold were reviewed. Cooperators were also given a brochure that described how to use the SMS technology and had contact information for any questions or concerns. The cooperators that were not selected to participate in the educational training received the brochure via mail.

2.8 | Data collection and analysis

Equipment and treatments were fully installed and implemented by October 2011, and the data collection was conducted from November 2011 through February 2017, totaling 64 months. The volume of irrigation water applied was compared between treatments and with the irrigation required to meet plant water needs, thus evaluating under- or overirrigation and its impact on turf quality.

For each cooperator, hourly readings of irrigation volume applied were collected using flowmeters' built-in AMR devices. The recorded irrigation volume was converted to a depth of water using the irrigated area measured during the initial irrigation evaluations. Irrigation values were then divided into days, weeks, months, and cumulative; averaged by treatment; and then compared between treatments.

When unusual amounts of water were recorded from a particular home, the individual hourly data were analyzed. Most of the time, a leak was responsible for high peaks in water use. According to the data, sometimes the leak was brief and repaired, but if project personnel became aware of a leak, the cooperator was notified. Other reasons for unusual water use were malfunctioning sensors, sodding, and controllers being turned off. These data were not used in the statistical analyses.

To benchmark the irrigation required during the study period, the NIR was calculated through a soil–water balance equation (Equation 1). To allow for a generous allocation for comparison purposes, it was assumed that the irrigated area was 80% turfgrass since it is the prevalent vegetation in most Florida landscapes, while established ornamentals can maintain quality under normal rainfall conditions (Gilman et al., 2009; Scheiber et al., 2008). Geocoded cooperator addresses were spatially joined with natural resources conservation service soil survey data (USDA, 1990) in ArcGIS to determine the dominant soil type for every cooperator.

To obtain the weather data needed for these calculations, three weather stations were installed in common areas or county facilities across the study area. In addition to the installed weather stations, the Florida Automated Weather Network maintained a weather station in the Apopka area that was used for the north location. Moreover, because of the localized nature of rainfall in Florida, two independent rain gauges were installed in the county to better estimate rainfall, and OCU provided manually collected rain gauge data from its Bonneville water treatment facility. The K_c monthly values used at this stage were those suggested by Jia, Dukes, and Jacobs (2009) for warm-season turfgrass in the region.

Finally, the NIR was divided by an assumed irrigation system efficiency to obtain the daily gross irrigation requirement (GIR). The GIR simulates well-watered conditions to minimize water stress in plants. Two scenarios were selected: an irrigation system with 80% efficiency and another with 60% efficiency.

Turfgrass quality ratings were performed seasonally, by the same person, using the National Turfgrass Evaluation Program procedures (Shearman & Morris, 1998). The rating scale ranged from 1 to 9, where 1 represented dead turfgrass or bare ground, 9 represented perfect turfgrass, and 5 was selected as the minimum acceptable quality for a single-family home landscape. Color and density were the main features judged for turfgrass quality ratings.

Statistical analyses were performed using SAS software (Cary, NC). Irrigation application and turfgrass quality were analyzed using the GLIMMIX procedure, and comparisons were made using the least mean-square differences by treatment, soil type, and season. Significance was determined at a 95% confidence level.

3 | RESULTS AND DISCUSSION

3.1 | Rainfall versus evapotranspiration

Reference ET (ET_o) was calculated for the 64-month study period through the ASCE-EWRI standardized equation (ASCE-EWRI, 2005). Daily ET_o values were summed into monthly totals and averaged across weather stations for comparison (Figure 1). As expected, the ET_o values were lower during November through February and higher from March through October. This trend was mainly driven by temperature and solar radiation, which followed a pattern similar to ET_o during the year. The ET_o was particularly high during 2012 as a result of sustained dry weather and high-temperatures.

Monthly rainfall totals from all rain gauges varied greatly between locations, indicating that rainfall events were generally localized during the study period. This was evidenced by the error bars of rainfall data shown in Figure 1. In general, monthly ET_o values showed a smaller variation (error bars) than rainfall. Overall, rainfall was lower during the cooler months (November through February) and higher during the warmer months (March through October). Exceptions to this occurred in January and December 2014, January and February 2015, and February and November 2016, when rainfall exceeded 2 in. per month. Conversely, rainfall totals below 2 in. per month occurred during the warmer months of March and April 2012, March and October 2013, October 2014, and April and June 2015, indicating dryer-than-normal weather conditions.

The monthly cumulative ET_o exceeded rainfall during most months. In only 10 of the 64 months of data collection, rainfall was higher than ET_o (Figure 1), particularly in 2014 during June, July, and September. This indicates that rainfall was unable to meet the ET demand, and therefore, irrigation was necessary to replenish the soil with water and maintain adequate turf quality.

