Water Conservation from Precise Irrigation Scheduling Using a Subsurface Electromagnetic Soil Moisture Sensor

J.M. Blonquist Jr.*, S.B. Jones andD.A. Robinson
Dept. of Plants, Soils and Biometeorology, Utah State University, Logan, Utah, USA.
*Corresponding Author; Email: (jmarkb@cc.usu.edu)

Abstract

Instrumented weather stations are often used for evapotranspiration (*ET*) prediction in order to estimate crop water use for irrigation scheduling. A direct estimate of crop water use by subsurface measurements of soil water content has been limited by the high cost of reliable soil moisture sensors. Recent advances in electromagnetic (EM) sensor technology have made automated irrigation scheduling based on state-of-the-art soil moisture sensing capability a reality. Our objectives were: i) to compare irrigation scheduling based on weather station *ET* estimates with those from a novel time domain transmission (TDT) soil moisture sensor, and ii) to apply a computer-based numerical model to simulate any drainage occurring below the plant rooting depth. The TDT sensor was designed to schedule irrigation based on a threshold θ value (θ_{Thresh}). The sensor circuitry controlled the irrigation schedule by allowing a preprogrammed schedule to operate whenever the sensor-estimated θ (θ_{Sensor}) dropped below θ_{Thresh}. The TDT sensor was installed under Kentucky bluegrass with a nearby weather station providing estimates of *ET* for comparison over a period of approximately seven weeks. The HYDRUS-2D numerical simulation model was used for predicting drainage in the soil profile. The model input requirements include the flow domain geometry and boundary conditions, along with estimates of evaporation, transpiration, precipitation, irrigation and root water uptake data. Relative to *ET*-based irrigation recommendations, the TDT system applied approximately 16% less water when irrigating with a sprinkler having an efficiency of 0.80, and relative to a fixed irrigation rate of 5 cm week^{-1}, the TDT system applied approximately 53% less water. Modeling results of the TDT sensor control indicated that no detectable water drained below the estimated 30 cm rooting depth of turf grass when uncontrolled application events (e.g. rainfall) were ignored. Performance of the TDT system is dependent on the sensor burial depth and θ_{Thresh}. The θ_{Thresh} value is soil-type dependent and should be established via consideration of θ at field capacity and permanent wilting point. The potential water savings with the TDT system is not only important to water conservation, but can save irrigators an estimated $5.00-$100.00 per month based on average water prices in the US and a 1000 m^2 irrigated turf grass plot.

Introduction

Water conservation in relation to crop and turf grass irrigation has recently received much attention, especially in the Western United States, where extensive growth coupled with drought conditions in recent years has reduced the amount of water available for irrigation use (Ervin and Koski, 1998; Kjelgren et al., 2000). Environmental measurements such as evapotranspiration (Allen et al., 1998) and soil water content (Topp and Ferre, 2002) are gaining more utility as a means to infer plant water use and to properly schedule agricultural, municipal and residential irrigation. Such measurements not only conserve water, but also save growers and irrigators money by ensuring that plants are not excessively irrigated.

In situ soil water content estimates are accomplished using a variety of methods and sensors (Or and Wraith, 2002). Measurements and estimates of water content for use in irrigation scheduling have in the past been performed via gravimetric, neutron scattering, gypsum block and tensiometer methods. In recent years, water content estimates have advanced to include electromagnetic (EM) techniques such as time domain reflectometry (TDR) (Topp et al., 1980; Topp and Ferre, 2002; Robinson et al., 2003), time domain transmissometry (TDT) (Topp et al., 2001; Harlow et al., 2003; Hook et al., 2004; Blonquist et al., 2005a), transmission line oscillators (Campbell and Anderson, 1998; Seyfried and Murdock, 2001; Kelleners et al., in review), impedance- (Hilhorst et al., 1993; Gaskin and Miller, 1996; Hilhorst, 2000; Seyfried and Murdock, 2004) and capacitance-based approaches (Dean et al., 1987; Paltineanu and Starr, 1997; Kelleners et al., 2004; McMichael and Lascano, 2004).

