Expanding Disk Rain Sensor Performance and Potential Irrigation Water Savings

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Abstract: Rain sensors (RSs) appear to be a useful tool for water conservation at a relatively low cost. However, little evidence related to RS performance and/or reliability exists. The objectives of this experiment were to: (1) evaluate two RS types with respect to the following: Accuracy of their set point, number of irrigation cycles bypassed, and duration in bypass mode; (2) quantify the amount of water that RSs could save; and (3) estimate their payback period. Mini-click (MC) and wireless rain-click (WL) rain sensor models were monitored. For the WL treatment, the dry-out ventilation windows were set half open, and for the MC treatments, rainfall set points of 3, 13, and 25 mm were established. On average, all treatments responded close to their set points with the WL, 3 mm MC, 13 mm MC, and 25 mm MC treatments averaging 1.4, 3.4, 10.0, and 24.5 mm, respectively. However, some replicates showed variable behavior. The number of times that these sensors shut off irrigation (81, 43, 30, and 8 times, respectively) was inversely proportional to the magnitude of their set point, with potential water savings following a similar trend. Where water costs exceed \$0.53 per cubic meter (\$2.00 per thousand gallons), the payback period is less than a year for WL and MCs set at 13 mm or less.

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Introduction

A rain sensor (RS), also called rain shut-off device or rain switch, is a device designed to interrupt a scheduled cycle of an automatic irrigation system controller (i.e., timer) when a specific amount of rainfall has occurred (Dukes and Haman 2002b; Hunter Industries, Inc. 2006). Rain shut-off devices are a common type of irrigation sensor, due to an increasing number of municipalities throughout the country that have mandates and/or cost-saving programs for their use, on new and existing residential and commercial irrigation systems. In addition, and except for the most arid environments, they appear to be a useful tool for water conservation, at a relatively low cost (Dewey 2003).

Currently, there are mandates for the use of RSs in various municipalities in New Jersey, North and South Carolina, Georgia, Texas, Minnesota, and Connecticut (Dewey 2003). However, Florida is the only state in the nation with an overall RS statute. Florida law requires an automatic rain sensor shut-off device that is properly installed and functioning on all automatic irrigation systems installed after May 1, 1991 (Florida Statutes 2006). Moreover, some local laws also require older systems to be retrofitted with rain shut-off switches [St. John's River Water Management District (SJRWMD) 2006].

Rain sensors can be easily hooked up to any automatic irrigation timer and mounted in an open area where they are exposed to rainfall. Many new irrigation timers have a connection specifically for a RS. If this connection is not available, it can always be "hard wired" into the controller, connecting the RS in series with the common wire. When a specific amount of rainfall has occurred, the RS will interrupt the system common wire, which disables the solenoid valves until the sensor dries out (Dukes and Haman 2002b).

According to Dukes and Haman (2002b), the use of RSs has several advantages such as: Elimination of unnecessary irrigation events, reduced wear on the irrigation system, reduced disease and weed pressure, and minimization of runoff and/or deep percolation that can carry pollutants, such as fertilizers and pesticides, into storm drains and groundwater. RSs also save money, because they reduce utility bills and turf maintenance costs. These benefits are supplemented by a relatively low cost, easy installation, low maintenance, and long life (more than 10 years according to manufacturers, and a 5-year warranty).

Several types and models of RSs, which differ in method of operation, have been developed. Some of them have a receptacle to weigh the amount of water. After a preset weight of water is collected, the connection to the automatic irrigation valve is interrupted until a portion of water in the receptacle evaporates, reducing the weight below a critical level. Other models also use a receptacle, but instead of weight, they detect the water level with a set of electrodes. The distance between the bottom of the receptacle and the electrodes can be adjusted so the irrigation system is not switched off by small rain events. The primary disadvantage of these types of devices is that any other external volume/weight (debris, small animals, etc.) can turn off the irrigation system (Dukes and Haman 2002b).

The third and most widely used method employs an expanding material to sense the amount of rainfall (Fig. 1). Hygroscopic disks absorb water and expand proportionally to rainfall amount.