3.2 | Weekly irrigation applied

Even when different locations were selected to carry out this study (Table 1), location cluster was not significant to the statistical model during the study period. However, the soil type was significant (p-value = .0377), as well as the treatment effect (p-value < .0001), indicating differences in irrigation applied over the different soils and the

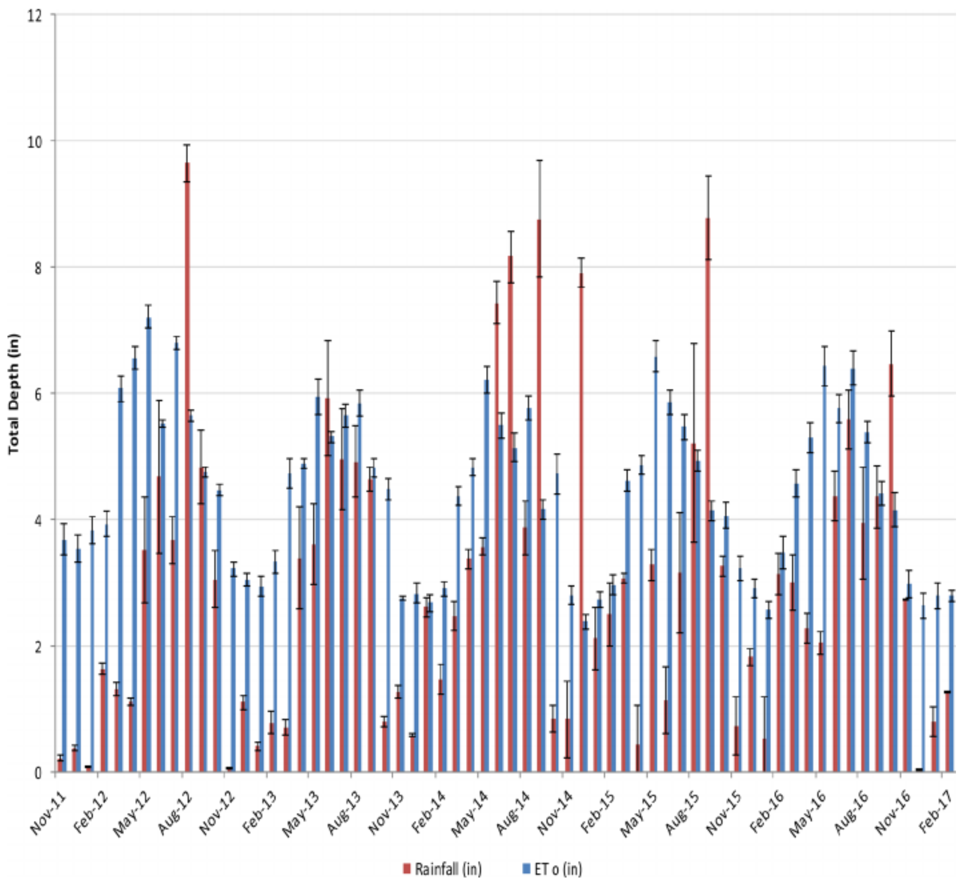

FIGURE 1 Monthly totals of rainfall and reference evapotranspiration (ET_o) calculated from weather station data using the ASCE-EWRI standardized reference evapotranspiration equation (ASCE-EWRI, 2005). ASCE-EWRI, american society of civil engineers–environmental water & resources institute

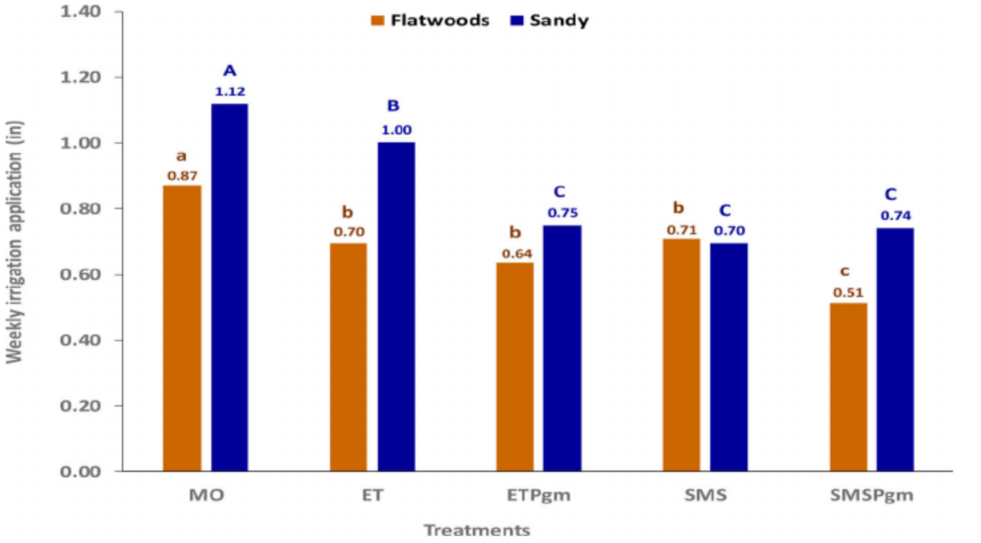

FIGURE 2 Average weekly irrigation application. Treatment differences are represented as lowercase letters for flatwoods soils and uppercase letters for sandy soils. ET, evapotranspiration; MO, monitored only; SMS, soil moisture sensor