Estimates of water content based on EM measurements provide real time, in situ measurements at a relatively affordable cost. Estimation of water content using EM sensors is based on the ability of sensors to measure the real part of the dielectric permittivity (ε), or an EM signal property directly relating to ε, which directly relates to volumetric soil water content (θ) owing to the ε contrast of soil constituents; $\varepsilon_a \approx 1$, $\varepsilon_s \approx$ 2-9 and $\varepsilon_w \approx$

80; where the subscripts *a*, *s* and *w* represent air, solids and water, respectively. The potential of EM θ sensors in irrigation scheduling has been demonstrated (Qualls et al., 2001; Paul, 2002; Leib et al., 2003).

The objectives of this research were: i) to compare cumulative water applications with irrigation scheduling based on evapotranspiration estimates from a weather station to scheduling based on soil moisture estimates from a time domain transmission (TDT) sensor, and ii) to apply a computer-based numerical model to simulate the water balance in the soil profile and estimate any drainage occurring below the plant rooting depth.

Materials and Methods

The Acclima® Digital TDT Sensor is a transmission line sensor that estimates θ based on bulk soil ε measurements, and has been shown to provide exceptional ε measurement accuracy when compared to research grade instrumentation (Blonquist et al., 2005a; Blonquist et al., 2005b). In order to make θ estimations and control irrigation, the Acclima Digital TDT Sensor must be connected to a custom controller; the Acclima CS3500 or Acclima RS500; in which is programmed a threshold soil water content value (θ_{Thresh}). The sensor makes continuous θ estimates, which are retrieved by the controller, and when the sensor estimates θ below θ_{Thresh}, the controller operates a preprogrammed irrigation schedule within the controller.

An Acclima Digital TDT Sensor was installed in an approximately 280 m^2 field plot of Kentucky bluegrass on the Utah State University Greenville Research Farm located in North Logan, Utah, USA. The sensor was installed in the soil horizontally with respect to the ground surface, approximately in the middle of the plot. The placement depth of the sensor was approximately 10 cm (Figure 1). The cross-section (Figure 1) displays the sensitivity of the sensor, or the soil cross-section in which 90% of the electromagnetic energy contributing to the θ estimation is contained. The sensor head measures approximately 9.0 cm in the horizontal direction and 2.0 cm in the vertical direction (Figure 1), which gives indication of the volume of soil contributing to the measurement, but the sensor is much more sensitive to the soil immediately surrounding the probe where the darker shaded area represents a greater concentration of electromagnetic energy (Figure 1). The θ_{Thresh} value was estimated using field capacity θ and permanent wilting point θ values for the soil type in the field plot and Kentucky Bluegrass. The θ values at field capacity and permanent wilting point for the soil were estimated to be 0.24 and 0.08, respectively, and the θ_{Thresh} value was estimated as 0.16, halfway between field capacity and permanent wilting point.

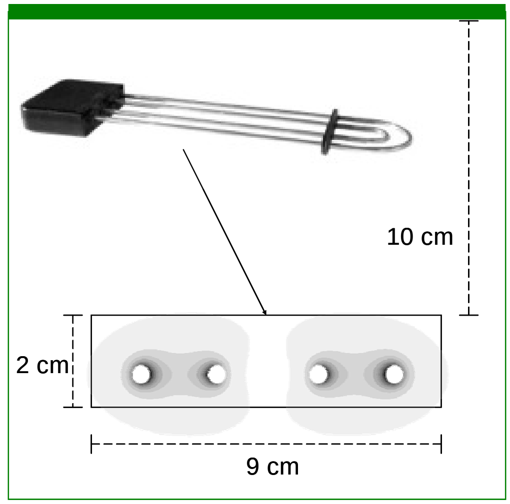

Figure 1. Cross-section of the TDT sensor oriented horizontally in relation to the ground surface. The cross-section shows the four rods and the area containing 90% of the electromagnetic energy that contributes to the measurement (gray-scale). The solid line surrounding the rods represents the sensor head and the approximate outer dimensions are outlined in black and labeled. The soil contributes less to the measurement further from the rods as indicated by the gray intensity scale, thus the water content estimation is largely dependent on soil properties adjacent to the rods.

