A Novel Electromagnetic Soil Moisture Sensor for Automated Irrigation Scheduling

J.M. Blonquist Jr.*

S.B. Jones

D.A. Robinson

Dept. of Plants, Soils and Biometeorology, Utah State University, Logan, Utah, USA.

*Corresponding Author

Email: (jmarkb@cc.usu.edu)

A Novel Electromagnetic Soil Moisture Sensor for Automated Irrigation Scheduling

Abstract

Instrumented weather stations are often used for evapotranspiration (*ET*) determination in order to estimate crop water use for irrigation scheduling. A direct measurement 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 coupled with improved analysis and communications capabilities has made automated irrigation scheduling based on state-of-the-art soil moisture sensing capability a reality. Our objective was to compare *ET*-based irrigation scheduling with a novel time domain transmission (TDT) soil moisture sensor. The TDT sensor is designed to directly connect to custom irrigation controllers and conventional irrigation timers and controls irrigation via an easily set threshold soil water content value (q_{Thresh}). The sensor circuitry allows the irrigation controller to operate its normal irrigation schedule whenever the estimated soil water content (q) drops below q_{Thresh}. The TDT sensor was installed under a small plot (~ 280 m^3) of Kentucky bluegrass. A nearby weather station provided estimates of *ET* for comparison. Relative to *ET*-based irrigation recommendations the TDT-based system conserved approximately 10.0 m^3 of water per month irrigating with a lower flow sprinkler head. Performance of the TDT-based system is dependent on the burial depth of the sensor and the q_{Thresh} value. The q_{Thresh} value is soil dependent and should be established via consideration of soil q at field capacity and permanent wilting point. The potential water savings with the TDT-based system is not only important to water

conservation, but can save irrigators money estimated at $10.00-$20.00 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 have reduced the amount of available water for irrigation use. Environmental measurements such as evapotranspiration and soil water content are gaining more utility as means to infer plant water use and 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 over-watered.

1.1 Energy Balance and Evapotranspiration

Evapotranspiration estimates are based on measurement of daily energy balance components according to the energy balance equation for an evaporating surface:

$$R_n = LET + H + G \qquad [1]$$

where R_n is net heat (radiation) flux; LET is the latent heat flux, coupling the latent heat of vaporization (L) and evapotranspiration (ET) term; H is sensible heat flux; G is the soil heat flux and all terms are in W m^{-2}. Energy balance components R_n, G and H are measured directly or estimated from meteorological data. Rearrangement of Eq. [1] to solve for LET allows for calculation of potential ET (ET_0) by dividing LET by the latent heat of vaporization (L) and the density of water (r_w) according to:

$$ET_0 = \frac{LET}{L \cdot r_w}, \quad [2]$$

where ET_0 is in m s^{-1} (daily potential ET_0 is derived by multiplying the ET_0 calculated in Eq. [2] by 86400 s), L is in J kg^{-1} and r_w ~ 1000 kg m^{-3}.

A mass transfer method is often used to estimate ET_0 values wherein the ratio of H to LE, known as the Bowen Ratio (Bowen, 1926), is calculated from the vertical gradients of air temperature and specific humidity, and is used in conjunction with R_n and G measurements to calculate ET_0. Penman (1948) combined the energy balance and with the mass transfer method to derive an equation which uses meteorological parameters; solar radiation, temperature, humidity and wind speed; to calculate ET_0 from an open-water surface. Penman's combination equation (Penman, 1948) was further developed by Monteith (1981); called the Penman-Monteith combination equation. The Penman-Monteith combination equation includes resistance factors accounting for aerodynamic and surface vapor flow resistance at soil and leaf surfaces and through leaf stomata, and allow the method to be used when considering cropped surfaces. The accepted standard method for ET_0 estimation is the FAO-56 Penman-Monteith combination equation (Allen et al., 1998), which is a modification of the Penman-Monteith combination equation (Monteith, 1981), using standard values for the reference surface and employing standard methods for the resistance factor calculations.

Irrigation recommendations are based on daily ET_0 values estimated from weather station data employing one of the described methods and are plant dependent owing to water use efficiencies varying with plant type. Plant water use efficiencies are dependent on the growth stage of the plant and soil water content (q) conditions (Jensen et al., 1990), and are accounted for with the use of dimensionless factors called crop coefficients (K_c):

$$K_C = \frac{ET_C}{ET_0}, \qquad [3]$$

where ET_C [m s^{-1}] is actual crop ET and ET_0 characterizes the evaporative demand determined by local conditions (i.e. meteorological and surface conditions). Essentially, K_C gives indication of a specific crop/soil surface's ability to meet ET_0 (Jensen et al., 1990) and is multiplied by ET_0 to yield ET_C (i.e. rearrange Eq. [3] to solve for ET_C). Thus ET_C is the amount of irrigation water a given crop should receive in order to meet it's water use demands.