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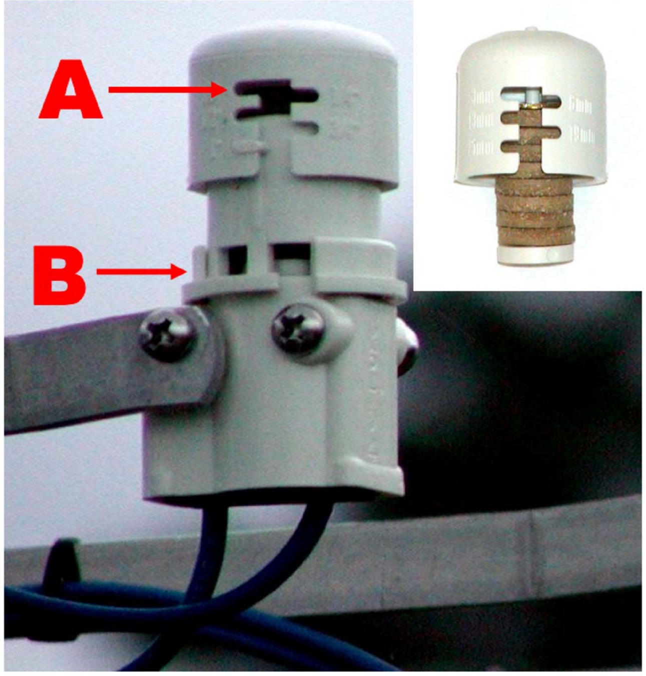

Fig. 1. Mini-click (Hunter Industries, Inc.) rain sensor: (a) Rain threshold set slots; (b) vent ring. The insert shows the expanding hygroscopic disks.

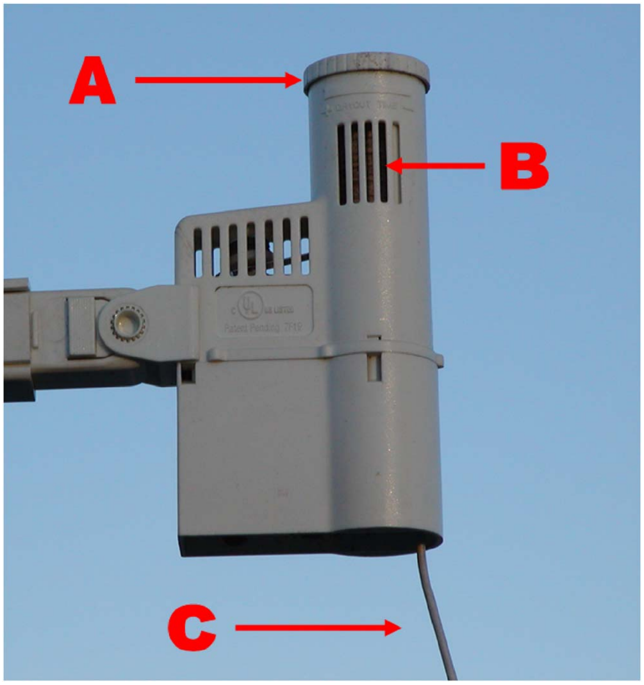

Fig. 2. Wireless rain-click (Hunter Industries, Inc.) rain sensor: (a) Ventilation window adjustment knob; (b) ventilation windows; and (c) antenna.

As the moisture-laden disks expand, they activate a switch that interrupts the programmed irrigation cycle. The switch remains open as long as the disks are swollen. When the rain has passed, the disks begin to dry out and the switch closes again (Hunter Industries, Inc. 2006).

Different RS models typically have some type of adjustment so that they can be set to react after a specific amount of rainfall. The expanding hygroscopic disks type mini-click (MC) model (Hunter Industries, Inc.), very common in Florida, has five different settings (Fig. 1) that can bypass an irrigation cycle after rainfall quantities of 3, 6, 13, 19, or 25 mm. To adjust to the desired shut-off quantity, it is necessary to rotate the cap on the switch housing, so that the pin is located in the proper slot. The time that it takes the MC to reset for normal sprinkler operation after the rain has stopped is determined by weather conditions (temperature, wind, sunlight, relative humidity, etc.), which will determine how fast the hygroscopic disks dry out. To adjust the drying rate of disks, these sensors have an adjustable vent ring (Fig. 1).

