Evaluation of Soil Moisture-Based on-demand Irrigation Controllers

Final Report

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Southwest Florida Water Management District

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Media Summary

More than 15% of all new homes in the U.S. were built in Florida between 2005 and 2006, most of them including an automatic irrigation system, resulting in an increase in the demand for limited potable water resources. Typically, outdoor water use accounts for up to 50 percent of total household water consumption. The development of Best Management Practices (BMPs) for irrigation water use in turf has become an undeniable strategic, economic, and environmental issue for the state. New soil moisture sensor (SMS) systems, for landscape irrigation control, could improve irrigation efficiency, promote water conservation, and reduce the environmental impacts of over irrigation.

A four-year research project, funded by the Southwest Florida Water Management District (SWFWMD), to evaluate a SMS-based irrigation system was recently completed. Four different SMS models/brands were initially tested and, later on, two more brands were included.

The research was conducted by Dr. Michael D. Dukes, Mr. Bernardo Cardenas-Lailhacar, and Dr. Grady Miller at the Agricultural and Biological Engineering Department research facilities at the University of Florida, in Gainesville, Florida. The research provided data on how much water can be saved by SMS-based irrigation systems when used on turfgrass.

Most SMS systems recorded significant irrigation water savings compared to time-based irrigation schedules typically used by homeowners. During normal/wet weather in Florida, savings ranged from 69% to 92% for three of four SMS brands tested. During dry weather conditions, savings ranged from 28% to 83%. All these water savings were achieved without decreasing turfgrass quality below acceptable levels. Therefore, SMSs represent a promising technology for water conservation. Moreover, one SMS brand enabled a flexible watering schedule for turf, without the need for seasonal adjustments by personnel.

A project team representative of affected stakeholders was established at the project's inception, to discuss the overall concept and objectives of the project. All agencies involved in addition to SWFWMD staff included: Pinellas County, Pinellas County Florida Yards & Neighborhoods, Institute of Food and Agricultural Sciences, Florida Nursery Growers and Landscape Association, Florida Irrigation Society, Tampa Bay Water, Florida Department of Agriculture and Consumer Services, and the City of St. Petersburg. In addition, the Florida Department of Agriculture and Consumer Services contributed funds toward the project. The following list acknowledges the individuals that provided guidance and input throughout the project: Kathy Scott, Melissa Musicaro, Jay Yingling, Lois Sorenson, Robert Peacock, James Spratt, Dave Bracciano, Dale Armstrong, Hugh Gramling, Gail Huff Ralph Craig, Christine Claus.

Executive Summary

The purpose of this report is to document and summarize the results of the research project entitled "Evaluation of Soil Moisture Based On-demand Irrigation Controllers", with SWFWMD Project Number B187 and University of Florida Project Number 00049860. This project was officially started in May 2004. The data collection occurred from July 2004 until October 2007.

The main goal of this research project was to find out if soil moisture sensor systems could reduce the water applied by residential automatic irrigation systems, compared to common time-based irrigation schedules implemented by homeowners, while maintaining acceptable turf quality

The initial objectives of this experiment were to quantify irrigation water use and to evaluate turf quality differences between: 1) a time-based irrigation schedule system with and without a rain sensor, 2) a time-based schedule compared to a soil moisture sensor-based irrigation system, and 3) different commercially available irrigation soil moisture sensor (SMS) systems. Later on, the consistency of the different SMS units within a brand to control irrigation was evaluated, as well as their potential to completely automate the irrigation systems without the need for seasonal time clock adjustment by personnel ("set and forget").

The research was conducted at the Agricultural and Biological Engineering Department research facilities at the University of Florida, in Gainesville, Florida. The experimental area consisted of common bermudagrass [*Cynodon dactylon* (L.) Pers.] plots (3.7 x 3.7 m). The sensors of four commercially available SMS systems (brands Acclima, Rain Bird, Irrometer, and Water Watcher) were buried at the 7 to 10 cm depth in 2004. During 2007, brands Rain Bird and Water Watcher were replaced by brands Baseline and Lawn Logic. For comparison purposes, time-based treatments with and without a rain sensor, and a non-irrigated treatment were implemented.

Significant differences in turfgrass quality among treatments were not detected during the testing periods of 2004 and 2005, due to sustained favorable weather conditions for the turf growth and development. During 2006 and 2007, due to drier weather conditions and/or less frequent rain events, the non-irrigated plots resulted in turfgrass quality below the minimum acceptable level, while the rest of the treatments had at a minimum acceptable turfgrass quality. The treatment with-rain-sensor resulted in 34% less water applied than the without-rain-sensor treatment during wet weather conditions, and between 13% and 24% during the dry seasons.

Most SMS brands also recorded significant irrigation water savings compared to the treatment without-rain-sensor feedback. During normal wet weather in Florida, savings ranged from 69% to 92% for three of four SMS brands tested. During dry weather conditions, savings ranged from 28% to 83% for the same brands.

Soil moisture sensor irrigation control represents a promising technology that could lead to a complete automation of residential irrigation systems, to substantial savings in irrigation water while maintaining acceptable turf quality, even during dry weather conditions. Moreover, one SMS brand enabled a watering schedule for turf, without the need for seasonal adjustments by personnel. Testing this technology in residential irrigation systems is recommended to validate these results.

1. INTRODUCTION

1.1 Background

This document serves as the final report for the project entitled "Evaluation of Soil Moisture Based On-demand Irrigation Controllers", with SWFWMD Project Number B187 and University of Florida Project Number 00049860. This project was officially started in May 2004 when the fully executed contract was sent to the University of Florida and ended October 2007.

1.2 Justification

Florida has dry and warm weather in spring and fall, as well as frequent rain events in summer (National Oceanic and Atmospheric Administration [NOAA], 2003). These climatic conditions, coupled with low water holding capacity of the predominately sandy soils in Florida, make irrigation common for the high quality landscapes desired by homeowners (National Research Council, 1996). More than 15% of all new homes in the U.S. were built in Florida between 2005 and 2006 (United States Census Bureau [USCB], 2007); most of them with automatic in-ground irrigation systems (Tampa Bay Water, 2005; Whitcomb, 2005); which has been reported to result in higher water use compared to manual irrigation or manually moved sprinklers (Mayer et al., 1999).

A recent study carried out by Haley et al. (2007) in Central Florida found that homeowners tended to irrigate by as much as 2-3 times the turfgrass requirements. It has been reported that over irrigation promotes the establishment and survival of some turfgrass weeds (Busey and Johnston, 2006), increases the severity of some pathogens (Davis and Dernoeden, 1991), and increases evapotranspiration (Biran et al., 1981). Control of irrigation by soil moisture or soil tension has been shown to reduce both over-irrigation (Augustin and Snyder, 1984) and nitrogen leaching below the root zone (Snyder et al., 1984). Moreover, over irrigation tends to have environmentally costly effects because of wasted water, energy, leaching of nutrients and/or agro-chemicals into groundwater supplies, degradation of surface water supplies by sediment-laden irrigation water runoff, and erosion. Moreover, water purveyors need to have the necessary infrastructure to pump, treat, and deliver water with potable quality that will ultimately be used to irrigate the landscape.

Modern commercially available soil moisture sensor (SMS) systems include not only a sensor to be buried in the soil but a controller that interfaces with the irrigation time clock. This controller is a milestone in the development of the soil moisture sensor industry because it sends a signal to the buried sensor, and converts the response to a "sensed" soil moisture content. At the same time, the controller acts as a switch that allows the operator to choose a desired soil moisture content threshold, above which the scheduled irrigation events will be bypassed. Typically, the adjustable threshold can be set between relatively dry to relatively wet soil moisture conditions; depending on the plant material, installation depth of the sensor, soil type, etc.

In sandy soils, where the storage of water is minimal, coupled with shallow turfgrass root depth, the continuous and accurate monitoring of the soil moisture status becomes of great consequence, and SMSs could be a useful tool for diminishing or avoiding over irrigation. Prior to this study, performance of SMS systems have not been reported for Florida conditions.

1.3 Goal

The main goal of this project was to determine if a residential automatic irrigation system, when receiving feedback from a soil moisture sensor system (sensor with a proprietary controller), could reduce irrigation water application, compared to common time-based irrigation schedules implemented by homeowners, while maintaining acceptable turf quality.

1.4 Objectives

The initial objectives of this experiment were to quantify irrigation water use and to evaluate turf quality differences between: 1) a time-based irrigation schedule system with and without a rain sensor, 2) a time-based schedule compared to a soil moisture sensor-based irrigation system, and 3) different commercially available irrigation soil moisture sensor (SMS) systems. Later on, the consistency of the different SMS units within a brand to control irrigation was evaluated, as well as their potential to completely automate the irrigation systems without the need for seasonal time clock adjustment by personnel ("set and forget").

2 MATERIALS AND METHODS

2.1 Project Initiation

During the late spring and early summer of 2004, the experiment was installed at the Agricultural and Biological Engineering Department research facilities, University of Florida, Gainesville, Florida (Figure 2-1). The soil is classified as an Arredondo fine sand (United States Department of Agriculture [USDA], 2007), with a field capacity of 7% volumetric water content (Cardenas-Lailhacar, 2006). A total of seventy-two 3.7 X 3.7 m plots were established on a field with mixed bahiagrass (*Paspalum notatum*) and common bermudagrass [*Cynodon dactylon* (L.) Pers.]. Much of the irrigation hardware was in place from a previous research project; however, extensive renovations were performed to make the equipment serviceable. Each plot was irrigated with four quarter-circle pop-up spray heads (Hunter 12A, Hunter Industries, Inc., San Marcos, CA), which were pressure regulated at 172 kPa, and with an average application rate of 38 mm/hr. Before data collection, the site was treated with appropriate pesticides to remove bahiagrass and assorted weed species. Turfgrass management was carried out according to recommendations by the University of Florida (Trenholm et al., 2003) and plots were mowed twice weekly at a height of 5.5 cm.

2.2 Uniformity Testing

Once the site was operational, a uniformity test of the irrigation distribution was performed on each plot with 16 catch-cans (15.9 cm dia., 20.3 cm depth), spaced on a 0.9 x 0.9 m square grid spacing (Figure 2-2). To minimize edge effects, this grid was positioned 0.4 m inside the plot boundaries. Pressure at the two farthest plots was measured to ensure pressure losses were within acceptable limits. The system was set to run for 35 min, to ensure that the average water application depth was at least 13 mm. Wind velocity during the test period was measured with a hand held anemometer. The American Society of Agricultural Engineers (ASAE) standards (ASAE, 2000) allow uniformity testing with wind speeds up to 5 m/s. However, if wind was over 2.5 m/s or the distribution was affected by wind gusts, the test was discontinued.

The low-quarter irrigation distribution uniformity (DU_{lq}) was calculated with the following equation (Merriam and Keller, 1978):

$$DU_{lq} = \frac{\overline{D}_{lq}}{\overline{D}_{tot}} \qquad [1]$$

where $\overline{D}_{lq}$ is the mean of the lowest 25% of a group of catch-can measurements, and $\overline{D}_{tot}$ is the overall mean of a group of catch-can measurements.

The irrigation uniformity tests resulted in a wide range of DU_{lq} values across the plots (0.15 to 0.79), with an average of 0.52±14 that, according to the Irrigation Association (2005) overall system quality ratings, is considered “fair” (Figure 2-3). The very low values (see Figure 2-3, plots A8, D1, and A12) denoted some performance problems (partially or completely clogged nozzles, spray heads below the mowing height, spray heads mis-aligned, etc.) that were fixed after the test was run. Even when a new DU_{lq} test was not performed after the repairs, observations denoted a substantial improvement on the plots with low DU_{lq} values. As a comparison, Baum et al. (2005) performed uniformity tests on irrigation systems of homes in Central Florida having spray heads, and found an average DU_{lq} of 0.41, with a range of 0.12 to 0.67. Thus, the irrigation uniformity of the experimental plots was representative of actual homes. In addition, Dukes et al. (2006) reported that catch can DU_{lq} as low as 0.40 did not result in reduced soil water DU_{lq} of approximately 0.75. The authors concluded that the soil system and plant canopy can buffer low catch can DU_{lq} values resulting in a higher effective soil moisture uniformity.

Furthermore, the catch cans placed on the edges of each plot resulted in 71% of the observations lower than 100 ml, indicating that substantial edge effects occurred in the testing; which is common for sprinkler irrigation systems. This attribute helped reduce overlapping irrigation between plots and did not impact the results, because soil moisture content and turf quality ratings were taken from the center of each plot.

2.3 Soil Moisture Sensor Systems

At the beginning of the experiment, four commercially available SMS systems were selected for evaluation (Figure 2-4): Acclima Digital TDT RS-500 (Acclima Inc., Meridian, ID), Watermark 200SS-5 (Irrometer Company, Inc., Riverside, CA), Rain Bird MS-100 (Rain Bird International, Inc., Glendora, CA), and Water Watcher DPS-100 (Water Watcher, Inc., Logan, UT), codified as AC, IM, RB, and WW, respectively. Before the 2007 testing season, sensors from brands RB and WW were removed from the plots, because they were commercially discontinued, and were replaced by two new SMS systems: Lawn Logic controller with a LL1004 probe (Alpine Automation) and Water Tec S100 controller with a biSensor probe (Baseline LLC, Meridian, ID); codified as LL and BL, respectively (Figure 2-5). Each one of these SMS systems included a controller that could be adjusted to different soil water content thresholds. The controllers were connected in series with common residential irrigation time clocks; model ESP-6 (Rain Bird International, Inc., Glendora, CA) (Figures 2-6 and 2-7).

2.3.1 Sensors installation

According to manufacturer recommendations, the SMSs should be buried in the driest zone of a multiple-zone system. Accordingly, to identify the driest and wettest plots in the experimental area, a volumetric soil moisture survey assessment was carried out on each plot. Because 64 plots were required, this analysis was also used to discard 8 plots from a pool of 72 plots available. On 12 March 2004, after 14 days without rainfall, a relatively “dry” soil moisture condition was evident. The volumetric moisture content was measured in each plot by means of a hand held TDR device, which measured the moisture in the top 20 cm (Field Scout 300, Spectrum Technologies, Inc., Plainfield, IL). Measurements were taken at five locations in the center 1 x 1 m of each plot and averaged. On 17 March 2004, 24 hr after a 23 mm rainfall filled the soil profile, the volumetric moisture content in a “wet” condition was measured as well. Two plots had significantly higher VMC, under both the wet and the dry condition, so they were discarded. Six plots were also discarded because they had the absolute lowest VMC values of all plots, even when they were not statistically different ($P>0.95$), coupled with a comparatively lower turfgrass quality before the beginning of the experiment. An ANOVA on the remaining 64 plots, indicated that only two plots were significantly wetter than the rest ($P>0.95$) in the wet condition, so they were discarded as locations for SMS placement. In the dry condition, there were not statistical differences ($P>0.95$) in the soil moisture levels. Thus, the plots selected to bury the SMSs were the absolute driest ones and/or the most convenient for sensor installation. Moreover, in the dry condition, the soil moisture content (5.2-6.8%) was not significantly different ($P>0.999$) across sensor control plots. In all cases, SMSs were installed in the center of the plots, in the top 7-10 cm of the soil, where most of the roots were observed. The plots with the sensors were used to control irrigation in three other plots for a total of four replications for each treatment.

2.3.2 Controllers set up

The IM controllers were set at number 1 (equivalent to 10 kPa of soil tension according to the manufacturer), whereas the AC and BL controllers were set on their display at a volumetric moisture content (VMC) of 7%, where a soil tension of 10 kPa and a VMC of 7% were taken as approximately field capacity (Cardenas-Lailhacar, 2006). Following manufacturer recommendations to find a set point close to field capacity, the RB and WW controllers were set at their thresholds 24 hours after a significant rainfall event (which happened on 20 July 2004, after four days of rain, with a total of 107 mm that filled the soil profile with water). The RB controllers have a scale from a dry (#1) to a wet (#9) condition, and their thresholds were found by moving and setting the knob at the driest point (#2.5, in this case) where it would bypass irrigation, as indicated by an LED. On the WWs, initially the threshold could not be set, since the soil moisture was below the measurement range of the controller. After discussion with the manufacturer, a 1000 Ω resistor was added between the solenoid valve port and the valve common port, which allowed the controller to read the low VMC at field capacity of this sandy soil. The calibration procedure consisted of setting the knob in the middle of the scale (dimensionless), and pushing the calibration button, which allowed its auto-set point. Finally, the LL controller thresholds were determined by pushing their set button that allows its auto-calibration in position #5, on a 1 to 9 scale. It is important to note that following these methods the thresholds on the RB, WW, and LL controllers could not be associated with a specific soil VMC prior to the experiment. However, in order to find similar outcomes to those that homeowners would encounter, SMS systems were used directly "out of the box", following manufacturer recommendations for installation and set points. Although we used procedures recommended by the manufacturers, it is likely that potential installers would need to be trained on specifics such as sensor location and burial procedures as well as time clock programming to take advantage of the SMS system.

2.4 Treatments

2.4.1 Basic Types

Two basic types of treatments were defined: time-based treatments and SMS-based treatments (Tables 2-1, 2-2, and 2-3). Within the time-based treatments, an irrigation frequency of 2 days per week was selected, since this frequency is common in Florida due to water restrictions (SWFWMD, 2003). Two of these treatments were connected to a rain sensor (2-WRS and 2-DWRS), to simulate requirements imposed on homeowners by Florida Statutes (2006). The rain sensor (Mini-click II, Hunter Industries, Inc., San Marcos, CA) was set at 6 mm rainfall threshold. In addition, a without-rain-sensor treatment (2-WORS) was included, in order to simulate household irrigation systems with a non-functional or absent rain sensor. This treatment was used as the main time-based comparison treatment, since rain sensors are thought to be absent or non-functional on many homes in Florida (Whithcomb, 2005). Finally, a non-irrigated treatment (0-NI) was also implemented as a control for turfgrass quality.

2.4.2 During 2004 and 2005

During 2004 and 2005 (Table 2-1), all four SMS-based treatments tested (brands AC, RB, IM, and WW) were analyzed at three irrigation frequencies: one, two, and seven days per week (1 d/w, 2 d/w and 7 d/w, respectively). The 1 d/w and 2 d/w watering frequencies represent typical watering restrictions imposed in Florida (Florida Department of Environmental Protection, 2006; SWFWMD, 2003). The 7 d/w watering frequency was chosen to analyze the possibility of allowing the SMS to decide when to irrigate according to plant needs, independent of the day of the week water restrictions.

2.4.3 During 2006

In 2006, after the winter dormancy of the bermudagrass, a variation in the irrigation frequency of the SMS-based experiments was carried out from 25 March through 15 July (Table 2-2). All the SMS-based treatments were set at an irrigation frequency of 2 d/w (Mondays and Thursdays). The objectives of this portion of the experiment were to analyze the behavior of the three units within a brand, and to compare the different brands against the control treatment. After 15 July (Table 2-1), the replicates from the different brands were re-set to their original irrigation schedule, this is, to run with three different irrigation frequencies (1, 2, and 7 d/w). Throughout 2006, irrigation thresholds were set consistent with earlier comparisons, except for the Irrometer units that were switched from position #1 to #2 to investigate if this new threshold would save more water.

2.4.4 During 2007

In 2007, some variations from previous seasons were made (Table 2-3). The manufacturer of the Water Watcher system was no longer in business, and the Rain Bird SMS system was no longer available. Therefore, during the winter dormancy, two new replacement soil moisture sensor systems were added: Lawn Logic controller with a LL1004 probe (Alpine Automation) and Water Tec S100 controller with a biSensor probe (Baseline). The different systems were set at 1, 2, and 7 d/w irrigation frequencies. It should be noted that when 1-RB and 2-RB probes were removed from the soil, their rods showed signs of degradation.

2.5 Weekly Irrigation

From 2004 through 2006, the weekly irrigation depth was programmed to replace 100% of the monthly net irrigation requirement, based on recommendations by Dukes and Haman (2002) for the area where this experiment was carried out (Table 2-4). All treatments were programmed to have an equal opportunity to apply the same amount of irrigation per week, except for treatments 2-DWRS (deficit-with-rain-sensor, 60% of this amount), and 0-NI (non-irrigated). Therefore, differences in water application among treatments would be the result of sensors bypassing scheduled irrigation cycles.

Throughout 2007, a different approach was established. The SMS-based treatments were set to apply the same amount of water (27 mm) every scheduled day (Table 2-5). The 27 mm was estimated as the maximum amount of irrigation to fill the root-zone up to field capacity. Since it was likely that a single 27 mm application in this sandy soil would result in over-irrigation, in order to make the SMS systems more efficient and to avoid deep percolation, the total amount per day (27 mm) was divided in two applications: 10 mm at 0600 h, and 17 mm at 2000 h. This schedule was intended to take advantage of the rain that usually falls in the afternoon/evening during the rainy season (summer and early fall). During the rainy period, it was theorized that the 2000 h irrigation cycle (17 mm) would be bypassed, increasing the water savings of the system.

Is important to note that, to allow comparisons between the different experiments established, from 2004 through 2007 the comparison treatment, set to run independently of the weather conditions (2-WORS [without rain sensor)], the treatment with a rain sensor (2-WRS), and the treatment 2-DWRS (programmed to apply 60% of 2-WRS) were kept unchanged (i.e. with an irrigation frequency of 2 d/w and following the schedule recommended by Dukes and Haman (2002) [Table 2-4]).

Finally, the irrigation cycles were programmed on two ESP-6 and three ESP-4Si model time clocks (Rain Bird International, Inc., Glendora, CA) (Figures 2-6 and 2-7), which were set to start between

0100 and 0500 h; with the purpose of diminishing wind drift and decreasing evaporation, and to mimic water use restrictions where this study was carried out, that prohibit irrigation between 1000 and 1600 h (SJRWMD, 2006).