various technologies and implementation approaches. In general, there was a tendency to apply more irrigation over the sandy soils compared with the flatwoods soils (Figure 2). This was expected because of the different AWHCs of the sandy versus the flatwoods soils, calculated in this study as 0.50 and 1.12 in., respectively.

In the locations of flatwoods soils, the MO group applied significantly higher weekly irrigation (averaging 0.87 in.) compared with all other treatments (Figure 2). Differences between the SMS treatment and the two ET controller treatments were not significant, averaging 0.70, 0.64, and 0.71 in. for ET, ETPgm, and SMS, respectively. The SMSPgm group, averaging 0.51 in., applied significantly less irrigation than all other treatments. Therefore, on flatwoods soils, the optimized site-specific settings significantly lowered the average irrigation application for the SMS technology, but this was not significant for the ET controllers.

In the sandy soil locations, the MO group also demonstrated a significantly higher weekly irrigation (averaging 1.12 in.) compared with all other treatments (Figure 2). The ET treatment irrigated significantly more (averaging 1.00 in.) than ETPgm and both SMS-based treatments. In addition, there were no significant differences between the remaining three treatments, with weekly average irrigation applications of 0.75, 0.70, and 0.74 in. for ETPgm, SMS, and SMSPgm, respectively. In the sandy soil locations, the optimized site-specific settings significantly lowered the average irrigation application only for the ET technology.

The SMSPgm treatment behaved differently depending on soil type. This treatment applied significantly less weekly irrigation than the other treatments on the flatwoods soils, whereas irrigation application was not significantly different from the ETPgm and SMS treatments on the sandy soils. A possible explanation for the difference could be that the sandy soils drain more quickly and lose more water by ET at a 3 in. sensor burial depth (compared with the 6 in. depth of the SMS treatment), resulting in more irrigation cycles allowed.

3.3 | Cumulative irrigation applied versus irrigation required and irrigation efficiency

3.3.1 | Flatwoods soils

The cumulative NIR for the flatwoods soils was calculated as 89 in. for the study period. All of the implemented treatments, however, applied more water than this theoretical amount required for adequate plant growth and quality. Overall, the MO group applied the most cumulative irrigation on the flatwoods soils, totaling 223 in. (Table 3). The ET, ETPgm, and SMS treatments, which were not statistically different in the average weekly irrigation (Figure 2), applied similar amounts of cumulative irrigation, totaling 176, 165, and 184 in., respectively, which correspond to between 18% and 26% less total water applied than MO. In addition, the SMSPgm group applied the least amount of water,with a total of 132 in., resulting in 41% water savings compared with the MO group.

In spite of the water savings achieved in the flatwoods soils, none of the smart irrigation controller treatments reached an irrigation efficiency of even 70% (applied irrigation versus NIR). Following the tendencies of the water applied, the MO treatment resulted in an irrigation efficiency of 40% and between 49% and 54% for treatments ET, ETPgm, and SMS, while the highest irrigation efficiency was achieved with the SMSPgm treatment, with 68% (Table 3).

TABLE 3 Flatwoods versus sandy soils: cumulative irrigation applied over 64 months, water savings compared to MO, and irrigation efficiency achieved by each treatment

Soil type	Treatment	Cumulative irrigation (in.)	Water savings (%)	Irrigation efficiency (%)
Flatwoods	MO	223	—	40
	ET	176	21	51
	ETPgm	165	26	54
	SMS	184	18	49
	SMSPgm	132	41	68
Sandy	MO	281	—	42
	ET	234	17	50
	ETPgm	193	31	61
	SMS	164	42	72
	SMSPgm	184	35	64

Abbreviations: ET, evapotranspiration; MO, monitored only; SMS, soil moisture sensor.