1.2 Water Balance and Soil Water Content

While ET_C is estimated from ET_0 estimates from weather stations and empirically determined K_C values, q estimates yield direct estimates of plant water use (i.e. ET_C) from a given depth of soil. For irrigation purposes this soil depth is considered the rooting depth of the plant. Estimates of q are a direct approximation of the change in soil water storage (DS) in the water balance equation:

$$I + P = ET + RO + DR + \Delta S, \qquad [4]$$

where I and P are irrigation and precipitation, respectively, and represent inputs to the system; ET, RO and DR are evapotranspiration, runoff and drainage, respectively, and generally represent outputs of the system. All terms in Eq. [3] have dimensions of length (i.e. depth) and are interpreted as positive water depths for inputs to the soil and negative water depths for outputs of the soil.

Water-wise irrigation aims to match ET via accounting for P and inputting enough irrigation water (I) to the system to yield a relatively constant DS. If RO and DR can be considered negligible and DS only changes as ET removes water and as I and P replenish water (i.e. no lateral water flow into the soil) then the water balance can be rewritten as:

$$\Delta S = I + P - ET \text{ ,} \tag{5}$$

where positive and negative DS indicate net water gain and loss from the soil, respectively. Over short time periods, DS fluctuates moderately, increasing immediately following I and P events and decreasing as ET occurs between I and P events, but over long time periods remains relatively constant. Thus, between I and P events, q estimates yield direct estimates of ET at the plant root zone:

$$ET = \Delta S = \Delta q \cdot D \text{ ,} \tag{6}$$

where D is the rooting depth of the plant and is a length value. This assumes the estimated q represents the average q across the plant root zone. Conversely, ET_C yields only an estimate of ET in the water balance via weather station ET_0 measurements and K_C values from empirical determinations.

Matching ET via irrigation scheduling with q estimates mandates selection of a threshold q value (q_{Thresh}) to which the soil is allowed to dry before the next I event. This value is soil and plant dependent and should be established by considering soil q at field capacity and permanent wilting point. Field capacity is the q at which gravitational water drainage is balanced by soil matric (suction) forces; as water in excess of field capacity drains it is not available to plants. Permanent wilting point is the q at which plants can no longer overcome soil matric forces in order to extract their required water amount and permanent wilting results. The average field capacity is generally taken as q at -0.033 MPa matric potential (negative pressure) and the average permanent wilting point is generally taken as q at -1.5 MPa matric potential. The difference between q at field capacity and permanent wilting point is the plant available water (*PAW*). Thus, q_{Thresh} lies between field capacity and permanent wilting point and can be established via selection of a management allowed depletion (*MAD*) value (Cuenca, 1989). The *MAD* is the percentage of *PAW* that is allowed to be removed from the plant root zone before irrigation is required, and can be used to calculate q_{Thresh}:

$$q_{Thresh} = q_{FC} - MAD \cdot \left(q_{FC} - q_{PWP}\right), \qquad [7]$$

where all q values are dimensionless values representing the percentage of water relative to the total volume of soil considered. Cuenca (1989) reports typical *MAD* values as 33% for shallow-rooted, high value crops; 50% for medium-rooted, moderate value crops; and 67% for deep-rooted, low value crops.

1.3 Soil Water Content Sensors

In situ q estimates are accomplished using a variety of methods and sensors (Or and Wraith, 2002). Measurements and estimates of q for use in irrigation scheduling have in the past been performed via gravimetric, neutron scattering, gypsum block and tensiometer methods. These methods have inherent disadvantages. Gravimetric q measurement is destructive and requires 24 hour oven drying of samples during which field conditions often change due to the time lag in retrieving data. Neutron scattering methods require use of radioactive equipment which mandates proper licensing and handling, and is expensive. Gypsum blocks and tensiometers measure matric potential and thus provide indirect determinations of θ. Gypsum blocks are sensitive to soil salinity and tensiometers are limited in the range they can measure.

In recent years θ 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., in review[a]), 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 (Dean et al., 1987; Platineanu and Starr, 1997; Kelleners et al., 2004; McMichael and Lascano, 2004). Estimates of θ based on EM measurements provide real time, in situ measurements at a relatively affordable cost. Estimation of θ using EM sensors is based on the ability of sensors to measure the real part of the dielectric permittivity (ε), or a EM signal property directly relating to ε, which directly relates to θ owing to the significant real permittivity 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.