Initially, irrigation was accomplished using a single impact sprinkler head (Rainbird® 30IBH with a 3/16” nozzle) outputting approximately 480 $cm^3\ s^{-1}$ (7.6 gpm), but midway through the experiment the sprinkler was changed to a lower flow rate gear-driven sprinkler head (Hunter® PGP with #9 nozzle) outputting approximately 375 $cm^3\ s^{-1}$ (5.9 gpm). The change was made in order to improve application efficiency. The application efficiencies of the impact and gear-driven sprinkler heads at the position of the TDT sensor, approximately 5.5 m from the sprinkler, were estimated at 0.50 and 0.80, respectively, by dividing the flow rate at the sprinkler head by the application rate measured at the position of the TDT sensor.

The experiment was conducted over a period of forty-nine days from July 30 through September 16, during which θ_{Sensor} and irrigation event data were estimated and logged with the CS3500 Controller. Evapotranspiration and precipitation were estimated and logged with a Campbell Scientific ET106 Evapotranspiration Station operated by Utah State

University and used by the State of Utah's Division of Water Resources to determine irrigation recommendations. The CS106 calculates *ET* via inputs from meteorological sensors onboard the station. The weather station is located approximately 200 m from the experimental plot under similar conditions over a large Kentucky bluegrass plot, thus the data supplied by the weather station are considered representative of the experimental plot.

We compared recommended irrigation amounts (including precipitation) based on *ET* estimates from the weather station to the actual amount of water applied to the plot using the θ estimates made with the TDT sensor, where the impact sprinkler head was used from July 31 to August 15 and the gear-driven sprinkler head was used from August 16 to September 16. We also compared irrigation amounts when applying water at a fixed rate of 5 cm week^{-1} over the duration of the experiment to the water applied using the TDT system. In addition to comparing irrigation amounts, we applied a computer program, HYDRUS-2D Model (Šimůnek et al., 1999), to simulate and compare drainage below the plant rooting depth under the three described irrigation strategies (recommendations based on weather station, TDT sensor θ estimates and 5 cm week^{-1}).

Results and Discussion

The ability of the TDT system to maintain θ above the established θ_{Thresh} is indicated by the field data presented in Figure 2 where changes in θ, irrigation events with the TDT system (water amount that the plot actually received) and recommended irrigation events (water amount the plot would have received had the recommendations been used) based on *ET* estimates from the weather station are plotted versus time (July 30-September 16).

The only time the sensor-estimated θ value did not increase following an irrigation event,

