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Evaluation of Evapotranspiration and Soil Moisture-based Irrigation Control on Turfgrass

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Abstract. *A variety of commercially available technologies for reducing residential irrigation water use are available to homeowners. These technologies include soil moisture sensors, rain sensors and evapotranspiration (ET) based controllers. The purpose of this research was to evaluate the effectiveness of these various technologies based on irrigation applied and turfgrass quality measurements. Testing was performed on two types of soil moisture sensors (SMS, LawnLogic® and the Acclima Digital TDT® RS500) at low, medium, and high soil moisture threshold settings. Mini-Clik® rain sensors comprised seven time-based treatments, with three treatments pre-set for 3 mm of rainfall and the remaining 4 rain sensor treatments had sensors pre-set to bypass irrigation for 6 mm of rainfall. Two ET controllers were also tested, the Toro Intelli-Sense controller and the Rain Bird® ET Manager™. A time-based treatment with two days of irrigation per week and no rain sensor (2-WORS) was established as a comparison. SMS-based treatments resulted in 0-63% reductions in water use compared to 2-WORS. Rain sensor treatments resulted in 7-33% reductions in water use. ET-based irrigation resulted in 36% to 59% reductions in water use compared to 2-WORS. The SMS treatments at the low threshold settings resulted in high water savings, but reduced turf quality to unacceptable levels. The medium threshold setting SMS-based, time-based and both of the ET-based treatments produced good turfgrass quality while reducing irrigation water use compared to 2-WORS. Savings for the medium SMS-based systems ranged from 11-28%.*

Keywords *turfgrass, soil moisture sensor, evapotranspiration, ET, rain sensor, residential irrigation, controller*

Introduction

Water conservation is a growing issue in the state of Florida due to increased water demands and limited resources. Water withdrawal in Florida, along with California and Texas, accounted for one-fourth of all water withdrawals in the nation for 2000 (Hutson et al., 2004). Florida's population was estimated at 17 million in 2004. That number is expected to increase to greater than 21 million by 2015, making Florida the third most populous state in the nation (United States Census Bureau [USCB], 2004a). Population growth means increases in landscaped area in Florida. Currently almost 11% of new homes being constructed in the U.S. are in Florida (USCB, 2004b). Many if not most of these new homes being built have automated irrigation systems. Studies show that the public supports finding more effective methods to conserve water. A recent survey conducted by Tampa Bay Water showed that 87 % of those polled agreed that more should be done in order to conserve water, but 93% of the people polled believed they were already doing all they could to conserve water (Florida Department of Environmental Protection [FDEP], 2002).

Sensors measure water content in the soil using one of two methods, tensiometric or volumetric. Most volumetric sensors are designed to estimate soil volumetric moisture content (VMC) based on the dielectric constant (soil bulk permittivity) of the soil (Muñoz-Carpena, 2004). The dielectric constant of the soil increases as the water content of the soil increases; this is due to the fact that the dielectric constant of water is much larger than the other soil components, including air. The presence of water in the soil profile largely predicts the dielectric constant for the soil (Muñoz-Carpena, 2004). Measuring the dielectric constant provides a measure of the soil moisture content. Data from the sensor is used to allow or bypass irrigation events. The sensor has an adjustable threshold setting and if the soil moisture content exceeds that setting the event is bypassed (Dukes, 2005). A single sensor can be used to control the irrigation for many zones or more than one sensor can be used to irrigate multiple zones. In the case of one sensor for several zones, the zone that is normally the driest, or most in need of irrigation, is selected for placement of the sensor in order to ensure adequate irrigation in all zones.

Evapotranspiration (ET)-based irrigation controllers ideally allow irrigation according to ET needs of the plant. ET is the water lost from the soil surface by the process of evaporation and lost from the plant by the process of transpiration. Since the two processes occur simultaneously and are very difficult to separate, they are combined into one process (Allen et al., 1998). There are various ways in which ET-based irrigation controllers are designed to work. Some systems are based on historical data developed for the site where irrigation is being applied (SWAT, 2004). Other systems use on-site sensors to measure weather information used to calculate ET while other systems receive reference ET information from nearby weather stations and adjust irrigation accordingly (SWAT, 2004). ET controllers can generally be programmed for various site specific conditions such as soil type, plant type, root depth, and sun exposure, etc. ET controllers can be purchased as an addition to an existing irrigation timer or as a single component to replace the standard timer.

Rain sensors open the circuit between the irrigation timer and the irrigation valves (bypassing timed irrigation events) after a specific amount of rainfall has occurred. The Mini-Clik® (Hunter Industries Incorporated, San Marcos, CA) is a rain sensor on the market for residential use and utilizes absorptive disks to measure precipitation. As the disks absorb water they expand in size proportionally to the amount of water absorbed. When the disks expand to a user adjustable set point a switch opens causing irrigation to be bypassed (Hunter®, 2005). When the rain sensor disks dry, they shrink, allowing timed irrigation events to occur. The amount of time it takes the disks to dry is determined by environmental conditions such as solar radiation and wind, many of the same conditions that affect evapotranspiration. (Hunter®, 2005)

Making residential irrigation more efficient would be cost effective for homeowners and decrease the public supply demand for water. The cost to the homeowner for the soil moisture sensor, ET controller or the rain sensor will likely be offset by the money saved in water costs.

The objectives of this experiment were to evaluate the differences in irrigation water application and the resulting quality of St. Augustine (*Stenotaphrum Secundatum*) turfgrass comparing irrigation scheduled using: i.) Two types of SMS-based controllers set at three soil moisture content thresholds; ii.) Two types of ET controllers; iii.) One type of rain sensor set for two thresholds of precipitation and three frequencies of irrigation events; iv.) A time-based irrigation system without a rain sensor.

Materials and Methods

This study was performed at the Plant Science Research and Education Unit in Citra, Florida. The three soil types present in the research area are Tavares sand, Candler sand, and Arredondo fine sand (Loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) (USDA, 2006). Arredondo fine sand has a field capacity of 10% (soil moisture content expressed as a volumetric basis in this manuscript), a permanent wilting point of 3% and is 94% sand, 2% silt and 4% clay. Candler sand has a field capacity of 6%, a permanent wilting point of 1% and is 96% sand, 2% silt and 2% clay. Tavares sand has a field capacity of 5%, a permanent wilting point of 1% and is 97% sand, 1% silt, and 2% clay (Carlisle et al., 1989)

The experimental area consists of 72 plots of ‘Floratam’ St. Augustinegrass (*Stenotaphrum secundatum*). In August 2005, sod was laid in the center 1.8 m X 1.8 m of each 4.27 m X 4.27 m plot. The plots are irrigated using four Toro 570™ Series (The Toro Company, Bloomington, MN.) quarter circle pop-up spray heads with an application rate of 51mm/hr. Rain Bird® ESP Modular Irrigation Controllers (Rain Bird International, Inc., Glendora, CA) were used for scheduling all of the treatments except where a time-based controller was not necessary. A 0.61m wide border was established between all plots and was used for irrigation pipe and control wire burial. This border was kept clear of vegetation by mechanical and chemical means. Plots were mowed once weekly at a height of 10 cm. Chemicals were applied as necessary identically to all plots. Applications included fertilizer and pesticides for chinch bug removal. To promote establishment and minimize contamination potential, fertilizer applications were based on University recommendations (Trenholm, 2004). Soluble nitrogen (N) was applied approximately every 60 days beginning in May with a total N rate of 196 kg ha^{-1}. Phosphorus and potassium was applied with N fertilizations at 22 and 45 kg ha^{-1} yr^{-1}, respectively.

