Soil Moisture Sensor Irrigation Controllers and Reclaimed Water; Part I: Field-plot Study

A Tribute to the Career of
Terry Howell, Sr.

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Abstract. *Most soil moisture sensor systems (SMSs) marketed for landscape irrigation respond to the dielectric permittivity of the soil. Compared to potable water (PW), reclaimed water (RW) may contain more salts, which can modify the dielectric permittivity of the soil and, hence, alter the readings of SMSs when measuring the soil water content. The main objectives of this experiment were to evaluate the functionality of four SMS brands and to quantify potential irrigation savings. Secondary objectives were to analyze the behavior consistency of three units within a brand to control irrigation, and to compare the brands. The experiment was carried out in Gainesville, Florida, under turfgrass plots irrigated with PW in 2009 and RW with an average salinity of 0.75 dS/m during 2010. Four SMS brands (Acclima, AquaSpy, Baseline, and Dynamax) were selected and compared to a treatment without sensor feedback (WOS). Even though replicates of AquaSpy were statistically different under both PW and RW, all SMSs tested applied significantly less water than WOS. Water savings ranged 46%-78% under PW, and 45%-68% under RW. Therefore, SMSs can be a useful tool for conserving water on turfgrass irrigated with either PW or RW.*

Keywords. *Irrigation scheduling, Irrigation water, Potable water, Reclaimed water, Soil moisture sensor, Turf quality, Turfgrass, Water use.*

Most single-family homes built in Florida include an in-ground time-based (automatic) irrigation system. In the United States, households that employ an automatic irrigation system apply, on average, 47% more water outdoors than homes that do not (Mayer et al., 1999). This could be mainly a result of homeowners not adjusting their timers to seasonal plant water requirements, lack of a rain sensor shut-off device, and/or the automatic irrigation system not receiving feedback from the actual soil water content conditions. To cope with this issue, the irrigation industry has developed different "smart controllers," including soil moisture sensor systems (SMSs).

The SMSs marketed for residential/light commercial landscape irrigation entail two devices. The first one is a probe that is buried—usually—in the root zone of the turf and is used to sense how wet or dry the soil is. The second device is a controller. Generally, the controller is an add-on type device that connects to the existing irrigation timer. In the controller, the user can define a soil water content threshold. If the soil water content exceeds that threshold (too wet), the irrigation cycle programmed in the timer would be bypassed, and vice versa (Dukes, 2012).

Previous studies have reported that the amount of potable water (PW) applied to landscapes can be significantly reduced when a typical time-based irrigation system receives feedback from an SMS. In Florida and North Carolina, research on turfgrass plots under normal to wet weather conditions have resulted in water savings between 39% and 72%, without compromising the turfgrass quality (Cardenas-Lailhacar et al., 2008; McCready et al., 2009; Cardenas-Lailhacar and Dukes, 2012; Grabow et al., 2013). However, during sustained dry weather conditions, lower water savings were obtained (-1% to 64%). Moreover, it was reported that the turfgrass quality could decline if the threshold is set too low or the run times are not adequately programmed (McCready et al., 2009; Cardenas-Lailhacar et al., 2010; Cardenas-Lailhacar and Dukes, 2012; Grabow et al., 2013).

Submitted for review in January 2015 as manuscript number NRES 11196; approved for publication by the Natural Resources & Environmental Systems Community of ASABE in July 2015. Presented at ASABE/IA Symposium: Emerging Technologies for Sustainable Irrigation in November 2015 as Paper No. 152145561 .

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  ISSN 0883-8542 DOI 10.13031/aea.32.11196

When SMSs were installed in homes, Haley and Dukes (2012) reported 65% PW savings compared to homes with typical timer irrigation control over 26 months of data collection in Florida. In North Carolina residences, when compared to other PW conservation methods/technologies, the SMS treatment achieved the maximum water savings: 42% less than the control group (Nautiyal et al., 2014).

Several municipalities in the United States are also delivering reclaimed water (RW) to a variety of users as the source for their landscape irrigation. Florida is ranked #1 in the United States both in the total reuse of RW, with 2.5 Mm^3/day (WateReuse Association, 2008), and in the per capita reuse, with 140 L/day/person (FL-DEP, 2014).