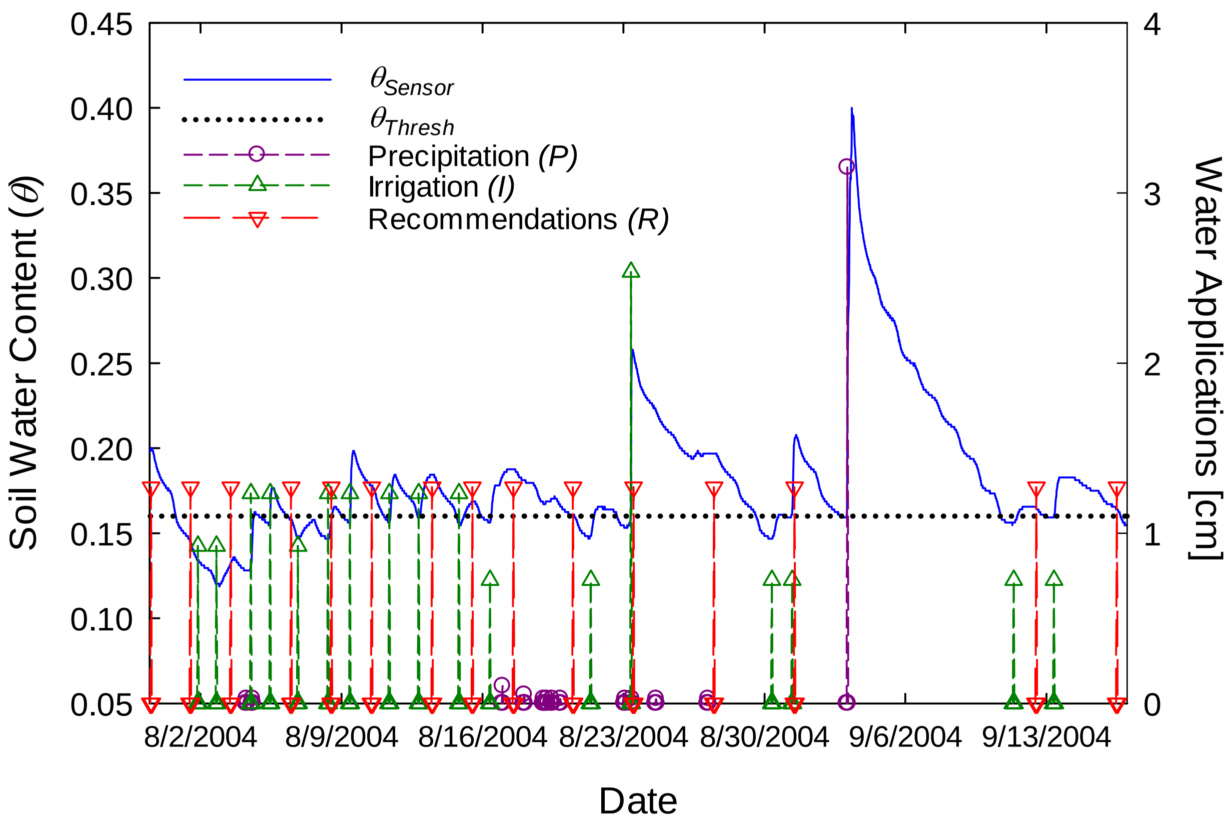

Figure 2. Volumetric soil water content estimated by the TDT sensor (θ_{Sensor}), threshold soil moisture content (θ_{Thresh}), irrigation, precipitation and irrigation recommendation events plotted over the entire experimental period (July 30-September 16). The θ values correspond to the left-hand y-axis and irrigation, precipitation and irrigation recommendation correspond to the right-hand y-axis.