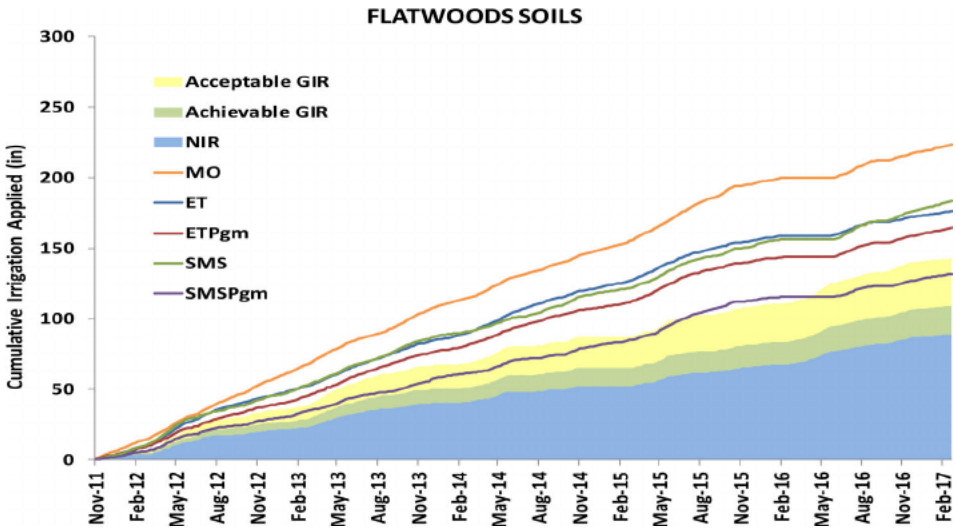

FIGURE 3 Cumulative irrigation for the study period averaged across locations for the flatwoods soils. ET, evapotranspiration; GIR, gross irrigation requirement; MO, monitored only; NIR, net irrigation requirement; SMS, soil moisture sensor

Irrigation efficiency of 100% is difficult, if not impossible, to achieve in the real world. The NIR is then divided by the irrigation system's efficiency to obtain the GIR and ensure well-watered conditions that could lead to good turfgrass and landscape plant quality. Two scenarios were selected in this study: an irrigation system with 80% efficiency (considered as “achievable efficiency”) and another system with 60% efficiency (estimated as “acceptable efficiency”).

All treatments applied more water than the calculated achievable 80% GIR efficiency, indicating overirrigation of between 18% and 65% for the smart technologies (ET/SMS) and 100% for the MO group (Figure 3). As expected, all treatments overirrigated less when evaluated against the theoretically acceptable 60% GIR. Except for the SMSPgm, the other treatments applied more than the acceptable 60% GIR efficiency. The MO group applied 50% more water, and treatments ET, ETPgm, and SMS overirrigated by 19%, 11%, and 23%, respectively. Conversely, the cumulative irrigation application for SMSPgm was 11% below the acceptable 60% GIR range. Overall, there appears to be a trend of water savings on the flatwoods soils due to the installation of a smart irrigation controller with additional savings from site-specific programing and settings.

3.3.2 | Sandy soils

The locations designated as sandy soils tended to apply more cumulative irrigation than the flatwoods soils locations (Table 3). This was expected due to the calculated 118 in. of NIR for the sandy soils versus the 89 in. of NIR for the flatwoods soils, driven by the different physical and chemical properties already described.

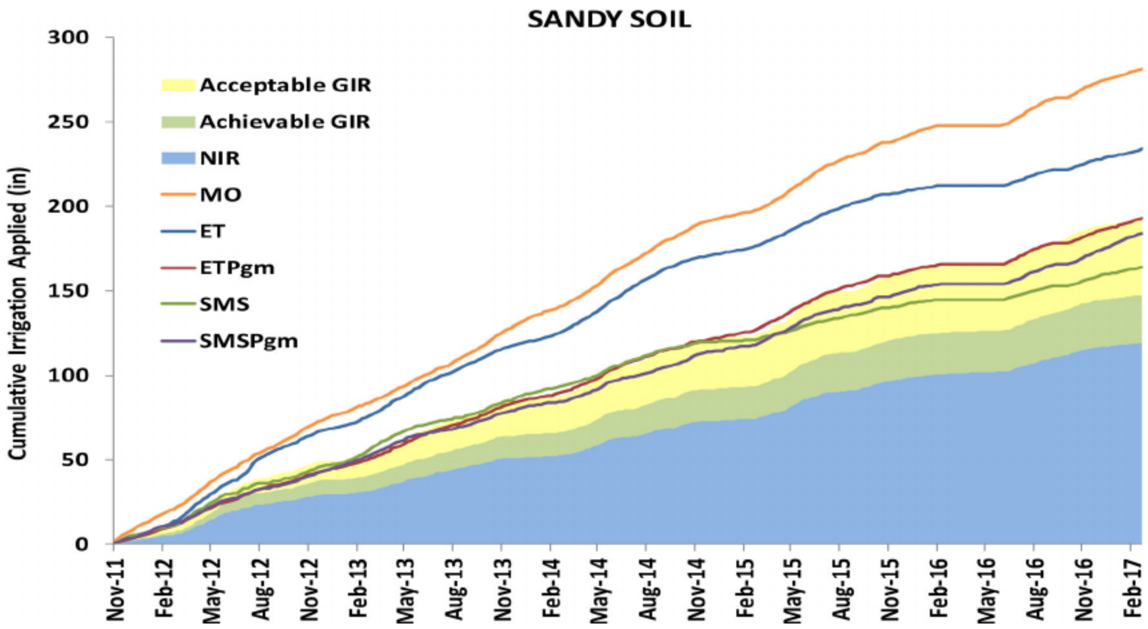

FIGURE 4 Cumulative irrigation for the study period averaged across locations for the sandy soils. ET, evapotranspiration; GIR, gross irrigation requirement; MO, monitored only; NIR, net irrigation requirement; SMS, soil moisture sensor