2.6 Irrigation Management and Data Collection

Figure 2-8 shows a general view of the irrigation management and data collection control board that includes the time clocks, SMS controllers, solenoid valves wiring, and data acquisition system for the flowmeters; used to record the irrigation volume on each plot. A customized relay and transformer were added to the control system so that up to 16 plots may be run at once (Figure 2-9).

2.6.1 Water application

Water application data were collected independently for each plot. Pulse-type positive displacement flowmeters (PSMT 20 x 190 mm, Amco Water Metering Systems, Inc., Ocala, FL) were connected to nine AM16/32 multiplexers (Campbell Scientific, Logan, UT), which were hooked up to a CR 10X model datalogger (Campbell Scientific, Logan, UT), to continually record the irrigation date and volume applied to each plot (Figure 2-10). In addition, flowmeters were read manually each week to verify automatically acquired data.

2.6.2 Weather data

Weather data were collected by an automated weather station (Campbell Scientific, Logan, UT), located beside the experimental site (Figure 2-11). Measurements, made every fifteen minutes, included air temperature, relative humidity, wind speed, wind direction, solar radiation, barometric pressure, and soil heat flux. Rainfall was recorded continuously by a tipping bucket rain gauge throughout the experiment period. In 2005, a manual rain gauge was also used for comparison purposes. Both methods agreed well (R^2=0.99) when measured over a period of 212 days, encompassing 73 rain events that ranged from 0.3 to 50.3 mm.

2.6.3 Actual Volumetric Moisture Content

A pre-calibrated capacitance probe (ECH_20 20 cm probe, Decagon Devices, Inc., Pullman, WA) was installed in the center of every plot so that soil volumetric moisture content could be measured in the top 15 cm of soil (Figure 2-12). Four of these probes were connected to a HOBO Micrologger (Onset Computer Corporation, Inc., Bourne, MA), which recorded the soil volumetric moisture content of each plot every 15 minutes.

2.6.4 Turfgrass quality

Turfgrass quality was visually assessed and rated using a scale of 1 to 9, where 1 represents brown, dormant, or dead turf, and 9 represents the best quality (Skogley and Sawyer, 1992). A rating of 5 was considered the minimum acceptable turf quality for lawn turfgrass. Ratings were carried out seasonally by the same person throughout the experiment.

2.6.5 Experiment Design and Statistical Analyses

Experimental treatments were replicated four times, for a total of 64 plots, in a completely randomized design. Statistical data analyses were performed using the general linear model (GLM) procedure of the Statistical Analysis System software (SAS, 2000). Analysis of Variance was used to determine treatment differences for a completely randomized design and Duncan's Multiple Range Test was used to identify mean differences.

Table 2-1. Treatments during 2004, 2005 and from 22 July through 10 December 2006.

Treatment Codes	Irrigation Frequency (days/week)	Soil Moisture Sensor Brand or Treatment Description	Set Point Position
Time-Based			
2-WORS	2	Without rain sensor	N/A
2-WRS	2	With rain sensor	6 mm
2-DWRS	2	Deficit with rain sensor, 60% of 2-WRS	6 mm
SMS-Based			
1-AC	1	Acclima	7% VMC
1-RB	1	Rain Bird	#2.5
1-IM	1	Irrometer	#1[a]
1-WW	1	Water Watcher	#0
2-AC	2	Acclima	7% VMC
2-RB	2	Rain Bird	#2.5
2-IM	2	Irrometer	#1[a]
2-WW	2	Water Watcher	#0
7-AC	7	Acclima	7% VMC
7-RB	7	Rain Bird	#2.5
7-IM	7	Irrometer	#1[a]
7-WW	7	Water Watcher	#0
0-NI	0	No irrigation	N/A

[a] During 2006 it was changed to position #2

Table 2-2. Treatments from 25 March through 15 July 2006.

Treatment Codes	Irrigation Frequency (days/week)	Soil Moisture Sensor Brand or Treatment Description	Set point
Time-Based			
2-WORS	2	Without rain sensor	N/A
2-WRS	2	With rain sensor	6 mm
2-DWRS	2	Deficit with rain sensor, 60% of 2-WRS	6 mm
SMS-Based			
AC	2	Acclima	7% VMC
RB	2	Rain Bird	Position #2.5
IM	2	Irrometer	Position #2
WW	2	Water Watcher	Position #0
0-NI	0	No irrigation	N/A

Table 2-3. Treatments during 2007.

Treatment Codes	Irrigation Frequency (days/week)	Soil Moisture Sensor Brand or Treatment Description	Set point
Time-Based			
2-WORS	2	Without rain sensor	N/A
2-WRS	2	With rain sensor	6 mm
2-DWRS	2	Deficit with rain sensor, 60% of 2-WRS	6 mm
SMS-Based			
1-AC	1	Acclima	7% VMC
1-BL	1	Baseline	7% VMC
1-IM	1	Irrometer	Position #2
1-LL	1	Lawn Logic	Position #5
2-AC	2	Acclima	7% VMC
2-BL	2	Baseline	7% VMC
2-IM	2	Irrometer	Position #2
2-LL	2	Lawn Logic	Position #5
7-AC	7	Acclima	7% VMC
7-BL	7	Baseline	7% VMC
7-IM	7	Irrometer	Position #2
7-LL	7	Lawn Logic	Position #5
0-NI	0	No irrigation	N/A

Table 2-4. Weekly irrigation depth to replace historical net irrigation requirement in the 2004 through 2006 experiments.

Month	Irrigation depth (mm)
January	0
February	0
March	28
April	28
May	46
June	36
July	34
August	45
September	34
October	31
November	23
December	23
Total per year	**1305**

Source: Based on Dukes and Haman (2002)

Table 2-5. Weekly irrigation depth, used on the 2007 experiments.

		Irrigation Frequency			
		1 d/w	2 d/w		7 d/w
Cycle/day	Time (h)	Monday (mm)	Monday (mm)	Thursday (mm)	Daily (mm)
1st	6:00	10	10	10	10
2nd	20:00	17	17	17	17
	TOTAL	**27**	**27**	**27**	**27**

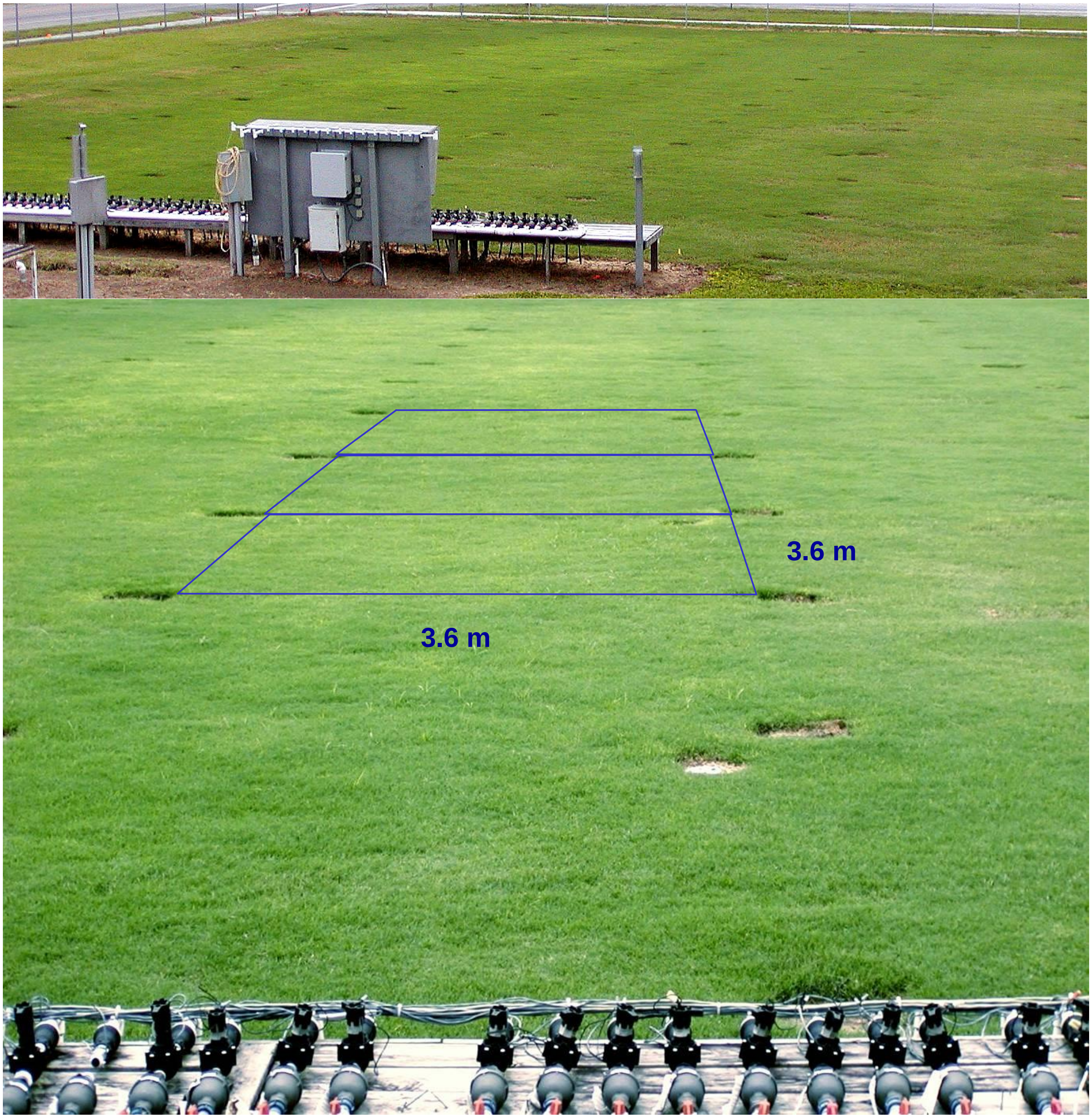

Figure 2-1. Bermudagrass plots established at the University of Florida in Gainesville.

Figure 2-2. Irrigation uniformity distribution test on turfgrass plots.

	A	B	C	D	E	F	
12	15	52	54	71	78	60	12
11	56	66	48	63	40	76	11
10	41	51	61	53	64	79	10
9	46	21	50	58	43	66	9
8	27	46	49	26	60	64	8
7	49	51	53	44	59	67	7
6	35	49	46	56	58	26	6
5	51	31	52	34	52	76	5
4	62	64	47	64	55	68	4
3	45	61	40	36	56	55	3
2	58	69	37	51	33	39	2
1	61	55	64	28	52	63	1
	A	B	C	D	E	F	

Figure 2-3. Low quarter distribution uniformity testing results on each plot.

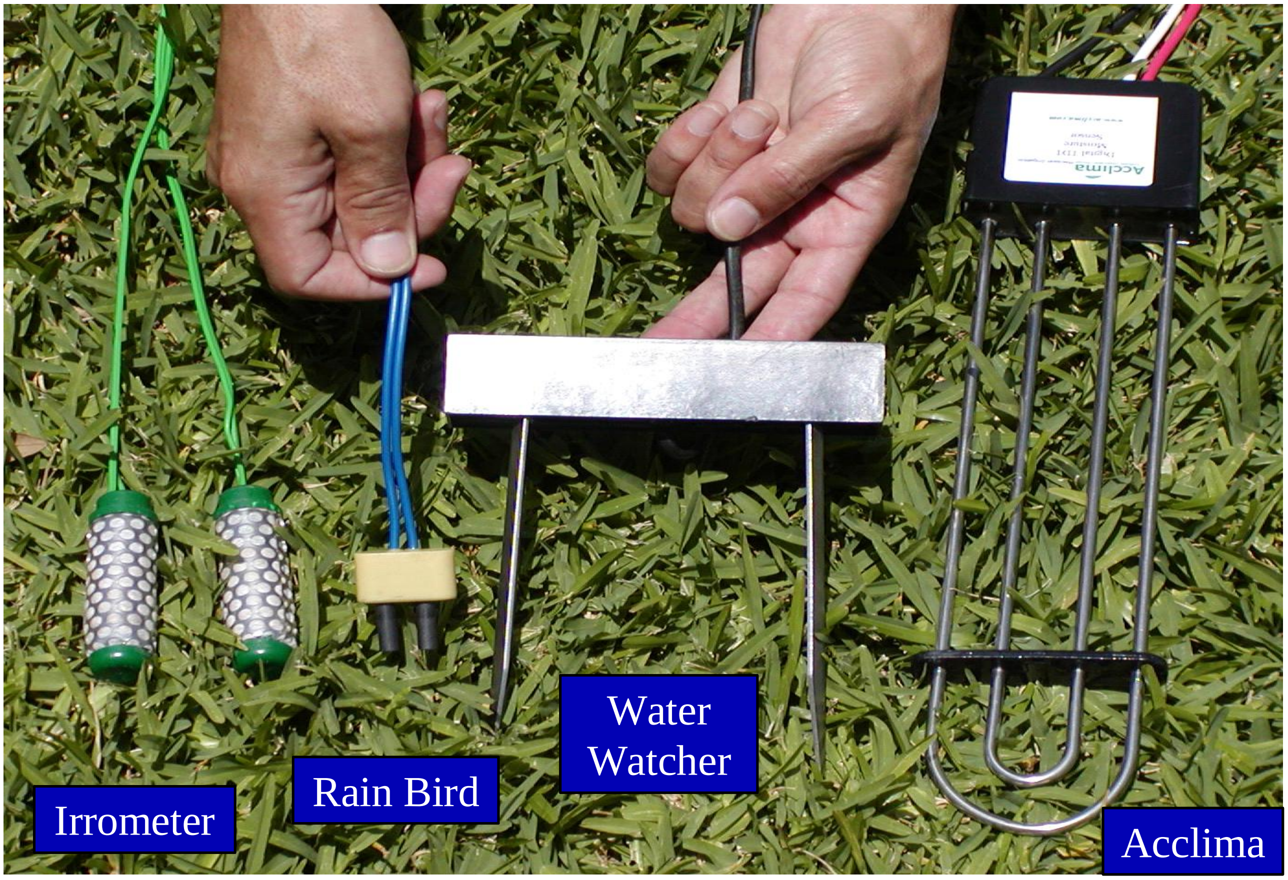

Figure 2-4. Sensors tested in the experiment: Irrometer, Rain Bird, Water Watcher and Acclima.

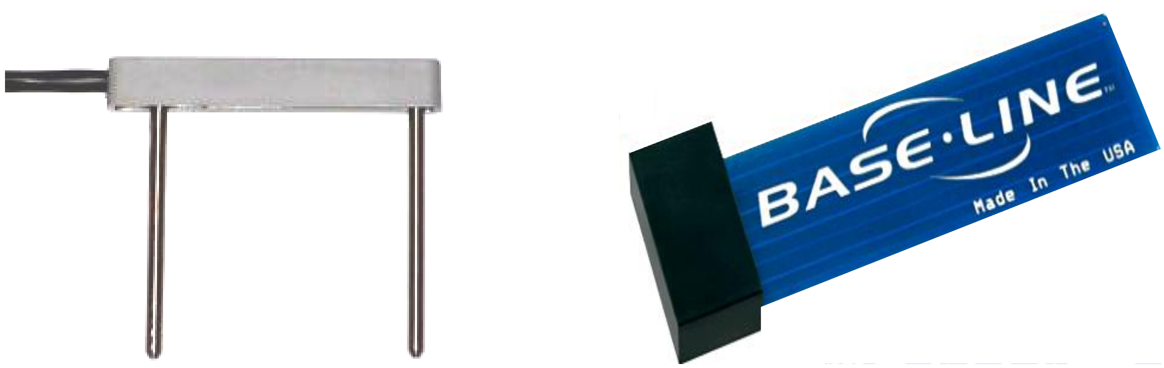

Figure 2-5. Soil moisture sensors (LL1004) from Alpine Automation (left) and soil moisture sensor (biSensor) from Baseline (right).

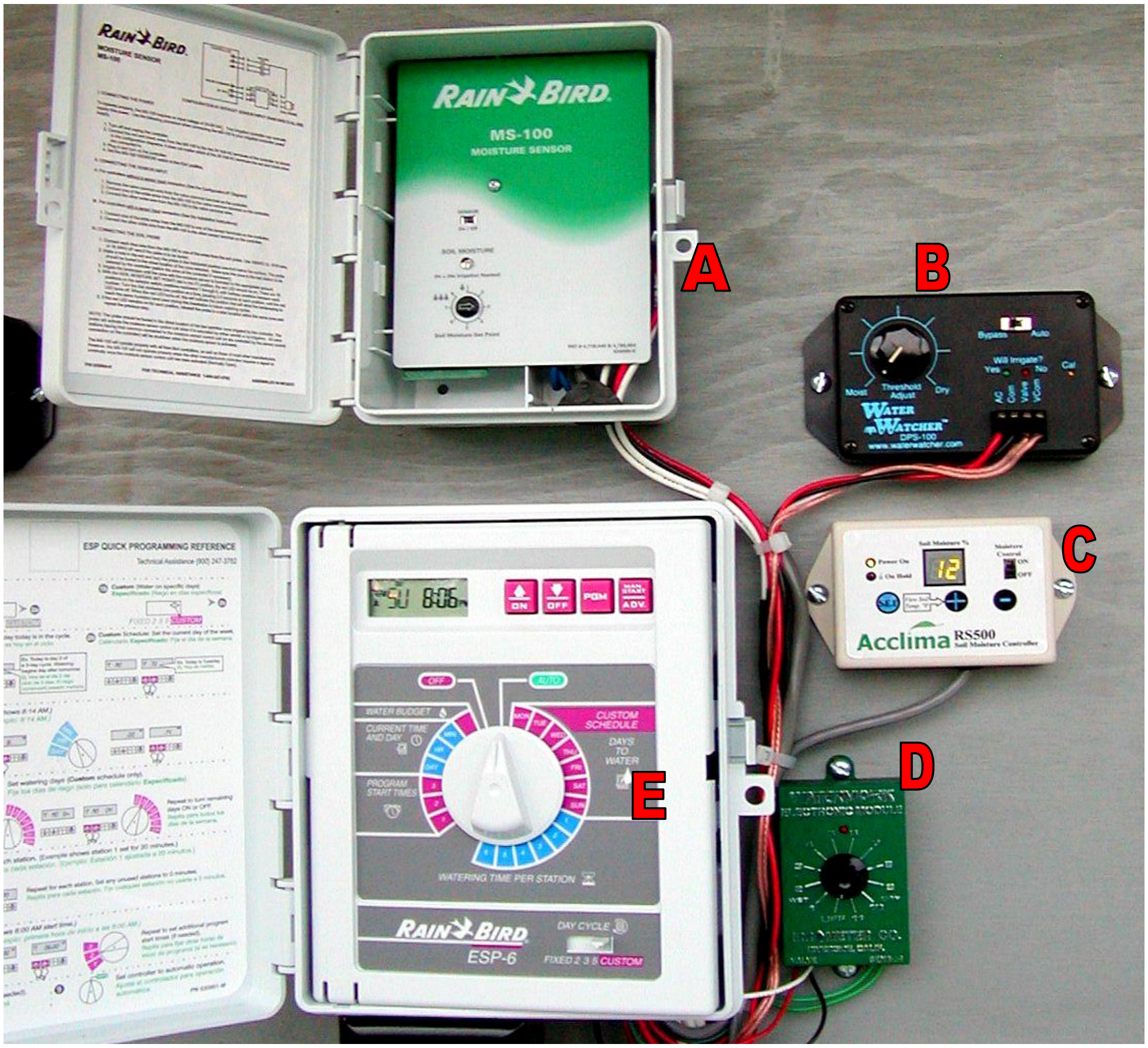

Figure 2-6. Irrigation controls as installed for this study: soil moisture sensor-controllers brands: A) Rain Bird, B) Water Watcher, C) Acclima, and D) Irrometer; and irrigation time clock E) Rain Bird.

Figure 2-7. Soil moisture sensor-controllers, brands Baseline and Lawn Logic.

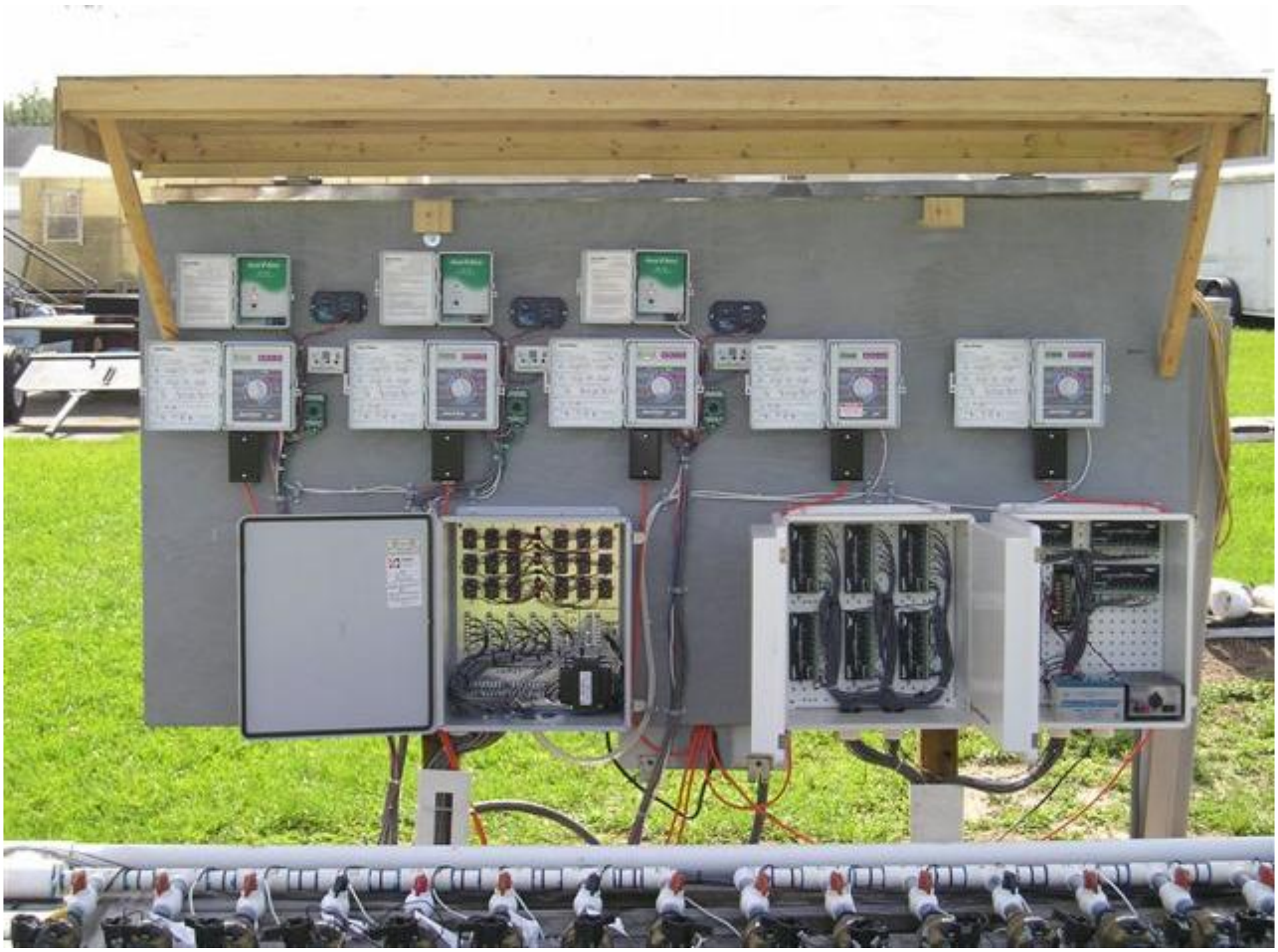

Figure 2-8. Control board showing time clocks, soil moisture sensor-controllers, solenoid valves wiring, and flowmeters data acquisition system (details are shown in the next Figures).

