Soil Water Sensors for Irrigation Scheduling: Can They Deliver a Management Allowed Depletion?

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Abstract

Soil water sensors are widely marketed in the farming sector as aids for irrigation scheduling. Sensors report either volumetric water content (θ_v, m^3 m^{-3}) or soil water potential, with θ_v sensors being more common. To obtain yield and quality goals, irrigations are scheduled to keep soil water in the root zone above a management allowed deficiency (MAD) level, which is specified as a percentage of the plant available water and which may change over the cropping season and with soil type and water quality. For example, representative values for maize grown in a silty clay loam and irrigated with good quality water may be (during pollination): MAD = 40%; field capacity = 0.33 m^3 m^{-3}; wilting point = 0.18 m^3 m^{-3}; and water content range of the MAD = 0.33 - 0.27 = 0.06 m^3 m^{-3}. In a sandy soil, the water content range of the MAD would be much smaller, e.g., 0.03 to 0.04 m^3 m^{-3}. An important question then is: are available soil water sensors accurate enough in the field to be reliable for irrigation scheduling using MAD? We evaluated the accuracy of several down-hole access tube type electromagnetic (EM) sensors (and the neutron probe) and several EM sensors that can be buried or inserted into the soil. All sensors required soil-specific calibration, with the possible exception of conventional time domain reflectometry (TDR with waveform reduction). The EM sensors based on capacitance measurements were found to be least accurate, most affected by soil bulk electrical conductivity and temperature, and generally ineffective for irrigation scheduling by MAD. The neutron moisture meter and gravimetric sampling were accurate enough to use with MAD. Some insertion type EM sensors showed promise for MAD-based irrigation scheduling. The capacitance sensors suffer from a fundamental problem in that their EM fields do not uniformly permeate the soil, instead preferentially following paths of greater bulk electrical conductivity. Because of differing arrangements of conductive pathways at each sampling location, the capacitance sensors exhibited a variability that did not reflect the actual field variability in water content.

INTRODUCTION

For many years it has been feasible to sense soil water content using electromagnetic (EM) sensors that respond to the large change in soil bulk dielectric permittivity, ε_a (-), that results from changes in θ_v (e.g., Kuráž et al., 1970; Matthews, 1963; Thomas, 1966). A successful example is the introduction of time domain reflectometry (TDR) for sensing θ_v in the early 1980s (e.g., Topp et al., 1980; Dalton et al.,1984). Most TDR instruments operate in a ~1 GHz frequency range in which interference from soil bulk electrical conductivity, σ_a (S m^{-1}), is small, which is fortunate since σ_a increases with both water content and temperature. Even so, TDR measurements in some soils are susceptible to soil temperature effects related to both σ_a and bound water unless corrected using concurrently measured values of σ_a and temperature (Evett et al., 2005; Schwartz et al., 2009). But lower cost alternative sensors based on capacitive measurements typically operate at frequencies a decade or more smaller than those of TDR, and interference from σ_a changes is more important. Also, the EM fields of

capacitance and other sensors using radiating EM fields may not evenly permeate the soil volume, which results in variability of sensed ε_a and θ_v not being representative of the soil water content variation (Evett et al., 2009). Evett et al. (2005, 2009) and Mazahrih et al. (2008) evaluated several down-hole soil water sensors used in access tubes to determine the soil profile water content and change in storage. However, sensors used in access tubes are not directly in contact with the soil, which likely resulted in poorer performance of these EM sensors.