There was a 17% difference in cumulative irrigation application between MO and ET treatments, totaling 281 and 234 in., respectively (Table 3). This resulted in irrigation efficiencies of 42% for MO and 50% for ET. When compared with the achievable 80% GIR efficiency range (Figure 4), overirrigation values of 91% for the MO group and 59% for the ET treatment were computed. Overirrigation decreased to 43% for the MO group and 19% for the ET treatment when compared with the acceptable 60% GIR efficiency.

The remaining three treatments applied a similar cumulative amount of water. Treatments ETPgm, SMS, and SMSPgm applied 193, 164, and 184 in., respectively (Table 3). There was no significant difference in average weekly irrigation between these three treatments in sandy soils (Figure 2), which resulted in total water savings of between 31% and 42% after more than 5 years of implementation (Table 3). When the site-specific programming and settings were included, the ET controllers resulted in significant water savings compared with ET controllers installed and set by the contractor (31% for ETPgm versus 17% for ET). At the flatwoods soils locations, however, this was not significant.

Even when the cumulative irrigation tended to be higher in the sandy soils (compared with the flatwoods soils), the irrigation efficiencies also tended to be higher, ranging between 61% and 72% for the treatments ETPgm, SMS, and SMSPgm. When comparing these treatments with the achievable 80% GIR efficiency (Figure 4), they overirrigated to between 11% and 31%, but when compared with the acceptable GIR efficiency, none of these treatments over-irrigated, applying between 2% and 16% less water than the theoretical requirement. These results show that these smart irrigation controllers successfully followed the water needs of the turfgrass throughout the study period (Figures 3 and 4), saving water, and positioning them as a valuable tool for long-term water conservation programs.

3.4 | Turfgrass quality

The turfgrass quality of each home was rated seasonally for a total of 24 times during the study period. Most of the time, the turfgrass quality was rated good or very good (above 6.5 on average, from a minimum acceptable rating of 5). Turfgrass quality ratings were not significantly different when evaluating treatments or over- or underirrigation.

Occasional ratings below 5 were observed, but these improved afterward and remained above the minimum quality. Other unmeasured factors, such as disease, pests, fertilizer application, mowing practices, or irrigation system maintenance, could have temporarily affected turfgrass quality.

3.5 | Technology concerns and issues

Some cooperators chose to report their concerns about the capabilities of the technologies they received.

TABLE 4 Number of stated reasons for contact made by cooperators since treatment installation, by year

	Year							
Stated reason for contact	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**
Too much irrigation/high water bill	12	13	4		2			31
Too little irrigation	8	8	2	1		1		20
Irrigating too soon after rain	7	5		1				13
Controller/sensor reading error	2	3	1	2				8
Nonfunctioning controller/sensor		4	3		1	1	1	10
Add new module			2	2				4
Disconnected sensor			1		1	1		3
Sensor in wrong location		1		2				3
Sensor not allowing irrigation			2					2
Sensor not preventing irrigation			1					1
Total	29	34	16	8	4	3	1	95

Cooperators contacted any groups directly involved with the technology installation, which included the installing contractor, OCU, and UF/IFAS. Once contact was made with one of these groups, the best course of action was determined. Typically, each instance of contact resulted in a follow-up visit by a UF/IFAS research technician and/or OCU representative to verify that the technology was functioning correctly.

There were 95 instances of contact occurring from 54 unique cooperators (Table 4). The majority of concerns occurred shortly after installation when the cooperator was learning the technology, resulting in a large number of concerns raised in 2011 (29) and early 2012 (34). Typical concerns included fear of a high water bill or too much irrigation, too little irrigation, and irrigation occurring too soon after rainfall. Validated reasons for too much irrigation were due to a contractor programing the default ET controller settings, causing extended runtimes and sensor thresholds that were too high, resulting in few bypassed irrigation events. Responses of too little irrigation were most applicable to the SMS treatments when the threshold was too low, resulting in too many bypassed events. Irrigation occurring too soon after rainfall was a valid concern specific to the ET controllers. Rain Bird was contacted about this concern, and the company concluded that rainfall was considered in the scheduling algorithms after 24 h, resulting in irrigation immediately after rainfall on the same day. New controller face plates with updated software were installed in November 2011 for all installed ET controllers to address this issue. Although this concern occurred in 2012 as well, there was just one more complaint—in 2014—regarding this issue.