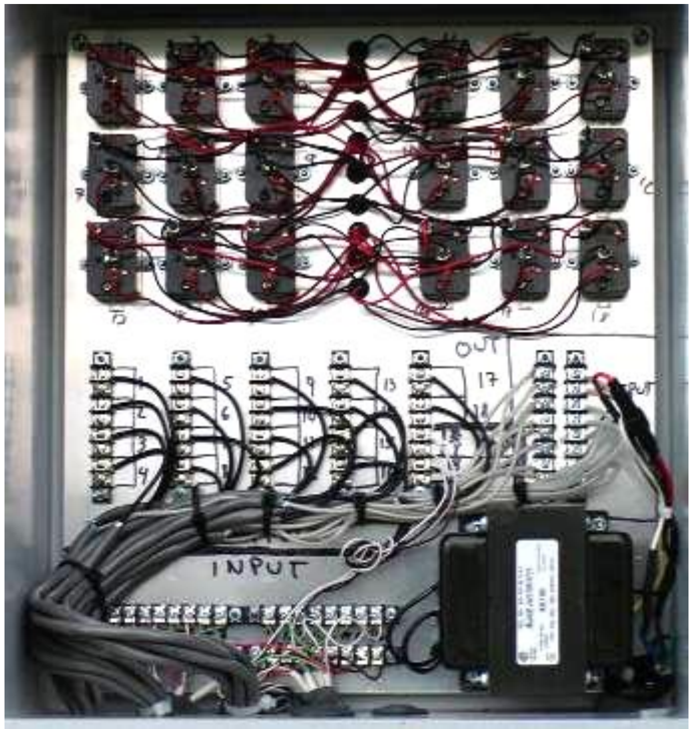

Figure 2-9. Control board detail showing the solenoid valves control box.

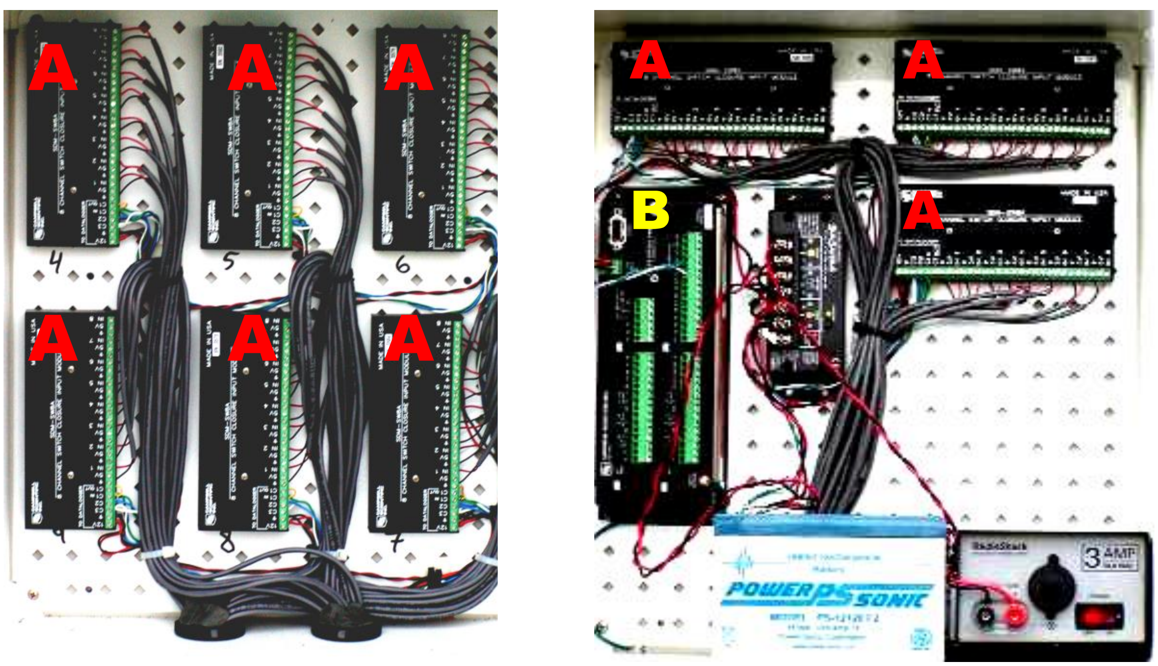

Figure 2-10. Control board detail, flowmeter-datalogger boxes showing A) multiplexers, B) CR 10X datalogger used for this study.

Figure 2-11. Automated weather station near turf plots for this study.

Figure 2-12. ECH_2O probe, capacitance soil moisture probe shown with a HOBO data logger as installed for this study.

3 WATER APPLICATION RESULTS (2004, 2005, AND SECOND HALF OF 2006)

3.1 Environmental Conditions

Figures 3-1 and 3-2 show the daily and cumulative rainfall in 2004 and 2005, respectively, and Figures 3-3 and 3-4 compare these values with the historic percent of rainy days per month and cumulative rainfall for the same periods. During 2004, a tropical storm and two hurricanes - Frances and Jeanne - passed over the research area during the experiment. In contrast, even while 2005 broke all records for the number of hurricanes and named tropical storms in the U.S., none of them directly hit the experiment site. In 2004, even though it rained less frequently (31% of the days) than a normal year (34% of the days), the cumulative rainfall for the experimental period was 944 mm, 73% more than historical records. However, most of the rainfall (56%) occurred during the tropical storm and the two hurricanes previously mentioned. If these events are not considered, a total of 414 mm would have fell during 2004. During the 2005 data collection period, 38% of the days had rainfall events compared to 37% of a normal year, and totaling 732 mm, which is 3% above historical rainfall for this time period. Therefore, both 2004 and 2005 resulted in high frequency of rainfall and a large amount of cumulative precipitation, which is not uncommon in this region.

Figure 3-5 shows the daily and cumulative rainfall for the second half of 2006 data collection period. It can be seen that three different weather conditions occurred: a) from 22 July to 14 September: a relatively high frequency and total amount of rain fell (36% of the days and 404 mm, respectively), b) from 15 September to 26 October: only 0.25 mm of rain were recorded in one day, coupled with high temperatures (data not shown), and c) from 27 October to 10 December: rain occurred in intermediate frequencies and amounts (27% of the days and 45 mm), with temperatures declining progressively. Even when the cumulative rain for the experimental period was 10% higher than a normal year (Figure 3-6), 76% of the rain fell in only six days (4% of the experimental days) (Figure 3-5). When taking into account the frequency of rainfall, it could be seen that from July through October a lesser amount of rainy days occurred compared to a normal year, coinciding with the time of the year when ET values are the highest. Therefore, this data collection period could be considered as dry, and a lesser amount of irrigation cycles bypassed by the SMS systems should be expected, compared to previous years.

3.2 Irrigation Application during 2004 and 2005

Table 3-1 shows the total cumulative irrigation depth applied to treatments, statistical comparisons, and percent water savings compared to 2-DWRS, 2-WRS, and 2-WORS, for years 2004 and 2005, when wet weather conditions prevailed.

3.2.1 Time-based treatments

Table 3-1; Comparison A, shows that the three time-based treatments (2-WORS, 2-WRS, and 2-DWRS) were significantly different ($P<0.0001$) from each other during this study. Treatment 2-WRS (two days/week, with a rain sensor) was established to mimic a homeowner complying with irrigation regulations and setting the time clock according to recommended practices. This treatment accounted for 995 mm of water, or an equivalent of 98 mm/month. Haley et al. (2007) found within this homeowner profile (also programmed to replace 100% of historical net irrigation requirements) an irrigation use of 105 mm/month.

The well-managed or water conservative homeowner profile, imitated by treatment 2-DWRS (two days/week, with a rain sensor, and 60% of 2-WRS), applied 63% of the water applied by 2-WRS, close to the target of 60%. The total depth was 623 mm, or an equivalent of 61 mm/month.

The treatment simulating an irrigation system with an absent or non-functional rain sensor (2-WORS) accounted for 1514 mm, or 148 mm/month. (As a comparison, Haley et al. (2007) found that homeowners within this profile applied 149 mm/month on average.) Thus, this treatment applied 52% more water than the treatment with a functional rain sensor (2-WRS), whereas 2-WRS saved 34% of the water applied by 2-WORS. These results demonstrate the importance of a functional and well-maintained rain shut-off device on all automated irrigation systems in Florida; where rainy weather is common (NOAA, 2003). Moreover, as the study prepared by Whitcomb (2005) recently found, just 25% of the surveyed homeowners in Florida with automatic irrigation systems reported having a rain sensor, and the author speculated that they are often incorrectly installed. Therefore, appropriately installed and properly working rain sensors could lead to substantial water savings for homeowners. Moreover, Cardenas-Lailhacar and Dukes (2007) found that rain sensors under the climate conditions of this study can have a payback period of less than a year when set at thresholds of 13 mm or less.

3.2.2 Time-based treatments vs. SMS-based treatments

Table 3-1 (Comparison B) shows that there was a significant ($P<0.0001$) difference between the averages of time-based and SMS-based treatments; with 1044 and 420 mm of cumulative irrigation depth, respectively. Thus, the SMS-based treatments, on average, significantly reduced the amount of irrigation water applied compared to the time-based treatments, even when an operative rain sensor was an important component on two of the three time-based treatments. Moreover, 72% of the water applied by 2-WORS was saved on average by the SMS-based treatments.

3.2.3 Comparisons between SMS-irrigation frequencies

When the averages of the three different SMS irrigation-frequencies were analyzed (Table 3-1, Comparison C), the 2 d/w frequency applied significantly ($P<0.0001$) more water, followed by the 1 d/w frequency, with 478 and 420 mm of total cumulative water depth, respectively. Although a wide range of variation was apparent across the sensor brands, the 7 d/w frequency resulted in a significantly lower depth applied of all three frequencies, with an average of 362 mm, because two of four 7 d/w treatments (7-AC and 7-RB) bypassed more scheduled irrigation events due to frequent rainfall (Figures 3-1 and 3-2).

3.2.4 Water savings

Table 3-1 shows the water savings (%) of each treatment compared to the time-based treatments 2-DWRS, 2-WRS, and 2-WORS. Treatments 7-AC and 7-RB achieved the highest amount of water savings throughout this experiment and, as expected, 2-WORS applied more water than all the other treatments. On the other hand, the IMs always allowed more water to be applied compared to the other brands in every frequency tested. This could be due to their reported limitations to timely sense differences in soil water content, their hysteretic behavior, their high variability of readings, and their limitations in sandy soils, where low tension values are necessary to prevent plant stress (Irmak and Haman 2001; Taber et al., 2002: Intrigliolo and Castel, 2004; McCann et al., 1992).

When compared to the water conservative 2-DWRS treatment, brands AC, RB and WW showed water savings that ranged from 44% to 80%, 55% to 76%, and 26% to 57%, respectively, depending on the irrigation frequency. On the other hand, all IM-frequencies applied more irrigation than 2-DWRS, with values that ranged from 15% to 77% more water.

Treatment 2-IM was the only SMS-based treatment that applied more water than the time-based 2-WRS (11%). Conversely, 1-IM and 7-IM reduced water application 20% and 28%, respectively, compared to 2-WRS. However, these last proportions were far from the water savings achieved by the other SMS-based treatments, when compared to 2-WRS: AC sensors recorded irrigation water savings ranging from 65% to 88%, RBs from 72% to 85%, and WWs from 54% to 73%. It is important to remark that these water savings were on top of those already achieved by 2-WRS. Therefore, these results show that, in general, SMSs can also act as rain shut-off devices, although with a superior performance than rain sensors in terms of water savings.

When the controllers were compared to a 2 d/wk irrigation schedule without a rain sensor (2-WORS), the difference in water savings increased, ranging from 77% to 92% for ACs (the range of savings is across the days of the week of allowed irrigation), 81% to 90% for RBs, 69% to 82% for WWs, and 27% to 53% for IMs. Even 2-IM (which applied 11% more water than 2-WRS) showed water savings (27%) with respect to 2-WORS, indicating that this sensor was operative but did not bypass as many scheduled irrigation cycles as other SMS-based treatments. Whitcomb (2005) has reported that more than 75% of the surveyed homeowners in Florida lacked a functional rain sensor, thus savings with respect to 2-WORS could be considered representative of many homes in Florida.

3.3 Irrigation Application during 2006

The cumulative irrigation allowed through time in this period by the time-based treatments is shown in Figure 3-7, and by the SMS-based treatments is shown in Figures 3-8 to 3-10. All of these treatments are compared to the control treatment (2-WORS), which applied a total of 659 mm. A summary of the cumulative irrigation depth applied to treatments, as well as statistical comparisons and percent water savings compared to 2-DWRS, 2-WRS, and 2-WORS, are presented in Table 3-2.

3.3.1 Time-based treatments

In general, 2-WORS always applied more water than the rest of the treatments (659 mm), because it was programmed to allow every single scheduled irrigation cycle, independently of the weather and/or soil moisture conditions, and was significantly different ($P<0.0001$) than the other time-based treatments. The treatment that included a rain sensor (2-WRS) applied a total of 500 mm, equivalent to 24% of water savings compared to the control treatment. In 2004 and 2005, this amount was higher (34%). However, it should be remembered that 2006 was a dry year (compared to 2004 and 2005) and, during this specific time period, more than a whole month (from 15 September to 26 October), almost no rain fell (Figure 3-5), even when frequent rainfall is common (Figure 3-6). The other time-based treatment, 2-DWRS (set to apply 60% of 2-WRS), was incorrectly programmed until the end of September. After that, this situation was rectified and it continued to apply the proper amount of water for a cumulative total savings of 34%.

3.3.2 Time-based treatments vs. SMS-based treatments

Consistent with previous years, the time-based treatments applied significantly ($P<0.0001$) more water than the SMS-based treatments, averaging 532 versus 303 mm, respectively (Table 3-2). This means that the average of the SMS-based treatments saved 54% of the water applied by 2-WORS, even during relatively dry weather conditions.

3.3.3 Comparisons between SMS-irrigation frequencies

When comparing the three SMS irrigation-frequencies tested (Table 3-2), all of them were significantly different (P<0.0001), with the 1 d/w frequency applying the most water (378 mm), followed by 2 d/w and then by 7 d/w, with 296 and 234 mm, respectively. This trend appears to be due to the dry weather conditions, and because a higher frequency of irrigation windows leads to a greater probability that rainfall will be utilized for plant needs. Also, the higher frequency irrigation schedules had lower amounts applied for a given irrigation event. Compared to 2004 and 2005, the 7 d/w irrigation frequency again resulted in the least irrigation.

3.3.4 Water savings

Considering the SMS-based treatments, some issues should be addressed before a detailed analysis. The three WW systems tested presented malfunctioning problems. The 7-WW system allowed almost every scheduled irrigation cycle to occur, applying practically the same amount of water as the control treatment (Figure 3-10). The same thing happened with 1-WW until 10 October, when the unit failed for unknown reasons and no more water was applied by this treatment (Figure 3-8). In the case of 2-WW, the broken probe was replaced by mid October, but did not begin to work properly until the end of that month (Figure 3-9). For these reasons, WW results were not considered for the statistical analyses (Table 3-2). It should be noted that this malfunctioning is consistent with previous behavior of these SMS systems. Throughout this experiment, two other probes and one controller from this brand failed and needed to be replaced. Note that this brand is no longer commercially available.

Considering the RB treatments (the other discontinued system), 1-RB applied a greater amount of water than the other frequencies, 474 mm, or 28% in water savings. The other two frequencies tested, 2-RB and 7-RB, applied a similar total amount of irrigation, 122 and 140 mm, respectively. These two last frequencies represent water savings of 81% and 79%, respectively, a slightly lesser amount than those recorded during the wetter weather conditions of 2004 and 2005, respectively 88% and 90%.

The IM treatments applied more water than the other brands, in every irrigation frequency tested. This is consistent with years 2004 and 2005, even when their controllers were set at position #2, instead of #1, which should have kept the lawn on a dryer condition[1]. The 2-IM treatment applied almost the same amount of water than 2-WORS, with water savings of just 9%, which are lower than those obtained with the rain sensor (24%). The other two frequencies tested, 1-IM and 7-IM, applied 484 and 448 mm, respectively, a respective savings of 27% and 32%. During 2004 and 2005, these water savings were higher, 48% and 53% for 1-IM and 7-IM, respectively. Again, this is consistent with the different weather conditions of both periods compared.

Finally, all the Acclima systems behaved similarly with respect to the total amount of water that they allowed to be applied during this testing period. Treatments 1-AC, 2-AC, and 7-AC applied 177, 166, and 114 mm, respectively, which represent water savings of 73%, 75%, and 83%, compared to the control treatment, respectively. These results are similar but lower to those obtained by the Acclima systems during the wetter 2004 and 2005 periods, when they recorded waters savings of 81%, 77%, and 92%, also respectively.

[1] The threshold for the IMs was set up at #6 for short periods to verify that the systems were functional.

In summary, from 22 July through 10 December of 2006, dry weather conditions prevailed which resulted in soil moisture sensors bypassing less scheduled irrigation cycles and saving a smaller amount of water compared to data from 2004 and 2005. Despite the dry conditions, all the properly working SMS-based treatments applied less water than the time-based treatment used for comparison (without sensor feedback), ranging from 9 to 83% water savings. Moreover, except for treatment 2-IM, all SMS-based treatments also saved more water compared to the treatment with a rain sensor (2-WRS). These results were consistent with those obtained during the previous wetter years and clearly demonstrate that the use of SMSs (along with traditional time clocks in residential irrigation systems) could lead to important water savings; more than twice as much as a rain sensor device alone.

3.4 Turfgrass Quality

Throughout the 2004 and 2005 periods, no differences in turfgrass quality were detected among treatments, including non-irrigated plots, and always exceeded the minimum acceptable rating of 5 (Table 3-3 and Figure 3-11). This result is explained in part by the generally wet weather conditions that prevailed through most of the experiment, which favored the growth and development of the bermudagrass (Figures 3-1 and 3-2). Another factor contributing to the good turf quality observed, even during the short dry periods, could be found in the species itself. Common bermudagrass is known as a more drought-tolerant grass compared to the pervasive St. Augustinegrass [Stenotaphrum secundatum (Walt.) Kuntze] found in North-Central Florida landscapes (Harivandi et al., 2001; Baldwin et al., 2006; Turgeon, 2005). As a result, the treatment effects were buffered with respect to the turfgrass quality parameters, and it could be concluded that irrigation was not necessary to maintain acceptable turf quality throughout this experimental time-period. Jordan et al. (2003) obtained similar results working with bentgrass, when frequent rainfall coupled with high relative humidity conditions overrode the effects of the irrigation frequency treatments on turf quality.

During 2006, stress and decline in turfgrass quality was detected in some SMS-based plots in the dry episode that occurred from 15 September through 26 October. Figure 3-12 shows the relationship between the amount of water applied and the resultant turfgrass quality during this period, averaged by treatment, where a linear regression of R^2= 0.85 was obtained. The trend of this regression is that the lesser amount of water applied, the lower the turfgrass quality obtained. Three treatments resulted in turfgrass quality below the minimum acceptable level (#5), where two of these were expected. One was the non-irrigated treatment (0-NI), and the other one was 2-WW (treatment with the broken probe, which did not begin to apply water until this dry period was over). The other treatment below the minimum acceptable level was 2-RB, which did not apply water until 4 October.