The use of SMSs in turfgrass irrigated with RW has not been previously reported. Most of the SMSs marketed for landscape irrigation respond to electromagnetic properties of the soil, more specifically, to the dielectric permittivity and bulk electrical conductivity. Compared to PW, RW may contain higher levels of salts, which can alter the dielectric permittivity and bulk electric conductivity of the soil and, hence, affect the readings of SMSs when measuring the soil water content. Cardenas-Lailhacar and Dukes (2015) reported the effects of different levels of water salinity on the precision and accuracy of different SMSs.

The main objectives of this experiment were to evaluate the functionality of four different SMS brands and to quantify potential irrigation savings. Secondary objectives were to analyze the behavior consistency of three units within a brand to control irrigation, and to compare the brands. Two stages were considered for these experiments. The first stage was performed using PW and the second used RW as the irrigation source.

Materials and Methods

The experiment was installed at the Agricultural and Biological Engineering Department research facilities in Gainesville, Florida. The soil is classified as an Arredondo fine sand (USDA, 2013). Seventy-two plots (3.7 × 3.7 m each) were sprinkler irrigated by four quarter-circle, 15 cm pop-up spray heads (Rain Bird sprinklers 1800 series, 12Q nozzles, Azusa, Calif.). The plots were covered with St. Augustinegrass (*Stenotaphrum secundatum [Walt.] Kuntze*) cultivar Floratam (Florida's most representative home turfgrass) and was maintained according to existing IFAS recommendations (Dukes, 2011).

Of the 72 plots available, 64 plots were selected for this experiment. Four SMS brands were selected for testing: Acclima (ACL), AquaSpy (AQU), Baseline (BAS), and Dynamax (DYN). Details on the SMSs sensing method, resolution, cost, etc., can be found in table 1. A requisite for the selected SMSs was that they should be an add-on type device, which could be connected to an existent time-based control system (i.e. time clock or timer). The SMSs were planned to be used directly "out of the box," following manufacturer recommendations for installation and threshold setting.

Three units (replicates) of each SMS brand were distributed on the experimental field in a completely randomized design. The probes were positioned close to the center of individual plots. They were inserted horizontally, in undisturbed soil, with the midpoint of their sensing portion at a depth of 8 cm. All probes were installed on 26 August 2009 and remained buried beyond the end of this study.

Threshold Setting

Both the ACL and BAS controllers show percent volumetric soil water content of the sampled soil on their display. The DYN controller, instead, is imprinted with a volumetric soil water content scale from 0 to 50% and the AQU controller is stamped with a numberless scale from dry to wet. Both DYN and AQU systems have a knob pointing to these scales, which allows the user to set the threshold for irrigation control. To obtain a reading on the DYN and AQU systems, the knob was turned clockwise until the "irrigate" LED-light on the controller turned off, and then turned counterclockwise until the LED-light turned on. This last reading was taken as the sensed soil water content for the DYN and AQU systems

Prior to installing the SMSs in the field, the probes were buried in air-dried soil (estimated as the permanent wilting point) and a reading was taken. Afterwards, the plots containing a sensor for irrigation control were saturated and allowed to drain for 24 hours, to reach a soil water content close to field capacity (Cardenas-Lailhacar and Dukes, 2010). Then, SMS readings were taken and the thresholds were set individually on each controller. The following procedure was conducted to determine the individual set points:

$$FC - PWP = AW \tag{1}$$

Table 1. Soil moisture sensor systems tested.

Manufacturer	Brand	Sensing Method[a]	Soil Probe Model	Controller: Model	Controller: Digital Display	Resolution ($m^3\ m^{-3}$)[b]	Measures Soil: Temp.[c]	Measures Soil: EC[d]	SMS[e] Cost (USD)
Acclima Inc., Idaho	Acclima	TDT	Digital TDT	SCX	Yes	0.01	Yes	Yes	150
AquaSpy Inc., Calif	AquaSpy	CAP	SMS-100	AquaBlu Regulator	No	NA[f]	No	No	245
Baseline Inc., Idaho	Baseline	TDT	BiSensor	WaterTec S100	Yes	0.01	No	No	160
Dynamax Inc., Tex.	Dynamax	ADR	SM200	IL200-MC	No	≥0.05	No	No	500

[a] TDT = time domain transmissometry, CAP = capacitance, ADR = amplitude domain reflectometry.
[b] Resolution in volumetric soil water content ($m^3\ m^{-3}$).
[c] Temp = temperature.
[d] EC = electrical conductivity.
[e] SMS = soil moisture sensor system; includes a soil probe and a controller.
[f] NA = Not applicable.

$$\text{Set Point} = [(1\text{-MAD}) \times AW] + PWP \quad (2)$$

where

FC = field capacity,

PWP = permanent wilting point,

AW = available water, and

MAD = maximum allowable depletion.