2. Materials and Methods

2.1 Sensor Description and Operation

The Acclima® Digital TDT Sensor (http://www.acclima.com/Products/Sensor.htm; verified 31 Jan 2005) is a transmission line sensor employing an EM measurement technique to estimate q. The Digital TDT Sensor works in a similar manner to TDR in that it measures signal travel time which is directly related to the apparent permittivity (K_a) of the sample in which the probe is embedded:

$$K_a = \left(\frac{c \cdot t}{L} \right)^2, \qquad [8]$$

where K_a ˜ e under lossless conditions, c is the speed of light in vacuum ($3{\cdot}10^8$ m s^{-1}), t is the travel time [s] of an EM signal propagating along the embedded probe and L is the probe length [m]. For most applications q can be estimated from K_a measurements using either empirical equations (Topp et al., 1980; Malicki et al., 1996) or dielectric mixing models (Roth et al., 1990; Dirksen and Dasberg, 1993; Friedman, 1998). The Acclima TDT was found to provide accurate permittivity measurements (for q estimation) in line with research grade instrumentation (e.g. Tektronix TDR). Further details concerning TDT measurements and the Acclima Digital TDT Sensor's measurement capabilities compared to conventional TDR are given in Blonquist et al. (in review[a]), and characterization of relaxation, electrical conductivity and temperature effects on K_a measurements with the Acclima Digital TDT Sensor is given in Blonquist et al. (in review[b]).

In order to make measurements and control irrigation, the Acclima Digital TDT Sensor must be connected to a custom controller; Acclima CS3500, Acclima RS500 (http://www.acclima.com/Products/CS3500.htm, http://www.acclima.com/Products/RS500.htm, respectively; verified 31 Jan 2005). The sensor makes continuous q estimates, which are retrieved by the controller in order to schedule irrigation. The Acclima CS3500 Controller is a commercial-type controller designed to connect to multiple Digital TDT Sensors in order to control irrigation and/or log measurements in multiple sites. The Acclima RS500 Controller is a residential-type controller designed to connect to one Digital TDT Sensor and control irrigation for one site. In order to schedule irrigation, the RS500 Controller must also connect to a conventional irrigation timer (e.g. Rainbird®, Toro®, Hunter®, Orbit®). The RS500 Controller is essentially a switch that completes an electrical circuit between the conventional irrigation timer and the solenoid valve connected to the line supplying the irrigation water to the system. The RS500 Controller works via programming a q_{Thresh} value into the controller. When the Digital TDT Sensor estimates q at a level below q_{Thresh}, the RS500 Controller completes the circuit between the conventional timer and solenoid valve and allows the conventional timer to operate its normal irrigation schedule. Thus, the conventional timer is programmed to irrigate each day for a specific time and duration, but can only open the solenoid valve when the q estimated by the Digital TDT Sensor is below the q_{Thresh} (i.e. when RS500 Controller has completed the circuit between the timer and the valve). The circuit remains complete until the Digital TDT Sensor estimates q above q_{Thresh}. When this occurs the RS500 Irrigation Controller disconnects the circuit until the q again drops below the q_{Thresh}.

2.2 Field Site and Experiment Description

The Acclima Digital TDT Sensor was installed in an approximately 280 m^2 (3000 ft^2) field plot on the Utah State University Greenville Research Farm located in North Logan, Utah, USA. The soil in the field plot is Millville Silt Loam which is classified as Coarse-silty, carbonatic, mesic Typic Haploxeroll. Kentucky bluegrass, *Poa pratensis,* was grown on the plot. The sensor was installed in the soil, approximately in the middle of the plot. The placement depth of the sensor was between 10.0 and 12.5 cm. The sensor placement depth recommended by Acclima is 10 cm. The Digital TDT Sensor used in the experiment was connected to a CS3500 Controller rather than an RS500 Controller owing to the CS3500's ability to log q estimates in addition to controlling irrigation. The CS3500 can be used in exactly the same manner as the RS500 by applying a q_{Thresh} to determine when to irrigate. The q_{Thresh} value was calculated with Eq. [7] using an *MAD* of 50% and q_{FC} and q_{PWP} values for Millville Silt Loam. The q_{FC} and q_{PWP} values for Millville Silt Loam were estimated to be 24% and 8% (Or, 1990), respectively, and the q_{Thresh} value was calculated as 16%.

The CS3500 Controller was connected to the solenoid valve on the irrigation line supplying water to plot's irrigation system. Initially, irrigation was accomplished using a single impact sprinkler head outputting approximately 0.478 cm^3 s^{-1} (7.57 gpm), but midway through the experiment the sprinkler was changed to a lower flow rate gear-driven sprinkler head outputting 0.374 cm^3 s^{-1} (5.93 gpm). The change was made in order to reduce the over-spray experienced with the first head. The reported flow rates of the two sprinkler heads were estimated via monitoring with a flow meter connected to the irrigation line and are the averages of four measurements. For the impact head the coefficient of variation (CV) was 0.0221 and for the gear-driven head the CV was 0.00860. From these average flow rates and the duration times of the irrigation events, the approximate amount of irrigation water applied to the plot was calculated. An Acclima Digital TDT Sensor, Acclima RS500 Controller and the gear-driven sprinkler head are shown in Figure 1. The flag marks the area in the plot where the Digital TDT Sensor controlling the irrigation is buried.