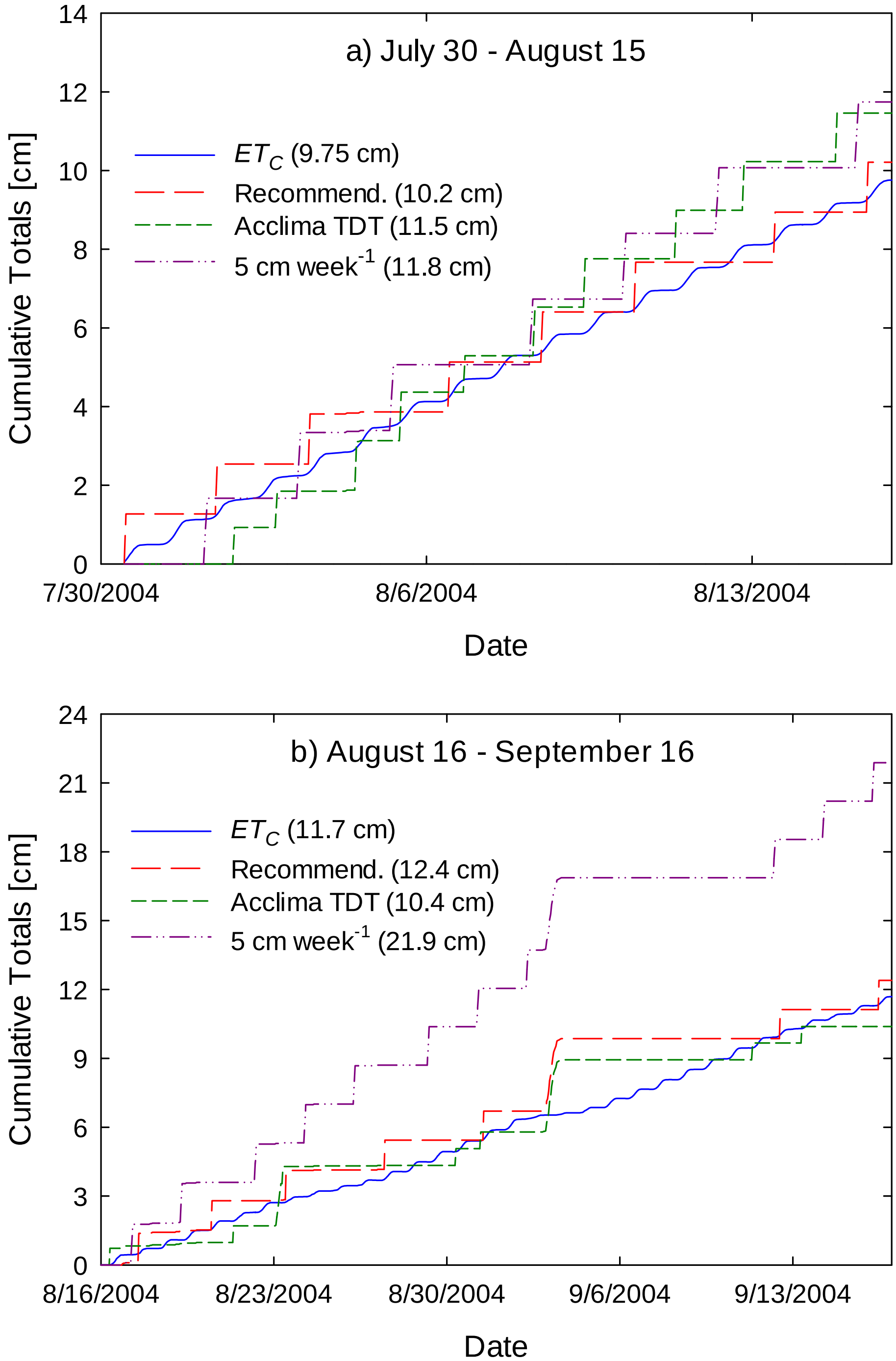

Figure 3. Cumulative crop evapotranspiration (ET_C) calculated from the weather station's *ET* estimates, cumulative irrigation recommendation (plus precipitation) based on ET_C and cumulative irrigation (plus precipitation) applied with the TDT system plotted from a) July 30-August 15 (impact sprinkler; 0.50 efficiency) and b) August 16-September 16 (gear-driven sprinkler; 0.80 efficiency). The cumulative totals at the end of each period are given in parentheses.

Table 1. Cumulative irrigation amounts and water conservation percentages using the Acclima Digital TDT Sensor to schedule irrigation.

	July 30-Aug. 15	Aug. 16-Sept. 16
Cumulative Amounts [cm]:		
ET_C	9.75	11.7
Recommendation	10.2	12.4
TDT System	11.5	10.4
5 cm week^{-1}	11.8	21.9
Water Conserved†:		
TDT vs. *ET*	-18%	11%
TDT vs. Recommendation	-13%	16%
TDT vs. 5 cm week^{-1}	2.5%	53%

†The percentages are for the TDT system relative to actual crop water use (*ET*) estimated with the weather station's *ET* estimates, recommendations based on *ET* and applying a fixed rate of 5 cm week^{-1}. Positive values indicate water conservation and negative values indicate over-application of water.

indicating the applied irrigation water did not reach the sensor, was on August 1 after which two irrigation events were required to bring θ back above θ_{Thresh}. The only times the sensor-estimated θ value dropped below θ_{Thresh} and remained below θ_{Thresh} following irrigation events was on August 1, 2 and 6. The reason the applied irrigation water did not reach the sensor on August 1, and the reason for θ_r not being recharged to a level above θ_{Thresh} following the irrigation events on August 1, 2 and 6, is attributed to the shorter irrigation durations (i.e. smaller water applications) and the lower efficiency of the impact sprinkler (0.50).

For comparison, cumulative *ET*, irrigation with the TDT system and recommended irrigation amounts are plotted versus time for July 30-August 15 when the impact sprinkler head was used (Figure 3a) and for August 16-September 16 when the gear-driven sprinkler head was used (Figure 3b). The cumulative values at the end of each time period are also listed (Table 1). After the first time period (July 30-August 15), approximately 1.3 cm of water in excess of the irrigation recommendations was applied by the TDT system, yielding an over-application of 13% relative to the recommendation (Table 1). After the second time period (August 16-September 16), approximately 2.0 cm of water was conserved by the TDT system, applying 16% less water (Table 1) relative to the irrigation recommendations. As a further comparison, the cumulative irrigation totals are listed in Table 1 assuming an average

Table 2. Average water cost in the US and in six cities in the Western US, and potential dollars saved per month using the TDT sensor to schedule irrigation.