When evaluating concerns on the basis of treatment, more frequent contact was made by cooperators in the education group, totaling 58, compared with the non-education group, totaling 37 instances of contact (Table 5). During the educational training, cooperators were made aware of the UF/IFAS contact information on the technology brochure. Direct contact with a cooperator established a professional relationship that resulted in increased feedback.

TABLE 5 Number of concerns made by cooperators since treatment installation, by treatment

Treatment	**Count**
ET	21
ETPgm	28
SMS	16
SMSPgm	30
Grand total	95

Abbreviations: ET, evapotranspiration; SMS, soil moisture sensor.

There were 49 ET controller cooperators and 46 SMS cooperators who expressed concerns regarding the technology received (Table 5). The main reason for an ET controller concern was attributed to the rainfall issue discussed previously. In addition, ET controller cooperators complained about too much irrigation due to the design of the technology, where there was no upper limit to the irrigation schedule. This issue became apparent during the characteristically hot and dry spring season when turfgrasses began growing after winter dormancy, and irrigation increased in response to high ET and low rainfall. Conversely, SMS had no command over the irrigation runtimes, resulting in no more irrigation than that already scheduled in the time clock.

3.6 | Cooperators' acceptance and adoption of smart irrigation technology

After the significant and sustained water savings achieved in this study, cooperators' feedback was considered critical to successfully promote the use of smart irrigation controllers. Two surveys were conducted, one in 2014 and the other in mid-2017, after ending the water use data collection. Results from the first survey indicated that a majority of the cooperators consistently praised the implemented technology for saving money and irrigating efficiently and planned to continue using the controllers (Morera, Monaghan, Dukes, Wells, & Davis, 2015). After more than 5 years of use, the experience of any challenges with the controllers was a barrier to their long-term adoption. Insufficient information or understanding was the second most frequent challenge experienced with ET controllers and the fourth most frequent with SMS controllers. Therefore, the likelihood of continued use after 2017 was almost 12 times higher if a respondent was satisfied with the controller and 82% lower if any challenge was experienced with it (Morera, Monaghan, & Dukes, 2019). Consequently, efforts to promote investing in smart irrigation controllers may be most effective by emphasizing their economic benefits, while long-term adoption might be increased by disseminating best management practices that facilitate their understanding and successful operation.

4 | SUMMARY AND CONCLUSIONS

Orange County is located in Central Florida, within an area of limited water resources, coupled with rapid population growth and increasing potable water demand. As a result, OCU has embarked on residential water conservation programs, including a study performed by UF/IFAS to evaluate smart irrigation controllers that showed potential to conserve water, including SMS and ET controllers. Previous studies recommended that ET controllers be installed preferably in homes that overirrigate their landscape; otherwise, irrigation water use could increase after installation. Therefore, OCU decided to target only excess irrigators to evaluate a possible rebate program. Consequently, the main objective of this study was to evaluate the long-term water conservation potential of two smart irrigation controllers when implemented in single-family homes with excess irrigation.

An important aspect of this study was the selection of potential single-family home cooperators that were considered excess irrigators, estimated from water billing data. From more than 140,000 accounts, a total of 7,408 accounts (5%) were found to be excess irrigators in the OCU service area. A letter was mailed to these excess irrigators, inviting them to be part of this water conservation program. Of the mailed accounts, 843 (11%) responded. According to these results, if a water entity or utility plans to create a rebate program for excess irrigators, the totality of this targeted population should be contacted.

A total of 167 residential cooperators with automated irrigation systems were finally selected. Nine location clusters were established in the area across the two dominant soil types: flatwoods and sandy. Five treatments were implemented in the homes: MO (monitored only), ET (homes with an ET controller), SMS (homes with an SMS controller) and ETPgm and SMSPgm (homes with an ET or SMS, which were optimized with onsite programing and where the cooperators were given educational training about the technology implemented).

Equipment and treatments were fully installed and implemented by October 2011, and the data collection was conducted from November 2011 through February 2017. Hourly irrigation data were totaled as weeks, months, and cumulative; averaged by treatment; and then compared between treatments. In addition, the water applied per treatment was compared with the estimated irrigation that was required to meet plants' water needs.

Location cluster was not significant to the statistical model during the study period. However, treatment and soil type were significant, indicating differences in irrigation applied by the different technologies and implementation approaches.

By the end of the study, after more than 5 years of data collection, all treatments with a smart irrigation technology, both optimized and nonoptimized, resulted in significant water savings compared with MO in both soil types but with different statistical outcomes. On average, ET controllers reduced irrigation across both flatwoods and sandy soils: 21% and 17%, respectively, for the ET group and 26% and 31%, respectively, for the ETPgm group.