The experiment was conducted over a period of forty-nine days from July 30 through September 16, during which q 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 (http://www.campbellscientific.com/eto.html; verified 31 Jan 2005) 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_0 with the FAO-56 Penman-Monteith combination equation (Allen et al., 1998) via inputs from meteorological sensors onboard the station. The CS106 *ET* Station is located near (~ 200 m) the experimental plot under similar conditions over a large Kentucky bluegrass plot, thus the data supplied by the CS106 are considered representative of the experimental plot. The CS106 *ET* station meteorological data and the Utah Division of Water Resources irrigation recommendations are available to download at http://www.conservewater.utah.gov/et/etsite/default.asp?summary.htm (verified 31 Jan 2005). The Utah Division of Water Resources makes irrigation recommendations (*R*) based on the ET106 station's ET_0 measurements and K_C values for Kentucky bluegrass. As described above, crop water requirements are estimated by ET_C (Eq. [3]), and herein *R* is a recommendation based on calculated ET_C values. We compared R (plus P) values to the actual amount of water applied to the plot, I (plus P), using the q estimates made with the Acclima Digital TDT Sensor. 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.

3. Results and Discussion

3.1 Sensor Placement

The soil from which a sensor derives a measurement and the rooting depth of the crop must be considered when determining the depth to which the sensor is buried. 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. Therefore the average rooting depth of the plant being irrigated is the logical choice for sensor burial depth. A burial depth of 10 cm for turf grass is recommended by Acclima due to the shallow rooting depth of most turf grass and 10 cm approximating an average rooting depth. The cross-section of the Acclima Digital TDT Sensor, where the sensor is oriented horizontally with respect to and buried 10.0-12.5 cm below the ground surface, simulating the position of the sensor in the experiment is displayed in Figure 2. The cross-section also displays the sensitivity of the sensor, or in essence the soil which contributes to the measurement. The sensitivity of the sensor was determined via transmission line modeling using the Arbitrary Transmission Line Calculator-ATLC (Kirkby, 1996; available at: http://atlc.sourceforge.net/ verified 31 Jan 2005) (Jones et al., in review). The sensitivity of the sensor measures approximately 9.00 cm in the horizontal direction (including gap in the middle) and 4.00 cm in the vertical direction (Figure 2), but the sensor is much more sensitive to the soil immediately surrounding the probe where the darker shaded area represents greater sensitivity (Figure 2).

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 q and in order to maintain q above an established q_{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.

3.2 Sensor Irrigation and ET-Based Irrigation Recommendations

The field data collected with the CS3500 Controller and CS106 *ET* Station over the course of the experiment from July 30-September 16 is shown in Figures 3, 4a and 4b. Soil water content (q) and irrigation (I), precipitation (P) and irrigation recommendation (R) events are plotted versus time (Figure 3), where I and P are the water amounts that the plot actually received and R is what the plot would have received instead of I had the ET-based irrigation recommendations been used. Cumulative ET, cumulative I plus P and cumulative R plus P are plotted versus time for July 30-August 15 when the impact sprinkler head was used (Figure 4a) and for August 16-Septermber 16 when the gear-driven sprinkler head was used (Figure 4b).

The ability of the Acclima Digital TDT Sensor connected to an irrigation controller to maintain q above the established q_{Thresh} is indicated by the field data (Figure 3). The only time the estimated q value did not increase following an irrigation event, implying the applied irrigation water did not reach the sensor, was on August 1 after which two irrigation events were required to bring q back above q_{Thresh}. The only times the estimated q value dropped below q_{Thresh} and remained below q_{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 q not being recharged to a level above q_{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 possibility of over-spray. Higher winds could have also contributed to the water not reaching the sensor on August 1 and 2. The average wind speeds recorded by the CS106 ET Station during the irrigation events on August 1 and 2 were ~ 3.30 and ~ 4.10 m s^{-1}, respectively, whereas all other irrigation events took place when the average wind speed was < 2.00 m s^{-1}.

The field data show from July 30-August 15 the cumulative I plus P applied via scheduling with q measurements from the Acclima Digital TDT Sensor was greater than the cumulative R plus P that would have been applied had the R derived from weather station ET estimates been used to schedule irrigation (Figure 4a). From August 16-September 16 the cumulative I plus P applied via scheduling with q estimates from the Acclima Digital TDT Sensor was less than the cumulative R plus P that would have been applied (Figure 4b). For reference, ET_C calculated with the weather station ET_0 estimates and K_C values are also displayed (Figures 4a and 4b). The cumulative ET, I plus P and R plus P values (depths and volumes) for July 30-August 15 and August 16-September 16 are listed in Table 1. For reference, the difference between ET_C and R plus P and the difference between ET_C and I plus P, shows the difference between actual (I plus P) and recommended (R plus P) water applications and estimated crop water requirements (ET_C). The difference between R plus P and I plus P is the water conserved using Digital TDT Sensor instead of R. From July 30-August 15 this difference is negative (Table 1) indicating that more than the recommended amount was applied, while from August 16-September 16 the difference is positive (Table 1) indicating water was conserved relative to ET-based irrigation recommendations. The described difference values on a volume [m^3] per month basis are also listed (Table 1). The volume is obtained by multiplying the water depth by the area over which it is applied, in this case 280 m^2.