A low MAD factor of 0.3 was chosen as suggested by previous studies in sandy soils (Cardenas-Lailhacar and Dukes, 2012).

TREATMENTS AND RUN TIMES

The SMS controllers were connected in series with common residential irrigation timers. All irrigation cycles were programmed on two model ESP-6Si, and three model ESP-4Si timers (Rain Bird Corporation, Azusa, Calif.), and set to start between 0500 and 0600 h, with the purpose of diminishing wind drift and decreasing evaporation. All treatments were set to run 3 days per week to mimic homes—as part of a companion study (Cardenas and Dukes, 2016)—using RW as its irrigation source in Pinellas County; which are allowed to irrigate 3 days per week (PCU, 2012). The runtimes were adjusted monthly, to replace 100% of the historical ET-based irrigation schedule recommended for the Gainesville area by Dukes and Haman (2002).

Two types of treatments were defined: time-based treatments and SMS-based treatments (table 2). Within the time-based treatments, a without-sensor-feedback treatment (WOS) was included, to mimic the most common situation of irrigation systems in Florida (Whitcomb, 2005). Treatment WOS, therefore, was used as the main comparison treatment. To simulate requirements imposed on homeowners by Florida Statutes (Chapter 373.62), two time-based treatments were connected to a rain sensor: with-rain-sensor (WRS) and deficit-with-rain-sensor (DWRS). This last treatment (DWRS) was established to simulate residences with a functional rain sensor, but with a deficit-irrigation strategy. The rain sensor (Mini-Clik, Hunter Industries, San Marcos, Calif.) was set at a 6 mm rainfall threshold.

All treatments were programmed to run for the same amount of time; except for treatment DWRS which was programmed to run for just 60% of this schedule (deficit irrigation). During 2009, however, the run time for DWRS was the same as the other treatments to avoid water stress and assure sod establishment. Therefore, differences in water application among treatments were the result of sensors bypassing scheduled irrigation cycles.

Table 2. Treatment codes and descriptions.

Treatment Codes	Soil Moisture Sensor Brand or Treatment Description	Replicates Codes
Time-Based		
WOS	Without sensor feedback	
WRS	With rain sensor	
DWRS	Deficit with rain sensor	
SMS-Based		
ACL	Acclima	1-ACL, 2-ACL, 3-ACL
AQU	AquaSpy	1-AQU, 2-AQU, 3-AQU
BAS	Baseline	1-BAS, 2-BAS, 3-BAS
DYN	Dynamax	1-DYN, 2-DYN, 3-DYN

DATA COLLECTION AND ANALYSIS

Date, time, and amount of irrigation applied to each plot was continually recorded through pulse-type positive displacement flowmeters (model PSMT 20 mm × 190 mm, Elster Amco Water, Ocala, Fla.) that were connected to nine model AM16/32 multiplexers (Campbell Scientific, Logan, Utah), which were wired to a model CR-10X datalogger (Campbell Scientific, Logan, Utah).

Weather data were collected by an automated weather station (Campbell Scientific, Logan, Utah), located within 1 m of the experimental site. Measurements made every 15 min included minimum and maximum air temperatures, relative humidity, wind speed and direction, and solar radiation. Rainfall was recorded continuously by a tipping bucket rain gauge on the weather station and a nearby manual rain gauge.

Turfgrass quality was visually assessed and rated using a scale of 1 to 9 where 1 represents brown, dormant turf, and 9 represents the best quality (Shearman and Morris, 1998). A rating of 5 was considered to be the minimum acceptable turf quality for a homeowner.