A new version of these devices (also with hygroscopic disks inside) is a radio-controlled or wireless RS (Fig. 2). The components of this system are a sensor/transmitter unit installed in an area subject to rainfall and a receiver unit connected to the timer. Some advantages of these sensors include a quicker and easier installation, and additional mounting locations to choose from (up to 90 m away from the receiver), especially for sites that present difficulty in routing wire as well as for retrofit applications (Hunter Industries, Inc. 2006). A new feature promoted by industry is the quick shut down of the irrigation system after it starts to rain (without preset adjustments for a certain precipitation amount), and their ability to bypass irrigation for a short period of time once it stops raining. Similar to the MCs, the wireless RSs can be adjusted to keep the irrigation system off after the rain stops by setting the adjustable ventilation windows (Fig. 2) that control the dry-out time (Hunter Industries, Inc. 2006).

Although RSs are mandated in many municipalities, little evidence related to RS performance and/or reliability exists in the literature. Therefore, the objectives of this experiment were as follows: (1) evaluate the reliability of two commercially available expanding disk RS types with respect to the number of irrigation cycles bypassed, accuracy of the set point with respect to rainfall depth, and duration in irrigation bypass mode; (2) quantify the amount of water that RSs could save compared to time-based irrigation schedules without RS; and (3) estimate the payback period of RSs at different set points.

Materials and Methods

Twelve MC and four wireless rain-click (WL) rain sensor models (Figs. 1 and 2, respectively) (Hunter Industries, Inc., San Marcos, CA) were placed at the Univ. of Florida Agricultural and Biological Engineering Dept. turfgrass research facility in Gainesville. The experiment took place from March 25 through December 31, 2005. Four treatments with four replications each were established. For the MCs, three set points were established: 3, 13, and 25 mm thresholds (treatment codes 3-MC, 13-MC, and 25-MC, respectively). The vent rings of the MCs were kept completely open. In the case of the WLs, the dry-out ventilation windows were set half open.

Each time a rain sensor changed status (from allowing irrigation, to bypass mode, or vice versa), the date and time were automatically recorded, at a 1-min sampling interval, by means of two AM16/32 multiplexers connected to a CR 10X model datalogger (Campbell Scientific, Logan, UT). Weather conditions were recorded by an automated weather station containing a CR 10X model data logger, located within 15 m of the experimental site. Rainfall was measured by means of a tipping bucket rain gauge, which was routinely checked against a manual rain gauge located nearby. Measured weather parameters included total rainfall, air temperature, relative humidity, wind speed and direction, and solar radiation recorded at 15 min intervals. However, because this sampling interval was too long to quantify the precise amount of precipitation that fell before the sensors switched off, rainfall data were recorded at intervals of 0.25 mm after June 29 (day of year, hour, and minute were logged). Therefore, when sensor activation could not be correlated with a rainfall event prior to June 29, data collected were not considered. The total time that each RS remained in the irrigation bypass mode was computed. Total rainfall before each RS switched to bypass mode was calculated, in order to evaluate the accuracy of the rainfall thresholds. According to Figliola and Beasley (2000), the accuracy of an instrument refers to its ability to indicate a true value exactly. Accuracy is related to absolute error ε, which is defined as the difference between the true value of a measurement and the indicated value of the instrument

$$\varepsilon = \text{true value} - \text{indicated value} \tag{1}$$

from which the percent accuracy A is found by

$$A = \left(1 - \frac{|\varepsilon|}{\text{true value}}\right) \times 100 \tag{2}$$

Since these RSs were not connected to an actual irrigation system, a parallel experiment was set up in order to estimate how many cycles these settings would have overridden and how much water could have been potentially saved. In this experiment, an automatic irrigation system was equipped with a residential irrigation timer ESP-4Si (Rain Bird International Inc., Glendora, CA), which was scheduled to run two days per week (Sunday and Thursday), beginning at 0100 h to simulate watering restrictions imposed in Florida [Florida Dept. of Environmental Protection (FDEP) 2006; Florida Statutes 2006]. The weekly irrigation depth was set to replace the monthly historical ET-based irrigation schedule, based on recommendations by Dukes and Haman (2002a) for the area where this experiment was carried out. However, this irrigation system did not include a rain sensor, thus simulating homeowner irrigation systems with an absent or nonfunctional rain sensor. Four pulse-type positive displacement flowmeters (PSMT 20 mm × 190 mm, Amco Water Metering Systems, Inc., Ocala, FL) were connected to a CR 10X datalogger to continually measure irrigation volume and frequency applied to the same number of plots, of 3.6 × 3.6 m each, covered with common bermudagrass [*Cynodon dactylon* (L.) Pers]. Potential water savings were computed, taking into account the volume of water that would have been saved from an irrigation cycle, when an individual RS was in bypass mode, at the same day and time when the irrigation cycles were scheduled.