Water use was monitored using pulse-type displacement flow meters, specifically AMCO PSMT 20 mm x 190 mm flow meters (Elster AMCO Water, Inc., Ocala, FL). These flow meters were wired to multiplexers connected to a CR-10X datalogger

(Campbell Scientific, Logan, UT.) to monitor daily water use. The meters were also read manually at least every two weeks.

Volumetric soil moisture content was recorded hourly using time domain reflectometry (TDR) sensors (CS616 Water Content Reflectometer, Campbell Scientific, Logan, UT). Measurements made with the TDR probes are accurate up to +/-2.5% VMC (Campbell Scientific, Inc., 2006). These sensors were connected to a CR-10X datalogger. The TDR sensors were buried in the center of every plot with the top of the sensor at a depth of 8 cm and the bottom of the sensor at a depth of 18 cm.

Weather data was collected using an automated weather station (Campbell Scientific, Logan, UT) within 900 m of the experimental site. This weather data was also used for calculating reference ET (ETo). Solar radiation, relative humidity, air temperature, and wind speed were used in the ETo calculations. Rainfall data at the weather station was collected with both a tipping bucket rain gauge and with a manual rain gauge located at the research plots. ETc was calculated according to equation 1 using a crop coefficient (Kc) of 0.85 (Allen et al., 1998).

$$ETc = ETo \cdot Kc \qquad [1]$$

ETo was calculated using the Standardized Reference Evapotranspiration Equation (Walter et al., 2002). ETo data was collected three days per week from the two ET controllers used for testing.

Turfgrass quality was rated at least once every two weeks, starting on May 8 in the spring and September 22 in the fall. Quality evaluations were made using the National Turfgrass Evaluation Program (NTEP) procedures (Morris and Shearman, 2006). The ratings were on a 1 to 9 scale, with 1 representing dead or dormant grass and 9 representing grass with good color and density, and without weeds (Morris and Shearman, 2006). A quality rating of 5 was considered minimally acceptable for a homeowner lawn. Statistical analyses for irrigation and turf quality data were performed using the General Linear Models (GLM) procedure and means separation was conducted with Duncan’s Multiple Range Test in SAS (SAS Institute, Inc., Cary, NC).

Experimental Design

There were 18 treatments with four replications arranged in a completely randomized block design due to inherent soil moisture differences in the research area. Treatment descriptions and codes are summarized in Table 1. Treatments were implemented in the spring and fall seasons of 2006. The spring treatments started on April 22, 2006 and ended June 30, 2006 (71 days), and the fall treatments began on September 23, 2006 and ended December 15, 2006 (84 days).

Soil moisture sensors were connected to an irrigation time clock to function in bypass mode operation so that a scheduled irrigation event would be bypassed if soil moisture exceeded the soil moisture sensor threshold (Dukes, 2005). The monthly irrigation schedule was based on recommendations for two day per week operation by Dukes and Haman (2002) and is presented in Table 2. The two day per week operation was used to emulate typical water restrictions in Florida. Two brands of soil moisture sensors were tested: Acclima Digital TDT® RS500 (Acclima Inc., Meridian, ID.) and the LawnLogic® LL1004 (Alpine Automation, Inc., Aurora, CO.) Each soil moisture sensor (SMS) based system was tested at three different volumetric moisture content thresholds. The three VMC threshold settings were considered low (dry), medium, and high (wet) VMC conditions. The settings for the Acclima Digital TDT sensors were 7%, 10%, and 13%. The LawnLogic, which uses site specific calibration methods, was set for relative low, medium and high levels of moisture content in the soil. The manufacturer suggests calibration 24 hours after a significant rainfall or irrigation event that fills the soil profile to field capacity. Once the calibration is performed, the controller has relative set points from 1 (dry) to 9 (wet). During calibration at field capacity, the controller is set at 5. The settings used as experimental treatments were 2, 5 and 8 for the spring and 4, 5 and 6 for the fall. Each SMS treatment utilized one sensor buried in the driest plot to control the irrigation for all plots in the treatment. One treatment, AC7-Ind, was set up with each plot having its own sensor controlling the irrigation.

Rain sensor treatments were also connected to a time clock in bypass mode similar to the description presented for soil moisture sensors. A Mini-Clik® (Hunter Industries Inc., San Marcos, CA.) rain sensor was used to establish seven treatments. The rain sensors were set for two depths of rainfall, 6 mm and 3 mm and three different frequencies of irrigation events, 1, 2 and 7 days of irrigation per week.

During the fall, ET controllers were tested at the site. Two commercially available controllers were selected for the study: the Toro Intelli-sense (The Toro Company, Bloomington, MN) formerly known as the Hydropoint WeatherTRAK^{TM} and the ET Manager^{TM} (Rain Bird Corporation, Glendora, CA). Both ET controllers utilize paging technology to gather reference ET information. The systems perform a moisture balance based on daily ET, rainfall, and other inputs and use the current moisture level for irrigation decisions. The Toro Intelli-sense controller (TORO) calculates irrigation runtime based on application rate and other inputs from the homeowner. The ET Manager is connected to an irrigation time clock in bypass mode. The ET manager does not calculate irrigation run time. This system either bypasses or allows irrigation as needed based on the soil moisture balance calculated using daily ET, rainfall, application depth and other inputs. The ET Manager (ETM) uses historical ET as a backup if the signal to the controller is lost. The ETM treatment was set for irrigation depths based on the same methods used for the time-based treatments. A summary of inputs for both ET controllers is provided (Table 3). Both the ET-based treatments were restricted to irrigating twice per week.

There was one control treatment in the experimental design and three time-based comparisons (Table 1). The control was a non-irrigated (0-NI) treatment. The comparison treatments consisted of time-based without a rain sensor (2-WORS), time-based with a rain sensor at 6 mm (2-WRS), and time based with a rain sensor at 6 mm and a deficit replacement schedule that was 60% of 2-WRS (2-DWRS).

The same total application depth per week was divided over the possible number of days of irrigation per week. Every treatment except for the TORO, 2-DWRS and the 0-NI treatments had the same possible total depth of irrigation application. Differences in irrigation application were due to bypassed irrigation events. A summary of weekly irrigation depths for each month is provided in Table 2. These application depths are based on historical monthly ET values (Dukes and Haman, 2002).