During the first stage (2009), PW was used for irrigation. In the second stage (2010), RW from the University of Florida Water Reclamation Facility was used. The electrical conductivity (a measurement of the water salinity) was 0.31 dS/m for the PW and averaged 0.75 dS/m (0.67 to 0.89 dS/m) for the RW (Clark Collins, 2010, University of Florida Water Reclamation Facility, personal communication). This salinity was considered adequate for this experiment since it was similar to the average salinity (0.70 dS/m) of the RW delivered to the vicinity of Palm Harbor (Bob Peacock, 2008, Pinellas County Utilities, personal communication); where a companion study was carried out (Cardenas and Dukes, 2016). Floratam, the St. Augustinegrass cultivar used in this experiment, has shown to tolerate a soil salinity level >20 dS/m (Dudeck et al., 1993).

Data analysis was performed using the general linear model (GLM) function of the Statistical Analysis System software (SAS, 2008). Analysis of variance was used to determine treatment differences and Duncan's Multiple Range Test was used to identify mean differences. Differences were considered significant at a confidence level of 95% or higher ($p \leq 0.05$).

RESULTS AND DISCUSSION

UNDER POTABLE WATER

The first stage of this experiment used PW as the irrigation source. Data presented here encompass 19 September through 15 November 2009.

Rainfall

During this experimental period, there were four rainfall events of between 7 and 10 mm, which fell with a frequency of around every 10 days (fig. 1). Both of these conditions (amount of rain per event and frequency) could be considered adequate for irrigation purposes. However, 14% of the days exhibited rainfall compared to a historical average of 23% (NOAA, 2002), and the cumulative precipitation was 39 mm, which represents more than 30%

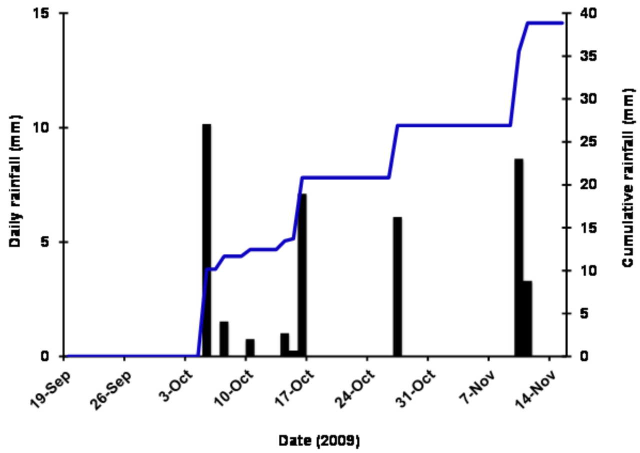

Figure 1. Daily and cumulative rainfall, during 19 September through 15 November 2009.

deficit compared to a historical average rainfall for the same period. Therefore, this was a relatively dry period.

Turfgrass Quality

The turfgrass quality across all plots was relatively uniform and generally above the rating of 6 during the experiment. An exception occurred for two weeks in October, when an herbicide with a growth regulator was applied and the grass tended to look browner across all the plots (which is normal after these applications), resulting in a turf quality around the minimum rating of 5. Afterwards, the quality improved and stabilized at ratings above 6. No statistical differences between the treatments were found during this period (data not shown).

Irrigation Bypass Proportion

All treatments were programmed to run 25 times during 2009. Table 3 shows the number and proportion (%) of the scheduled irrigation cycles (SICs) that were bypassed by the different treatments, as well as the average proportion bypassed by the different SMS brands. The time-based treatment without sensor feedback (WOS) was scheduled to run independently of the weather and/or soil moisture conditions, so no (0%) SIC was bypassed. The two time-based treatments that were receiving feedback from the same rain sensor (WRS and DWRS) bypassed 16% of the SICs; which was consistent with the proportions bypassed by the rain sensors during dry weather conditions (13%), as reported in previous experiments (Cardenas-Lailhacar et al., 2010). Conversely, 61% of the SICs were bypassed on average by the SMS-based treatments, compared to 71% during wetter years (Cardenas-Lailhacar et al., 2008) and 44% during dry periods (Cardenas-Lailhacar et al., 2010).