Data were analyzed as a completely randomized design using the general linear model (GLM) procedure of the Statistical Analysis System (SAS) software (SAS 2003). If significant F values ($P < 0.05$) were detected, Duncan's multiple range test was used to separate means.

Results and Discussion

Weather Conditions

Fig. 3 shows the daily and cumulative rainfall during the experiment. During the 282-day experiment, 174 days exhibited rainfall (62%), including 11 days with more than 25 mm. The cumulative precipitation was 1,112 mm, an amount that is not uncommon in this region. However, there was one dry period in the late fall, from October 25 through November 20, when just one event of 0.5 mm occurred. Over the entire monitoring period, the tipping bucket rain gauge was very accurate ($R^2 = 0.99$) compared to the manual rain gauge across a range of rainfall events from less than 1 mm up to 60 mm.

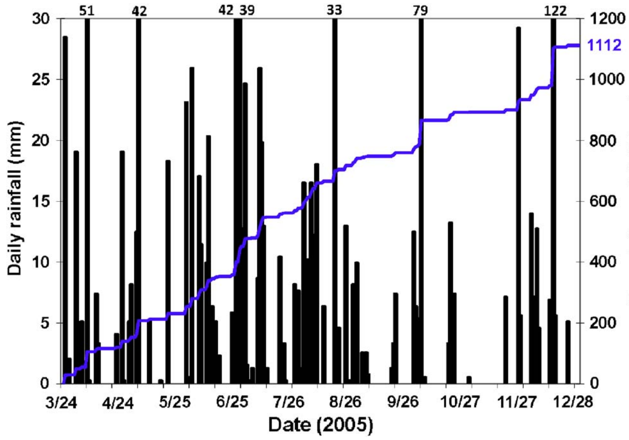

Fig. 3. Daily and cumulative rainfall

Number of Times in Bypass Mode

The cumulative number of times that sensors switched to bypass mode, averaged by treatment, is shown in Fig. 4. It can be seen that the cumulative number of times in bypass mode were statistically different, where WL > 3-MC > 13-MC > 25-MC, with 81, 43, 30, and 8 events, respectively, in the 282-day experiment. However, as seen in Fig. 5, the number of times in bypass mode within treatments was variable, with 3-MC and 13-MC the most variable treatments.

The four replications of the WL treatment [Fig. 5(a)] were extremely consistent, with a similar number of events in bypass mode (between 78 and 83). However, this was not the case of 3-MC [Fig. 5(b)]. All four 3-MC sensors behaved similarly for the first 13 rainfall events. After June 3, two units (1 and 2)

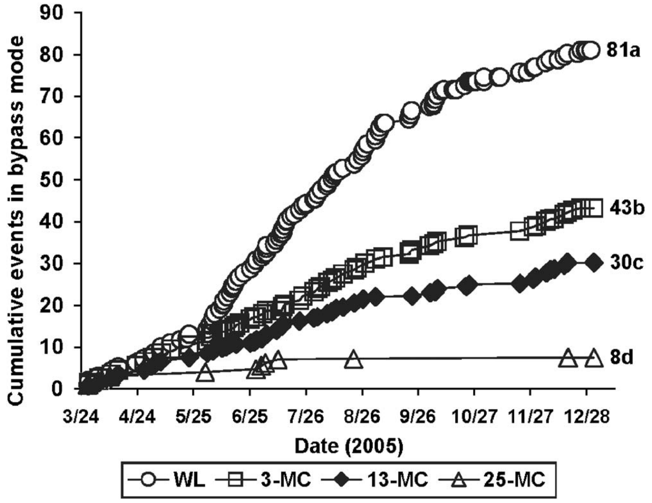

Fig. 4. Cumulative number of times rain sensors switched to bypass mode; average per treatment. Different letters indicate a significant difference by Duncan's multiple range test ($P < 0.05$).

