# SENSOR-BASED AUTOMATION OF IRRIGATION OF BERMUDAGRASS

By

BERNARD CARDENAS-LAILHACAR

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2006

To my parents and sons

# ACKNOWLEDGMENTS

In the first place, I wish to thank my parents for their always enormous and unconditional love, support, and guidance; my sons for being the most adorable human beings I have ever met; my ex-wife for taking care of them while I was completing my studies, her understanding, patience, and sacrifice; and my amorcita for her enormous support, understanding, patience and, most of all, her immense love. Next, I would like to thank all my thesis committee members for being not just professors, but great human beings: Dr. Dorota Z. Haman and Dr. Grady L. Miller, also for their guidance and patience, and a huge thank you goes to Dr. Michael D. Dukes, for giving me the opportunity to work with him, which was always a lot of work, but also a pleasure. Also, I wish to give a special thank you to Melissa B. Haley for being always ready to help me. Lastly, I would also like to thank Engineer Larry Miller, Senior Engineering Technician Danny Burch, and students Mary Shedd, Stephen Hanks, Clay Coarsey, Brent Addison, Jason Frank, and Clay Breazeale for their assistance on this research. This research was supported by the Pinellas-Anclotte Basin Board of the Southwest Water Management District, the Florida Nursery and Landscape Growers Association, and the Florida Agricultural Experiment Station.

## TABLE OF CONTENTS

page

APPENDIX

# LIST OF TABLES

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Science

# SENSOR-BASED AUTOMATION OF IRRIGATION OF BERMUDAGRASS

By

Bernard Cardenas-Lailhacar

August 2006

Chair: Michael D. Dukes
Major Department: Agricultural and Biological Engineering

Turfgrass in landscapes contributes to substantial cropped area in Florida. New irrigation technologies could improve irrigation efficiency, promoting water conservation and reducing the environmental impacts. The objectives of this research were to quantify differences in irrigation water use and turf quality among 1) a soil moisture sensor-based irrigation system compared to a time-based scheduling, 2) different commercial irrigation soil moisture sensor (SMSs), 3) a time-based scheduling system with or without a rain sensor (RS), and 4) the reliability of two commercially available expanding disk RS-types. The experimental area consisted of common bermudagrass (*Cynodon dactylon L.*) plots (3.66 x 3.66 m) in a completely randomized design, located in Gainesville, Florida. The monitoring period for the irrigation treatments took place from 20 July through 14 December of 2004 and from 25 March through 31 August of 2005. Treatments consisted of irrigating one, two, or seven days a week, each with four different commercial SMSs brands. A non-irrigated control and time-based treatments were also implemented. In addition, twelve Mini-Click (MC) and four Wireless Rain-Click (WL) rain sensor models not connected to irrigation were monitored from 25 March through 31 December 2005. For the MCs, three different thresholds were established: 3, 13, and 25 mm (codes 3-MC, 13-MC, and 25-MC, respectively). No significant differences in turfgrass quality among irrigation treatments were detected. On average, SMS-based treatments reduced irrigation water application compared to time-based treatments. The treatment without-rain-sensor (2-WORS) used significantly (52%) more water than the with-rain-sensor treatment (2-WRS). Most brands recorded significant irrigation water savings compared to 2-WRS, which ranged from 54% to 88%, for the best performing sensors, and depending on the irrigation frequency. Therefore SMS-systems represent a promising technology, because of the water savings that they can accomplish, while maintaining an acceptable turfgrass quality during rainy periods (944 and 732 mm of rainfall, for seasons 2004 and 2005, respectively). On average, RS treatments WL, 3-MC, 13-MC, and 25-MC responded close to their rainfall set points (1.4, 3.4, 10.0, and 24.5 mm, respectively). However, some replications showed erratic behavior through time. The number of times that these sensors shut off irrigation was inversely proportional to the magnitude of their set point (81, 43, 30, and 8 times, respectively) with potential water savings following a similar trend (363, 245, 142, and 25 mm, respectively). Under the relatively wet testing conditions typical to Florida, the payback period could be less than a year, except for 25-MC (around 7 years). Consequently, RSs are strongly recommended for use by homeowners as a means to save water, but not when accuracy is required.

# CHAPTER 1
# INTRODUCTION

Turfgrass is the main cultivated crop in Florida with nearly four times the acreage as the next largest crop, citrus (Hodges et al., 1994; United States Department of Agriculture [USDA], 2005). Irrigation of residential, industrial, commercial, and recreational turf areas is necessary to ensure acceptable turf quality. As a consequence of problems related to drought, coupled with a steadily increasing demand for water resources, the state of Florida has imposed restrictions on irrigation water use. Water used for turfgrass irrigation, however, remains to be publicly discussed. The development of Best Management Practices (BMPs) for irrigation water use in landscapes has become an undeniable strategic, economic, and environmental issue for the state. New irrigation technologies could improve irrigation efficiency, promoting water conservation and reducing the environmental impacts of turfgrass culture, which is a major component of landscapes in Florida.

## Water

Florida receives an average of around 1400 mm of rainfall a year (National Oceanic and Atmospheric Administration [NOAA], 2003). Unlike many areas dependent on irrigation, annual rainfall in Florida typically exceeds evapotranspiration. Nevertheless, irrigation is required because total annual rainfall for Florida typically varies both geographically and temporally (USDA, 1981; Carriker, 2000). Such rainfall variation has a direct impact on surface water and groundwater supplies. Lack of rainfall for even a few days causes depletion of moisture in sandy soils commonly found in Florida; along with reduction of stream flow and groundwater recharge (Carriker, 2000; National Research Council, 1996).

## Water Demand

Florida has the second largest withdrawal of groundwater for public supply in the United States (Solley et al., 1998). Groundwater was the source of more than 88% of the water withdrawn for public supply in 1990 (Carriker, 2000). In 1995, nearly 93% of population in Florida used groundwater as a drinking water source (Solley et al., 1998). Water withdrawals for public supply in Florida have increased rapidly, from 600,000 $m^3$/day in 1950 to 7.3 million $m^3$/day in 1990 (Carriker, 2000). The population served by public-supply systems increased from 5.42 million in 1970 to 11.23 million in 1990 (Marella, 1992).

Florida has a fast-growing population with a net inflow of more than 1100 people a day, and ranks as the second largest net gain in the nation. The population of 17 million in 2004 is projected to exceed 21 million people by 2015, becoming the third most populous state in the nation (United States Census Bureau [USCB], 2004a). The U.S. Census Bureau estimated 156.8 thousand single-family housing starts and 56.7 thousand multi-family housing starts in Florida in 2003, accounting for approximately 11% of all new homes constructed in the United States, the largest amount in any single state in the U.S. (USCB, 2004b). As urban populations swell, pressures on limited supplies of clean water are increasing, and it may become a scarce resource.

## Water Use

Indoor water use per person in the U.S. is relatively constant across all geographic and social lines. Depending on climate, residential outdoor water use can account for 22% to 67% of total annual water use (Mayer et al., 1999). The primary use of residential outdoor water is irrigation. Historically, Florida exhibit dry and warm spring and fall weather, as well as sporadic large rain events in the summer. These climatic conditions, coupled with low water holding capacity of the soil, make irrigation indispensable for the high quality landscapes desired by homeowners (Haley et al., 2006; National Research Council, 1996).

Recent studies in the U.S. indicate that, on average, 58% of potable water is used for landscape irrigation (Mayer et al., 1999). In the Central Florida Ridge, this average has been show to be as high as 74% (Haley et al., 2006). Consequently, proper irrigation water use clearly represents a substantial opportunity for residential water savings.

Furthermore, residential water use research, carried out by Mayer et al. (1999), found that homeowners with a standard landscape used 77 mm per month, on average, for irrigation purposes in U.S. However, in Central Florida, Haley et al. (2006) found that typical homeowners with a standard landscape for the region, which consisted of approximately three-quarters turfgrass across the irrigated area, used an average of 149 mm per month. Therefore, opportunities that result in better irrigation scheduling by homeowners may lead to substantial savings in irrigation water use.

## Water Use Restrictions

The Florida Water Resources Act of 1972 established a form of administrative water law that brought all waters of the state under regulatory control. Five Water Management Districts (WMDs) were formed, encompassing the entire state (National Research Council, 1996; Burney et al., 1998). These agencies have the legal authority and financial capacity to manage water comprehensively, and can impose conservation and water shortage management (National Research Council, 1996).

The Florida Department of Environmental Protection (FDEP, 2002) specifies some water use classifications to be employed when implementing water use restrictions, describing landscape irrigation as “the outdoor irrigation of grass, trees and other plants in places such as residences, businesses, golf courses, parks, recreational areas, cemeteries, and public buildings.”

When a WMD declares a water shortage, it will impose water use restrictions in different phases depending upon the severity of the shortage. The phase names and their specific goals in water use reduction are: I Moderate: 15%, II Severe: 30%, III Extreme: 45%, and IV Critical: 60%. Moreover, any local government has the right to impose even stronger water restrictions (FDEP, 2002).

Where there is a year-round watering rule, it applies to everyone who uses water outdoors–homes, businesses, parks, golf courses, etc.–regardless of the water source, whether private well, public utility or surface water. However, there are some exceptions to the water restrictions, such as when reclaimed or reuse water is being used (St. John’s River Water Management District [SJRWMD], 2006).

Much of Florida is under Phase II water restrictions. Basically, this means that lawn watering is limited to two days a week (Wednesdays and Saturdays for odd-number addresses, Thursdays and Saturdays for evens), and restricted to certain hours to reduce evaporative and wind losses (before 1000 h and after 1600 h in the Orlando area, for instance, or before 0800 h and after 1600 h in parts of South Florida). As of the end of March 2001, the densely populated southernmost part of the state–including Palm Beach, Broward, Dade and Monroe counties–was under even tougher regulations. Lawn watering was allowed for only three hours, one day a week (SJRWMD, 2006). Since

1991, there have been water restrictions enforced by the St. Johns River Water Management District (SJRWMD), district where this study was carried out. Residential irrigation is limited to two days per week and prohibited between 1000 h and 1600 h, regardless of the water source (SJRWMD, 2006).

Violating Florida's water restrictions is punishable with penalties of up to $500, with additional fees as applicable. South Florida is enforcing a tough zero-tolerance policy (SJRWMD, 2006).

## Landscapes in Florida

Florida homeowners now maintain more than 1.5 million hectares of lawn with 20,000 hectares of new grass planted every year (American Water Works Association [AWWA], 2005).

In an effort to meet Florida's water conservation goals, Volusia County has passed an ordinance requiring new homes to have less grass. The ordinance mandates that new yards at homes and businesses have landscapes requiring little or no irrigation. Homeowners can have up to 75% of the yard with grass if the rest of the landscape retains the original, natural vegetation without irrigation. Under the ordinance, 50 percent of a new landscape can be irrigated up to 25 mm of water per week (AWWA, 2005). Likewise, in Sarasota County, according to its Ordinance #2001-081, from year 2001, new single and multi-family residences will have no more than 50% of the total irrigated landscape dedicated to high irrigation water use zones including turf, annuals and vegetable gardens (Sarasota County, 2006). Similar restrictions have been in effect in the Tampa Bay area (Tampa Bay Water, 2005).

These types of ordinances that limit plant type assume that turfgrass water needs are responsible for excessive water application. However, recent research in Central

Florida indicates that excessive water application is due to homeowner mis-management of irrigation (Haley et al., 2006). Similar conclusions were found in the Tampa Bay region, where approximately 30 percent of irrigation water use is wasted due to inefficient irrigation system design, installation, operation, or maintenance (Tampa Bay Water, 2005).

## Irrigation

An efficient irrigation schedule is the application of water in the correct amount and only when needed. Under-irrigation and over-irrigation can negatively affect turfgrass quality. Over-irrigation tends to have environmentally costly effects because of wasted water and energy, leaching of nutrients and/or agricultural chemicals into groundwater supplies, degradation of surface water supplies by sediment-laden irrigation water runoff, and erosion (Ley et al., 2000), and increased evapotranspiration (Biran et al., 1981). Increasing irrigation efficiency, using just the appropriate amount of water to irrigate lawns, can be achieved by a number of different methods.

### Irrigation Timers

Irrigation time clock controllers, or timers, are an integral part of an automatic irrigation system. They are an essential tool to apply water in the necessary quantity and at the right time; however, through incorrect programming, timers can result in over-irrigation. Time clock controllers have been available for many years in the form of mechanical and electromechanical irrigation timers. These devices have evolved into electronic systems that rely on solid state and integrated circuits, so they tend to be very flexible and provide a large number of features at a relatively low cost, allowing accurate control of water, while responding to environmental changes and plant demands (Zazueta et al., 2002; Boman et al., 2002).

Two general types of timers are used in automatic irrigation systems: Open Control Loop systems and Closed Control Loop systems. Open Control Loop systems apply a preset action, as is done with simple mechanical irrigation timers. In a Closed Control Loop (CCL) the system receives feedback from one or more sensors, make decisions, and apply the results of these decisions to the irrigation system (Zazueta et al., 2002). First, it is necessary to set up a general strategy in the timer. Then, the control system takes over and makes decisions of whether or not to apply water based on data from the sensor(s). For example, soil moisture sensors can avoid irrigation when adequate soil moisture is already present, rain sensors can prevent irrigation during or after significant rain, wind sensors can stop the system when a speed-threshold is surpassed, sensors can be used to detect pressure and shut the system down if the pump is not primed or to initiate flush cycles in filters, etc. (Zazueta et al., 2002; Boman et al., 2002).

The simplest form of a CCL system is to set up a high-frequency irrigation in the timer, which could be interrupted by a soil moisture sensor. The sensor is wired into the line that supplies power from the timer to the electric solenoid valve (Figure 1-1). The sensor operates as a switch that responds to soil moisture content. When sufficient soil-moisture is available, the sensor maintains an open circuit between the timer and the solenoid valve. When soil-moisture drops below a certain threshold, the sensing device closes the circuit. Thus, the irrigation control system can bypass a pre-programmed schedule, or maintain the soil water content within a specified range. These two approaches are known as bypass and on-demand, respectively (Dukes and Muñoz-Carpena, 2005). Bypass configurations skip an entire timed irrigation event based on the soil water status at the beginning of that event or by checking the soil water status at intervals within a time-based event (Muñoz-Carpena and Dukes, 2005).

### Soil Moisture Content Measurement

The standard method of measuring soil moisture content is the thermogravimetric method, which requires oven drying of a known volume of soil at 105 °C and determining the weight loss. This method is time consuming and destructive to the sampled soil, meaning that it cannot be used for repetitive measurements at the same location. However, it is indispensable as a standard method for calibration and evaluation purposes (Walker et al., 2004).

Among the widely used on-site soil moisture measurement techniques are neutron scattering, gamma ray attenuation, soil electrical conductivity (including electrical conductivity probes, electrical resistance blocks and electromagnetic induction), tensiometry, hygrometry (including electrical resistance, capacitance, piezoelectric sorption, infra-red absorption and transmission, dimensionally varying element, dew point, and psychometric), and soil dielectric constant (including capacitance and time domain reflectometry). Reviews on the advantages, disadvantages, and basis of these measurement techniques may be found in Schmugge et al., 1980; Campbell and Mulla, 1990; Charlesworth, 2000; Ley et al., 2000; Topp, 2003; Muñoz-Carpena, 2004; and Walker et al., 2004.

### Granular matrix sensor

The granular matrix sensor (GMS) is a device that measures soil electrical resistance, that can be converted to soil water tension (SWT), either using a calibration formula provided in the literature for sandy soils (Irmak and Haman 2001) and silt loam soils (Eldredge et al., 1993), or calibrating them for a specific soil type (Hanson et al., 2000b; Intrigliolo and Castel, 2004).

The GMS (Figure 1-2) is made of a porous ceramic external shell with an internal granular matrix material, which approximates compressed fine sand, containing two electrodes. A synthetic porous membrane for protection against deterioration surrounds the matrix material. The GMS includes an internal gypsum cylindrical tablet, which provides buffering against salinity effects that may cause erroneous readings. A stainless steel casing, with holes drilled in it, surrounds the synthetic porous membrane.

The GMS operates on the electrical resistance principle: water conditions in the unit change with corresponding variations in water conditions in the soil, and changes within the block are reflected by differences in resistance between the electrodes.

The transmission matrix material was designed to respond faster than gypsum blocks to SWT in the 0 to 100 kPa range. Some commercial GMSs exhibit good sensitivity to SWT over a range from 0 to 200 kPa. This makes them more adaptable to a wider range of soil textures and irrigation regimes than traditional gypsum blocks and tensiometers (Thomson et al., 1996; Charlesworth, 2000). Also, the GMSs are much more stable and have a longer life than gypsum blocks and, compared to tensiometers, require little maintenance and can be left in the soil under freezing conditions (Ley et al., 2000).

### Modern soil moisture sensors

The concept of connecting to timers one or more soil moisture sensors (SMSs) to determine irrigation needs, and to automate irrigation systems, has moved forward in recent years. Over the last decade, the SMS industry has advanced dramatically. Two basic reasons can explain this advancement. The first has been the major development of computer technology (with more powerful, smaller and economical integrated circuits). The other phenomenon has been the significant advances in the application of electromagnetic methods to the measurement of soil water content. These methods make use of the high relative permittivity (dielectric constant) of the water in soil for estimating the water content. The relative permittivity of water is about 80, whereas the other components in soil, including air, have relative permittivities in the range of one to seven. Hence, methods that measure the relative permittivity are effective for the measurement of soil water content (Topp, 2003).

Combining the computer technology and the soil dielectric concept has allowed manufacturers to produce a number of different types of inexpensive SMSs for irrigation scheduling. An increasing adoption of the dielectric methods has been observed, because they are non-destructive, provide almost instantaneous measurements, do not require maintenance, and can provide continuous readings through automation. However, they have important differences in terms of calibration requirements, accuracy, cost, installation and maintenance requirements, etc. (Muñoz-Carpena and Dukes, 2005).

The main techniques used by these sensors can be classified as Time Domain Reflectometry (TDR) and Frequency Domain Reflectrometery (FDR) (Leib et al., 2003).

**Time domain reflectometry.** The speed of an electromagnetic signal passing through a material varies with the dielectric of the material. Most TDR instruments operate by sending a step pulse signal down steel rods (called wave-guides) buried in the soil. The signal reaches the end of the probes and is reflected back to the TDR control unit where it is detected and analyzed. The time taken for the pulse to return varies with the soil dielectric, which is related to the water content of the soil surrounding the probe (Topp, 2003).

According to Charlesworth (2000) and Edis and George (2000), TDR instruments give the most robust soil water content data, with little need for recalibration between different soil types. An important advantage of TDRs in turfgrass irrigation management, is that accurate measurements may be made near the surface compared to techniques such as the neutron probe (Ley et al., 2000).

**Frequency Domain Reflectometry.** Frequency domain reflectometry (FDR) measures the soil dielectric by placing the soil (in effect) between two electrical plates to form a capacitor. Hence ‘capacitance’ is the term commonly used to describe what these instruments measure. When a voltage is applied to the electric plates a frequency can be measured. This frequency varies with the soil dielectric (Charlesworth, 2000).

In spite of the advances and advantages of these modern SMSs, when comparing the performance of different brand/types, significant differences were found in respect to set-up requirements, accuracy, data interpretation, maintenance, and initial cost (Ley et al., 2000) and the ability to repeat measurements accurately over time and under various moisture regimes after initial calibration (Yoder et al., 1998).

### Controllers

Modern commercially available SMS-systems include a controller. This piece of equipment is the one that sends the signal to the buried SMS and reads the soil moisture content. The controller has an adjustable threshold (Figure 1-3), which can be set between relatively dry to wet soil moisture conditions; depending on the plant material, soil type, depth-installation of the SMS, etc. In general, manufacturers recommend setting the thresholds 24 hours after a significant rainfall event or after an irrigation that filled the soil profile with water to field capacity. The controller is connected in series with the residential irrigation timer and acts as a switch depending on the pre-set soil moisture threshold.

## Automatic Control of Irrigation

An automatic SMS-based irrigation system seeks to maintain a desired soil moisture range in the root zone that is optimal or adequate for plant growth and/or quality. This type of system adapts the amount of water applied according to plant requirements without managers having to undertake daily monitoring or make adjustments according to actual weather conditions (Muñoz-Carpena and Dukes, 2005; Pathan et al., 2003).

The continuous monitoring of the soil moisture status becomes particularly important in sandy soils. A wide range of applications to automatically control irrigation events has been investigated in coarse textured soils. In Florida, switching tensiometers have been studied for agricultural production (Smajstrla and Koo, 1986, Clark et al., 1994; Smajstrla and Locascio, 1994; Muñoz-Carpena et al., 2003, Muñoz-Carpena et al., 2005), and for maintaining bermudagrass turf (Augustin and Snyder, 1984). Although they found water savings, these investigations suggest that tensiometers require calibration and frequent maintenance, up to twice per week. Consequently, the adoption of this technology will not lead to automatically controlled irrigation since it will not eliminate human interaction in irrigation management.

Other types of sensors have been adapted to automate irrigation based on soil moisture status. Nogueira et al. (2002) used TDR sensors to maintain soil moisture within two preset limits (upper and lower soil moisture thresholds). Dukes and Scholberg (2005) and Dukes et al. (2003) found 11% and 50% in water savings, without diminishing yields on sweet corn and green bell pepper, using TDR probes and a commercially available dielectric sensor, respectively. Granular matrix sensors (GMSs) have also been used to automatically irrigate agricultural products (Muñoz-Carpena et al., 2003; Shock et al., 2002) and, as with other solid-state sensors, do not require as much maintenance as tensiometers. Although TDR and GMS, as well as similar types of sensors, have been successfully used in agriculture, they have found limited use in residential landscape irrigation (Qualls et al., 2001).

### Rain Sensors

A rain sensor (RS), also called rain shut-off device (Figure 1-4), is a piece of equipment designed to interrupt a scheduled cycle of an automatic irrigation system controller when a specific amount of rainfall has occurred and, depending on the weather conditions, after the said rainfall (Dukes and Haman, 2002b; Hunter Industries Inc., 2006).

Florida law requires a RS device on all automatic lawn sprinkler systems (Florida Statutes, Chapter 373.62, n.d.). The original text said: “Any person who purchases and installs an automatic lawn sprinkler system after May 1, 1991, shall install a rain sensor device or switch which will override the irrigation cycle of the sprinkler system when adequate rainfall has occurred.” In 2001, this Chapter was amended to require the owner not only to install, but also to maintain and operate a RS device or switch (Florida Statutes, 2001). Moreover, some local laws also require older systems to be retrofitted with rain shut-off switches (SJRWMD, 2006).

Florida is the only state in the nation with an overall RS statute. However, recently, Georgia Gov. Sonny Perdue has signed into law H1277 requiring RSs on newly installed irrigation systems in the Atlanta metro region. The new law affects systems installed after January 1, 2005 (AWWA, 2004).

As with soil moisture sensors, rain sensors can be connected to any automatic irrigation system controller and mounted in an open area where they are exposed to rainfall. The new irrigation timers have a special connection, which allows a RS to be attached directly. If it is not available, or the sensor does not work with a given timer, the sensor can always be “hard-wired” into the controller, wiring the RS in series with the common wire. When a specific amount of rainfall has occurred, the RS will interrupt the irrigation system common wire, which disables the solenoid valves until the sensor dries (Dukes and Haman, 2002b).

Figure 1-4 shows a simple and low cost RS. Rain causes the hygroscopic porous disks in the device to swell and open a micro-switch (Figure 1-5). The switch remains open as long as the disks are swollen. When the rain has passed and the disks dry out, the switch will close again.

According to Dukes and Haman (2002b), the use of rain sensors has several advantages: they conserve water, preventing irrigation after recent rain events; reduce wear on the irrigation system, because the system runs only when necessary; reduce disease and weeds development, by eliminating unnecessary irrigation events; help protect surface and groundwater, by reducing the runoff and deep percolation that carries pollutants, such as fertilizers and pesticides; and, finally, RSs save money, because they reduce utility bills and maintenance costs.

Rain sensors should be mounted on any surface where they will be exposed to unobstructed rainfall, but should not be in the path of sprinkler spray. These sensors are typically installed near the roofline on the side of a building, but manufacturers recommend mounting it in a location that receives about the same amount of sun and shade as the turf (Hunter Industries Inc., 2006).

## Irrigation and Turfgrass Quality

Under-irrigation and over-irrigation can negatively affect turfgrass quality. It has been reported that, deeper and reduced irrigation frequency improves turfgrasses quality. Augustin and Snyder (1984) concluded that this practice tends to reduce N leaching in sandy soils, increasing N utilization, resulting in a better color rating (better quality). Bonos and Murphy (1999) reported an increase in a Kentucky bluegrass (*Poa pratensis L.*) cultivar root growth as drought stress was imposed. Recently, Jordan et al. (2003) found that bentgrass irrigated every 4 days produced a significantly denser and deeper root system, a higher shoot density, and greater overall plant health, resulting in better turf quality, than grass watered every 1 or 2 days (even under putting green management conditions). McCarty (2005) summarizes that drier conditions slow shoot growth and increase root growth and leaf water content.

Moreover, limitations to establishment and survival of some turfgrass weeds (Colbaugh and Elmore, 1985; Youngner et al., 1981), and reduction of some pathogens severity (Davis and Dernoeden, 1991; Kackley et al., 1990) has been associated with deep, infrequent irrigation.

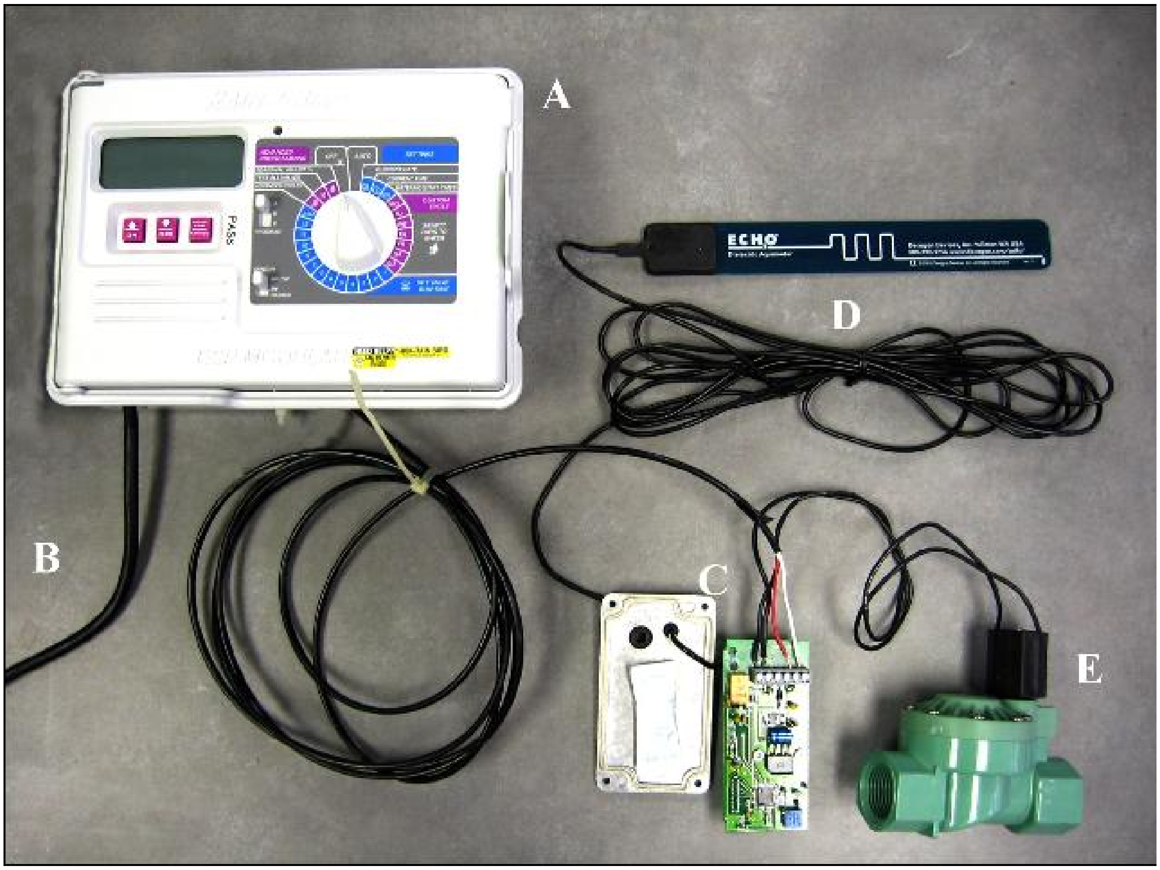


Figure 1-1. Components of an automated irrigation system: A) timer, B) power supply, C) soil moisture sensor-controller circuitry, D) soil moisture sensor, and E) solenoid valve.

Figure 1-2. Granular matrix sensors (GMS)

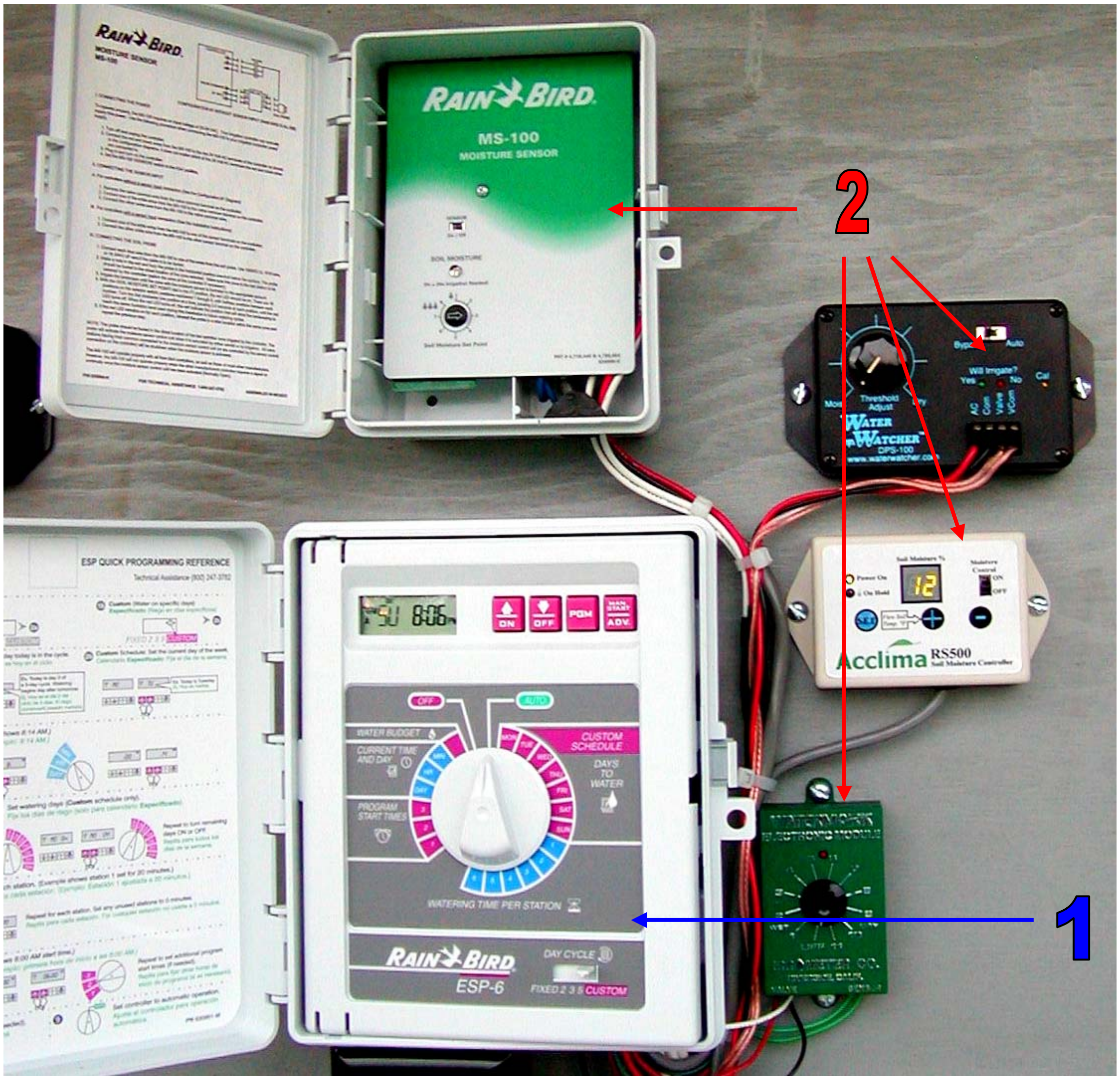


Figure 1-3. Components of an automated irrigation system. 1) Timer, and 2) soil moisture sensor-controllers from different brands.

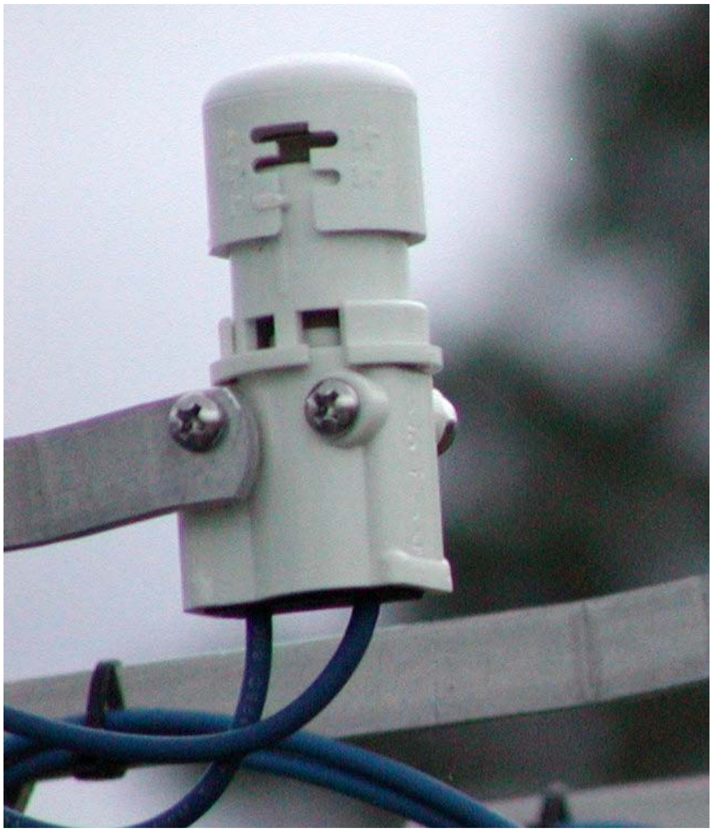


Figure 1-4. Rain shut-off switch.

Figure 1-5. The expanding material of a rain shut-off switch.

# CHAPTER 2
# SENSOR-BASED AUTOMATION OF IRRIGATION OF BERMUDAGRASS

## Introduction

Turfgrass in landscape applications is the most extensively cultivated crop in Florida (Hodges et al., 1994; USDA, 2005). Irrigation of residential, industrial, commercial, and recreational turf areas is commonly employed to ensure acceptable turf quality. As a consequence of problems related to drought, coupled with a steadily increasing demand for water, the state of Florida has imposed restrictions on irrigation water use. 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 irrigation technologies could improve irrigation efficiency promoting water conservation and reducing the environmental impacts of the landscapes, which are often composed of turfgrass as a major portion of the irrigated area.

Florida receives an average of around 1400 mm of rainfall a year, which typically exceeds evapotranspiration. Nevertheless, irrigation is required because total annual rainfall for Florida typically varies both geographically and temporally (USDA, 1981; Carriker, 2000; NOAA, 2003), and lack of rainfall for even a few days causes depletion of moisture in Florida's predominately sandy soils (Carriker, 2000; National Research Council, 1996).

Florida has the second largest withdrawal of groundwater for public supply in the United States. In 1995, nearly 93% of population in Florida used groundwater as a drinking water source (Solley et al., 1998). Florida has a fast-growing population with a net inflow of more than 1100 people a day. By 2025, it is projected to be the third most populous state in the nation (Office of Economic and Demographic Research [ODR], 2006; USCB 2004a). The U.S. Census Bureau estimated that Florida accounted for approximately 11% of all new homes constructed in the U.S. in 2003, the largest amount in any single state in the U.S. (USCB, 2004b), the majority of them with in-ground irrigation systems[1] (Tampa Bay Water, 2005). As urban populations swell, pressures on limited supplies of clean water are increasing. Even saltwater intrusion in groundwater from the Floridan aquifer have been found in coastal Hillsborough, Manatee and Sarasota counties (Southern Water Use Caution Area Recovery Strategy [SWUCA], 2006)

The primary use of residential outdoor water is irrigation. Recent studies in the U.S. indicate that, on average, 58% of potable water is used for landscape irrigation, that households that use automatic timers to control their irrigation systems used 47% more water outdoors than those without timers, and that homes with in-ground sprinkler systems use 35% more water outdoors than those without in-ground systems (Mayer et al., 1999). In the Central Florida Ridge, the potable water used for landscape irrigation is as high as 74%, with an average of 64% (Haley et al., 2006), and even when irrigation is restricted to two days a week and from 1000 h to 1600 h (SJRWMD, 2006), typically homeowners tended to over-irrigate (Haley et al., 2006).

Over-irrigation or under-irrigation can negatively affect turfgrass quality. It has been reported that deeper and reduced irrigation frequency improves turfgrass quality. Augustin and Snyder (1984) concluded that this practice tended to reduce N leaching in

---

[1] 57% and 85% of new homes built in Pasco and Hillsborough counties, respectively, have in-ground irrigation systems. Actual percentages may be higher since many homeowners install irrigation systems after moving into the home. In the Tampa region, 70% of homes are estimated to have in-ground irrigation.

sandy soils, increasing N utilization, resulting in a better color rating (better quality). Bonos and Murphy (1999) reported an increase in a Kentucky bluegrass (*Poa pratensis L.*) cultivar root growth as drought stress was imposed. Recently, Jordan et al. (2003) found that bentgrass irrigated every 4 days produced a significantly larger and deeper root system, a higher shoot density, and an overall plant health–resulting in greater turf quality–than that watered every 1 or 2 days (even under golf putting green management conditions). McCarty (2005) summarizes that drier conditions slow shoot growth, and increase root growth and leaf water content. Moreover, limitations to the establishment and survival of some turfgrass weeds (Colbaugh and Elmore, 1985; Youngner et al., 1981), and reduction of some pathogens severity (Davis and Dernoeden, 1991; Kackley et al., 1990) have been associated with deep, infrequent irrigation. Hence, better irrigation scheduling by homeowners may lead to improved turfgrass quality coupled with potential savings in irrigation water use.

Over the last decade, the soil moisture sensor (SMS) industry has advanced dramatically. Two basic reasons can explain this advancement. The first has been the major development of computer technology (with more powerful, smaller and more economical integrated circuits), and the other phenomenon has been the significant advances in the application of electromagnetic methods to the measurement of soil water content. These methods make use of the high relative permittivity (dielectric constant) of the water in soil for estimating the water content. The relative permittivity of water is about 80, whereas the other components in soil, including air, have relative permittivities in the range of one to seven. Hence, methods that measure the relative permittivity are effective for the measurement of the soil water content (Topp, 2003).

Combining the computer technology and the soil dielectric concept has allowed manufacturers to design and produce a number of different types of inexpensive SMSs for irrigation scheduling. However, when comparing the performance of different brand/types of sensors for measurement of soil moisture, differences were found. For example, Ley et al. (2000) found significant differences between sensors with respect to set-up requirements, accuracy, data interpretation, maintenance, and initial cost. Yoder et al. (1998) obtained differences related with error, accuracy, reliability, durability, installation factors, and the ability to repeat measurements accurately over time and under various moisture regimes after initial calibration.

Automation of irrigation systems, based on SMSs, has the potential to provide maximum water use efficiency, by maintaining soil moisture between a desired range that is optimal or adequate for plant growth and/or quality; allowing irrigation only when necessary (Muñoz-Carpena and Dukes, 2005).

A wide range of applications to automatically control irrigation events have been investigated in coarse textured soils. In Florida, switching tensiometers have been studied for agricultural production (Smajstrla and Koo, 1986, Clark et al., 1994; Smajstrla and Locascio, 1994; Muñoz-Carpena et al., 2003; Muñoz-Carpena et al., 2005), and for maintaining bermudagrass turf (Augustin and Snyder, 1984). Although they found water savings, these investigations suggest that tensiometers require calibration and frequent maintenance, up to twice per week. Consequently, the adoption of this technology will not lead to an automatically controlled irrigation system, since it will not eliminate human interaction in irrigation management.

Other types of sensors have been adapted to automate irrigation based on soil moisture status in Florida. Nogueira et al. (2002) used TDR sensors to maintain soil moisture within two preset limits (upper and lower soil moisture thresholds). Dukes and Scholberg (2005) and Dukes et al. (2003) found 11% and 50% in water savings–without diminishing yields–using TDR probes on sweet corn, and a commercially available dielectric sensor on green bell pepper, respectively. Granular matrix sensors (GMSs) have also been used to automatically irrigate agricultural products (Muñoz-Carpena et al., 2003; Shock et al., 2002) and, as with other solid-state sensors, do not require as much maintenance as tensiometers.

Although SMSs have been successfully used in agriculture, they have found limited use in residential landscape irrigation and further investigation is required to provide evidence of their potential use in this area. A study using GMSs to control urban landscape irrigation in Colorado, used 533 mm of water for irrigation when compared to the theoretical requirement of 726 mm, a reduction of 27% (Qualls et al., 2001).

Since 1991, Florida law requires a rain sensor device or switch hooked up to all automatic lawn sprinkler systems (Florida Statutes, Chapter 373.62, n.d.). A rain sensor (RS) is a piece of equipment designed to interrupt a scheduled cycle of an automatic irrigation system controller when a specific amount of rainfall has occurred (Dukes and Haman, 2002b; Hunter Industries Inc., 2005). Benefits and advantages of its use are similar to those of SMSs, and have been summarized by Dukes and Haman (2002b). Even when this law has been in effect for a long time, and RSs have been commercially available for many years, little evidence related to their usefulness and/or to quantify their water savings exists

The goals of this research were to find out if different SMS-systems (sensor with a proprietary controller) could reduce irrigation water application–while maintaining acceptable turf quality–compared to current practices. The objectives of this experiment were to quantify differences in irrigation water use and turf quality between: 1) a SMS-based irrigation system compared to a time-based scheduling, 2) different commercial irrigation SMSs, and 3) a time-based scheduling system with or without a RS.

## Materials and Methods

The experimental area was located at the Agricultural and Biological Engineering Department facilities, University of Florida, Gainesville, Florida; on an Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) (Thomas et.al, 1985; USDA, 2003). This soil has a field capacity of 7% (Figure 2-1), as determined from repacked soil columns (see Chapter 4 for methodology details).

Seventy-two 3.66 m x 3.66 m plots were established on a field covered with common bermudagrass (*Cynodon dactylon L.*). Each plot was sprinkler irrigated by four quarter-circle pop-up spray heads, with an application rate of 38 mm/hr and regulated at 172 kPa (Hunter 12A, Hunter Industries, Inc., San Marcos, CA). Much of the irrigation hardware was in place from a previous research project; however, extensive renovations were performed to make the equipment serviceable.

Plots were mowed twice weekly at a height of 5.5 cm. Chemicals were applied as needed to control weeds and pests. Nutrient applications were made using ammonium sulfate (21-0-0), at a N rate of 50 kg ha$^{-1}$, on April and May of 2004, before the beginning of the experiment. Then, a granulated N controlled-release fertilizer (Polyon, PTI, Sylacauga, AL) [2] was applied at a rate of 180 kg ha$^{-1}$, on July 2004 and April 2005.

Four commercially available SMSs were selected for evaluation (Figure 2-2): 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. In order to find similar outcomes to those that homeowners would encounter, sensors were not calibrated, and were used directly "out of the box."

Each one of these SMSs systems includes a SMS and a controller (Figure 2-3). The controller's thresholds can be adjusted between "dry" and "wet" on the RB (on a 1 to 8 scale), and between "moist" and "dry" on the WW (on a -3 to 3 scale). The IM can be set at a specific soil water tension (kPa) and the AC can be set directly to a specific soil volumetric moisture content (VMC), expressed in percent.

As recommended by manufacturers, all controller thresholds, except for the AC, were set 24 hours after a significant rainfall event (on 20 July 2004, after four days of rain with a total of 107 mm) that filled the soil profile with water. On RB controllers, the thresholds were set by adjusting the dial until the LED turned off and on. On the WW, initially the unit could not be calibrated since the soil moisture was outside the range of the controller. After discussion with the manufacturer, a resistor was added between the solenoid valve wire and the valve common wire. The calibration procedure consisted of activating the reset button, which allowed its auto-calibration. The IM controller was set

---

[2] The mention of trade and company names is for the benefit of the reader and does not imply an endorsement of the product.

at number 1 (equivalent to 10 kPa, and approximately to field capacity, according to the manufacturer), whereas the AC controller was set on their display at a VMC of 7%, based on the measured soil water release curve of the soil. All these controllers were connected in series with typical residential irrigation timers (see description of timers under Treatments sub-heading).

### Treatments

Two basic types of treatments were defined: SMS-based treatments, and time-based treatments (Table 2-1). In the SMS-based treatments, all four brands were tested with 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 (FDEP, 2002; SJRWMD, 2006).

Within the time-based treatments, a frequency of 2 d/w was defined (the most common in Florida, and current watering restriction in the area of study). Two treatments were connected to a rain sensor (2-WRS and 2-DWRS), to simulate requirements imposed on homeowners by Florida Statutes (Chapter 373.62, n.d.). The rain sensor (Figure 2-4) (Mini-click II, Hunter Industries, Inc., San Marcos, CA) was set at 6 mm rainfall threshold. A without-rain-sensor treatment (2-WORS) was also included, in order to simulate homeowner irrigation systems with an absent or non-functional rain sensor. Finally, a non-irrigated treatment (0-NI) was also implemented as a control for turfgrass quality. All experimental treatments were repeated four times, for a total of 64 plots, in a modified completely randomized design[3].

---

[3] See **Dry-Wet Analysis** subheading for details

The weekly irrigation depth was set to replace the historical ET-based irrigation schedule recommended by Dukes and Haman (2002a) for the area where this experiment was carried out (Table 2-2). All treatments were programmed to have the 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). The irrigation depths were adjusted monthly.

The irrigation cycles were programmed on two ESP-6, and three ESP-4Si model timers (Rain Bird International, Inc., Glendora, CA) (Figure 2-3). They were programmed to start between 0100 and 0500 h, with the purpose of diminishing wind drift and decreasing evaporation.

**Uniformity Test**

An irrigation uniformity test measures the relative distribution application of water depth over a given area. This concept results in a numeric value to quantify the variability in depth of sprinkler irrigation over a target area. Two methods have been developed to quantify uniformity: distribution uniformity (DU) and Christiansen's coefficient of uniformity (CU).

According to Merriam and Keller (1978), the low-quarter irrigation distribution uniformity ($DU_{lq}$) can be calculated with the following equation:

$$DU_{lq} = \frac{\overline{D}_{lq}}{\overline{D}_{tot}} \tag{2-1}$$

where $\overline{D}_{lq}$ is the lower quarter of the average of a group of catch-can measurements, and $\overline{D}_{tot}$ is the total average of a group of catch-can measurements. This method emphasizes the areas that receive the least irrigation by focusing on the lowest quarter. Although a system may have even distribution, over-irrigation can occur because of mismanagement (Burt et al., 1997).