Regarding the different SMS brands, on average, AQU bypassed the least amount of SICs, with an average of 41%, followed by BAS and ACL, with 64% and 69%, respectively. Brand DYN bypassed the greatest amount of SICs, with an average of 71%. These results verified that the SMS treatments worked under these conditions, but with variable results. All SMS replicates bypassed more SICs compared to the treatments with rain sensor feedback; which was consistent with previous findings (Cardenas-Lailhacar et al., 2008 and 2010).

Table 3. Scheduled irrigation cycles (SICs) bypassed, total cumulative irrigation depth applied, statistical comparisons, and percent water savings by treatment, compared to WOS; under potable water during 2009.

Treatment	SICs Bypassed (No.)	SICs Bypassed (%)	Cumulative Depth (mm)	Comparisons[a] A	B	C	D	Water Savings (%)
Time-Based								
WOS	0	0	340	ns[b]				--
WRS	4	16	274	ns				--
DWRS[c]	4	16	286	ns				--
Time-Avg			**300**		**a**			
SMS-Based								
1-ACL	19	76	80			b		77
2-ACL	19	76	80			b		77
3-ACL	14	56	151			a		55
ACL-Avg		**69**	**104**				**ab**	**69**
1-AQU	6	24	235			a		31
2-AQU	15	60	111			b		67
3-AQU	10	40	185			a		46
AQU-Avg		**41**	**177**				**a**	**48**
1-BAS	17	68	105			ns		69
2-BAS	15	60	128			ns		62
3-BAS	16	64	124			ns		63
BAS-Avg		**64**	**119**				**ab**	**65**
1-DYN	19	76	81			ns		76
2-DYN	17	68	108			ns		68
3-DYN	17	68	103			ns		70
DYN-Avg		**71**	**97**				**b**	**71**
SMS-Avg		**61**	**124**		**b**			**63**

[a] A = between time-based treatments; B = time-based treatments versus SMS-based treatments; C = between replicates of a SMS brand; and D = between brand averages.

[b] Different letters within a column indicate statistical difference at P<0.05 (Duncan's multiple range test).

[c] The run time of DWRS was the same as the other treatments during 2009, to assure the establishment of the sod.

Irrigation Depth

The cumulative irrigation depth allowed by the time-based treatments and by the SMS-based treatments was compared to the reference treatment (WOS). As programmed, treatment WOS applied a cumulative irrigation of 340 mm. The two treatments connected to the same rain sensor, WRS and DWRS, applied 274 and 286 mm, respectively; which were not statistically different from the result for WOS (table 3, Comparison A). Treatment DWRS (deficit with rain sensor) originally was planned to turn on for just 60% of the run time programmed for all the other treatments; however, to assure the establishment of the new sod, its run time was not different from those of the other treatments during 2009. Differences in water application between WRS and DWRS were due to the fact that not all the individual plots irrigated at exactly the same rate (mm/hour) due to minor hydraulic differences; however, statistically, they were not different.

Even when this experiment was carried out under a relatively dry period, all SMS-based treatments applied less water than the time-based treatments, as a consequence of the SMS replicates bypassing the SICs (table 3, Comparison B). The different replicates from brands BAS and DYN behaved similarly through time, resulting in comparable

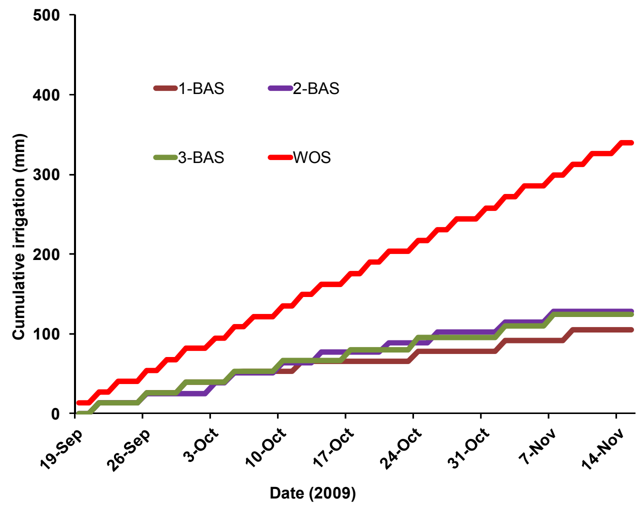

Figure 2. Cumulative irrigation applied by treatment with SMS from brand Baseline (BAS) from 19 September through 15 November 2009. (Numbers before -BAS indicate the number for the different replicates, and WOS = time-based control treatment without sensor feedback.)