Results and Discussion

Rainfall

Both treatment periods were relatively dry compared to historical rainfall for the research area. The total rainfall was 138 mm from 16 rainfall events in the spring. This amount can be compared to the recorded rainfall for the same time period the previous spring which totaled 348 mm with 30 rainfall events, almost twice as many events and more than two times the total depth. Historical average rainfall data for the same time period as the spring treatments was 298mm (NOAA, 2006). In the fall 92 mm from 15 events occurred. The previous fall had a total rainfall depth of 265 mm with 22 events and the historical average rainfall is 188 mm for the same time period (NOAA, 2006). Both treatment periods had total rainfall depths less than half that of the historical depths for the area. Figure 1 shows the cumulative rainfall depth for the spring and fall along with cumulative ETc. The infrequency of rainfall events and minimal total depth of rainfall led to dry conditions for the research site. In the beginning of the spring season the volumetric moisture content of the soil in the 0-NI plots was as low as 3% to 4% (Figure 2), which is the permanent wilting point of the Arredondo fine sand. All water savings reported are the amount of irrigation water applied compared to the 2-WORS treatment.

Spring Results

Water savings for this treatment period ranged from 0% to 63% for all treatments; the treatments with acceptable turf quality had water savings ranging from 0% to 36% (Table 4). Analyzing water use and turfgrass quality data showed a relationship between turf quality and water use during the spring treatments where turf quality reached a relatively flat level (6) after approximately 200 mm of irrigation (Figure 3). Both SMS-based treatments with medium and high thresholds resulted in better than minimally acceptable turf quality. Some deterioration in turf quality at the end of the season was due to chinch bugs present at the site. The biggest impact from the chinch bugs occurred in the plots with low water application, especially the LL-2 plots and the non-irrigated plots. The experiment was concluded June 30, 2006 before most of the damage from chinch bugs occurred.

Soil moisture sensors

Generally, higher threshold settings resulted in higher water use and increased turf quality. Among the medium and high threshold treatments the water savings were between 0% and 20%. Figure 4 shows the cumulative water use for the SMS-based treatments during the spring. Neither of the high threshold SMS treatments (LL-8 and AC-13) showed reductions in irrigation water applied. The AC-13 treatment did not save any water since it not bypass any irrigation events. The LL-8 treatment bypassed two irrigation events but did not result in water savings due to problems with the irrigation control system that caused the irrigation zone to run longer than programmed. End of season turf quality for the AC-13 and the LL-8 treatments was 6 and 7 respectively. The AC-7 treatment reduced irrigation water by 40% and LL-2 had water savings of 63%, but both of these treatments did not maintain acceptable turf quality throughout the treatment period. The water applied by the LL-2 and the AC-7 treatments was well below the calculated ETc (Figure 4). The LL-2 treatment applied water to replace only 38% of the total ETc. The AC-7 treatment applied water to replace 60% of the total ETc. The medium threshold settings for both sensors resulted in 11% and 20% water savings for the AC-10 and the LL-5 treatments respectively. Water use by these treatments and the AC-13 treatment followed closely with calculated ETc (Figure 4). Treatment AC-13 applied 8% more irrigation than ETc. The LL-5 and AC-10 treatments applied 18% and 9% less irrigation than ETc. The LL-5 turf quality rating (7) was slightly higher than the AC-10 rating (6), but both were above minimally acceptable. The low threshold settings for both the LL and AC treatments resulted in poor turf quality ratings of 3 and 4 respectively, although only the LL-2 treatment was significantly lower than the best quality treatments such as LL-8 and LL-5. These ratings were below the minimally acceptable value. Ultimately, the LL-2 plots resulted in almost complete death of the turfgrass and had to later be re-sodded.

Correlation of TDR data with the timing of irrigation events, as seen in Figure 5, showed the threshold of volumetric water contents at which the sensor would bypass irrigation. The AC-7 treatment (Figure 5a) and AC7-Ind plots, bypassed irrigation when the VMC was either 7% +/-2%. The range of soil moistures at which irrigation was bypassed is within the range of accuracy of the probes used for measurement (Campbell Scientific, Inc., 2006). The percentage of irrigation events bypassed by the AC7-Ind sensors ranged from 20% to 35%. TDR data showed that the sensors bypassed events at similar water contents (6-7%) even though they produced different water savings ranging from 21% to 45%. Differences in the number of irrigation events bypassed by the AC7-Ind sensors can be accounted for by the inherent differences in soil moisture content across the field (i.e. between blocks of treatments). The AC-10 treatment bypassed three irrigation events, and the bypassed events occurred when soil moisture content was 12% or higher. Conversely, when the soil moisture content was 11% or lower, irrigation was allowed (Figure 5b). AC-13 did not bypass any irrigation events during the testing period and VMC for the plot was never above 11%.

The LawnLogic sensors did not bypass irrigation as predictably as the Acclima sensors. The range of VMC values at which the LL treatment sensors did not bypass irrigation was larger than the AC treatments. The LL-2 sensor bypassed irrigation events when the soil VMC was as low as 5% and did not bypass irrigation when the VMC was as high as 10%. Typically, the sensor bypassed irrigation when VMC was at 7% or higher. LL-5 bypassed irrigation with a VMC as low as 7% and allowed irrigation when the VMC was as high as 10%. LL-8 bypassed some irrigation events when the soil moisture content was 10% or 11% but allowed other irrigation events when the VMC was as high as 13%. All of the LawnLogic treatments bypassed more irrigation events during the spring treatments than the comparable Acclima treatments.

Rain sensors

Water savings for the rain sensor treatments ranged from 11% to 36% (Table 4). The highest water savings occurred in the 2-DWRS treatment, reducing water application by 36%. This treatment was set to apply 60% of the water compared to the other time-based treatments. The 2-DWRS treatment had a lower percentage of irrigation events bypassed than the other rain sensor treatments by 5% to 10%, as seen in Table 4, but saved water due to the decreased depth of application per irrigation event. Turfgrass quality for this treatment was a 6 which is above minimally acceptable. The next highest water savings was seen in the 1 day/week 3 mm treatment, applying 32% less water than 2-WORS; however, the end of season turf quality was less than acceptable (Table 4). The 1 day/week 6 mm treatment only reduced water application by 20%. Both of the 1 day/week treatments had low turf quality ratings at the end of the season. The time-based treatments set for two and seven days of irrigation per week had similar water savings compared to each other. Frequency of irrigation seemed to have a more direct impact on quality than the rain sensor threshold setting. The best overall turf quality ratings for the season were seen in the 2-DWRS treatment and the RS7-3 mm treatment, with water savings of 36% and 24% respectively. The total water depth applied for the rain sensor treatments was within 18% to 31% of the calculated ETc (Figure 6). As seen in the figure, the treatments applied irrigation water similarly.