After seventeen days of irrigating with a higher flow rate approximately 25.6 mm of water in excess of R was applied to the plot (Table 1). After thirty-two days of irrigating with a lower flow rate 38.2 mm of water was conserved. By multiplying these depth values by the area of the plot (280 m^2) and converting the time period to months, this translates to 6.14 m^3 $month^{-1}$ and 9.98 m^3 $month^{-1}$, respectively. This 9.98 m^3 $month^{-1}$ water conserved value 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 Acclima Digital TDT Sensor. The water conserved over the course of a month on a 1000 m^2 plot employing the Digital TDT Sensor to schedule irrigation, the average water price for the US and for six cities in the Western US, and the potential amount of money saved is listed (Table 2).

Relative to *ET*-based irrigation recommendations (*R*), over-irrigation was occurring between July 30-August 15 and under-irrigation was occurring between August 16-September 16 (Figures 3 and 4; Table 1). With the higher flow rate more water was required to maintain q above q_{Thresh}, whereas under the lower flow rate less water was applied in order to maintain q above q_{Thresh}. As already discussed, the over-irrigation between July 30-August 15 is attributed to the higher flow rate leading to over-spray. The under-irrigation relative to *R* observed using a lower flow rate is only under-irrigation when compared to recommendations derived from ET_0 estimates and K_C values, and thus represents water conservation. Even though less water than the estimated ET_C was applied to the plot from August 16-September 16 via irrigation scheduling with the Acclima Digital TDT Sensor, the grass did not show signs of water stress. Field observations of the grass in the plot showed a green, healthy lawn.

Whether over-irrigation or under-irrigation relative to irrigation recommendations occurs is dependent on q_{Thresh}. It is easily observed from the data (Figure 3) that a q_{Thresh} value less than 16%, obtained by increasing the *MAD* value in Eq. [7], would have conserved even more water than that reported from August 16-September 16, owing to less frequent irrigation events required to maintain q above q_{Thresh}. Conversely, a q_{Thresh} value above 16%, obtained by decreasing the *MAD* value in Eq. [7], would have mandated more frequent irrigation events to maintain q above q_{Thresh}. For turf grass and most crops we suggest determining the q_{Thresh} value using Eq. [7] with *MAD* = 50%, depleting 50% of *PAW* and maintaining q between q_{FC} and a level well above q_{PWP} where the plants grown will likely not experience water stress. If necessary, q_{Thresh} can be subsequently adjusted based on observations of crop or turf grass growth and quality.

Conclusions

Electromagnetic (EM) measurements of apparent permittivity with transmission line sensors provide means to estimate soil water content (q) at the plant root zone and directly infer evapotranspiration (*ET*) for use in irrigation scheduling. The Acclima Digital TDT Sensor is an EM-based q sensor which can be employed to schedule irrigation via connection to custom irrigation controllers and conventional irrigation timers. A threshold q value (q_{Thresh}) is 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 q changes with respect to q_{Thresh}. Herein irrigation control and scheduling with the Acclima Digital TDT Sensor and custom controller was compared to *ET*-based irrigation recommendations derived from weather station measurements of potential *ET* and empirical crop coefficients. The Acclima system under-irrigated relative to *ET*-based irrigation recommendations when a lower flow rate sprinkler head was used, thus conserving water and saving money. Performance of the system is dependent on the burial depth of the sensor and

q_{Thresh}. The q_{Thresh} value is soil dependent and should be established via consideration of soil q at field capacity and permanent wilting point.

Acknowledgements

The authors would like to extend special thanks to Bill Mace for assistance with plot maintenance, and to Scott Anderson for his help in setting up the CS3500 Controller. The authors would like to acknowledge funding provided in part by USDA NRI grant 2002-35107-12507.

References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FOA Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy. pp. 300.

Blonquist Jr., J.M., S.B. Jones, and D.A. Robinson. In review[a]. A time domain transmission sensor with TDR performance characteristics. J. of Hydrology.

Blonquist Jr., J.M., S.B. Jones, and D.A. Robinson. In review[b]. Characterization and calibration of seven electromagnetic water content sensors: Part II. Evaluation. Vadose Zone J.

Bowen, I.S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Physics Review 27:779-787.

Campbell, G.S., and R. Y. Anderson. 1998. Evaluation of simple transmission line oscillators for soil moisture measurement. Comput. Electron. Ag. 20:31-44.