Water Conserved Relative to Recommendation = 18.8 m^3 month^{-1}†			
Water Conserved Relative to 5 cm week^{-1} = 108 m^3 month^{-1}†			
City	**Water Costs [$ m^{-3}]**	**Savings Relative to Recommendation‡ [$ month^{-1}]**	**Savings Relative to 5 cm week^{-1}‡ [$ month^{-1}]**
US Average	0.52	9.78	56.06
Denver	0.45	11.12	63.72
Las Vegas	0.40	5.31	30.45
Phoenix	0.28	7.52	43.10
Salt Lake City	0.36	8.42	48.25
Spokane	0.39	6.76	38.71
Tucson	0.59	7.01	40.16

†Water conserved per month value is calculated by taking the difference between the cumulative irrigation amounts reported in Table 1 and multiplying by a 1000 m^2 area (assumed value for the average size of a lawn).
‡Savings will vary with the size of plot being irrigated; calculations here are based on a 1000 m^2 area.

summertime peak residential irrigation rate of 5 cm week^{-1}. We assume this application rate is not reduced due to user negligence, even though *ET* rates decrease later in the season. Compared to this constant irrigation rate, the TDT system reduced water applications by 0.3 cm and 11.5 cm from July 30-August 15 and August 16-September 16, respectively, yielding 2.5% and 53% water savings, respectively.

By multiplying the 2.0 cm (0.02 m; relative to recommendations) and 11.5 cm (0.115 m; relative to 5 cm week^{-1}) of water conserved for the second time period (August 16-September 16) by the area of a larger plot, 1000 m^2, and converting the time period to months, this translates to 18.8 m^3 month^{-1} and 108 m^3 month^{-1} of water savings relative to the irrigation recommendations and fixed irrigation rate, respectively. These values can be multiplied by average water prices to estimate the amount of money saved over the course of a month via irrigation scheduling with the TDT system (Table 2) relative to irrigation recommendations and a fixed irrigation rate.

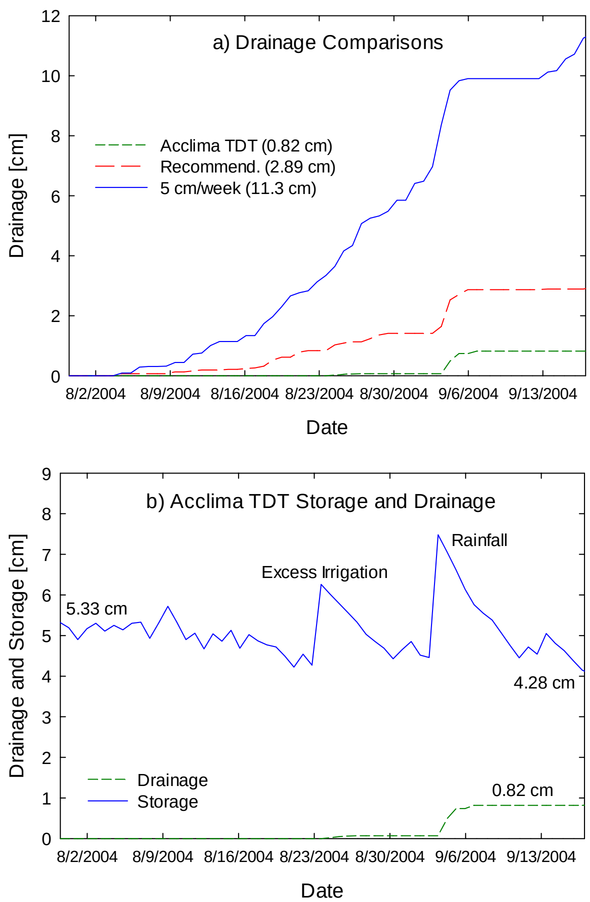

Figure 4. HYDRUS-2D predictions of a) drainage below the plant rooting depth (30 cm) in the profile for irrigation with the TDT system, the recommendation based on weather station *ET* estimates and a fixed application rate of 5 cm week^{-1}, and b) soil water storage over the entire time period of the experiment irrigating with the TDT system showing the drainage from a) only occurs when soil storage increases significantly following major water application events (August 23 and September 3) (beginning and ending values of storage are reported on the plot).