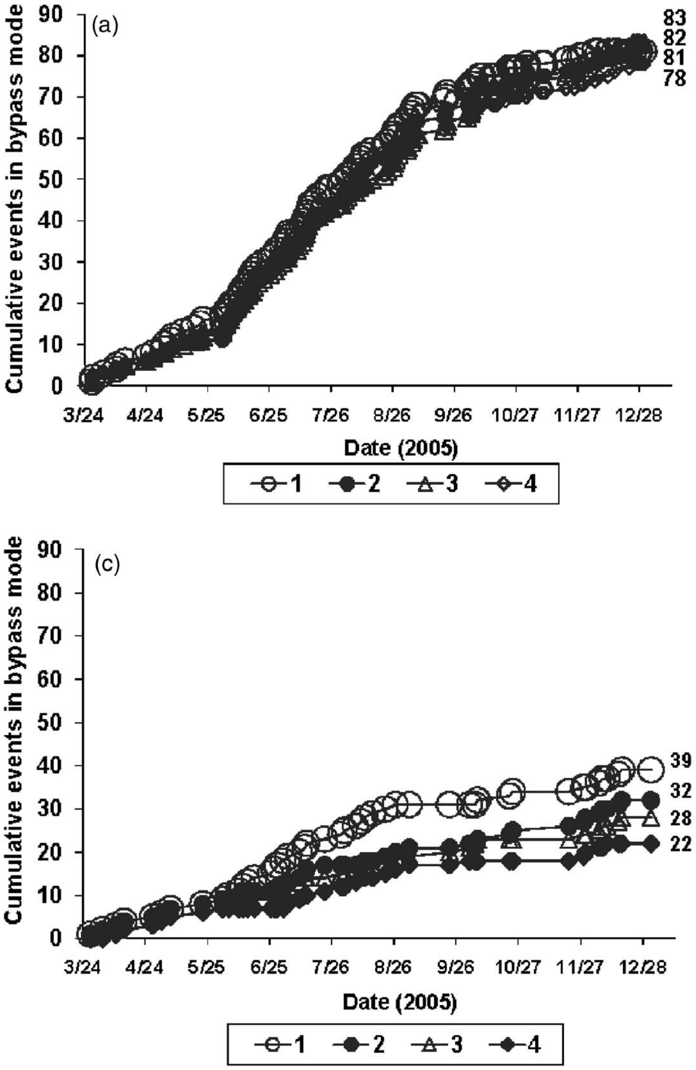

Fig. 5. Cumulative number of times rain sensors switched to bypass mode, with replicates indicated by 1–4; where (a) WL; (b) 3-MC; (c) 13-MC; and (d) 25-MC treatments

continued to have the same behavior, while replicates 3 and 4 had similar performance to each other, but did not bypass as many events as replicates 1 and 2, with 30–36 versus 53–54 times, respectively. Similar to 3-MC, treatment 13-MC also showed irregular performance between replicates [Fig. 5(c)]. With the exception of the first two rain events, which were not sensed by replicate 4, all replicates switched to bypass mode on the same dates until June 3 (similar to 3-MC). After that date, replicate 1 bypassed more times than the other replicates (39 times versus 32, 28, and 22 times, for replicates 1, 2, 3, and 4, respectively). No recorded weather data or physical evidence was found to explain the different performances after June 3.

Replicates from treatment 25-MC performed similarly [Fig. 5(d)], shutting off between seven to eight times. All sensors worked identically for the first four rainfall events and then replicates 1 and 3 operated similarly, while the performance of the other two replicates was slightly different. The difference in sensor performance for the 25-MC treatment was not as pronounced as the other MC-treatments, in part due to fewer rain events (11) greater than 25 mm.

Depth of Rainfall before Shutoff

The average depth of rainfall before the rain sensors switched to bypass mode is shown in Table 1. Treatment WL shut off after 1.4 mm of rain on average but, because this model does not have a specific set point, accuracy cannot be calculated. Treatments 3-MC, 13-MC, and 25-MC shut off after 3.4, 10.0, and 24.5 mm, resulting in accuracies of 88, 77, and 98%, respectively. These

Table 1. Average Depth of Rainfall before Rain Sensors Switched to Bypass Mode

Treatment	Set point (mm)	Rainfall depth (mm)	Accuracy (%)
3-MC	3	3.4	88
13-MC	13	10.0	77
25-MC	25	24.5	98
WL	—	1.4	—[a]

[a] Because these instruments do not declare a specific set point, accuracy cannot be calculated.