amounts of cumulative irrigation water applied by the end of the experiment (table 3, Comparison C). An example of a consistent behavior through time between the replicates is shown on figure 2, for BAS during 2009. Conversely, replicate 3-ACL showed a dissimilar control of irrigation compared to the other two ACL replicates (table 3, Comparison C). Even when all probes were carefully installed three weeks before the beginning of this experiment (on 26 August 2009), a lack of proper soil/probe contact might have occurred with 3-ACL, which improved through time (see results for 2010). Brand AQU resulted in a wider range of cumulative water applied between replicates (fig. 3), showing inconsistency for reading the soil water content and/or for taking the correct decision of allowing or bypassing the SICs (table 3, Comparison C).

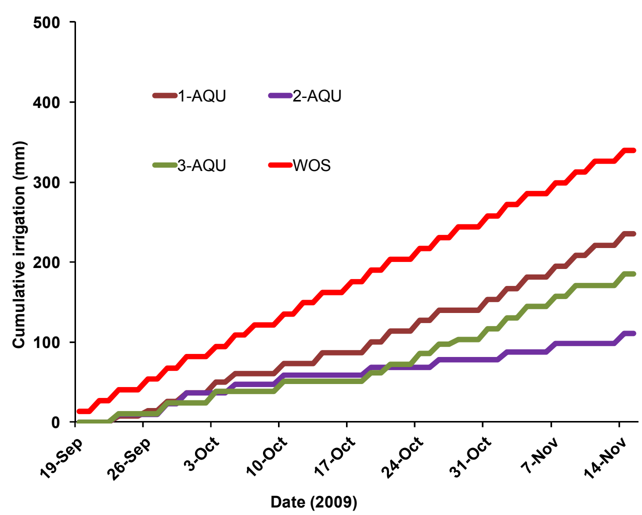

Figure 3. Cumulative irrigation applied by treatment with SMS from brand AquaSpy (AQU) from 19 September through 15 November 2009. (Numbers before -AQU indicate the number for the different replicates, and WOS = time-based control treatment without sensor feedback.)

The brands that, on average, allowed the least cumulative irrigation depth were DYN, ACL, and BAS, with totals of cumulative irrigation of 97, 104, and 119 mm, respectively, which were not statistically different. The AQU system allowed an average of 177 mm, which resulted in a significant difference ($P<0.05$) from DYN. If AQU was not considered in the analysis, ACL, BAS, and DYN were not significantly different (data not shown). The irrigation water savings compared to WORS averaged 48%, 69%, 65%, and 71% for AQU, ACL, BAS, and DYN, respectively, which were related to the proportion of bypassed SICs.

UNDER RECLAIMED WATER

This experiment was a continuation of the work performed in 2009, but this time the irrigation source utilized was RW. In July 2010, the RW source was connected to the turfgrass plots research facility. Data presented here encompasses the period 17 August through 23 November 2010.

Rainfall

During this experiment, two different and defined rainfall conditions occurred (fig. 4). From 17 August to 29 September (44 days) the number, frequency, and depth of rainfall events were considered adequate for irrigation purposes and, compared to historical records (NOAA, 2002), estimated as a normal/wet weather condition. Conversely, from 30 September until the end of this experiment on 23 November (55 days) only 10 mm of rain fell (compared to 110 mm in a normal year), including more than a month with no rain at all. Therefore, this second period was considered dry for this site.

Turfgrass Quality

As in 2009, no significant differences in turfgrass quality were found between the treatments during 2010, which were all rated as ≥6 (good or above; data not shown).