On the other hand, the CU treats over-irrigation and under-irrigation equally as compared to the mean, and can be calculated by the Christiansen (1942) formula:

$$CU = 1 - \frac{\sum_{i=1}^{n} \left| V_i - \overline{V} \right|}{\sum_{i=1}^{n} V_i} \qquad [2\text{-}2]$$

where $V_i$ equals the volume in a given catch-can, and $\overline{V}$ refers to the mean volume.

To carry out the uniformity test on the field, 16 catch-cans on a 0.9 m x 0.9 m square grid pattern were placed on each plot. To minimize edge effects, this grid was positioned 0.4 m inside the plot boundaries (Figure 2-5). The cans had an opening diameter of 15.9 cm and a depth of 20.3 cm. Pressure at the two farthest plots was verified with a pressure gauge. 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.

### Dry-Wet Analysis

In accordance with manufacturer recommendations for the products tested, the SMS should be buried in the driest zone of a multiple-zone system. Thus, that particular zone would receive sufficient irrigation, whereas the other zones would be slightly over-irrigated. Accordingly, to identify the driest and wettest plots in the experimental area, a survey was carried out on each plot, before the beginning of the experiment. In addition, because a total of 64 plots were required, this analysis was 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 VMC 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 m X 1 m of each plot and averaged. On 17 March 2004, 24 hr after a 23 mm rainfall filled the soil profile, the VMC on a “wet” condition was measured as well. After selecting the driest plots, the SMS that controlled a particular treatment was buried in the center of one of these plots, thereby controlling all four replications. In all cases, SMSs were installed in the top 7-10 cm of the soil, where most of the roots were present.

### Plot Irrigation Management and Data Collection

Figures 2-6 to 2-10 show the set up of the different control features of the experiment. Each plot was managed individually, and data were collected independently from each plot as well. Pulse-type positive displacement flowmeters (PSMT 20mm x 190mm, 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 measure irrigation volume and frequency applied to each plot (Figure 2-10). In addition, meters were read manually each week.

Weather data were collected by an automated weather station (Campbell Scientific, Logan, UT), located within 1 m of 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 manual rain gauge during 2004 and by a tipping bucket rain gauge in 2005.

Reference evapotranspiration ($ET_o$) was calculated from the Penman–Monteith equation described in FAO-56 (Allen et al., 1998) as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad [2\text{-}5]$$

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \qquad [2\text{-}6]$$

$$R_n = R_{ns} - R_{nl} \qquad [2\text{-}7]$$

$$R_{nl} = \sigma\left[\frac{T_{\max,K}^4 + T_{\min,K}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \qquad [2\text{-}8]$$

$$R_{ns} = (1 - \alpha)R_s \qquad [2\text{-}9]$$

$$R_{so} = (0.75 + z(2 \text{ x } 10^{-5}))R_a \qquad [2\text{-}10]$$

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \sin(\omega_s)\cos(\varphi)\cos(\delta)\right] \qquad [2\text{-}11]$$

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \qquad [2\text{-}12]$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \qquad [2\text{-}13]$$

$$\omega_s = \text{arcos}\,[-\tan(\varphi)\tan(\delta)] \qquad [2\text{-}14]$$

$$e_s = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2} \qquad [2\text{-}15]$$

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2} \qquad [2\text{-}16]$$

$$e^o(T) = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \qquad [2\text{-}17]$$

where:
$ET_o$ = Potential evapotranspiration, mm/day
$\Delta$ = slope of the vapor pressure curve, kPa $^oC^{-1}$
$R_n$ = net radiation of the turf surface, MJ $m^{-2}$ $day^{-1}$
$R_{nl}$ = net outgoing longwave radiation, MJ $m^{-2}$ $day^{-1}$
$R_{ns}$ = net solar or shortwave radiation, MJ $m^{-2}$ $day^{-1}$
$R_{so}$ = clear sky solar radiation, MJ $m^{-2}$ $day^{-1}$
$R_s$ = measured solar radiation $W/m^2$ x 0.0864, MJ $m^{-2}$ $day^{-1}$
$R_a$ = extraterrestrial radiation, MJ $m^{-2}$ $day^{-1}$
G = measured soil heat flux density, MJ $m^{-2}$ $day^{-1}$
$G_{sc}$ = solar constant, 0.0820 MJ $m^{-2}$ $min^{-1}$
T = measured air temperature at a 1.5 m height, $^oC$
$u_2$ = measured wind speed at a 2 m height, m $s^{-1}$
$e_s$ = saturation vapor pressure, kPa
$e_a$ = actual vapor pressure, kPa
$e^o(T)$ = saturation vapour pressure at air temperature, kPa
RH = relative humidity at 1.5 m height, %
$d_r$ = inverse relative distance Earth-Sun
$\omega_s$ = sunset hour angle, rad
$\delta$ = solar declination, rad
$\gamma$ = psychrometric constant, 0.067 kPa $^oC^{-1}$
$\sigma$ = Stefan-Boltzmann constant, 4.903 x $10^{-9}$ MJ $K^{-4}$ $m^{-2}$
J = Julian day
$\varphi$ = latitude, radians

The soil moisture content was monitored with a capacitance soil water probe (20 cm $ECH_20$, Decagon Devices, Inc., Pullman, WA) installed in each plot (Figure 2-12). These probes were connected to HOBO micro-loggers (Onset Computer Corp., Bourne, MA). Each HOBO datalogger had four probes connected to it, and readings were recorded every 15 minutes during 2004 and every hour in 2005.

Before the beginning of the experiment, calibration of the ECH$_2$O probes was performed at the research site using the thermogravimetric soil sampling method (Gardner, 1986). Four probes connected to a HOBO datalogger were installed in the field. Undisturbed soil samples were collected from the field at less than 20 cm from the probes, and at the same depth where the probes were placed. Samples were taken from a saturated through a dry condition. When each sample was removed, date and time was recorded. The volumetric soil water content of each sample was then compared to the ECH$_2$O probe readings at the same date and time when the samples were taken (see Chapter 4 for methodology details) and a site-specific calibration curve was developed.

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 a homeowner. Ratings were carried out in July, October and December of 2004, and in April, May and July of 2005.

The data were obtained from 20 July through 14 December of 2004–when the turfgrass went dormant due to cool temperatures, and irrigation was discontinued–and from 25 March through 31 August of 2005.

## Data Analysis

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 and Duncan's Multiple Range Test was used to identify mean differences. The combined data from both years were analyzed. When interactions between years and other parameters were detected, each year's data were analyzed separately and, when needed, a monthly data analysis was made as well.

# Results and Discussion

## Uniformity Tests

The uniformity tests resulted in a wide range of $DU_{lq}$ values across the plots (15% to 78%), with an average of 52% that, according to the Irrigation Association (2003) overall system quality ratings, is considered "fair." Obvious problems such as leaks and broken heads were repaired prior to testing, but in some cases problems were discovered as a result of testing (Figure 2-13, plots A8, A12, B9, and D1) and action was taken to correct the problem. Baum et al. (2003) performed uniformity tests on irrigation systems of homes in Central Florida having spray heads. That research found an average $DU_{lq}$ of 41%, with a range of 12% to 67%.

The average CU for all the plots was 71%, with a range of 50% to 89%. Baum et al. (2003), found a CU average of 59%, with a range between 50% and 72%. Therefore, these experimental plots had a better distribution application of water depth, expressed as $DU_{lq}$ and CU, than actual spray irrigation zones on homes sampled in Central Florida.

It is interesting to mention that, considering all the catch-cans of the experiment responsible for the lowest readings, 99% of them were placed on the edges of the plots, indicating that substantial edge effects occurred in the testing. This is common for sprinkler irrigation systems and did not negatively impact the results, because soil moisture and turf quality ratings of each plot were always taken inside this perimeter. In addition, this situation tended to minimize the effect of irrigation overlapping between plots.

## Dry-Wet Analysis

The data collected during the dry-wet analysis are shown in Figures 2-14 and 2-15. The statistical analysis (Appendix B, Dry) revealed that at the dry condition, plots A11 and A12 were similar, but had significantly higher VMC than the other plots. Under the wet condition, again plots A11 and A12 were significantly different from the rest, also having a higher VMC.

Therefore, plots A11 and A12 were discarded for this experiment because they were too “wet” (Figures 2-14 and 2-15). On the other hand, plots A4, A5, A7, A8, F11, and F12 were also discarded, because they appeared to have the lowest VMC values of all plots, coupled with a comparatively lower turfgrass quality before the beginning of the experiment. These discarded plots appear in red in the plot plans shown in Figures 2-14 and 2-15. Consequently, a total of 64 plots were left for this research. When a statistical analysis was performed (Appendix B, Wet) with the 64 plots included, the only significant difference was that F1 and E1 showed higher values at the wet condition than the rest, so they were discarded as locations for SMS placement.

The green plots shown in Figures 2-14 and 2-15 were selected to bury the SMS for the control plots, because they appeared to be similarly dry and on the dryer end, and because of the practical convenience of burying the cables of the different SMS on the same trench, at the same time, and closer to the control board (Figure 2-8). A statistical analysis on these plots (Appendix B, Plots with SMS) indicated that they were not statistically different (P>0.94). Figure 2-16 shows the plot plan containing all the treatments and repetitions, in a modified completely randomized design, where the same color depicts treatment repetitions (plots showing an X were the discarded ones).

### Rainfall

Both 2004 and 2005 were rainy years (Figures 2-17 and 2-18), with high frequency rainfall events and a large amount of cumulative precipitation, which is not uncommon in this region. During 2004, a tropical storm and two hurricanes–Frances and Jeanne–passed over the research area during the experiment, resulting in 159, 286, and 157 mm of rainfall, respectively. Year 2005 broke all records for the number of hurricanes and named tropical storms in U.S., but none of them directly hit the area where the experiment was carried out.

Nonetheless, during the data collection period of 2005, 40% of the days had rainfall events, with a considerable amount of precipitation, 732 mm, and an average of 135 mm/month (Figure 2-18). In the course of 2004, (Figure 2-17) even when it rained less frequently, 31% of the days, the cumulative rainfall for the experimental period was even larger, with 944 mm, and 190+ mm/month on average. However, most of this rainfall (530 mm, or 56%) occurred during the tropical storm and the two hurricanes. If these events were not considered, an average of 84 mm/month fell during 2004.

Figure 2-17 shows that in 2004 most of the rain fell during August and September (793 mm), and the least rain fell in October and November (116 mm). A relatively “dry” period occurred from 21 October to 24 November (35 days), with only two small rainfall events of 1.5 and 2.5 mm. A similar situation happened in 2005 (Figure 2-18) during April and May, when 223 mm fell over 17 rainfall events. On the other hand, June, July, and August were rainier months with 478 mm on 44 rainfall events.

## Irrigation Events

Figures 2-19 and 2-20 show the evolution of the cumulative number of irrigation events allowed per treatment in 2004 and 2005, respectively. There were a greater number of irrigation events as the irrigation frequency increased (Parts B vs. C vs. D, from Figures 2-19 and 2-20). The treatment without-rain-sensor (2-WORS) was programmed to run 2 d/w, independently of the weather and/or soils moisture conditions and, as expected, irrigation cycles were not bypassed. However, to avoid possible damage to the equipment, power was turned off and no data were collected from 26 September through 30 September 2004, due to hurricane Jeanne. This is reflected on Figure 2-19, Part A, when through these dates the slope of the curves looks horizontal (no irrigation events). Nevertheless, this period was rainy and very short in proportion, so final results should not be significantly affected.

Treatments 2-WRS and 2-DWRS were controlled by the same rain sensor and set to run the same days so, not surprisingly, they overrode the same amount of irrigation cycles, and only one line can be seen for both treatments (Figure 2-19, Part A).

In spite of this result, it is important to know what proportion of the scheduled irrigation cycles (SIC) were finally overridden by the different treatments (Table 2-3). The statistical analysis ($P<0.0001$) showed that, as expected, 2-WORS was different from the rest of the treatments (overriding 0% of the SIC), and that 2-WRS and 2-DWRS were not statistically different. These last two treatments bypassed 30% and 37% of the possible irrigation events in 2004 and 2005, respectively, and more than a third as an average for both seasons.

Regarding the SMS-based treatments, there was not a clear difference between them, except for the IMs. Sensors from brands AC, RB, and WW, overrode significantly more SIC than 2-WRS and 2-DWRS, ranging from 70% to 92% in total, and considering all frequencies tested. The proportion of SIC overridden by IMs, however, ranged from 32% to 50% the first year, from 24% to 70% in 2005, and from 28% to 56% for both years together.

In the first year, 2-IM overrode almost the same proportion of irrigation cycles than the control 2-WRS (32% vs. 30%, respectively). In 2005, however, 2-IM was the only treatment that resulted in more irrigation cycles than the control treatment, overriding only 24% of the possible ones compared to 37% by 2-WRS. As a result, 2-IM was not statistically different from 2-WRS. The other two IM treatments did not differ statistically, but overrode more irrigation cycles compared to 2-WRS and less than the rest of the SMS-based treatments. These results suggest that IMs, except for the said 2-IM in 2005, would be able to respond to rainfall events at least in a similar proportion than a rain sensor device set at 6 mm.

In order to corroborate the effectiveness of the SMSs, it was important to detect when actual irrigation cycles occurred and how were they related to rainfall and evapotranspiration conditions.

Figures 2-21 and 2-22 show the maximum weekly irrigation water requirement–or weekly rainfall – ETo difference (RED)–for years 2004 and 2005, respectively. In 2004, August and September had only one week each with a negative RED. However, after 2 October, eight of eleven weeks showed a negative RED. On the other hand, in 2005, it can be seen that every month had at least one deficitary week. However, the longest negative REDs happened in April, May, and July of 2005, with three, four, and two consecutive weeks, respectively.

Table 2-4 shows the percent of irrigation cycles allowed by the SMS-based treatments through the experimental months of 2004 and 2005. In 2004, on average, a lesser amount of irrigation events were allowed in August and September (21% and 18%, respectively) compared to October and November (44% and 46%, respectively). In 2005, a greater proportion of irrigation cycles were allowed in April, May, and July (31% and 46%, and 24%, respectively), and a fewer proportion in June and August (13% and 17%, respectively). These tendencies were concordant with the dryer/rainier periods and, when correlating the monthly RED values and the percent of irrigation cycles allowed per month, r values of –0.93 and –0.76 were found for 2004 and 2005, respectively (Table 2-4).

Looking in detail, for 2004, ACs followed this tendency allowing fewer irrigation cycles during the rainy months of August and September, and more cycles during the dryer period between October and November. In the case of 1-AC, the only irrigation cycles allowed occurred in November. 2-AC allowed less irrigation cycles on August and September (22% and 11%) and more cycles during October and November (22% and 33%, respectively); the same tendency as 7-AC (10%, 0%, 3%, and 17%, for the same months, respectively).

RBs also responded to this tendency on the 1 d/w and 7 d/w frequencies, allowing a greater proportion of SIC to occur during the end of the year; but 2-RB did not follow this, and actually run more cycles at the beginning and at the end of the year (33% vs. 22%), with no irrigation cycles during September and October.

A similar situation occurred with the IM treatments. The first and second half of the season were clearly different for 1-IM (between 20% - 25% vs. 50% - 100% of the SIC, respectively), and for 2-IM (33% vs. 100%, respectively). However, 7-IM showed a more even conduct for the first three months (84%, 73%, 87%, respectively), and then dropped down in November (23%).

Finally, for 2004, WW treatments were also more active at the end of the season, allowing between 33% and 75% of the SIC (with the exception of 2-WW, on November, with 11%), compared to 0% to 29% for the first two months.

During 2005, ACs also followed the dryer/wetter period's tendency in every frequency tested. In the case of 1-AC, it ran 50% and 75% of the possible times on April and May (the driest months), and did not allow irrigations on June, July, and August (the wetter months). On these same last three months, 2-AC and 7-AC treatments allowed no more than 13% and 10% of the potential irrigation cycles respectively.

A similar situation happened with WW sensors. No irrigation cycles were allowed during the rainy months of June, July, and August by the 1 and 2 d/w frequencies. In the case of 7-WW, it followed this tendency in June and August (with 10% and 6%, respectively), but in July–month that had two consecutive weeks of negative RED–it showed a higher number of irrigation events (32%).

In 2005, RB sensors allowed few irrigation cycles to start during all the different months. The 1 d/w frequency permitted between 20 and 25% of the SIC, the 2 d/w frequency resulted in 11%, and 7 d/w frequency between 6% and 19%. Nevertheless, all the frequencies had a month when they did not allow any irrigation cycles (April, June, and August for 1, 2, and 7 d/w, respectively).

IM, in general, permitted more irrigation cycles than the other sensors. The 1-IM treatment showed similar behavior to the other brands during April, May, and June. Nevertheless, during July and August, 60% and 75% of irrigation events were allowed, respectively. Even in the rainy months of June, July, and August, 2-IM allowed 75% to 89% of the potential irrigation cycles to occur. A smaller variation in the number of irrigation events allowed between the different months was shown by 7-IM (from 16% to 45%), and exhibited a closer pattern to the other brands, being more active in the months of April and May. However, it also permitted a greater amount of irrigation cycles per month than the other brands at this frequency.

These relationships are clearer when looking at the VMC of the plots for year 2004, when evident differences in weather conditions through time were found. Figure 2-23 shows the VMC of treatment 0-NI where all the increments in VMC were due to rainfall events. The differences between the dry and the wet periods were reflected in the soil moisture content. Figures 2-24 to 2-35 show the VMC in plots that contained the SMSs controlling the irrigation treatments. These figures, show the results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed. When an increment in the VMC does not have a red dot, it means that a rainfall event occurred.

These results show that, in general, the SMS-based treatments were able to follow the dryer and wetter periods, controlling the amount of water to be delivered to the different treatments, and suggesting that this technology could be a useful tool to achieve automation of landscape-turfgrass irrigation, even when a RS is not present or non-functional. However, these are not precision instruments, which was evident because sometimes they bypassed irrigation cycles, and sometimes they did not, even reading the same or lower VMC. Moreover, according to the range of VMC over which the different SMS brands allowed irrigation, AC and RB had the narrowest average range (2.8% and 3.6%, respectively) suggesting that they were more accurate and consistent to measure the VMC than WW and IM (that had and average range of 7.0 and 8.9%, respectively).

The IM controllers were set at position #1, which corresponds to –10 kPa (e.g. field capacity) according to the manufacturer. However, according to the results obtained in Chapter 4, at –10 kPa the GMSs were actually sensing a dryer soil condition, between -17 and -23 kPa. This explains why the IMs allowed irrigation cycles when not necessary. Therefore, setting the IM controllers at position #2 or #3 would have resulted in increased irrigation savings.

### Irrigation Application Comparisons

Tables 2-5, 2-6, and 2-7 show (for years 2004, 2005, and 2004+2005, respectively) the irrigation depth applied to treatments, statistical comparisons between them, and percent of water savings achieved by the treatments compared to 2-WRS, 2-DWRS, and 2-WORS. All the statistical analyses in these Tables showed a high level of confidence ($P<0.0001$), and are discussed below.

### Time-based treatments vs. SMS-based treatments

Comparing the average of the time-based treatments with the average of the SMS-based treatments, Table 2-7 (Column A) shows that there was a significant difference between them; with 1044 and 420 mm of cumulative irrigation depth, respectively. The same statistical difference was found in 2004 and 2005 (Tables 2-5 and 2-6). This means that the SMS-based treatments, on average, were more efficient as a means to save water than the time-based treatments, even when a rain sensor was an important component on two of the three time-based treatments.

### Time-based treatments

The three time-based treatments (2-WORS, 2-WRS, and 2-DWRS) were significantly different from each other during the whole period of study (Tables 2-5, 2-6 and 2-7; Column B).

Treatment 2-WRS (two days/week, with a rain sensor) was established to mimic a homeowner who complies with the irrigation laws and regulations and sets the timer according to recommended practices; therefore, it was employed as the control treatment for water use volume. During the first season, this treatment accounted for 481 mm of water, or an equivalent of 98 mm/month, and 514 mm, or 96 mm/month, for 2005. A recent study, carried out by Haley et al. (2006) in Central Florida, within the St. Johns River Water Management District (SJRWMD), found that homeowners with automatic irrigation systems applied 149 mm/month on average. Therefore, the comparisons made here may be considered conservative and differences in the results for actual homeowners could be larger[4].

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 64% and 61% of the water used by 2-WRS in years 2004 and 2005, respectively, close to the 60% desired[5]. The yearly depths were 310 and 313 mm (or an equivalent of 63 and 59 mm/month), in 2004 and 2005, respectively. Haley et al. (2006) found within this homeowner profile (also programmed to replace 60% of historical ET) an irrigation water use of 105 mm/month[6].

The treatment simulating an irrigation system with an absent or non-functional rain sensor (2-WORS) accounted for 696 and 818 mm in the first and second season, or 141

---

[4] Differences could be due to a better irrigation scheduling in this experiment, which was adjusted monthly. In the Haley et al. (2006) experiment, these homeowners set their own controller run times, which generally were not adjusted seasonally, and tended to over-irrigate in the late fall.

[5] Equivalent to 36% and 39% in water savings compared to 2-WRS (Tables 2-4 and 2-5).

[6] This difference could be due to less rainfall (an average of 122 mm/month during Haley's research vs. 163 mm/month in this one), different soil conditions, or because some of the homeowners in this profile probably did not have a rain sensor, or maybe they had one, but it may have been non-functional.

and 153 mm/month, respectively. It means that this treatment applied 45% and 59% more water than the treatment with a functional RS (2-WRS), and 52% more water during both years, on average. These results demonstrate the importance not only for the presence, but also for the need of a functional and well-maintained rain shut-off device on all automated irrigation systems in Florida; where rainy weather, particularly in the warm months, 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 RS, and the author suggests that they are often incorrectly installed. Therefore, appropriately installed and properly working rain sensors could signify not only substantial water savings to homeowners, but could also lead to sound environmental and economic benefits to the state. In addition, their payback period could be less than a year; depending on the weather conditions, the area to be irrigated, the cost of water, and the cost of installed rain sensors (see Chapter 3).

### Comparisons between SMS-irrigation frequencies

When the averages of the three different SMS irrigation-frequencies were analyzed (Tables 2-5 to 2-7, Column C), the 2 d/w frequency used a significantly higher volume of water, followed by the 1 d/w frequency during both seasons and as a total, with 478 and 420 mm of total cumulative water depth, respectively. The 7 d/w frequency was as high as the 2 d/w frequency in 2004, but resulted in the least water applied in 2005 (mostly due to the decrease in water application by 7-IM between 2004 and 2005). Therefore, 7 d/w was significantly the lowest of all three frequencies, with an average of 362 mm, in total cumulative water applied in this experiment (Table 2-7). This was probably because more frequently scheduled irrigation events can be bypassed as a result of frequent rainfall.

These results suggest that, in a long run, to schedule low volume-high frequency irrigation cycles (7 d/w) in Closed Control Loop irrigation systems[7], appears to be a better strategy regarding water conservation in turfgrass irrigation, than to schedule them for some specific days during the week (1 or 2 d/w) and with a higher volume during each irrigation cycle.

### Soil moisture sensor-brands comparison

The different brands were compared in terms of irrigation water applied. Figure 2-36 shows the cumulative water applied by brand on years 2004 and 2005. As an overall comparison, IM sensors resulted in significantly more irrigation during 2004 ($P<0.0001$), with 420 mm on average, followed by WWs, 188 mm, and then by sensors from brands AC and RB–which were not statistically different–and showed the lowest water use rate, with 116 and 100 mm, respectively. The same relationship was found in 2005, except that in this year, AC used a significantly higher irrigation depth than RB, with all four brands statistically different, with 451, 164, 135 and 105 mm on average for IMs, WWs, ACs and RBs, respectively. However, these averages could not be directly compared to find out which brand was better in every case, because an interaction between brand and frequency was evidenced by the statistical analysis ($P<0.0001$). This implies that some SMS brands performed better at a certain frequency than other ones, but not as good at another frequency. Hence, differences between SMSs brands were evaluated separately within each irrigation frequency.

---

[7] In Closed Control Loop irrigation systems the decision to whether initiate or not an irrigation cycle is regulated by a SMS.

## Brand comparisons within irrigation frequencies

From Tables 2-5 to 2-7 (Column D), it can be seen that there were statistical differences between brands within each frequency, for 2004, 2005, and as a total cumulative depth for both seasons. In 2004, the highest water use rate in the 1 d/w frequency was displayed by IM, and then by WW, RB, and AC, respectively; all statistically different from each other. A similar trend was exhibited at the 7 d/w, except that AC and RB were not significantly different at this frequency. At the 2 d/w frequency, however, the least amount of water was applied by brands RB and WW (not statistically different between them), then by AC, and then by IM.

During 2005, results from 1 and 2 d/w frequencies were similar. At 1 d/w all four brands were statistically different from each other. However, comparatively, WW applied less water than in 2004 and, conversely, AC applied more. So, for 2005, IM applied the most, followed by AC, RB, and WW, respectively. Finally, at the 7 d/w frequency, the same statistical differences between brands from 2004 were found in 2005, showing a high consistency through time.

These similarities and differences, comparing both years, could have happened because the number of total SIC was relatively greater in the 7 d/w frequency, and relatively smaller in the 2 and 1 d/w frequencies (302, 87, and 43 times, respectively). This means that timing of the rain events could have had a higher impact at the 1 d/w and 2 d/w level, but lower at the 7 d/w frequency. Basically, these differences took place in the dry months of April and May 2005, when 1-AC, 1-WW, and 2-WW allowed some of the SIC to run (Table 2-4).

The total cumulative irrigation depth applied in both seasons (Table 2-7, Comparison Column D) showed that, in the 1 d/w frequency, only IM used significantly more water than the other brands. For the 2 d/w frequency, all brands were significantly different, where IM applied more water, and then, in decreasing order, AC, WW, and RB. As 2004 and 2005, IM was the brand that significantly applied more water at the 7 d/w frequency, followed by WW, and then by AC and RB (which were not statistically different).

Summarizing, IMs always applied significantly more water than the other brands in every frequency tested, and in both seasons. This could be because of their reported limitations to timely sense the differences in soil water content, their hysteretic behavior, the high variability of its readings, and their drawbacks for its use 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). Therefore, IMs do not appear to be the best choice for these climatic-soil conditions.

Regarding the other brands, the best choice depends on the local restrictions and regulations concerning the frequency of landscape irrigation. When irrigation is limited to 1 d/w, no differences appeared to be evident between the brands. For 2 d/w restrictions, according to these results, the best choice would be, in decreasing order, RB, WW, and AC. If no frequency limitations were present, AC or RB looks like the best choice, followed by WW.

### Overall comparison

Tables 2-5, 2-6 and 2-7, (Column E), show the statistical differences between every irrigation treatment, independently if they were time-based or SMS-based. As expected, 2-WORS always applied significantly more water than the other treatments. During 2004, following 2-WORS, were 2-WRS, 2-IM, and 7-IM, with no significant difference between them, and these treatments were followed by 2-DWRS and 1-IM, which were similar between them. However, during 2005 and 2004 + 2005, all these six treatments were significantly different between them, and showed significantly higher levels of water use than the rest of the treatments. On the other extreme, 7-AC and 7-RB always resulted in significantly less cumulative irrigation depth throughout this experiment.

Table 2-7 shows that 2-IM was the only SMS-based treatment that applied significantly more water (11%) than the control treatment 2-WRS. Conversely, the other two IM treatments saved a significant amount of water (20% and 28%, by 1-IM and 7-IM, 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%, depending on the irrigation frequency tested. 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 sensors”, but with a superior performance in terms of water savings.

When the irrigation treatments were compared to almost 75% of the surveyed homeowners in Florida (Whitcomb, 2005), this is with a non-functional or absent rain sensor (2-WORS), the significant difference in water savings increased, ranging from 77% to 92% for ACs, 81% to 90% for RBs, and 69% to 82%, for WWs. Even 2-IM (which applied 11% more water than 2-WRS) showed significant water savings, 27% with respect to 2-WORS, indicating that this sensor was working but did not bypass as much SIC as other SMS-based treatments.

Moreover, when compared to the water conservative 2-DWRS, treatments from brands AC, RB and WW also showed significant water savings, that ranged from 44% to

80%, 55% to 76%, and 26 to 57%, respectively. On the other hand, all IM-frequencies applied significantly more irrigation than 2-WORS, with values that ranged from 15% to 77% more water.

These results clearly demonstrate that the use of SMSs, along with traditional timers in residential irrigation systems, could lead to important water savings. However, the correct choice of the SMS, and its technology to measure or “sense” the soil water status, is of great consequence.

## Automation of Irrigation Systems

A complete automation of a residential irrigation system, based on SMSs, could be achieved programming the timer to run every day as a scheduling strategy. Then, the SMSs will allow the system to initiate the irrigation cycles only when it is actually needed by the turfgrass, and override them when the sensed water content is over a pre-set threshold.

In this experiment, this was confirmed when most of the SMS-based treatments were able to follow the dry and rainy periods–controlling the amount of water to be delivered to the different treatments (Table 2-4)–when the 7 d/w irrigation frequency used significantly less water than the other frequencies (Table 2-7, Column C), and when two of the SMS-based treatments programmed to run 7 d/w consistently used the smallest amount of water (Tables 2-5, 2-6, and 2-7). 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 (Tables 2-7).

It is interesting to note that this concept (with a potential irrigation frequency of seven days a week) is 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 choosing the right type of sensor, and programming the automatic irrigation system to run everyday for a short period of time (allowing the SMS to decide whether or not to irrigate), could save large amounts of potable water used for irrigation purposes, and looks like a better BMP than the current ones.

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) finally overrode more than 85% of the SIC (Table 2-4), resulting in a low actual irrigation frequency, which was supplemented by large rainfall events.

### Turfgrass Quality

No differences in turfgrass quality, including non-irrigated plots, were found among treatments. This could be explained in part by the generally wet climatic conditions that happened through almost all the time of the experiment, which favored the growth and development of the bermudagrass. Another factor contributing to this, even during the “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., 2005; Turgeon, 2005). As a result, the treatment effects were buffered with respect of the turfgrass quality parameters, and it could be concluded that no irrigation was necessary to maintain an acceptable turf quality during the experiment time-period. Figure 2-37 shows, in Part A, an homogeneous good quality between the different plots, and, in Part B, when bermudagrass went dormant on all plots at the same time. Having analogous weather conditions, Jordan et al. (2003) obtained similar results working with bentgrass.

## Summary and Conclusions

High frequency rainfall events and a large amount of cumulative precipitation prevailed during the time frame of this research, except for some weeks at the end of 2004 and at the early spring of 2005, when ETo exceeded rainfall. When the monthly deficit rainfall values (relative to ETo) were correlated with the percent of irrigation cycles allowed per month, r values of –0.93 and –0.76 were found for 2004 and 2005, respectively. It was inferred that most of the SMS-based treatments automatically canceled the majority of the irrigation cycles during the rainy periods, and responded to dry periods by allowing irrigations to occur.

The three time-based treatments (2-WORS, 2-WRS, and 2-DWRS) were significantly different from each other during the whole study period. The treatment without a rain sensor (2-WORS) used, on average, 52% more water than the treatment with a functional one (2-WRS), showing the importance of a well-maintained rain shut-off device in all automated irrigation systems in Florida. On the other hand, treatment 2-DWRS, applied close to 60% of the water applied by 2-WRS.

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 homeowners' actual operation practices in the Central Florida Ridge. Therefore, results in water use from this experiment can be considered conservative and differences for actual homeowners could be even larger.

When the time-based treatments were compared to the SMS-based treatments, results showed that, on average, the SMS-based treatments were significantly more efficient as a means to save water than the traditional time-based treatments. However, not all SMS-treatments tested performed the same. The 2-IM treatment was the only SMS-based treatment that applied significantly more water than the control 2-WRS (11% more). The other two IM treatments, 1-IM and 7-IM, used significantly less water than 2-WRS (20% and 28%, respectively), but always applied significantly more water than the other brands/treatments in every frequency tested. Therefore, IMs do not appear to be the best choice for the weather and soil conditions of this study.

All the other brands (AC, RB, and WW) recorded significant irrigation water savings compared to the control 2-WRS, which ranged from 54% to 88%, depending on the irrigation frequency. These results showed that most SMSs, except for 2-IM, can also act as rain sensors, with superior performance in terms of water savings. When these last brands were compared to 2-WORS, the differences in water savings increased, and ranged from 69% to 92% over the 308-days study period.

Irrigation frequencies were also compared at the end of the study. All three frequencies tested (1, 2, and 7 d/w) were significantly different. The 2 d/w frequency used the highest volume of water, followed by the 1 d/w frequency, and 7 d/w was the one that used the least amount of water. Moreover, and being part of this last frequency, treatments 7-AC and 7-RB significantly and consistently used the smallest amount of water regarding all treatments, during both seasons. They recorded total water savings of 85% or more, when compared to 2-WRS, and 90% or more when compared to 2-WORS.

These results suggest that scheduling low volume-high frequency irrigation cycles (7 d/w) in Closed Control Loop irrigation systems, appears to be a better strategy regarding water conservation for turfgrass irrigation in Florida’s sandy soils during rainy periods, than scheduling irrigation cycles one or two days per week. Moreover, it was concluded that no irrigation was necessary to maintain an acceptable turf quality during the experimental period, which was evidenced by acceptable quality in non-irrigated plots. Therefore, SMS-based technology could lead not only to a complete automation of residential irrigation systems, but to save substantial irrigation water if implemented.

Table 2-1. Irrigation treatment codes and descriptions.

| Treatment Codes | Irrigation Frequency (days/week) | Soil Moisture Sensor Brand or Treatment Description |
|---|---|---|
| Soil Moisture Sensor-Based | | |
| 1-AC | 1 | Acclima |
| 1-RB | 1 | Rainbird |
| 1-IM | 1 | Irrometer |
| 1-WW | 1 | Water Watcher |
| 2-AC | 2 | Acclima |
| 2-RB | 2 | Rainbird |
| 2-IM | 2 | Irrometer |
| 2-WW | 2 | Water Watcher |
| 7-AC | 7 | Acclima |
| 7-RB | 7 | Rainbird |
| 7-IM | 7 | Irrometer |
| 7-WW | 7 | Water Watcher |
| Time-Based | | |
| 2-WRS | 2 | With rain sensor |
| 2-WORS | 2 | Without rain sensor |
| 2-DWRS | 2 | Deficit with rain sensor, 60% of 2-WRS |
| 0-NI | 0 | No irrigation |

Table 2-2. Monthly irrigation depth to replace historical evapotranspiration, assuming system efficiency of 60%, and considering effective rainfall.

| Month | Irrigation depth (mm) |
|---|---|
| January | 0 |
| February | 0 |
| March | 112 |
| April | 112 |
| May | 183 |
| June | 142 |
| July | 137 |
| August | 178 |
| September | 137 |
| October | 122 |
| November | 91 |
| December | 91 |

Source: Based on Dukes and Haman (2002a)

Table 2-3. Total number and percent of overridden scheduled irrigation cycles; 2004 and 2005.

| | 2004 | | 2005 | | 2004 + 2005 | | |
|---|---|---|---|---|---|---|---|
| Treatment | Scheduled (#) | Overridden (%) | Scheduled (#) | Overridden (%) | Scheduled (#) | Overridden (%) | |
| 2-WORS | 40 | 0 | 46 | 0 | 86 | 0 | ***f*** |
| 2-WRS | 40 | 30 | 46 | 37 | 86 | 34 | ***e*** |
| 2-DWRS | 40 | 30 | 46 | 37 | 86 | 34 | ***e*** |
| 2-IM | 41 | 32 | 46 | 24 | 87 | 28 | ***e*** |
| 1-IM | 20 | 50 | 23 | 48 | 43 | 49 | ***d*** |
| 7-IM | 142 | 41 | 160 | 70 | 302 | 56 | ***d*** |
| 1-RB | 20 | 55 | 23 | 83 | 43 | 70 | ***c*** |
| 1-WW | 20 | 63 | 23 | 87 | 43 | 76 | ***c*** |
| 7-WW | 142 | 65 | 160 | 75 | 302 | 71 | ***c*** |
| 2-AC | 41 | 73 | 46 | 83 | 87 | 78 | ***bc*** |
| 1-AC | 20 | 85 | 23 | 78 | 43 | 81 | ***abc*** |
| 2-WW | 41 | 85 | 46 | 78 | 87 | 82 | ***abc*** |
| 2-RB | 41 | 85 | 46 | 91 | 87 | 89 | ***ab*** |
| 7-AC | 142 | 92 | 160 | 92 | 302 | 92 | ***a*** |
| 7-RB | 142 | 89 | 160 | 93 | 302 | 91 | ***a*** |

$P<0.0001$

Table 2-4. Percent of irrigation cycles allowed by the SMS-based treatments through the experimental months of 2004 and 2005.

| Treatment | Year 2004 (%) | | | | Year 2005 (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Aug | Sep | Oct | Nov | Apr | May | Jun | Jul | Aug |
| 1-AC | 0 | 0 | 0 | 75 | 50 | 75 | 0 | 0 | 0 |
| 2-AC | 22 | 11 | 22 | 33 | 22 | 33 | 13 | 11 | 11 |
| 7-AC | 10 | 0 | 3 | 17 | 17 | 10 | 0 | 6 | 10 |
| 1-RB | 0 | 40 | 100 | 75 | 0 | 25 | 20 | 25 | 20 |
| 2-RB | 33 | 0 | 0 | 22 | 11 | 11 | 0 | 11 | 11 |
| 7-RB | 6 | 3 | 13 | 17 | 7 | 19 | 7 | 6 | 0 |
| 1-IM | 25 | 20 | 50 | 100 | 25 | 100 | 20 | 75 | 60 |
| 2-IM | 33 | 33 | 100 | 100 | 67 | 100 | 75 | 89 | 67 |
| 7-IM | 84 | 73 | 87 | 23 | 40 | 45 | 17 | 35 | 16 |
| 1-WW | 0 | 20 | 75 | 50 | 25 | 50 | 0 | 0 | 0 |
| 2-WW | 11 | 0 | 33 | 11 | 67 | 44 | 0 | 0 | 0 |
| 7-WW | 29 | 20 | 42 | 33 | 37 | 42 | 10 | 32 | 6 |
| Average | 21 | 18 | 44 | 46 | 31 | 46 | 13 | 24 | 17 |
| RED (mm) | 184 | 397 | -16 | -17 | -14 | -23 | 76 | -25 | 30 |
| CC (r) | | -0.93 | | | | | -0.76 | | |

RED = Rainfall - ETo difference

CC = Correlation coefficient

Table 2-5. Cumulative irrigation depth applied to treatments, statistical comparisons between them, and percent of water savings compared to 2-WRS, 2-DWRS, and 2-WORS; year 2004.

| Treatment | Cumulative depth 2004 (mm) | Comparisons[+] | | | | | Water savings (%) vs. | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ***A*** | B | ***C*** | D | ***E*** | 2-WRS | 2-WORS | 2-DWRS |
| SMS-Based | | | | | | | | | |
| 1-AC | 95 | | | | d | ***g*** | 80 | 86 | 69 |
| 1-RB | 128 | | | | c | ***f*** | 73 | 82 | 59 |
| 1-IM | 318 | | | | a | ***c*** | 34 | 54 | -3 |
| 1-WW | 209 | | | | b | ***e*** | 57 | 70 | 33 |
| 1-Avg | 188 | | | ***b*** | | | | | |
| 2-AC | 196 | | | | b | ***e*** | 59 | 72 | 37 |
| 2-RB | 87 | | | | c | ***gh*** | 82 | 88 | 72 |
| 2-IM | 470 | | | | a | ***b*** | 2 | 32 | -52 |
| 2-WW | 94 | | | | c | ***g*** | 81 | 87 | 70 |
| 2-Avg | 212 | | | ***a*** | | | | | |
| 7-AC | 57 | | | | c | ***h*** | 88 | 92 | 82 |
| 7-RB | 85 | | | | c | ***gh*** | 82 | 88 | 73 |
| 7-IM | 471 | | | | a | ***b*** | 2 | 32 | -52 |
| 7-WW | 261 | | | | b | ***d*** | 46 | 63 | 16 |
| 7-Avg | 218 | | | ***a*** | | | | | |
| SMS-Avg | 206 | ***b*** | | | | | | | |
| Time-Based | | | | | | | | | |
| 2-WORS | 696 | | a | | | ***a*** | -45 | 0 | -125 |
| 2-WRS | 481 | | b | | | ***b*** | 0 | 31 | -55 |
| 2-DWRS | 310 | | c | | | ***c*** | 36 | 55 | 0 |
| Time-Avg | 496 | ***a*** | | | | | | | |

SMS=Soil moisture sensor P<0.0001

Avg=Average

[+] A=Time-based treatments vs. SMS-based treatments

B=Between time-based treatments

C=Between irrigation frequency averages

D=Within irrigation frequency

E=Overall comparison

Table 2-6. Cumulative irrigation depth applied to treatments, statistical comparisons between them, and percent of water savings compared to 2-WRS, 2-DWRS, and 2-WORS; year 2005.

| Treatment | Cumulative depth 2005 (mm) | Comparisons[+] | | | | | Water savings (%) vs. | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ***A*** | B | ***C*** | D | ***E*** | 2-WRS | 2-WORS | 2-DWRS |
| <u>SMS-Based</u> | | | | | | | | | |
| 1-AC | 188 | | | | b | ***gh*** | 63 | 77 | 40 |
| 1-RB | 153 | | | | c | ***i*** | 70 | 81 | 51 |
| 1-IM | 475 | | | | a | ***d*** | 7 | 42 | -52 |
| 1-WW | 114 | | | | d | ***j*** | 78 | 86 | 64 |
| 1-Avg | 232 | | | ***b*** | | | | | |
| 2-AC | 152 | | | | b | ***i*** | 70 | 81 | 51 |
| 2-RB | 101 | | | | c | ***j*** | 80 | 88 | 68 |
| 2-IM | 635 | | | | a | ***b*** | -24 | 22 | -103 |
| 2-WW | 177 | | | | b | ***h*** | 66 | 78 | 44 |
| 2-Avg | 266 | | | ***a*** | | | | | |
| 7-AC | 65 | | | | c | ***k*** | 87 | 92 | 79 |
| 7-RB | 62 | | | | c | ***k*** | 88 | 92 | 80 |
| 7-IM | 244 | | | | a | ***f*** | 52 | 70 | 22 |
| 7-WW | 202 | | | | b | ***g*** | 61 | 75 | 36 |
| 7-Avg | 143 | | | ***c*** | | | | | |
| SMS-Avg | 214 | ***b*** | | | | | | | |
| <u>Time-Based</u> | | | | | | | | | |
| 2-WORS | 818 | | a | | | ***a*** | -59 | 0 | -161 |
| 2-WRS | 514 | | b | | | ***c*** | 0 | 37 | -64 |
| 2-DWRS | 313 | | c | | | ***e*** | 39 | 62 | 0 |
| Time-Avg | 548 | ***a*** | | | | | | | |

SMS=Soil moisture sensor P<0.0001

Avg=Average

[+] A=Time-based treatments vs. SMS-based treatments

B=Between time-based treatments

C=Between irrigation frequency averages

D=Within irrigation frequency

E=Overall comparison

Table 2-7. Total cumulative irrigation depth applied to treatments, statistical comparisons between them, and percent of water savings compared to 2-WRS, 2-DWRS, and 2-WORS; years 2004 + 2005.

| Treatment | Total cumulative depth 2004+2005 (mm) | Comparisons[+] | | | | | Water savings (%) vs. | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ***A*** | B | ***C*** | D | ***E*** | 2-WRS | 2-WORS | 2-DWRS |
| SMS-Based | | | | | | | | | |
| 1-AC | 283 | | | | b | ***i*** | 72 | 81 | 55 |
| 1-RB | 281 | | | | b | ***i*** | 72 | 81 | 55 |
| 1-IM | 793 | | | | a | ***d*** | 20 | 48 | -27 |
| 1-WW | 323 | | | | b | ***h*** | 68 | 79 | 48 |
| 1-Avg | 420 | | | ***b*** | | | | | |
| 2-AC | 348 | | | | b | ***h*** | 65 | 77 | 44 |
| 2-RB | 188 | | | | d | ***j*** | 81 | 88 | 70 |
| 2-IM | 1105 | | | | a | ***b*** | -11 | 27 | -77 |
| 2-WW | 270 | | | | c | ***i*** | 73 | 82 | 57 |
| 2-Avg | 478 | | | ***a*** | | | | | |
| 7-AC | 122 | | | | c | ***k*** | 88 | 92 | 80 |
| 7-RB | 147 | | | | c | ***k*** | 85 | 90 | 76 |
| 7-IM | 715 | | | | a | ***e*** | 28 | 53 | -15 |
| 7-WW | 463 | | | | b | ***g*** | 54 | 69 | 26 |
| 7-Avg | 362 | | | ***c*** | | | | | |
| SMS-Avg | 420 | ***b*** | | | | | | | |
| Time-Based | | | | | | | | | |
| 2-WORS | 1514 | | a | | | ***a*** | -52 | 0 | -143 |
| 2-WRS | 995 | | b | | | ***c*** | 0 | 34 | -60 |
| 2-DWRS | 623 | | c | | | ***f*** | 37 | 59 | 0 |
| Time-Avg | 1044 | ***a*** | | | | | | | |

SMS=Soil moisture sensor P<0.0001

Avg=Average

[+] A=Time-based treatments vs. SMS-based treatments

B=Between time-based treatments

C=Between irrigation frequency averages

D=Within irrigation frequency

E=Overall comparison

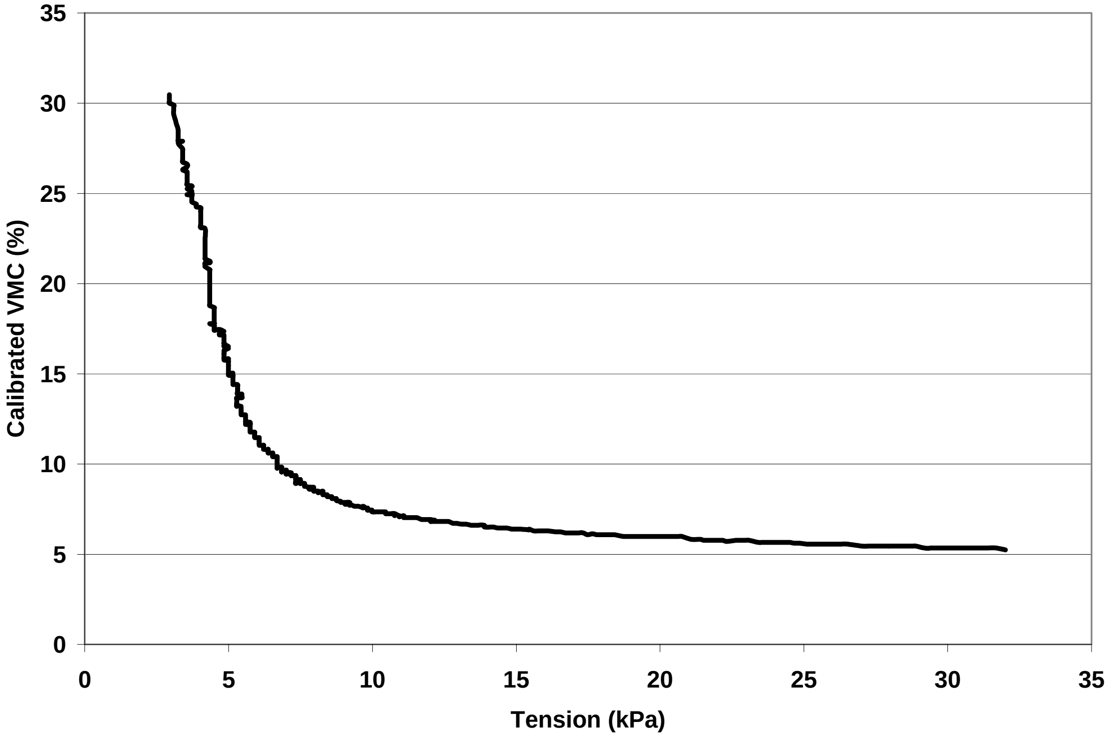


Figure 2-1. Soil water retention curve from tensiometers and calibrated $ECH_2O$ probe readings.