The SMS-based treatments also resulted in significant irrigation reduction. The SMS group reduced irrigation by 18% and 42% in flatwoods and sandy soils, respectively, compared with the MO group. Likewise, the SMSPgm treatment applied 41% and 35% less water in flatwoods and sandy soils, respectively, compared with the homes without a smart irrigation controller.

Overall, the SMS technology tended to be more efficient than the ET controllers. Three of the four SMS treatments applied the least amount of water during this study. Conversely, only ETPgm in sandy soils was part of the group of treatments that applied the least amount of water (together with SMS and SMSPgm). When contractors and end users were educated on the technology and when research-based practices were used to install and program any of the controller types, the irrigation efficiency and water savings tended to increase.

These results demonstrated the long-term ability of SMS and ET controllers to regulate the amount and frequency of water applied by automated irrigation systems on the basis of real-time soil moisture content or weather conditions in single-family homes with excess irrigation, without detriment to the turf quality.

Encouraging the initial acquisition of smart irrigation controllers might be most effective by promoting their economic benefits. The long-term adoption might be promoted by disseminating best management practices that would enable their successful operation.

ACKNOWLEDGMENT

This research was supported by the Orange County Utilities Water Division. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Florida and does not imply approval of a product or exclusion of others that may be suitable.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

ORCID

Bernardo Cardenas https://orcid.org/0000-0001-5959-6476
Michael D. Dukes https://orcid.org/0000-0002-9340-5968

REFERENCES

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. ASCE-EWRI* (Vol. 1801). Reston, VA: ASCE.

Boyer, M. J., Dukes, M. D., Duerr, I., & Bliznyuk, N. (2018). Water conservation benefits of long-term residential irrigation restrictions in Southwest Florida. *Journal AWWA*, *110*(2), E2–E17. https://doi.org/10.5942/jawwa.2018.110.0019

Cardenas-Lailhacar, B., & Dukes, M. D. (2008). Expanding disk rain sensor performance and potential irrigation water savings. *Journal of Irrigation and Drainage Engineering*, *134*, 67–73. https://doi.org/10.1061/(ASCE)0733-9437(2008)134:1(67)

Cardenas-Lailhacar, B., & Dukes, M. D. (2010). Precision of soil moisture sensor irrigation controllers under field conditions. *Agricultural Water Management*, *97*(3), 666–672. https://doi.org/10.1016/j.agwat.2009.12.009

Cardenas-Lailhacar, B., Dukes, M. D., & Miller, G. L. (2008). Sensor-based automation of irrigation on bermudagrass, during wet weather conditions. *Journal of Irrigation and Drainage Engineering*, *134*(2), 120–128. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000153

Cardenas-Lailhacar, B., Dukes, M. D., & Miller, G. L. (2010). Sensor-based automation of irrigation on bermudagrass, during dry weather conditions. *Journal of Irrigation and Drainage Engineering*, *136*(3), 184–193.

CFCA. (2010). Central Florida Coordination Area (CFCA) Work Plan Phase II. Retrieved from http://swfwmd.state.fl.us/files/database/site_file_sets/60/CFCA_Work_Plan_Phase_II.pdf

Davis, S. L., Dukes, M. D., & Miller, G. L. (2009). Landscape irrigation by evapotranspiration-based irrigation controllers under dry conditions in Southwest Florida. *Agricultural Water Management*, *96*(12), 1828–1836. https://doi.org/10.1016/j.agwat.2009.08.005

Dukes, M. D. (2012). Water conservation potential of landscape irrigation smart controllers. *Transactions of the ASABE*, *55*(2), 563–569. https://doi.org/10.13031/2013.41391

Friedman, K., Heaney, J. P., Morales, M., & Palenchar, J. E. (2013). Predicting and managing residential potable irrigation using parcel-level databases. *Journal AWWA*, *105*(7), E372–E386. https://doi.org/10.5942/jawwa.2013.105.0087

Gilman, E. F., Wiese, C. L., Paz, M., Shober, A. L., Scheiber, S. M., Moore, K. A., & Brennan, M. (2009). Effects of irrigation volume and frequency on shrub establishment in Florida. *Journal of Environmental Horticulture*, *27*(3), 149–154. https://doi.org/10.24266/0738-2898-27.3.149

Huang, B., Duncan, R., & Carrow, R. N. (1997). Drought-resistance mechanisms of seven warm-season turfgrasses under surface soil drying: II. Root aspects. *Crop Science*, *37*, 1863–1869. https://doi.org/10.2135/cropsci1997.0011183X003700060033x

Irrigation Association (2005). Landscape irrigation scheduling and water management. In *Irrigation Association Water Management Committee*. Falls Church, VA: Irrigation Association.