Using the HYDRUS-2D model the water balance for the plot was solved to calculate the change in soil water storage (ΔS). This value was used with irrigation, precipitation and *ET* values in order to estimate the drainage (*DR*) from the plant rooting depth of the profile. The *DR* values for irrigation with the TDT system, recommendations based on the weather station *ET* estimates and a fixed irrigation rate of 5 cm week^{-1} are plotted for comparison (Figure 4a). The simulation comparisons indicate no drainage would have occurred based on irrigation control with the TDT sensor, but with one excess irrigation event and rainfall, drainage was 0.82 cm. using the *ET*-based irrigation recommendations, intermediate drainage of 2.89 cm occurred and significant drainage of 11.3 cm occurred with the fixed irrigation rate of 5 cm week^{-1}. To illustrate when the drainage occurs, ΔS in the plant rooting depth of the profile was simulated for the TDT system, and is plotted along with *DR* (Figure 4b). This shows that drainage occurs when large amounts of water are applied to the plot, immediately following large irrigation or precipitation events (Figure 3; August 23 and September 3). The ΔS (Figure 4b) also confirms the TDT system's ability to maintain a relatively constant amount of water in the soil profile.

The soil volume from which the sensor derives a measurement (Figure 1) and the rooting depth of the crop must be considered when determining the depth to which the sensor is buried. Several studies have been performed to demonstrate the importance of sensor burial depth under different crops with differing irrigation methods (Haise and Hagan, 1967; Phene and Howell, 1984; Stieber and Shock, 1995; Coelho and Or, 1996). Burying the sensor too shallow will likely lead to too frequent irrigations owing to the relatively short drying time of the surface soil, while burying the sensor below the crop rooting depth will likely lead to too infrequent irrigations owing to the increased time required for deeper soil to dry. To illustrate these points, 1.27 cm of water (considered an average value for a single irrigation event) was applied to the profile and θ over the 30 cm plant rooting depth was plotted at different times for up to four days following the irrigation event (Figure 5). The data show that the θ contrast with time decreases significantly with profile depth. Below a profile depth of 20 cm, less than 0.03 θ units separate the entire range of θ_{Sim} values at different times, whereas between 0 and 10 cm at least 0.08 θ units separate the entire range θ_{Sim} values at different times. Keeping in mind that the root distribution density for the turf grass was maximum in the top 5 cm, sensors located too deep in the profile run the risk of a time lag response, leading to excess drying near the surface and potential drainage below the root zone. Also, if the sensor burial depth is increased, θ at the sensor increases and there is a narrower θ range between irrigation events. If the sensor burial depth is decreased, θ at the sensor decreases and there is a wider θ range between irrigation events. This indicates that as the burial depth of the sensor increases θ_{Thresh} should increase owing to a greater time requirement for deeper soil to dry, and as the burial depth of the sensor decreases θ_{Thresh} should