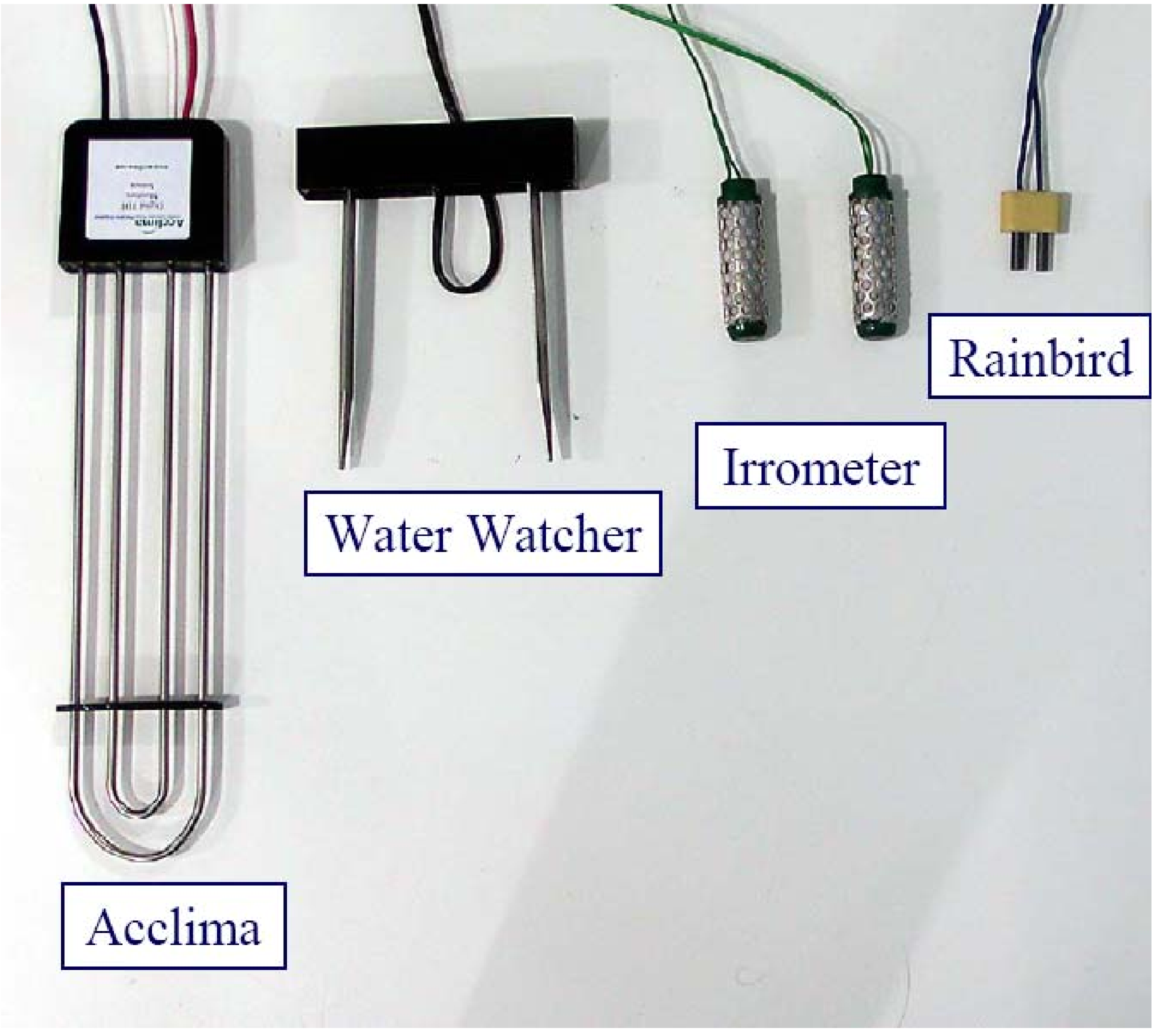


Figure 2-2. Soil moisture sensor brands tested in this study.

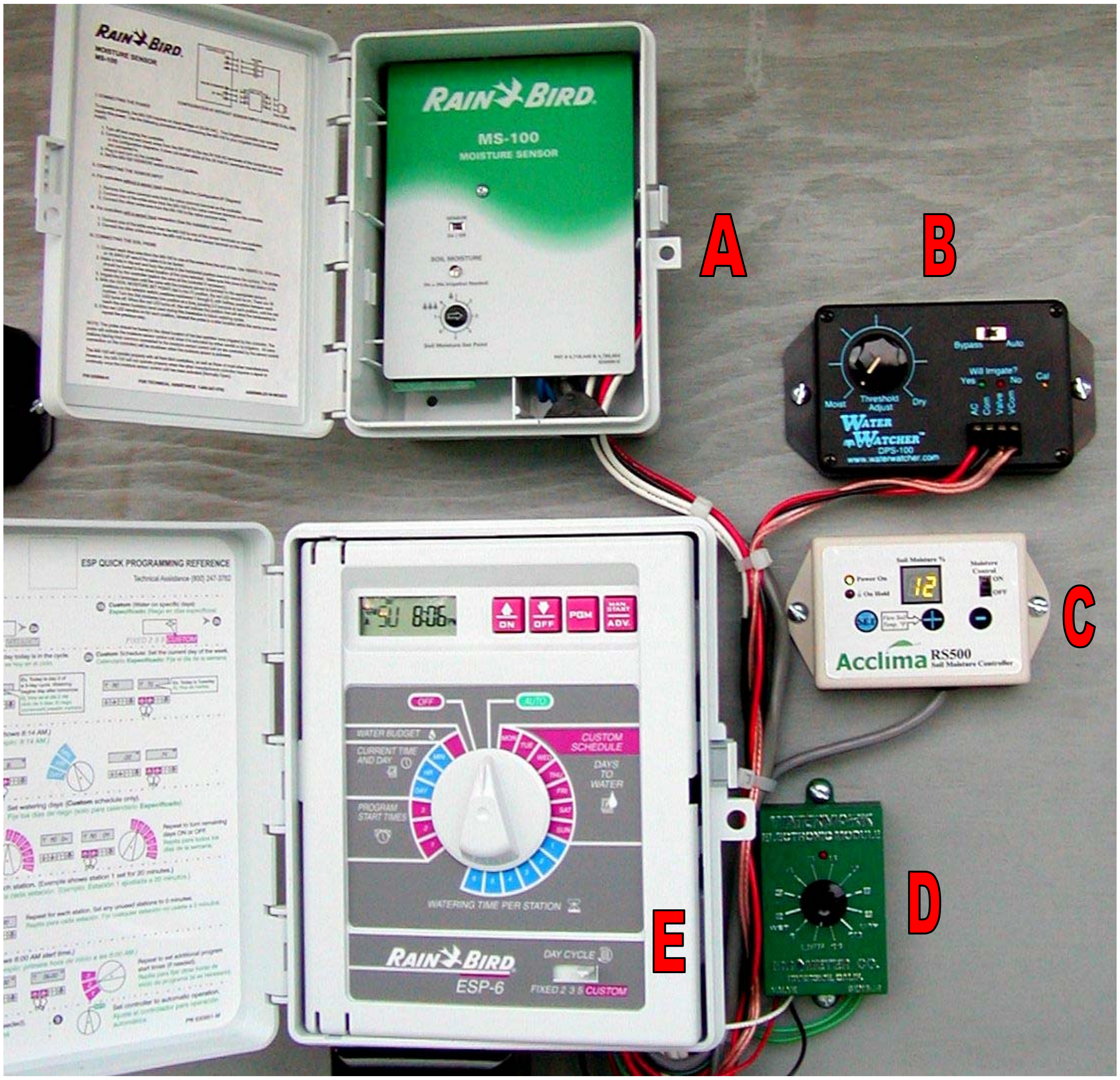


Figure 2-3. Irrigation controls as installed for this study: soil moisture sensors-controllers brands: A) Rain Bird, B) Water Watcher, C) Acclima, and D) Irrometer, and irrigation timer E) Rain Bird.

Figure 2-4. Rain sensor installed for this study.

Figure 2-5. Catch-can display for uniformity tests on turfgrass plots.

Figure 2-6. General view of the irrigation controls used in this study.

Figure 2-7. Pipes, flowmeters, valves, and wirings for this study.

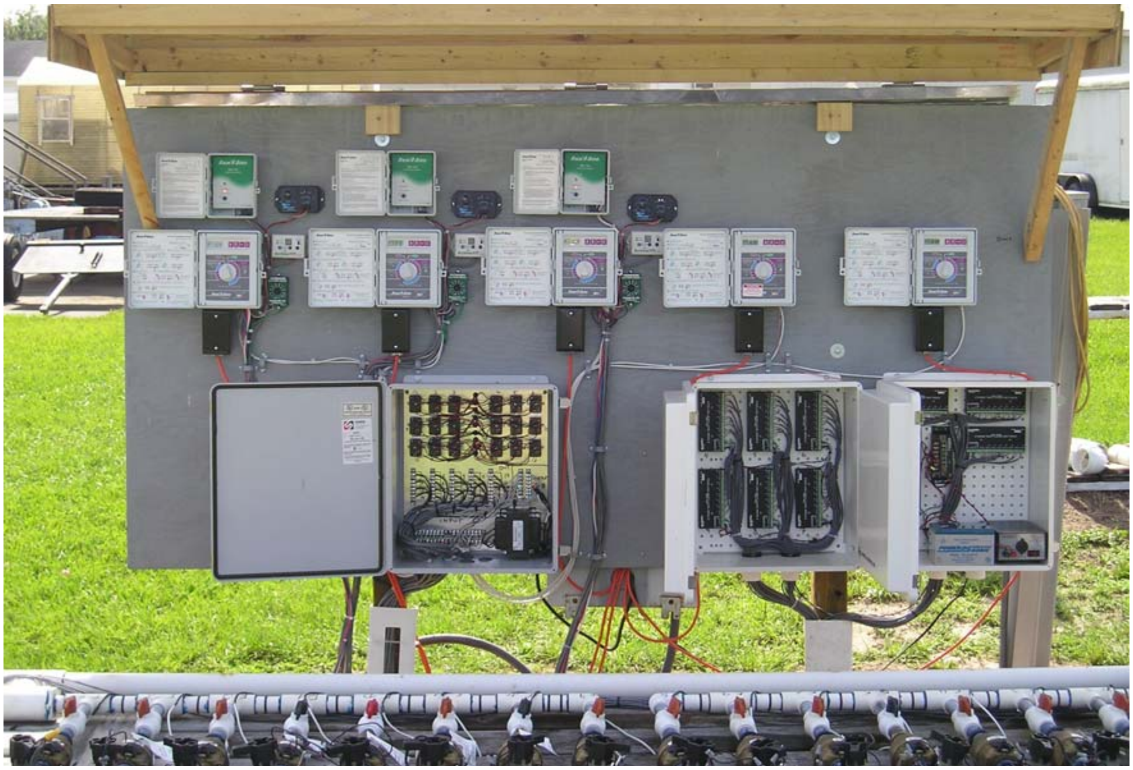


Figure 2-8. Control board showing timers, soil moisture sensor-controllers, solenoid valves wiring, and flowmeters-datalogger (details are shown in the next Figures).

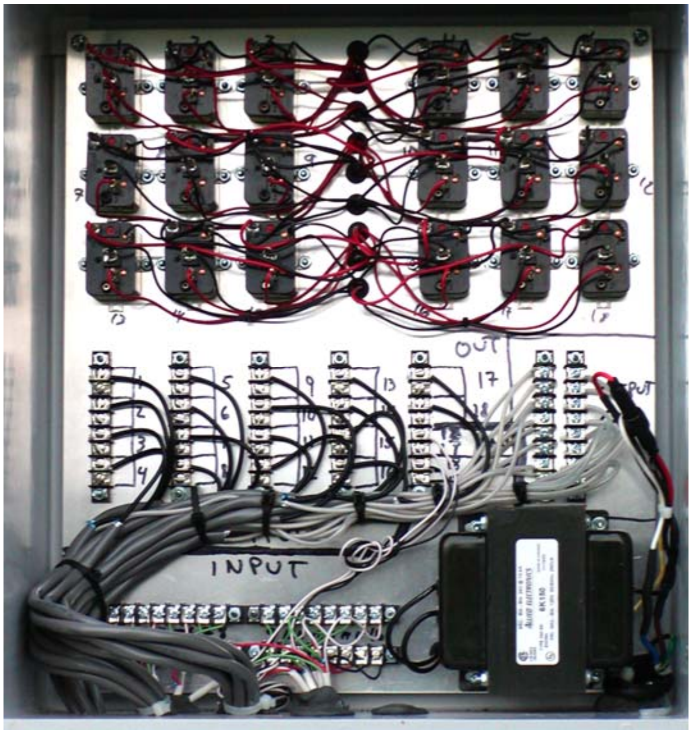


Figure 2-9. Control board detail showing the solenoid valves control box.

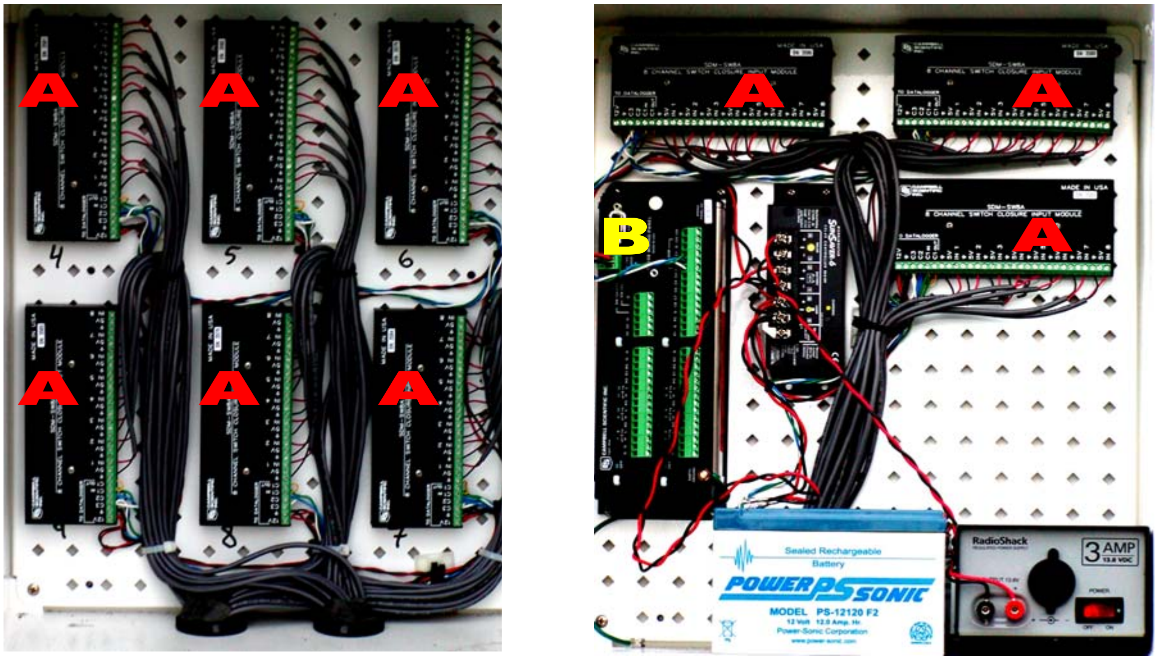


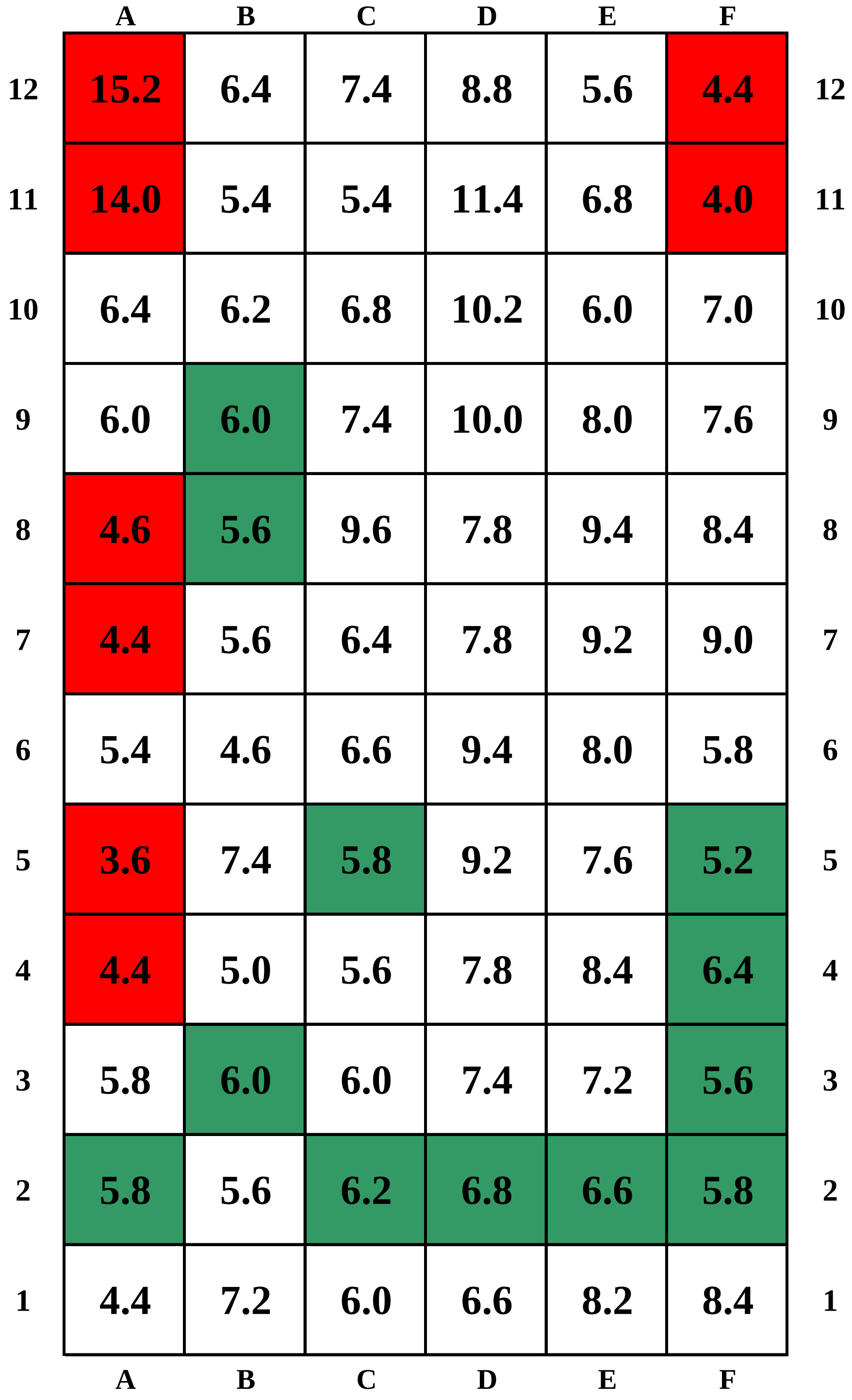
Figure 2-10. Control board detail, flowmeter-datalogger boxes showing A) multiplexers, B) CR 10X datalogger used for this study.

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.

| | 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 2-13. Plot plan showing the low-quarter distribution uniformity testing results on each plot.

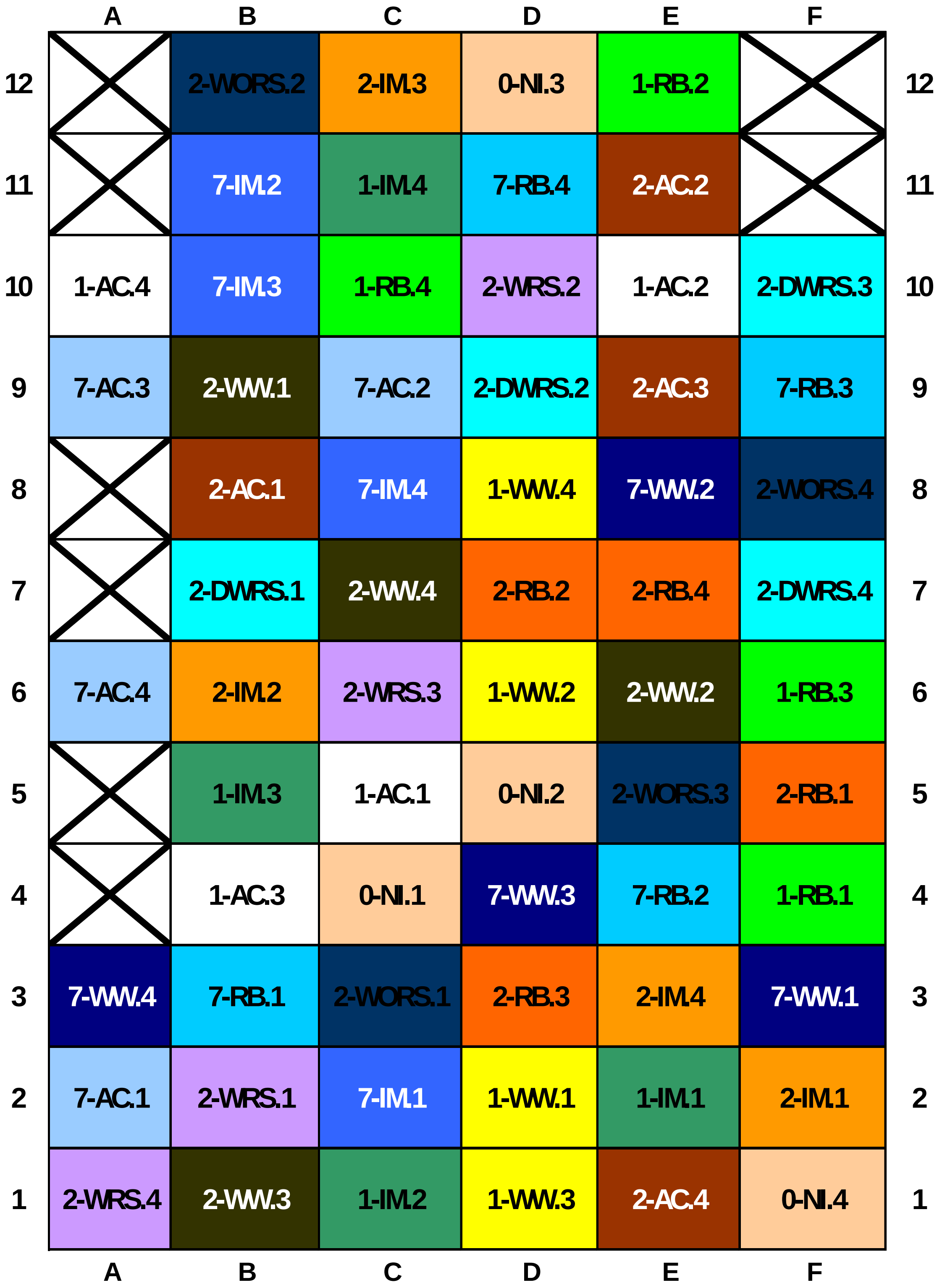


|  | A | B | C | D | E | F |  |
|---|---|---|---|---|---|---|---|
| 12 | 15.2 | 6.4 | 7.4 | 8.8 | 5.6 | 4.4 | 12 |
| 11 | 14.0 | 5.4 | 5.4 | 11.4 | 6.8 | 4.0 | 11 |
| 10 | 6.4 | 6.2 | 6.8 | 10.2 | 6.0 | 7.0 | 10 |
| 9 | 6.0 | 6.0 | 7.4 | 10.0 | 8.0 | 7.6 | 9 |
| 8 | 4.6 | 5.6 | 9.6 | 7.8 | 9.4 | 8.4 | 8 |
| 7 | 4.4 | 5.6 | 6.4 | 7.8 | 9.2 | 9.0 | 7 |
| 6 | 5.4 | 4.6 | 6.6 | 9.4 | 8.0 | 5.8 | 6 |
| 5 | 3.6 | 7.4 | 5.8 | 9.2 | 7.6 | 5.2 | 5 |
| 4 | 4.4 | 5.0 | 5.6 | 7.8 | 8.4 | 6.4 | 4 |
| 3 | 5.8 | 6.0 | 6.0 | 7.4 | 7.2 | 5.6 | 3 |
| 2 | 5.8 | 5.6 | 6.2 | 6.8 | 6.6 | 5.8 | 2 |
| 1 | 4.4 | 7.2 | 6.0 | 6.6 | 8.2 | 8.4 | 1 |
|  | A | B | C | D | E | F |  |

Figure 2-14. Plot plan showing average volumetric water content (%) on each plot during a relatively “dry” period. Plots in red were discarded, and plots in green were used for placement of SMSs.

| | A | B | C | D | E | F | |
|---|---|---|---|---|---|---|---|
| 12 | 20.8 | 11.0 | 11.6 | 12.2 | 11.0 | 12.4 | 12 |
| 11 | 27.8 | 11.6 | 12.2 | 12.8 | 10.8 | 9.4 | 11 |
| 10 | 12.4 | 8.8 | 10.4 | 10.4 | 10.8 | 9.8 | 10 |
| 9 | 11.4 | 11.2 | 11.0 | 11.4 | 10.4 | 10.8 | 9 |
| 8 | 11.4 | 10.6 | 12.6 | 12.2 | 11.8 | 10.6 | 8 |
| 7 | 10.2 | 9.6 | 12.0 | 11.0 | 11.0 | 11.2 | 7 |
| 6 | 10.6 | 11.6 | 10.2 | 10.8 | 9.6 | 9.2 | 6 |
| 5 | 9.2 | 12.2 | 10.4 | 9.6 | 10.4 | 9.8 | 5 |
| 4 | 9.8 | 10.2 | 9.8 | 9.4 | 8.8 | 9.2 | 4 |
| 3 | 9.8 | 9.8 | 12.0 | 10.4 | 10.8 | 8.6 | 3 |
| 2 | 12.0 | 11.2 | 10.2 | 11.2 | 14.0 | 10.6 | 2 |
| 1 | 12.2 | 11.6 | 11.2 | 12.0 | 14.8 | 15.8 | 1 |
| | A | B | C | D | E | F | |

Figure 2-15. Plot plan showing average volumetric water content (%) on each plot during a relatively “wet” condition. Plots in red were discarded, and plots in green were used for placement of SMSs.



|  | A | B | C | D | E | F |  |
|---|---|---|---|---|---|---|---|
| 12 | ☒ | 2-WORS.2 | 2-IM.3 | 0-NI.3 | 1-RB.2 | ☒ | 12 |
| 11 | ☒ | 7-IM.2 | 1-IM.4 | 7-RB.4 | 2-AC.2 | ☒ | 11 |
| 10 | 1-AC.4 | 7-IM.3 | 1-RB.4 | 2-WRS.2 | 1-AC.2 | 2-DWRS.3 | 10 |
| 9 | 7-AC.3 | 2-WW.1 | 7-AC.2 | 2-DWRS.2 | 2-AC.3 | 7-RB.3 | 9 |
| 8 | ☒ | 2-AC.1 | 7-IM.4 | 1-WW.4 | 7-WW.2 | 2-WORS.4 | 8 |
| 7 | ☒ | 2-DWRS.1 | 2-WW.4 | 2-RB.2 | 2-RB.4 | 2-DWRS.4 | 7 |
| 6 | 7-AC.4 | 2-IM.2 | 2-WRS.3 | 1-WW.2 | 2-WW.2 | 1-RB.3 | 6 |
| 5 | ☒ | 1-IM.3 | 1-AC.1 | 0-NI.2 | 2-WORS.3 | 2-RB.1 | 5 |
| 4 | ☒ | 1-AC.3 | 0-NI.1 | 7-WW.3 | 7-RB.2 | 1-RB.1 | 4 |
| 3 | 7-WW.4 | 7-RB.1 | 2-WORS.1 | 2-RB.3 | 2-IM.4 | 7-WW.1 | 3 |
| 2 | 7-AC.1 | 2-WRS.1 | 7-IM.1 | 1-WW.1 | 1-IM.1 | 2-IM.1 | 2 |
| 1 | 2-WRS.4 | 2-WW.3 | 1-IM.2 | 1-WW.3 | 2-AC.4 | 0-NI.4 | 1 |
|  | A | B | C | D | E | F |  |

Figure 2-16. Plot plan with the modified completely randomized design (same color depicts treatment repetitions).

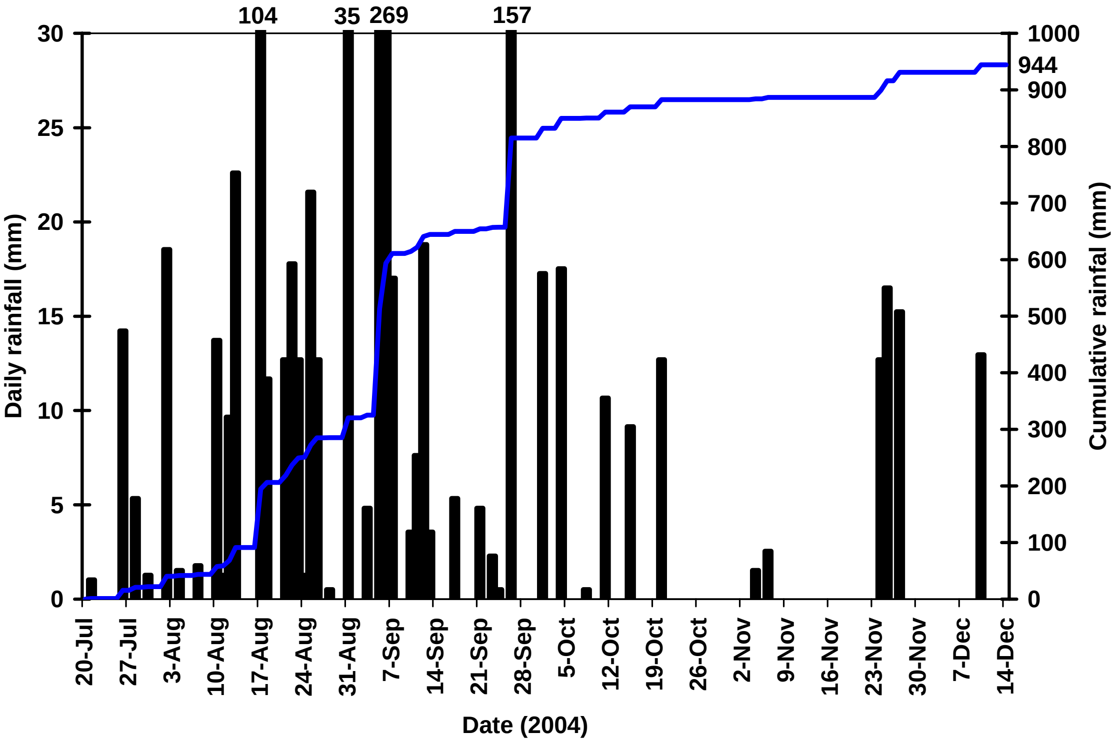


Figure 2-17. Daily and cumulative rainfall in 2004. Note: rainfall for 5 Sep. (188 mm) and 6 Sep. (81 mm) is shown as a cumulative total (269 mm).

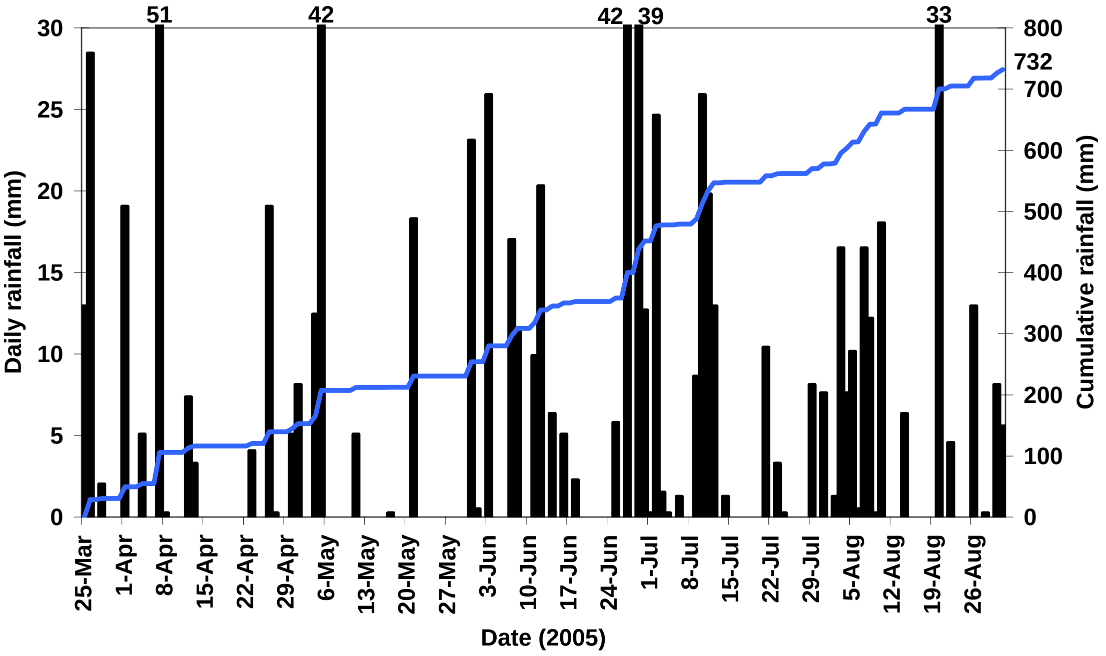


Figure 2-18. Daily and cumulative rainfall in 2005.

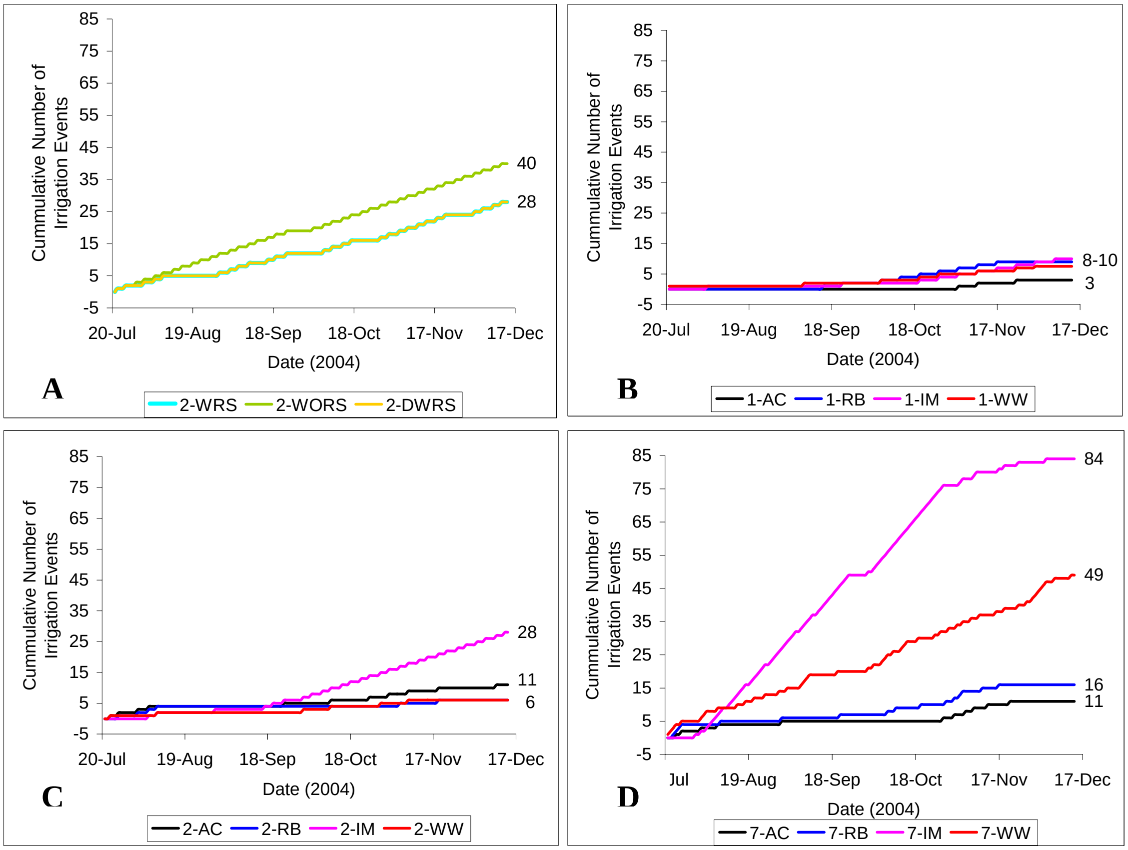


Figure 2-19. Cumulative number of irrigation events per treatment in 2004; A) time-based treatments, and soil moisture sensor-based treatments at irrigation frequencies of B) 1 d/w, C) 2 d/w, and D) 7 d/w. Note: In part A), treatments 2-WRS and 2-DWRS were controlled by the same rain sensor and were set to run at the same days, so only one line can be seen for both treatments.

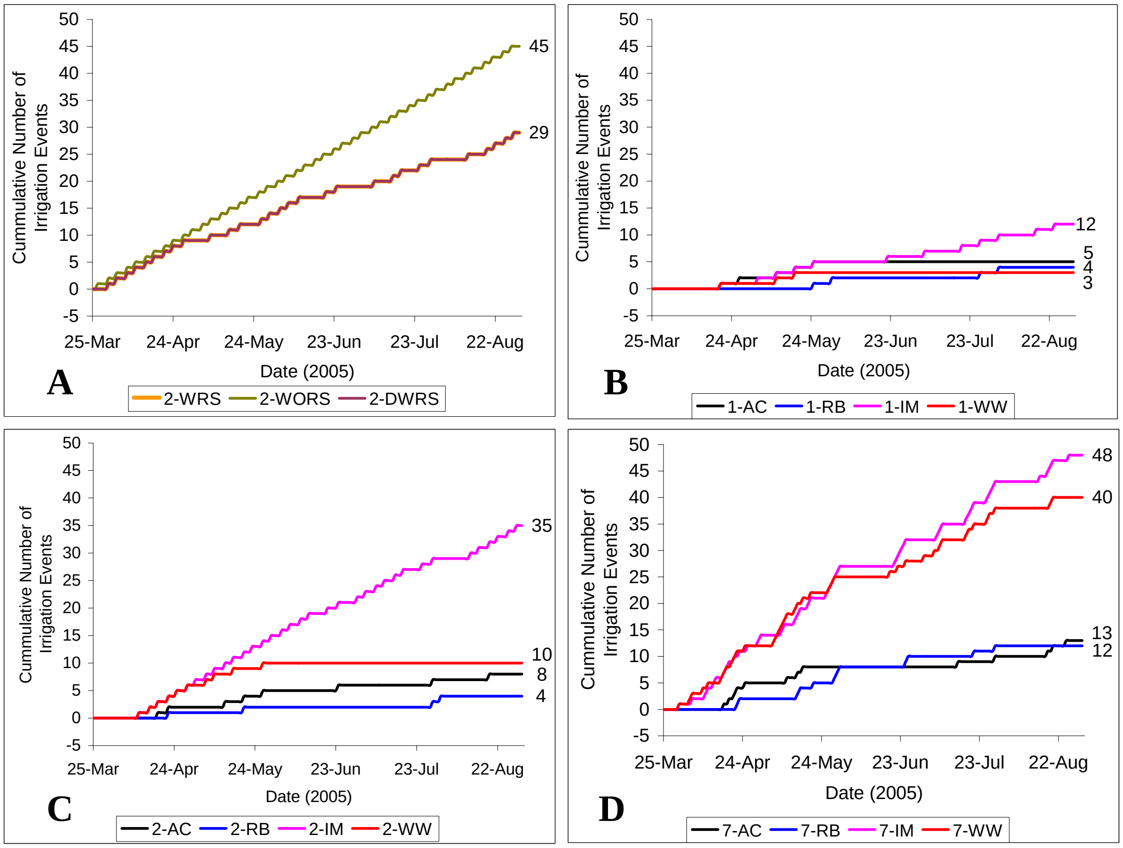


Figure 2-20 Cumulative number of irrigation events per treatment in 2005; A) time-based treatments, and soil moisture sensor-based treatments at irrigation frequencies of B) 1 d/w, C) 2 d/w, and D) 7 d/w. Note: In part A), treatments 2-WRS and 2-DWRS were controlled by the same rain sensor and were set to run at the same days, so only one line can be seen for both treatments.

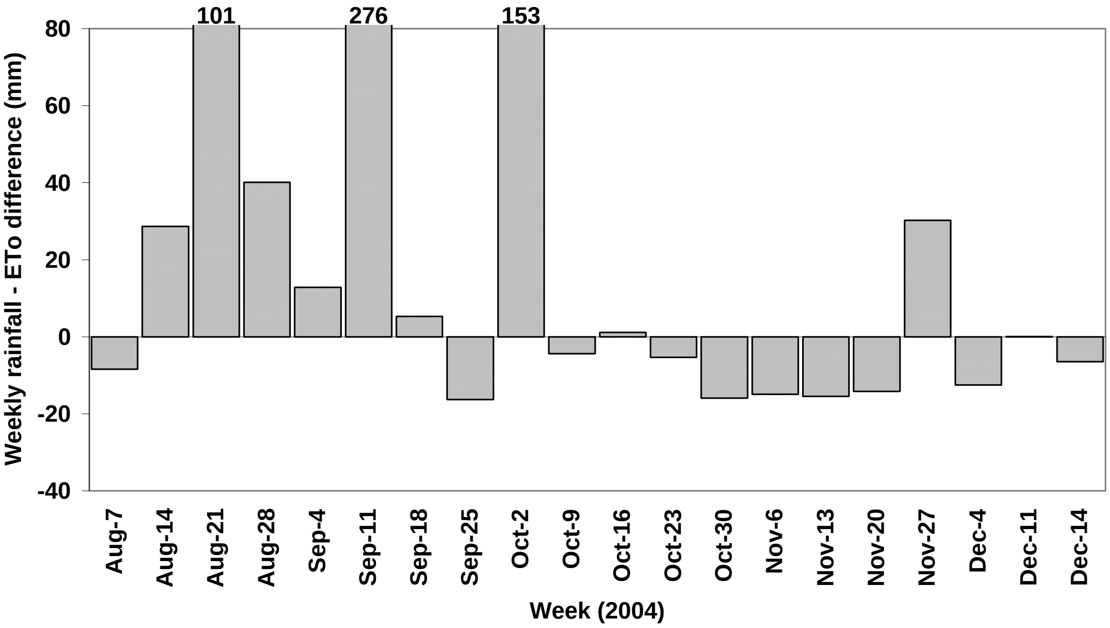


Figure 2-21. Maximum weekly irrigation water requirement (rainfall - ETo difference); year 2004.

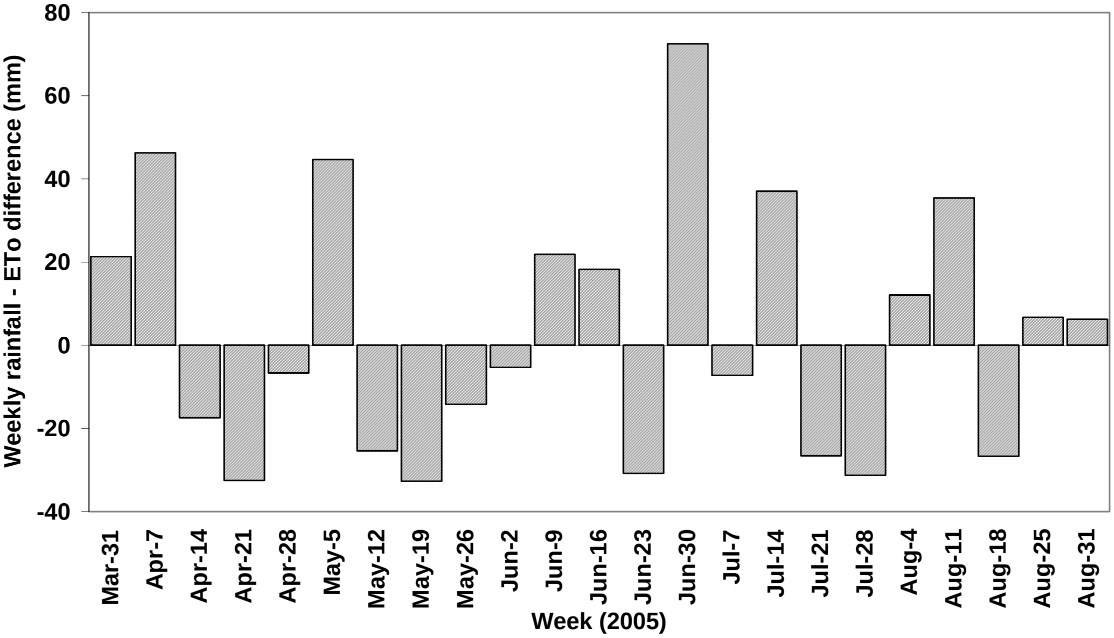


Figure 2-22. Maximum weekly irrigation water requirement (rainfall - ETo difference); year 2005.