Fall Results

During the fall treatment period, the LL-4 and the 0-NI treatments were ended in the third week of the experiment due to very low turf quality ratings of 2. End of season turf quality was not significantly different between the remaining treatments. All of the treatments had a turf quality rating of 6 or 7, which are above minimally acceptable. Water savings during the treatment period ranged from 0% to 49% for all treatments (Table 4). Overall, turf quality was better in the fall than the spring due to lower temperatures and more rainfall than the spring. The LL-6 had an error in the setting of the irrigation schedule and so the treatment was excluded.

Soil moisture sensors

Reductions in water application among the SMS treatments ranged from 0% to 49%. The low threshold AC treatment (AC-7) used only 6% less water than 2-WORS. This treatment bypassed very few events and used more water than the AC-10 treatment. According to TDR data collected the sensor did not appear to be working properly for the AC-7 treatment in the fall. Treatment AC-10 had a 28% savings in water use and AC-13 had a 10% reduction. During fall treatments AC-13 did not produce any water savings. The LL-5 treatment had irrigation reduction of 17% which is lower than the water savings seen for the AC-10 treatment. AC7-Ind had water savings ranging from 21% to 67%. The range in water savings can be attributed to the inherent soil moisture differences across the field similar to the data collected in the spring.

The LL-2 sensor bypassed every irrigation event during the first two weeks of the experiment, and during that time the VMC was low as 4%. Due to the low VMC turfgrass quality was declining and so the treatment was ended. Treatment AC-7 only bypassed two irrigation events during the treatments and these were bypassed when the soil VMC was 16% or higher. As mentioned earlier the sensor for AC-7 did not appear to be working properly. LL-5 bypassed 4 irrigation events with soil VMC anywhere between 8% and 13%. Some irrigation events for LL-5 were allowed when VMC was at 9% and 10%, while other events were bypassed at a soil VMC of 8% The medium threshold AC treatment (AC-10) bypassed eight irrigation events with soil VMC at 12% or higher prior to irrigation. The sensor for treatment AC-13 bypassed three irrigation events when the soil VMC was at 12% or higher prior to irrigation events. AC-7 treatments, including AC7-Ind plots, bypassed irrigation when the VMC was either 7% +/-2%.

ET controllers

The ET Manager had a water savings of 36%, bypassing 50% of the possible irrigation events, while the Toro Intelli-Sense controller had a water savings of 59%, while not irrigating 29% of the possible irrigation days. The ET Manager treatment (ETM) reduced water use by bypassing events and thereby irrigating less frequently than the TORO treatment, but more deeply. Comparatively, the Toro Intelli-Sense treatment (TORO) had 30% fewer irrigation events bypassed than the ETM treatment. This treatment reduced water use by reducing run times for the irrigation system. The TORO treatment applied 30% less water than the cumulative ETc (Figure 7) and the ETM treatment applied 9% more water than the cumulative ETc. The ETM seemed to follow the calculated ETc more closely than the TORO. Both treatments had an average turf quality rating of 7 at the end of the season. TDR data for the TORO treatment showed that soil moisture was typically between 5% and 15% VMC and data for the ETM treatment showed that soil moisture was between 5% and 20%. The average VMC was higher for the ETM treatment than the TORO treatment. Both ET-based treatments resulted in water savings higher than the SMS-based systems with the exception of the AC7-Ind treatment (water savings of 49%)

and the time-based systems with the exception of 2-DWRS treatment (water savings of 38%) while maintaining high turf quality ratings (Table 4).

Rain sensors

Water use reductions for the rain sensor based treatments in the fall ranged from 7% to 38%. All of the treatments had an average end of season turf quality of at least 6 and there were no significant differences found in the turf quality (Table 4). The highest water savings were in the 2-DWRS, RS1-3mm, RS1-6mm, and RS7-3mm treatments. The water savings for the 2-DWRS treatment was 38% which was the third highest water savings for all treatments and turf quality was high. The 2-DWRS treatment bypassed the same percentage of irrigation events as the 2-WRS treatment, but used 38% less water than the 2-WORS treatment and 34% less water then the 2-WRS treatment. During the treatment period 2-DWRS and 2-WRS only bypassed two irrigation events. The average turf quality at the end of the season was 7 for the 2-DWRS treatment. The water savings for the RS1-3mm, RS1-6mm, and RS7-3mm treatments were between 27% and 30% (Table 4). Water savings in these three treatments varied little even though they were set for two different irrigation frequencies. The remaining time based treatments (RS2-3mm, RS7-6mm, and the 2-WRS) had water savings ranging from 7% to 9%. These water savings did not vary significantly even though the systems were set for different frequencies of irrigation events. More events were bypassed by the RS7-6mm than the comparable treatments with two days of irrigation per week, but water savings and turf quality did not vary significantly between these treatments. The higher water savings for RS1-3mm, RS1-6mm, and RS7-3mm compared to the other time-based treatments is primarily due to a power outage in the irrigation system controlling the treatments, resulting in missed irrigation events. These treatments were on the same irrigation controller.

The depth setting of the rain sensor and the frequency of irrigation did not affect turf quality or amount of water applied during the fall. Figure 8 shows the VMC for plots with irrigation frequencies of one, two and seven days per week. The flat line on these graphs represents a VMC of 13% which was chosen from inspection of TDR data for a non-irrigated plot (Figure 2) to represent the water content above which rapid drainage occurs. Any water applied leading to a moisture content exceeding 13% is assumed to drain rapidly and is inaccessible to the plant. With the exception of an irrigation event for fertilizer incorporation (October 6, 2006), the two and seven day per week treatments only had moisture contents over 13% when a rainfall event occurred. The one day per week (d/wk) treatment had moisture contents over 13% during irrigation events resulting in wasted irrigation.

ET comparisons

Comparisons of daily reference ET (ETo) readings for both controllers with calculated reference ET are shown in Figure 9. Cumulative calculated ETo for the fall was 76 mm. The cumulative calculated ETo for the TORO and ETM treatments were 84 mm and 86 mm respectively. Both ET-based controllers measured cumulative

ET values higher than the calculated reference ET from an onsite weather station. There was only a 2.4% difference between the cumulative ETo calculations for the two ET-based treatments with the ETM having the higher of the two readings. The ETM treatment also applied more water than the TORO treatment (36%). Total water applied by the treatment ETM was 205 mm and the calculated ETc was 188mm, which is a difference of 17 mm (8%). The total water applied by the TORO treatment was 131 mm, which is 57 mm (30%) less water than the calculated ETc.

Conclusion

Even though both seasons were relatively dry, all of the technologies tested managed to reduce water application compared to the 2-WORS treatment, with some treatments also maintaining acceptable turf quality. These experiments were performed during two relatively dry seasons when the treatments were expected to produce little water savings. The medium threshold SMS-based treatments produced water savings and good quality turf during both treatment periods. The highest overall water savings with high quality turf were seen in the ET-based treatments and the 2-DWRS. ET-based treatments managed to use between 36% and 59% less water than the control treatment 2-WORS. Time-based treatments in the spring showed that frequency may have an impact on quality of turf, with more frequent irrigation to a shallow depth providing higher quality but not necessarily higher water savings. The 2-DWRS treatment managed to provide good quality turf both seasons. With more frequent irrigation events it may be possible to increase the efficiency of irrigation application by allowing a more constant soil moisture level in time.