Table 3-4 shows statistical comparisons between treatments for the resultant turfgrass quality on 26 October 2006 ($P<0.05$). The control treatment for quality purposes (0-NI) resulted in a lower quality when compared to time-based and SMS-based treatments (Comparison A) meaning that, contrary to 2004 and 2005, irrigation was necessary to maintain an acceptable turf quality. The time-based treatments resulted in a better turf quality than the SMS-based treatments (Comparison B), although all of them resulted in acceptable quality. No differences between the time-based treatments were detected (Comparison C), with average quality ratings that ranged between 6.3 and 7.0. Differences in the irrigation frequency on the SMS-based treatments were found (Comparison D), where the average of the 2 d/w resulted in a lower turf quality than the other frequencies. However, these results were influenced by the previously mentioned issues with treatments 2-WW and 2-RB. If these treatments were not included in the statistical analysis, no differences on turf quality were found between irrigation frequencies. Finally, statistical differences were found between all treatments and between SMS-based treatments (Comparisons E and F, respectively). The lowest qualities were found on 0-NI and 2-WW, and then on 2-RB, as a result of the low amount of water applied to these treatments (Figure 3-12). Treatment 7-RB was just in the level of the minimum acceptable turf quality and a similar situation happened with all the Acclima systems, with turf quality between 5 and 5.5. Considering these results, the set points and/or the run times for these systems (mainly for the 2 and 7 d/w irrigation frequencies) were possibly at the limit for dry weather conditions. In the case of the Irrometer and the Water Watcher systems, which allowed more irrigation water than the other brands, a higher turfgrass quality (6.0 to 7.5) was observed, even when no statistical differences were found between brands ($P>0.90$). Figures 3-13 through 3-18 show pictures of different turfgrass quality rating examples used in this study, and Figure 3-19 shows a general view of the experimental site, where plots with different turfgrass qualities can be seen.

3.5 Automation of Irrigation Systems

Complete automation of a residential irrigation system, based on SMSs, could be achieved by programming the time clock to run every day as a scheduling strategy. Then, SMSs will allow the system to initiate the scheduled irrigation cycles only when needed by the turfgrass (or other irrigated plant type), and override cycles when the sensed water content is over a pre-set threshold. During wet weather conditions, this type of control was confirmed when the 7 d/w irrigation frequency applied significantly less water than the other frequencies (Table 3-1, Comparison C), and when two of the SMS-based treatments, programmed to run 7 d/w, consistently applied the smallest amount of water. In effect, treatments 7-AC and 7-RB recorded total water savings of 85% or more, when compared to 2-WRS and 90% or more when compared to 2-WORS. Even during the dry weather conditions of 2006, these treatments resulted in water savings of 79% or more (Figure 3-10, Table 3-2), while maintaining acceptable turfgrass qualities (Tables 3-3 and 3-4). (Note that 2-RB was not working properly at the beginning of this experiment.)

This concept (with a potential irrigation frequency of seven days a week) seems contradictory to the water use regulations and restrictions imposed by the Water Management Districts and/or municipalities in Florida (where irrigation is allowed only one or two days per week). However, these results suggest that setting the correct threshold, and programming the automatic irrigation system to run every day for the proper amount of time (allowing the SMS to decide whether to irrigate), could save large amounts of water, and may be a more effective water conservation strategy than day-of-the-week watering windows. Moreover, this concept is not in opposition to the general recommendation for deeper and less frequent irrigation for turfgrass, because these treatments (7-AC and 7-RB) overrode almost every scheduled irrigation cycle, resulting in a low actual irrigation frequency, which was supplemented by large and/or frequent rainfall events that filled the profile (Figures 3-1, 3-2, and 3-5). Under current day of the week water restrictions, enforcement of this technology would be difficult if random sites were fitted with controllers. The recommended approach would be installation of SMS controllers on homes within a defined boundary (i.e. subdivision) where water use can be tracked to verify the effectiveness of the controllers at water conservation relative to homes without controllers in the region.

Table 3-1. Total cumulative irrigation depth applied to treatments, statistical comparisons, and percent water savings compared to 2-DWRS, 2-WRS, and 2-WORS, years 2004 and 2005.

Treatment	Cumulative depth (mm)	Comparisons[a]			Water savings (%) vs.		
		A	B	***C***	2-DWRS	2-WRS	2-WORS
Time-Based							
2-WORS	1514	***a***			-143	-52	0
2-WRS	995	***b***			-60	0	34
2-DWRS	623	***c***			0	37	59
Time-Avg	**1044**		a				
SMS-Based							
1-AC	283				55	72	81
1-RB	281				55	72	81
1-IM	793				-27	20	48
1-WW	323				48	68	79
1-Avg	**420**			***b***			
2-AC	348				44	65	77
2-RB	188				70	81	88
2-IM	1105				-77	-11	27
2-WW	270				57	73	82
2-Avg	**478**			***a***			
7-AC	122				80	88	92
7-RB	147				76	85	90
7-IM	715				-15	28	53
7-WW	463				26	54	69
7-Avg	**362**			***c***			
SMS-Avg	**420**		b				**72**

SMS = Soil moisture sensor
Avg = Average
[a]A = Between time-based treatments
B = Time-based treatments vs. SMS-based treatments
C = Between irrigation frequency averages

Different letters within a column indicate statistical difference at P<0.05 (Duncan's Multiple Range Test).

Table 3-2. Total cumulative irrigation depth applied to treatments, statistical comparisons, and percent water savings compared to 2-DWRS, 2-WRS, and 2-WORS, from 22 July through 10 December 2006.

Treatment	Cumulative depth (mm)	Comparisons[a]			Water savings (%) vs.		
		A	B	***C***	2-DWRS	2-WRS	2-WORS
Time-Based							
2-WORS	659	***a***			-51	-32	0
2-WRS	500	***b***			-14	0	24
2-DWRS	437	***b***			0	13	34
Time-Avg	**532**		a				
SMS-Based							
1-AC	177				59	65	73
1-RB	474				-8	5	28
1-IM	484				-11	3	27
1-WW	N/A				N/A	N/A	N/A
1-Avg	**378**			***a***			
2-AC	166				62	67	75
2-RB	122				72	76	81
2-IM	600				-37	-20	9
2-WW	N/A				N/A	N/A	N/A
2-Avg	**296**			***b***			
7-AC	114				74	77	83
7-RB	140				68	72	79
7-IM	448				-3	10	32
7-WW	N/A				N/A	N/A	N/A
7-Avg	**234**			***c***			
SMS-Avg	**303**		b				**54**

N/A = SMS units presented malfunctioning problems to an extent that they were not considered for the statistical analyses
SMS = Soil moisture sensor
Avg = Average
[a]A = Between time-based treatments
B = Time-based treatments vs. SMS-based treatments
C = Between irrigation frequency averages

Different letters within a column indicate statistical difference at $P<0.05$ (Duncan's Multiple Range Test).

Table 3-3. Turfgrass quality ratings per treatment during 2004 and 2005.

Treatment	May-04*	Jul-04*	Oct-04*	Dec-04*	May-05*	Jul-05*
Time-Based						
2-WORS	7.3	8.5	6.8	6.3	6.0	7.5
2-WRS	8.5	8.8	7.0	6.5	6.8	7.3
2-DWRS	7.5	8.0	7.0	6.5	6.8	6.8
Time-Avg	**7.8**	**8.4**	**6.9**	**6.4**	**6.5**	**7.2**
SMS-Based						
1-AC	8.0	8.8	6.5	5.5	6.5	7.5
1-RB	6.5	7.3	5.8	6.0	5.5	6.0
1-IM	7.0	8.5	6.3	6.0	5.5	5.5
1-WW	8.5	8.3	7.0	6.3	6.5	5.8
1-Avg	**7.5**	**8.2**	**6.4**	**5.9**	**6.0**	**6.2**
2-AC	6.5	7.5	6.3	5.8	6.5	5.8
2-RB	8.0	7.3	6.3	5.8	5.3	5.5
2-IM	7.0	8.3	6.3	5.8	5.0	6.3
2-WW	8.3	8.5	7.0	6.0	5.8	6.0
2-Avg	**7.4**	**7.9**	**6.4**	**5.8**	**5.6**	**5.9**
7-AC	7.3	8.5	5.8	5.3	5.0	5.8
7-RB	8.3	8.5	7.3	6.8	6.5	7.3
7-IM	7.8	8.8	7.3	6.8	6.0	7.0
7-WW	8.5	8.0	7.0	6.0	5.3	5.5
7-Avg	**7.9**	**8.4**	**6.8**	**6.2**	**5.7**	**6.4**
SMS-Avg	**7.6**	**8.2**	**6.5**	**6.0**	**5.8**	**6.1**
Control						
0-NI	8.3	8.3	6.0	5.3	5.5	6.3

* = No statistical difference at P>0.90.

Table 3-4. Turfgrass quality ratings per treatment on 26 October 2006.

Treatment	Rating (#)	Comparisons[a] *A*	B	*C*	D	*E*	F
Time-Based							
2-WORS	7.0			***NS***			ab
2-WRS	6.3			***NS***			bc
2-DWRS	6.5			***NS***			abc
Time-Avg	**6.6**	***a***	a				
SMS-Based							
1-AC	5.5					***cd***	cd
1-RB	6.8					***ab***	ab
1-IM	6.0					***bcd***	bcd
1-WW	6.0					***bcd***	bcd
1-Avg	**6.1**				a		
2-AC	5.5					***cd***	cd
2-RB	4.0					***ef***	ef
2-IM	6.8					***ab***	ab
2-WW	3.3					***f***	f
2-Avg	**4.9**				b		
7-AC	5.0					***de***	de
7-RB	5.0					***de***	de
7-IM	6.5					***abc***	abc
7-WW	7.5					***a***	a
7-Avg	**6.0**				a		
SMS-Avg	**5.6**	***a***	b				
Control							
0-NI	3.3	***b***					f
CV (%)		22	22	22	15	13	14

SMS = Soil moisture sensor
Avg = Average
NS = No statistical difference at P>0.90
[a]A = Time-based vs. SMS-based vs. Non-irrigated treatments
B = Time-based vs. SMS-based treatments
C = Between irrigation frequency averages
D = Between time-based treatments
E = Between SMS-based treatments
F = Between all treatments

Different letters within a column indicate statistical difference at P<0.05 (Duncan's Multiple Range Test).

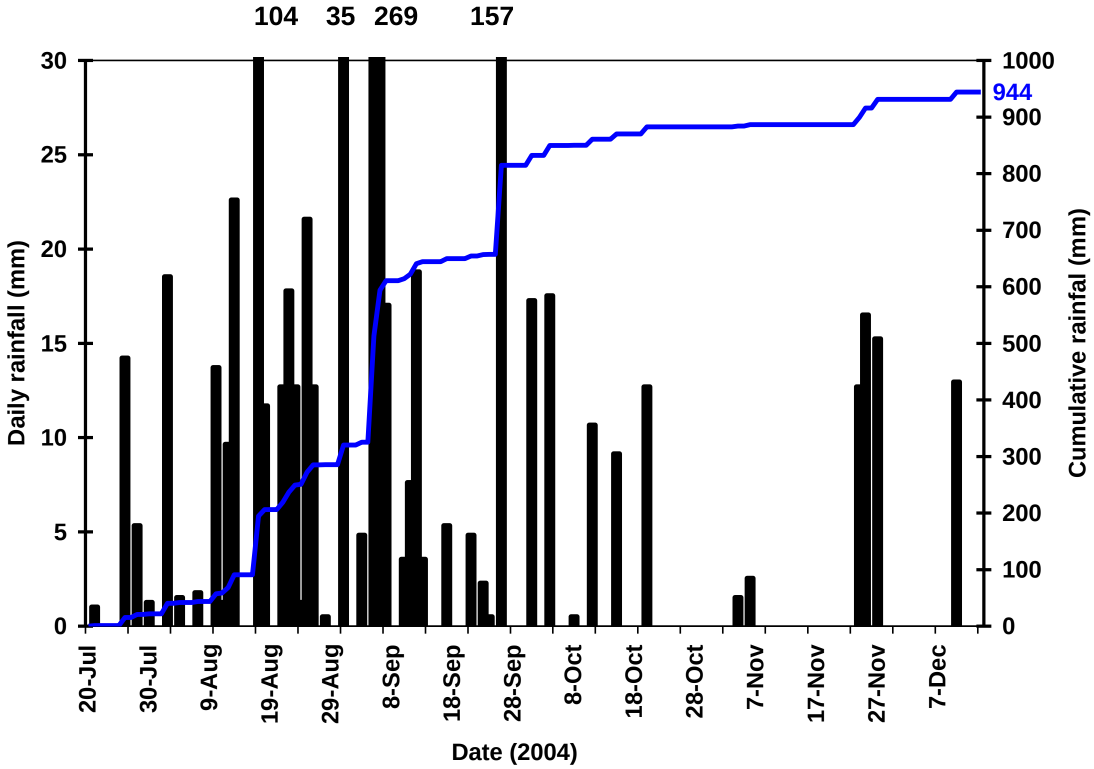

Figure 3-1. Daily and cumulative rainfall in 2004. Note: rainfall for 5 Sep. (188 mm) and 6 Sep. (81 mm) is shown as a cumulative total (269 mm).

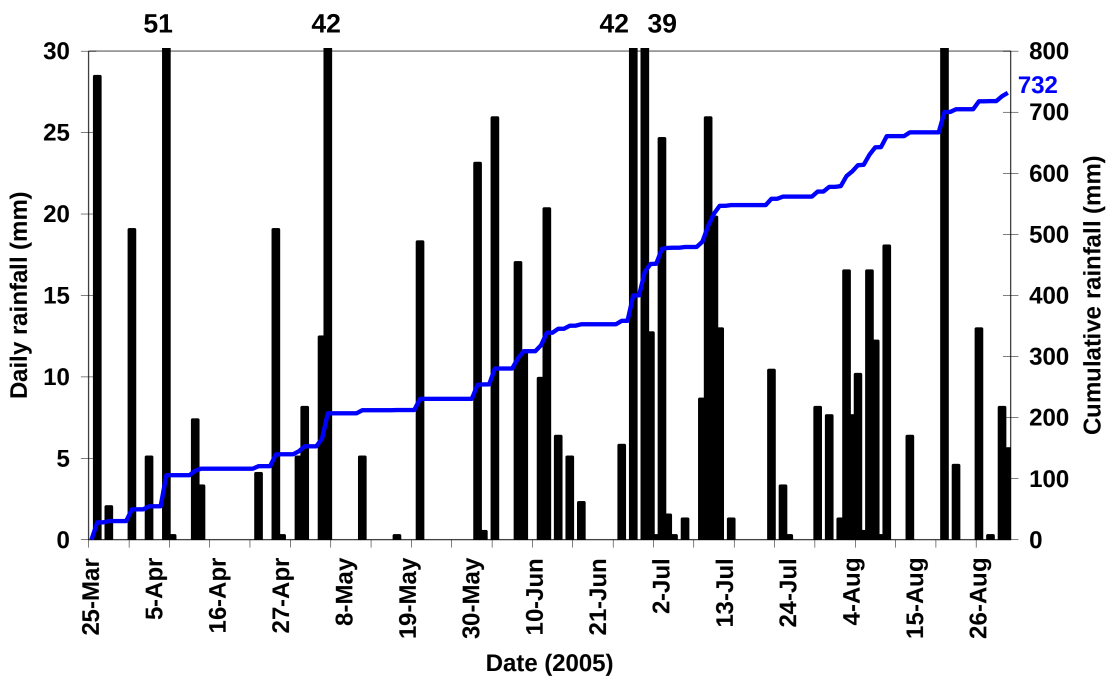

Figure 3-2. Daily and cumulative rainfall in 2005.

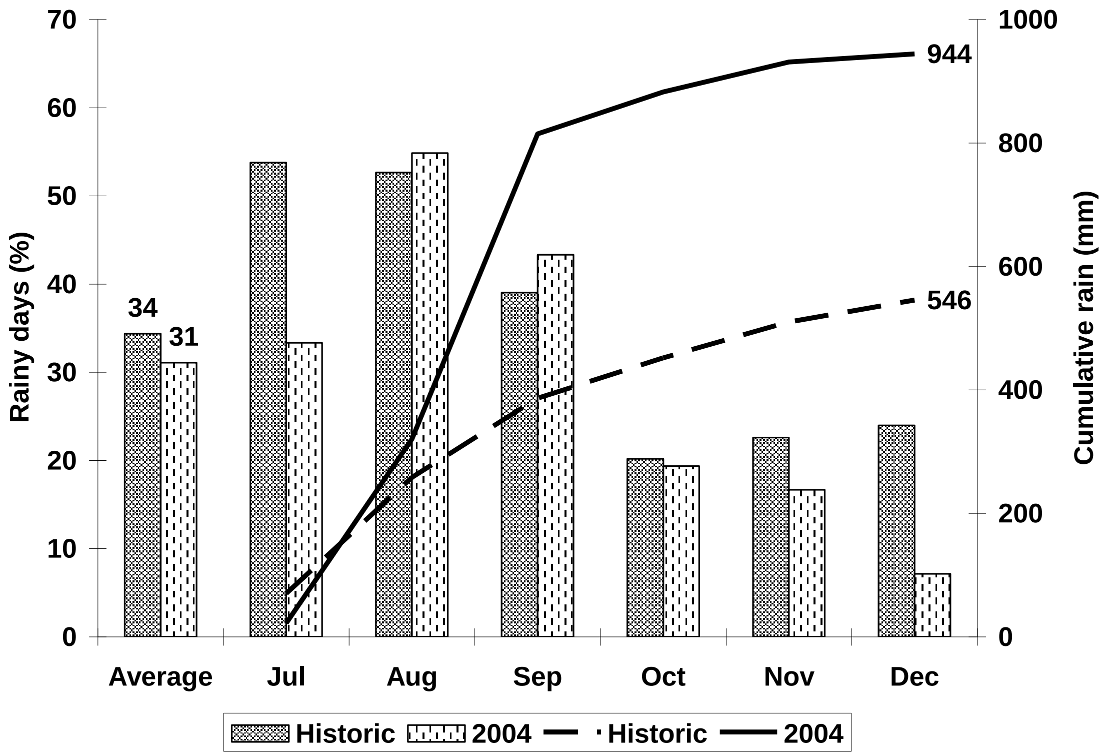

Figure 3-3. Rainy days per month and cumulative rainfall 2004 compared to historic values.

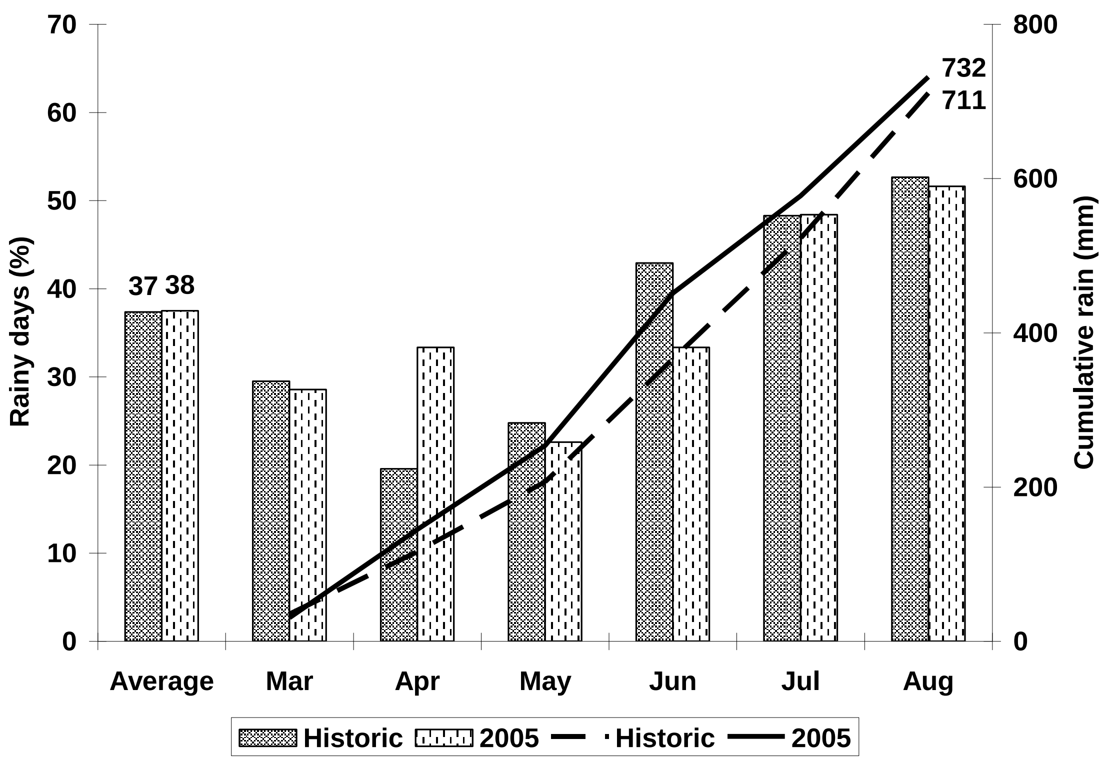

Figure 3-4. Rainy days per month and cumulative rainfall 2005 compared to historic values.

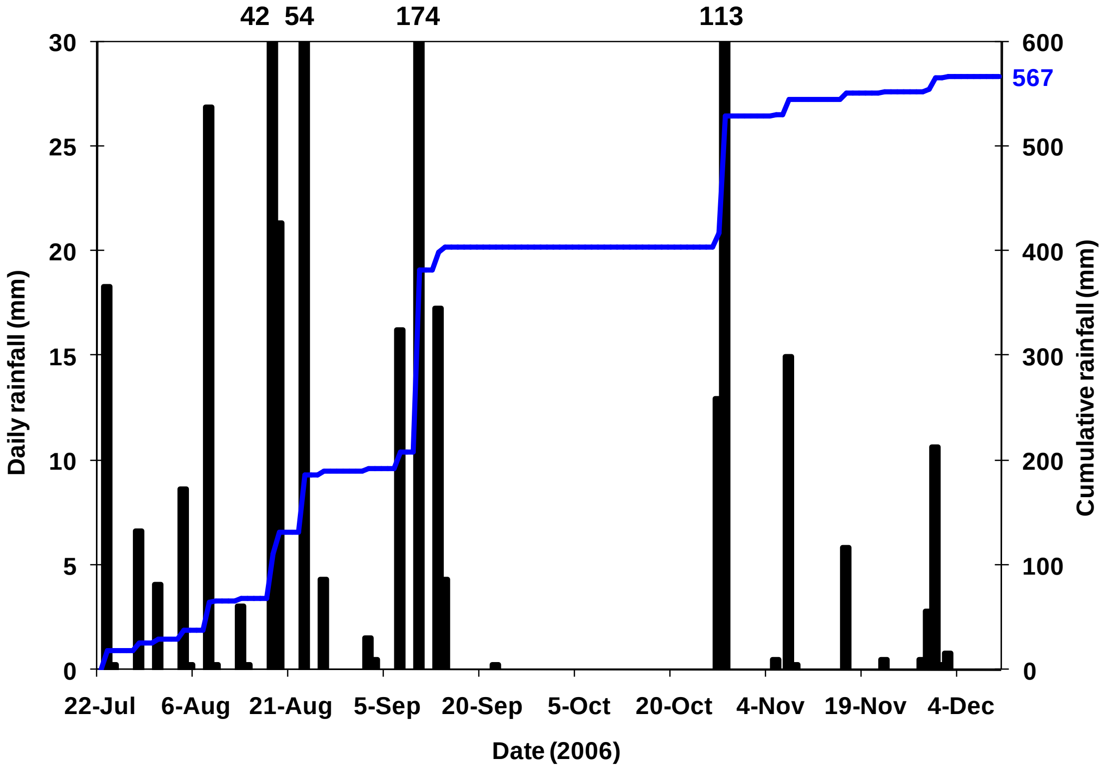

Figure 3-5. Daily and cumulative rainfall, 22 July through 10 December 2006.