Irrigation Bypass Proportion

Every treatment was programmed to run a total of 42 irrigation cycles during this experiment. Table 4 shows the number and proportion of the SICs that were bypassed

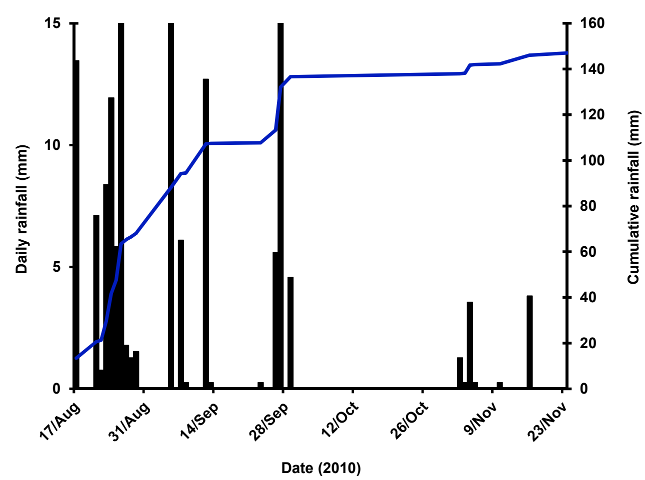

Figure 4. Daily and cumulative rainfall, during 17 August through 23 November 2010.

Table 4. Scheduled irrigation cycles (SICs) bypassed, total cumulative irrigation depth applied, statistical comparisons, and percent water savings by treatment, compared to WOS; under reclaimed water during 2010.

Treatment	SICs Bypassed (#)	SICs Bypassed (%)	Cumulative Depth (mm)	Comparisons[a] A	B	C	D	Water Savings (%)
Time-Based								
WOS	0	0	461	a[b]				0
WRS	9	21	340	b				26
DWRS	9	21	223	c				52
Time-Avg			**341**		**a**			
SMS-Based								
1-ACL	29	69	126			ns		73
2-ACL	25	60	162			ns		65
3-ACL	26	62	153			ns		67
ACL-Avg		**63**	**147**				**b**	**68**
1-AQU	19	45	246			a		47
2-AQU	23	55	199			b		57
3-AQU	13	31	319			a		31
AQU-Avg		**44**	**255**				**a**	**45**
1-BAS	27	64	159			ns		66
2-BAS	23	55	182			ns		60
3-BAS	23	55	192			ns		58
BAS-Avg		**58**	**178**				**ab**	**61**
1-DYN	23	55	187			ns		59
2-DYN	26	62	155			ns		66
3-DYN	22	52	200			ns		57
DYN-Avg		**56**	**181**				**ab**	**61**
SMS-Avg		**55**	**190**		**b**			**59**

[a] A = between time-based treatments; B = time-based treatments versus SMS-based treatments; C = between replicates of a SMS brand; and D = between brand averages.

[b] Different letters within a column indicate statistical difference at P<0.05 (Duncan's multiple range test).

by the different treatments, as well as the average proportion bypassed by the different SMS brands and replications. Treatment WOS bypassed no (0%) SIC because it did not receive feedback of the weather and/or soil moisture conditions. The two time-based treatments that were receiving feedback from the same rain sensor (WRS and DWRS) bypassed 21% of the SICs. In comparison, 55% of the SICs were bypassed on average by the SMS-based treatments.

Regarding the different SMS brands, on average, AQU bypassed the least amount of SICs, with an average of 44%, followed by DYN and BAS, with 56% and 58%, respectively. Brand ACL bypassed the greatest amount of SICs, with an average of 63%. The majority of the irrigation cycles bypassed by the SMS-based treatments occurred during the rainy period, verifying that the tested SMSs worked under RW conditions. In addition, all SMS-replicates bypassed more SICs compared to the treatments with rain sensor feedback, which is consistent with previous findings in the same research facility (Cardenas-Lailhacar et al., 2008 and 2010).

Irrigation Depth

The cumulative irrigation depths applied by the time-based treatments were statistically different from each other (table 4, Comparison A). As designed, treatment WOS applied a cumulative irrigation depth of 461 mm. The two treatments connected to the same rain sensor, WRS and DWRS, applied 340 and 223 mm, respectively; representing 26% and 52% of water savings compared to WOS, respectively. These water savings were achieved as a result of the bypassed irrigation cycles only during the rainy period, from the beginning of the experiment until 29 September (fig. 4). After 29 September, no SIC was bypassed by the rain sensor due to the absence of rain events close or greater than 6 mm (threshold set on the rain sensor). Treatment DWRS applied 66% of the total water applied by WRS, which was close to the target of 60%. These results are consistent with those achieved by rain sensor treatments, in the same experimental field, in previous studies (Cardenas-Lailhacar et al., 2008 and 2010).