Cuenca, R.H. 1989. Irrigation System Design Prentice Hall, Englewood, NJ, USA.

Dean, T.J., J.P. Bell, and A.J.B. Baty. 1987. Soil moisture measurement by an improved capacitance technique, part I. Sensor design and performance. J. of Hydrology 93:67-78.

Dirksen, C., and S. Dasberg. 1993. Improved calibration of time domain reflectometry soil water content measurements. Soil Sci. Soc. Am. J. 57:660-667.

Friedman, S.P. 1998. A saturation degree-dependent composite spheres model for describing the effective dielectric constant of unsaturated porous media. Water Resour. Res. 34:2949-2961.

Gaskin, G.J., and J.D. Miller. 1996. Measurement of soil water content using a simplified impedance measuring technique. J. Ag. Engr. Res. 63:153-159.

Harlow, R.C., E.J. Burke, and T.P.A. Ferre. 2003. Measuring water content in saline soils using impulse time domain transmission techniques. Vadose Zone J. 2:433-439.

Hilhorst, M.A., J. Balendonck, F.H.W. Kampers. 1993. A broad-bandwidth mixed analog/digital integrated circuit for the measurement of complex impedances. IEEE J. Solid-State Circuits 28:764-769.

Hilhorst, M.A. 2000. A pore water conductivity sensor. Soil Sci. Soc. Am. J. 64:1922-1925.

Hook, W.R., T.P.A. Ferre, and N.J. Livingston. 2004. The effects of salinity on the accuracy and uncertainty of water content measurement. Soil Sci. Soc. Am. J. 68:47-56.

Jensen, M.E., R.D. Burman, and R.G. Allen. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practices No. 70. Am. Soc. Civil Engrs., New York, NY, USA. pp 322.

Jones, S.B., J.M. Blonquist Jr., D.A. Robinson, V.P. Rasmussen, and D. Or. In review. Towards Standardizing Characterization and Calibration of Electromagnetic Sensors for Porous Media Water Content Determination: Part I. Methodology. Vadose Zone J.

Kelleners, T.J., R.O.W. Soppe, D.A. Robinson, M.G. Schaap, J.E. Ayers, and T.H. Skaggs. 2004. Calibration of Capacitance Probe Sensors Using Electric Circuit Theory. Soil Sci. Soc. Am. J. 68:430-439.

Kelleners, T.J., M.S. Seyfried, J.M. Blonquist Jr., J. Bilskie, and D.G. Chandler. In review. Permittivity measurements in air, fluids, and soils using water content reflectometers. Soil Sci. Soc. Am. J.

Malicki, M.A., R. Plagge, and C.H. Roth. 1996. Improving the calibration of dielectric TDR soil moisture determination taking into account the solid soil. European J. of Soil Sci. 47:357-366.

McMichael, B., and R.J. Lascano. 2003. Laboratory evaluation of a commercial dielectric soil water sensor. Vadose Zone J. 2:650-654.

Monteith, J.L. 1981. Evaporation and surface temperature. Quarterly J. Royal Meteorological Soc. 107:1-27.

Or, D. 1990. Irrigation Management Considering Soil Variability and Climatic Uncertainty. Dissertation, Utah State University, Logan, UT.

Or, D., and J.M. Wraith. 2002. Soil Water Content and Water Potential Relationships, p. 49-84, In A.W. Warrick, ed. Soil Physics Companion, Vol. 1. CRC Press, Boca Raton, Florida.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London A193:120-146.

Platineanu, I.C., and J.L. Starr. 1997. Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. Soil Sci. Soc. Am. J. 61:1576-1585.

Robinson, D.A., S.B Jones, J.M. Wraith, D. Or, and S.P. Friedman. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone J. 2:444-475.

Roth, K., R. Schulin, H. Fluhler, and W. Attinger. 1990. Calibration of time domain reflectometry for water content measurement using composite dielectric approach. Water Resour. Ress 26:2267-2273.

Seyfried, M.S., and M.D. Murdock. 2001. Response of a new soil sensor to variable soil, water content, and temperature. Soil Sci. Soc. Am. J. 65:28-34.

Seyfried, M.S., and M.D. Murdock. 2004. Measurement of soil water content with a 50-MHz soil dielectric sensor. Soil Sci. Soc. Am. J. 68:394-403.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res. 16:574-582.

Topp, G.C., D.R. Lapen, G.D. Young, and M. Edwards. 2001. Evaluation of shaft-mounted TDT readings in disturbed and undisturbed media, Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, Available at: http://www.iti.northwestern.edu/tdr/tdr2001/proceedings/ (verified 23 Nov 2004). Infrastructure Technology Institute-Northwestern University, Evanston, Illinois.