Jia, X., Dukes, M. D., & Jacobs, J. M. (2009). Bahiagrass crop coefficients from Eddy correlation measurements in Central Florida. *Journal of Irrigation Science*, *28*(1), 5–15. https://doi.org/10.1007/s00271-009-0176-x

Kennedy/Jenks Consultants. (2008). *Pilot implementation of smart timers: Water conservation, urban runoff reduction, and water quality. Report to Municipal Water District of Orange County*. Irvine, CA: Kennedy/Jenks Consultants Retrieved from https://www.mwdoc.com/wp-content/uploads/2017/06/Report__Pilot_Implementation_of_Smart_Timers.pdf

Mayer, P., W. DeOreo, M. Hayden, R. Davis, E. Caldwell, T. Miller, and P. J. Bickel. (2009). Evaluation of California weather-based "smart" irrigation controller programs. Final report for the California Department of Water Resources. Sacramento, CA: California Urban Water Conservation Council. Retrieved from www.aquacraft.com/sites/default/files/pub/Aquacraft-%282009%29-Evaluation-of-California-Weather-Based-Smart-Irrigation-Controller-Programs.pdf

Mayer, P. W., DeOreo, W. B., Opitz, E. M., Kiefer, J. C., Davis, W. Y., Dziegielewski, B., and Nelson, J. O., (1999). Residential End Uses of Water. AWWA Res. Foundation, Denver, CO. NCDC, 2010. Surface data from 1980 to 2009. Retrieved from http://www.waterrf.org/publicreportlibrary/rfr90781_1999_241a.pdf

McCready, M. S., Dukes, M. D., & Miller, G. L. (2009). Water conservation potential of smart irrigation controllers on St. Augustinegrass. *Agricultural Water Management*, *96*(11), 1623–1632. https://doi.org/10.1016/j.agwat.2009.06.007

Meeks, L., Dukes, M. D., Migliaccio, K. W., & Cardenas-Lailhacar, B. (2012a). Expanding-disk rain sensor dry-out and potential irrigation savings. *Journal of Irrigation and Drainage Engineering*, *138*, 972–977. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000487

Meeks, L., Dukes, M. D., Migliaccio, K. W., & Cardenas-Lailhacar, B. (2012b). Long-term expanding-disk rain sensor accuracy. *Journal of Irrigation and Drainage Engineering*, *138*, 16–20. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000381

Morera, M. C., Monaghan, P. F., & Dukes, M. D. (2019). Evolving response to smart irrigation controllers in high water-use Central Florida homes. *AWWA Water Science*, *1*(1), e1111. https://doi.org/10.1002/aws2.1111

Morera, M. C., Monaghan, P. F., Dukes, M. D., Wells, O., & Davis, S. L. (2015). Evaluating Florida homeowner response to smart irrigation controllers. *HortTechnology*, *25*(4), 511–521.

Romero, C. C., & Dukes, M. D. (2014). Estimation and analysis of irrigation in single-family homes in Central Florida. *Journal of Irrigation and Drainage Engineering*, *140*, 04013011. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000656

Scheiber, S. M., Gilman, E. F., Sandrock, D. R., Paz, M., Wiese, C., & Brennan, M. M. (2008). Postestablishment landscape performance of Florida native and exotic shrubs under irrigated and nonirrigated conditions. *HortTechnology*, *18*(1), 59–67. https://doi.org/10.21273/HORTTECH.18.1.59

Shearman, R. C., & Morris, K. N. (1998). NTEP turfgrass evaluation workbook. In *National turfgrass evaluation procedures turfgrass evaluation workshop*. Beltsville, MD: National Turfgrass Evaluation Program.

Shedd, M. L., Dukes, M. D., & Miller, G. L. (2008). Evaluation of irrigation control on turfgrass quality and root growth. *Proceedings of the Florida State Horticultural Society*, *121*(2008), 340–345.

Stewart, E. H., & Mills, W. C. (1967). Effect of depth to water table and plant density on evapotranspiration rate in southern Florida. *Transactions of ASAE*, *10*(6), 746–747. https://doi.org/10.13031/2013.3977

USCB, (2006). National Population Estimates, U.S. Census Bureau. Retrieved from http://www.census.gov/popest/estimates.php

USCB, (2010). County Intercensal Tables: 2000–2010, U.S. Census Bureau. Retrieved from https://www.census.gov/data/tables/time-series/demo/popest/intercensal-2000-2010-counties.html

USDA. (1989). Soil Survey of Orange County, Florida. Retrieved from http://soils.usda.gov/survey/online_surveys/florida/

USDA. (1990). Soil Survey Geographic Database of Florida. Retrieved from http://SoilDataMart.nrcs.usda.gov/

How to cite this article: Cardenas B, Dukes MD, Breder E, Torbert JW. Long-term performance of smart irrigation controllers on single-family homes with excess irrigation. *AWWA Wat Sci*. 2021;e1218. https://doi.org/10.1002/aws2.1218