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Table 1. Irrigation treatment codes and descriptions.

Spring Treatment Code	Irrigation Frequency (days/ week)	Treatment Description	Fall Treatment Code	Irrigation Frequency (days/ week)	Treatment Description
SMS-Based			SMS-Based		
AC-7	2	Acclima 7% VWC	AC-7	2	Acclima 7% VWC
AC-10	2	Acclima 10% VWC	AC-10	2	Acclima 10% VWC
AC-13	2	Acclima 13% VWC	AC-13	2	Acclima 13% VWC
AC-7ind	2	Acclima 7% VWC ind rep	AC-7ind	2	Acclima 7% VWC ind rep
LL-2	2	Lawn Logic #2 setting	LL-4	2	Lawn Logic #4 setting
LL-5	2	Lawn Logic #5 setting	LL-5	2	Lawn Logic #5 setting
LL-8	2	Lawn Logic #8 setting			
Time-Based			Time-Based		
RS1-3mm	1	Rain Sensor 3 mm setting	RS1-3mm	1	Rain Sensor 3 mm setting
RS2-3mm	2	Rain Sensor 3 mm setting	RS2-3mm	2	Rain Sensor 3 mm setting
RS7-3mm	7	Rain Sensor 3 mm setting	RS7-3mm	7	Rain Sensor 3 mm setting
RS1-6mm	1	Rain Sensor 6 mm setting	RS1-6mm	1	Rain Sensor 6 mm setting
RS2-6mm	2	Rain Sensor 6 mm setting	RS7-6mm	7	Rain Sensor 6 mm setting
2-WRS	2	With rain Sensor	2-WRS	2	With rain Sensor
2-DWRS	2	Deficit WRS = 60% of WRS	2-DWRS	2	Deficit WRS = 60% of WRS
2-WORS	2	Without rain sensor	2-WORS	2	Without rain sensor
0-NI	0	Non-irrigated	0-NI	0	Non-irrigated
			ET-Based		
			ETM	2	ET Manager
			TORO	2	TORO WeatherTRAK

Table 2. Weekly irrigation depth and run time by month to replace historical ET

Month	January	February	March	April	May	June	July	August	September	October	November	December
Irrigation Depth (mm)	0	0	0	29	46	36	34	44	34	30	22	22
Run Time (min)	0	0	0	34	54	42	40	52	40	36	26	26

Table 3. Summary of Inputs for ET controllers

	TORO	ET Manager
Soil Type	Sandy	
Irrigation	Spray head	
Root Depth	6 inches	
Plant Type	Warm Season Turfgrass	
Sun Exposure	Sunny all day	NA
Application	Rate 2 inches/hr	Depth variable by month

Table 4. Cumulative irrigation depth applied to treatments, water savings compared to treatment 2-WORS, total number of irrigation events and percentage of irrigation events bypassed for spring (April 22, 2006 to June 30, 2006) and fall (September 23, 2006 to December 05, 2006) treatments.

	Spring					Fall				
Treatment Code	Total Irrigation (mm)	Water Savings Compared to 2-WORS (%)	Total No. Irrigation Events	Irrigation Events Bypassed (%)	End of Season Turf Quality	Total Irrigation (mm)	Water Savings Compared to 2-WORS (%)	Total No. Irrigation Events	Irrigation Events Bypassed (%)	End of Season Turf Quality
SMS-Based										
AC-7	178	40	12	40	4 *ab*	301	6	22	8	7 *a*
AC-10	265	11	18	14	6 *ab*	231	28	16	33	7 *a*
AC-13	316	-6	21	0	6 *ab*	287	10	21	13	7 *a*
AC-7ind	203	32	15	30	6 *ab*	162	49	11	54	7 *a*
LL-low	111	63	8	60	3 *bc*	*NA*	*NA*	*NA*	*NA*	*NA*
LL-med	237	20	16	27	7 *a*	265	17	20	17	7 *a*
LL-high	396	-33	23	8	7 *a*	*NA*	*NA*	*NA*	*NA*	*NA*
ET-Based										
ETM	*NA*	*NA*	*NA*	*NA*	*NA*	205	36	12	50	7 *a*
TORO	*NA*	*NA*	*NA*	*NA*	*NA*	131	59	17	29	7 *a*
Time-Based										
RS1-3mm	202	32	7	30	4 *ab*	225	30	8	36	6 *a*
RS2-3mm	232	22	16	20	5 *ab*	292	9	22	8	7 *a*
RS7-3mm	228	23	52	27	6 *a*	233	27	51	39	6 *a*
RS1-6mm	237	20	8	20	5 *ab*	224	30	8	33	6 *a*
RS2-6mm	240	19	16	20	6 *a*	*NA*	*NA*	*NA*	*NA*	*NA*
RS7-6mm	*NA*	*NA*	*NA*	*NA*	*NA*	296	8	67	20	6 *a*
2-WRS	266	11	18	10	5 *ab*	297	7	22	8	6 *a*
2-DWRS	192	36	17	15	6 *ab*	197	38	22	8	7 *a*
2-WORS	298	0	20	0	6 *ab*	320	0	24	0	6 *a*
0-NI	0	100	0	100	2 *c*	*NA*	*NA*	*NA*	*NA*	*NA*
CV (%)					29					17