Topp, G.C., and T.P.A. Ferre. 2002. Water Content, p. 417-545, In J.H. Dane, and G.C. Topp. ed. Methods of Soil Analysis Part 4 Physical Methods. Soil Sci. Soc. Am. Inc., Madison, WI, USA.

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

	July 30-Aug. 15	**Aug. 16-Sept. 16**
Cumulative Amounts [mm]:		
ET_C	97.5	117
I plus *P*	115	85.8
R plus *P*	89.4	124
Cumulative Differences [mm]:		
ET_C – *I* plus *P*	-17.5	31.2
ET_C– *R* plus *P*	8.10	-7.00
R plus *P* – *I* plus *P*	-25.6	38.4
Water Conserved† [m^3 $month^{-1}$]:		
R plus *P* – *I* plus *P*	-6.14	9.98

†The water conserved amounts are calculated by multiplying the cumulative difference between *R* plus *P* and *I* plus *P* by the area of the plot. The negative value indicates over-application of water relative to recommendations (*R*).

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

Water conserved per month = 35.8 m^3†		
City	**Water Costs [$ m^{-3}]**	**Savings‡ [$ $month^{-1}$]**
US Average	0.52	18.61
Denver	0.45	16.02
Las Vegas	0.40	14.31
Phoenix	0.28	10.11
Salt Lake City	0.36	12.85
Spokane	0.39	13.34
Tucson	0.59	21.16

†Water conserved per month value is based on a 1000 m^2 area being irrigated and is calculated from the 9.98 m^3 $month^{-1}$ water conserved value reported in Table 1 for the 280 m^2 area irrigated in the experiment.
‡Savings will vary with the size of plot being irrigated; calculations here are based on a 1000 m^2 area being irrigated.

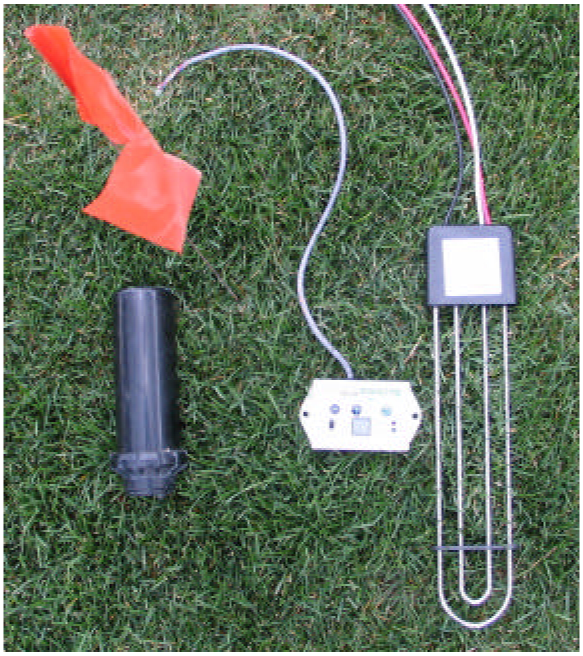

Figure 1: Photograph displaying an Acclima Digital TDT Sensor, RS500 Controller and gear-driven sprinkler head. The flag marks the area in the plot where the Acclima Digital TDT Sensor is buried.

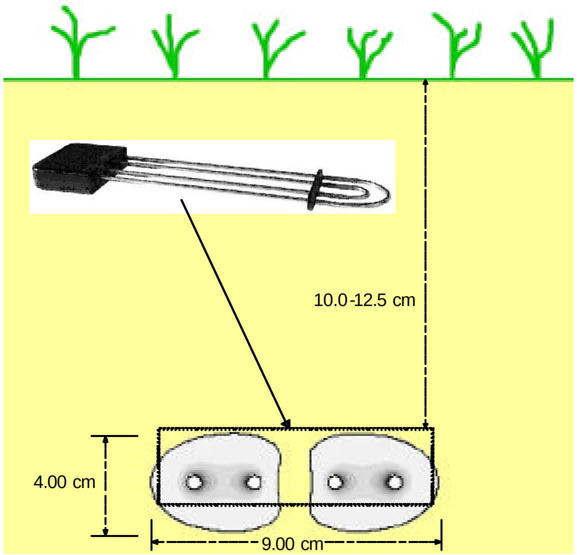

Figure 2: Drawing displaying the cross-section of the Acclima Digital TDT Sensor oriented horizontally in relation to the ground surface. The cross-section of the rods (the dotted line surrounding the rods represents the sensor head) shows the area containing soil which contributes to the measurement, or the sensitivity of the sensor (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 measurement is largely dependent on soil surrounding the rods. Inset is a picture of the Acclima Digital TDT Sensor.