The management allowed deficiency (MAD, $m^3\ m^{-3}$) is the depletion of soil water content below field capacity (F_C, $m^3\ m^{-3}$) that is allowable before plant water stress causes unacceptable declines in crop yield and/or quality (Fig. 1). Merriam (1966) provided guidance for setting MAD levels according to crop, soil, crop water use rate, rooting depth, salinity, drainage, irrigation practice, soil fertility, etc. Because soils rapidly drain to F_C after precipitation or irrigation, irrigation management normally has to work with θ_v values within the MAD range, which may be narrow, particularly for very clayey or sandy soils (Table 1). For irrigation scheduling using the management allowed depletion (MAD) concept (Fig. 2-7), irrigation is initiated when soil water has decreased to the θ_{MAD} level. The θ_{MAD} value may be chosen such that the soil never becomes dry enough to limit plant growth and yield, or it may be a smaller value that allows some plant stress to develop. It is common to irrigate at some value of θ_v, θ_{MAD+}, that is larger than θ_{MAD}. This is done to ensure that the error in θ_v measurement, which may cause inadvertent over estimation of θ_v, is not likely to cause irrigation to be delayed until after θ_v is actually smaller than θ_{MAD}. Minimizing the difference, $d = \theta_{MAD+} - \theta_{MAD}$, allows irrigation interval to be increased. It is desirable to know the number of samples required to estimate θ_v to within d of θ_{MAD} at the $(1 - \alpha)$ probability level. Knowing the standard deviation, s, of θ_v measurements, the required number of samples, n, for the standard normal distribution evaluated at probability level α is

$$n = \left(\frac{u_{\alpha/2} s}{d} \right)^2 \qquad [1]$$

Our objective was to compare the accuracy and variability of the previously studied down-hole soil water sensors with five EM soil water sensors made for direct burial or insertion that were tested under conditions that ensured spatially uniform θ_v subject to large temporal variations of θ_v, temperature (T, °C) and σ_a.

MATERIALS AND METHODS

At the USDA-ARS, Conservation & Production Research Laboratory, Bushland, Texas (35° 11' N, 102° 06' W, 1170 m a.s.l.), a 1-m × 2-m field area was delineated with straight, parallel rails leveled end-to-end to side-to-side with the rail upper surface at soil surface elevation. Soil was removed between the rails to a depth of 5.4 cm using a purpose-built tool, leaving a firm surface. Six sensors of each type were installed horizontally on this surface, after which soil was manually packed over the sensors, filling the space between the rails so that all sensors were buried at 5.4 cm depth. Excess soil was removed with a straight edge, leaving the compacted soil surface level with the tops of the rails. The soil was a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll). Sensors included TDR (20-cm, planar, trifilar probes) as described by Evett (2000a) except that RG6 cable was used to reduce attenuation due to low-pass filtering; water content reflectometers (model CS616[1], Campbell Scientific Inc., Logan, UT, USA); Acclima sensors (model ACC-SEN-TDT, Acclima, Inc., Meridian, ID, USA), which are described as digital time domain transmissivity sensors; 5TE sensors (Part # 40557, model 5TE, Decagon Devices, Pullman, WA, USA), which report θ_v, T and σ_a values; and Hydra Probe sensors (Stevens Water Monitoring Systems, Inc., Portland, OR, USA),

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

which report values of the real (ε_r) and imaginary (ε_i) components of permittivity, T and σ_a; and six type-T thermocouples (hand made). The TDR probes were connected to a TDR instrument (model 1502C, Tektronix, Inc., Redmond, OR, USA) through a coaxial multiplexer (Evett, 1998); and θ_v and σ_a were determined automatically using the TACQ software and methods described by Evett (2000b) and Evett et al. (2005), including the soil-specific calibration and the σ_a and effective frequency based temperature correction of Evett et al. (2005). Dataloggers were used to measure sensor and thermocouple outputs (model CR3000, CSI, Logan, UT, USA in the case of Hydra Probe, CS616, 5TE and thermocouple sensors; and model ACC-AGR-007, Acclima, Inc., Meridian, ID, USA for the Acclima sensors). All measurements were made every 0.5 h for a four-week period, during which two irrigations were applied. Factory recommended calibrations were used for sensors other than TDR. This included the "general" calibration of Seyfried et al. (2005), which the manufacturer recommended for the Hydra Probe. The plot area was surrounded by a low berm and flooded on the fifth (day of year (243) and 28th day (day of year 267) after sensor installation. Minor soil settling occurred after the 1st flooding, indicating that the bulk density (ρ_b, Mg m^{-3}) was <1.54, the target ρ_b to achieve a porosity of 0.42 m^3 m^{-3}; and soil was added to the plot and leveled between the rails to achieve the target depth of 5.4 cm.