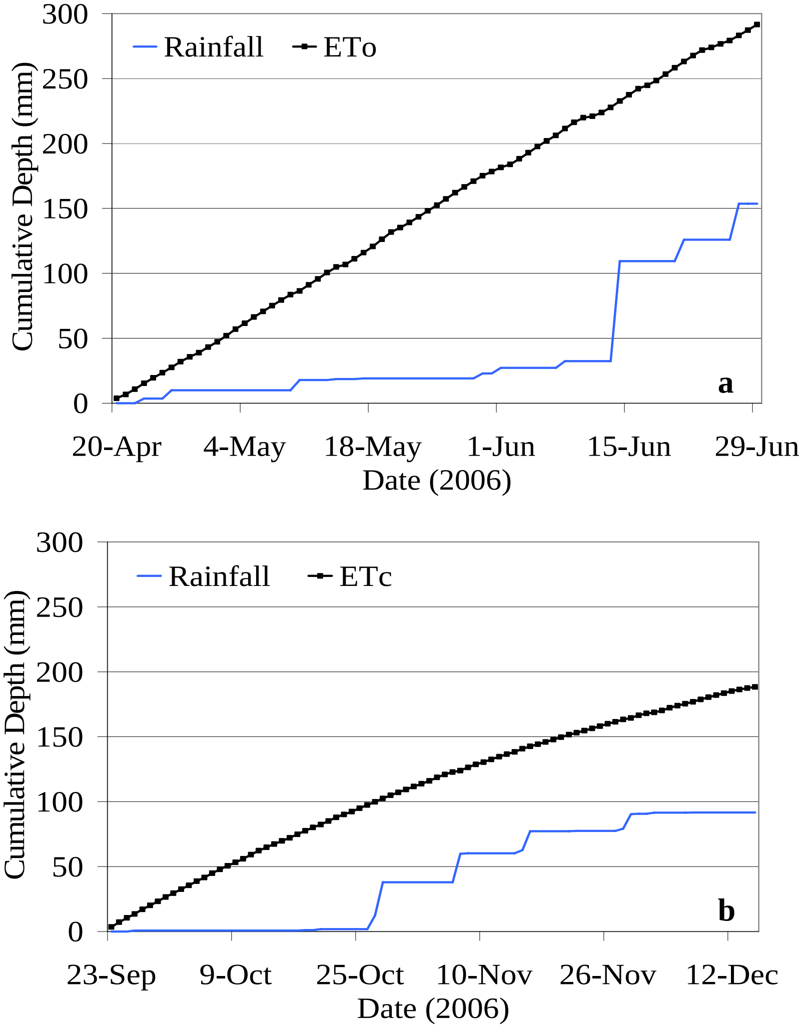

Figure 1. Graph showing the cumulative rainfall and ETc for the (a) spring and the (b) fall 2006 treatment periods.

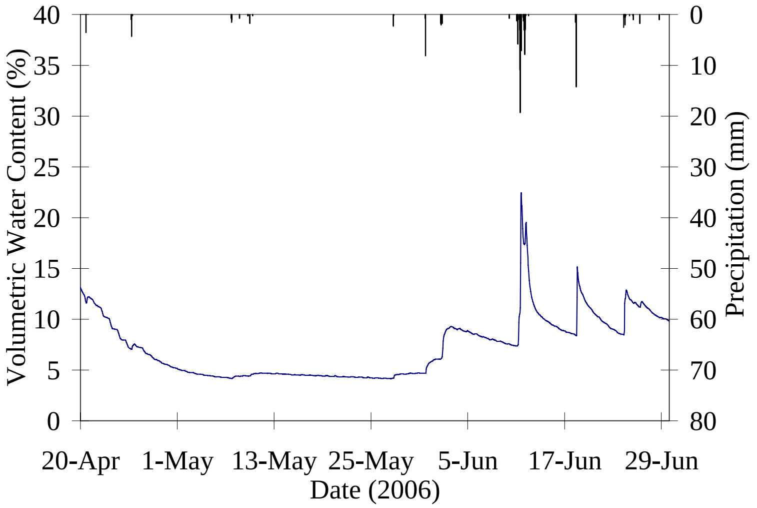

Figure 2. Volumetric moisture content and rainfall in a non-irrigated plot.

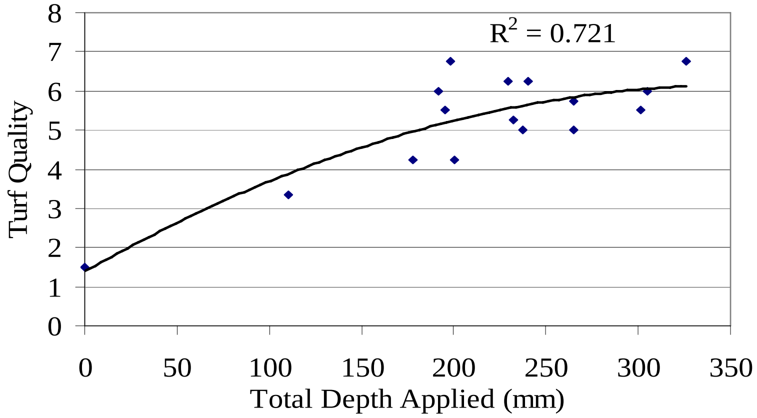

Figure 3. Graph showing the correlation between total depth of irrigation water applied and spring average turfgrass quality ratings.

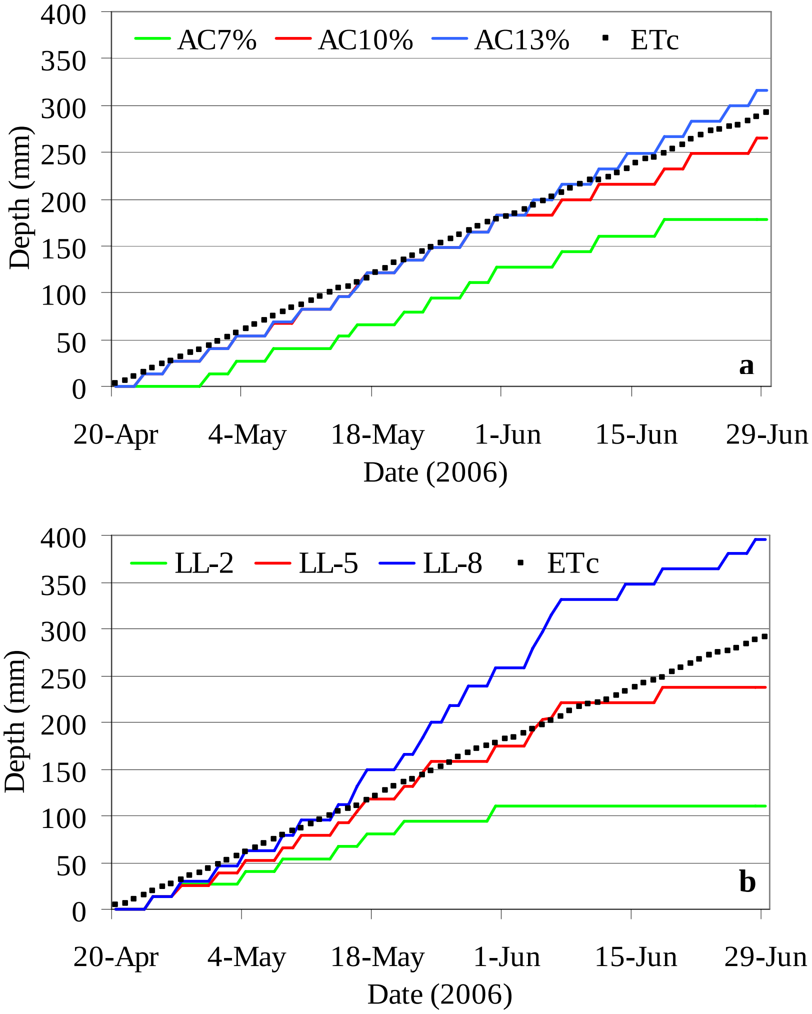

Figure 4. Graph of cumulative water use plotted alongside cumulative ETc for the treatments (a) AC-7, AC-10, AC-13 and (b) LL-2, LL-5 and LL-8 in the spring of 2006.