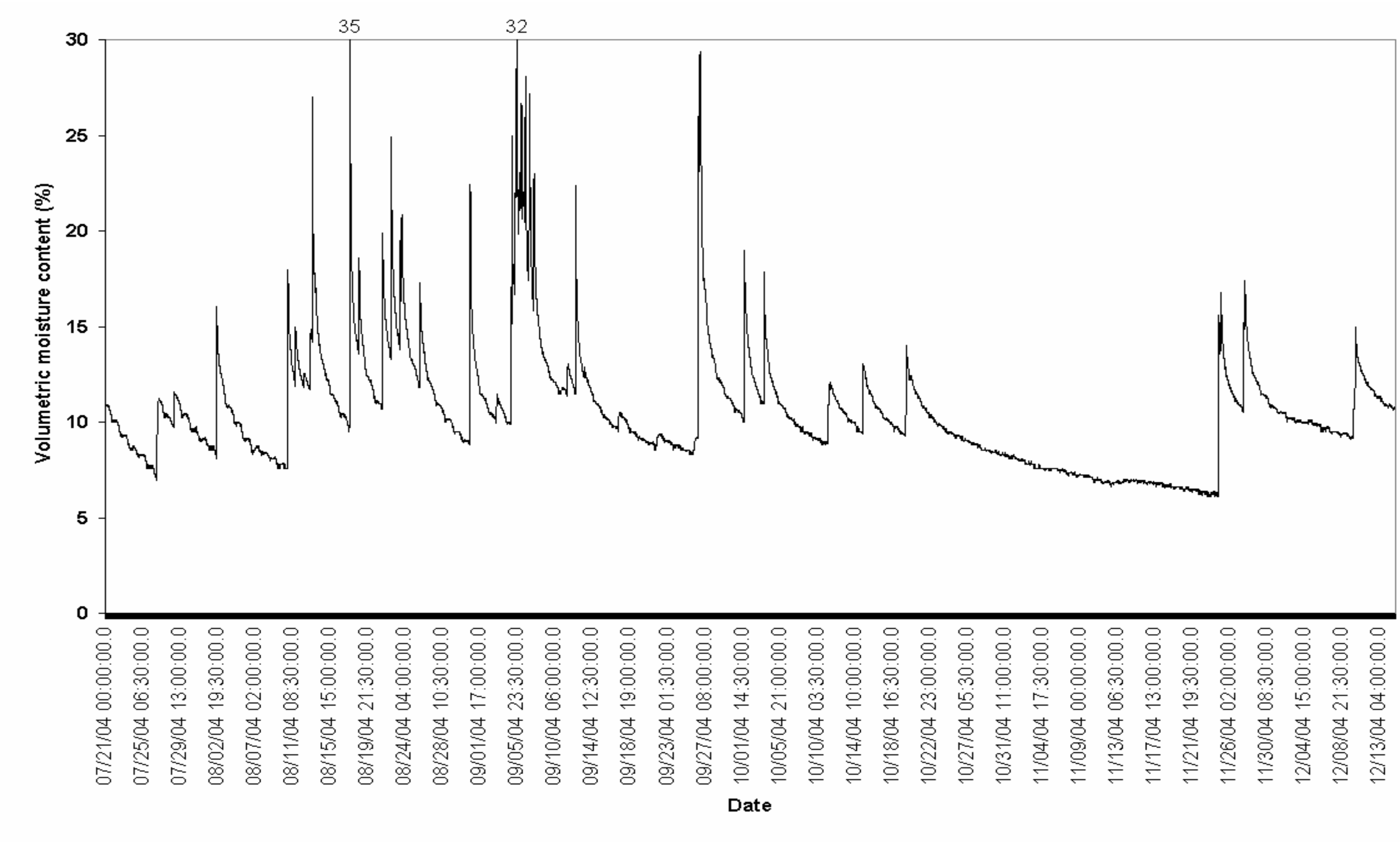


Figure 2-23. Volumetric moisture content through time, on treatment 0-NI, year 2004.

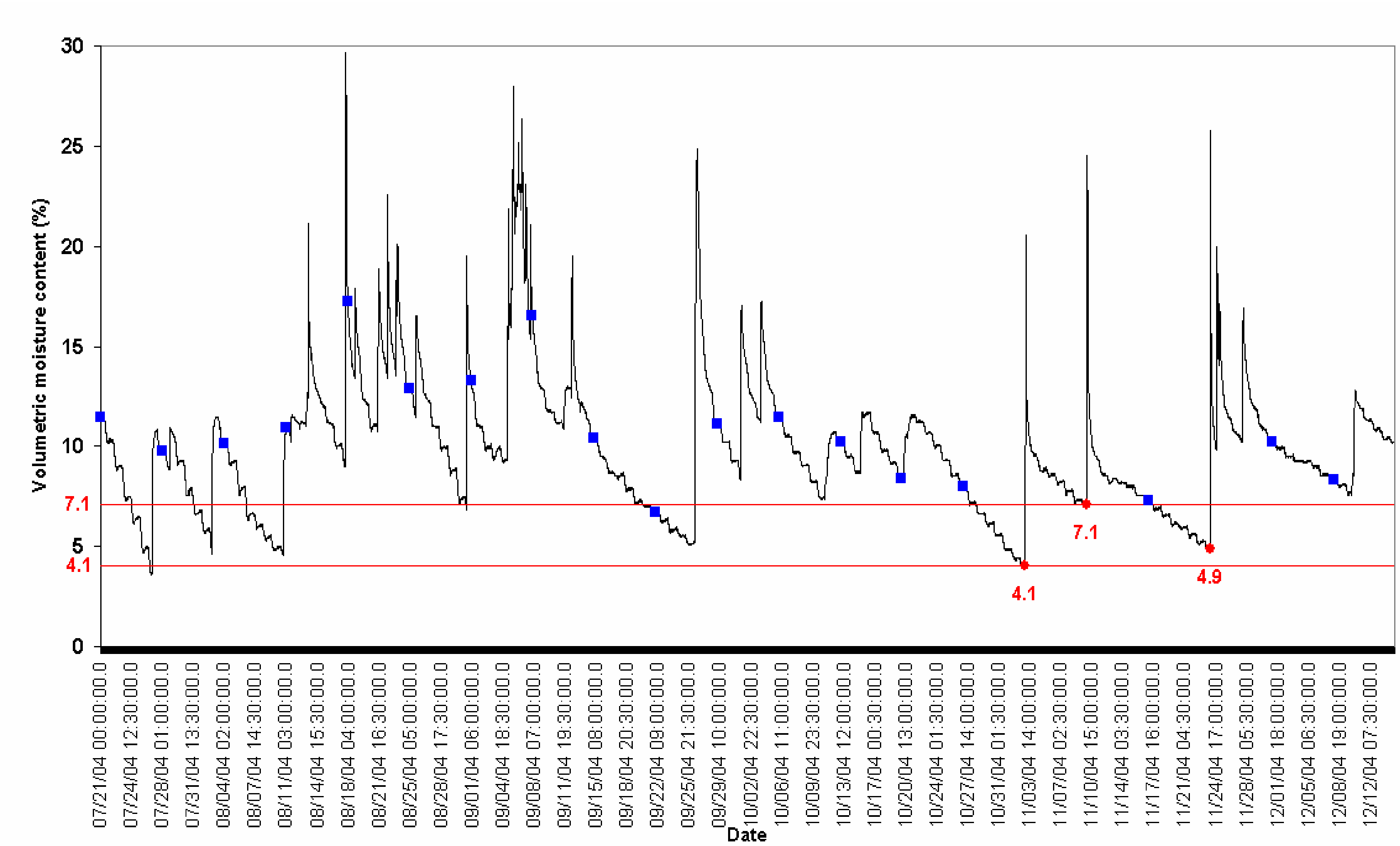


Figure 2-24. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 1-AC, year 2004.

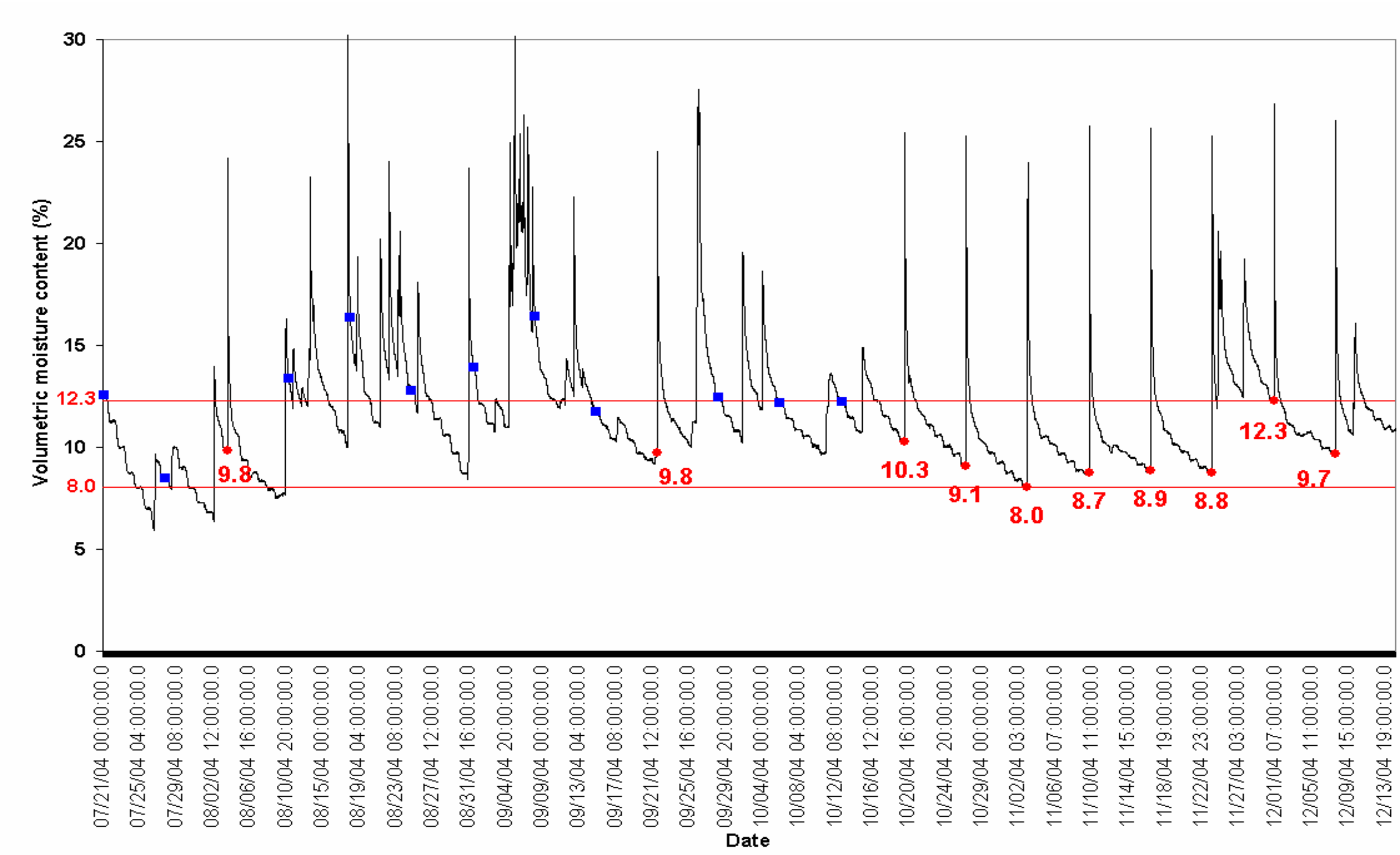


Figure 2-25. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 1-IM, year 2004.

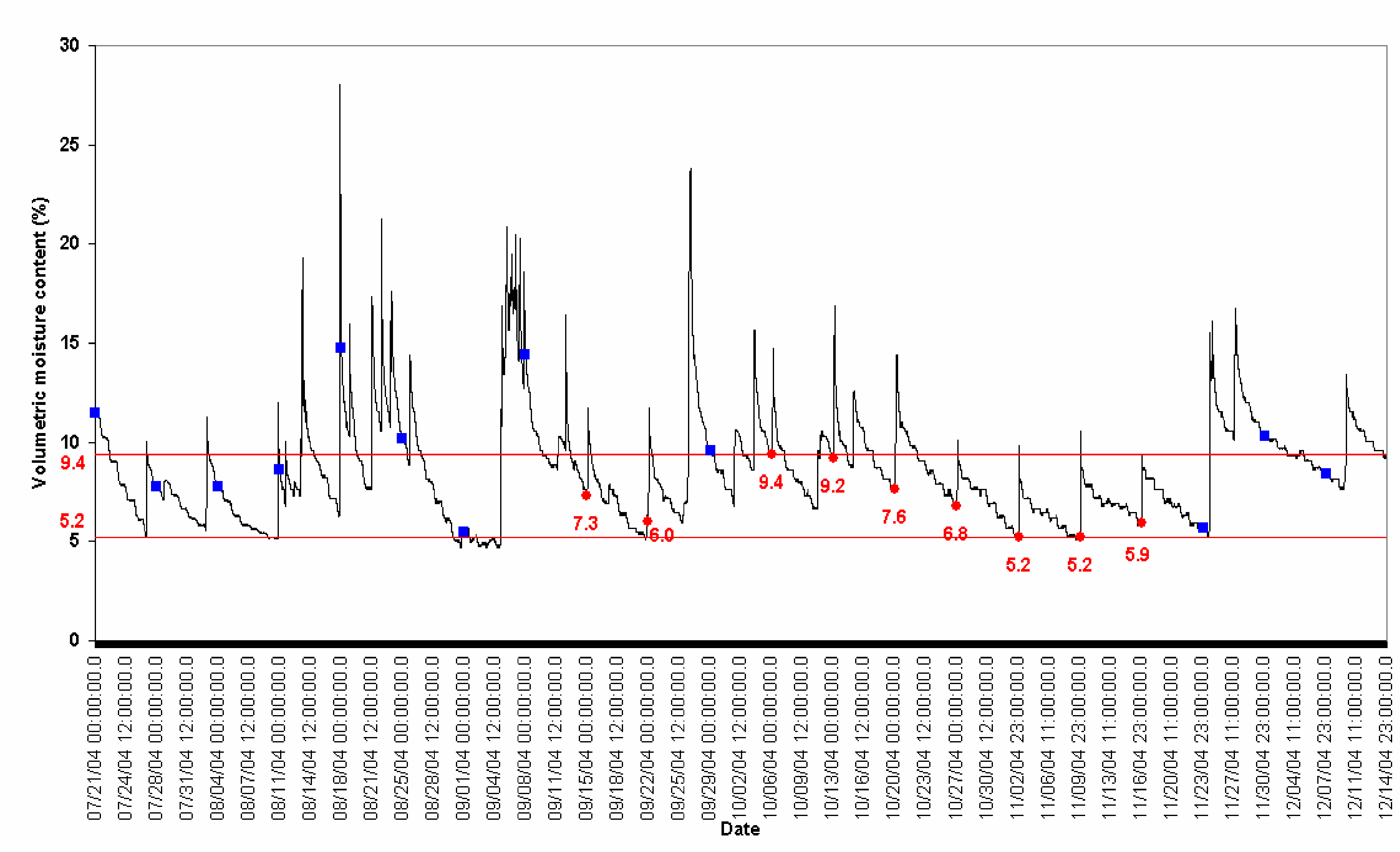


Figure 2-26. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 1-RB, year 2004.

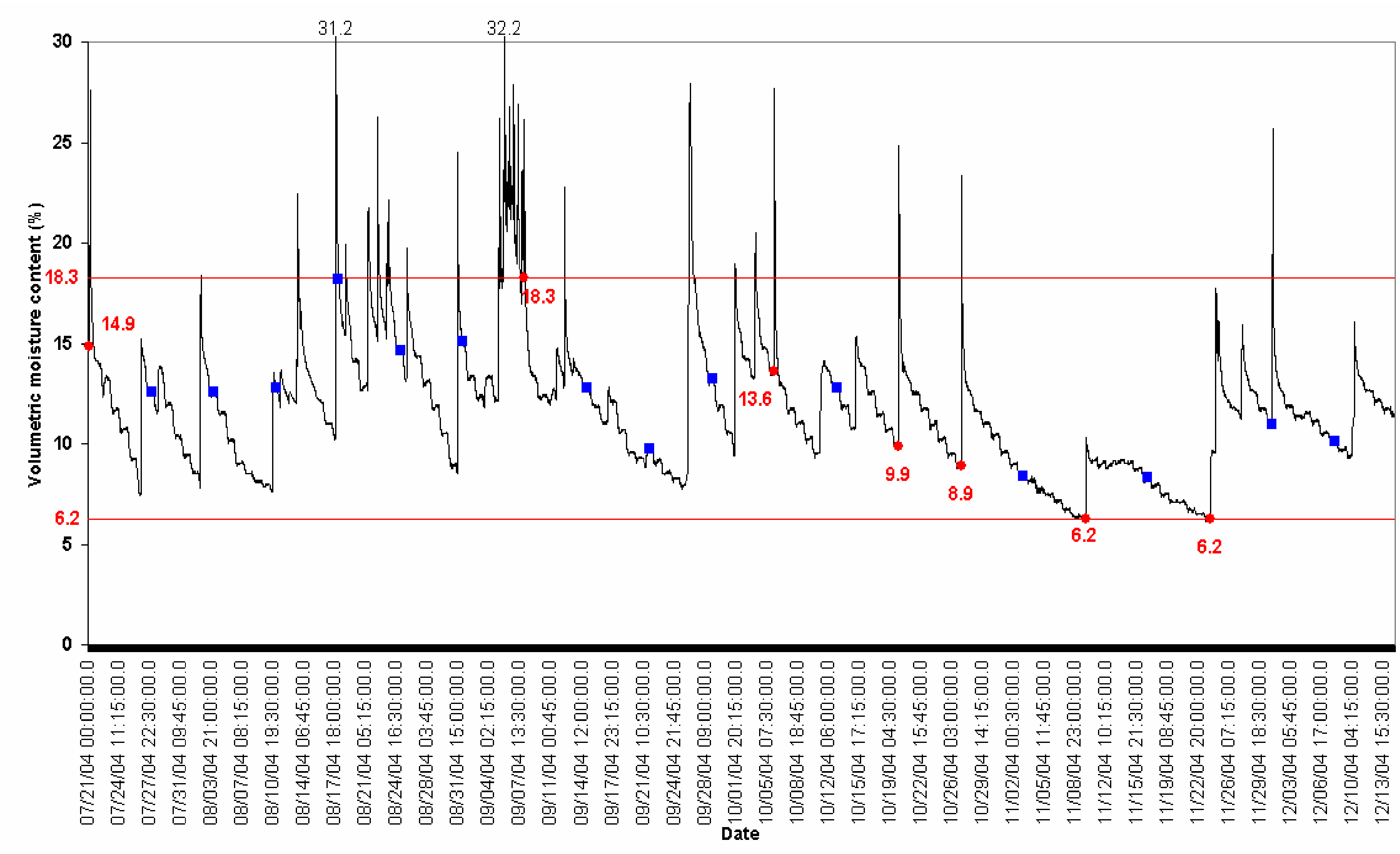


Figure 2-27. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 1-WW, year 2004.

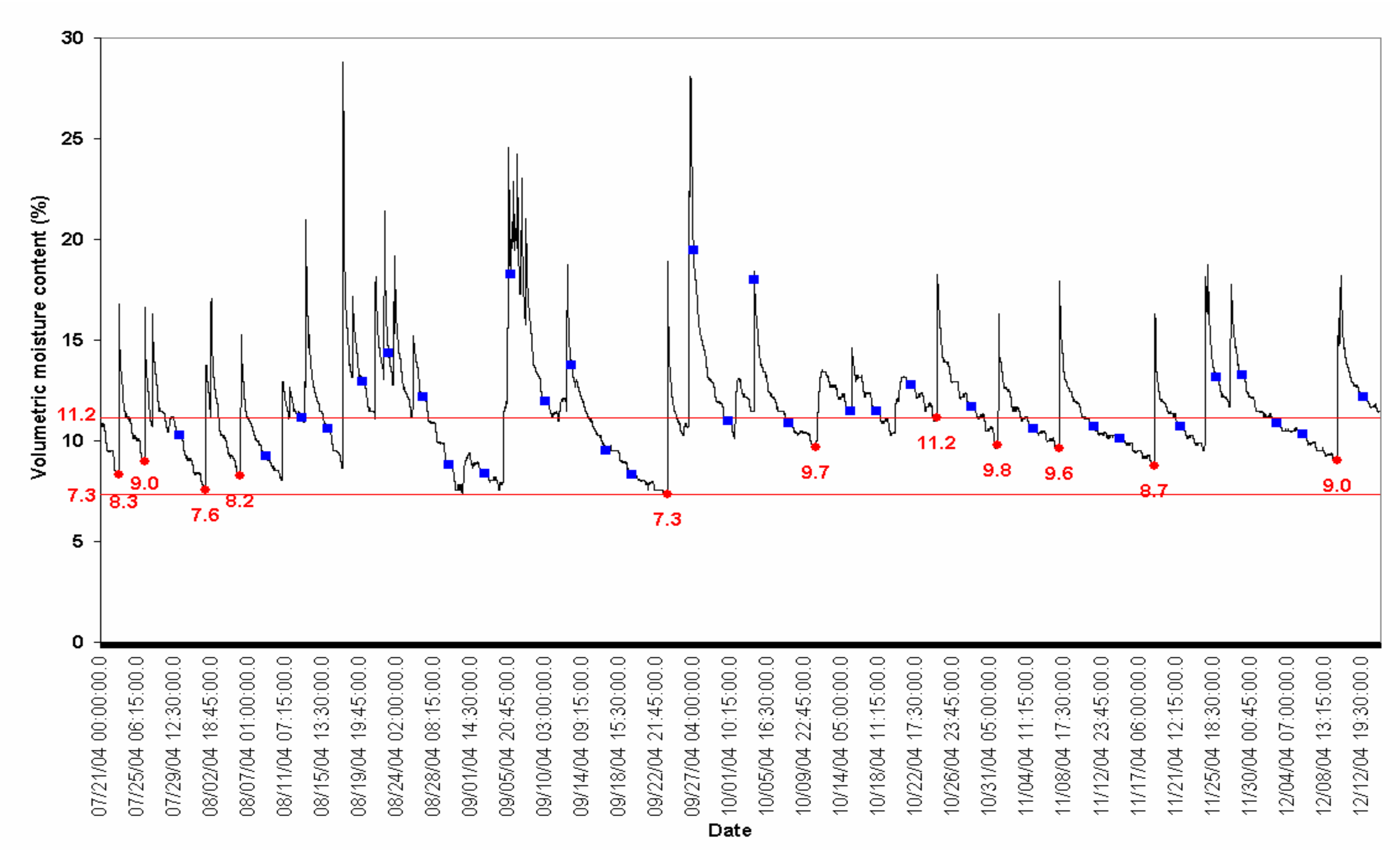


Figure 2-28. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 2-AC, year 2004.

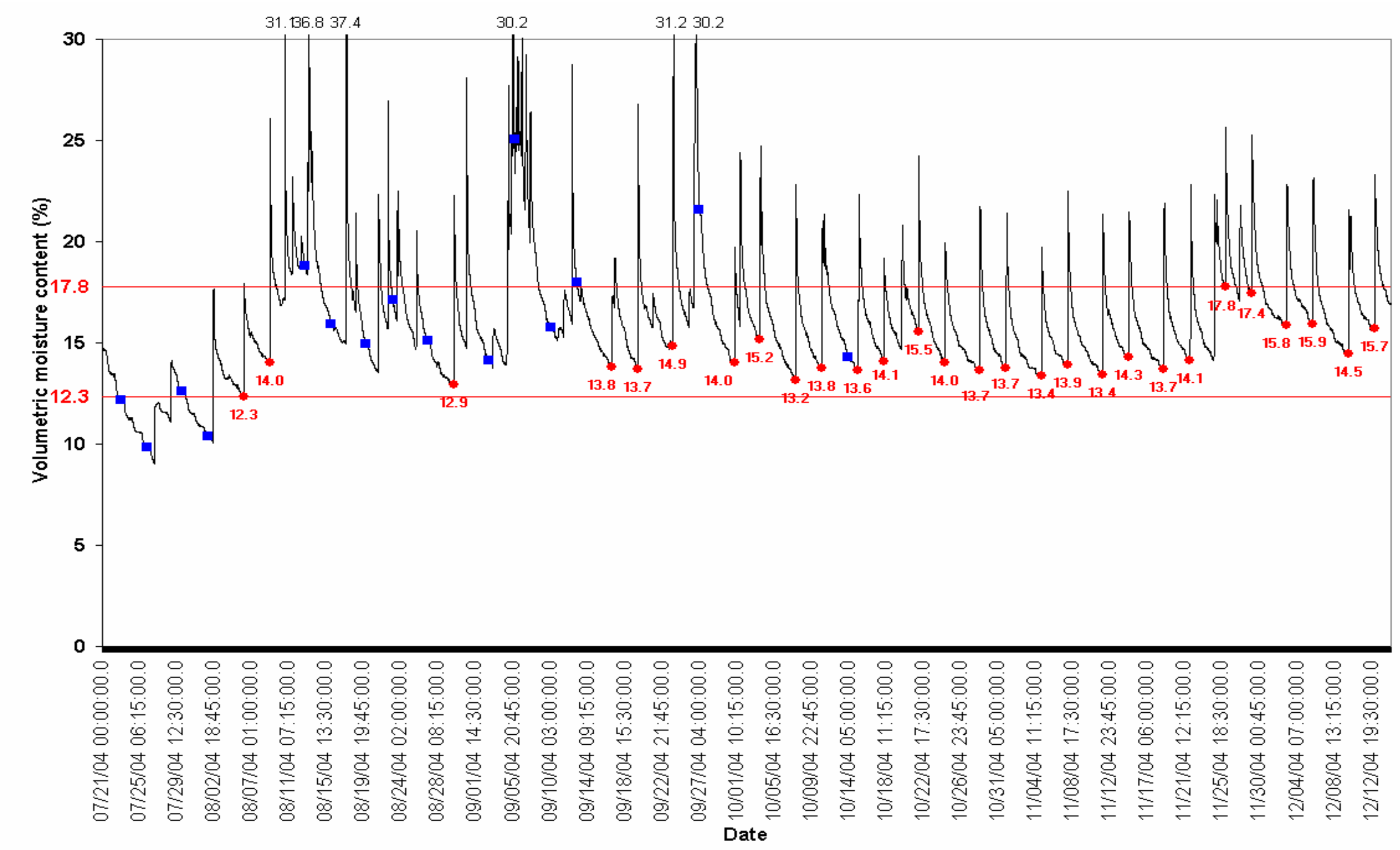


Figure 2-29. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 2-IM, year 2004.

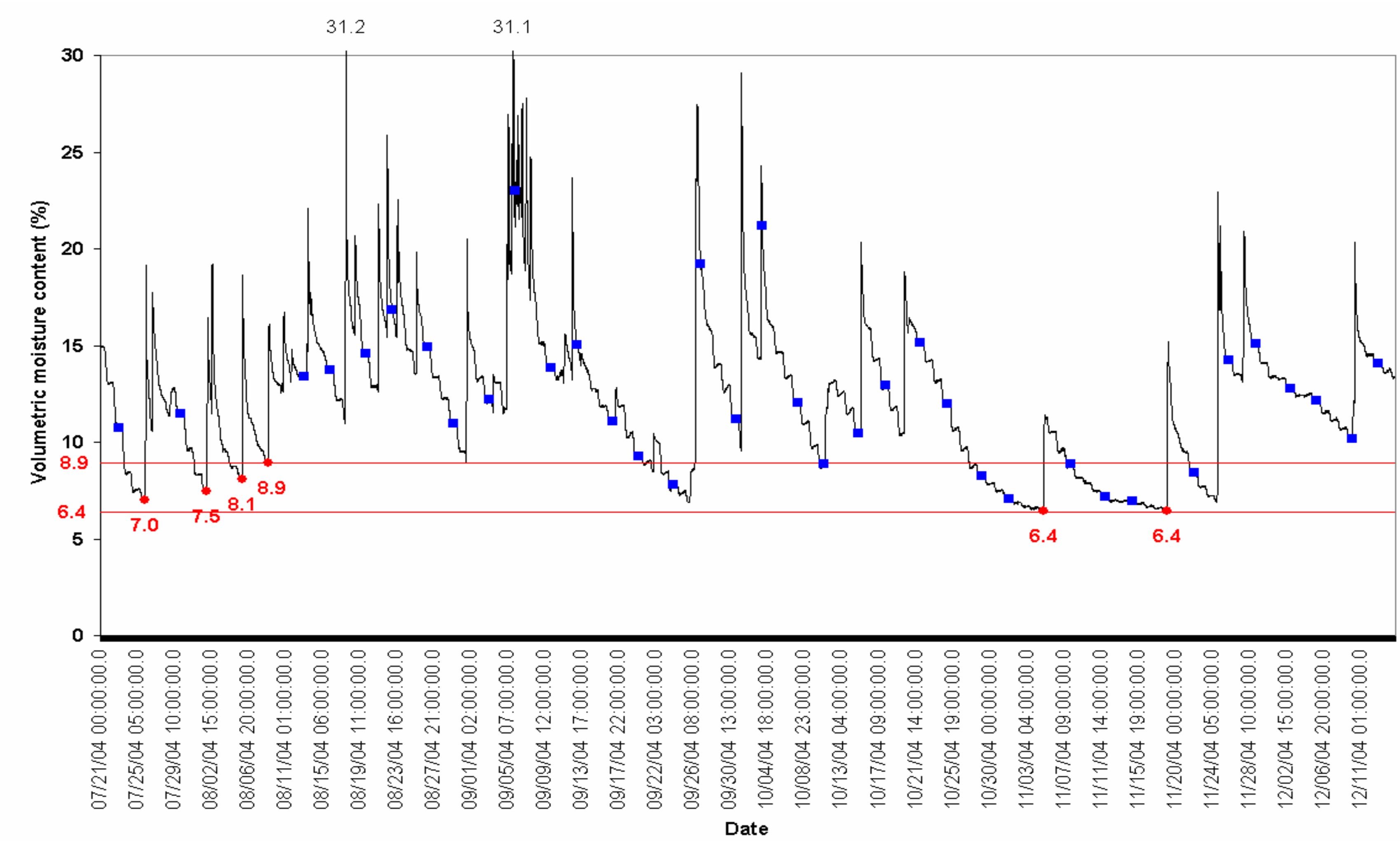


Figure 2-30. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 2-RB, year 2004.

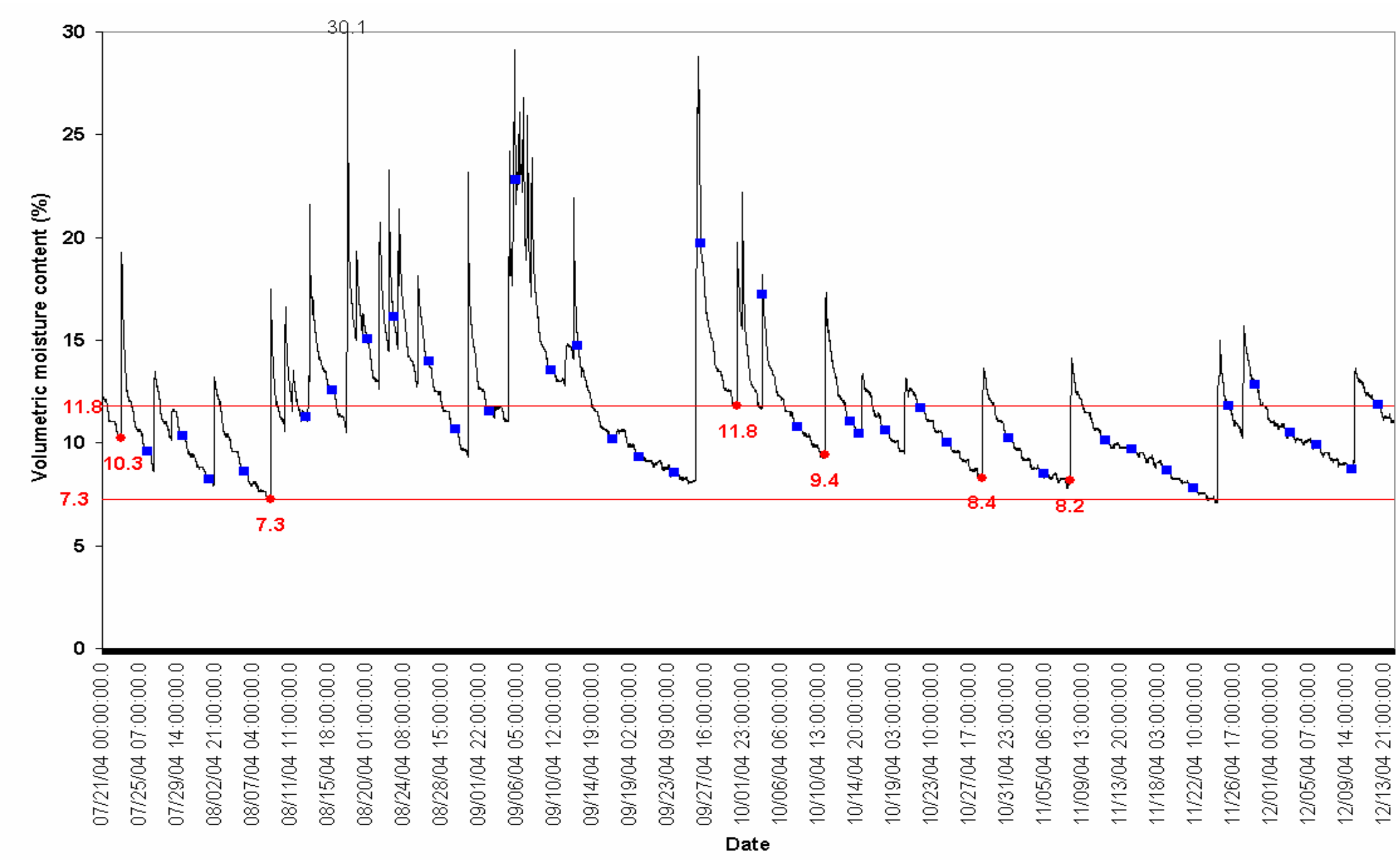


Figure 2-31. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the blue dots represent bypassed SIC, the red dots represent allowed SIC, and the red lines represent the range of VMC when the SIC were allowed; treatment 2-WW, year 2004.

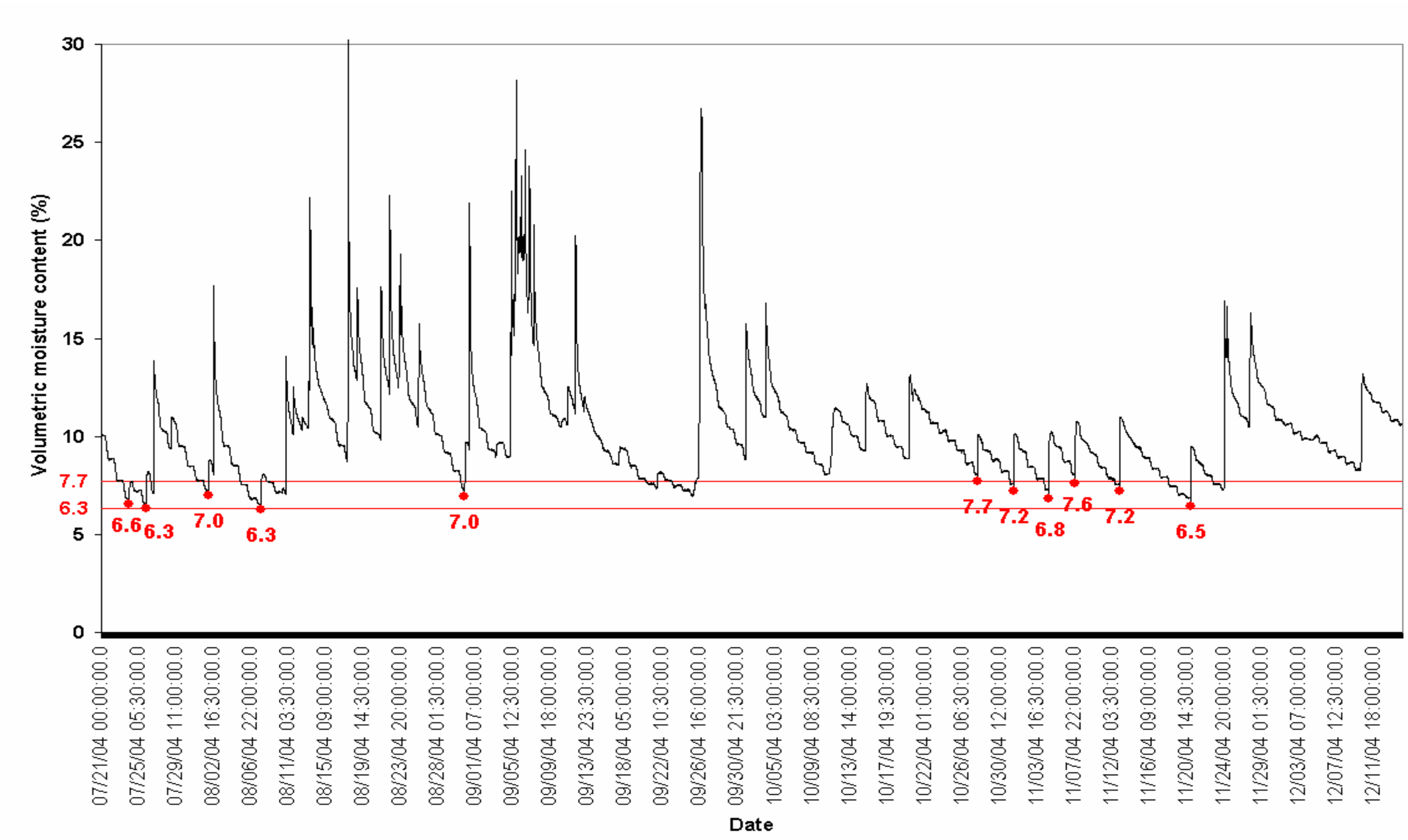


Figure 2-32. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the red dots represent allowed SIC (8% of the SIC), and the red lines represent the range of VMC when the SIC were allowed; treatment 7-AC, year 2004.

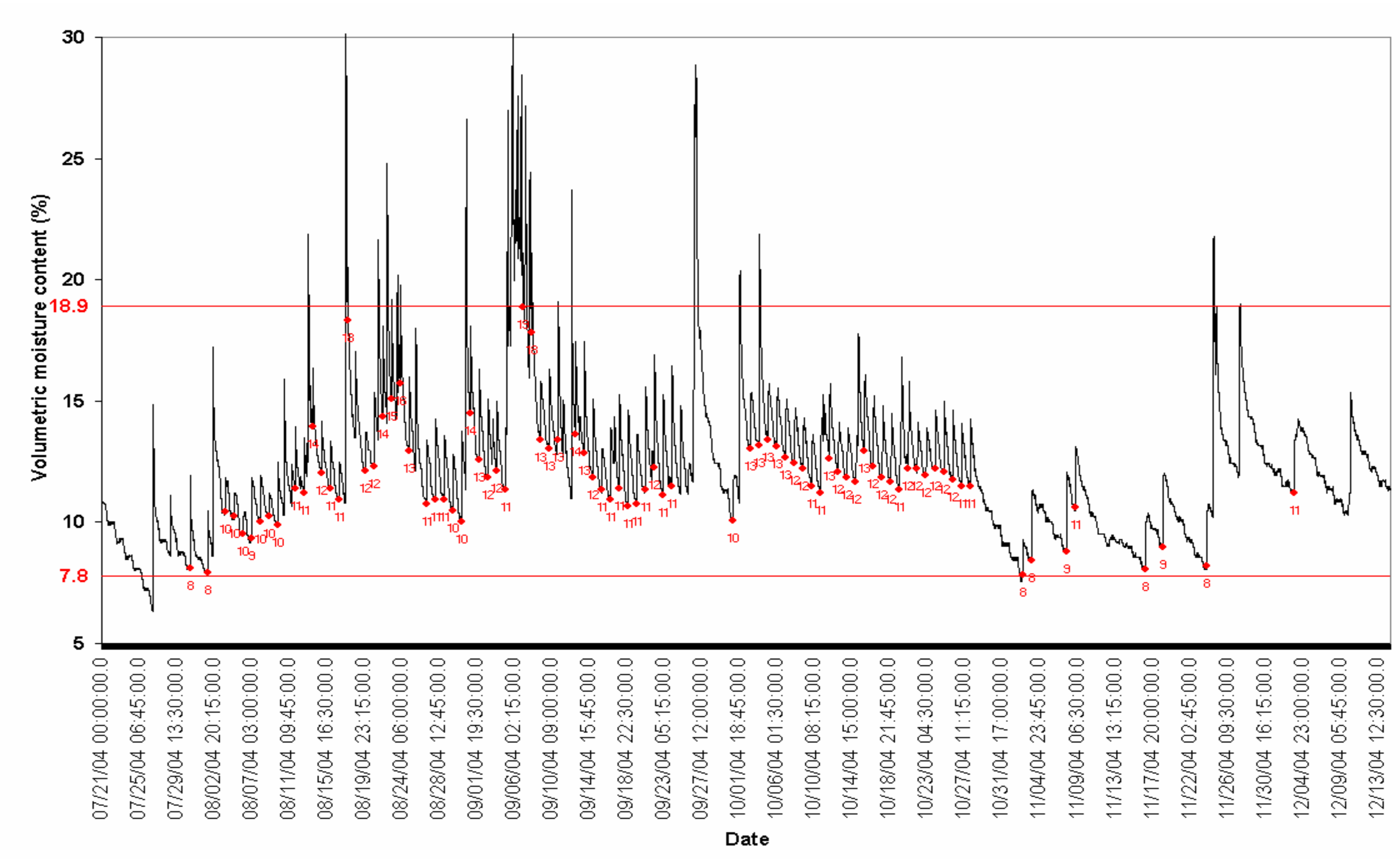


Figure 2-33. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the red dots represent allowed SIC (59% of the SIC), and the red lines represent the range of VMC when the SIC were allowed; treatment 7-IM, year 2004.

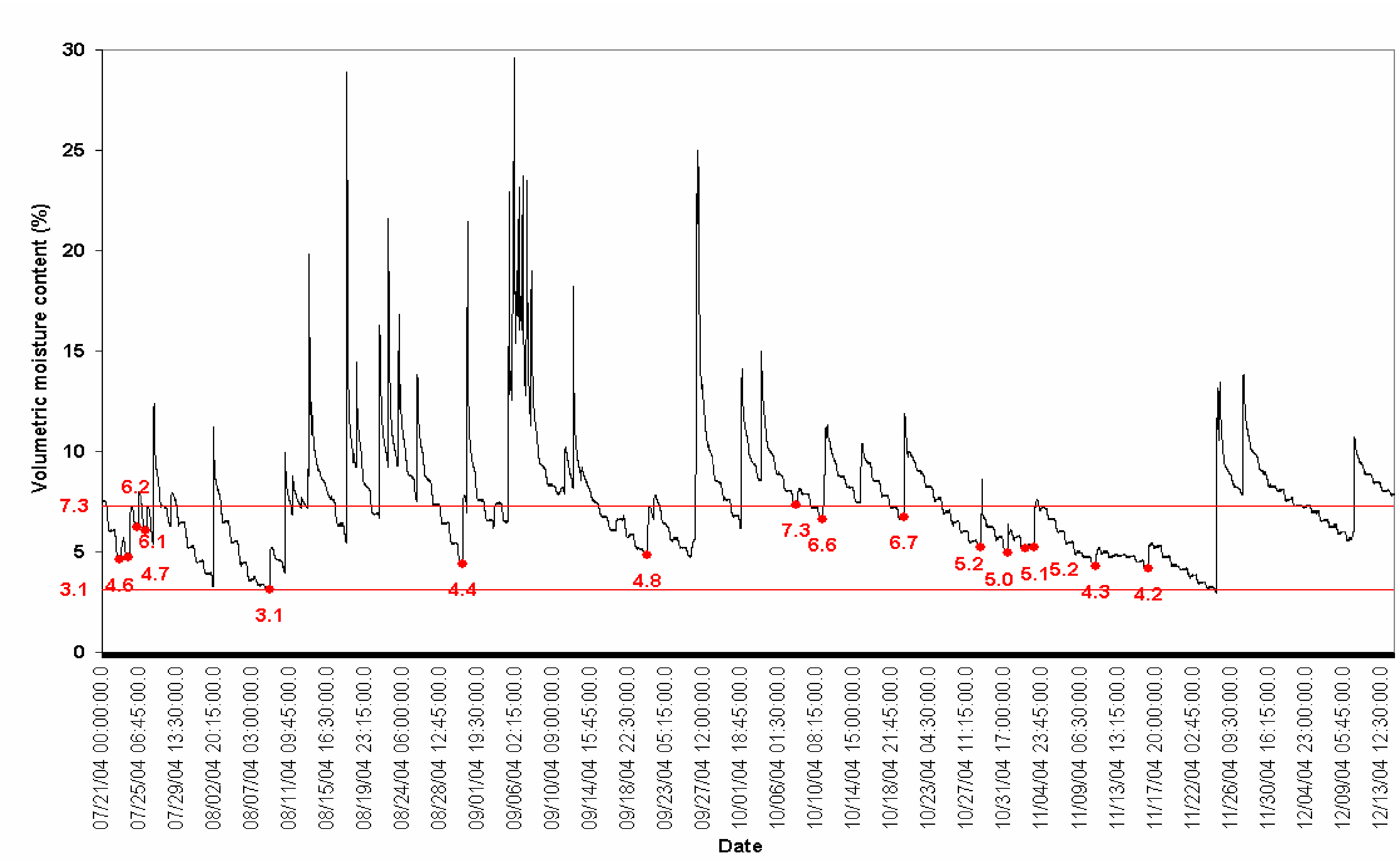


Figure 2-34. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the red dots represent allowed SIC (11% of the SIC), and the red lines represent the range of VMC when the SIC were allowed; treatment 7-RB, year 2004.

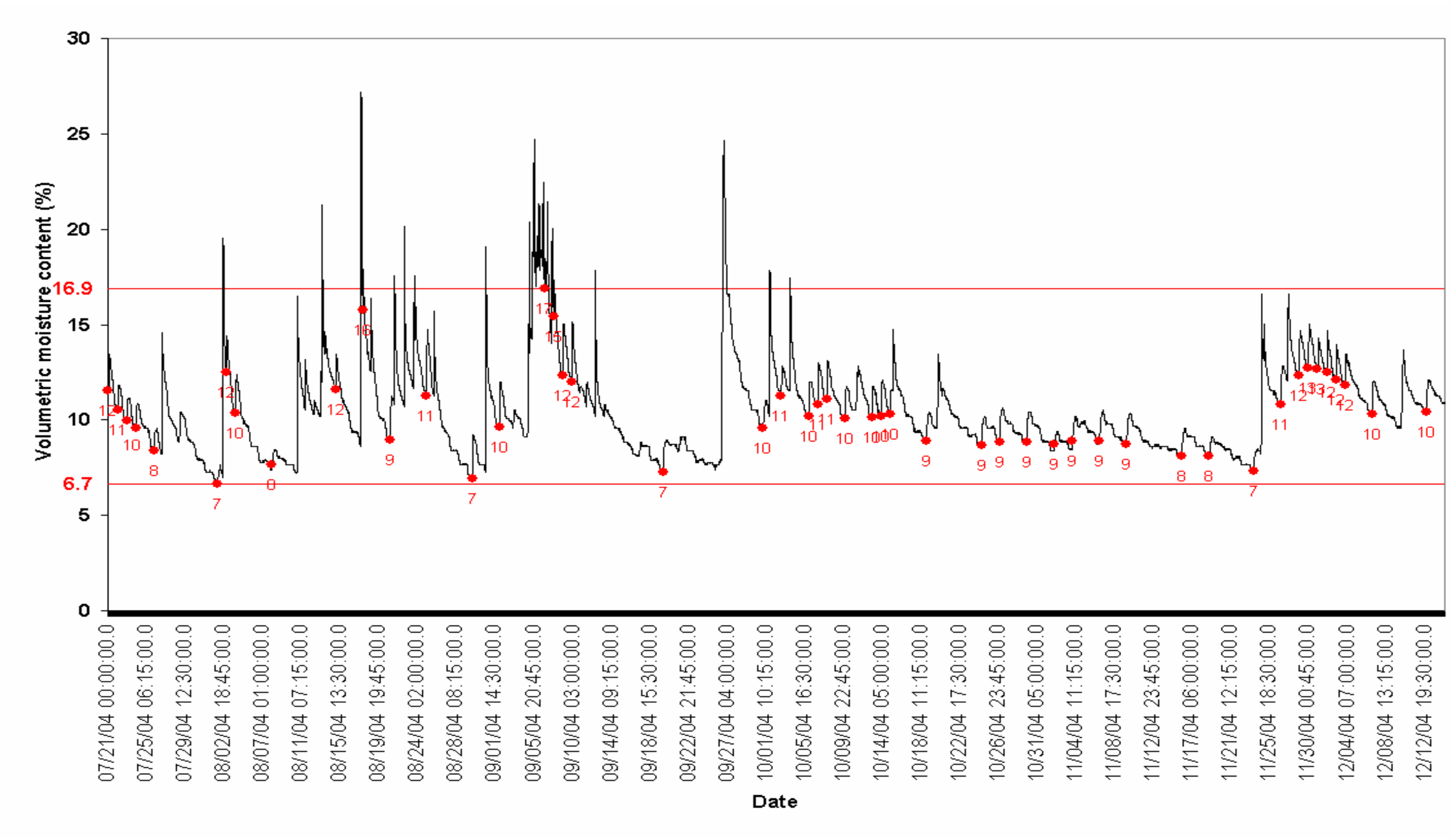


Figure 2-35. Volumetric moisture content (VMC) through time, showing results of the scheduled irrigation cycles (SIC), where the red dots represent allowed SIC (35% of the SIC), and the red lines represent the range of VMC when the SIC were allowed; treatment 7-WW, year 2004.