Table 2. Large Rainfall Events Not Bypassed by Rain Sensors

Date	Rainfall (mm)	Treatments		
		3–MC	13–MC	25–MC
Mar. 26	29		3,4[a]	
April 1	19		3,4	
May 5	42		3[b],4[b]	
June 7	17	3,4		
June 8	11	3,4		
June 12	20	3,4	2,4	
June 27	42			3
June 29	39			4
July 2	25	3,4	2,3,4	
Aug. 3	16	3,4		
Aug. 7	17	3,4		
Aug. 8	12	3,4		
Aug. 10	18	3,4		
Aug. 20	33			1,2,3
Oct. 6	79	3,4	3,4	1,2,3,4
Dec. 17	122	3,4	2,4	1,2,3

[a] 1,2,3, or 4=one of four replicates per treatment.

[b] Shut off after 45 mm of rainfall.

average accuracies suggest that, in general, the MCs responded close to their settings, with 25-MC and 3-MC operating closest to their set point.

However, some rainfall events, large enough to meet the RS settings and to theoretically shut off the irrigation system, were not detected by some units, as seen in Table 2. For example, on treatment 3-MC, replicates 3 and 4 did not detect rainfall events between 11.4 and 122.0 mm on ten occasions. On treatment 13-MC, one or more of three units did not bypass some rain events between 19.1 and 122.0 mm on seven different occasions. In the case of 25-MC, five rain events larger than 33 mm were not sensed by one or more units. If any of these rain events would have been coincident with a scheduled irrigation cycle, irrigation would have been allowed, when actually not needed. A relationship between this behavior and rain intensity, relative humidity, or speed wind was not found. In addition, the mechanical parts of the rain sensors were investigated and differences were not apparent.

On seven occasions, some units from 3-MC (Table 3) shut off several hours after the rain had stopped (even more than 24 h later). The same situation happened with some units from 13-MC on twelve different occasions (Table 4). Moreover, on April 7, replicate 4 from 13-MC switched to bypass mode after 11.7 mm of rain, then switched to ON when it was still raining, and did not switch to bypass mode again, even when it rained an additional 28 mm.

Table 3. Hours after Rain Stopped and Sensors Switched to Bypass Mode; Treatment 3-MC

Date	Replicate (*h*)			
	1	2	3	4
July 3				6
Aug. 1			6	
Sept. 21	6	4		
Nov. 30			18	
Dec. 10			X	
Dec. 16			18	
Dec. 20			X	X

Note: X=more than 24 h.

Table 4. Hours after Rain Stopped and Sensors Switched to Bypass Mode; Treatment 13-MC

Date	Replicate (*h*)			
	1	2	3	4
Apr. 7				X[a]
May 6				X
July 4		X	10	X
Aug. 6		19		
Aug. 7			14	
Aug. 11			18	
Aug. 14	7			
Aug. 31			10	
Sept. 2				X
Oct. 5		5		
Nov. 21			3	
Dec. 10				X

Note: X=more than 24 h.

[a] Switched to ON when it was raining. After that, it rained 28 mm extra.

In contrast to MC performance, WL treatments sometimes switched to bypass mode in the absence of rainfall. The number of times that this happened ranged between 11 and 22 for the different replications, with an average of 16 times. The sensors remained in bypass mode for a minimum of 1 min, a maximum exceeding 10 h, and an average of more than 3 h. These situations were triggered when high relative humidities occurred (95% on average) or, on five occasions, minutes before a rainfall event began. Therefore, these sensors appear to be very sensitive to Central Florida weather conditions, with the drawback that they could bypass a scheduled irrigation cycle even when no rainfall occurred, a situation that happened twice during this experiment. Moreover, if no rainfall and high relative humidity occur at the same time for a long period, it could result in damage to plants in the irrigated area.

Duration in Irrigation Bypass Mode (Dry-Out Period)

Fig. 6 shows histograms and frequency distribution for 6 h intervals in bypass mode for treatments WL, 3-MC, and 13-MC. Because of the small number of occurrences for 25-MC (seven to eight times), the number of occurrences for a time interval was not greater than five, hence a histogram and frequency distribution could not be plotted (Figliola and Beasley 2000).