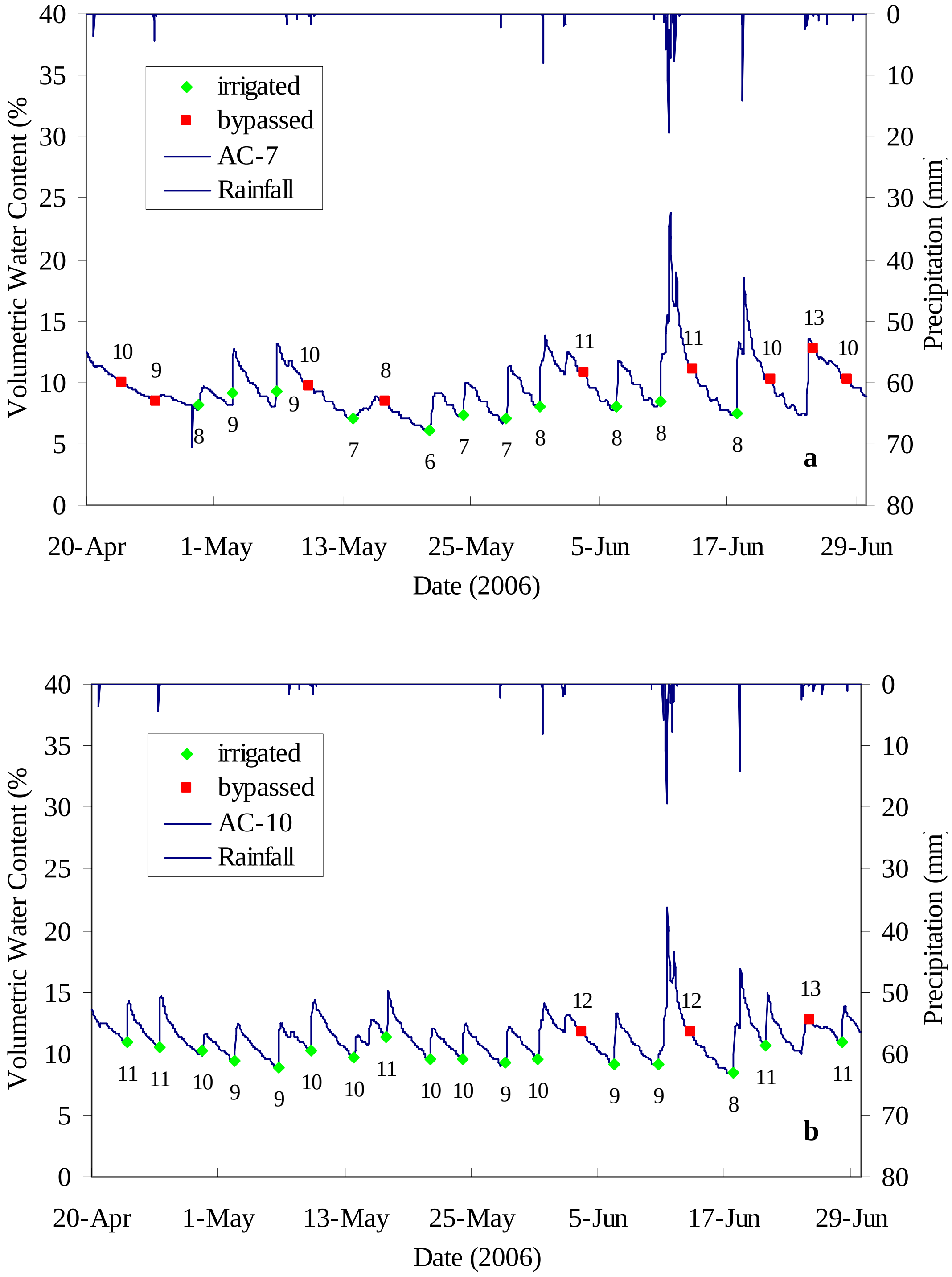

Figure 5. Plotted TDR data for spring 2006 for two treatments (a) AC-7 (b) AC-10. Irrigation events are marked with green diamonds and red squares and the VMC at the start of the event is listed next to it. Green diamonds represent events that were allowed by the sensor and red squares are events that were bypassed by the sensor.

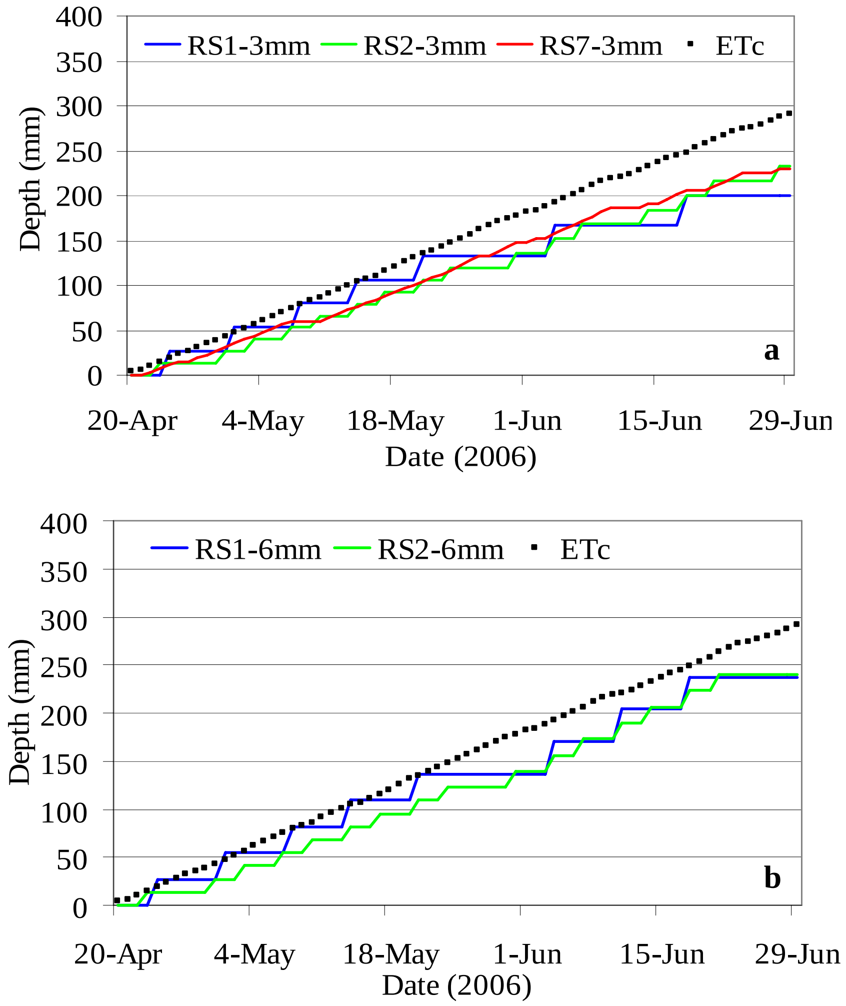

Figure 6. Graph of cumulative water use and ETc for time-based irrigation system treatments (a) RS 1-3mm, RS 2-3mm, RS 7-3mm and (b) RS 1-6mm and RS 2-6mm.