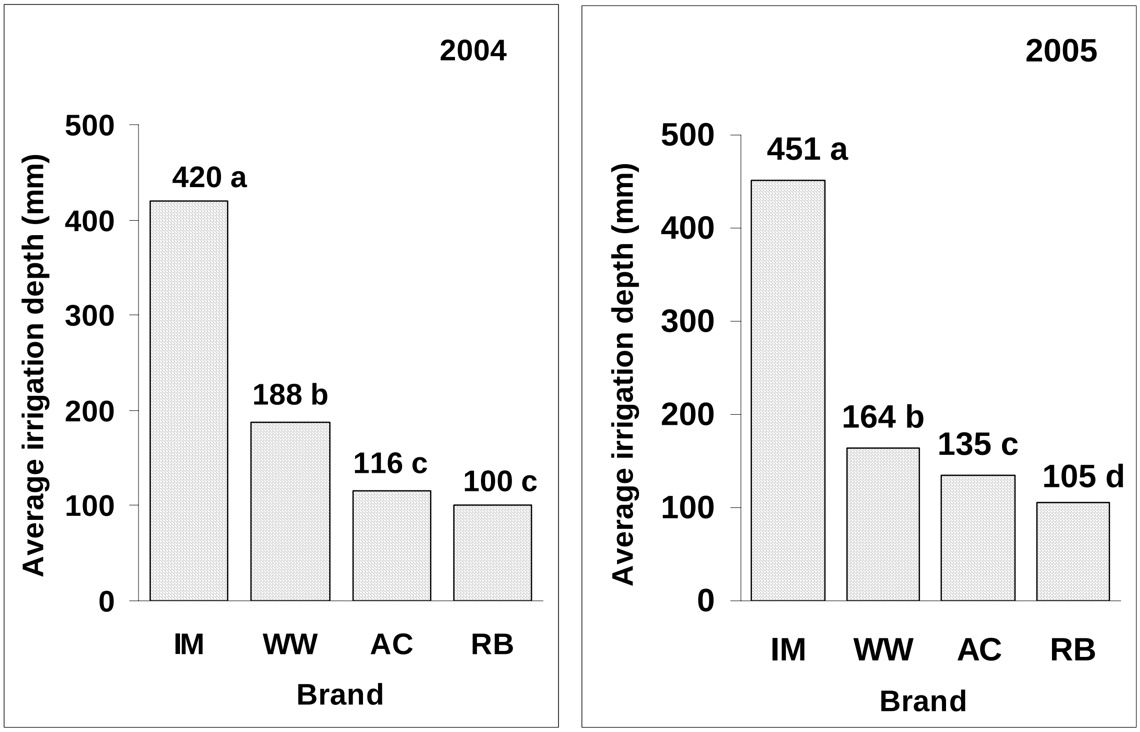


Figure 2-36. Average irrigation depth applied by brand; years 2004 and 2005 (P<0.0001).

Figure 2-37. View of different plots where no evident turfgrass quality differences could be detected; A) good quality, B) dormant.

# CHAPTER 3
# EXPANDING DISK RAIN SENSOR PERFORMANCE AND POTENTIAL IRRIGATION WATER SAVINGS

## Rain Sensors

A rain sensor (RS), also called rain shut-off device or rain switch (Figures 3-1 and 3-2), 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 the most 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 1 May 1991 (Florida Statutes, Chapter 373.62, n.d.; Florida Statutes, 2001). Moreover, some local laws also require older systems to be retrofitted with rain shut-off switches[1] (SJRWMD, 2006).

---

[1] Soil Moisture Sensors, could also be considered as "rain shut-off switches" because they can bypass irrigation cycles after sufficient rainfall (see Chapter 2, Soil moisture sensor-based treatments). However, in this chapter, rain sensors are referred as their most common usage; i.e., those devices that directly sense rainfall.

Rain sensors can be easily hooked up to any automatic irrigation system controller and mounted in an open area where they are exposed to rainfall. Some new irrigation controllers have a special connection, which allows a RS to be attached directly. 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).

## Advantages

According to Dukes and Haman (2002b) the use of RSs has several advantages: by eliminating unnecessary irrigation events they conserve water, reduce wear on the irrigation system, reduce disease and weed pressure, and reduce the runoff and/or deep percolation that carries pollutants–such as fertilizers and pesticides–into storm drains and groundwater. RSs also save money, because they reduce utility bills and turf maintenance costs. It could be added that these benefits are supplemented by a relatively low cost, easy installation, low maintenance, and long durability (more than ten years according to manufacturers, and a 5-year warranty).

## Types and Methods

Several types and models of RSs, which differ in their operation method, have been developed. Some of them have a receptacle to weigh the amount of water and, 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 this type of device 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 (Figure 3-1). Hygroscopic disks (Figure 3-3) absorb water and expand proportionally to rainfall amount. 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, they contract, and the switch closes again (Hunter Industries, Inc., 2006).

Different RS models have, in general, some kind of regulation to activate them after a specific amount of rainfall. The expanding hygroscopic disks-type Mini Click model (Hunter Industries, Inc.), very common in Florida, has five different settings (Figure 3-1) 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 (Figure 3-1).

The time that it takes the Mini Click to reset for normal sprinkler operation after the rain has stopped is determined by weather conditions (temperature, wind, sunlight, humidity, etc.), which will determine how fast the hygroscopic discs dry out. To compensate for the drying rate of the site's soil or for an “overly sunny” installation location, these sensors have an adjustment capability, the “vent ring” (Figure 3-1). By closing it, the hygroscopic discs will dry more slowly. However, drying time has not been quantitatively evaluated.

Finally, a new version of these devices (also with hygroscopic discs inside) is the radio-controlled or wireless RS (Figure 3-2). The components of this system are a sensor unit installed in an area subject to rainfall and a receiver unit hooked up 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 with regard to wireless RSs is their quick shut down of the irrigation system after it starts to rain (they do not include specific 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 Mini Clicks, the wireless RSs can be adjusted to keep the irrigation system off after the rain stops, depending on the climatic conditions and by setting its adjustable ventilation windows (Figure 3-2), which control the dry-out time (Hunter Industries, Inc., 2006).

## Installation

In residential and light commercial irrigation applications, a RS is typically installed near the roofline on the side of a building. Nevertheless, manufacturers recommend mounting it on any surface where it will be exposed to unobstructed rainfall. The RS location should receive about the same amount of sun and shade as the turf, but should not be in the path of sprinkler spray (Hunter Industries, Inc., 2006).

## Objectives

The objectives of this experiment were as follows: a) evaluate the reliability of two commercially available expanding disk RS-types with respect to number of irrigation cycles bypassed, accuracy of set point with rainfall depth, and duration in irrigation bypass mode, b) quantify the amount of water that RSs could save compared to time-based irrigation schedules without RS, and c) estimate the payback period of RSs at different set points.

## Materials and Methods

Twelve Mini-Click (MC) and four Wireless Rain-Click (WL) rain sensor models (Figures 3-1 and 3-2), for a total of sixteen devices (Hunter Industries, Inc., San Marcos, CA) were placed in a completely randomized design (Figure 3-4) at the Agricultural and Biological Engineering Department turfgrass research facility, University of Florida, Gainesville, Florida. The experiment took place from 25 March through 31 December 2005.

### Data

Each time a rain sensor changed status (from allowing irrigation, to bypass mode, or vice versa), the date and time was automatically recorded, at a one-minute sampling interval, by means of two AM16/32 multiplexers (Campbell Scientific, Logan, UT), which were hooked up to a CR 10X model datalogger (Campbell Scientific, Logan, UT) (Figure 3-4).

Climatic conditions were recorded by an automated weather station containing a CR 10X model data logger (Campbell Scientific, Logan, UT), located within 15 m of the experimental site. Rainfall was measured by means of a tipping bucket rain gauge, which was calibrated against a manual rain gauge. Results show that both methods were highly similar ($R^2$= 0.998) (Figure 3-5).

Total rainfall data, as well as the other weather measurements (see Chapter 2), were collected every 15 minutes. 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 29 June (day of year, hour, and minute were logged). Therefore, total rainfall before each RS switched to bypass mode was calculated, in order to evaluate the accuracy of the rainfall thresholds. The total time that each RS remained in the irrigation bypass mode was also computed.

### Treatments

Four treatments with four replications each were established (Table 3-1). For the MCs, three different settings 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.

None of these treatments were connected to irrigation timers. So, in order to estimate how many cycles these settings would have overridden and how much water could have been potentially saved, they were compared to the treatment With-Rain-Sensor from the SMS-experiment (code 2-WRS, Chapter 2). In that experiment, treatment 2-WRS used a Mini Click rain sensor set at 6 mm, so, in this chapter, it will be referred as 6-MC. Treatment 6-MC was hooked up to a timer, which was scheduled to run two days per week (Sunday and Thursday), beginning at 0100 h; to simulate watering restrictions imposed in Florida (FDEP, 2002; Florida Statutes, Chapter 373.62, n.d.). Thus, if the rain sensors were in bypass mode as a result of rainfall during a scheduled irrigation event, this bypass was considered “potential” irrigation savings. The weekly irrigation depth (see Table 2-2) was set to replace the historical ET, as recommended by Dukes and Haman (2002a).

### Statistical Analysis

Data were analyzed using the General Linear Model (GLM) procedure of SAS (SAS, 2000). If significant F values ($P < 0.05$) were detected, Duncan's Multiple Range Test was used to separate means.

## Results and Discussion

### Climatic Conditions

Figure 3-6 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 1112 mm, an amount that is not uncommon in this region. However, there was one dry period in the late fall, from 25 October through 20 November, when just one event of 0.5 mm occurred.

### Number of Times in Bypass Mode

The cumulative number of times that sensors switched to bypass mode, averaged by treatment, is shown in Figure 3-7. 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 Figures 3-8 to 3-11, the number of times in bypass mode within treatments was variable. The most variable treatments were 3-MC and 13-MC (between 30 and 54 times, and between 22 and 39 times, respectively).

The four replications of the WL treatment (Figure 3-8) 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 (Figure 3-9). All four 3-MC sensors behaved similarly for the first thirteen rainfall events. After 3 June, two units (A and B) continued to have the same behavior, while C and D units had similar performance to each other but did not bypass as many events as A and B, with 30-36 vs. 53-54 times, respectively. Similar to 3-MC, treatment 13-MC also showed an irregular performance between replicates (Figure 3-10). With the exception of the first two rain events, which were not sensed by replicate D, all replications switched to bypass mode on the same dates until 3 June (similar to 3-MC). After that date, replicate A bypassed more times than the other replicates (39 times versus 32, 28, and 22 times, for replications A, B, C, and D, respectively).

Replicates from treatment 25-MC performed similarly (Figure 3-11), shutting off between 7 to 8 times. All sensors worked identically for the first four rainfall events and then replicates A and C 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 the fewer number of rain events greater than 25 mm. It should be noted that although these RS units would have bypassed irrigation 7 to 8 times, there were 11 rainfall events greater than 25 mm.

## Depth of Rainfall Before Shut Off

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, $\varepsilon$, which is defined as the difference between the true value of a measurement and the indicated value of the instrument:

$$\varepsilon = \text{true value} - \text{indicated value} \qquad [3\text{-}1]$$

from which the percent accuracy, $A$, is found by:

$$A = \left(1 - \frac{|\varepsilon|}{true\ value}\right) \times 100 \qquad [3\text{-}2]$$

The average depth of rainfall before the rain sensors switched to bypass mode is shown in Table 3-2. Treatment WL shut off on average after 1.4 mm of rain but, because this model does not have a specific set point, accuracy was not 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 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. For example, on treatment 3-MC (Table 3-3) replications C and D did not detect rainfall events between 11.4 and 122.0 mm on ten occasions. On treatment 13-MC (Table 3-4), 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 (Table 3-5). No relationship between this behavior and rain intensity or other climatic condition was found.

In addition, on seven occasions some units from 3-MC (Table 3-6) 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 in twelve different occasions (Table 3-7). Moreover, on 7 April, replication D 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.

These observations clearly show that some MC-units tested had different sensitivities to specific settings and, additionally, sometimes they responded properly according to their settings, and sometimes they did not. Moreover, units that had inconsistent behavior showed problems when they were fairly new, and these units had the most of both types of behaviors (i.e. not bypassing events or bypassing events after rainfall stopped).

On the other hand, WL treatments switched to bypass mode in absence of rainfall (Table 3-8). The number of times that this happened ranged between 11 and 22, with an average of 16 times; remaining in that mode for a minimum of one minute, a maximum exceeding 10 hours, and an average of more than 3 hours. These situations were triggered when high relative humidities occurred (95% on average) or, on five occasions, minutes before a rainfall event began. This shows that sometimes these sensors are too sensitive, with the drawback that they could bypass a scheduled irrigation cycle, even when no rainfall occurred, a situation that happened twice during this experiment.

### Duration in Irrigation Bypass Mode (Dry-Out Period)

Figures 3-12 to 3-14 show histograms and frequency distribution for intervals of time of 6 h in bypass mode for treatments WL, 3-MC and 13-MC. In the case of 25-MC, because of the small number of occurrences (7-8 times)**,** no interval of time had a number of occurrences ≥5, hence no histogram and frequency distribution could be plotted (Figliola and Beasley, 2000).

Results showed that half the time WL-sensors remained in bypass mode between 0 and 12 h (Figure 3-12), 80% of 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 manufacturers' advertisements, in order that WL will remain in that status shortly after the rain stops (Hunter Industries, Inc., 2006). Treatment 3-MC (Figure 3-13) remained in bypass mode less than 24 h most of the time (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, similar to 3-MC, and more than 80% of time they did not stay in that status for more than 36 h (Figure 3-14). 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 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

Treatment 6-MC bypassed the irrigation system on 16 occasions (37% of all the scheduled irrigation cycles), accounting for 304 mm in water savings[2]. The total potential water savings for the other treatments, by replication and as an average per treatment, are shown in Table 3-9. Results revealed that, even when treatment averages showed logical and statistical differences between them (363, 245, 142, and 25 mm for WL, 3-MC, 13-MC, and 25-MC, respectively), replications from MC treatments were highly variable, with CVs of 28%, 61%, and 34%, for 3-MC, 13-MC, and 25-MC, respectively.

Table 3-9 also shows that, on treatment 3-MC, the final amount of the potential water savings was 304 mm for two replications, and 195 and 178 mm for the other two, resulting in a treatment average of 245 mm, compared to 304 mm for 6-MC, contrary to what was expected. Again, this is a consequence of the erratic behavior of units C and D from 3-MC.

---

[2] This corresponds to the difference between treatments 2-WORS and 2-WRS (2 days-per-week Without Rain Sensor vs. 2 days-per-week With Rain Sensor, respectively) detailed in Chapter 2.

Treatment 13-MC showed potential water savings ranging from 78 to 266 mm. As expected, all replications showed lesser total potential water savings than 6-MC. Conversely, replication A from 13-MC showed larger water savings (266 mm) than two of the 3-MC replications (C and D, with 195 and 178 mm, respectively), again demonstrating the variability between different MC units (Table 3-9).

The 25-MC replications showed small potential water savings (between 12 and 29 mm) compared to the other treatments (Table 3-9), despite the fact that there were 11 rain events of 25 mm or more. However, these events would have had to occur a maximum of 30 h or less before the irrigation window so that the RS would bypass the scheduled irrigation event.

Conversely to the erratic behavior of the MC treatments, WL showed a high consistency among its replications and accounted for the highest potential water savings among the treatments, between 342 and 380 mm (Table 3-9), and between 38 and 76 more mm of irrigation water savings than 6-MC.

## Payback Period

In spite of the variability found, it is interesting to quantify how much money the potential water savings could represent, and also to calculate a payback period for the rain sensors. According to Augustin (2000), the historical net irrigation requirements for this period of study, for the Gainesville area, are around 65% of the total requirements per year; therefore, the water savings per year would have been 558, 377, 468, 218, and 38 mm for WL, 3-MC, 6-MC, 13-MC, and 25-MC, respectively. If a system irrigates 1000 $m^2$ of turf, each mm of water applied is equivalent to 1 $m^3$ applied to this surface. Assuming a cost of $75 for the WL and $25 for the MC units, plus $50 for installation, Table 3-10 shows the potential payback period per treatment at different water costs. If the water cost was \$0.264/m$^3$ (\$1.00/TG), the payback period would have been less than a year for WL, 3-MC, and 6-MC; and between 1.3 and 7.4 years for treatments 13-MC and 25-MC, respectively.

According to this analysis, except for 25-MC, the installation and maintenance of a RS appears to be strongly justified. However, this contrasts profoundly with reality. 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 speculates that they are often incorrectly installed.

Finally, it is important to remember that in the soil moisture sensor-experiment, due to favorable weather conditions, no irrigation was necessary to maintain an acceptable turf quality during the experiment's time-period; hence, every bypassed irrigation cycle would have led to valuable water savings. In this example, 363, 245, 142, and 25 m$^3$ of fresh water that could have been lost to deep percolation or runoff, would have been saved by WL, 3-MC, 13-MC, and 25-MC, respectively.

## Summary and Conclusions

The experiment 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 suggest that, on average, the MCs responded close to their set points. However, some replications showed erratic behavior, sometimes responding properly according to their settings, and sometimes not detecting rainfall events five or more times their set points, or even shutting off several hours after the rain had stopped. This explains the range of variation in the number of times that individual RSs switched to bypass mode. On the other hand, high relative humidities some times caused WL units to switch to bypass mode, in absence of rainfall.

In general, the lower set points on the MC treatments tended to stay in bypass mode for a longer period of time, because of the larger number of successive small rainfall events that occurred. 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 and on the cost of water, the payback period would have been close to 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, rain sensors, depending on their set points, showed that they 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.

Table 3-1. Treatments description.

| Treatment | Model | Set point | Vent window |
|---|---|---|---|
| 3-MC | Mini-click II | 3 mm | completely open |
| 13-MC | Mini-click II | 13 mm | completely open |
| 25-MC | Mini-click II | 25 mm | completely open |
| WL | Wireless | ---[z] | half open |

[z] WL does not have an adjustable set point.

Table 3-2. 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 | ---[z] |

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

Table 3-3. Large rainfall events not bypassed by treatment 3-MC.

| Date | Rainfall (mm) | Replicate | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| 7-Jun | 17.0 | | | X | X |
| 8-Jun | 11.4 | | | X | X |
| 12-Jun | 20.3 | | | X | X |
| 2-Jul | 24.6 | | | X | X |
| 3-Aug | 16.3 | | | X | X |
| 7-Aug | 16.5 | | | X | X |
| 8-Aug | 12.1 | | | X[z] | X[z] |
| 10-Aug | 17.5 | | | X | X |
| 6-Oct | 79.2 | | | X | X |
| 17-Dec | 122.0 | | | X | X |

[z] The day before it rained 16.5 mm extra.

Table 3-4. Large rainfall events not bypassed by treatment 13-MC.

| Date | Rainfall (mm) | Replicate | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| 26-Mar | 28.5 | | | X | X |
| 1-Apr | 19.1 | | | X | X |
| 5-May | 41.7 | | | X[z] | X[z] |
| 12-Jun | 20.3 | | X | | X |
| 2-Jul | 24.6 | | X | X | X |
| 6-Oct | 79.2 | | | | X |
| 17-Dec | 122.0 | | X[y] | | X |

[z] Shut off after 45 mm of rainfall.

[y] The day before it rained 12.5 mm extra.

Table 3-5. Large rainfall events not bypassed by treatment 25-MC.

| Date | Rainfall (mm) | Replicate | | | |
|---|---|---|---|---|---|
| | | A | B | C | D |
| 27-Jun | 41.7 | | | X | |
| 29-Jun | 38.6 | | | | X |
| 20-Aug | 33.3 | X | X | X | |
| 6-Oct | 79.2 | X | X | X | X |
| 17-Dec | 122.0 | X | X | X | |

Table 3-6. Hours after rain stopped and sensors switched to bypass mode; treatment 3-MC.

| Date | Replicate (h) | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 3-Jul | | | | 6 |
| 1-Aug | | | 6 | |
| 21-Sep | 6 | 4 | | |
| 30-Nov | | | 18 | |
| 10-Dec | | | X | |
| 16-Dec | | | 18 | |
| 20-Dec | | | X | X |

X = more than 24 h.

Table 3-7. Hours after rain stopped and sensors switched to bypass mode; treatment 13-MC.

| Date | Replicate (h) | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 7-Apr | | | | X[z] |
| 6-May | | | | X |
| 4-Jul | | X | 10 | X |
| 6-Aug | | 19 | | |
| 7-Aug | | | 14 | |
| 11-Aug | | | 18 | |
| 14-Aug | 7 | | | |
| 31-Aug | | | 10 | |
| 2-Sep | | | | X |
| 5-Oct | | 5 | | |
| 21-Nov | | | 3 | |
| 10-Dec | | | | X |

X = more than 24 h.

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

Table 3-8. WL replications that switched to bypass mode in absence of rainfall, elapsed time that they remained in bypass mode, and relative humidity at the time when this occurred.

| | Elapsed time in bypass mode (hh:mm) | | | | | Relative Humidity (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Replications | | | | | Replications | | | | |
| | A | B | C | D | **Avg** | A | B | C | D | **Avg** |
| Minimum | 01:25 | 00:01 | 01:51 | 00:08 | **00:51** | 91 | 86 | 89 | 86 | **88** |
| Maximum | 07:10 | 10:34 | 06:27 | 07:34 | **07:56** | 98 | 98 | 97 | 98 | **98** |
| Average | 03:41 | 02:34 | 03:16 | 02:54 | **03:06** | 96 | 95 | 96 | 93 | **95** |
| Times (#) | 17 | 22 | 12 | 11 | **16** | 17 | 22 | 12 | 11 | **16** |

Table 3-9. Total potential water savings per treatment.

| Treatment | Replications (mm) | | | | | CV (%) |
|---|---|---|---|---|---|---|
| | A | B | C | D | Average | |
| WL | 380 | 365 | 364 | 342 | 363***a*** | 4 |
| 3-MC | 304 | 304 | 195 | 178 | 245***b*** | 28 |
| 13-MC | 266 | 133 | 89 | 78 | 142***c*** | 61 |
| 25-MC | 29 | 29 | 29 | 12 | 25***d*** | 34 |

$P < 0.05$

Table 3-10. Potential payback period per treatment.

| Water cost | | Payback period per treatment (years) | | | | |
|---|---|---|---|---|---|---|
| ($/TG) | ($/m3) | WL | 3-MC | 6-MC | 13-MC | 25-MC |
| 0.50 | 0.13 | 1.7 | 1.5 | 1.2 | 2.6 | 14.8 |
| 1.00 | 0.26 | 0.8 | 0.8 | 0.6 | 1.3 | 7.4 |
| 1.50 | 0.40 | 0.6 | 0.5 | 0.4 | 0.9 | 4.9 |
| 2.00 | 0.53 | 0.4 | 0.4 | 0.3 | 0.7 | 3.7 |

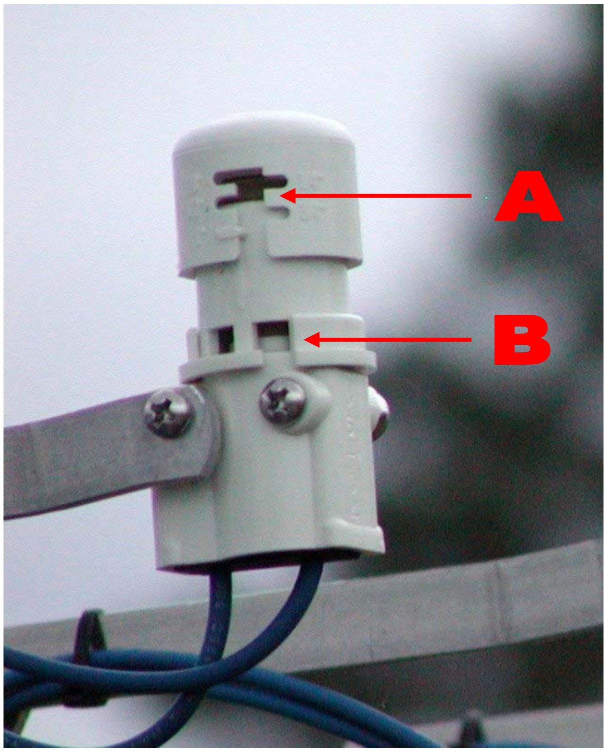


Figure 3-1. Mini-Click (Hunter Industries, Inc.) rain sensor. A) Rain threshold set slots, B) vent ring.

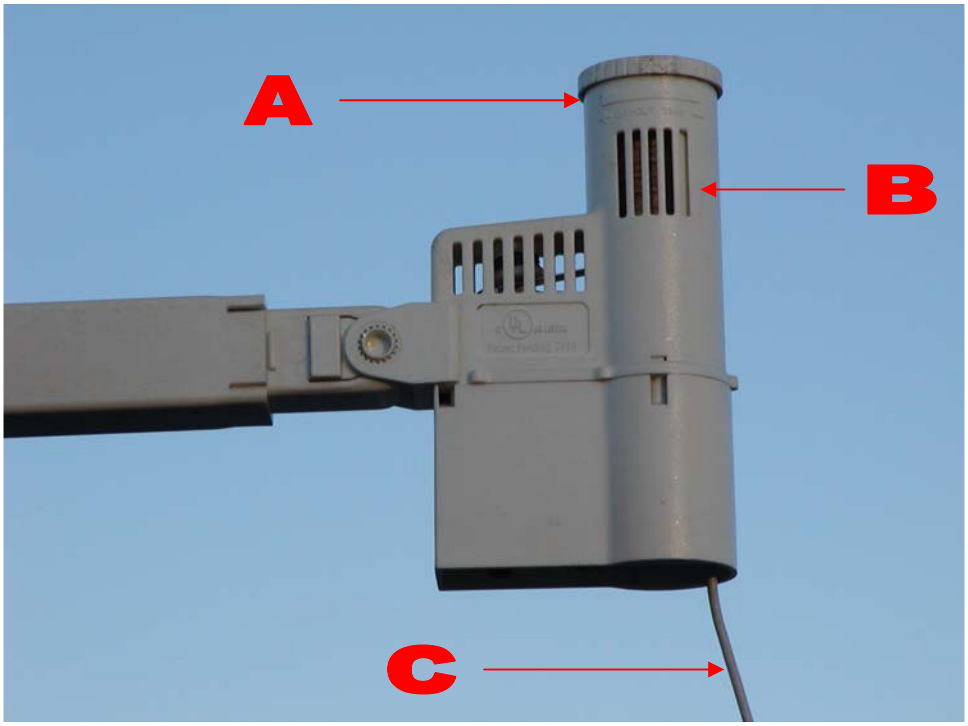


Figure 3-2. Wireless Rain-Click (Hunter Industries, Inc.) rain sensor. A) Ventilation window adjustment knob, B) ventilation windows, C) antenna.

Figure 3-3. The expanding material of a rain shut-off switch.

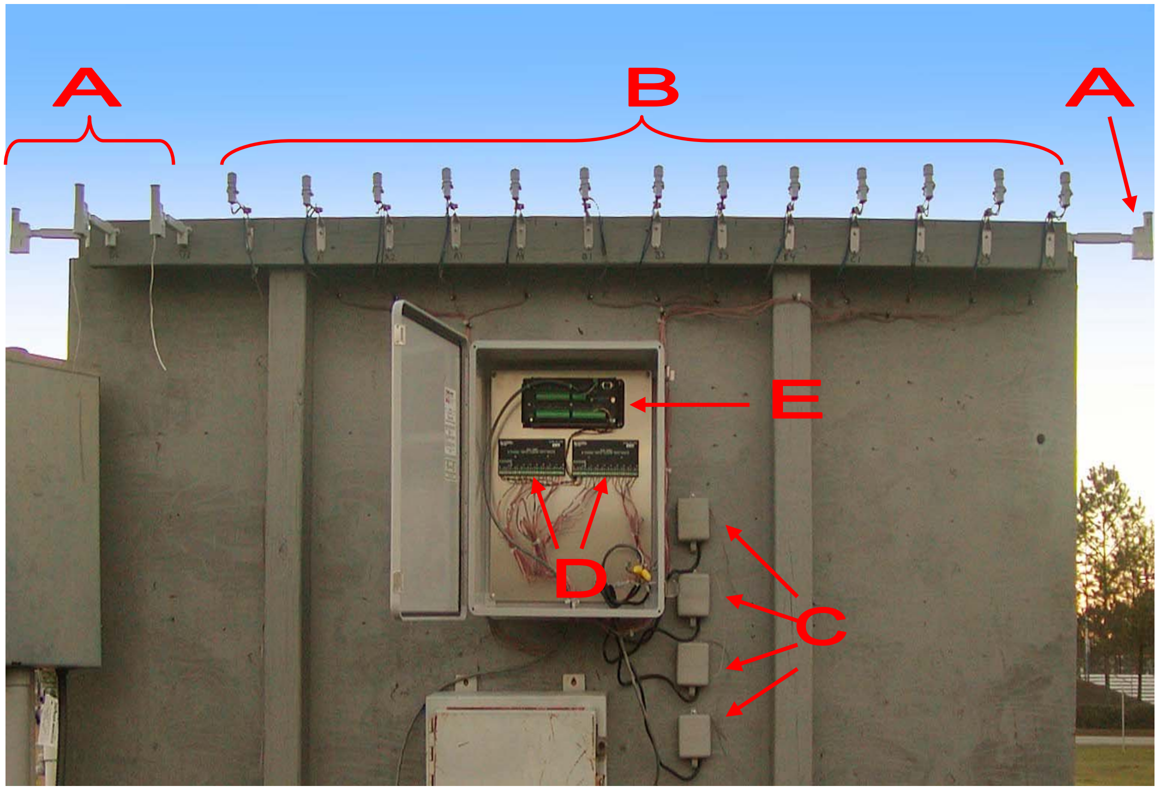


Figure 3-4. Rain sensor experiment layout: A) Wireless Rain-Click rain sensors, B) Mini-Click rain sensors, C) Wireless Rain-Click receivers, D) multiplexers, E) CR 10X datalogger.

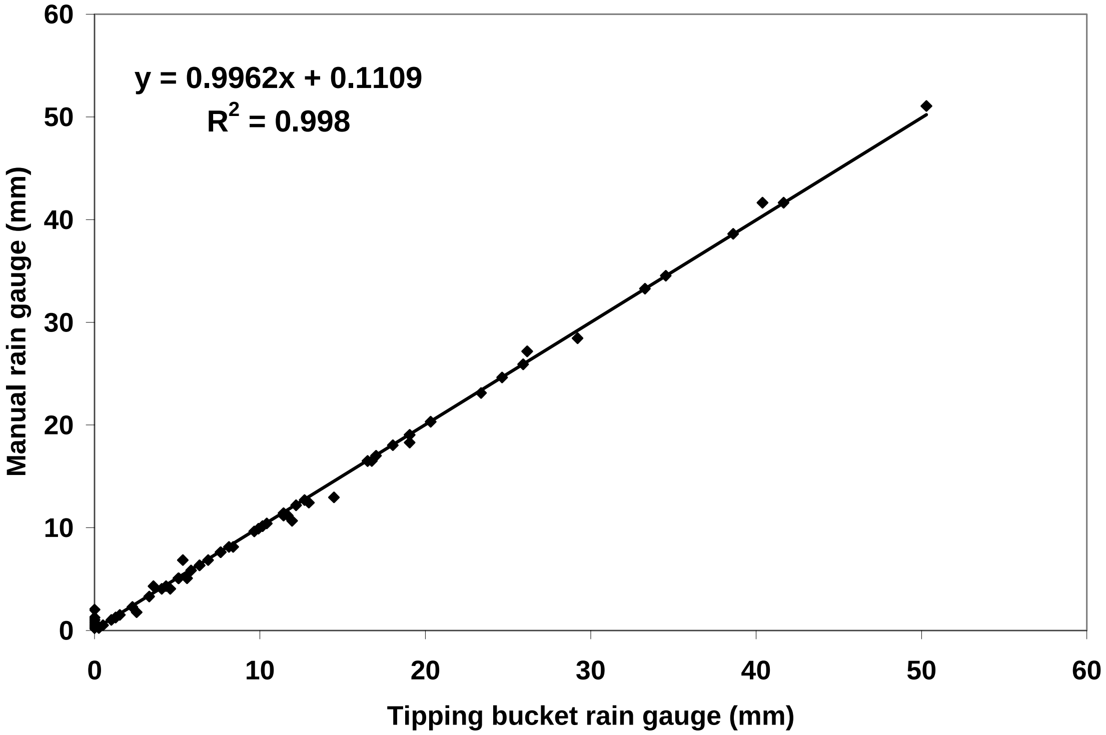


Figure 3-5. Manual rain gauge measurements compared to tipping bucket rain gauge measurements.

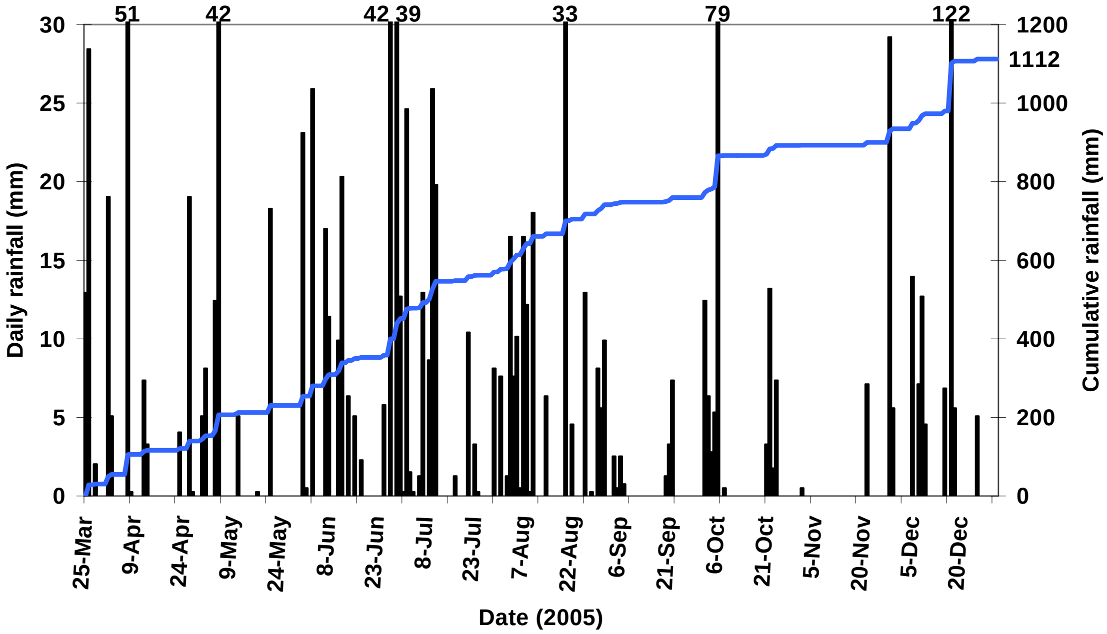


Figure 3-6. Daily and cumulative rainfall.

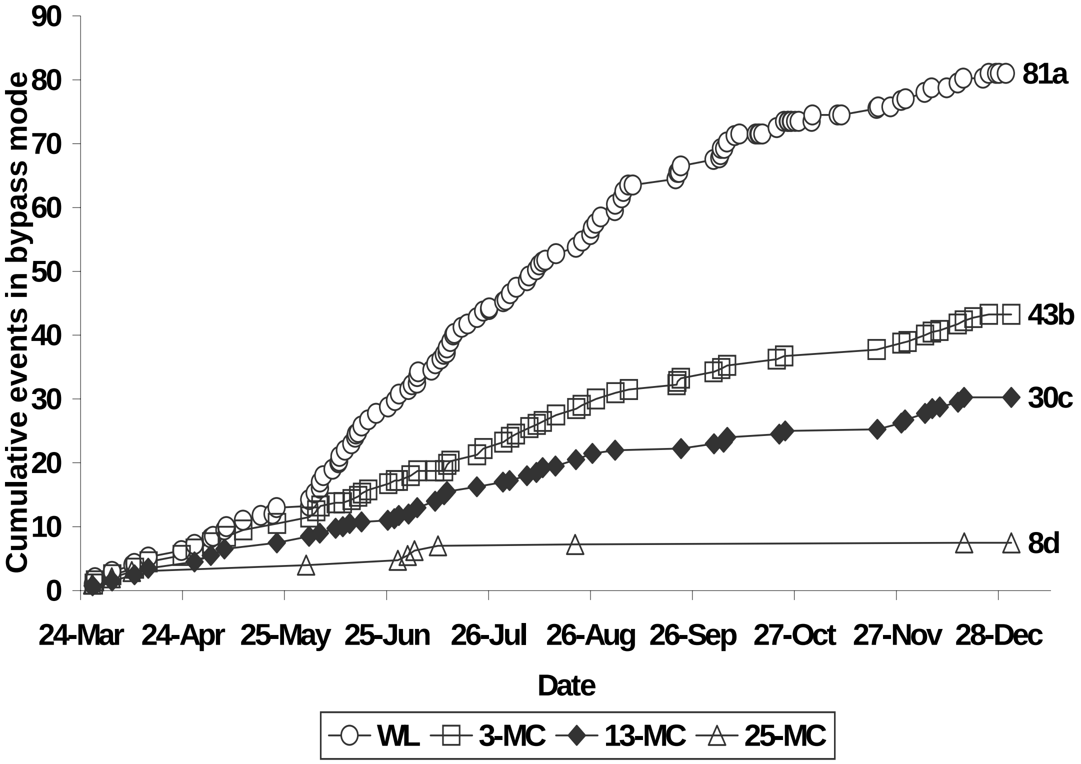


Figure 3-7. Cumulative number of times rain sensors switched to bypass mode; average per treatment. Different letters indicate a significant difference by Duncan's Multiple Range Test ($P<0.05$)

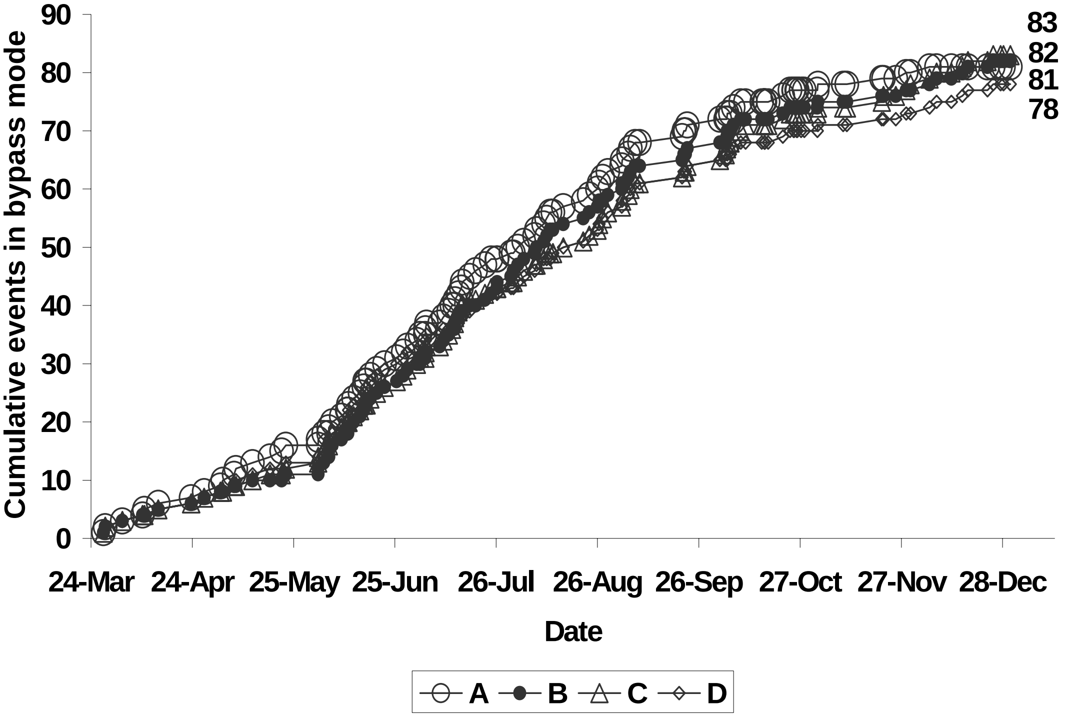


Figure 3-8. Cumulative number of times rain sensors switched to bypass mode; WL treatment, with replicates indicated by A-D.

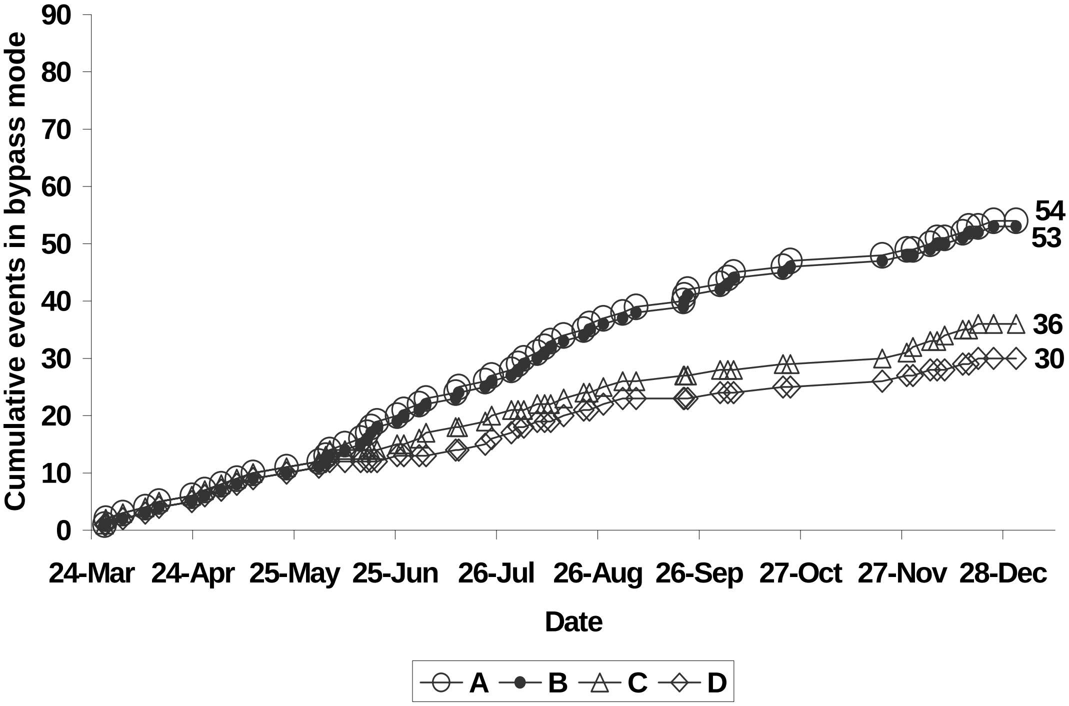


Figure 3-9. Cumulative number of times rain sensors switched to bypass mode; 3-MC treatment, with replicates indicated by A-D.

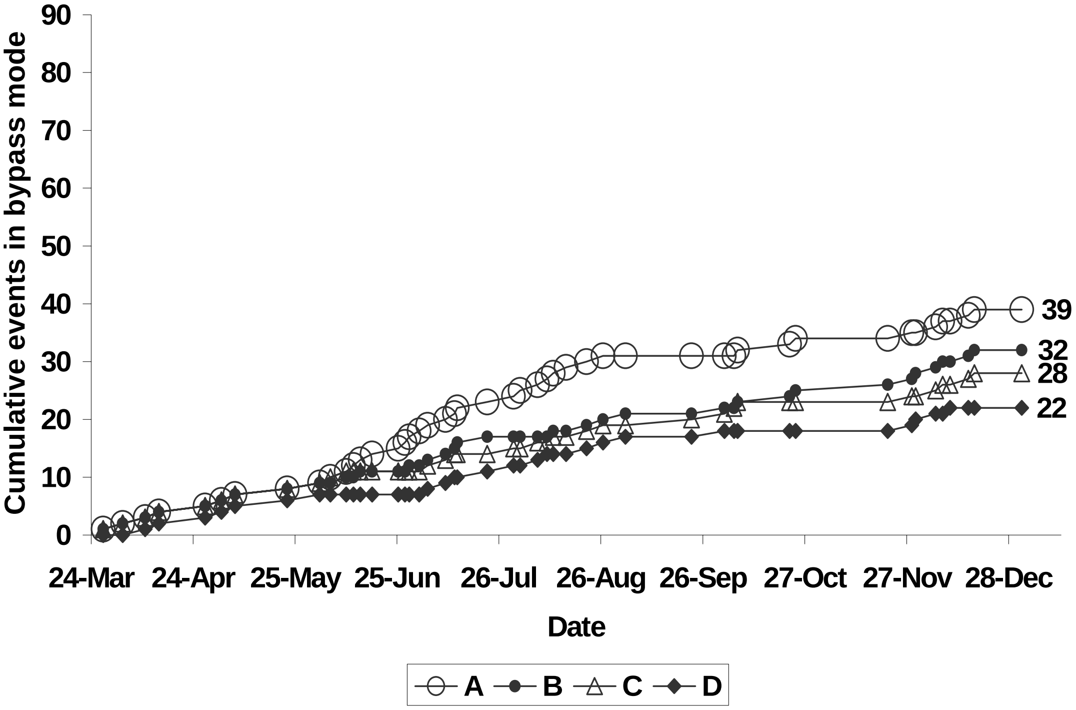


Figure 3-10. Cumulative number of times rain sensors switched to bypass mode; 13-MC treatment, with replicates indicated by A-D.