Results showed that half the time WL-sensors remained in bypass mode between 0 and 12 h [Fig. 6(a)], 80% of the time they remained in that status for less than 24 h, and only 5% of the events lasted between 54 and 78 h. This is concordant with manufacturer claims that the WL sensors will remain in that status shortly after the rain stops (Hunter Industries, Inc. 2006). Treatment 3-MC [Fig. 6(b)] remained in bypass mode less than 24 h most of the time (51%, with a peak between 18 and 24 h), and more than 80% of the time remained in that status for less than 48 h. For 13-MC, most of the time in bypass mode was for less than 24 h (57%), similar to 3-MC, and more than 80% of the time they did not stay in that status for more than 36 h [Fig. 6(c)]. Although it was not possible to generate a histogram for 25-MC, the maximum length in bypass mode was just over 30 h. Hence, the lower set points tended to stay in bypass mode for a longer

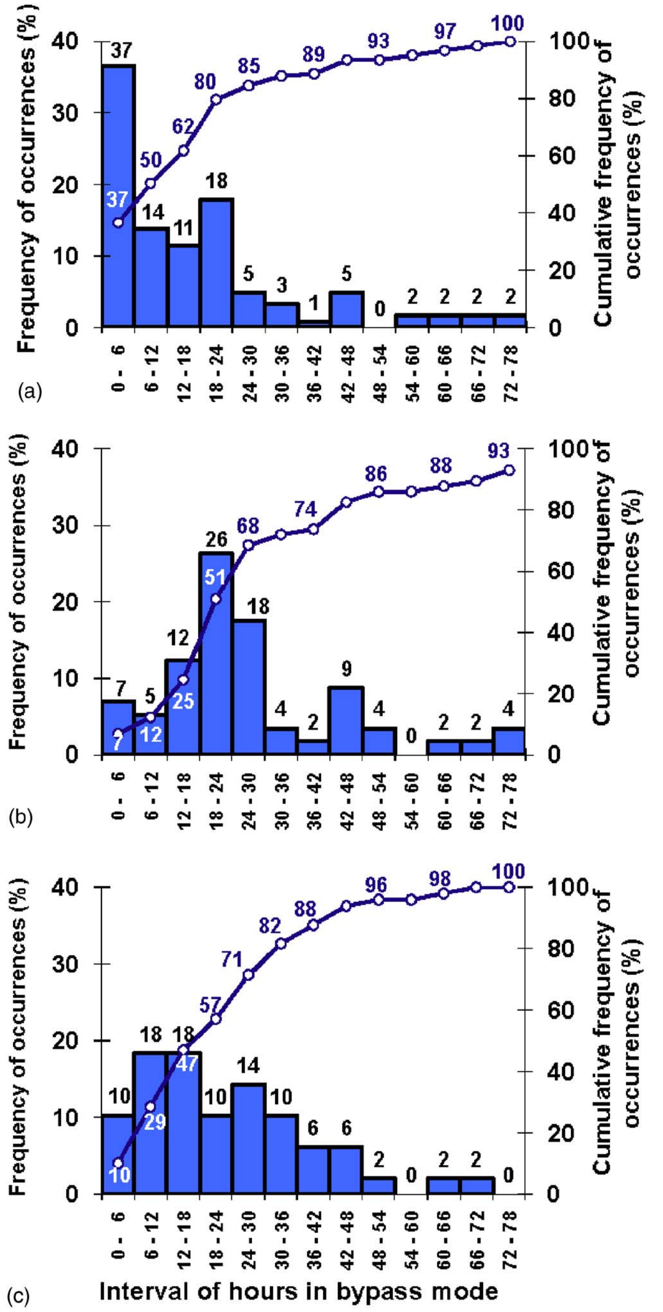

Fig. 6. Histogram and frequency distribution for 6-h intervals in bypass mode; where (a) WL; (b) 3-MC; and (c) 13-MC

period of time. This is explained by the larger number of successive small rainfall events that occurred, keeping the sensors with lower settings in bypass mode for a longer period of time.

Potential Water Savings

The total irrigation depth allowed by the irrigation system without a rain sensor was 818 mm, during the time frame of this experiment (Table 5). Treatments WL, 3-MC, 13-MC, and 25-MC would have allowed 455, 573, 676, and 793 mm, respectively, if connected to this system. This represents 363, 245, 142, and 25 mm of potential water savings, respectively, compared to a system without a RS. Therefore, treatment WL accounted for the highest potential water savings among the treatments (44%), followed by 3-MC (30%), and 13-MC (17%). Treatment 25-MC showed small potential water savings (3%) compared to the other treatments.