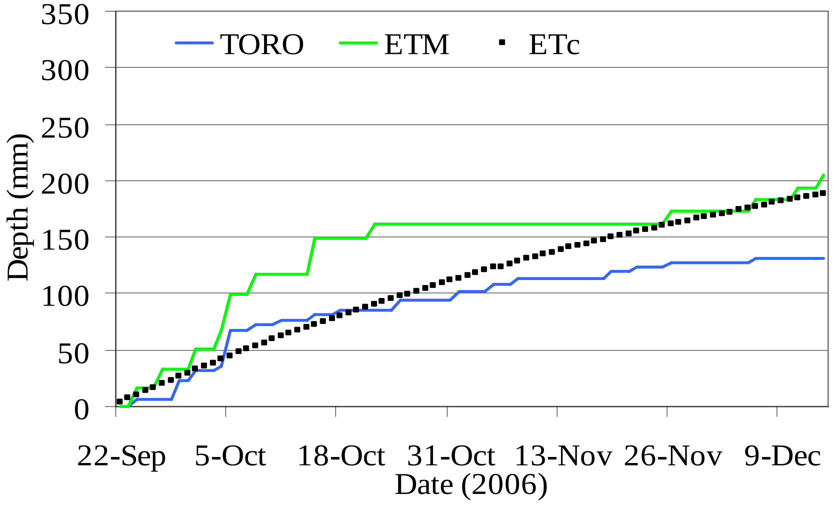

Figure 7. Graph of cumulative water use for Toro and ET Manager treatments plotted alongside cumulative ETc for the fall of 2006.

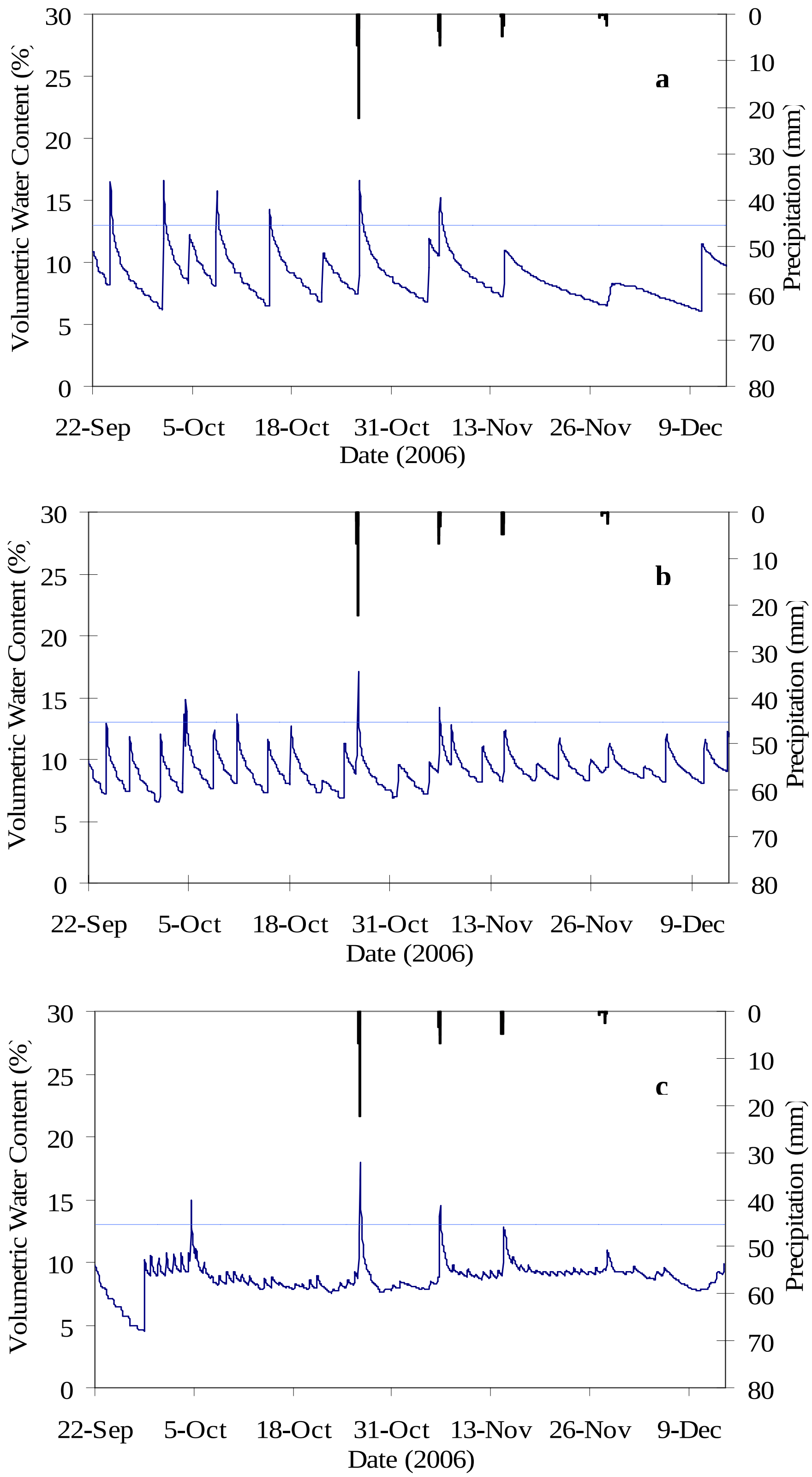

Figure 8. Plotted TDR data for treatments (a) RS1-3mm (b) WRS (c) RS7-6mm blue lines indicate 13% VMC.

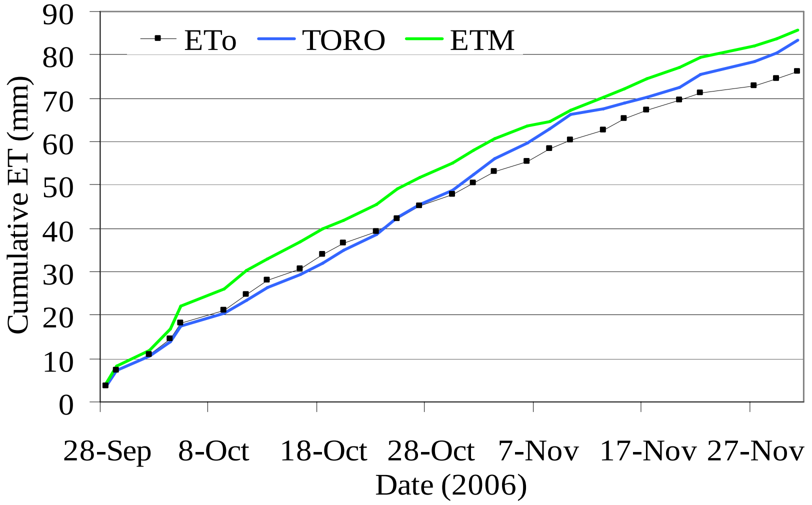

Figure 9. Comparisons between ETo measured by TORO and ETM controllers against calculated values of ETo.