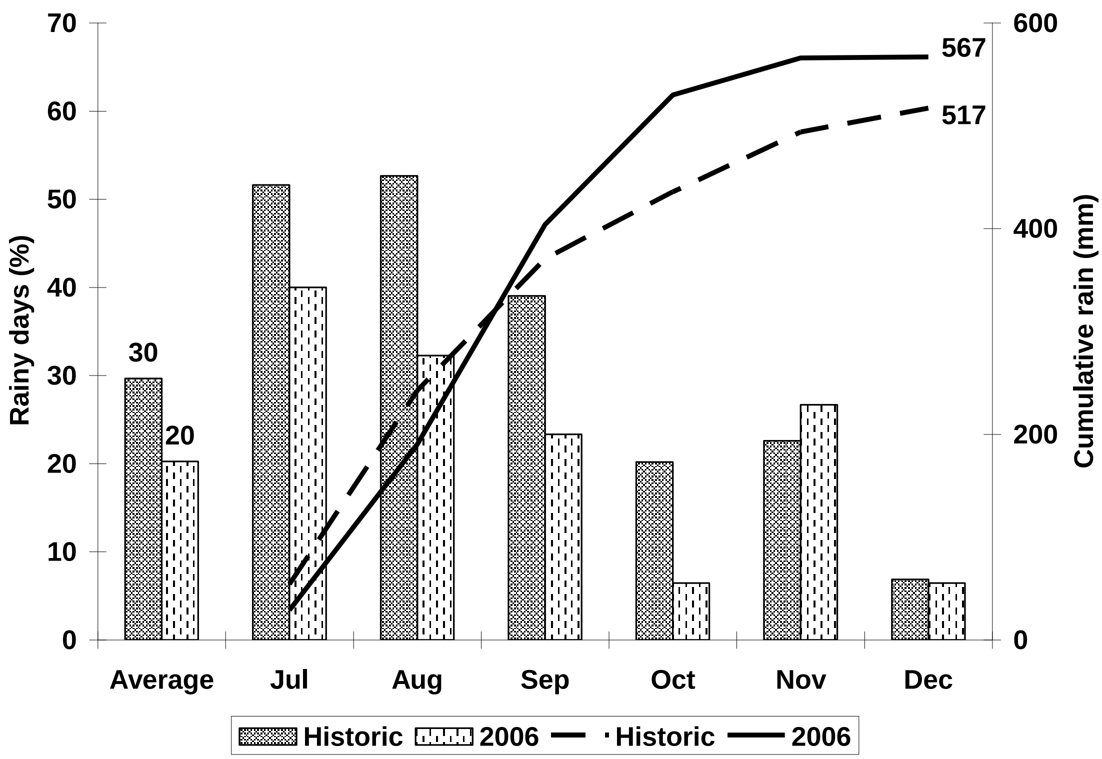

Figure 3-6. Rainy days per month and cumulative rainfall; 22 July through 10 December 2006 versus historic values.

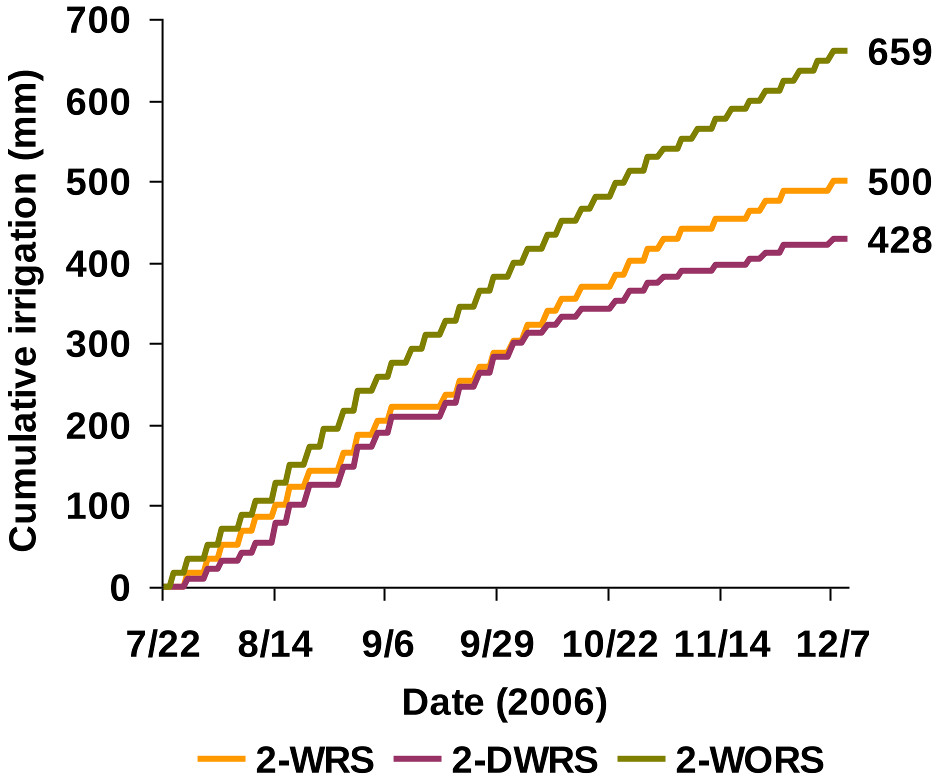

Figure 3-7. Cumulative irrigation applied to time-based treatments from 22 July through 10 December 2006. Note 2-DWRS (set to apply 60% of 2-WRS), was incorrectly programmed until the end of September, when this situation was rectified.

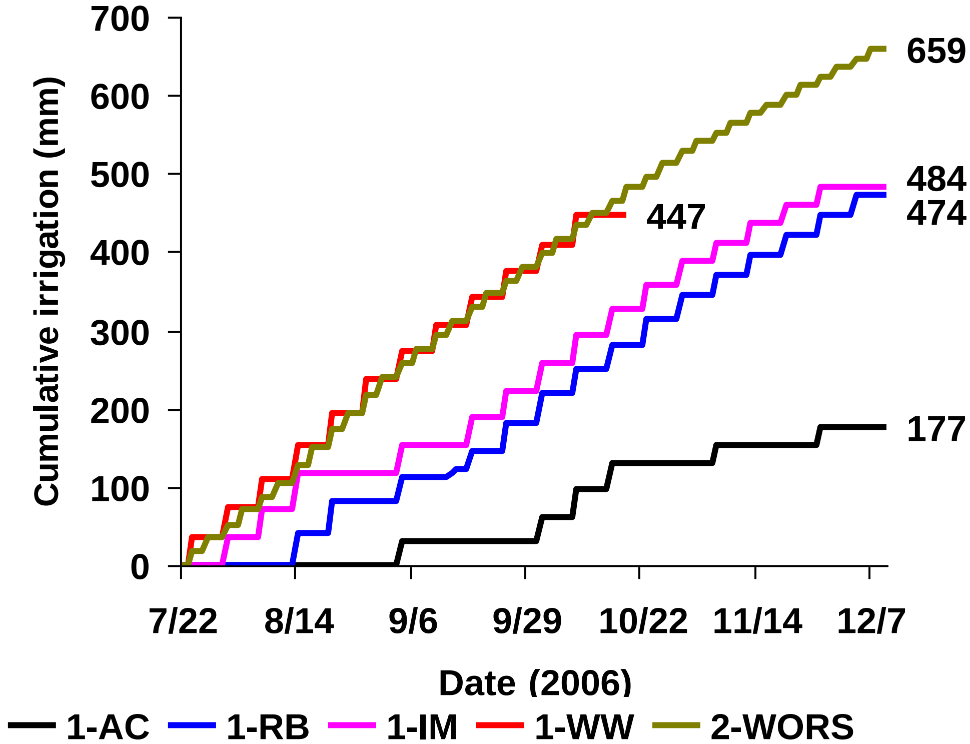

Figure 3-8. Cumulative irrigation applied to SMS-based treatments from 22 July through 10 December 2006. One day per week irrigation frequency. Note: 1-WW sensor broke on 10 October for unknown reasons and was not replaced.

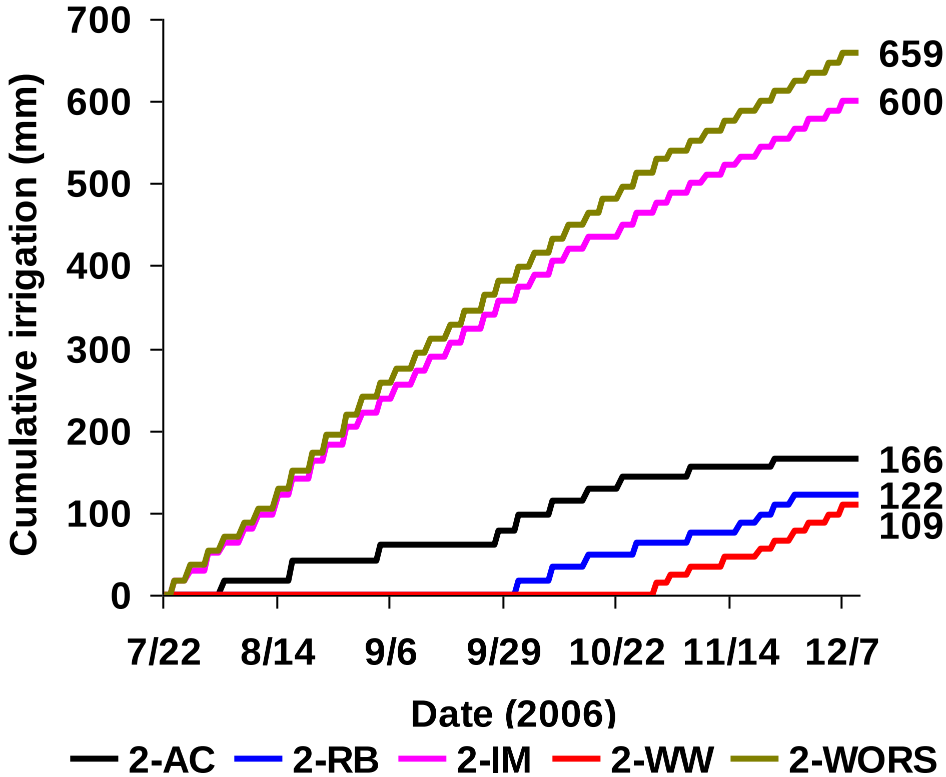

Figure 3-9. Cumulative irrigation applied to SMS-based treatments from 22 July through 10 December 2006. Two days per week irrigation frequency. Note: 2-WW was not working and was replaced by mid October, but did not begin to work properly until the end of that month.

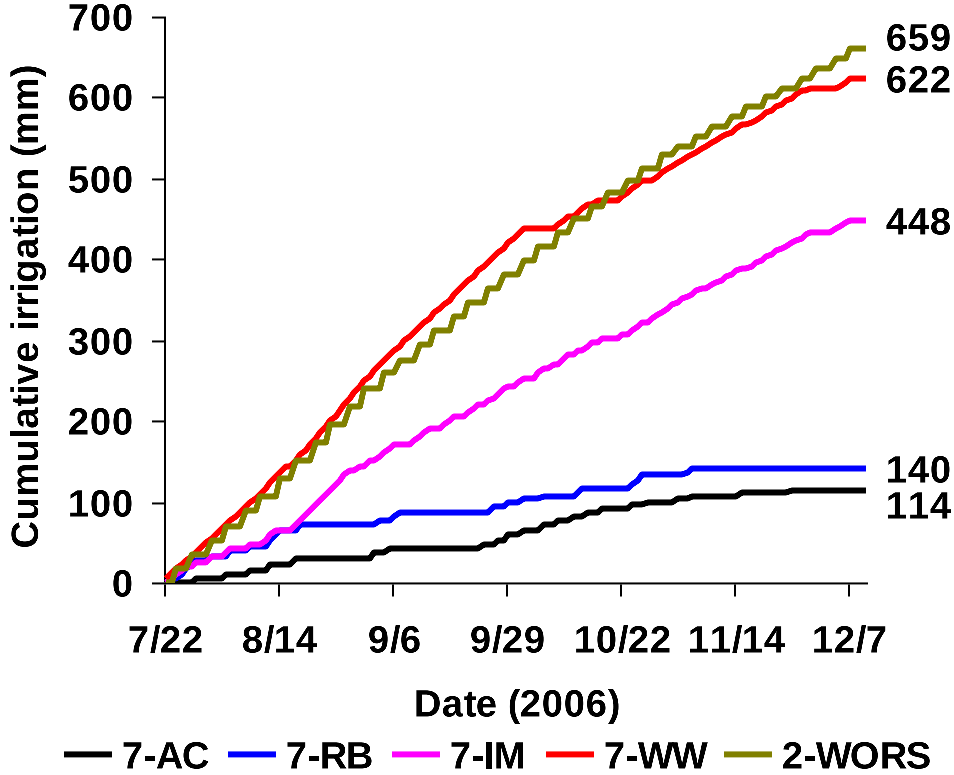

Figure 3-10. Cumulative irrigation applied to SMS-based treatments from 22 July through 10 December 2006. Three days per week irrigation frequency. Note: 7-WW presented malfunctioning problems during the whole experiment.

Figure 3-11. View of different plots where no evident turfgrass quality differences could be detected; A) actively growing, B) dormant.

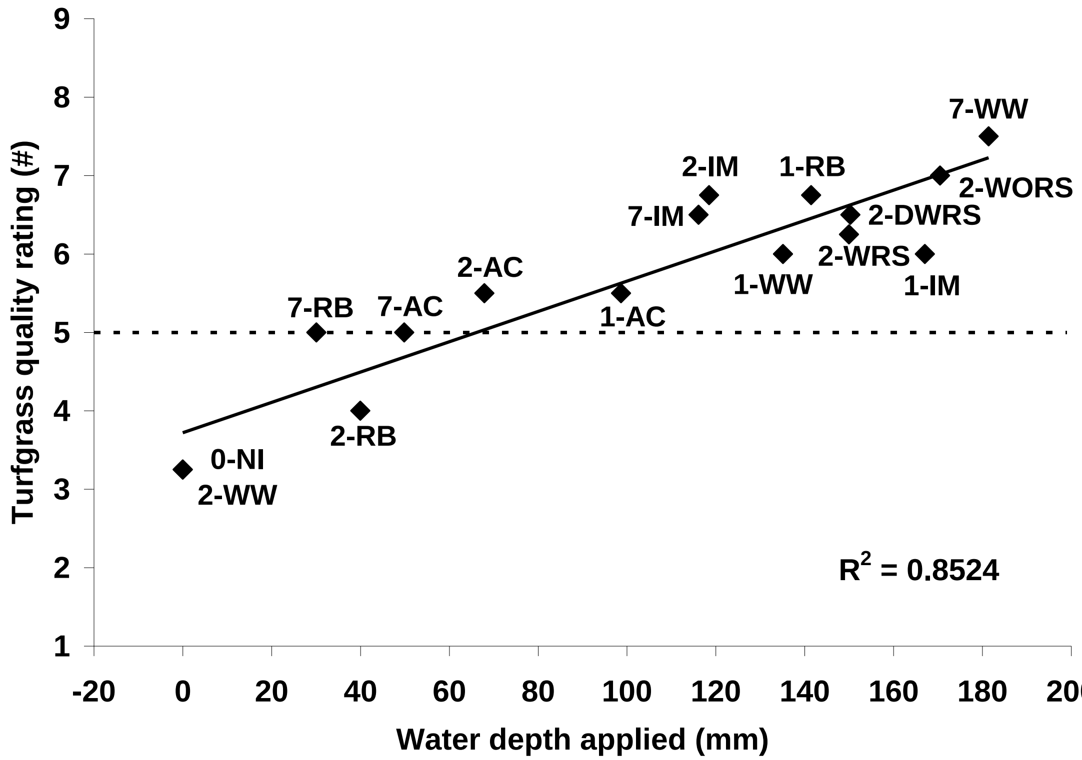

Figure 3-12. Relationship between water depth applied and turfgrass quality, averaged by treatments, during 15 September through 26 October 2006. All treatments above the dotted line resulted in acceptable turfgrass quality, and vice versa.

Figure 3-13. Turfgrass quality rated as #2

Figure 3-14. Turfgrass quality rated as #3

Figure 3-15. Turfgrass quality rated as #4

Figure 3-16. Turfgrass quality rated as #5

Figure 3-17. Turfgrass quality rated as #6

Figure 3-18. Turfgrass quality rated as #7

Figure 3-19. General view of the experimental site. Lighter plots show drought stress.

4 SMS SYSTEMS PERFORMANCE RESULTS (FIRST HALF OF 2006)

After the winter dormancy of the bermudagrass in 2005, a variation of the original experiment was carried out from 25 March through 15 July 2006. In the original experiment, three units of soil moisture sensors from brands AC, RB, IM, and WW were scheduled to run with three different irrigation frequencies (1, 2, or 7 d/w). During the spring of 2006, all of them were set at a 2 d/w irrigation frequency (Mondays and Thursdays). Controller thresholds were kept unchanged, except for the IM units that were set at #2 (set at #1 in all previous testing). The control treatment, set to run independently of the weather conditions (2-WORS [without rain sensor)], and the treatment with a rain sensor (2-WRS), were scheduled identically to the other treatments (Table 2-4). The objectives of this experiment were to analyze the behavior consistency of the three units within a brand to control irrigation, and to compare the different brands against each other.

4.1 Environmental Conditions

Figure 4-1 shows the daily and cumulative rainfall for this experimental period, and Figure 4-2 compares these values to a normal year. During the 123-day experiment, 18% of the days exhibited rainfall compared to a normal of 35%, and the cumulative precipitation was 322 mm, which represents a 38% of deficit rainfall. Moreover, 77% of this amount (247 mm) fell in only 5 rain events (4% of the total days). Therefore, it can be considered that this was a relatively dry period, and it could be expected that the SMSs would have bypassed a lower number of scheduled irrigation cycles than years 2004 and 2005.

4.2 Irrigation application

Figure 4-3 compares the cumulative irrigation applied by the time-based treatments. Results show that when a rain sensor was connected to the irrigation system, the volume of water applied decreased from 602 to 525 mm (2-WORS vs. 2-WRS, respectively). However, this reduction was only 13%, compared to 34% reported for 2004 and 2005. Again, these results were clearly influenced by the rainfall conditions. Moreover, except for IM, the different SMS brands saved more water compared to the treatment with rain sensor. The 2-DWRS treatment resulted in 21% less water applied.

Figures 4-4 to 4-7 show the cumulative irrigation allowed by the different units from the four brands tested. All of them are also compared to the control treatment (2-WORS), which applied a total of 602 mm. Even when this was a relatively dry period, it can be seen that, with the exception of 1-IM, which applied 630 mm (Figure 4-6), all units and brands applied less water than the control treatment, ranging from 201 to 552 mm. The 2-WW unit failed for unknown reasons (Figure 4-6), and is not considered in the remaining discussion for this experimental section.

The brands that allowed the least irrigation were AC and RB, with 279 and 266 mm on average, respectively. On the contrary, the brands that allowed more irrigation were IM and WW, with averages of 552 and 505 mm, respectively. The irrigation savings compared to 2-WORS averaged 54%, 56%, 8%, and 16%, for AC, RB, IM, and WW, respectively. The lower irrigation savings compared to previous results (27% - 92%) were due to the dry weather conditions in the spring (Figure 4-1) and it is remarkable that there were still irrigation savings during this dry period.

4.3 Turfgrass Quality

Figure 4-8 shows the relationship between the amount of water applied and the resultant turfgrass quality during this period, averaged by treatment, with a linear regression of R^2= 0.89. Congruent with results from the end of 2006, the trend of this regression is that the lesser amount of water applied, the lower the turfgrass quality obtained. Table 4-1 shows statistical comparisons between treatments for the resultant turfgrass quality on 15 July 2006 ($P<0.05$). For these analyses, the broken 2-WW was considered as a separate treatment. The turf qualities from 0-NI and 2-WW treatments declined to unacceptable levels, and were statistically different from the time-based and the SMS-based treatments, which remained above the minimum quality ratings (Comparison A). Significant differences were not found between the average of the time-based and the SMS-based treatments (Comparison B), neither between the time-based treatments (Comparison C). Although turf quality did vary across treatments (Comparison D), all SMS treatments resulted in average quality that was at least acceptable (rated as #5 or above) over this monitoring period. It is important to note that, similar to previously mentioned results from the end of 2006, some SMS-based repetitions were just in the acceptable quality level or slightly above--as was the case of some AC and RB repetitions-- suggesting that these thresholds/run times were precisely in the limit to maintain acceptable quality during dry weather conditions. Since bermudagrass is considered drought tolerant, the results may have varied if the more common lawn grass and less drought tolerant, St. Augustinegrass, were used. However, on cooperating homes with SMS controllers and St. Augustinegrass (Phase II of this project; data not shown here), acceptable quality has been maintained with St. Augustinegrass lawns on cooperating homes.