Previous experiments involving down-hole EM sensors used in access tubes were described by Evett et al. (2009) and Mazahrih et al. (2008). The former involved three seasons of field experiments in uniform Pullman clay loam soil at Bushland, Texas involving transects of between 10 and 20 access tubes for each model of sensor and differential irrigation of plots such that one half was irrigated and the other was dryland or deficit irrigated. The sensors' ability to distinguish the wetter irrigated soils from the dryer dryland or deficit irrigated soils was tested. Sensor evaluated included the neutron probe (NP), Sentek EnvironSCAN, Sentek Diviner 2000, Delta-T Devices PR1/6, and IMKO Trime T3 tube probe. Soil-specific calibrations for the Pullman soil (Evett et al., 2006) were used in these field tests.

RESULTS AND DISCUSSION

The EM devices for use in access tubes produced larger s values than did the NP and gravimetric sampling, and numbers of access tubes needed to obtain the mean θ_v within a given precision were larger in dry soil than in well-irrigated soil (Table 2). Between 1 and 7 access tubes would be required to obtain a precision of 0.02 m^3 m^{-3} for the EnvironSCAN, Diviner 2000 and Trime T3 systems, which would be cost prohibitive in some situations. For the PR1/6 and Sentry 200 systems the numbers of access tubes required would be even more costly; and for precision of 0.01 m^3 m^{-3}, none of the EM sensors would be economical. The larger s values for EM sensors were due to spatial variability in the readings, such that point θ_v values and profile (over a range of soil depth) θ_v values were variable in space, whereas the NP and gravimetrically determined θ_v were not or were only slightly spatially variable. Also, EM sensor θ_v was strongly correlated across sensors, indicating that sensors responded to soil properties reproducibly at each point. Although the gravimetric sampling volume was smaller than those of the EM sensors, the θ_v from gravimetric (and NP) sampling showed very little spatial variability in the uniform soil at Bushland. Numerous studies show that θ_v variability increases as sample size decreases. Thus, there is strong inferential evidence that the spatial variability reported by EM sensors was not due to actual θ_v variability at the scale of sensor sampling volume, but was due to non-uniform EM field response within the sampling volume, probably related to preferential EM field penetration of more electrically conductive (wetter) peds within the sampling volume. Logsdon (2009), working with the CS616 EM sensor, demonstrated that such preferential response does in fact occur, a fact that is well established in other fields of study (Baveye et al., 2002; Panteny et al., 2005). Mazahrih et al. (2008) conducted a field calibration of these down-hole sensors in a deep clay and clay loam soil in the San Joaquin Valley of central California. They found that that sensor calibrations changed rapidly with depth and that

the devices were relatively inaccurate even when field-calibrated (RMSE of 0.015 to 0.063 m^3 m^{-3}) and likely dependent on σ_a, which varied with depth and with space and time in that drip-irrigated field.

Values of σ_a ranged from 0.02 to 0.13 S m^{-1} over the course of the study, due to variation in both θ_v and T. Comparison of the point sensors at 5.4-cm depth revealed inter-sensor variability of to 0.08 m^3 m^{-3} for both the Hydra Probe and CS616 (Fig. 2). Both were also temperature sensitive, with the CS616 exhibiting diurnal variations associated with T (and due to σ_a dependency on T) of up to 0.05 m^3 m^{-3} compared with 0.02 m^3 m^{-3} for the Hydra Probe. Values of θ_v from the TDR system were the most accurate and free from T interference, as expected from its soil-specific calibration that accounted for σ_a effects. Similarly, the Acclima exhibited little dependence on T and minor inter-sensor variability (Fig. 3). Also, the Acclima was the most highly correlated with TDR data, indicating that a linear soil-specific calibration would suffice to correct it to be useful in scheduling according to MAD.