Table 5. Total Irrigation Depth and Potential Water Savings per Treatment Compared to a 2 d/wk Irrigation System without a Rain Sensor

Treatment	Irrigation depth (mm)	Water savings (mm)	Water savings (%)
WL	455	363	44
3-MC	573	245	30
13-MC	676	142	17
25-MC	793	25	3
No rain sensor	818	0	0

Payback Period

In order to quantify how much money the potential water savings could represent, and to calculate the payback period for the rain sensors, some assumptions were made. According to Augustin (2000), the historical net irrigation requirements for this period of study, for the Gainesville area, are around 97% of the total requirements per year, so no corrections to the final amounts were made. The current commercial cost for a WL unit is \$75, and \$22 for a MC unit. Assuming an installation cost of \$50, and 1,000 m^2 of turf to be irrigated, Table 6 shows the potential payback period per treatment at different water costs. Water costs in Florida for single-family homes, inside-city limits, no taxes included, ranged from \$0.15 to \$1.18/m^3 (\$0.50 to \$10.31/thousand gallons) in 2003 and average \$0.60/m^3 (\$2.28/thousand gallons) when considering monthly use less than 2.6 m^3 (Whitcomb 2005). These cost estimates are conservative since sewer rates are typically determined from water use, which would double the cost in many cases. If the water cost was \$0.66/m^3 (\$2.28/thousand gallons), the payback period would have been less than a year for WL, 3-MC, and 13-MC treatments, but greater than four years for 25-MC.

According to this analysis, except for 25-MC, the installation and maintenance of a RS appears to be strongly justified as a means to save water in Florida. However, few people appear to be realizing the savings. As the study by Whitcomb (2005) recently found, just 25% of the surveyed homeowners in Florida with automatic irrigation systems reported having a RS, and the author speculated that they are often incorrectly installed. Therefore, appropriately installed and maintained rain sensors could result in not only substantial water savings to homeowners, but also sound environmental and economic benefits to the state.

Table 6. Potential Payback Period per Treatment Assuming Annual Water Savings over 1,000 m^2 of Irrigated Area

Water cost		Payback period per treatment (years)			
(\$/TG)[a]	(\$/m^3)	WL	3-MC	13-MC	25-MC
0.5	0.13	2.6	2.2	3.7	21.2
1.0	0.26	1.3	1.1	1.9	10.6
1.5	0.40	0.9	0.7	1.2	7.1
2.0	0.53	0.7	0.5	0.9	5.3
2.5	0.66	0.5	0.4	0.7	4.2

[a] TG=thousand gallons.

Summary and Conclusions

A study to quantify performance of rain sensors was carried out during a rainy period, where 62% of the days had rainfall. The cumulative number of times that sensors switched to bypass mode, when averaged by treatment, were inversely proportional to their set points. Accuracy test results suggested that, on average, the MCs responded close to their set points. However, replicates at a particular set point were variable, sometimes responding properly according to their settings, sometimes not detecting rainfall events five or more times their set points, and sometimes even shutting off several hours after the rain had stopped. This explains the range of variation in the number of times that individual RS units switched to bypass mode. On the other hand, high relative humidities sometimes caused WL units to switch to bypass mode in absence of rainfall, suggesting that they may be too sensitive for Central Florida weather conditions. In general, the lower set points on the MC treatments tended to stay in bypass mode for a longer period of time, due to the larger number of successive small rainfall events that kept them in this condition. Treatment WL tended to stay in bypass mode for a shorter period of time than MC treatments.

The potential water savings of the various RS set points were inversely proportional to their set point. Depending on the area to be irrigated, the cost of the installed RS, the weather conditions, and on the cost of water, the payback period would be less than a year for WL, 3-MC, and 13-MC. However, setting the MC at 25 mm is not recommended in Central Florida, because it showed small potential water savings, even in a rainy year. Finally, this study showed that RSs can be a useful and highly recommended tool when used by homeowners as a means to save water in Florida, but not when accuracy is required.

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Notation

The following symbols are used in this paper:

A = accuracy; and
ε = error.

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