4.4 SMS systems performance

Throughout this experiment (again, with the exception of the broken 2-WW), the different units within a brand tended to behave in the same way through time, and with similar cumulative amounts of water applied by the end of the data collection period (Figures 4-4 through 4-7). This was particularly true for brands RB and WW as demonstrated when an ANOVA was carried out ($P<0.05$), indicating consistent performance (Table 4-2). A comparable situation occurred within the AC units, when they behaved similarly through time, but two of them were statistically similar and one was different regarding the total amount of water applied. The IR repetitions, however, were all significantly different, showing variability between the different units. This performance is consistent with what has been reported for IR units in coarse textured soils, where a hysteretic behavior (Thompson et al., 2006) and high variability of readings between units has been found (Taber et al., 2002; Intrigliolo and Castel, 2004), and when is suggested that individual sensors should be calibrated for accurate readings (Egbert et al., 1992; Leib et al., 2003).

In spite of this individual behavior, the average of the brands that allowed the least amount of irrigation were AC and RB (which were not significantly different), compared to WW and IM (Figure 4-9), which allowed more water to be applied. The inverse tendency was reflected in the turfgrass quality that resulted from these water applications (Table 4-1, Comparison E), where AC and RB resulted in a significantly lower turfgrass quality, but above the minimum of #5.

Table 4-1. Turfgrass quality ratings per treatment on 15 July 2006.

Treatment	Rating (#)	Comparisons[a]				
		A	B	***C***	D	***E***
Time-Based						
2-WORS	6.8			***NS***	ab	
2-WRS	6.0			***NS***	ab	
2-DWRS	6.3			***NS***	ab	
Time-Avg	**6.4**	***a***	NS			
SMS-Based						
AC	5.7				b	***b***
RB	5.8				b	***b***
IM	7.0				a	***a***
WW	7.0				a	***a***
SMS-Avg	**6.4**	***a***	NS			
2-WW	4.3	***b***			c	
Control						
0-NI	3.8	***b***			c	
CV (%)		17	16	14	14	***14***

SMS = Soil moisture sensor
Avg = Average
NS = No statistical difference at P>0.90
[a]A = Time-based vs. SMS-based vs. 2-WW vs. Non-irrigated treatments
B = Time-based vs. SMS-based treatments
C = Between time-based treatments
D = Between brands
E = Between all treatments
Different letters within a column indicate statistical difference at P<0.05 (Duncan's Multiple Range Test).

Table 4-2. Soil moisture sensor systems performance per brand during the first half of 2006.

Brand	**Replication (#)**	**Cumulative depth (mm)**	
Acclima	1	201	***b***
	2	304	***a***
	3	332	***a***
Rain Bird	1	261	***NS***
	2	251	***NS***
	3	285	***NS***
Irrometer	1	630	***a***
	2	552	***b***
	3	474	***c***
Water Watcher	1	523	***NS***
	3	486	***NS***

NS = not significant at P>0.95
Different letters within a brand indicate statistical difference at P<0.05 (Duncan's Multiple Range Test).

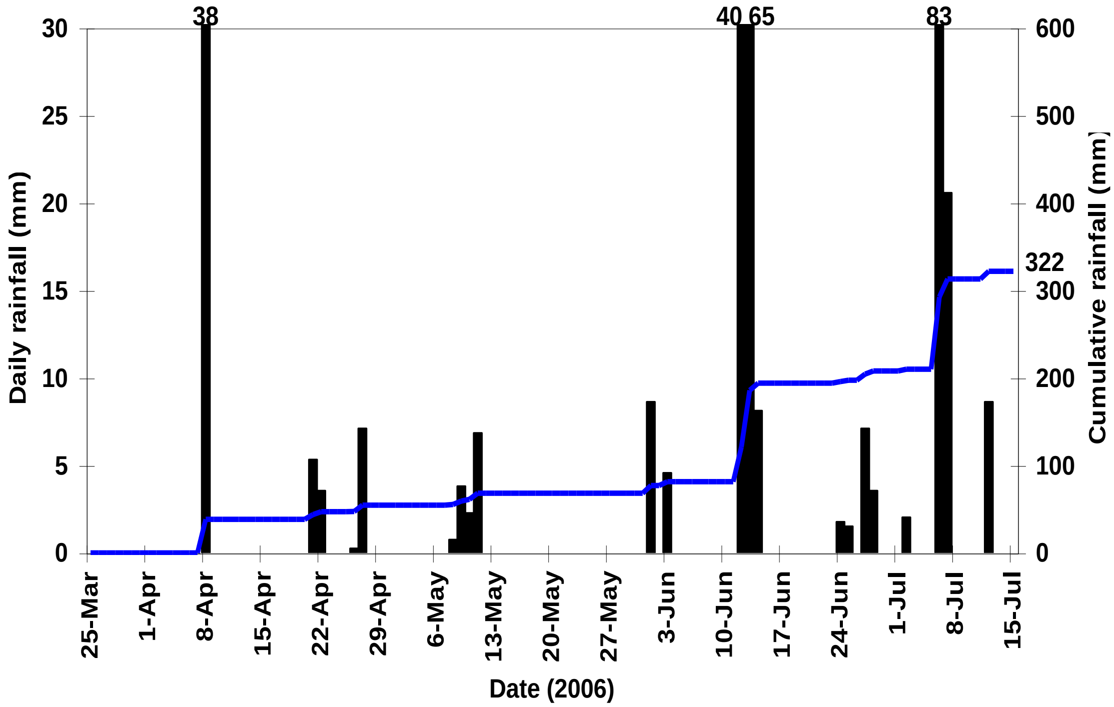

Figure 4-1. Daily and cumulative rainfall, during 25 March through 15 July 2006.

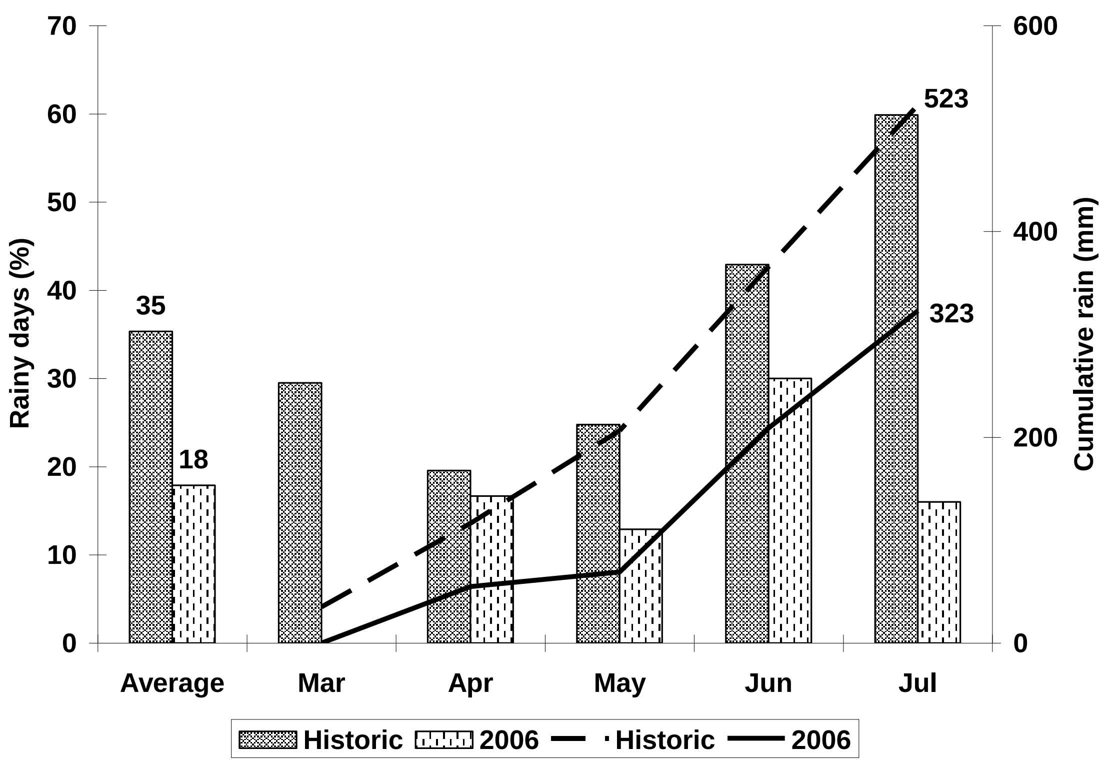

Figure 4-2. Rainy days per month and cumulative rainfall; 25 March through 15 July 2006 versus historic values.

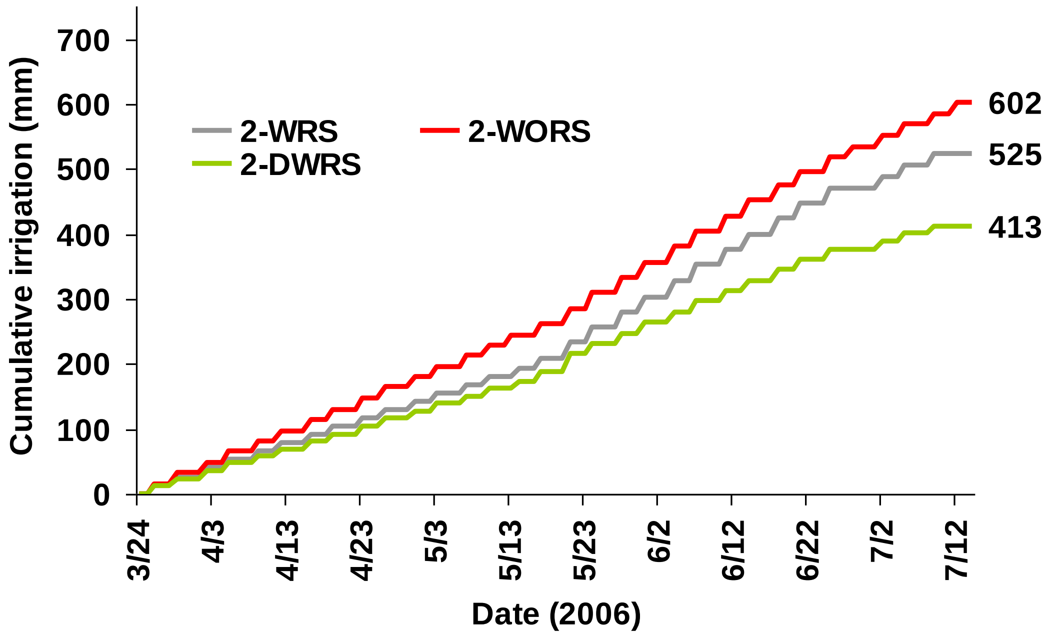

Figure 4-3. Cumulative irrigation applied from 25 March through 15 July 2006 by treatments 2-WORS = time-based treatment without rain sensor, 2-WRS = time-based treatment with rain sensor set at 6 mm threshold, and 2-DWRS 60% of 2-WRS.

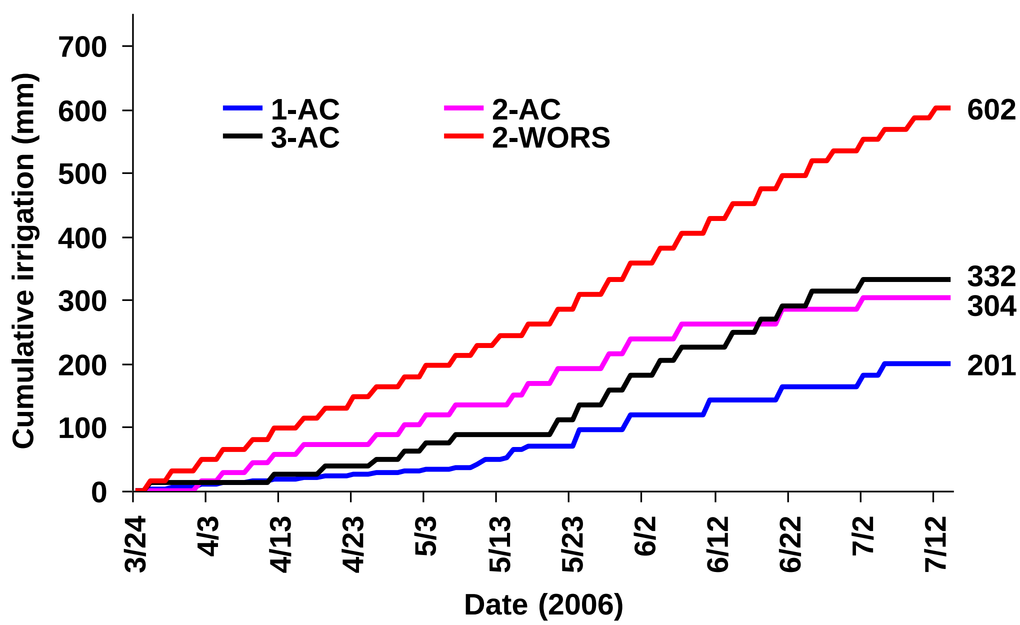

Figure 4-4. Cumulative irrigation applied by treatments with soil moisture sensors from brand Acclima (AC) from 25 March through 15 July 2006. (Numbers before -AC indicate the number of the different units, and 2-WORS = time-based control treatment without rain sensor.)

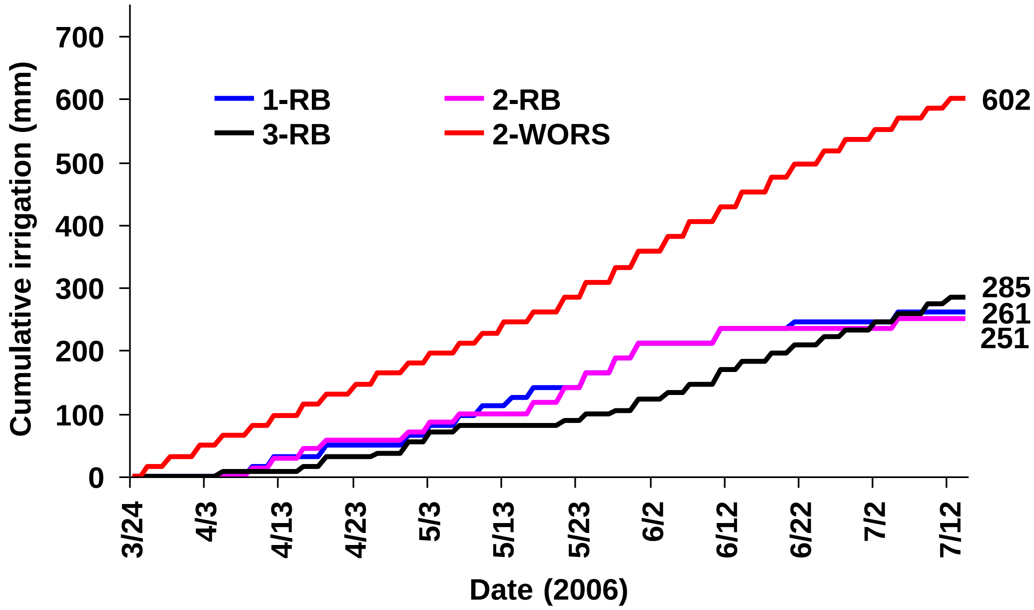

Figure 4-5. Cumulative irrigation applied by treatments with soil moisture sensors from brand Rain Bird (RB) from 25 March through 15 July 2006. (Numbers before -RB indicate the number of the different units, and 2-WORS = time-based control treatment without rain sensor.)

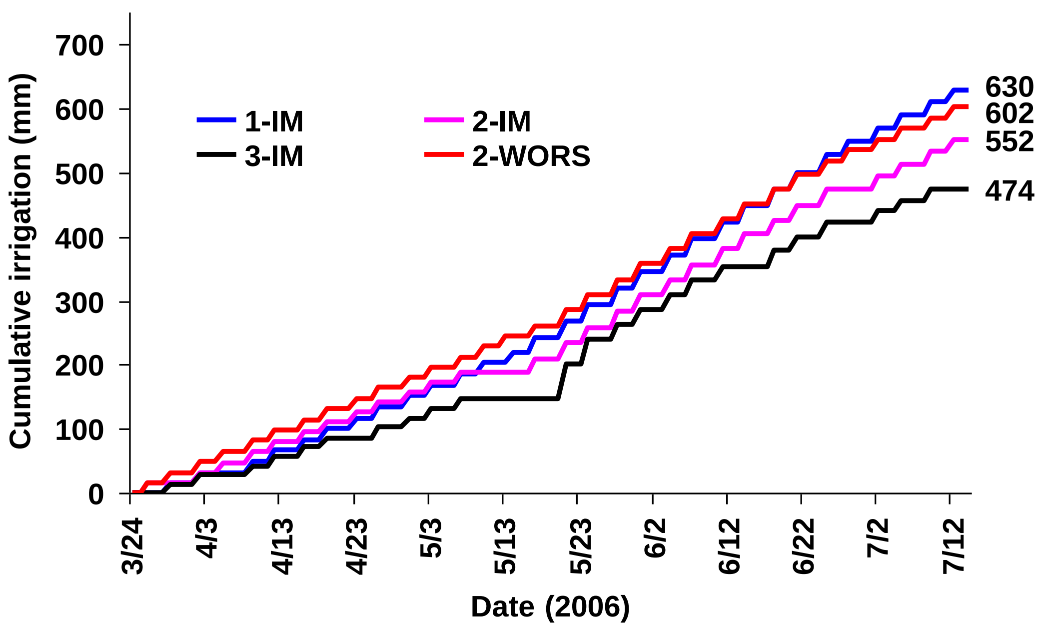

Figure 4-6. Cumulative irrigation applied by treatments with soil moisture sensors from brand Irrometer (IM) from 25 March through 15 July 2006. (Numbers before -IM indicate the number of the different units, and 2-WORS = time-based control treatment without rain sensor.)

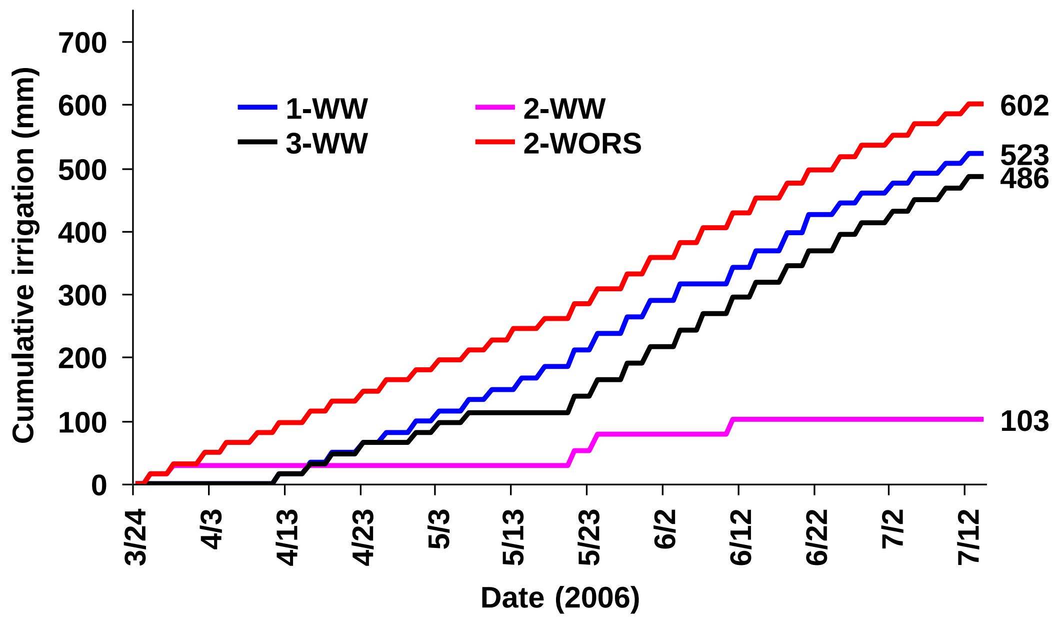

Figure 4-7. Cumulative irrigation applied by treatments with soil moisture sensors from brand Water Watcher (WW) from 25 March through 15 July 2006. (Numbers before -WW indicate the number of the different units, and 2-WORS = time-based control treatment without rain sensor.) Note: unit #2 was not working properly.