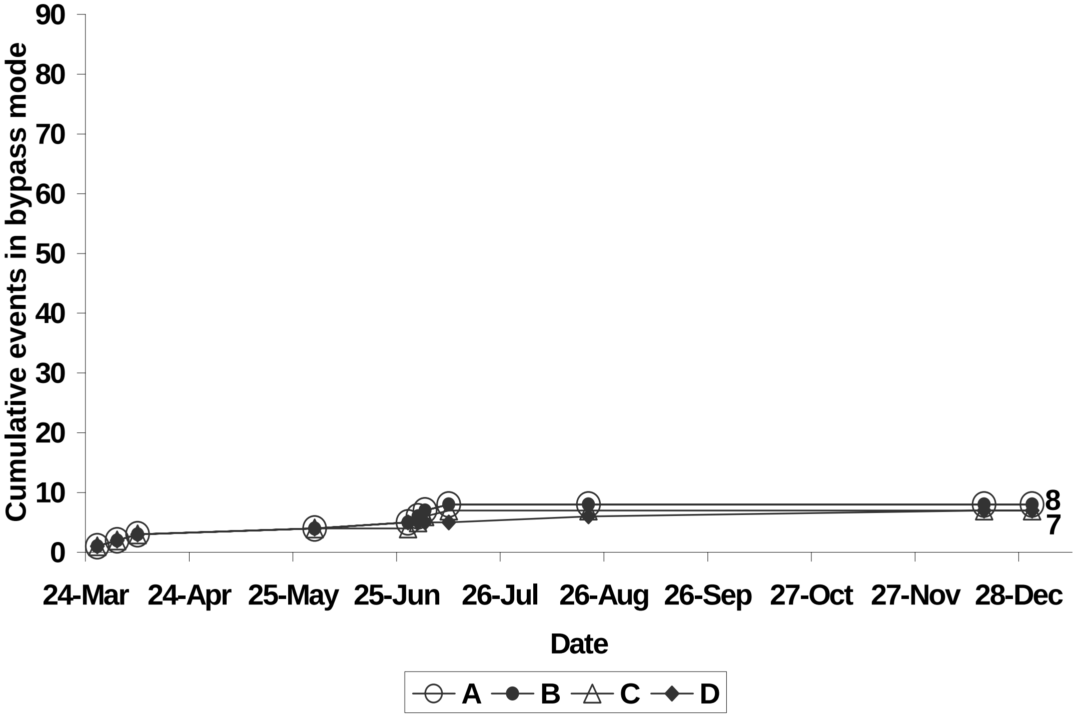


Figure 3-11. Cumulative number of times rain sensors switched to bypass mode; 25-MC treatment, with replicates indicated by A-D.

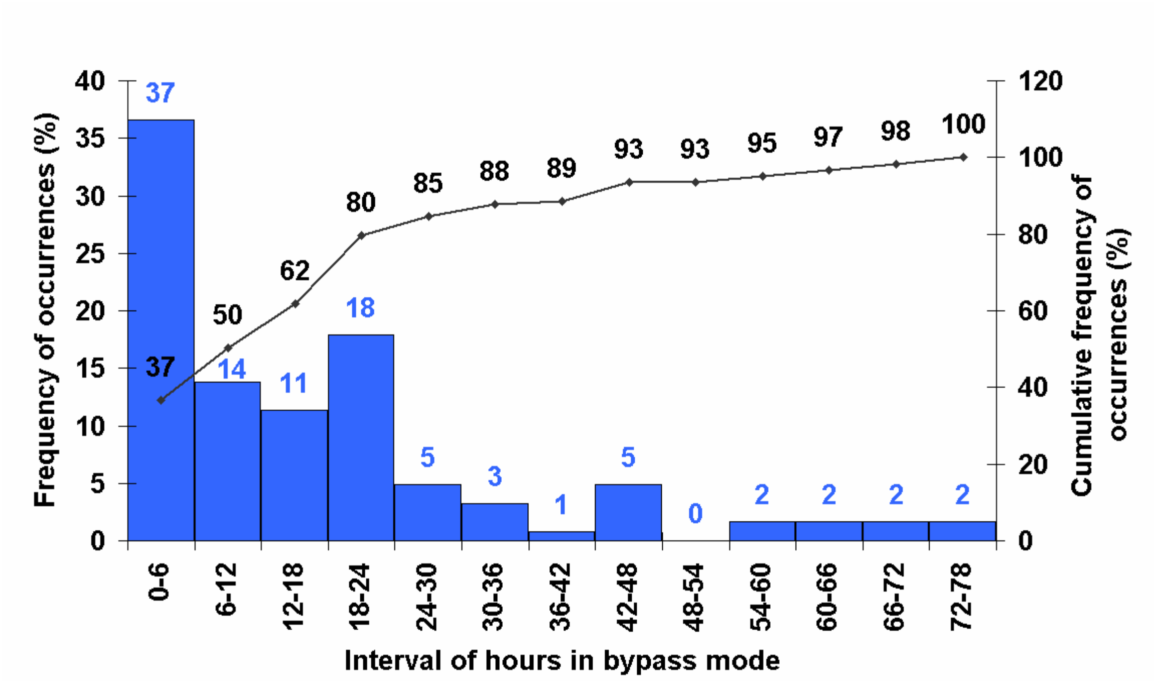


Figure 3-12. Histogram and frequency distribution for 6-hour intervals in bypass mode; WL.

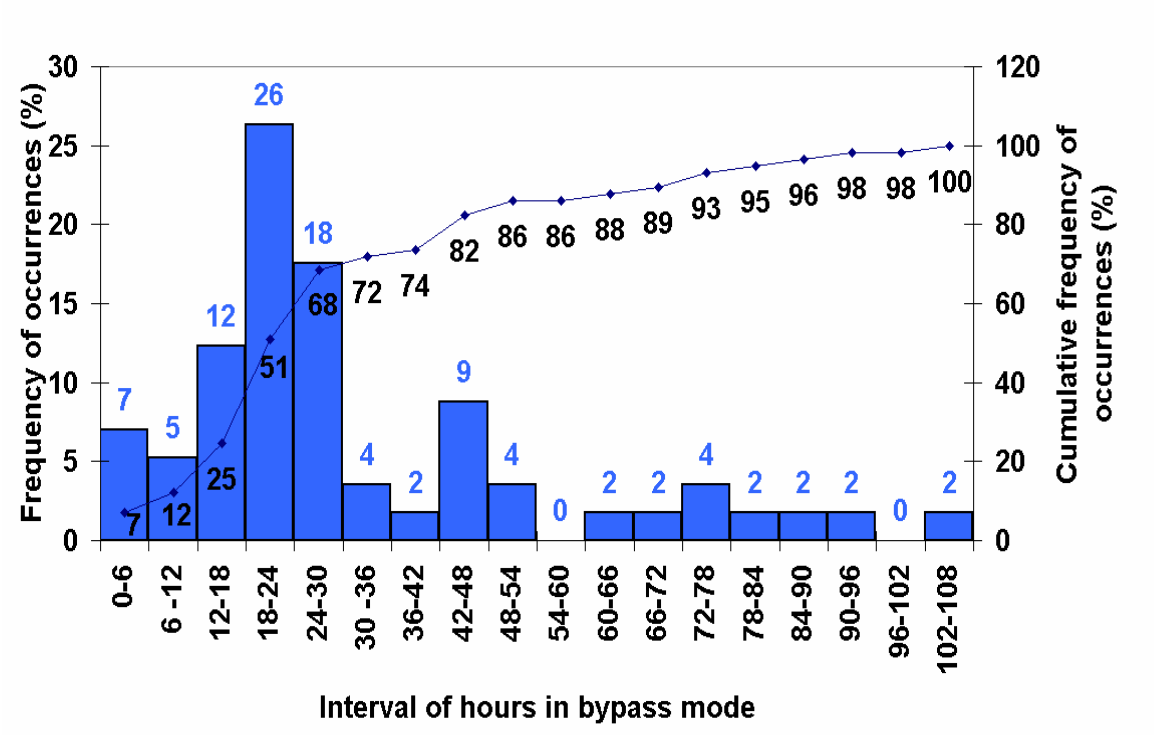


Figure 3-13. Histogram and frequency distribution for 6-hour intervals in bypass mode; 3-MC.

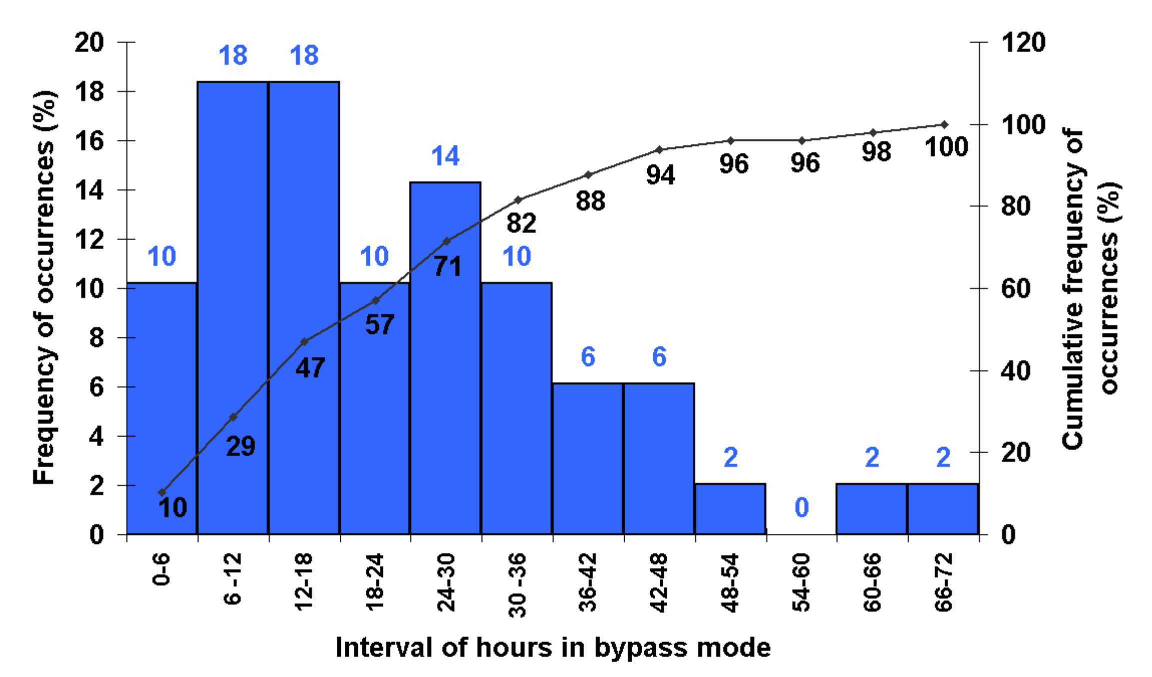


Figure 3-14. Histogram and frequency distribution for 6-hour intervals in bypass mode; 13-MC.

# CHAPTER 4
# GRANULAR MATRIX SENSOR PERFORMANCE COMPARED TO TENSIOMETER IN A SANDY SOIL

Numerous methods exist to measure soil water content, including gravimetric measurements, neutron scattering, resistance blocks, tensiometers, and granular matrix sensors (GMS). These methods are fairly common, some of them have been used for several decades, and continue to be used extensively in irrigation scheduling (Gardner, 1986; Seyfried, 1993; Leib et al., 2002; Leib et al., 2003; Or, 2001).

In this research, two of these methods were compared, tensiometers and granular matrix sensors (GMS), in a sandy soil.

## Tensiometers

Tensiometers have been used for many years to measure soil water tension in the field. Of all the methods available for monitoring water potential for irrigation, the tensiometers are perhaps the most widely used (Campbell and Mulla, 1990).

A tensiometer (Figure 4-1) consists of a sealed, water-filled tube with a permeable porous cup on one end, an airtight seal on the other end and some means of measuring tension (a gauge, manometer, or electronic pressure transducer). The device is installed in the soil with the ceramic tip in close contact with the soil at the desired depth. Water is pulled out through the ceramic tip into the soil creating a tension in the closed tube. As the soil is re-wetted (e.g., from rain or irrigation), the tension gradient reduces, causing water to flow into the ceramic tip (Ley et al., 2000). At equilibrium, the water pressure (tension) in the tensiometer is equal in magnitude to the soil matric potential (Cassell and

Klute, 1986). When tensiometers installed at the root zone reach a certain reading, they can be used as indicators of the need for irrigation, based on soil texture and crop type (Ley et al., 2000).

Most commercially available tensiometers use a vacuum gauge to read the tension created and have a scale from 0 to 100 kiloPascals (kPa) (100 kPa = 100 centibars = 1 bar = 14.7 psi). The practical operating range is from 0 to 75 kPa. If the water column is intact, a zero reading indicates saturated soil conditions. Readings of around 10 kPa correspond to field capacity for coarse-textured soils, while readings of around 30 kPa can approximate field capacity for some finer-textured soils. The upper limit of 75 kPa corresponds to as much as 90% depletion of total available water for the coarse-textured soils, but is only about 30% depletion for silt loam, clay loams, and other fine-textured soils. This limits the practical use of tensiometers to coarse-textured soils or to high frequency irrigation where soil water content is maintained high (Ley et al., 2000).

Tensiometers have been designed for use in situations where tensions above 30 kPa are rarely expected (e.g. sandy soils), when finer resolution near saturation is needed, and/or in conditions where rapidly changing moisture tensions need to be observed. This is the case of the MLT-RSU (Miniature Low Tension – Remote Sensing Unit)-tensiometer developed by Irrometer (Irrometer Company, Inc., Riverside, CA), shown on Figure 4-1.

Careful installation of tensiometers is required for reliable results. The ceramic tip must be in intimate and complete contact with the soil, and installation sites should represent the field in terms of water application patterns, soil types, slopes, and exposure; and should be installed out of the way of traffic and cultivation. In freezing climates, tensiometers must be insulated or removed during winter months, because it takes only a small frost to knock the vacuum gauges out of calibration (Ley et al., 2000).

## Granular Matrix Sensors

The GMS (Figure 4-2) is a device that measures soil electrical resistance, that can be converted to soil water tension (SWT), either using a calibration formula provided in the literature for sandy soils (Irmak and Haman, 2001) and silt loam soils (Eldredge et al., 1993), or calibrating them for a specific soil type (Hanson et al., 2000b; Intrigliolo and Castel, 2004).

Since the development of the GMS, many researchers (Eldredge et al., 1993; Mitchell and Shock, 1996; Bausch and Bernard, 1996) have used it in agricultural water management, including irrigation scheduling. However, some limitations in its use have been found. For example, in coarse–textured soils (e.g. sand) a lack of soil–sensor interface might be observed, and consequently may lead to incorrect estimation of SWT (Irmak and Haman, 2001). Also, GMS has a high uncertainty in the wet range and do not respond to changes at a SWT lower than 10 kPa and, therefore, may not be a suitable tool in those cases where irrigation practices maintain a low SWT (Irmak and Haman, 2001; Taber et al., 2002: Intrigliolo and Castel, 2004). In addition, McCann et al. (1992) found that GMS has a hysteretic behavior when induced to rapid drying or partial rewetting of the soil, which could affect the performance of the GMS in estimating the actual soil water status. Moreover, there is also evidence that the most important drawback on its use for irrigation scheduling is the high variability of its readings (CV of 35–50%), increasing at the lower SWT range (Taber et al., 2002; Intrigliolo and Castel, 2004). Finally, calibration appears to be exclusive for each individual sensor (Egbert et al., 1992; Hanson et al., 2000b; Leib et al., 2003; Intrigliolo and Castel, 2004).

In spite of all these limitations, GMS may be useful when a relative indication of soil wetness is needed, as indicated by reports of their successful use for irrigation scheduling in onion (Shock et al., 1998a), potato (Shock et al., 1998b), tomato, and walnut trees (Hanson et al., 2000a).

## GMS – Tensiometer Comparison

Previous research found that GMSs functioned consistently over a range of SWT from 10 kPa to 200 kPa (Hanson et al., 2000a; Leib et al., 2003; Intrigliolo and Castel, 2004). So, GMS can operate in a drier range than tensiometers, but with a lower resolution at the wet end of SWT (Egbert et al., 1992; Irmak and Haman, 2001). This is an important limitation for the use of GMS in the predominantly coarse-textured soils of Florida.

Bausch and Bernard (1996) evaluated the validity of the granular matrix sensor SWT values calculated using Thomson and Armstrong (1987) and Shock et al. (1996) calibration equations with the tensiometer-measured SWT. However, both equations underestimated SWT for sandy clay loam soil. Thomson et al. (1996) compared Thomson and Armstrong (1987) and McCann et al. (1992) equations and indicated that the equations deviated significantly for estimating SWT.

## Objectives

The objectives of this research were to: a) compare GMS to tensiometer readings on a sandy soil, b) establish a relationship between them, if any, and c) evaluate the performance of the GMSs in a sandy soil.

## Materials and Methods

The experiment was conducted in 2004 in the Water Resources Lab at the University of Florida, Gainesville, Florida. Three PVC cylinders [19.14 L (0.30 m high ×

0.285 m diameter)], were hand-packed with an Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) (USDA, 2003), taken from the field where the soil moisture sensor experiment was carried out.

### Experimental Set-Up

In each PVC cylinder, three 200SS model Watermark GMSs (Irrometer Company, Inc., Riverside, CA) were installed vertically, in a uniformly spaced pattern. (Prior to installation, GMSs were immersed in water for two days, according to manufacturer instructions.) A temperature sensor (Irrometer Company, Inc., Riverside, Calif.) was installed in the center of the PVC cylinders to correct the GMS readings. In addition, three MLT-RSU model Tensiometers (Irrometer Company, Inc., Riverside, CA), hereafter-called tensiometers, were also placed near the GMSs. Finally, a capacitance ECH$_2$O probe (Decagon Devices, Inc., Pullman, WA) was also placed in each PVC cylinder. Figures 4-1 through 4-4 show pictures of the devices. GMSs were placed with their center at 9 cm soil depth. All other devices were installed with their sensing section at the depth of GMS centers. The experimental layout is shown in Figure 4-5.

### ECH$_2$O Probes Calibration

Before the experiment was carried out, the ECH$_2$O probes were calibrated through the thermogravimetric soil sampling method (Gardner, 1986). Undisturbed soil samples were collected (using a core sampler of 137.4 cm$^3$) from each PVC cylinder at the same depth where ECH$_2$O probes were placed. Samples were taken from a saturated through a dry condition (28.4% to 4.8% of VMC, respectively, based on gravimetric data).

The samples were weighed and then oven-dried at 104°C for 24 h. Then, the dry samples were re-weighed. Percent soil water content on a dry mass or gravimetric basis, *Pw*, was determined by the following formula:

$$Pw = \frac{wet\ sample\ weight\ \text{-}\ dry\ sample\ weight}{dry\ sample\ weight} x100 \qquad [4\text{-}1]$$

To convert from a gravimetric basis to water content on a volumetric basis, *Pv*, the gravimetric soil water content was multiplied by the soil bulk density (*BD*):

$$Pv = Pw\ x\ BD \qquad [4\text{-}2]$$

and soil bulk density was determined by:

$$BD = \frac{weight\ of\ dry\ sample}{volume\ of\ dry\ soil} \qquad [4\text{-}3]$$

The volumetric soil water content of each sample was then compared to the $ECH_2O$ probe readings at the same date and time when the samples were taken and, then, these data were compared to calibrate the $ECH_2O$ probe readings.

### Treatments

All three PVC cylinders had a ceramic porous plate placed at the bottom to withdraw water from the cylinders to accelerate drying. Suction was applied, using a vacuum pump connected to the porous plate. A different initial suction time was applied to each cylinder to create different rates of soil drying, defining the treatments (Table 4-1): 0, 5, 15, and 50 min for treatments T0, T5, T15, and T50, respectively.

### Data

The tensiometers, GMSs, and temperature sensor were connected to a Watermark Monitor (Figure 4-6). This is a data logger developed by Irrometer (Irrometer Company, Inc., Riverside, Calif.), which includes an automatic temperature compensation of the soil moisture readings, and gives GMS and tensiometer readings in kPa. The $ECH_2O$ probes were connected to a HOBO Micro Station (Figure 4-7) data logger (Onset Computer Corporation, Bourne, MA). All sensor data were recorded every 15 minutes.

## Results and Discussion

### Calibration of the $ECH_2O$ Probe

Data from the three ECH2O probes compared to thermogravimetric measurements is given in Figure 4-8. It can be seen that $ECH_2O$ measurements and gravimetric measurements were highly correlated ($R^2 = 0.95$). However, the $ECH_20$ probes under predicted the gravimetric water content by about 20% as seen in Figure 4-8.

### GMSs versus Tensiometers.

In previous research, when comparing GMS with other SMC-methods, authors took electrical resistance measurements from GMS, and then converted these data to tension, through calibration equations (Irmak and Haman, 2001; Eldredge et al., 1993; Hanson et al., 2000b). In this research, the Watermark Monitor-datalogger gave the GMS readings expressed immediately in tension, so no conversion with a calibration curve was theoretically necessary.

The results from the different treatments are displayed in Figures 4-9 through 4-16. It can be seen that the curves of GMSs and tensiometers followed a similar trend, but tension readings were different. Their soil water tension curves crossed at average values in the range of 5.8 through 6.7 kPa, depending on the treatment, with an overall average of 6.2 kPa (Table 4-2). At tensions less than this level, GMSs gave lower tensions than the tensiometers, and the opposite occurred at tensions higher than these values, where GMSs showed a consistently drier estimate of the soil moisture content compared to tensiometers.

Relating the average of GMS and tensiometer readings (Figure 4-17), a coefficient of determination of $R^2=0.9582$ was found for a linear relationship between them, and a coefficient of determination of $R^2=0.9916$ for a logarithmic relationship between them.

Previous studies reported that GMSs do not respond accurately at tensions less than 10 kPa (Egbert et al., 1992; Irmak and Haman, 2001). Moreover, Eldredge et al. (1993) did not include these data when performing their analysis. In the present experiment, GMS values at tensions less than 7 kPa were not stable, showing fluctuations between ±1kPa (Figures 4-13 and to 4-14). When replotting the average of GMS and tensiometer readings without including tensions below 10 kPa (Figure 4-18) the coefficient of determination increased to $R^2$=0.9809 for a linear relationship, and increased to $R^2$=0.9956 for a logarithmic relationship.

In the sandy soils of North-Central Florida, the trigger point to start an irrigation cycle is often reported as 10-30 kPa. If that is the case, when tensiometers were reading 10 kPa, GMSs were reading between 17 and 23 kPa, and an average of 20 kPa. This could have a major consequence if an automatic irrigation system is controlled by a GMS, because is highly probable that they would allow irrigation cycles when actually they are not necessary, which is exactly what happened with the GMS-controlled irrigation in Chapter 2. According to these results, it is evident that calibration of GMS units in this type of soil is necessary.

## Conclusions

Tension readings from tensiometers and GMSs were the same, at levels close to 6.2 kPa. Below this tension, GMSs readings were lower than those from tensiometers, and the opposite occurred at tensions higher than this value. At the same time as tensions continued to increase, the difference between both methods increased. In addition, GMS readings below 7 kPa were not stable, fluctuating between ±1kPa.

The set point (kPa) to initiate irrigation could be of great consequence regarding water use efficiency, when GMSs are set to control an automatic irrigation system.

According to these results, it was evident that calibration of GMS units in this type of soil is necessary to obtain readings closer to reality, and achieve adequate irrigation management.

Table 4-1. Treatments.

| **Treatment** | **Suction Time (minutes)** |
|---|---|
| **A** | **0** |
| **B** | **5** |
| **C** | **15** |
| **D** | **15** |
| **E** | **50** |

Table 4-2. GMS-Tensiometer crossing points.

| GMS # | Tensiometer # | Treatment (-kPa) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | T0 | | T5 | | T15 | | T50 | | Avg |
| | | Each | Avg | Each | Avg | Each | Avg | Each | Avg | |
| 1 | 1 | | | 5.5 | | 5.3 | | 6.2 | | |
| | 2 | | | 6.1 | 6.1 | 5.6 | 5.8 | 6.4 | 6.4 | 6.1 |
| | 3 | | | 6.6 | | 6.4 | | 6.5 | | |
| 2 | 1 | | | 5.6 | | 5.5 | | 6.8 | | |
| | 2 | | | 6.2 | 6.1 | 5.8 | 6.0 | 6.8 | 6.8 | 6.3 |
| | 3 | | | 6.7 | | 6.6 | | 6.8 | | |
| 3 | 1 | 6.2 | | 5.3 | | 5.3 | | 6.2 | | |
| | 2 | 6.4 | 6.4 | 6.0 | 5.9 | 5.6 | 5.8 | 6.4 | 6.4 | 6.1 |
| | 3 | 6.7 | | 6.5 | | 6.4 | | 6.5 | | |
| | Average | | 6.4 | | 6.0 | | 5.8 | | 6.5 | 6.2 |

Figure 4-1. MLT-RSU Tensiometer.

Figure 4-2. Watermark GMS.

Figure 4-3. Temperature sensor.

Figure 4-4. $ECH_2O$ probe

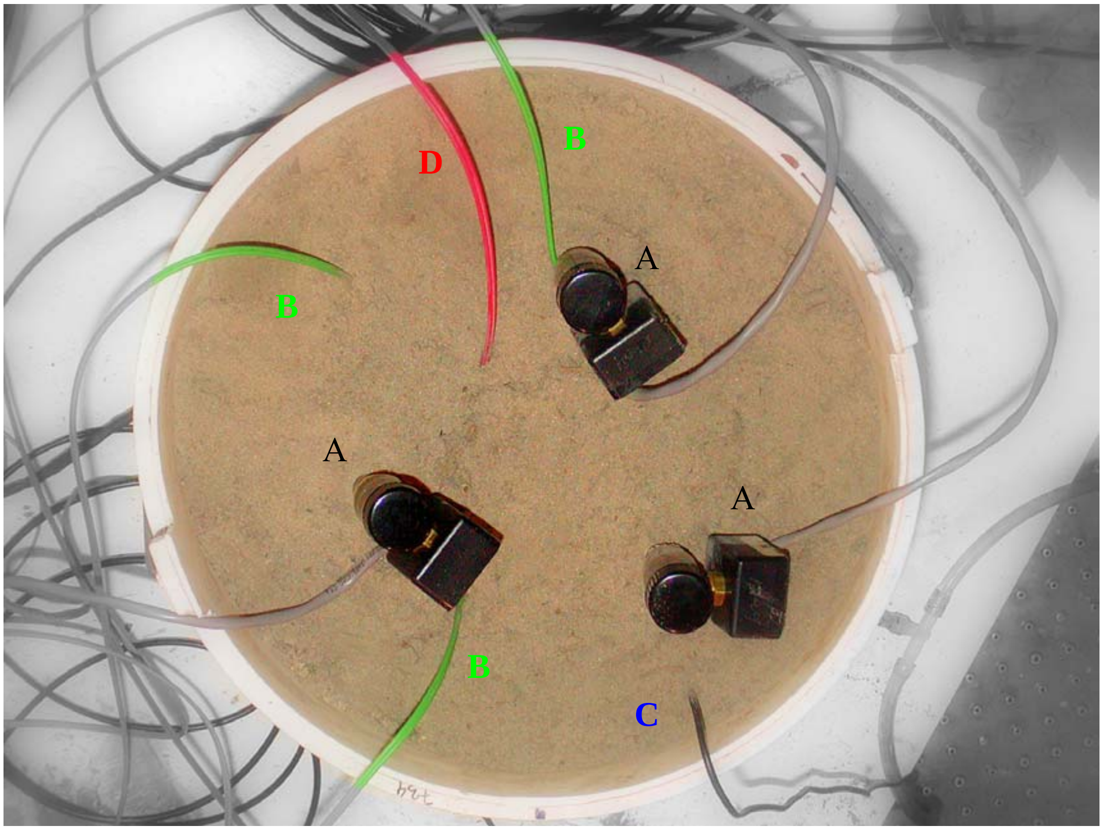


Figure 4-5. Experimental layout (top view). A) Tensiometers, B) Granular matrix sensors, C) $ECH_2O$ probe, and D) Thermometer.

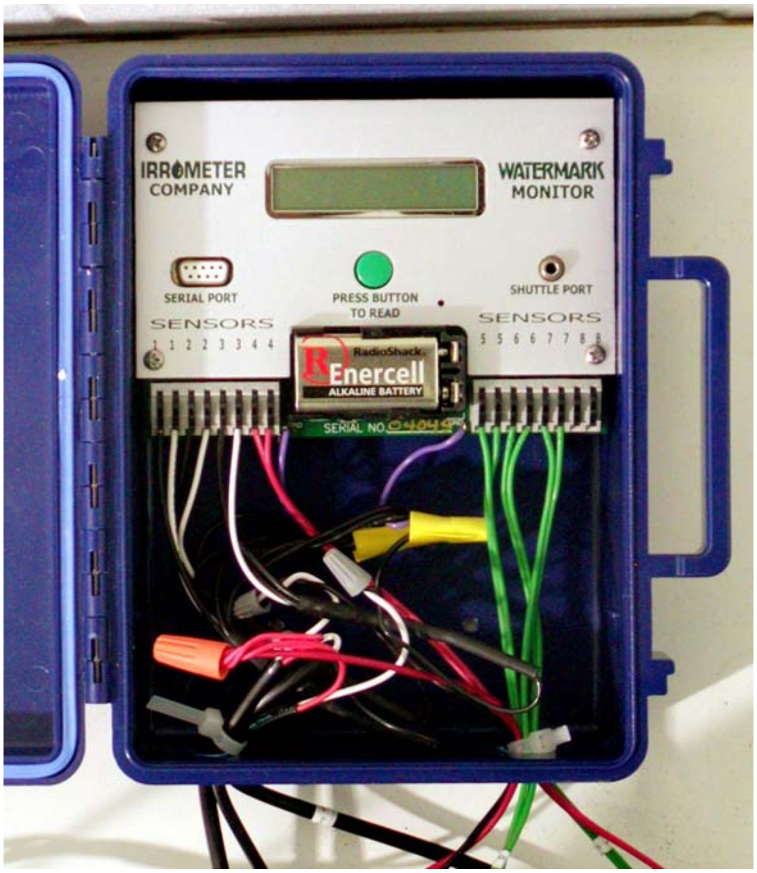


Figure 4-6. Watermark monitor.

Figure 4-7. $ECH_2O$ probe hooked up to a HOBO Micro Station datalogger.

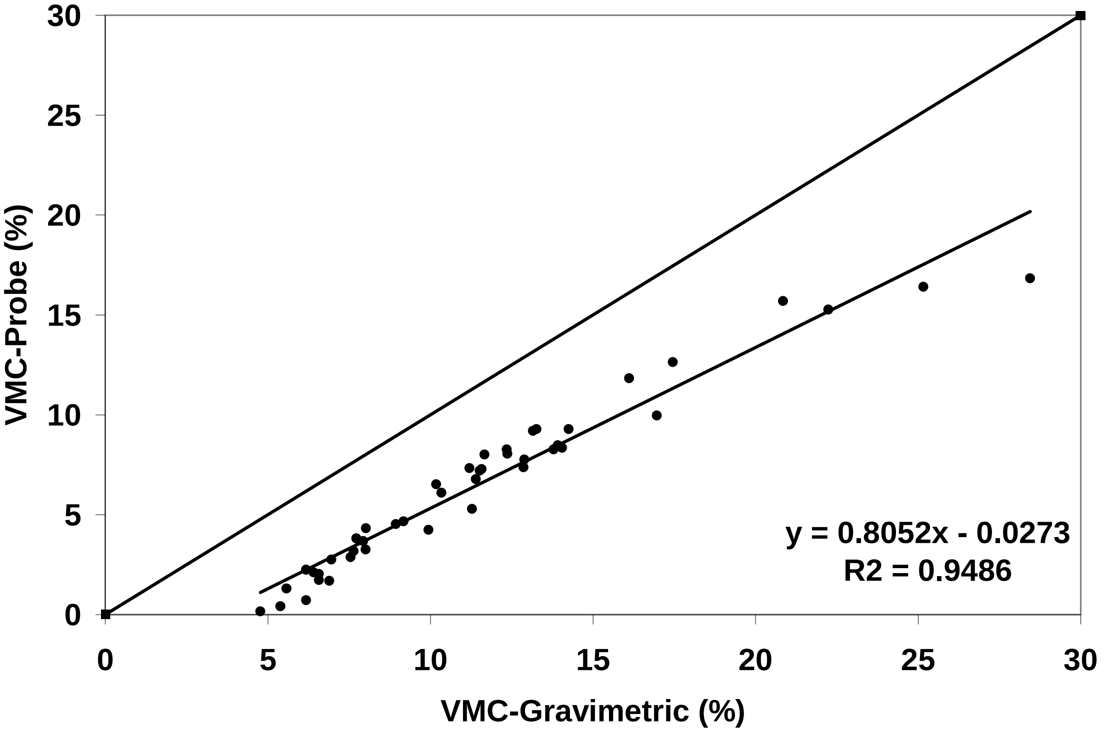


Figure 4-8. Volumetric moisture content (VMC) from all three $ECH_2O$ probes compared to gravimetric measurements.

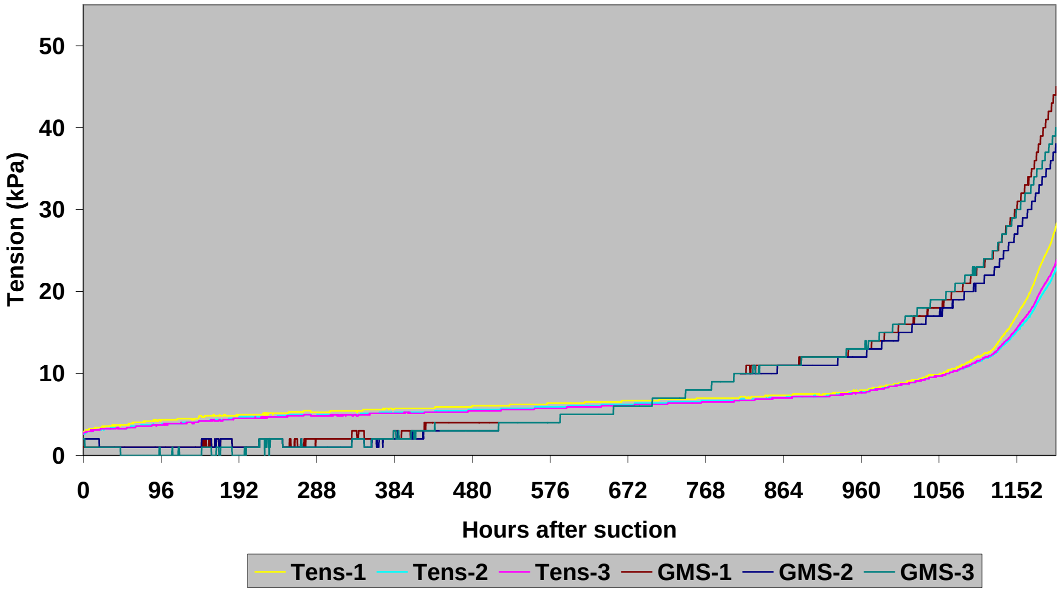


Figure 4-9. Soil water tension through time; treatment T0.

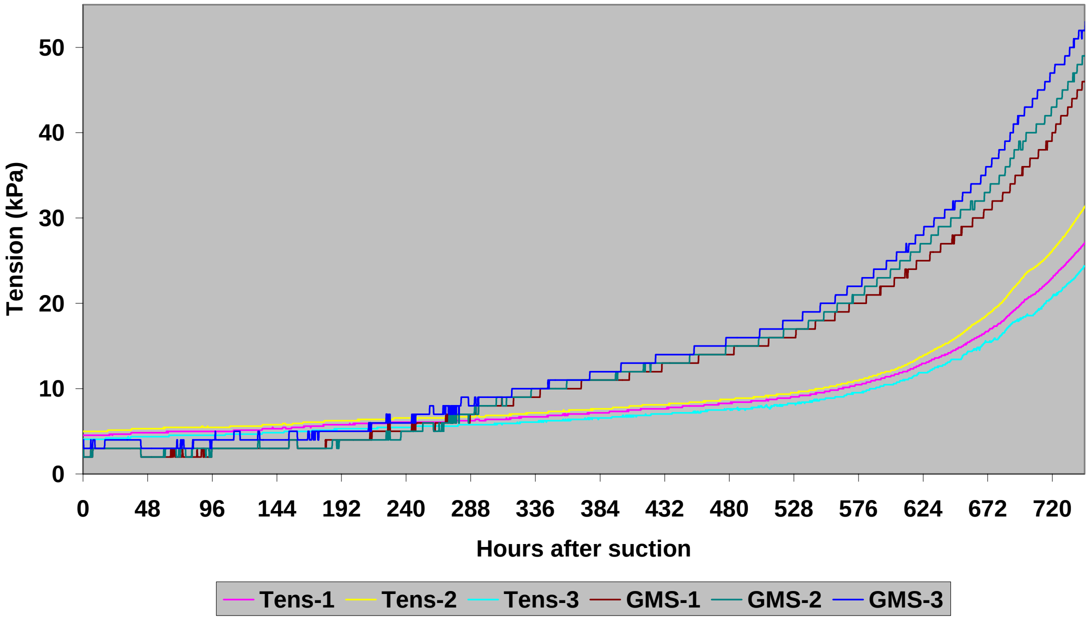


Figure 4-10. Soil water tension through time; treatment T5.

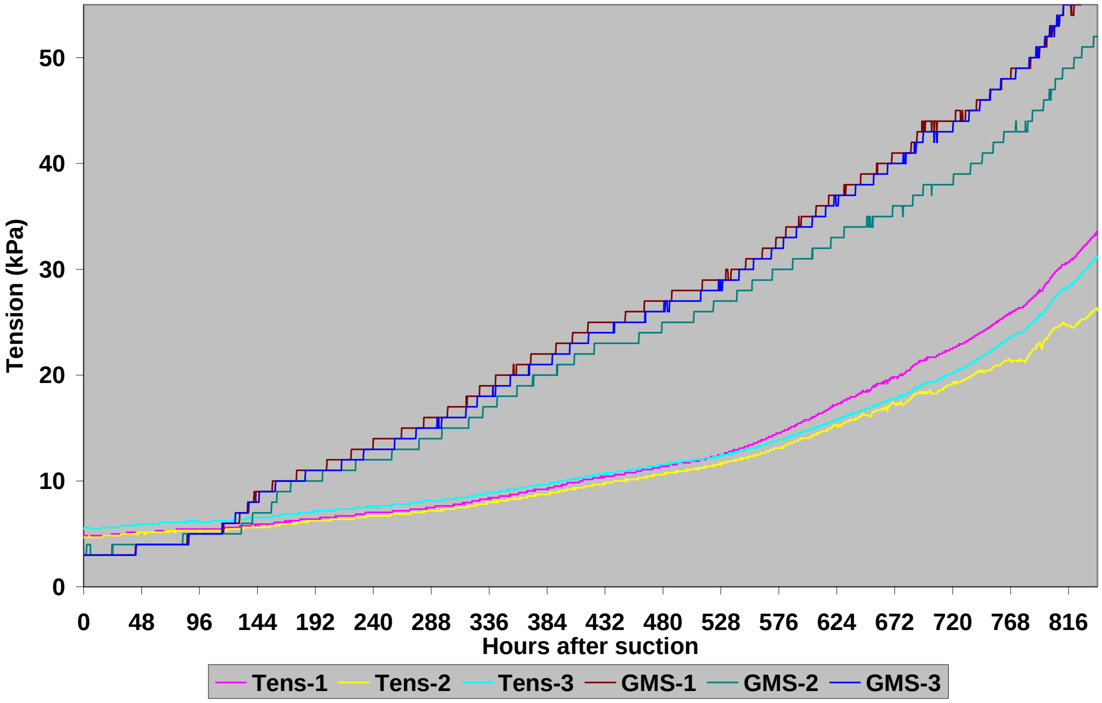


Figure 4-11. Soil water tension through time; treatment T15.

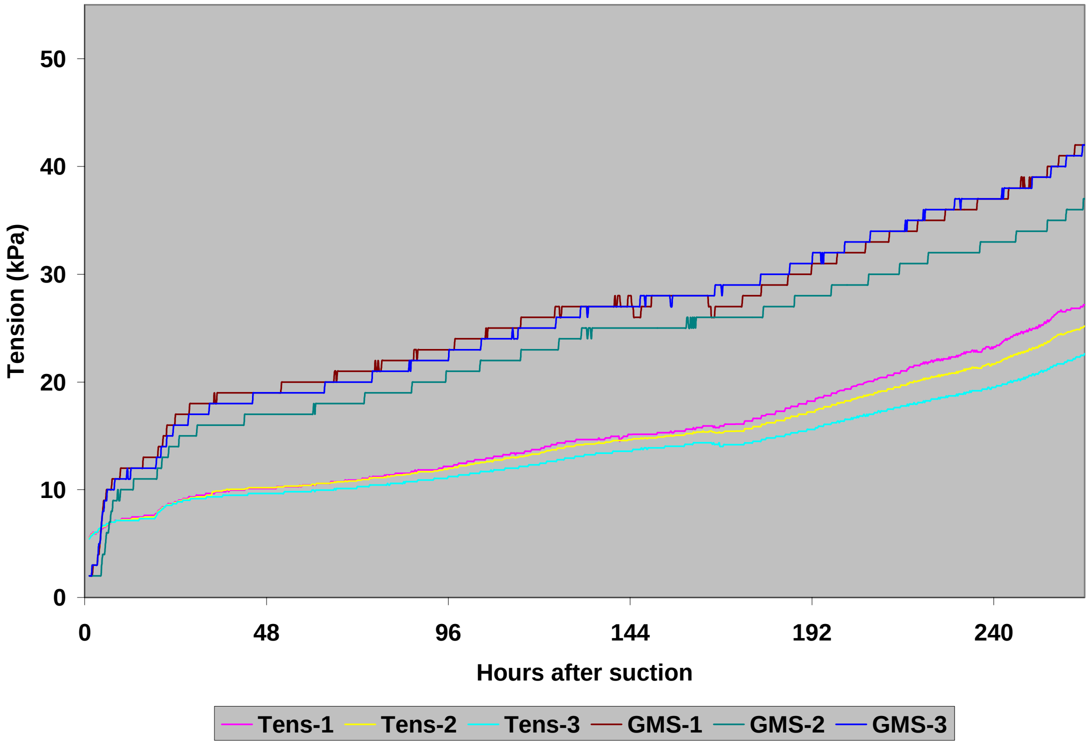


Figure 4-12. Soil water tension through time; treatment T50.

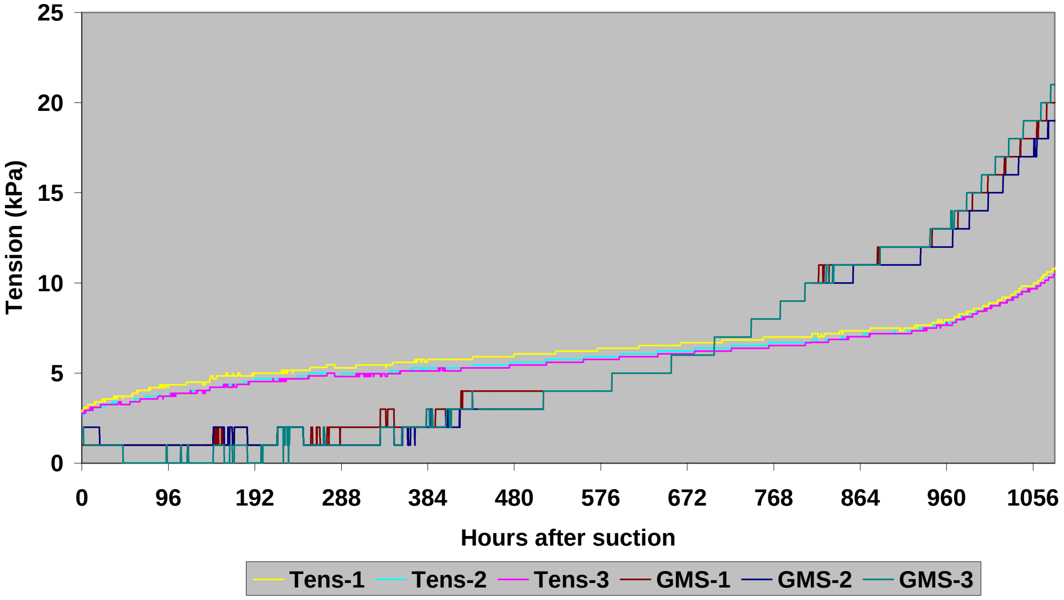


Figure 4-13. Soil water tension through time; detail showing when curves from GMS and tensiometers cross; treatment T0.

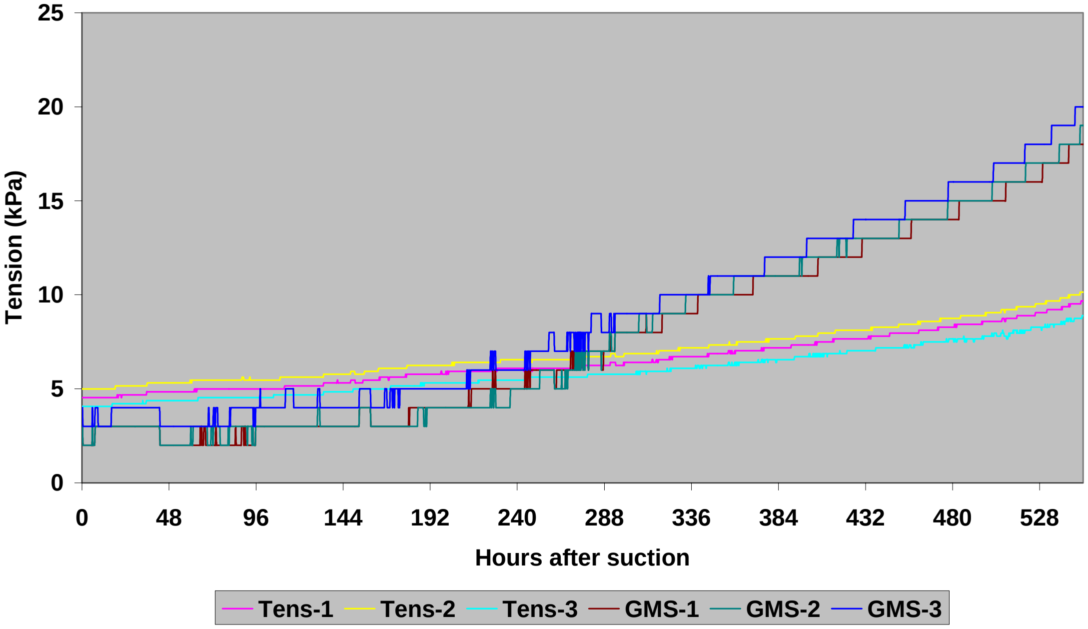


Figure 4-14. Soil water tension through time; detail showing when curves from GMS and tensiometers cross; treatment T5.