The average of the SMS-based treatments applied significantly less water than the time-based treatments (table 4, Comparison B), confirming than even under RW (with a salinity of 0.75 dS/m) SMSs could be a useful tool to conserve water. Moreover, all SMS brands and replicates applied less cumulative irrigation depth than the comparison treatment (WOS), as a consequence of the SMSs bypassing scheduled irrigation cycles. The different replicates from brands ACL, BAS, and DYN behaved similarly through time, resulting in comparable amounts of cumulative irrigation water applied by the end of the research period. The range of water savings between the replicates fluctuated by 8, 7, and 10 percentage points for brands ACL, BAS, and DYN, respectively; making them consistent, reliable, and not statistically different within a sensor brand (table 4, Comparison C). Conversely, brand AQU resulted in a wider range of cumulative water applied between replicates, resulting in statistical differences (table 4, Comparison C), with a variation range of 26 percentage points in water savings; a similar behavior compared to the previous year under PW (table 3).

The brand that, on average, allowed the least cumulative irrigation depth was ACL, followed by BAS and DYN, with totals of cumulative irrigation of 147, 178, and 181 mm, respectively. The AQU system allowed more irrigation than any other brand, with an average of 255 mm; which resulted in a significant difference ($P<0.05$) with ACL (table 4, Comparison D). If AQU was not considered for this analysis, ACL, BAS, and DYN were not significantly different (data not shown).

The irrigation water savings compared to WOS averaged 45%, 61%, 61%, and 68% for AQU, BAS, DYN, and ACL respectively. The average water saved by all SMS-based treatments compared to WOS was 59%, which is consistent with previous results (Cardenas-Lailhacar et al., 2008 and 2010). Furthermore, Cardenas-Lailhacar and Dukes (2015) recently published a lab study where they tested the ACL, BAS, and DYN systems under different water salinities and temperatures. They suggested that even under those fluctuating conditions, these SMSs might achieve an adequate irrigation control, which was corroborated by this study.

Conclusions

Even when AQU saved a significant amount of water, their replicates were statistically different from each other under both PW and RW. Replicates from BAS and DYN were consistent under both PW and RW, while one replicate of ACL was different under PW, probably due to poor sensor-soil contact, which was observed to improve over time.

The majority of the irrigation cycles bypassed by the SMS-based treatments occurred during the rainy periods. The water savings obtained under RW were less than under PW. However, this appeared to be related to the dry weather that prevailed for more than half of the total experimental period, rather than to the different water source. Even when RW with a salinity of 0.75 dS/m was used as the irrigation source during the second stage of these experiments, results of the different treatments and brands were consistent with those of the previous studies, when PW was used to irrigate the turf. Water savings, under both water sources (PW and RW) and considering variable weather conditions, averaged 21% for rain sensors and 61% for SMSs.

All the water savings were achieved without a decline in the turfgrass quality, which remained always above minimum acceptable levels (rating ≥ 6). These results verified that the SMSs tested responded properly to differing agro-climatic conditions. Therefore, SMSs can be a useful tool for conserving water on turfgrass irrigated with either PW or RW of around 0.75 dS/m on a sandy soil. Results in other soils could differ.

Acknowledgements

The authors would like to extend their gratitude to Robert Peacock, Sean Hannigan, from the Pinellas County Utilities Conservation Department, to Dave Bracciano from Tampa Bay Water, and from the University of Florida, Michael Gutierrez, for their assistance on this project.

This research was supported by: the Pinellas-Anclote Basin Board of the Southwest Water Management District, the Florida Department of Agriculture and Consumer Services, and the Florida Nursery Growers and Landscape Association.

Agencies involved in addition to SWFWMD included: Pinellas County Utilities, Florida Yards & Neighborhoods, Florida Nursery Growers and Landscape Association, Tampa Bay Water, and Florida Department of Agriculture and Consumer Services.

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NOMENCLATURE

ACL = Acclima
AQU = AquaSpy
BAS = Baseline
DWRS = deficit with rain sensor
DYN = Dynamax
PW = potable water
RW = reclaimed water
SIC = scheduled irrigation cycle
SMS = soil moisture sensor system
WOS = without sensor feedback
WRS = with rain sensor