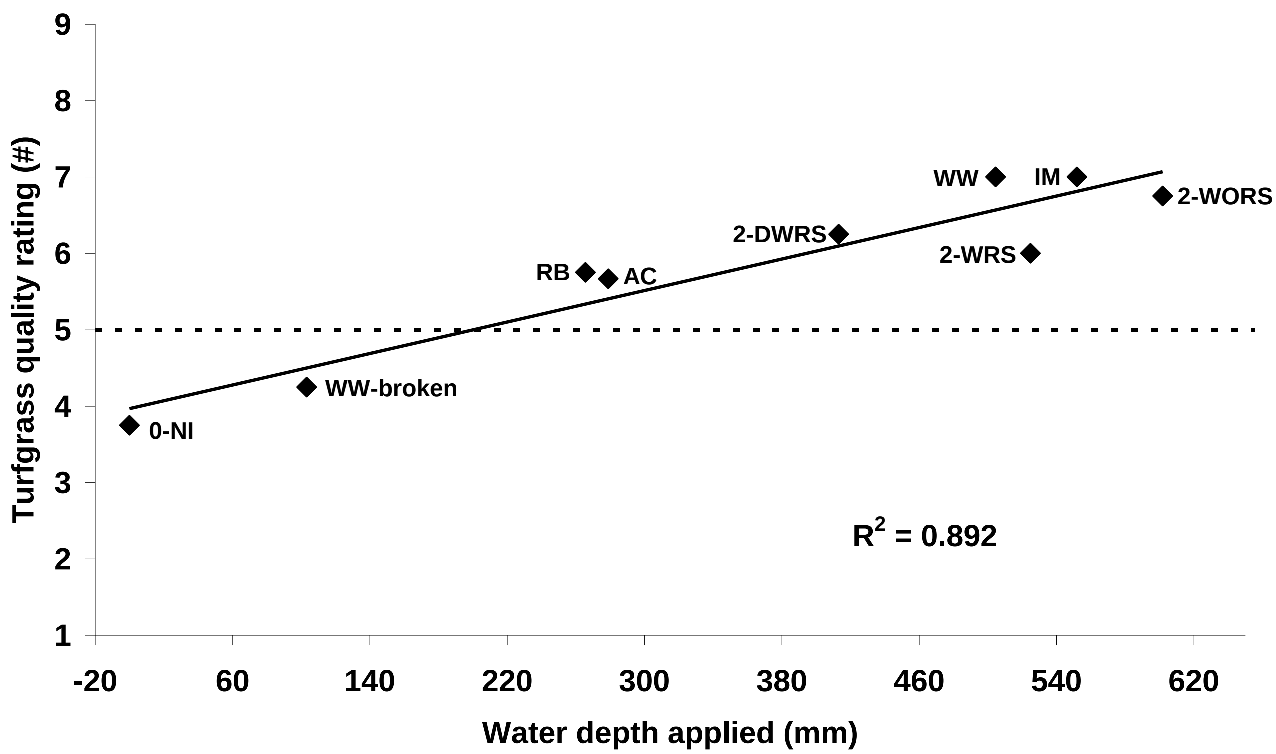

Figure 4-8. Relationship between water depth applied and turfgrass quality, averaged by treatments, during 25 March through 15 July 2006. All treatments above the dotted line resulted in acceptable turfgrass quality, and vice versa.

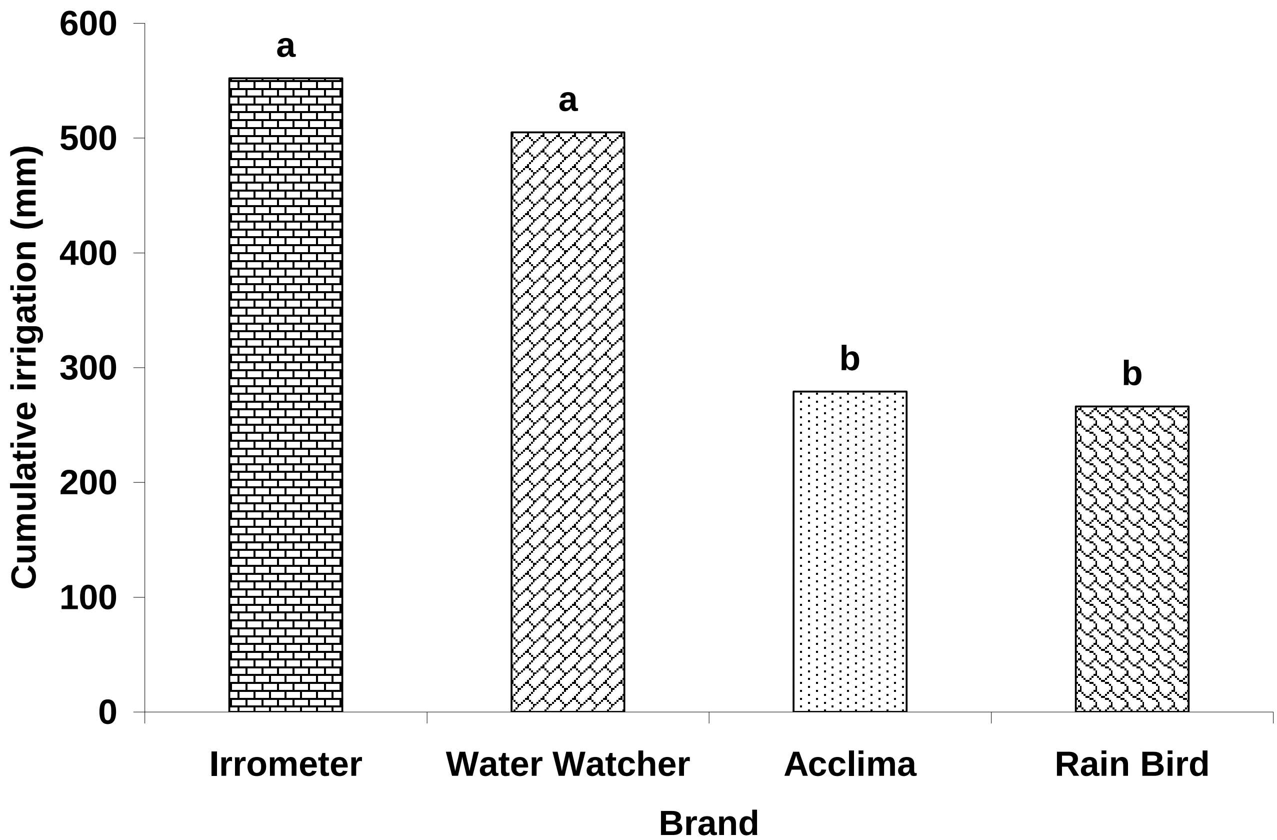

Figure 4-9. Average irrigation depth applied by brand during 25 March through 15 July 2006. (Different letters above the chart columns indicate statistical difference at P<0.05; Duncan's Multiple Range Test.)

5 COMPLETE AUTOMATION RESULTS (2007)

For this experiment, SMS brands RB and WW were replaced by brands Baseline (BL) and Lawn Logic (LL), and the weekly irrigation was programmed to apply 27 mm on every scheduled day (Table 2-5). These 27 mm were divided in two applications, 10 mm at 0600 h and 17 mm at 2000 h, trying to take advantage of the normal rain that falls during the afternoons/evenings in the summertime.

After the winter dormancy, the bermudagrass began to green-up by mid March. However, dry weather conditions coupled with relatively low temperatures resulted in slow re-growth (Figure 5-1). To increase the growth rate, all plots were irrigated every other day from 27 March until 11 April 2007, when the turfgrass quality was uniform across all plots, and a new testing season began. Data were collected from 12 April through 31 October 2007.

5.1 Weather Conditions

Figure 5-2 shows the daily and cumulative rainfall for this experiment period. Compared to a normal year (Figure 5-3), 2007 could be considered as normal, with a similar amount of rainy days (35% and 36% for 2007 and historical records, respectively) and a cumulative rainfall of 827 mm versus 832 mm for a normal year. However, a relatively dry period occurred until October, with a lower frequency of rain events during May, June, August and September than a normal year.

5.2 Irrigation Bypass Proportion

Tables 5-1 and 5-2 show the proportion (%) of scheduled irrigation cycles that were bypassed by the different treatments at 0600 h (AM) and at 2000 h (PM), sorted by irrigation frequency and by brand, respectively. From both tables it can be seen that the bypassed cycles, as a total average for the AM and PM treatments, were similar (58% and 54%, respectively).

Regarding the irrigation frequencies (Table 5-1), the 7 d/w irrigation frequency bypassed a greater proportion of the scheduled irrigation cycles (58%) than the 2 d/w (56%), and the 1 d/w frequency bypassed the least amount of cycles (41%). This could be explained because the higher irrigation frequencies, in general, took advantage of the rain that fell, overriding a greater amount of irrigation cycles. These results are consistent with the previous experimental periods, when the 7 d/w irrigation frequency bypassed a greater amount of scheduled irrigation cycles than the other frequencies tested. However, the proportion of bypassed irrigation cycles was very similar for the AM and PM scheduling (40% vs. 43%, 55% vs. 57%, and 61% vs. 55%, respectively, for the 1, 2, and 7 d/w frequencies, also respectively).

When analyzed by brand (Table 5-2), AC bypassed more cycles in average than the other brands (88%), followed by BL (73%), IM (49%), and finally by LL (14%). Comparing the AM versus the PM cycles, AC, BL, and IM bypassed a greater proportion of irrigation cycles in the morning than in the evening (92% vs. 85%, 76% vs. 70%, and 51% vs. 46%, respectively), showing that these brands did not take advantage of the afternoon/evening rainfalls. The LL brand, on the contrary, bypassed slightly more cycles in the afternoons (12% vs. 15%, for AM and PM, respectively).

5.3 Irrigation Application

Figure 5-4 shows the cumulative irrigation applied through time by the time-based treatments, and by the SMS-based treatments is shown in Figures 5-5 through 5-7. Treatment 2-WORS is used as a comparison with the other treatments. Table 5-3 summarizes the total cumulative irrigation depth applied to treatments, as well as statistical comparisons and percent water savings compared to the time-based treatments 2-DWRS, 2-WRS, and 2-WORS.

5.3.1 Time-based treatments

All the time-based treatments were significantly different to each other (P<0.05). The treatment without sensor feedback (2-WORS) applied the most irrigation, with a total of 1125 mm. The treatments that included a rain sensor, 2-WRS and 2-DWRS, applied 781 mm and 507mm, respectively. Treatment 2-DWRS applied 65% of 2-WRS, close to the designed goal of 60%.

5.3.2 Time-based treatments vs. SMS-based treatments

Table 5-3 shows that the time-based treatments were not statistically different (P>0.99) to the SMS-based treatments, when both averaged 804 mm applied. This was mainly affected by the 7 d/w irrigation frequency, which applied an average of 64% more water than the time-based average. Conversely, the other two SMS-based irrigation frequencies tested, 1 d/w and 2 d/w, applied less water than the time-based average, with 46% and 18% of water savings, respectively.

5.3.3 Comparisons between SMS-irrigation frequencies

Contrary to previous years (with different scheduling programs), the 7 d/w irrigation frequency applied significantly (P<0.0001) more water than the 2 d/w and the 1 d/w frequencies, with 1320 versus 659 and 432 mm, respectively. However, it is important to remember that in previous tests all the irrigation frequencies were programmed to apply the same amount of water per week. In contrast, in these tests, the 7 d/w irrigation frequency was programmed to apply 7 and 3.5 times more water per week than the 1 and 2 d/w frequencies, respectively. This situation did not happen, because the SMS systems set at 7 d/w actually bypassed most of the scheduled irrigation cycles (Tables 5-1 and 5-2), and finally applied 3.1 and 2.0 times more water than 1d/w and 2 d/w, respectively.

5.3.4 Water savings

Table 5-3 shows the water savings (%) of each treatment compared to the time-based treatments 2-DWRS, 2-WRS, and 2-WORS. The control treatment applied a total of 1125 mm during this testing season. The treatment with a rain sensor feedback (2-WRS) applied a total of 766 mm, equivalent to 32% of water savings compared to the control treatment. This amount is similar to that recorded in 2004 and 2005 (34%), even when in those years rainfall frequency was higher and closer to a normal year than in 2007.

Regarding the SMS-based treatments, for the 1 d/w irrigation frequency all brands resulted in water savings compared to 2-WORS. The total amount of water applied were 145, 456, 479, and 648 mm, for AC, BL, IM, and LL, respectively; which represents water savings respect to 2-WORS of 87%, 59%, 57%, and 42%, also respectively. A similar situation occurred within the 2 d/w frequency. Irrigation water savings of 75%, 65%, and 32%, were reported for AC, BL, and IM, respectively; whereas LL applied 6% more water than the control treatment, (the same brand decreasing order as in the 1 d/w irrigation frequency); with total amounts of water applied of 284, 397, 764, and 1189 mm, respectively. In the 7 d/w irrigation frequency; however, only the AC system showed water savings (61%) compared to the control treatment. The systems from brands BL and LL, applied almost the same amount than the control (2% less and 1% more water), and the IM system applied 129% more water than the control treatment. Results suggest that these last three SMS systems are not accurate enough for the high frequency/high volume schedule established for these tests, or that they lack a quick time-response to changes in the soil moisture content as needed, or their set points/burial depths were not the same as the other frequencies or, maybe, a combination of these factors could have affected their outcome. Only the Acclima SMS system appears to be operative under these conditions; meaning that it could fully automate an irrigation system, without need for human intervention for monthly or seasonally rescheduling of the irrigation cycles.

Regarding the SMS brands, the AC system was the only one that consistently showed water savings in every frequency tested (87%, 75%, and 61%, for 1, 2, and 7 d/w, respectively), compared to the control 2-WORS. The BL system saved water in the 1 and 2 d/w irrigation frequencies (59% and 65%, respectively), but at the 7 d/w the water savings were negligible (2%). The LLs showed an erratic behavior; they saved water in the 1 d/w scheduling (42%), but applied slightly more water than the control in the 2 and 7 d/w frequencies (6% and 1%, respectively). Similarly, the IM systems saved water in the 1 and 2 d/w irrigation frequencies (57% and 32%, respectively), but in the 7 d/w frequency they applied 129% more water than 2-WORS. Again, these results suggest that only the AC system is suitable for scheduling high irrigation frequency (7 d/w) with high volume of water. The other brands appear to be more appropriate for lower irrigation frequencies (1 or 2 d/w).

5.4 Turfgrass Quality

After the plots were irrigated every other day until April 11, 2007, the turfgrass quality across all plots was relatively uniform and above the minimum rating of 5. Table 5-4 shows the turfgrass quality ratings per treatment on May, August, and October 2007, and statistical comparisons between treatments ($P<0.05$). By the end of May, all the irrigated plots maintained a good quality, ranging from 5.3 to 6.8, where the time-based were significantly better than the SMS-based treatments (6.3 and 5.9, respectively, Comparison B). The non-irrigated plots, however, resulted in a significantly lower and unacceptable quality (3.8) due to the relatively dry weather that occurred during this period (Comparison A). No significant differences were found between the time-based treatments (Comparison C), between the different irrigation frequencies (Comparison C), nor between the SMS-based treatments (Comparison E). These patterns remained the same for the rest of the experimental period, except that, after May 2007, no more significant differences between the time-based and SMS-based treatments were found, and when the rainy days became more frequent, the non-irrigated plots tended to improve their quality, but remained below the minimum acceptable quality and significantly different from the rest of the treatments.

Table 5-1. Proportion (%) of irrigation cycles that were bypassed in 2007 by the different treatments at 0600 h (AM) and at 2000 h (PM); treatments sorted by irrigation frequency.

Treatment	Bypassed %		
	AM	PM	Avg
1-AC	59	90	74
1-BL	38	38	38
1-IM	45	41	43
1-LL	17	3	10
1-Avg	**40**	**43**	**41**
2-AC	80	78	79
2-BL	75	66	70
2-IM	36	61	48
2-LL	31	22	26
2-Avg	**55**	**57**	**56**
7-AC	100	87	93
7-BL	81	76	79
7-IM	57	42	50
7-LL	6	15	10
7-Avg	**61**	**55**	**58**
TOTAL-Avg	**58**	**54**	**56**

Table 5-2. Proportion (%) of irrigation cycles that were bypassed in 2007 by the different treatments at 0600 h (AM) and at 2000 h (PM); treatments sorted by brand.

Treatment	Bypassed %		
	AM	PM	Avg
1-AC	59	90	74
2-AC	80	78	79
7-AC	100	87	93
AC-Avg	**92**	**85**	**88**
1-BL	38	38	38
2-BL	75	66	70
7-BL	81	76	79
BL-Avg	**76**	**70**	**73**
1-IM	45	41	43
2-IM	36	61	48
7-IM	57	42	50
IM-Avg	**51**	**46**	**49**
1-LL	17	3	10
2-LL	31	22	26
7-LL	6	15	10
LL-Avg	**12**	**15**	**14**
TOTAL-Avg	**58**	**54**	**56**

Table 5-3. Total cumulative irrigation depth applied to treatments, statistical comparisons, and percent water savings compared to 2-DWRS, 2-WRS, and 2-WORS, year 2007.

Treatment	Cumulative depth (mm)	Comparisons[a]			Water savings (%) vs.		
		A	B	***C***	2-DWRS	2-WRS	2-WORS
Time-Based							
2-WORS	1125	***a***			-122	-44	0
2-WRS	781	***b***			-54	0	31
2-DWRS	507	***c***			0	35	55
Time-Avg	**804**		a				
SMS-Based							
1-AC	145				71	81	87
1-BL	456				10	42	59
1-IM	479				6	39	57
1-LL	648				-28	17	42
1-Avg	**432**			***c***			
2-AC	284				44	64	75
2-BL	397				22	49	65
2-IM	764				-51	2	32
2-LL	1189				-135	-52	-6
2-Avg	**659**			***b***			
7-AC	437				14	44	61
7-BL	1107				-118	-42	2
7-IM	2579				-409	-230	-129
7-LL	1158				-128	-48	-3
7-Avg	**1320**			***a***			
SMS-Avg	**804**		a				**28**

SMS =Soil moisture sensor
Avg =Average
[a]A = Between time-based treatments
B = Time-based treatments vs. SMS-based treatments
C = Between irrigation frequency averages

Different letters within a column indicate statistical difference at $P<0.05$ (Duncan's Multiple Range Test).

Table 5-4. Turfgrass quality ratings per treatment on May, August, and October 2007.

Treatment	May-07							Aug-07							Oct-07						
	Rating	Comparisons[a]						Rating	Comparisons[a]						Rating	Comparisons[a]					
	(#)	***A***	B	***C***	D	***E***	F	(#)	***A***	B	***C***	D	***E***	F	(#)	***A***	B	***C***	D	***E***	F
Time-Based																					
2-WORS	6.3			***NS***			abc	6.3			***NS***			ab	6.5			***NS***			ab
2-WRS	6.8			***NS***			a	6.3			***NS***			ab	6.3			***NS***			ab
2-DWRS	6.0			***NS***			abc	6.3			***NS***			ab	6.0			***NS***			ab
Time-Avg	**6.3**	***a***	a					**6.3**	***a***	NS					**6.3**	***a***	NS				
SMS-Based																					
1-AC	6.0					***NS***	abc	5.0					***d***	c	5.8					***NS***	ab
1-BL	6.0					***NS***	abc	5.5					***bcd***	abc	7.0					***NS***	a
1-IM	5.8					***NS***	abc	6.3					***ab***	ab	5.5					***NS***	bc
1-LL	5.5					***NS***	bc	5.3					***cd***	bc	5.5					***NS***	bc
1-Avg	**5.8**				NS			**5.5**				NS			**5.9**				NS		
2-AC	6.0					***NS***	abc	5.8					***abcd***	abc	5.8					***NS***	ab
2-BL	5.8					***NS***	abc	5.3					***cd***	bc	6.0					***NS***	ab
2-IM	6.0					***NS***	abc	6.5					***a***	a	5.8					***NS***	ab
2-LL	6.0					***NS***	abc	5.8					***abcd***	abc	6.5					***NS***	ab
2-Avg	**5.9**				NS			**5.8**				NS			**6.0**				NS		
7-AC	5.3					***NS***	c	6.0					***abc***	abc	6.0					***NS***	ab
7-BL	5.8					***NS***	abc	6.0					***abc***	abc	6.0					***NS***	ab
7-IM	6.5					***NS***	ab	6.3					***ab***	ab	6.0					***NS***	ab
7-LL	6.3					***NS***	abc	6.0					***abc***	abc	6.0					***NS***	ab
7-Avg	**5.9**				NS			**6.1**				NS			**6.0**				NS		
SMS-Avg	**5.9**	***a***	b					**5.8**	***a***	NS					**6.0**	***a***	NS				
Control																					
0-NI	3.8	***b***					d	3.8	***b***					d	4.3	***b***					c
CV (%)		11	11				11		13				10	12		14					14

SMS = Soil moisture sensor Avg = Average NS = No statistical difference at P>0.90

[a]A = Time-based vs. SMS-based vs. Non-irrigated treatments
B = Time-based vs. SMS-based treatments
C = Between irrigation frequency averages
D = Between time-based treatments
E = Between SMS-based treatments
F = Between all treatments

Different letters within a column indicate statistical difference at P<0.05 (Duncan's Multiple Range Test).

Figure 5-1. Slow green-up after winter dormancy in turf plots by 28 March 2006.

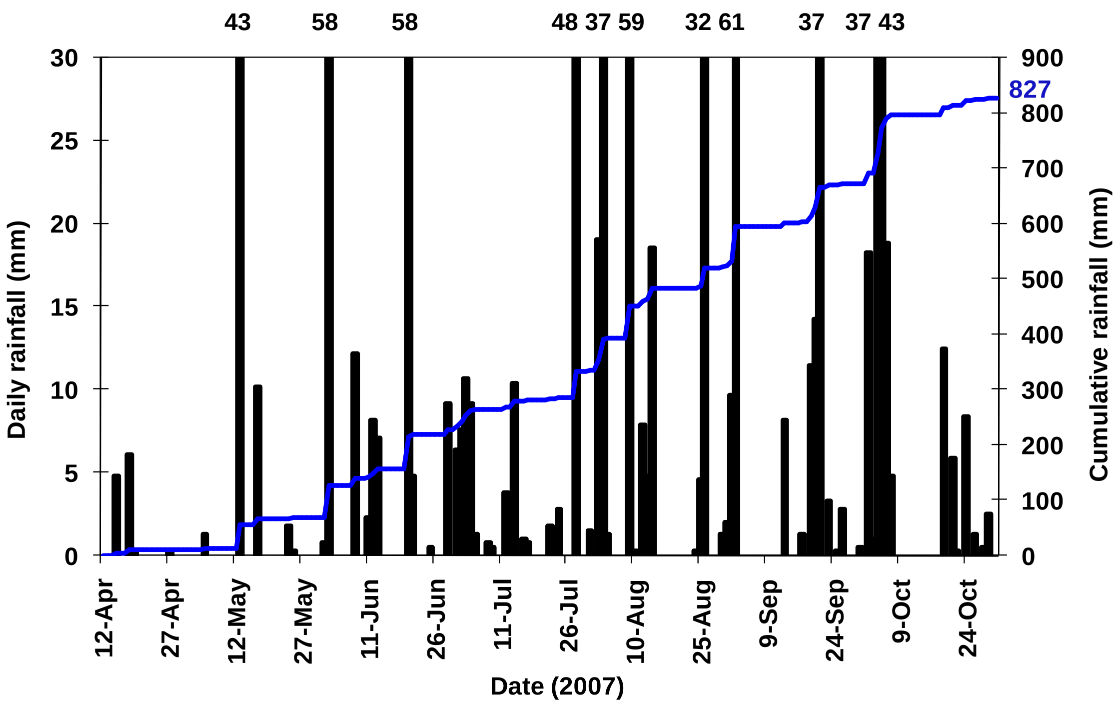

Figure 5-2. Daily and cumulative rainfall from 12 April through 31 October 2007.