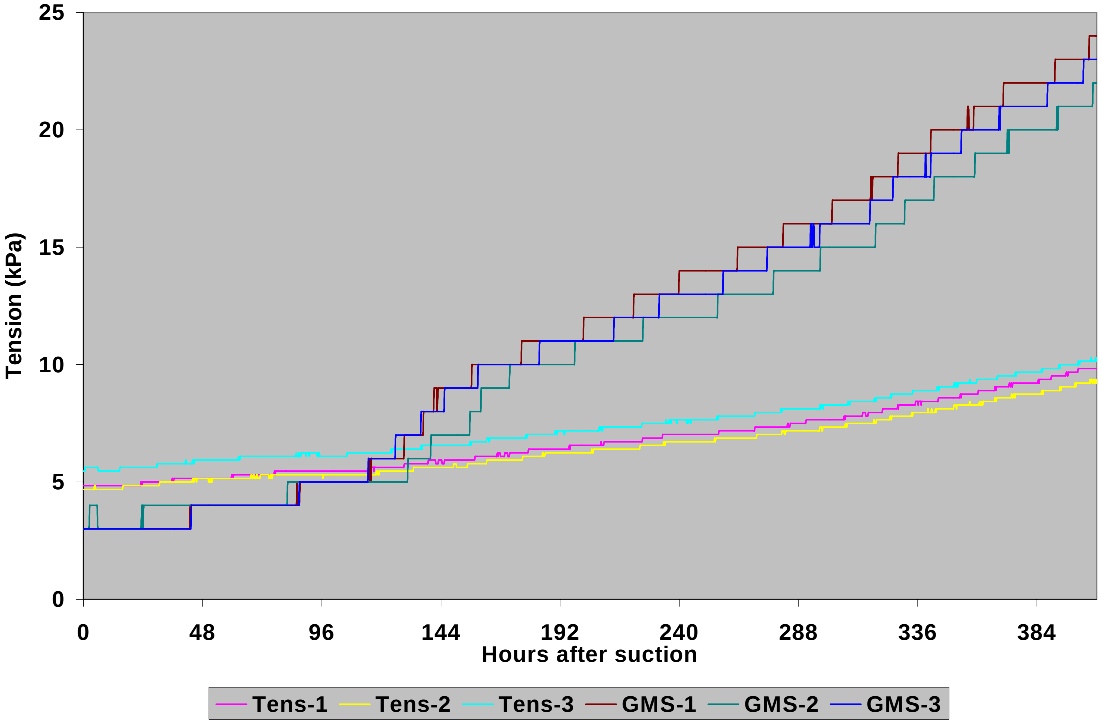


Figure 4-15. Soil water tension through time; detail showing when curves from GMS and tensiometers cross; treatment T15.

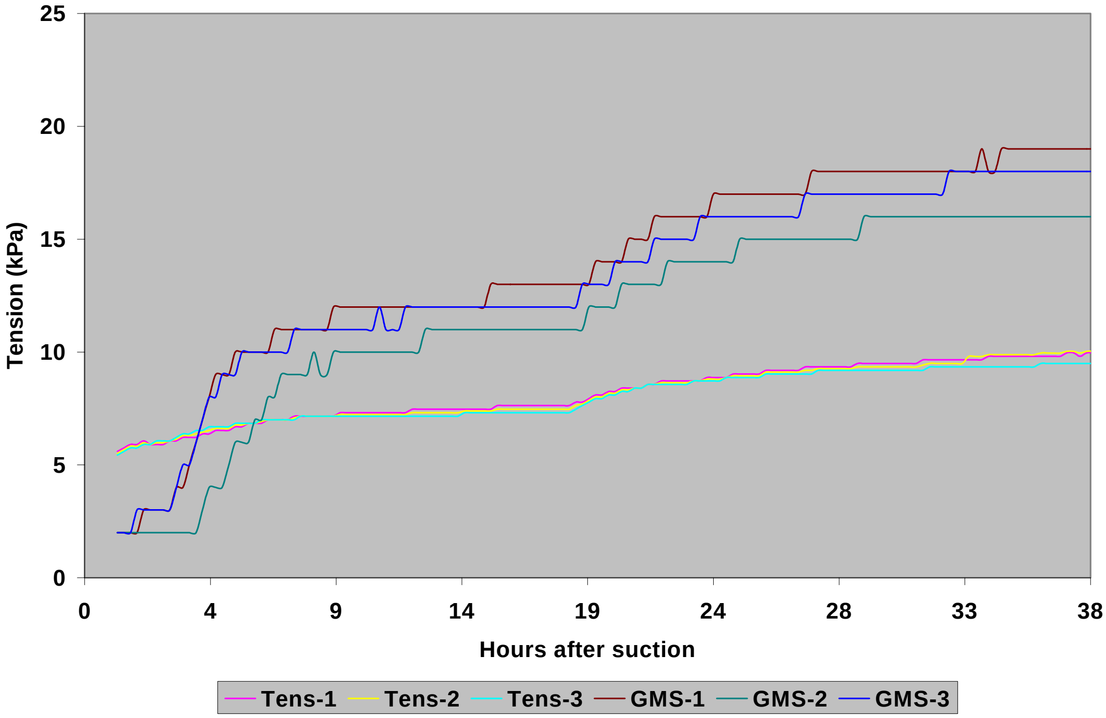


Figure 4-16. Soil water tension through time; detail showing when curves from GMS and tensiometers cross; treatment T50.

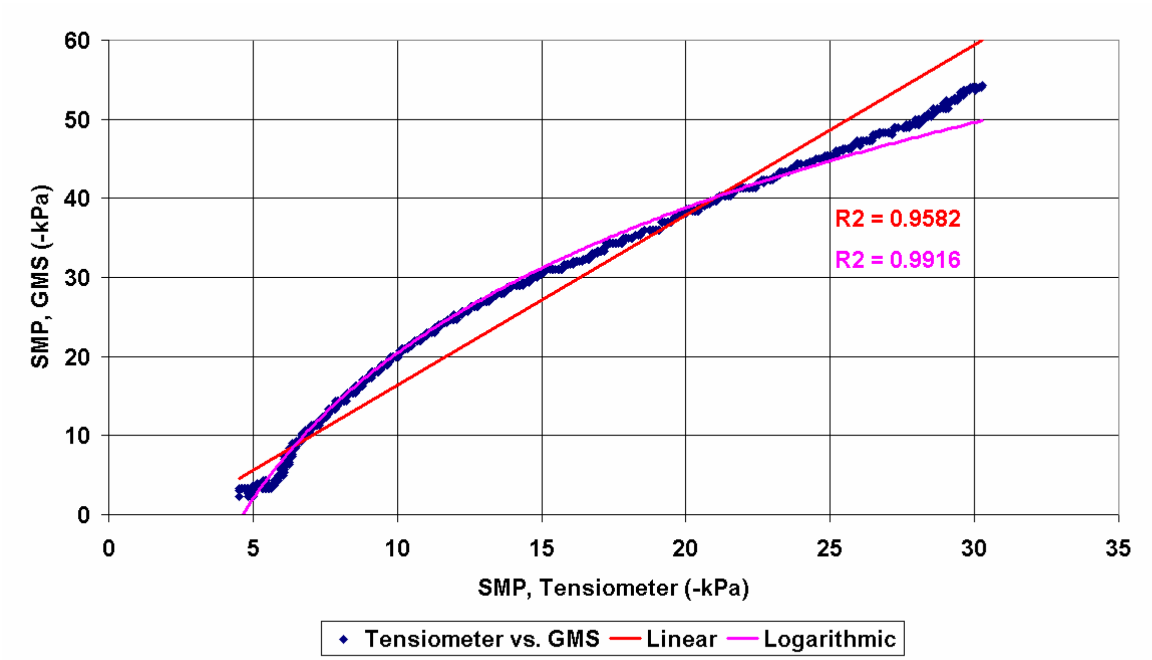


Figure 4-17. Relation between the average soil matric potential (SMP) from tensiometers and GMS.

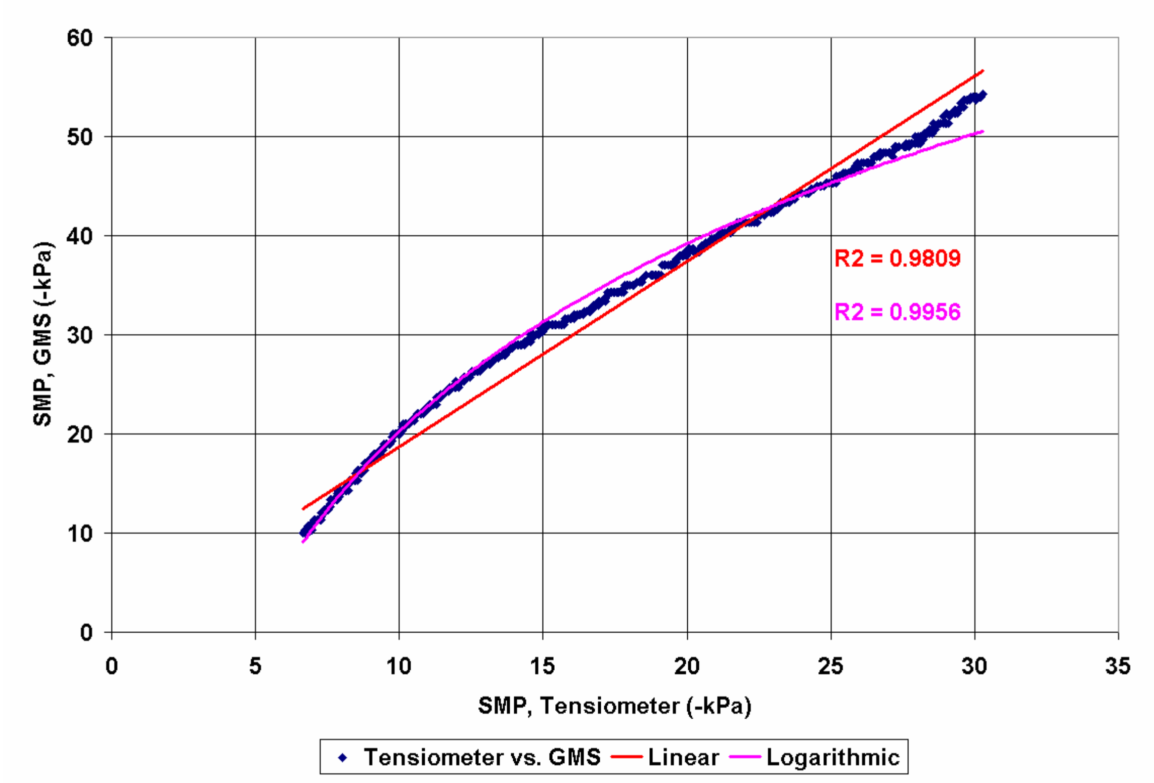


Figure 4-18. Relation between the average soil matric potential (SMP) from tensiometers and GMS; excluding GMS data < 10 kPa.

# CHAPTER 5
# CONCLUSIONS AND FUTURE WORK

## Conclusions

The goals of this research were to find out if different SMS-systems (sensor with a proprietary controller) could reduce irrigation water application–while maintaining acceptable turf quality–compared to current practices and, on the other hand, to collect evidence related to RS performance and reliability. The main objectives of this experiment were to quantify differences in irrigation water use and turf quality between: 1) a soil moisture sensor-based irrigation system compared to a time-based scheduling, 2) different commercial irrigation soil moisture sensor (SMSs), and 3) a time-based scheduling system with or without a rain sensor (RS). The secondary objectives were to: a) evaluate the reliability of two commercially available expanding disk RS-types, b) quantify the amount of water that RSs could save compared to time-based irrigation schedules without RS, and c) estimate the payback period of RSs at different set points.

Results showed that no significant differences in turfgrass quality among treatments were detected, which was evidenced by good quality in non-irrigated plots. This was a consequence of the high frequency rainfall events and large amount of cumulative precipitation that prevailed during the time frame of this research and, on the other hand, because of the documented characteristics of bermudagrass as a drought-tolerant plant.

Regarding the time-based treatments, 2-WORS (without-rain-sensor) used significantly (52%) more water than 2-WRS (with-rain-sensor), showing the importance not only for the presence but also for the need of a well-maintained rain shut-off device in all automated irrigation systems. However, treatment 2-WRS was fairly well managed and conservative, compared to homeowners' actual operation practices, so "real" water savings on residential landscapes could be even larger.

It was inferred that, in general, SMS-based treatments were able to follow and detect fairly well when sufficient rain occurred, overriding pre-set irrigation cycles, and allowing the rest of them to run when necessary.

SMS-based treatments were, on average, significantly more efficient as a means to save water than the time-based treatments. However, not all SMSs tested performed the same. Sensors from brand Irrometer always applied significantly more water than the other brands/treatments in every frequency. All the other brands (AC, RB, and WW) recorded significant irrigation water savings compared to 2-WRS, which ranged from 54% to 88%, depending on the irrigation frequency. When compared to 2-WORS, the differences increased, and ranged from 69% to 92% in water savings.

Therefore SMS-systems represent a promising technology, because of the water savings that they can accomplish, while maintaining an acceptable turfgrass quality. The correct choice of a SMS should take into consideration features like its technology, response-time, irrigation scheduling strategy, and cost, among other aspects.

Regarding the RS treatments, on average, treatments WL, 3-MC, 13-MC, and 25-MC responded close to their rainfall set points (1.4, 3.4, 10.0, and 24.5 mm, respectively). However, some replications showed erratic behavior through time.

The number of times that these sensors shut off irrigation was inversely proportional to the magnitude of their set point (81, 43, 30, and 8 times, respectively) with potential water savings following a similar trend (363, 245, 142, and 25 mm, respectively).

Under the relatively wet testing conditions typical to Florida, the payback period of the RSs tested could be less than a year, except for 25-MC (around 7 years). Consequently, RSs are strongly recommended for use by homeowners as a means to save water, but not when accuracy is required.

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 RS, and the author suggests that they are often incorrectly installed. Therefore, appropriately installed and properly working rain sensors could signify not only substantial water savings to homeowners, but could also lead to sound environmental and economic benefits to the state.

## Future Work

The SMS-system technology should be tested under real homeowner conditions in order to validate these results. Also, future information obtained from the same research field will give an evaluation of this SMS-based system performance over a longer period of time, regarding its consistency and durability, and its response under different weather conditions.

In addition, these SMSs were buried at 7-10 cm, meaning that they were placed where the soil is more susceptible to changes in its moisture content. Theoretically (and this should be tested), burying them a little bit deeper and/or setting the SMS-controllers to a dryer condition could promote the turfgrass to produce a longer root system and, consequently, could result in even less actual irrigation frequency and water use.

Finally, these SMS-based results, reinforced by other experiments using this technology, open the possibility of redefining the BMPs for residential turfgrass irrigation, and for review and further discussion of the state’s watering restrictions as well.

# APPENDIX A
# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | : Acclima |
| BMP | : Best Management Practices |
| CCL | : Closed Control Loop |
| DWRS | : 60% deficit with rain sensor |
| d/w | : days per week |
| ET | : Evapotranspiration |
| $ET_o$ | : Potential or Reference Evapotranspiration |
| FDR | : Frequency Domain Reflectrometery |
| GMS | : Granular Matrix Sensor |
| IM | : Irrometer |
| MC | : Mini-Click rain sensor |
| NI | : No irrigation |
| RB | : Rain Bird |
| RS | : Rain Sensor |
| SIC | : Scheduled Irrigation Cycles |
| SJRWMD | : St. Johns River Water Management District |
| SMS | : Soil Moisture Sensor |
| SWB | : Simplified Water Balance |
| SWT | : Soil Water Tension |
| TDR | : Time Domain Reflectometry |
| U.S. | : United States of America |
| VMC | : Volumetric Moisture Content |
| WL | : Wireless Rain-Click rain sensor |
| WMD | : Water Management District |
| WORS | : Without rain sensor |
| WRS | : With rain sensor |
| WW | : Water Watcher |

# APPENDIX B
# STATISTICAL ANALYSES

The following are the SAS codes and the output text files for the statistical analyses performed.

## DRY-WET CODES

```
options nodate nonumber center formdlim="*"linesize=85;
data sms;
input plot$ rep$ dry wet;
cards;
/* Data is inputted here */
;
data sms;
set sms;
proc glm data=sms;
title 'Dry';
class plot;
model dry = plot /ss3;
means plot/duncan;
run;
data sms;
set sms;
proc glm data=sms;
title 'Wet';
class plot;
model wet = plot /ss3;
means plot/duncan;
run;
```

# DRY-WET ANALYSIS OUTPUT

```
**************************************************************************************

                                       Dry

                                 The GLM Procedure

                              Class Level Information

Class       Levels  Values

plot            72  A01 A02 A03 A04 A05 A06 A07 A08 A09 A10 A11 A12 B01 B02 B03 B04
                    B05 B06 B07 B08 B09 B10 B11 B12 C01 C02 C03 C04 C05 C06 C07 C08
                    C09 C10 C11 C12 D01 D02 D03 D04 D05 D06 D07 D08 D09 D10 D11 D12
                    E01 E02 E03 E04 E05 E06 E07 E08 E09 E10 E11 E12 F01 F02 F03 F04
                    F05 F06 F07 F08 F09 F10 F11 F12


                       Number of Observations Read         360
                       Number of Observations Used         360

**************************************************************************************

                                   At once Dry

                                 The GLM Procedure

Dependent Variable: dry

                                        Sum of
 Source                      DF        Squares     Mean Square    F Value    Pr > F

 Model                       71    1524.922222       21.477778       7.19    <.0001

 Error                      288     860.800000        2.988889

 Corrected Total            359    2385.722222


                R-Square     Coeff Var      Root MSE      dry Mean

                0.639187      24.79612      1.728840      6.972222


 Source                      DF    Type III SS     Mean Square    F Value    Pr > F

 plot                        71    1524.922222       21.477778       7.19    <.0001

**************************************************************************************
```

```
                                      Dry

                                The GLM Procedure

                         Duncan's Multiple Range Test for dry

          NOTE: This test controls the Type I comparisonwise error rate, not the
                                experimentwise error rate.


                            Alpha                        0.05
                            Error Degrees of Freedom      288
                            Error Mean Square        2.988889


  Number of Means      2     3     4     5     6     7     8     9    10    11    12
  Critical Range  2.152 2.266 2.341 2.397 2.441 2.476 2.506 2.531 2.553 2.572 2.589

  Number of Means     13    14    15    16    17    18    19    20    21    22    23
  Critical Range  2.605 2.618 2.631 2.642 2.653 2.663 2.671 2.680 2.687 2.695 2.701

  Number of Means     24    25    26    27    28    29    30    31    32    33    34
  Critical Range  2.708 2.714 2.719 2.725 2.730 2.734 2.739 2.743 2.747 2.751 2.755

  Number of Means     35    36    37    38    39    40    41    42    43    44    45
  Critical Range  2.758 2.761 2.765 2.768 2.771 2.773 2.776 2.779 2.781 2.784 2.786

  Number of Means     46    47    48    49    50    51    52    53    54    55    56
  Critical Range  2.788 2.790 2.792 2.794 2.796 2.798 2.800 2.801 2.803 2.804 2.806

  Number of Means     57    58    59    60    61    62    63    64    65    66    67
  Critical Range  2.807 2.809 2.810 2.811 2.813 2.814 2.815 2.816 2.817 2.818 2.819

          Number of Means    68         69         70         71         72
          Critical Range  2.820      2.821      2.822      2.823      2.824


              Means with the same letter are not significantly different.


                     Duncan Grouping                           Mean      N    plot

                               A                             15.200      5    A12
                               A
                               A                             14.000      5    A11

                               B                             11.400      5    D11
                               B
                C              B                             10.200      5    D10
                C              B
                C              B          D                  10.000      5    D09
                C              B          D
                C         E    B          D                   9.600      5    C08
                C         E    B          D
      F         C         E    B          D                   9.400      5    D06
      F         C         E    B          D
      F         C         E    B          D                   9.400      5    E08
```

```
      F           C           E           B           D
      F           C           E           B           D     G                   9.200       5     D05
      F           C           E           B           D     G
      F           C           E           B           D     G                   9.200       5     E07
      F           C           E           B           D     G
      F           C           E           B     H     D     G                   9.000       5     F07
      F           C           E                 H     D     G
      F           C           E           I     H     D     G                   8.800       5     D12
      F           C           E           I     H     D     G
      F           C           E     J     I     H     D     G                   8.400       5     F01
      F           C           E     J     I     H     D     G
      F           C           E     J     I     H     D     G                   8.400       5     F08
      F           C           E     J     I     H     D     G
      F           C           E     J     I     H     D     G                   8.400       5     E04
      F           C           E     J     I     H     D     G
      F           C     K     E     J     I     H     D     G                   8.200       5     E01
      F           C     K     E     J     I     H     D     G
      F     L     C     K     E     J     I     H     D     G                   8.000       5     E09
      F     L     C     K     E     J     I     H     D     G
      F     L     C     K     E     J     I     H     D     G                   8.000       5     E06
      F     L     C     K     E     J     I     H     D     G
M     F     L     C     K     E     J     I     H     D     G                   7.800       5     D07
M     F     L     C     K     E     J     I     H     D     G
M     F     L     C     K     E     J     I     H     D     G                   7.800       5     D08
M     F     L     C     K     E     J     I     H     D     G
M     F     L     C     K     E     J     I     H     D     G                   7.800       5     D04
M     F     L     C     K     E     J     I     H     D     G
M     F     L     C     K     E     J     I     H     D     G     N             7.600       5     F09
M     F     L     C     K     E     J     I     H     D     G     N
M     F     L     C     K     E     J     I     H     D     G     N             7.600       5     E05
M     F     L           K     E     J     I     H     D     G     N
M     F     L           K     E     J     I     H     D     G     N             7.400       5     C12
M     F     L           K     E     J     I     H     D     G     N
M     F     L           K     E     J     I     H     D     G     N             7.400       5     D03
M     F     L           K     E     J     I     H     D     G     N
M     F     L           K     E     J     I     H     D     G     N             7.400       5     C09
M     F     L           K     E     J     I     H     D     G     N
M     F     L           K     E     J     I     H     D     G     N             7.400       5     B05
M     F     L           K     E     J     I     H           G     N
M     F     L     O     K     E     J     I     H           G     N             7.200       5     E03
M     F     L     O     K     E     J     I     H           G     N
M     F     L     O     K     E     J     I     H           G     N             7.200       5     B01
M     F     L     O     K     E     J     I     H           G     N
M     F     L     O     K     E     J     I     H     P     G     N             7.000       5     F10
M     F     L     O     K           J     I     H     P     G     N
M     F     L     O     K           J     I     H     P     G     N             6.800       5     C10
M     F     L     O     K           J     I     H     P     G     N
M     F     L     O     K           J     I     H     P     G     N             6.800       5     D02
M     F     L     O     K           J     I     H     P     G     N
M     F     L     O     K           J     I     H     P     G     N             6.800       5     E11
M           L     O     K           J     I     H     P     G     N
M           L     O     K     Q     J     I     H     P     G     N             6.600       5     E02
M           L     O     K     Q     J     I     H     P     G     N
M           L     O     K     Q     J     I     H     P     G     N             6.600       5     C06
M           L     O     K     Q     J     I     H     P     G     N
M           L     O     K     Q     J     I     H     P     G     N             6.600       5     D01
M           L     O     K     Q     J     I     H     P           N
```

```
M       L   O   K   Q   J   I   H   P       N         6.400      5   A10
M       L   O   K   Q   J   I   H   P       N
M       L   O   K   Q   J   I   H   P       N         6.400      5   B12
M       L   O   K   Q   J   I   H   P       N
M       L   O   K   Q   J   I   H   P       N         6.400      5   C07
M       L   O   K   Q   J   I   H   P       N
M       L   O   K   Q   J   I   H   P       N         6.400      5   F04
M       L   O   K   Q   J   I       P       N
M   R   L   O   K   Q   J   I       P       N         6.200      5   C02
M   R   L   O   K   Q   J   I       P       N
M   R   L   O   K   Q   J   I       P       N         6.200      5   B10
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         6.000      5   B03
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         6.000      5   C03
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         6.000      5   A09
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         6.000      5   E10
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         6.000      5   C01
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         6.000      5   B09
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         5.800      5   A02
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         5.800      5   F02
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         5.800      5   A03
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         5.800      5   F06
M   R   L   O   K   Q   J           P       N
M   R   L   O   K   Q   J           P       N         5.800      5   C05
M   R   L   O   K   Q               P       N
M   R   L   O   K   Q               P       N         5.600      5   C04
M   R   L   O   K   Q               P       N
M   R   L   O   K   Q               P       N         5.600      5   F03
M   R   L   O   K   Q               P       N
M   R   L   O   K   Q               P       N         5.600      5   B08
M   R   L   O   K   Q               P       N
M   R   L   O   K   Q               P       N         5.600      5   B07
M   R   L   O   K   Q               P       N
M   R   L   O   K   Q               P       N         5.600      5   E12
M   R   L   O   K   Q               P       N
M   R   L   O   K   Q               P       N         5.600      5   B02
M   R   L   O       Q               P       N
M   R   L   O       Q               P       N         5.400      5   B11
M   R   L   O       Q               P       N
M   R   L   O       Q               P       N         5.400      5   C11
M   R   L   O       Q               P       N
M   R   L   O       Q               P       N         5.400      5   A06
M   R       O       Q               P       N
M   R       O       Q               P       N         5.200      5   F05
    R       O       Q               P       N
    R       O       Q               P       N         5.000      5   B04
    R       O       Q               P
    R       O       Q               P                 4.600      5   A08
```

```
     R         O         Q                   P
     R         O         Q                   P                    4.600      5    B06
     R                   Q                   P
     R                   Q                   P                    4.400      5    A01
     R                   Q                   P
     R                   Q                   P                    4.400      5    A07
     R                   Q                   P
     R                   Q                   P                    4.400      5    A04
     R                   Q                   P
     R                   Q                   P                    4.400      5    F12
     R                   Q
     R                   Q                                        4.000      5    F11
     R
     R                                                            3.600      5    A05

************************************************************************************

                                        Wet

                                 The GLM Procedure

                              Class Level Information

Class       Levels  Values

plot            72  A01 A02 A03 A04 A05 A06 A07 A08 A09 A10 A11 A12 B01 B02 B03 B04
                    B05 B06 B07 B08 B09 B10 B11 B12 C01 C02 C03 C04 C05 C06 C07 C08
                    C09 C10 C11 C12 D01 D02 D03 D04 D05 D06 D07 D08 D09 D10 D11 D12
                    E01 E02 E03 E04 E05 E06 E07 E08 E09 E10 E11 E12 F01 F02 F03 F04
                    F05 F06 F07 F08 F09 F10 F11 F12


                       Number of Observations Read         360
                       Number of Observations Used         360

************************************************************************************
```

```
                                         Wet

                                 The GLM Procedure

Dependent Variable: wet

                                         Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                       71     2421.600000       34.107042      18.19    <.0001

 Error                      288      540.000000        1.875000

 Corrected Total            359     2961.600000


                R-Square     Coeff Var      Root MSE      wet Mean

                0.817666      12.11776      1.369306      11.30000


 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 plot                        71     2421.600000       34.107042      18.19    <.0001

**************************************************************************************

                                       Wet

                                 The GLM Procedure

                          Duncan's Multiple Range Test for wet

       NOTE: This test controls the Type I comparisonwise error rate, not the
                               experimentwise error rate.


                           Alpha                          0.05
                           Error Degrees of Freedom        288
                           Error Mean Square             1.875


  Number of Means     2     3     4     5     6     7     8     9    10    11    12
  Critical Range  1.705 1.794 1.854 1.899 1.933 1.961 1.985 2.005 2.022 2.037 2.051

  Number of Means    13    14    15    16    17    18    19    20    21    22    23
  Critical Range  2.063 2.074 2.084 2.093 2.101 2.109 2.116 2.122 2.129 2.134 2.140

  Number of Means    24    25    26    27    28    29    30    31    32    33    34
  Critical Range  2.145 2.149 2.154 2.158 2.162 2.166 2.169 2.173 2.176 2.179 2.182

  Number of Means    35    36    37    38    39    40    41    42    43    44    45
  Critical Range  2.185 2.187 2.190 2.192 2.194 2.197 2.199 2.201 2.203 2.205 2.206

  Number of Means    46    47    48    49    50    51    52    53    54    55    56
  Critical Range  2.208 2.210 2.211 2.213 2.215 2.216 2.217 2.219 2.220 2.221 2.222
```

```
Number of Means    57    58    59    60    61    62    63    64    65    66    67
Critical Range  2.224 2.225 2.226 2.227 2.228 2.229 2.230 2.231 2.231 2.232 2.233

        Number of Means    68         69         70         71         72
        Critical Range  2.234      2.235      2.235      2.236      2.237


           Means with the same letter are not significantly different.


                  Duncan Grouping                     Mean      N    plot

                            A                      27.8000      5    A11

                            B                      20.8000      5    A12

                            C                      15.8000      5    F01
                            C
                            C                      14.8000      5    E01

                            D                      12.8000      5    D11
                            D
             E              D                      12.6000      5    C08
             E              D
             E              D         F            12.4000      5    A10
             E              D         F
             E              D         F            12.4000      5    F12
             E              D         F
             E              D         F            12.2000      5    A01
             E              D         F
             E              D         F            12.2000      5    D08
             E              D         F
             E              D         F            12.2000      5    C11
             E              D         F
             E              D         F            12.2000      5    D12
             E              D         F
             E              D         F            12.2000      5    B05
             E              D         F
             E    G         D         F            12.0000      5    A02
             E    G         D         F
             E    G         D         F            12.0000      5    C07
             E    G         D         F
             E    G         D         F            12.0000      5    E02
             E    G         D         F
             E    G         D         F            12.0000      5    D01
             E    G         D         F
             E    G         D         F            12.0000      5    C03
             E    G         D         F
        H    E    G         D         F            11.8000      5    E08
        H    E    G         D         F
        H    E    G         D         F    I       11.6000      5    B06
        H    E    G         D         F    I
        H    E    G         D         F    I       11.6000      5    B01
        H    E    G         D         F    I
        H    E    G         D         F    I       11.6000      5    C12
        H    E    G         D         F    I
        H    E    G         D         F    I       11.6000      5    B11
```

```
H   E   G       D       F   I
H   E   G       D   J   F   I       11.4000      5   A08
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.4000      5   A09
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.4000      5   D09
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.2000      5   D02
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.2000      5   B02
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.2000      5   F07
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.2000      5   C01
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.2000      5   B09
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.0000      5   E12
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.0000      5   B12
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.0000      5   E07
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.0000      5   D07
H   E   G       D   J   F   I
H   E   G       D   J   F   I       11.0000      5   C09
H   E   G       D   J   F   I
H   E   G   K   D   J   F   I       10.8000      5   E10
H   E   G   K   D   J   F   I
H   E   G   K   D   J   F   I       10.8000      5   D06
H   E   G   K   D   J   F   I
H   E   G   K   D   J   F   I       10.8000      5   E03
H   E   G   K   D   J   F   I
H   E   G   K   D   J   F   I       10.8000      5   E11
H   E   G   K   D   J   F   I
H   E   G   K   D   J   F   I       10.8000      5   F09
H   E   G   K       J   F   I
H   E   G   K   L   J   F   I       10.6000      5   A06
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.6000      5   F02
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.6000      5   B08
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.6000      5   F08
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.4000      5   D10
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.4000      5   D03
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.4000      5   C10
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.4000      5   E09
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.4000      5   E05
H   E   G   K   L   J   F   I
H   E   G   K   L   J   F   I       10.4000      5   C05
H       G   K   L   J   F   I
```

```
H          G    K    L    J    F    I       10.2000      5    C06
H          G    K    L    J    F    I
H          G    K    L    J    F    I       10.2000      5    B04
H          G    K    L    J    F    I
H          G    K    L    J    F    I       10.2000      5    C02
H          G    K    L    J    F    I
H          G    K    L    J    F    I       10.2000      5    A07
H          G    K    L    J         I
H          G    K    L    J         I        9.8000      5    A04
H          G    K    L    J         I
H          G    K    L    J         I        9.8000      5    B03
H          G    K    L    J         I
H          G    K    L    J         I        9.8000      5    F10
H          G    K    L    J         I
H          G    K    L    J         I        9.8000      5    A03
H          G    K    L    J         I
H          G    K    L    J         I        9.8000      5    C04
H          G    K    L    J         I
H          G    K    L    J         I        9.8000      5    F05
H               K    L    J         I
H               K    L    J         I        9.6000      5    E06
H               K    L    J         I
H               K    L    J         I        9.6000      5    B07
H               K    L    J         I
H               K    L    J         I        9.6000      5    D05
                K    L    J         I
                K    L    J         I        9.4000      5    D04
                K    L    J         I
                K    L    J         I        9.4000      5    F11
                K    L    J
                K    L    J                  9.2000      5    F06
                K    L    J
                K    L    J                  9.2000      5    F04
                K    L    J
                K    L    J                  9.2000      5    A05
                K    L
                K    L                       8.8000      5    B10
                K    L
                K    L                       8.8000      5    E04
                     L
                     L                       8.6000      5    F03
```

## PLOTS WITH SMS CODES

```
options nodate nonumber center formdlim="*"linesize=85;
data sms;
input plot$ rep$ dry wet;
cards;
/* Data is inputted here */
;
data sms;
set sms;
proc glm data=sms;
title 'Plots with SMS-Dry';
class plot;
model dry = plot /ss3;
means plot/duncan;
run;
data sms;
set sms;
proc glm data=sms;
title 'Plots with SMS-Wet;
class plot;
model wet = plot /ss3;
means plot/duncan;
run;
```

## PLOTS WITH SMS ANALYSIS OUTPUT

```
*************************************************************************************

                              Plots with SMS-Dry

                                  The GLM Procedure

                              Class Level Information

      Class         Levels    Values

      plot              12    A02 B03 B08 B09 C02 C05 D02 E02 F02 F03 F04 F05


                       Number of Observations Read          60
                       Number of Observations Used          60

*************************************************************************************

                              Plots with SMS-Dry

                                  The GLM Procedure

Dependent Variable: dry

                                         Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                       11      11.3833333       1.0348485       0.43    0.9350

 Error                       48     115.6000000       2.4083333

 Corrected Total             59     126.9833333


                 R-Square     Coeff Var      Root MSE      dry Mean

                 0.089644      25.93672      1.551881      5.983333


 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 plot                        11     11.38333333      1.03484848       0.43    0.9350

*************************************************************************************

                              Plots with SMS-Dry

                                  The GLM Procedure

                        Duncan's Multiple Range Test for dry

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.
```

```
                         Alpha                       0.05
                         Error Degrees of Freedom      48
                         Error Mean Square       2.408333


 Number of Means     2     3     4     5     6     7     8     9    10    11    12
 Critical Range  1.973 2.075 2.143 2.191 2.228 2.258 2.282 2.302 2.320 2.334 2.347


           Means with the same letter are not significantly different.


           Duncan Grouping          Mean      N    plot

                         A        6.8000      5    D02
                         A
                         A        6.6000      5    E02
                         A
                         A        6.4000      5    F04
                         A
                         A        6.2000      5    C02
                         A
                         A        6.0000      5    B03
                         A
                         A        6.0000      5    B09
                         A
                         A        5.8000      5    A02
                         A
                         A        5.8000      5    C05
                         A
                         A        5.8000      5    F02
                         A
                         A        5.6000      5    F03
                         A
                         A        5.6000      5    B08
                         A
                         A        5.2000      5    F05
************************************************************************************

                                 Plots with SMS-Wet

                                The GLM Procedure

                              Class Level Information

     Class         Levels    Values

     plot              12    A02 B03 B08 B09 C02 C05 D02 E02 F02 F03 F04 F05


                       Number of Observations Read          60
                       Number of Observations Used          60

************************************************************************************
```

```
                              Plots with SMS-Wet

                             The GLM Procedure

Dependent Variable: wet

                                        Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                       11      59.3333333       5.3939394       5.22    <.0001

 Error                       48      49.6000000       1.0333333

 Corrected Total             59     108.9333333

                R-Square     Coeff Var      Root MSE      wet Mean

                0.544676      9.712070      1.016530      10.46667

 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 plot                        11     59.33333333      5.39393939       5.22    <.0001

*************************************************************************************

                              Plots with SMS-Wet

                             The GLM Procedure

                     Duncan's Multiple Range Test for wet

       NOTE: This test controls the Type I comparisonwise error rate, not the
                           experimentwise error rate.


                         Alpha                        0.05
                         Error Degrees of Freedom       48
                         Error Mean Square        1.033333


  Number of Means     2     3     4     5     6     7     8     9    10    11    12
  Critical Range  1.293 1.360 1.403 1.435 1.460 1.479 1.495 1.508 1.519 1.529 1.537


            Means with the same letter are not significantly different.


                 Duncan Grouping          Mean      N    plot

                          A            12.0000      5    A02
                          A
                          A            12.0000      5    E02
                          A
```

```
                    B    A          11.2000      5    D02
                    B    A
                    B    A          11.2000      5    B09
                    B    A
                    B    A    C     10.6000      5    F02
                    B    A    C
                    B    A    C     10.6000      5    B08
                    B         C
                    B         C     10.4000      5    C05
                    B         C
                    B         C     10.2000      5    C02
                    B         C
                    B    D    C      9.8000      5    B03
                    B    D    C
                    B    D    C      9.8000      5    F05
                         D    C
                         D    C      9.2000      5    F04
                         D
                         D           8.6000      5    F03

***************************************************************************************
```

## CUMULATIVE IRRIGATION DEPTH, YEAR 2004

```
options nodate nonumber center formdlim="*"linesize=85;
data sms;
input tmt$ day$ brand$ type$ based$ timeb$ mm;
cards;
/* Data is inputted here */
;
data sms2;
set sms(where=(type = 'sms'));
proc glm data=sms2;
title 'TOTAL Cumulative mm (21 July 2004 – 14 Dec 2004)';
class brand day;
model mm = day brand day(brand) /ss3;
test h=brand e=day(brand);
means day/duncan;
means brand/duncan;
means brand/duncan e=day(brand);
run;
proc glm data=sms2;
title 'Comparison of Interaction';
class brand day;
model mm = brand*day /ss3;
means brand*day/duncan;
run;
data sms3;
set sms(where=(day = '1'));
proc glm data=sms3;
title 'Cumulative mm-- Once per Week';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms3;
set sms(where=(day = '2'));
proc glm data=sms3;
title 'Cumulative mm-- Twice per Week';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms3;
set sms(where=(day = '7'));
proc glm data=sms3;
title 'Cumulative mm-- Everyday';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms;
set sms;
proc glm data=sms;
title 'Comparison of Time-based treatments';
class timeb;
model mm = timeb /ss3;
```

```
means timeb/duncan;
run;
proc glm data=sms;
title 'Comparison of Sensor Type -- By Individual Treatment (SMS, WRS,
WORS, DWRS)';
class tmt;
model mm = tmt /ss3;
means tmt/duncan;
run;
```

```
*************************************************************************************

                  TOTAL Cumulative mm (21 July 2004 - 14 Dec 2004)

                                  The GLM Procedure

                              Class Level Information

                        Class          Levels    Values

                        brand               4    ac im rb ww

                        day                 3    1 2 7


                       Number of Observations Read          48
                       Number of Observations Used          48

*************************************************************************************

                  TOTAL Cumulative mm (21 July 2004 - 14 Dec 2004)

                                  The GLM Procedure

Dependent Variable: mm

                                            Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                       11      950553.2500      86413.9318     201.04    <.0001

 Error                       36       15474.0000        429.8333

 Corrected Total             47      966027.2500


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.983982      10.07039      20.73242      205.8750
```

```
Source                      DF     Type III SS     Mean Square    F Value    Pr > F

day                          2       8419.6250       4209.8125       9.79    0.0004
brand                        3     784008.7500     261336.2500     607.99    <.0001
day(brand)                   6     158124.8750      26354.1458      61.31    <.0001


     Tests of Hypotheses Using the Type III MS for day(brand) as an Error Term

Source                      DF     Type III SS     Mean Square    F Value    Pr > F

brand                        3     784008.7500     261336.2500       9.92    0.0097
```

```
*************************************************************************************

                 TOTAL Cumulative mm (21 July 2004 - 14 Dec 2004)

                                The GLM Procedure

                        Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                            experimentwise error rate.


                         Alpha                        0.05
                         Error Degrees of Freedom       36
                         Error Mean Square        429.8333


                       Number of Means          2          3
                       Critical Range       14.87      15.63


            Means with the same letter are not significantly different.


             Duncan Grouping         Mean      N    day

                          A       218.438     16    7
                          A
                          A       211.625     16    2

                          B       187.563     16    1

*************************************************************************************

                 TOTAL Cumulative mm (21 July 2004 - 14 Dec 2004)

                                The GLM Procedure

                        Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                            experimentwise error rate.
```

```
                  Alpha                          0.05
                  Error Degrees of Freedom         36
                  Error Mean Square          429.8333


          Number of Means          2          3          4
          Critical Range       17.17      18.05      18.62


    Means with the same letter are not significantly different.


    Duncan Grouping          Mean      N    brand

                  A       419.667     12    im

                  B       187.917     12    ww

                  C       116.000     12    ac
                  C
                  C        99.917     12    rb
*************************************************************************************
          TOTAL Cumulative mm (21 July 2004 - 14 Dec 2004)

                         The GLM Procedure

                 Duncan's Multiple Range Test for mm

NOTE: This test controls the Type I comparisonwise error rate, not the
                     experimentwise error rate.


                  Alpha                          0.05
                  Error Degrees of Freedom          6
                  Error Mean Square          26354.15


          Number of Means          2          3          4
          Critical Range       162.2      168.1      171.0


    Means with the same letter are not significantly different.


    Duncan Grouping          Mean      N    brand

                  A        419.67     12    im

                  B        187.92     12    ww
                  B
                  B        116.00     12    ac
                  B
                  B         99.92     12    rb
```

```
*************************************************************************************

                              Comparison of Interaction

                                  The GLM Procedure

                              Class Level Information

                        Class         Levels    Values

                        brand              4    ac im rb ww

                        day                3    1 2 7


                       Number of Observations Read          48
                       Number of Observations Used          48

*************************************************************************************

                              Comparison of Interaction

                                  The GLM Procedure

Dependent Variable: mm

                                            Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                       11      950553.2500      86413.9318     201.04    <.0001

 Error                       36       15474.0000        429.8333

 Corrected Total             47      966027.2500


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.983982      10.07039      20.73242      205.8750


 Source                      DF      Type III SS     Mean Square    F Value    Pr > F

 brand*day                   11      950553.2500      86413.9318     201.04    <.0001

*************************************************************************************

                              Comparison of Interaction

                                  The GLM Procedure

            Level of     Level of            --------------mm-------------
            brand        day           N            Mean          Std Dev

            ac           1             4       95.250000        2.0615528
            ac           2             4      196.000000        8.7939373
            ac           7             4       56.750000        2.6299556
```

```
            im          1           4       318.000000       23.1084400
            im          2           4       470.000000       12.8322510
            im          7           4       471.000000       62.4980000
            rb          1           4       127.750000       12.3659479
            rb          2           4        86.750000        6.0759087
            rb          7           4        85.250000        6.6520673
            ww          1           4       209.250000        8.9953692
            ww          2           4        93.750000        7.8049130
            ww          7           4       260.750000        9.4295634

*************************************************************************************

                            Cumulative mm-- Once per Week

                                  The GLM Procedure

                               Class Level Information

                          Class         Levels    Values

                          brand              4    ac im rb ww


                         Number of Observations Read          16
                         Number of Observations Used          16

*************************************************************************************

                            Cumulative mm-- Once per Week

                                  The GLM Procedure

Dependent Variable: mm

                                            Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                        3      118333.6875      39444.5625     204.35    <.0001

 Error                       12        2316.2500        193.0208

 Corrected Total             15      120649.9375


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.980802      7.407234      13.89319      187.5625


 Source                      DF      Type III SS     Mean Square    F Value    Pr > F

 brand                        3      118333.6875      39444.5625     204.35    <.0001
```

```
                    Cumulative mm-- Once per Week

                         The GLM Procedure

                Duncan's Multiple Range Test for mm

     NOTE: This test controls the Type I comparisonwise error rate, not the
                        experimentwise error rate.


                 Alpha                         0.05
                 Error Degrees of Freedom        12
                 Error Mean Square         193.0208


          Number of Means          2          3          4
          Critical Range       21.40      22.40      23.01


        Means with the same letter are not significantly different.


        Duncan Grouping          Mean      N    brand

                      A       318.000      4    im

                      B       209.250      4    ww

                      C       127.750      4    rb

                      D        95.250      4    ac
**************************************************************************************
                    Cumulative mm-- Twice per Week

                         The GLM Procedure

                      Class Level Information

                   Class         Levels    Values

                   brand              4    ac im rb ww


                Number of Observations Read          16
                Number of Observations Used          16
**************************************************************************************
                    Cumulative mm-- Twice per Week

                         The GLM Procedure

Dependent Variable: mm
```

```
                                      Sum of
Source                      DF       Squares     Mean Square    F Value    Pr > F

Model                        3   385960.2500     128653.4167    1514.31    <.0001

Error                       12     1019.5000         84.9583

Corrected Total             15   386979.7500


                R-Square     Coeff Var      Root MSE       mm Mean

                0.997365      4.355480      9.217284      211.6250


Source                      DF   Type III SS     Mean Square    F Value    Pr > F

brand                        3   385960.2500     128653.4167    1514.31    <.0001

*************************************************************************************

                          Cumulative mm-- Twice per Week

                                 The GLM Procedure

                        Duncan's Multiple Range Test for mm

      NOTE: This test controls the Type I comparisonwise error rate, not the
                              experimentwise error rate.


                          Alpha                        0.05
                          Error Degrees of Freedom       12
                          Error Mean Square        84.95833


                  Number of Means          2          3          4
                  Critical Range       14.20      14.86      15.27


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    brand

                           A       470.000      4    im

                           B       196.000      4    ac

                           C        93.750      4    ww
                           C
                           C        86.750      4    rb
```

```
                          Cumulative mm-- Everyday

                             The GLM Procedure

                          Class Level Information

                      Class         Levels    Values

                      brand              4    ac im rb ww


                     Number of Observations Read          16
                     Number of Observations Used          16

*************************************************************************************

                          Cumulative mm-- Everyday

                             The GLM Procedure

Dependent Variable: mm

                                        Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                        3     437839.6875     145946.5625     144.28    <.0001

 Error                       12      12138.2500       1011.5208

 Corrected Total             15     449977.9375


                R-Square     Coeff Var      Root MSE       mm Mean

                0.973025      14.55996      31.80442      218.4375


 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 brand                        3     437839.6875     145946.5625     144.28    <.0001

*************************************************************************************

                          Cumulative mm-- Everyday

                             The GLM Procedure

                     Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                         experimentwise error rate.


                        Alpha                         0.05
                        Error Degrees of Freedom        12
                        Error Mean Square         1011.521
```

```
                  Number of Means           2          3          4
                  Critical Range        49.00      51.29      52.68


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    brand

                            A       471.00      4    im

                            B       260.75      4    ww

                            C        85.25      4    rb
                            C
                            C        56.75      4    ac

**************************************************************************************

                         Comparison of Time-based treatments

                                  The GLM Procedure

                              Class Level Information

                       Class         Levels    Values

                       timeb              3    dwrs wors wrs


                       Number of Observations Read          60
                       Number of Observations Used          12

**************************************************************************************

                         Comparison of Time-based treatments

                                  The GLM Procedure

Dependent Variable: mm

                                          Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                        2      299253.5000     149626.7500     251.96    <.0001

 Error                        9        5344.7500        593.8611

 Corrected Total             11      304598.2500


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.982453      4.915636      24.36927      495.7500
```

```
 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 timeb                        2     299253.5000     149626.7500     251.96    <.0001

************************************************************************************

                         Comparison of Time-based treatments

                                  The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.


                          Alpha                       0.05
                          Error Degrees of Freedom       9
                          Error Mean Square       593.8611


                        Number of Means          2          3
                        Critical Range       38.98      40.69


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    timeb

                           A        696.00      4    wors

                           B        481.25      4    wrs

                           C        310.00      4    dwrs

************************************************************************************

     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                  The GLM Procedure

                               Class Level Information

Class       Levels  Values

tmt             15  1ac 1im 1rb 1ww 2ac 2dwrs 2im 2rb 2wors 2wrs 2ww 7ac 7im 7rb 7ww


                       Number of Observations Read          60
                       Number of Observations Used          60

************************************************************************************

     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)
```

```
                                The GLM Procedure

Dependent Variable: mm

                                         Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                       14     2056470.900      146890.779     317.51    <.0001

 Error                       45       20818.750         462.639

 Corrected Total             59     2077289.650


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.989978      8.151996      21.50904      263.8500


 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 tmt                         14     2056470.900      146890.779     317.51    <.0001

*************************************************************************************

     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.


                          Alpha                        0.05
                          Error Degrees of Freedom       45
                          Error Mean Square        462.6389


Number of Means         2          3          4          5          6          7          8
Critical Range      30.63      32.21      33.25      34.00      34.58      35.03      35.41

Number of Means         9         10         11         12         13         14         15
Critical Range      35.72      35.98      36.20      36.40      36.56      36.71      36.84


             Means with the same letter are not significantly different.


               Duncan Grouping          Mean      N    tmt

                             A        696.00      4    2wors

                             B        481.25      4    2wrs
                             B
                             B        471.00      4    7im
```

```
     B
     B        470.00      4    2im

     C        318.00      4    1im
     C
     C        310.00      4    2dwrs

     D        260.75      4    7ww

     E        209.25      4    1ww
     E
     E        196.00      4    2ac

     F        127.75      4    1rb

     G         95.25      4    1ac
     G
     G         93.75      4    2ww
     G
H    G         86.75      4    2rb
H    G
H    G         85.25      4    7rb
H
H              56.75      4    7ac
```