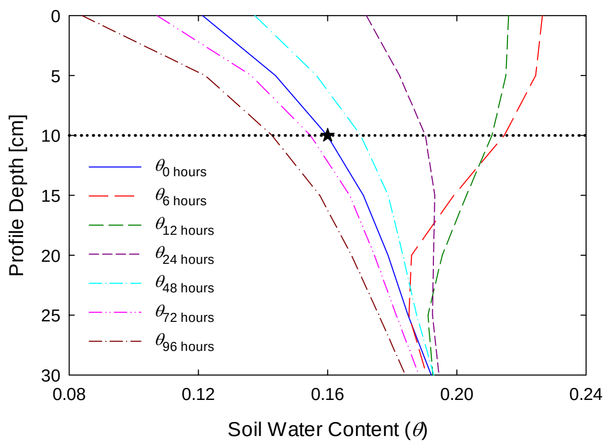

Figure 5. Simulated soil water contents (θ) in the plant rooting depth (0-30 cm) of the profile immediately before (0 hours) a water application of 1.27 cm and at several times (6-96 hours) following the application, showing the relationship between the threshold water content (θ_{Thresh}) and the sensor burial depth. The dotted horizontal line shows a burial depth of 10 cm and the star shows marks the threshold water content (θ_{Thresh}) of 0.16. As the burial depth of the sensor increases θ_{Thresh} should increase owing to a greater time requirement for deeper soil to dry, and as the burial depth of the sensor decreases θ_{Thresh} should decrease owing to a smaller time requirement for shallower soil to dry.

decrease owing to a smaller time requirement for shallower soil to dry. Under this simulation, increasing burial depth while keeping θ_{Thresh} equal to 0.16, would increase the time between irrigation events, whereas decreasing burial depth decreases time between irrigation events. At a constant depth, if θ_{Thresh} is increased, less time elapses between irrigation events and water is applied more often, and if θ_{Thresh} is decreased, more time elapses between irrigation events and water is applied less often.

In addition to depth, sensor placement with respect to location within a given plot is a critical factor to consider. In this experiment the sensor was located in the middle of the plot owing to the plot homogeneity. Sensor placement within a plot characterized by soil or microclimatic heterogeneities (e.g. differing soil textures; vegetation or structures shading areas) should be considered in light of conditions and the sensor should be placed in the driest area of the plot. As discussed above, irrigation should recharge θ in order to maintain θ_{Sensor} above an established θ_{Thresh} and balance *ET*. In heterogeneous plots this can be difficult via a single irrigation system, thus to ensure all areas within the plot receive required water amounts, irrigation should be controlled using the driest area. Ideally, different irrigation zones can be established for the same plot with zone delineations being based on soil and microclimatic heterogeneities. All zones are controlled by a single sensor within the driest zone and necessary irrigation adjustments (e.g. irrigation event duration) can be made to those zones outside the driest zone. Herein lies another advantage of θ estimations in irrigation scheduling, they are site-specific, whereas *ET* estimates derived from weather stations are often applied to sites far from the stations where climatic conditions may be different.

Conclusions

Electromagnetic (EM) measurements of bulk soil permittivity (ε) provide a means to estimate volumetric soil water content (θ), and therefore storage within the plant root zone, and directly infer evapotranspiration (*ET*) for use in irrigation scheduling. The Acclima Digital TDT Sensor is an EM-based θ sensor that provides exceptional ε measurement accuracy at a reduced cost. The sensor can be employed to schedule irrigation via connection to custom irrigation controllers. A threshold θ value (θ_{Thresh}) must be determined via consideration of soil properties and crops to be grown, and is programmed into the custom controller. The controller operates the irrigation system via communication with the sensor in response to θ changes with respect to θ_{Thresh}. When a gear-driven sprinkler head having an efficiency of 0.80 was used with the TDT sensor for irrigation control and scheduling, 16% less water was applied relative to using irrigation recommendations based on *ET* estimates from a weather station and 53% less water was applied using a fixed irrigation rate of 5 cm week^{-1}, thus conserving water and saving money. Despite the reduced application of water relative to irrigation recommendations, the grass plot was healthy and did not show signs of water stress. Performance of the system is dependent on the burial depth of the sensor and θ_{Thresh}. The θ_{Thresh} value is soil type dependent and should be established via consideration of θ at field capacity and permanent wilting point.

A numerical computer model (HYDRUS-2D) was used with estimated irrigation and precipitation inputs and estimated *ET* outputs to solve the soil profile water balance and predict drainage occurring below the estimated plant rooting depth of 30 cm. The simulated drainage from the 30 cm plant rooting depth in the soil profile was small for the TDT system, 0.82 cm, and only occurred following uncontrolled water application events. Drainage with the irrigation *ET*-based recommendations was intermediate, 2.89 cm, and drainage with the fixed irrigation rate was significant, 11.3 cm. The model provides a useful irrigation research tool for estimating the amount of water draining below the plant rooting depth and in demonstrating how θ_{Thresh} may vary with the sensor burial depth.

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