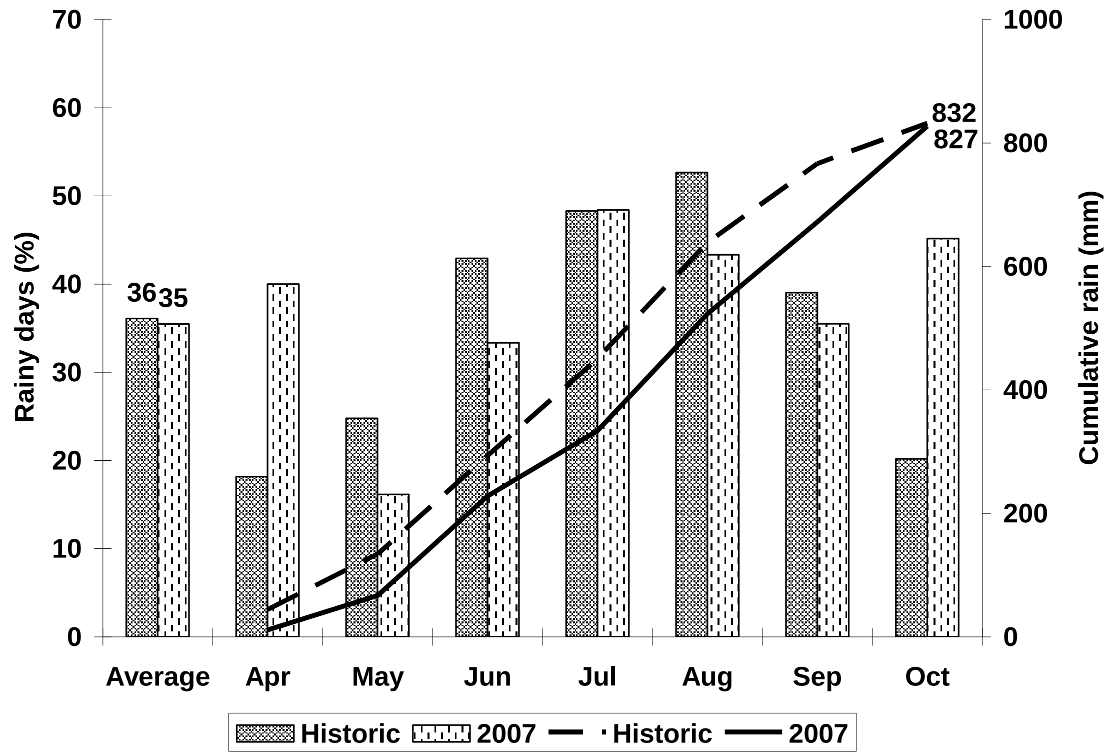

Figure 5-3. Rainy days per month and cumulative rainfall; 12 April through 31 October 2007 versus historic values.

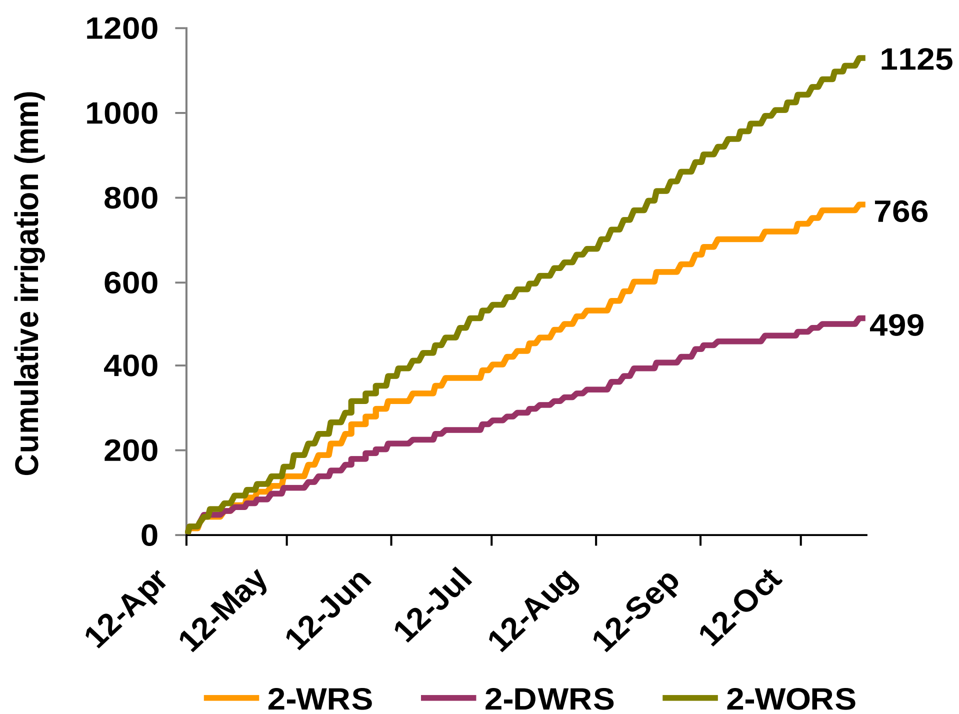

Figure 5-4. Cumulative irrigation applied to experimental plots in 2007; time-based treatments.

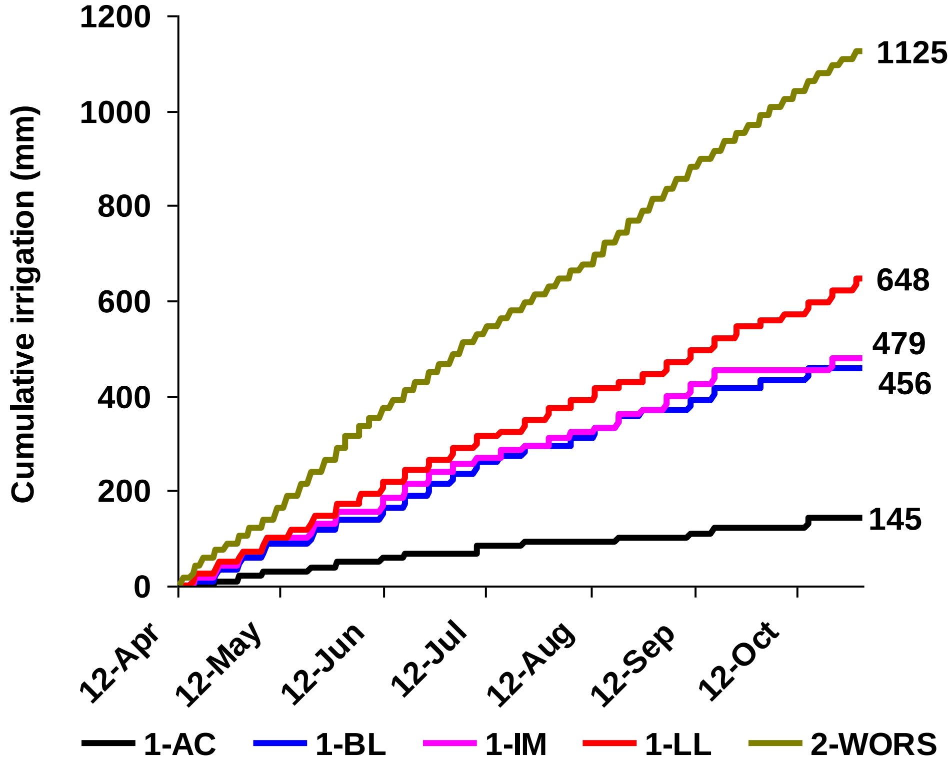

Figure 5-5. Cumulative irrigation applied to experimental plots in 2007; one day per week irrigation frequency treatments.

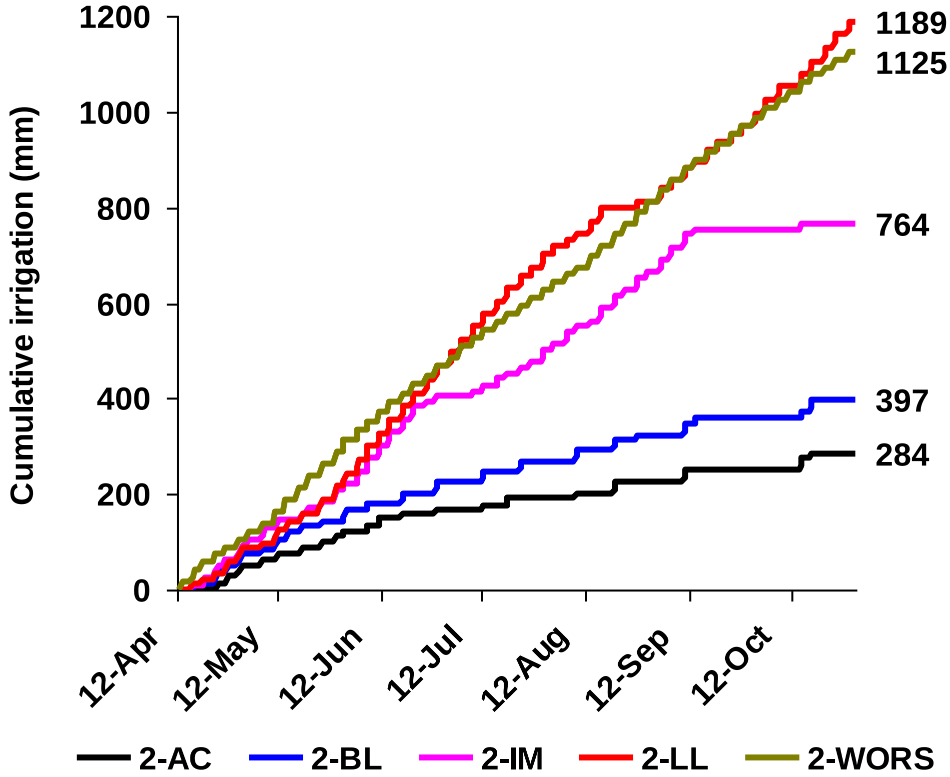

Figure 5-6. Cumulative irrigation applied to experimental plots in 2007; two days per week irrigation frequency treatments.

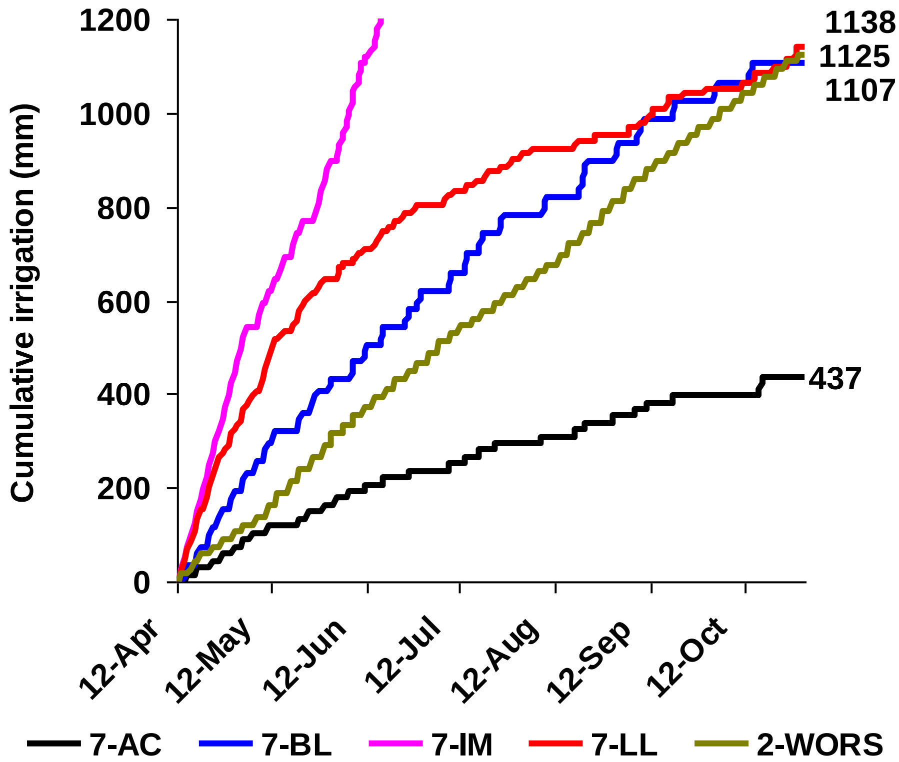

Figure 5-7. Cumulative irrigation applied to experimental plots in 2007; seven days per week irrigation frequency treatments. (Note: The cumulative irrigation applied by 7-IM was 2,579 mm.)

6 SUMMARY AND CONCLUSIONS

High frequency rainfall events and a large amount of cumulative precipitation, which are not uncommon for this region, coupled with favorable environmental conditions, promoted the growth and development of the bermudagrass in 2004 and 2005. During 2006, however, dry weather conditions prevailed and, in 2007, the frequency of rain events was below a normal year.

The three time-based treatments were significantly different from each other during the whole study period in terms of water applied; except for a programming error in part of 2006 when 2-WRS and 2-DWRS were statistically similar. The treatment with a functional rain sensor (2-WRS), set at a 6 mm threshold, applied between 31% and 34% less water than the without-rain-sensor treatment (2-WORS) during wet/normal weather conditions, and between 13% and 24% during dry weather conditions. These results show the importance and usefulness of a well-maintained rain shut-off device in all automated irrigation systems in Florida, where a functional rain sensor is required by law. On the other hand, treatment 2-DWRS, applied close to the desired 60% of the water applied by 2-WRS throughout the experimental period (except for the aforementioned period in 2006). Moreover, these time-based treatments were established to mimic the operation of irrigation systems carried out by different homeowner profiles. However, according to the results of this research, these treatments were fairly well managed compared to documented homeowner practices in the Central Florida Ridge. In this study, the irrigation run times were adjusted monthly but, most homeowners only adjust their clock several times each year at most. Therefore, assuming all else is equal, results in water use from this experiment may be conservative and differences for actual homeowners could be even larger.

All the time-based treatments resulted in turfgrass quality above the minimal acceptable rating (#5) during the whole experimental time frame and were never statistically different from each other. This means that using a rain sensor and reducing recommended time clock irrigation schedules can reduce water applied (2-WORS vs. 2-WRS vs. 2-DWRS), while maintaining the same turfgrass quality.

Throughout the experiments carried out from 2004 through 2006 (with wet and dry weather conditions) results showed that the SMS-based treatments, on average, were significantly more efficient as a means to save water than the time-based treatments; even when an operative rain sensor was an important component on two of the three time-based treatments. However, not all SMS-treatments tested performed the same. The 2-IM treatment was the only SMS-based treatment that applied more water than the treatment with-rain-sensor, 2-WRS (11% and 20% under wet and dry conditions, respectively). The other two IM treatments applied less water than 2-WRS (which ranged from 20% to 28% in 2004/2005, and from 3% to 10%, in 2006), but they consistently applied more water than the other SMS brands/treatments (except for 1-RB during the 2006 test). The other brands (AC, RB, and WW) resulted in irrigation water savings compared to 2-WRS, which ranged from 54% to 88% and from 5% to 77%, under wet and dry conditions, respectively. It is important to remark that these water savings were on top of those already achieved by the treatment with-rain-sensor. These results show that most SMSs can also act as rain shut-off devices, but with a superior performance than rain sensors in terms of water savings.

On the other hand, treatment 2-WORS was intended to simulate household irrigation systems with a non-functional or absent rain sensor; which is common in Florida. On average, 72% and 54% of the water applied by 2-WORS was saved by the SMS-based treatments during wet and dry weather conditions, respectively. When excluding brand IM, water savings ranged from 69% to 92% over the first two years, and from 28% to 83% during the dry 2006 year. In summary, during dry weather conditions, the SMS-based treatments bypassed a lesser amount of scheduled irrigation cycles and saved a smaller amount of water than during wet conditions. In spite of this, it is remarkable that all SMS-based treatments applied less water than the time-based control treatment, 2-WORS. Moreover, except for 2-IM, the different SMS-based treatments also saved more water compared to the treatment with a rain sensor. These results clearly demonstrate that the use of SMSs (along with traditional time clocks in residential irrigation systems) could lead to important water savings; more than twice as much as a rain sensor device alone.

All three irrigation frequencies tested (1, 2, and 7 d/w) were significantly different during the 2004 through 2006 experiments; being the 7 d/w the one that consistently applied the least amount of water. These results suggest that to schedule high-frequency/low-volume irrigation cycles (7 d/w), in closed control loop irrigation systems, appears to be a viable strategy regarding water conservation for turfgrass irrigation in Florida's sandy soils, even during dry weather conditions. However, run times should be adjusted to allow refill of the soil water reservoir.

During the first half of 2006, a different experiment was set to analyze the behavior and consistency of the SMS system units. It was found that the different units from brands RB and WW tended to behave in the same way through time, and applied a similar amount of water by the end of the data collection period. A comparable situation occurred within the AC units, when they behaved similarly through time, but two of them were statistically similar and one was different regarding the total amount of water applied. The IR repetitions, however, were all significantly different; which is consistent with documented variability between the IR units. Moreover, when the different brands were compared against each other, the brands that allowed significantly less irrigation to be applied were AC and RB, followed by WW and IM.

All SMS-based treatments resulted in average turfgrass qualities that were above the minimum acceptable over the monitoring period, with the exception of some short periods due to broken SMS systems. After replacement, turfgrass quality improved on these treatments and remained above the minimum acceptable. During wet weather conditions, no differences in turfgrass quality were detected among SMS-based treatments, and always exceeded the minimum acceptable rating of 5. It was concluded that irrigation was not necessary to maintain acceptable turf quality during that experimental period, which was evidenced by acceptable quality in non-irrigated plots. However, during dry weather conditions, the RB and AC treatments resulted in turf quality at or slightly above the minimum acceptable level. This means that the thresholds set on these controllers might be too low for sustained drought situations or less drought-tolerant turfgrass, and/or that the run times might be increased to assure or improve turf quality above the minimum acceptable level.

Treatments for 2007 were modified to take advantage of the common rainfall that occurs in the afternoons/evenings of the rainy season in Florida. This modified schedule resulted in water savings, compared to 2-WORS, for the 1 and 2 d/w irrigation frequencies. However, most of the SMS systems set to run at a high-volume/high-frequency (7 d/w) resulted in the same or more water applied than 2-WORS, for unknown reasons. Therefore, in the case of a broken SMS system, this irrigation strategy could lead to over irrigation, far beyond the plant needs. Only the AC system appears to be suitable for this irrigation strategy (it applied 61% less water than 2-WORS) that could fully automate an irrigation system, without need for human intervention for seasonal adjustments of the irrigation cycles. The other brands appear to be more appropriate for lower irrigation frequencies perhaps at 2 or 3 d/w schedules to balance horticultural needs with potential water conservation.

Finally, it should be noted that specific performance of the individual sensors largely depends on the threshold setting and the sensor burial depth. Even when sensor burial depths were as similar as practically possible in this experiment, the sensor thresholds might have varied slightly, hence affecting the results to some extent. In any case, the goal of this research was fulfilled, when correctly installed and programmed, the SMS systems appear to be a technology that could lead to a complete automation of the irrigation systems, to substantial savings in residential irrigation water, and to maintain acceptable turf quality at the same time (even during dry weather conditions). Testing this technology on actual household irrigation systems is recommended to validate these results. In addition, a simple recommendation for the time clock program is needed for contractors and homeowners.

7 TECHNOLOGY TRANSFER

During this project, and as a result of partial data that were being obtained, numerous activities of extension were developed. Several field days and site visits from government organizations, industry, researchers, graduate and undergraduate students, etc., were carried out. In addition, articles were published on newspapers from Florida. Moreover, talks and papers were developed to be presented in conferences and scientific journals. The more significant publications were:

- M.D. Dukes, B. Cardenas-Lailhacar and G. Miller. 2005. *Residential Irrigation Based on Soil Moisture*. Resource; ASABE 12 (5): 4-6.
- B. Cardenas-Lailhacar, M.D. Dukes and G. Miller. 2005. *Sensor-Based Control of Irrigation in Bermudagrass.* Paper Number: 052180, 2005 ASABE Annual International Meeting.
- B. Cardenas-Lailhacar and M.D. Dukes. 2008. *Expanding-Disk Rain Sensor Performance and Potential Water Savings*. Journal of Irrigation and Drainage Engineering 134 (1): 67-73.
- B. Cardenas-Lailhacar, M.D. Dukes and G. Miller. 2008. *Sensor-Based Automation of Irrigation on Bermudagrass, during Wet Weather Conditions*. Journal of Irrigation and Drainage Engineering (in press).
- M.D. Dukes, B. Cardenas-Lailhacar, S. Davis, M.B. Haley and M. Shedd. 2007. *Smart Water Application Technology (SWAT™) Evaluation in Florida*. Paper Number: 072250, 2007 ASABE Annual International Meeting.
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9 LIST OF ABBREVIATIONS

AC : Acclima
Avg : average
BL : Baseline
BMPs : best management practices
d/w : days per week
DU_{lq} : low-quarter irrigation distribution uniformity
DWRS : deficit with rain sensor
IM : Irrometer
LL : Lawn Logic
NI : non irrigated
RB : Rain Bird
SIC : scheduled irrigation cycle
SMS : soil moisture sensor
VMC : volumetric moisture content
WORS : without rain sensor
WRS : with rain sensor
WW : Water Watcher