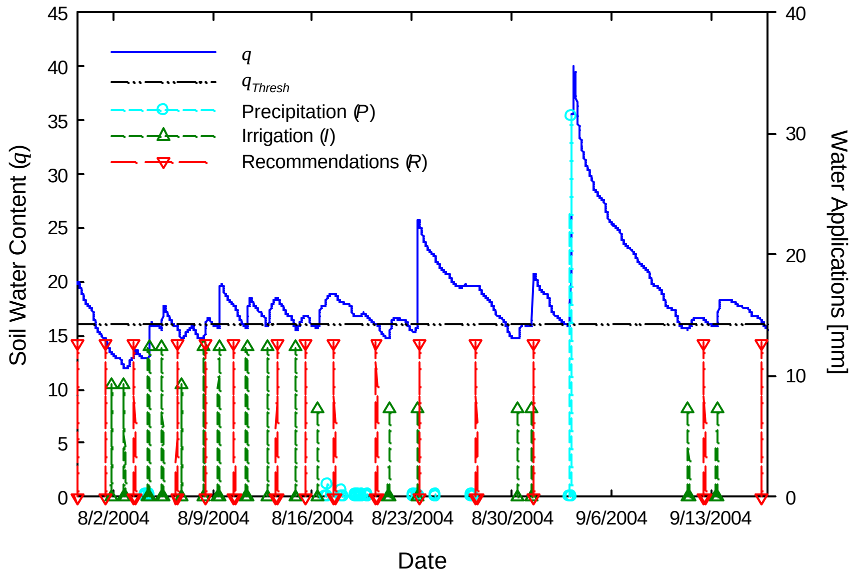

Figure 3: Soil water content (*q*) and irrigation (*I*), precipitation (*P*) and irrigation recommendation (*R*) events plotted over the experimental period (July 30-September 17). The *q* values correspond to the left-hand y-axis and *I*, *P* and *R* correspond to the right-hand y-axis.

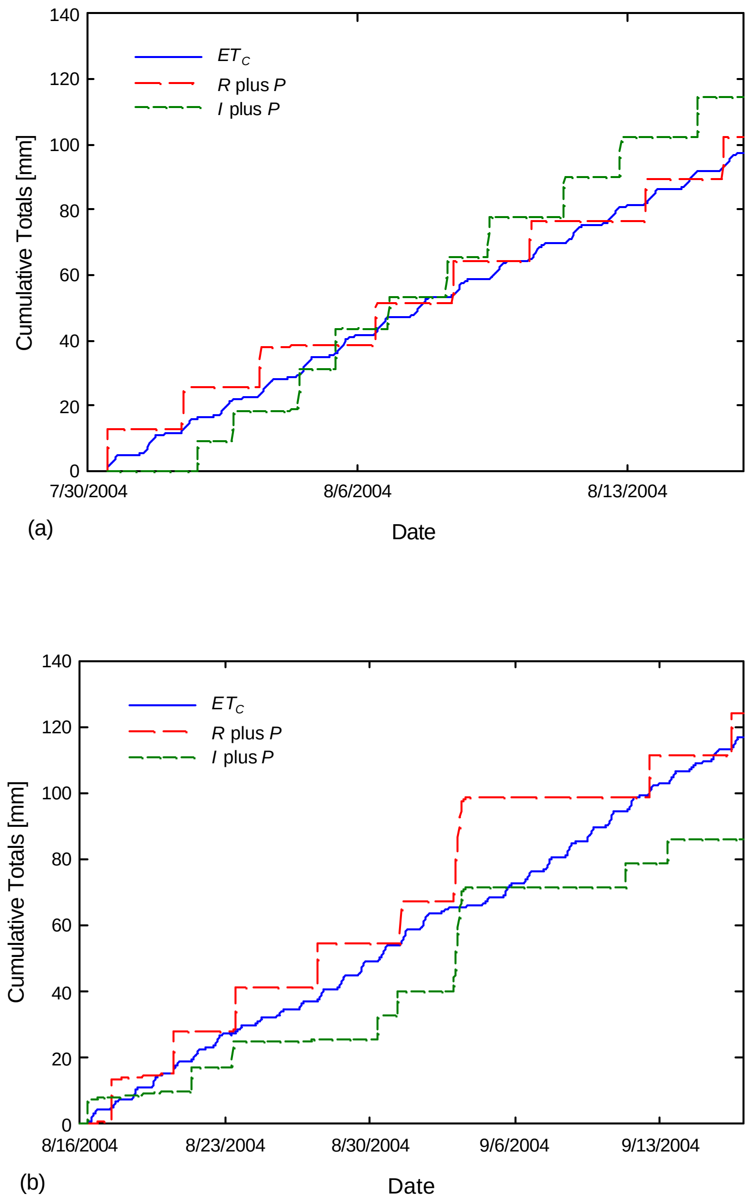

Figure 4: Cumulative crop evapotranspiration (ET_C), cumulative irrigation recommendation (*R*) plus precipitation (*P*) and cumulative irrigation (*I*) plus precipitation (*P*) plotted from (a) July 30-August 15 and (b) August 16-September 16.