## CUMULATIVE IRRIGATION DEPTH, YEAR 2005

```
options nodate nonumber center formdlim="*"linesize=85;
data sms;
input tmt$ day$ brand$ type$ based$ timeb$ mm;
cards;
/* Data is inputted here */
;
data sms2;
set sms(where=(type = 'sms'));
proc glm data=sms2;
title 'Cumulative mm (March 25 - Aug 31/2005)';
class brand day;
model mm = day brand day(brand) /ss3;
test h=brand e=day(brand);
means day/duncan;
means brand/duncan;
means brand/duncan e=day(brand);
run;
proc glm data=sms2;
title 'Comparison of Interaction';
class brand day;
model mm = brand*day /ss3;
means brand*day/duncan;
run;
data sms3;
set sms(where=(day = '1'));
proc glm data=sms3;
title 'Cumulative mm-- Once per Week';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms3;
set sms(where=(day = '2'));
proc glm data=sms3;
title 'Cumulative mm-- Twice per Week';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms3;
set sms(where=(day = '7'));
proc glm data=sms3;
title 'Cumulative mm-- Everyday';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms;
set sms;
proc glm data=sms;
title 'Comparison of Time-based treatments';
class timeb;
model mm = timeb /ss3;
means timeb/duncan;
```

```
run;
proc glm data=sms;
title 'Comparison of Sensor Type -- By Individual Treatment (SMS, WRS,
WORS, DWRS)';
class tmt;
model mm = tmt /ss3;
means tmt/duncan;
run;
```

```
**************************************************************************************

                       Cumulative mm (March 25 - Aug 31/2005)

                                  The GLM Procedure

                              Class Level Information

                        Class          Levels    Values

                        brand               4    ac im rb ww

                        day                 3    1 2 7


                       Number of Observations Read          48
                       Number of Observations Used          48

**************************************************************************************

                       Cumulative mm (March 25 - Aug 31/2005)

                                  The GLM Procedure

Dependent Variable: mm

                                              Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                       11      1296396.167      117854.197     620.33    <.0001

 Error                       36         6839.500         189.986

 Corrected Total             47      1303235.667


                  R-Square     Coeff Var      Root MSE       mm Mean

                  0.994752      6.443418      13.78354      213.9167
```

```
Source                      DF     Type III SS     Mean Square    F Value    Pr > F

day                          2     128785.0417      64392.5208     338.93    <.0001
brand                        3     923152.6667     307717.5556    1619.68    <.0001
day(brand)                   6     244458.4583      40743.0764     214.45    <.0001


     Tests of Hypotheses Using the Type III MS for day(brand) as an Error Term

Source                      DF     Type III SS     Mean Square    F Value    Pr > F

brand                        3     923152.6667     307717.5556       7.55    0.0184

*************************************************************************************

                        Cumulative mm (March 25 - Aug 31/2005)

                                 The GLM Procedure

                          Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                              experimentwise error rate.


                          Alpha                       0.05
                          Error Degrees of Freedom      36
                          Error Mean Square       189.9861


                        Number of Means          2          3
                        Critical Range        9.88      10.39


             Means with the same letter are not significantly different.


              Duncan Grouping          Mean      N    day

                            A       266.125     16    2

                            B       232.313     16    1

                            C       143.313     16    7

*************************************************************************************

                        Cumulative mm (March 25 - Aug 31/2005)

                                 The GLM Procedure

                          Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                              experimentwise error rate.
```

```
                Alpha                       0.05
                Error Degrees of Freedom      36
                Error Mean Square       189.9861


        Number of Means          2          3          4
        Critical Range       11.41      12.00      12.38


     Means with the same letter are not significantly different.


     Duncan Grouping          Mean      N    brand

                   A       451.417     12    im

                   B       163.917     12    ww

                   C       135.083     12    ac

                   D       105.250     12    rb

**************************************************************************************

                   Cumulative mm (March 25 - Aug 31/2005)

                             The GLM Procedure

                     Duncan's Multiple Range Test for mm

  NOTE: This test controls the Type I comparisonwise error rate, not the
                           experimentwise error rate.


                Alpha                       0.05
                Error Degrees of Freedom       6
                Error Mean Square       40743.08


        Number of Means          2          3          4
        Critical Range       201.6      209.0      212.6


     Means with the same letter are not significantly different.


     Duncan Grouping          Mean      N    brand

                   A        451.42     12    im

                   B        163.92     12    ww
                   B
                   B        135.08     12    ac
                   B
                   B        105.25     12    rb

**************************************************************************************
```

```
                       Comparison of Interaction

                          The GLM Procedure

                       Class Level Information

                 Class         Levels    Values

                 brand              4    ac im rb ww

                 day                3    1 2 7


                Number of Observations Read          48
                Number of Observations Used          48

*************************************************************************************

                       Comparison of Interaction

                          The GLM Procedure

Dependent Variable: mm

                                           Sum of
 Source                      DF           Squares     Mean Square    F Value    Pr > F

 Model                       11       1296396.167      117854.197     620.33    <.0001

 Error                       36          6839.500         189.986

 Corrected Total             47       1303235.667


                R-Square     Coeff Var      Root MSE       mm Mean

                0.994752      6.443418      13.78354      213.9167


 Source                      DF       Type III SS     Mean Square    F Value    Pr > F

 brand*day                   11       1296396.167      117854.197     620.33    <.0001

*************************************************************************************

                       Comparison of Interaction

                          The GLM Procedure

            Level of     Level of           --------------mm-------------
            brand        day          N             Mean          Std Dev

            ac           1            4       188.000000       13.5892114
            ac           2            4       152.000000       14.1185457
            ac           7            4        65.250000        2.9860788
            im           1            4       475.250000       25.5000000
```

```
            im           2           4       634.750000       29.8817112
            im           7           4       244.250000        5.0579970
            rb           1           4       152.500000       10.5356538
            rb           2           4       101.250000        1.2583057
            rb           7           4        62.000000        3.5590261
            ww           1           4       113.500000        9.3273791
            ww           2           4       176.500000        7.1414284
            ww           7           4       201.750000        7.4105780

*************************************************************************************

                         Cumulative mm-- Once per Week

                               The GLM Procedure

                            Class Level Information

                        Class         Levels    Values

                        brand              4    ac im rb ww


                       Number of Observations Read          16
                       Number of Observations Used          16

*************************************************************************************

                         Cumulative mm-- Once per Week

                               The GLM Procedure

Dependent Variable: mm

                                        Sum of
 Source                      DF        Squares     Mean Square    F Value    Pr > F

 Model                        3    325874.6875     108624.8958     420.65    <.0001

 Error                       12      3098.7500        258.2292

 Corrected Total             15    328973.4375


                R-Square     Coeff Var      Root MSE       mm Mean

                0.990581      6.917196      16.06951      232.3125


 Source                      DF    Type III SS     Mean Square    F Value    Pr > F

 brand                        3    325874.6875     108624.8958     420.65    <.0001
```

```
                            Cumulative mm-- Once per Week

                                  The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.


                          Alpha                        0.05
                          Error Degrees of Freedom       12
                          Error Mean Square        258.2292


                  Number of Means          2          3          4
                  Critical Range       24.76      25.91      26.61


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    brand

                           A        475.25      4    im

                           B        188.00      4    ac

                           C        152.50      4    rb

                           D        113.50      4    ww
*************************************************************************************
                           Cumulative mm-- Twice per Week

                                  The GLM Procedure

                              Class Level Information

                        Class         Levels    Values

                        brand              4    ac im rb ww


                       Number of Observations Read          16
                       Number of Observations Used          16
■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■■

                           Cumulative mm-- Twice per Week

                                  The GLM Procedure

Dependent Variable: mm

                                         Sum of
```

```
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        3     736501.2500     245500.4167     857.77    <.0001

Error                       12       3434.5000        286.2083

Corrected Total             15     739935.7500


                R-Square     Coeff Var      Root MSE       mm Mean

                0.995358      6.357048      16.91769      266.1250


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

brand                        3     736501.2500     245500.4167     857.77    <.0001

*************************************************************************************

                          Cumulative mm-- Twice per Week

                                 The GLM Procedure

                        Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                              experimentwise error rate.


                         Alpha                        0.05
                         Error Degrees of Freedom       12
                         Error Mean Square        286.2083


                 Number of Means          2          3          4
                 Critical Range       26.06      27.28      28.02


            Means with the same letter are not significantly different.


            Duncan Grouping          Mean      N    brand

                          A        634.75      4    im

                          B        176.50      4    ww
                          B
                          B        152.00      4    ac

                          C        101.25      4    rb
```

```
                          Cumulative mm-- Everyday

                            The GLM Procedure

                          Class Level Information

                       Class         Levels    Values

                       brand              4    ac im rb ww


                      Number of Observations Read          16
                      Number of Observations Used          16

**********************************************************************************

                          Cumulative mm-- Everyday

                            The GLM Procedure

Dependent Variable: mm

                                        Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                        3     105235.1875      35078.3958    1374.50    <.0001

 Error                       12        306.2500         25.5208

 Corrected Total             15     105541.4375

                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.997098      3.525034      5.051815      143.3125

 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 brand                        3     105235.1875      35078.3958    1374.50    <.0001

**********************************************************************************

                          Cumulative mm-- Everyday

                            The GLM Procedure

                      Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                          experimentwise error rate.


                         Alpha                        0.05
                         Error Degrees of Freedom       12
                         Error Mean Square        25.52083
```

```
                  Number of Means           2           3           4
                  Critical Range        7.783       8.147       8.367


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    brand

                           A       244.250      4    im

                           B       201.750      4    ww

                           C        65.250      4    ac
                           C
                           C        62.000      4    rb

*************************************************************************************

                         Comparison of Time-based treatments

                                  The GLM Procedure

                              Class Level Information

                       Class         Levels    Values

                       timeb              3    dwrs wors wrs


                       Number of Observations Read          60
                       Number of Observations Used          12

*************************************************************************************

                         Comparison of Time-based treatments

                                  The GLM Procedure

Dependent Variable: mm

                                         Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                        2     517260.6667     258630.3333    1654.35    <.0001

 Error                        9       1407.0000        156.3333

 Corrected Total             11     518667.6667


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.997287      2.280936      12.50333      548.1667
```

```
 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 timeb                        2     517260.6667     258630.3333    1654.35    <.0001

*************************************************************************************

                         Comparison of Time-based treatments

                                  The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.


                          Alpha                        0.05
                          Error Degrees of Freedom        9
                          Error Mean Square        156.3333


                        Number of Means          2          3
                        Critical Range       20.00      20.88


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    timeb

                           A       818.000      4    wors

                           B       513.500      4    wrs

                           C       313.000      4    dwrs

*************************************************************************************

     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                  The GLM Procedure

                               Class Level Information

Class       Levels  Values

tmt             15  1ac 1im 1rb 1ww 2ac 2dwrs 2im 2rb 2wors 2wrs 2ww 7ac 7im 7rb 7ww


                       Number of Observations Read          60
                       Number of Observations Used          60

*************************************************************************************

     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                  The GLM Procedure
```

```
Dependent Variable: mm

                                            Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                       14      2886198.233      206157.017    1124.97    <.0001

 Error                       45         8246.500         183.256

 Corrected Total             59      2894444.733


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.997151      4.821510      13.53719      280.7667


 Source                      DF      Type III SS     Mean Square    F Value    Pr > F

 tmt                         14      2886198.233      206157.017    1124.97    <.0001

************************************************************************************

     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                 The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.


                          Alpha                         0.05
                          Error Degrees of Freedom        45
                          Error Mean Square         183.2556


Number of Means         2          3          4          5          6          7          8
Critical Range      19.28      20.27      20.93      21.40      21.76      22.05      22.28

Number of Means         9         10         11         12         13         14         15
Critical Range      22.48      22.64      22.79      22.91      23.01      23.11      23.19


             Means with the same letter are not significantly different.


               Duncan Grouping          Mean      N    tmt

                            A        818.000      4    2wors

                            B        634.750      4    2im

                            C        513.500      4    2wrs
```

```
     D        475.250       4    1im

     E        313.000       4    2dwrs

     F        244.250       4    7im

     G        201.750       4    7ww
     G
H    G        188.000       4    1ac
H
H             176.500       4    2ww

     I        152.500       4    1rb
     I
     I        152.000       4    2ac

     J        113.500       4    1ww
     J
     J        101.250       4    2rb

     K         65.250       4    7ac
     K
     K         62.000       4    7rb
```

## CUMULATIVE IRRIGATION DEPTH, YEAR 2004 + 2005

```
options nodate nonumber center formdlim="*"linesize=85;
data sms;
input tmt$ day$ brand$ type$ based$ timeb$ mm;
cards;
/* Data is inputted here */
;
data sms2;
set sms(where=(type = 'sms'));
proc glm data=sms2;
title 'TOTAL Cumulative mm (21 July 2004 - Aug 31/2005)';
class brand day;
model mm = day brand day(brand) /ss3;
test h=brand e=day(brand);
means day/duncan;
means brand/duncan;
means brand/duncan e=day(brand);
run;
proc glm data=sms2;
title 'Comparison of Interaction';
class brand day;
model mm = brand*day /ss3;
means brand*day/duncan;
run;
data sms3;
set sms(where=(day = '1'));
proc glm data=sms3;
title 'Cumulative mm-- Once per Week';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms3;
set sms(where=(day = '2'));
proc glm data=sms3;
title 'Cumulative mm-- Twice per Week';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms3;
set sms(where=(day = '7'));
proc glm data=sms3;
title 'Cumulative mm-- Everyday';
class brand ;
model mm =  brand/ss3;
means brand/duncan;
run;
data sms;
set sms;
proc glm data=sms;
title 'Comparison of Time-based treatments';
class timeb;
```

```
model mm = timeb /ss3;
means timeb/duncan;
run;
proc glm data=sms;
title 'Comparison of Sensor Type -- By Individual Treatment (SMS, WRS,
WORS, DWRS)';
class tmt;
model mm = tmt /ss3;
means tmt/duncan;
run;
```

```
*********************************************************************************

                  TOTAL Cumulative mm (21 July 2004 - Aug 31/2005)

                                The GLM Procedure

                            Class Level Information

                        Class         Levels    Values

                        brand              4    ac im rb ww

                        day                3    1 2 7


                       Number of Observations Read          48
                       Number of Observations Used          48

*********************************************************************************

                  TOTAL Cumulative mm (21 July 2004 - Aug 31/2005)

                                The GLM Procedure

Dependent Variable: mm

                                               Sum of
 Source                       DF          Squares     Mean Square    F Value    Pr > F

 Model                        11      3957976.917      359816.083     574.61    <.0001

 Error                        36        22543.000         626.194

 Corrected Total              47      3980519.917


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.994337      5.961023      25.02388      419.7917


 Source                       DF      Type III SS     Mean Square    F Value    Pr > F

 day                           2       107648.167      53824.083      85.95    <.0001
```

```
brand                        3     3393706.750     1131235.583    1806.52    <.0001
day(brand)                   6      456622.000       76103.667     121.53    <.0001


     Tests of Hypotheses Using the Type III MS for day(brand) as an Error Term

Source                      DF     Type III SS     Mean Square    F Value    Pr > F

brand                        3     3393706.750     1131235.583      14.86    0.0035
```

```
*************************************************************************************

                  TOTAL Cumulative mm (21 July 2004 - Aug 31/2005)

                                The GLM Procedure

                         Duncan's Multiple Range Test for mm

      NOTE: This test controls the Type I comparisonwise error rate, not the
                            experimentwise error rate.


                         Alpha                        0.05
                         Error Degrees of Freedom       36
                         Error Mean Square        626.1944


                       Number of Means          2          3
                       Critical Range       17.94      18.86


             Means with the same letter are not significantly different.


              Duncan Grouping          Mean      N    day

                            A       477.750     16    2

                            B       419.875     16    1

                            C       361.750     16    7

*************************************************************************************

                  TOTAL Cumulative mm (21 July 2004 - Aug 31/2005)

                                The GLM Procedure

                         Duncan's Multiple Range Test for mm

      NOTE: This test controls the Type I comparisonwise error rate, not the
                            experimentwise error rate.


                         Alpha                        0.05
                         Error Degrees of Freedom       36
                         Error Mean Square        626.1944
```

```
                  Number of Means          2          3          4
                  Critical Range       20.72      21.78      22.47


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    brand

                           A        871.08     12    im

                           B        351.83     12    ww

                           C        251.08     12    ac

                           D        205.17     12    rb

*************************************************************************************

                  TOTAL Cumulative mm (21 July 2004 - Aug 31/2005)

                                  The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.


                          Alpha                         0.05
                          Error Degrees of Freedom         6
                          Error Mean Square         76103.67


                  Number of Means          2          3          4
                  Critical Range       275.6      285.6      290.6


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    brand

                           A         871.1     12    im

                           B         351.8     12    ww
                           B
                           B         251.1     12    ac
                           B
                           B         205.2     12    rb

*************************************************************************************

                              Comparison of Interaction
```

```
                              The GLM Procedure

                          Class Level Information

                    Class         Levels    Values

                    brand              4    ac im rb ww

                    day                3    1 2 7


                   Number of Observations Read          48
                   Number of Observations Used          48

*************************************************************************************

                          Comparison of Interaction

                              The GLM Procedure

Dependent Variable: mm

                                         Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                       11     3957976.917      359816.083     574.61    <.0001

 Error                       36       22543.000         626.194

 Corrected Total             47     3980519.917


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.994337      5.961023      25.02388      419.7917


 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 brand*day                   11     3957976.917      359816.083     574.61    <.0001

*************************************************************************************

                          Comparison of Interaction

                              The GLM Procedure

            Level of     Level of          --------------mm-------------
            brand        day          N            Mean          Std Dev

            ac           1            4       283.25000       14.6600364
            ac           2            4       348.00000       17.4547033
            ac           7            4       122.00000        3.8297084
            im           1            4       793.25000       47.0345618
            im           2            4      1104.75000       28.2297125
            im           7            4       715.25000       57.4536045
            rb           1            4       280.25000       16.5201897
```

```
            rb           2           4         188.00000         4.8304589
            rb           7           4         147.25000         8.1802608
            ww           1           4         322.75000        12.4465524
            ww           2           4         270.25000         9.6046864
            ww           7           4         462.50000         7.7244202

************************************************************************************

                        Cumulative mm-- Once per Week

                              The GLM Procedure

                           Class Level Information

                        Class         Levels    Values

                        brand              4    ac im rb ww


                       Number of Observations Read          16
                       Number of Observations Used          16

************************************************************************************

                        Cumulative mm-- Once per Week

                              The GLM Procedure

Dependent Variable: mm

                                        Sum of
 Source                      DF         Squares     Mean Square    F Value    Pr > F

 Model                        3     748014.7500     249338.2500     349.34    <.0001

 Error                       12       8565.0000        713.7500

 Corrected Total             15     756579.7500

                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.988679      6.362870      26.71610      419.8750

 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 brand                        3     748014.7500     249338.2500     349.34    <.0001

************************************************************************************

                        Cumulative mm-- Once per Week

                              The GLM Procedure

                     Duncan's Multiple Range Test for mm
```

```
      NOTE: This test controls the Type I comparisonwise error rate, not the
                                experimentwise error rate.


                           Alpha                       0.05
                           Error Degrees of Freedom      12
                           Error Mean Square         713.75


                   Number of Means          2          3          4
                   Critical Range       41.16      43.08      44.25


              Means with the same letter are not significantly different.


              Duncan Grouping          Mean      N    brand

                            A        793.25      4    im

                            B        322.75      4    ww
                            B
                            B        283.25      4    ac
                            B
                            B        280.25      4    rb

*************************************************************************************

                            Cumulative mm-- Twice per Week

                                   The GLM Procedure

                               Class Level Information

                          Class         Levels    Values

                          brand              4    ac im rb ww


                         Number of Observations Read          16
                         Number of Observations Used          16

*************************************************************************************

                            Cumulative mm-- Twice per Week

                                   The GLM Procedure

Dependent Variable: mm

                                              Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                        3      2147901.500      715967.167    2352.90    <.0001

 Error                       12         3651.500         304.292
```

```
 Corrected Total             15     2151553.000

                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.998303      3.651273      17.44396      477.7500

 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 brand                        3     2147901.500      715967.167    2352.90    <.0001

*************************************************************************************

                           Cumulative mm-- Twice per Week

                                  The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.


                          Alpha                        0.05
                          Error Degrees of Freedom       12
                          Error Mean Square        304.2917


                  Number of Means          2          3          4
                  Critical Range       26.88      28.13      28.89


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    brand

                           A       1104.75      4    im

                           B        348.00      4    ac

                           C        270.25      4    ww

                           D        188.00      4    rb
```

```
                              Cumulative mm-- Everyday

                                 The GLM Procedure

                              Class Level Information

                        Class         Levels    Values

                        brand              4    ac im rb ww


                       Number of Observations Read          16
                       Number of Observations Used          16

************************************************************************************

                              Cumulative mm-- Everyday

                                 The GLM Procedure

Dependent Variable: mm

                                            Sum of
 Source                      DF          Squares     Mean Square    F Value    Pr > F

 Model                        3      954412.5000     318137.5000     369.69    <.0001

 Error                       12       10326.5000        860.5417

 Corrected Total             15      964739.0000


                 R-Square     Coeff Var      Root MSE       mm Mean

                 0.989296      8.109189      29.33499      361.7500


 Source                      DF      Type III SS     Mean Square    F Value    Pr > F

 brand                        3      954412.5000     318137.5000     369.69    <.0001

************************************************************************************

                              Cumulative mm-- Everyday

                                 The GLM Procedure

                         Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                              experimentwise error rate.


                         Alpha                         0.05
                         Error Degrees of Freedom        12
                         Error Mean Square         860.5417
```

```
          Number of Means          2          3          4
          Critical Range       45.20      47.31      48.59


     Means with the same letter are not significantly different.


     Duncan Grouping          Mean      N    brand

                   A        715.25      4    im

                   B        462.50      4    ww

                   C        147.25      4    rb
                   C
                   C        122.00      4    ac

*************************************************************************************

                   Comparison of Time-based treatments

                           The GLM Procedure

                        Class Level Information

                    Class         Levels    Values

                    timeb              3    dwrs wors wrs


                    Number of Observations Read          60
                    Number of Observations Used          12

*************************************************************************************

                   Comparison of Time-based treatments

                           The GLM Procedure

Dependent Variable: mm

                                        Sum of
 Source                      DF        Squares     Mean Square    F Value    Pr > F

 Model                        2    1602266.167     801133.083    1127.52    <.0001

 Error                        9       6394.750        710.528

 Corrected Total             11    1608660.917

                R-Square     Coeff Var      Root MSE       mm Mean

                0.996025      2.553434      26.65573      1043.917
```

```
 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 timeb                        2     1602266.167      801133.083    1127.52    <.0001

************************************************************************************

                        Comparison of Time-based treatments

                                 The GLM Procedure

                        Duncan's Multiple Range Test for mm

       NOTE: This test controls the Type I comparisonwise error rate, not the
                            experimentwise error rate.


                         Alpha                         0.05
                         Error Degrees of Freedom         9
                         Error Mean Square         710.5278


                       Number of Means          2          3
                       Critical Range       42.64      44.50


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    timeb

                           A       1514.00      4    wors

                           B        994.75      4    wrs

                           C        623.00      4    dwrs

************************************************************************************

     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                 The GLM Procedure

                              Class Level Information

Class       Levels  Values

tmt             15  1ac 1im 1rb 1ww 2ac 2dwrs 2im 2rb 2wors 2wrs 2ww 7ac 7im 7rb 7ww


                      Number of Observations Read          60
                      Number of Observations Used          60
```

```
     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                 The GLM Procedure

Dependent Variable: mm

                                        Sum of
 Source                      DF        Squares     Mean Square    F Value    Pr > F

 Model                       14     9299750.433      664267.888    1032.98    <.0001

 Error                       45       28937.750         643.061

 Corrected Total             59     9328688.183


                R-Square     Coeff Var      Root MSE       mm Mean

                0.996898      4.656238      25.35865      544.6167


 Source                      DF     Type III SS     Mean Square    F Value    Pr > F

 tmt                         14     9299750.433      664267.888    1032.98    <.0001
*************************************************************************************
     Comparison of Sensor Type -- By Individual Treatment (SMS, WRS, WORS, DWRS)

                                 The GLM Procedure

                         Duncan's Multiple Range Test for mm

      NOTE: This test controls the Type I comparisonwise error rate, not the
                               experimentwise error rate.


                         Alpha                        0.05
                         Error Degrees of Freedom       45
                         Error Mean Square        643.0611


Number of Means         2         3         4         5         6         7         8
Critical Range      36.12     37.98     39.20     40.09     40.77     41.30     41.74

Number of Means         9        10        11        12        13        14        15
Critical Range      42.11     42.42     42.68     42.91     43.11     43.28     43.44


             Means with the same letter are not significantly different.


             Duncan Grouping          Mean      N    tmt

                          A       1514.00      4    2wors
```

```
B       1104.75       4   2im

C        994.75       4   2wrs

D        793.25       4   1im

E        715.25       4   7im

F        623.00       4   2dwrs

G        462.50       4   7ww

H        348.00       4   2ac
H
H        322.75       4   1ww

I        283.25       4   1ac
I
I        280.25       4   1rb
I
I        270.25       4   2ww

J        188.00       4   2rb

K        147.25       4   7rb
K
K        122.00       4   7ac
```

# LIST OF REFERENCES

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

ASAE (American Society of Agricultural Engineers). 2000. Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles. American Society of Agricultural Engineers Standards, ANSI/ASAE S436.1, 48th ed. St. Joseph, MI.

Augustin, B.J. 2000. Water requirements of Florida turfgrasses. BUL200, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. Available at: http://edis.ifas.ufl.edu/EP024. Accessed 7 January 2006.

Augustin, B.J. and G.H. Snyder. 1984. Moisture sensor-controlled irrigation for maintaining bermudagrass turf. *Agron. J.* 76: 848-850.

AWWA (American Water Works Association). 2004. Florida County restricts lawns. WaterWiser, September 2004. Available at: http://www.awwa.org/waterwiser/watch/archive.cfm. Accessed 7 January 2006

Baldwin, C.M., H. Liu, L.B. McCarty and W.L. Bauerle. 2005. Drought Tolerance of Six Bermudagrass Cultivars. TurfGrass Trends, Apr 1, 2005. Available at: http://www.turfgrasstrends.com/turfgrasstrends/article/articleDetail.jsp?id=156340. Accessed 7 January 2006.

Baum, M.C., M.D. Dukes, and G.L. Miller. 2003. Residential irrigation uniformity and efficiency in Florida. ASAE Meeting Paper FL03-100. St. Joseph, MI: ASAE.

Bausch, W.C., and T.M. Bernard. 1996. Validity of the Watermark sensor as a soil moisture measuring device. In: Proc. of the Intl. Conf. Evapotranspiration and Irrigation Scheduling. C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.). St. Joseph, MI: ASAE. pp. 933-938.

Biran, I., B. Bravdo, I. Bushkin-Harav, and E. Rawitz. 1981. Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency and soil moisture. *Agron. J.* 73: 85–90.

Boman, B., S. Smith, and B. Tullos. 2002. Control and automation in citrus microirrigation systems. CH194, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. Available at: http://edis.ifas.ufl.edu/CH194. Accessed 7 January 2006.

Bonos, S.A. and J.A. Murphy. 1999. Growth responses and performance of Kentucky bluegrass under summer stress. *Crop Sci*. 39:770-774.

Burney, L., T. Swihart, and J. Llewellyn. 1998. Water Supply Planning in Florida. *Florida Water Resource Journal*, October 1998: 27-28.

Burt, C.M.; A.J. Clemmens, and K.H. Strelkoff. 1997. Irrigation performance measurements: efficiency and uniformity. *Journal of Irrigation and Drainage Engineering* 123(6): 423-442.

Campbell, G.S., and D.J. Mulla. 1990. Measurement of soil water content and potential. In: Irrigation of agricultural crops. Agronomy Monograph No. 30. ASA-CSSA-SSSA, Madison, WI. pp. 127-142.

Carriker, R.R. 2000. Florida's water: supply, use, and public policy. Department of Food and Resource Economics, Report FE 207, University of Florida, Gainesville, FL.

Cassell, D.K., and A. Klute. 1986. Water potential: tensiometry. In: A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agronomy 9. American Society of Agronomy, Madison, WI. pp. 563-596.

Charlesworth, P. 2000. Soil water monitoring. Irrigation Insights No.1. CSIRO Land and Water, Griffith, NSW. 96 p.

Christiansen, J.E. 1942. Irrigation by sprinkling. California Agric. Exp. Stn. Bull. 670. University of California, Berkley, CA.

Clark, G.A., C.D. Stanley, and D.N. Maynard. 1994. Tensiometer control vs. tomato crop coefficients for irrigation scheduling. ASAE Meeting Paper 94-2118, St. Joseph, MI: ASAE.

Colbaugh, P.F., and C.L. Elmore. 1985. Influence of water on pest activity. *In* V.A. Gibeault and S.T. Cockerham (ed.) Turfgrass water conservation. Cooperative Extension, University of California. pp. 113-129.

Davis, D.B., and P.H. Dernoeden, 1991. Summer patch and Kentucky bluegrass quality as influenced by cultural practices. *Agron. J.* 83:6702677.

Dewey, C. 2003. Sensors at work. Irrigation and green industry, September 2003. Available at: http://www.igin.com/Irrigation/0903sensors.html. Accessed 7 January 2006.

Dukes, M. D., E.H. Simonne, W.E. Davis, D.W. Studstill, and R. Hochmuth. 2003. Effect of sensor-based high frequency irrigation on bell pepper yield and water use. In Proceedings 2nd International Conference on Irrigation and Drainage, Phoenix, AZ: 665-674.

Dukes, M.D. and D. Z. Haman. 2002a. Operation of residential irrigation controllers. CIR1421, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL.

Dukes, M.D. and D.Z. Haman. 2002b. Residential irrigation system rainfall shutoff devices. ABE325, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. Available at: http://edis.ifas.ufl.edu/AE221. Accessed 7 January 2006.

Dukes, M.D. and J.M. Scholberg. 2005. Soil moisture controlled subsurface drip irrigation on sandy soils. *Applied Engineering in Agriculture* 21(1): 89-101.

Dukes, M.D. and R. Muñoz-Carpena. 2005. Soil water sensor-based automatic irrigation of vegetable crops. In: Encyclopedia of Water Science. S.W. Trimble, B.A. Stewart and T.A. Howell (eds). Marcel-Dekker, Inc., NY. pp. 1-5.

Edis, R. and B. George, 2000. Time-domain reflectometry: an introduction. In: Soil water monitoring. P. Charlesworth (ed.). Irrigation Insights No.1. CSIRO Land and Water, Griffith, NSW. pp. 74-81.

Egbert, J.A., S. Baker, J.M. Baker. 1992. Calibration of Watermark soil moisture sensors for soil matrix potential and temperature. *Plant Soil* 143:213–217.

Eldredge, E.P., C.C. Schock, and T. Stieber. 1993. Calibration of granular matrix sensors for irrigation management. *Agron. J.* 85:1228–1232.

FDEP (Florida Department of Environmental Protection). 2002. Official notice of rule development: water shortage, NO 62-40.412. Publication Date: July 19, 2002. Available at: http://tlhora6.dep.state.fl.us/onw/publications/2-62-40RuleNoticewithruletextRevisedJuly2DT.pdf. Accessed 26 January 2005.

Figliola, R.S. and D.E. Beasley. 2000. Theory and design for mechanical measurements. 3rd ed. John Wiley and Sons, Inc. New York.

Florida Statutes, Part VI, Chapter 373.62. n.d. Water Conservation; automatic sprinkler systems. Available at: http://www.floridadep.org/water/stormwater/npdes/docs/ch373.pdf. Accessed 16 February 2006.

Florida Statutes. 2001. Changes to Chapter 373. Available at: http://www.dep.state.fl.us/cmp/federal/files/373ana01.pdf. Accessed 16 February 2006.

Gardner, W.H. 1986. Water content. In: Methods of soil analysis. Part 1. Physical and Mineralogical Methods, 2nd ed. A. Klute (ed.). Agronomy Monogr. No. 9. ASA and SSSA, Madison, WI. pp. 635–662.

Haley, M.B., M.D. Dukes, and G.L. Miller. 2006. Residential irrigation water use in Central Florida. *Journal of Irrigation and Drainage Engineering* (in press).

Hanson R.B., S. Orloff, and D. Peters. 2000a. Monitoring soil moisture helps refine irrigation management. *Calif. Agric*. 54:38–42

Hanson R.B., S. Orloff, and D. Peters. 2000b. Effectiveness of tensiometers and electrical resistance sensors varies with soil condition. *Calif. Agric*. 54:47–50

Harivandi, M.A., V.A. Gibeault, M.J. Henry, L. Wu, P.M. Geisel, and C.L. Unruh. 2001. Turfgrass selection for the home landscape. Publication 8035, University of California, Division of Agriculture and Natural Resources. Available at http://anrcatalog.ucdavis.edu/pdf/8035.pdf. Accessed 16 February 2006.

Hodges, A.W., J.J. Haydu, P.J. van Blokland, and A.P. Bell. 1994. Contribution of the turfgrass industry to Florida's economy, 1991-1992: A value-added approach. University of Florida, Institute of Food and Agricultural Sciences, Food and Resource economics Department. Economic Report ER.

Hunter Industries, Inc. 2006. Products information. Available at: http://www.hunterindustries.com. Accessed 16 February 2006.

Irmak, S. and D.Z. Haman. 2001. Performance of the Watermark granular matrix sensor in sandy soils. *Appl. Eng. Agric*. 17: 787–795.

Irrigation Association. 2003. Landscape irrigation scheduling and water management. Irrigation Association Water Management Committee. Falls Church, VA.

Intrigliolo, D.S. and J.R. Castel. 2004. Continuous measurement of plant and soil water status for irrigation scheduling in plum. *Irrig. Sci*. 23: 93–102.

Jordan, J.E., R.H. White, D.M. Vietor, T.C. Hale, J.C. Thomas, and M.C. Engelke. 2003. Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. *Crop Science* 43: 282–287. http://crop.scijournals.org/cgi/reprint/43/1/282

Kackley, K.E., A.P. Grybauskas, P.H. Dernoeden, and R.L. Hill. 1990. Role of drought stress in the development of summer patch in field inoculated Kentucky bluegrass. *Phytopathology* 80: 655-658.

Leib, B.G., M. Hattendorf, T. Elliott, and G. Matthews. 2002. Adoption and adaptation of scientific irrigation scheduling: trend from Washington, USA as of 1998. *Agric. Water Manage*. 55:105–120.

Leib, B.G., J.D. Jabro, and G.R. Matthews. 2003. Field evaluation and performance comparison of soil moisture sensors. *Soil Science*: 168(6) 396-408.

Ley, T.W., R.G. Stevens, R.R. Topielec and W.H. Neibling. 2000. Soil water monitoring and measurement. Pacific Northwest, WA. 33 p. Available at: http://cru.cahe.wsu.edu/CEPublications/pnw0475/pnw0475.html. Accessed 13 November 2003.

Marella, R.L. 1992. Water withdrawals, use, and trends in Florida, 1990. Water Resources Investigations Report 92-4140. United States Department of the Interior, U.S. Geological Survey, Tallahassee, FL.

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

McCann, I.R., D.C. Kincaid, and D. Wang. 1992. Operational characteristics of the watermark model 200 soil water potential sensor for irrigation management. *Appl. Eng. Agric*. 8:603–609

McCarty, L.B. 2005. Best Golf Course Management Practices. 2nd ed. Upper Saddle River, NJ. Prentice-Hall Inc.

Merriam, J.L., and J. Keller. 1978. Farm irrigation system evaluation: a guide for management. Department of Agricultural and Irrigation Engineering, Utah State University, Logan, UT.

Mitchell, A.R., and C.C. Shock. 1996. A Watermark datalogging system for ET measurement. In: Proc. of the Intl. Conf. Evapotranspiration and Irrigation Scheduling. C. R. Camp, E. J. Sadler, and R. E. Yoder (eds.). St. Joseph, MI: ASAE. pp. 468-473.

Muñoz-Carpena, R. 2004. Field devices for monitoring soil water content. BUL343, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. Available at: http://edis.ifas.ufl.edu/AE266. Accessed 7 January 2006.

Muñoz-Carpena, R. and M.D. Dukes. 2005. Automatic irrigation based on soil moisture for vegetable crops. ABE356, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. Available at: http://edis.ifas.ufl.edu/AE354. Accessed 7 January 2006.

Muñoz-Carpena, R., H. Bryan, W. Klassen, and M.D. Dukes. 2003. Automatic soil moisture-based drip irrigation for improving tomato production. Proceedings of the Florida State Horticultural Society 116: 80-85.

Muñoz-Carpena, R., M.D. Dukes, Y. Li, and W. Klassen. 2005. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. *HortTechnology* 15(3): 584-590.

National Research Council. 1996. A new era in irrigation. National Academies Press. Washington D.C.

NOAA (National Oceanic and Atmospheric Administration). 2003. Monthly station normals of temperature, precipitation, and heating and cooling degree days 1971 – 2000; 08 Florida. Climatography of The United States No. 81. 28p. Available at: http://hurricane.ncdc.noaa.gov/climatenormals/clim81/FLnorm.pdf. Accessed 29 April 2006.

Nogueira, L.C., M.D. Dukes, D.Z. Haman, J.M. Scholberg, and C. Cornejo. 2002. Data acquisition and irrigation controller based on CR10X datalogger and TDR sensor. Proceedings Soil and Crop Science Society of Florida 2002, 62: 38-46.

ODR (Office of Economic and Demographic Research.). 2006. Demographic Estimating Conference; Florida Demographic Forecast. Available at: http://edr.state.fl.us/conferences/population/demographic.htm Accessed 29 April 2006

Or, D. 2001. Who invented the tensiometer? *Soil Sci. Soc. Am. J.* 65: 1–3.

Pathan, S.M., L. Barton and T.D. Colmer. 2003. Evaluation of a soil moisture sensor to reduce water and nutrient leaching in turf. Horticulture Australia project number TU 02006. 21p.

Qualls, R.J., J.M. Scott, and W.B. DeOreo. 2001. Soil moisture sensors for urban landscape irrigation: effectiveness and reliability. *Journal of the American Water Resources Association* 37(3): 547-559.

Sarasota County. 2006. Water efficient landscaping ordinance; Ordinance #2001-081. Available at: http://sarasota.extension.ufl.edu/WEL/ord/docs/ord.htm. Accessed 24 April 2006.

SAS (Statistical Analysis System). 2000. SAS/STAT User's Guide, Ver. 9. Cary, N.C.: SAS Institute, Inc.

Schmugge, T.J., T.J. Jackson, and H.L. McKim. 1980. Survey of methods for soil moisture determination. *Water Resour. Res.* 16: 961-979.

Seyfried, M.S. 1993. Field calibration and monitoring of soil water content with fiberglass electrical resistance sensors. *Soil Sc. Soc. Am. J.* 57: 1432–1436.

Shock, C.C., E. Fibert, and M. Saunders. 1996. Malheur Experiment Station Annual Report. Special Report 964, Oregon State University, Ontario, OR.

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1998a. Onion yield and quality affected by soil water potential as irrigation threshold. *HortScience* 33: 1188–1191

Shock, C.C., E.B.G. Feibert, and L.D. Saunders. 1998b. Potato yield and quality response to deficit irrigation. *HortScience* 33: 655–659

Shock, C.C., E.B.G. Feibert, L.D. Saunders, and E.P. Eldredge. 2002. Automation of subsurface drip irrigation for crop research. In: Proceedings of the World Congress of Computers in Agriculture and Natural Resources. F.S. Zazueta and J. Xin eds. Iguacu Falls, Brazil. pp. 809-816

SJRWMD (Saint John's River Water Management District). 2006. Waterwise Florida landscapes. Available at: http://sjrwmd.com/programs/outreach/conservation/landscape/principle5.html. Accessed 29 January 2006.

Skogley, C.R., and C.D. Sawyer. 1992. Field research. In: Turfgrass. Agron. Monogr. 32. D.V. Waddington, R.N. Carrow, and R.C. Shearman (eds.). ASA, CSSA, and SSSA, Madison, WI. pp. 589–614

Smajstrla, A.G. and R.C. Koo. 1986. Use of tensiometers for scheduling of citrus irrigation. Proceedings of the Florida State Horticultural Society 99: 51-56.

Smajstrla, A.G. and S.J. Locascio. 1994. Irrigation cutback effects on drip-irrigated tomato yields. Proceedings of the Florida State Horticultural Society 107: 113-118.

Solley, W.B., R.R. Pierce, and H.A. Perlman. 1998. Estimated use of water in the United States in 1995. United States Geological Survey Circular 1200. 78 p.

SWUCA (Southern Water Use Caution Area Recovery Strategy). 2006. Southwest Florida Water Management District. Revised Draft, March 2006. 145 p. Available at: http://www.swfwmd.state.fl.us/waterman/swuca/SWUCA.htm. Accessed 29 January 2006.

Taber H.G., V. Lawson, B. Smith, and D. Shogren. 2002. Scheduling microirrigation with tensiometers or Watermarks. *Int. Water Irrig*. 22: 22–26

Tampa Bay Water. 2005. Evaluating implementation of multiple irrigation and landscape ordinances in the Tampa Bay region. April 2005. Available at: http://www.tampabaywater.org/conservation/reportsdocs.aspx. Accessed 19 January 2006.

Thomas, B.D., E. Cummings, and W.H. Whittstruck. 1985. Soil survey of Alachua County, Florida. USDA/NRCS in cooperation with the University of Florida, Institute of Food and Agricultural Sciences, Soil Science Department and the Florida Department of Agriculture and Consumer Services.

Thomson, S.J., and C.F. Armstrong. 1987. Calibration of the Watermark model 200 soil moisture sensor. *Applied Engineering in Agriculture* 3(2): 186–189.

Thomson, S.J., T. Younos, and K. Wood. 1996. Evaluation of calibration equations and application methods for the Watermark granular matrix soil moisture sensor. *Applied Engineering in Agriculture* 12(1): 99–103.

Topp, G.C. 2003. State of the art of measuring soil water content. *Hydrological Processes* 17: 2993–2996.

Turgeon, A.J. 2005. Turfgrass Management. 7th ed. Upper Saddle River, NJ. Prentice-Hall Inc. 415p.

USCB (United States Census Bureau). 2004a. Population estimates. Washington, DC. Available at: http://www.census.gov/popest/estimates.php. Accessed 19 January 2006.

USCB (United States Census Bureau). 2004b. Housing unit estimates. Washington, DC. Available at: http://www.census.gov/popest/housing/. Accessed 19 January 2006.

USDA (United States Department of Agriculture). 1981. Land resource regions and major land resource areas of the united states. Soil Conservation Service Handbook 256. USDA, Washington, DC.

USDA (United States Department of Agriculture). 2003. Official soil series descriptions. Natural Resource and Conservation Service, Washington, DC. Available at: http://soils.usda.gov/technical/classification/osd/index.html. Accessed 13 April 2005.

USDA (United States Department of Agriculture). 2005. Florida State agriculture overview – 2005. National Agricultural Statistics Service. Available at: http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_FL.pdf Accessed 13 April 2006.

Walker, J.P., G.R. Willgoose and J.D. Kalma. 2004. In situ measurement of soil moisture: a comparison of techniques. *Journal of Hydrology* 293: 85-99.

Whitcomb, J.B. 2005. Florida water rates evaluation of single-family homes. Southwest Florida Water Management District. Available at: http://www.swfwmd.state.fl.us/documents/reports/water_rate_report.pdf. Accessed 29 January 2006.

Yoder, R.E., D.L. Johnson, J.B. Wilkerson, and D.C. Yoder. 1998. Soil water sensor performance. *Appl. Eng. Agric*. 14: 121-133.

Youngner, V.B., A.W. Marsh, R.A. Strohman, V.A. Gibeault, and S. Spaulding. 1981. Water use and turfgrasses. *Calif. Turfgrass Cult*. 31: 1-4.

Zazueta, F.S., A.G. Smajstrla and G.A. Clark. 2002. Irrigation system controllers. SS-AGE-22, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL. Available at: http://edis.ifas.ufl.edu/AE077. Accessed 10 April 2005.

# BIOGRAPHICAL SKETCH

Bernard Cardenas-Lailhacar was born in Santiago, Chile. He received a Bachelor of Science degree in agricultural engineering from the Universidad Austral de Chile. Later, he accepted a graduate assistantship position in the Agricultural and Biological Engineering Department at the University of Florida, and began studying toward a Master of Science degree. On August 2006, Cardenas-Lailhacar received his M.Sc. degree after defending his dissertation untitled “Sensor-based Automation of Irrigation of Bermudagrass.”

While at the University of Florida, he obtained the highest grade of his class (GPA: 4.0), received five awards, and was invited to be part of two Honor Societies, on the basis of his class performance. Moreover, he obtained the second place at the 2006 Graduate Student Research Award of the American Society of Agricultural and Biological Engineers (ASABE).

He is proficient in three languages (English, Spanish, and French), and has traveled to 12 different countries in Europe and the Americas.