The CS616 overestimated θ_v more than did the Acclima or Hydra Probe. The Hydra Probe overestimated ε_a compared with TDR (slope = 1.437, r^2 = 0.966, RMSE = 1.08); more so than did the Acclima, which was highly corrected with TDR derived ε_a (slope = 1.108, r^2 = 0.996, RMSE = 0.256). Values of σ_a from the Acclima were most highly correlated (r^2 = 0.953) with those from the TDR systems, but were over estimated by 100%, probably due to relaxation effects since the Acclima effective measurement frequency is much larger than that of the Hydra Probe. The Hydra Probe under estimated σ_a by 13% (9% when temperature corrected), but was less highly correlated with TDR (r^2 = 0.865, 0.883 when temperature corrected). Values of T from both the Acclima and Hydra Probe sensors were highly correlated with those measured by thermocouple, but the Hydra Probe over estimated T by 2.9°C.

CONCLUSIONS

Electromagnetic (EM) sensors have the advantages of ease of use, little regulatory burden and less cost for point measurements when compared with neutron probe or time domain reflectometry methods. However, sensor inaccuracy renders most EM sensors unsuitable for irrigation scheduling within the water content limits prescribed by a management allowed depletion paradigm for most soils. Several factors increase inaccuracy in EM sensors, including 1) inter-sensor variation due to manufacturing problems, 2) temperature sensitivity due to variations in bulk electrical conductivity that is both temperature and water content dependent, 3) inaccuracy due to BEC interference, 4) uneven and variable EM field penetration of the sampling volume, and 5) inaccurate measurement of water content dependent or covarying soil properties such as temperature, apparent dielectric permittivity and bulk electrical conductivity that might be used to correct or estimate water content. All require soil-specific calibration. Sensors like the Acclima that read a true electrical pulse travel time, are more likely to be useful when a soil-specific calibration is made. And, sensors that accurately report σ_a and T offer the possibility of correcting θ_v for interference from these.

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Tables

Table 1. Example calculation† of management allowed depletion (MAD, $m^3\ m^{-3}$) in three soils with widely different textures. The small range of MAD severely tests the abilities of most soil water sensors, particularly for the loamy sand soil.

Horizon	θ_{FC}	θ_{PWP}	θ_{PAW}		MAD fraction		MAD $m^3\ m^{-3}$
	---------- $m^3\ m^{-3}$	----------					
Silt loam	0.086	0.295	0.209	×	0.6	=	0.126
Loamy sand	0.066	0.103	0.037	×	0.6	=	0.022
Clay	0.190	0.332	0.142	×	0.6	=	0.085

† θ_{FC}, θ_{PWP}, and θ_{PAW} are the soil water content at field capacity and the permanent wilting point and the plant-available water.

Table 2. Calculation of number of access tubes (n) needed to find the mean water content in a field to a precision d ($m^3\ m^{-3}$) at the ($1 - \alpha = 95\%$) probability level for a given field-measured standard deviation (s, $m^3\ m^{-3}$) of water content. Calculated using Eq. [1]. The parameter $\mu_{\alpha/2} = 1.96$ is the value of the standard normal distribution at $\alpha/2$. Data are from ten access tubes for each device, spaced at 10-m intervals in transects that were 5-m apart.

		s	n	
Method	Soil condition	$m^3\ m^{-3}$	$d = 0.01\ m^3\ m^{-3}$	$d = 0.02\ m^3\ m^{-3}$
Diviner 2000†	Irrigated	0.0131	6.6	1.6
	Dry	0.0242	22.5	5.6
EnviroSCAN†	Irrigated	0.0152	8.9	2.2
	Dry	0.0266	27.2	6.8
Delta-T PR1/6†	Irrigated	0.0272	28.4	7.1
	Dry	0.1216	568.0	142
Sentry 200AP†‡	Overall	0.0378	54.9	13.7
Trime T3	Irrigated	0.0075	2.2	≤1
	Dry	0.0238	21.8	5.4
Gravimetric by push tube	Irrigated	0.0045	≤1	≤1
	Dry	0.0070	1.9	≤1
Neutron probe	Irrigated	0.0015	≤1	≤1
	Dry	0.0027	≤1	≤1

† Capacitance type sensors
‡ Estimated from data of Evett and Steiner (1995)

Figures

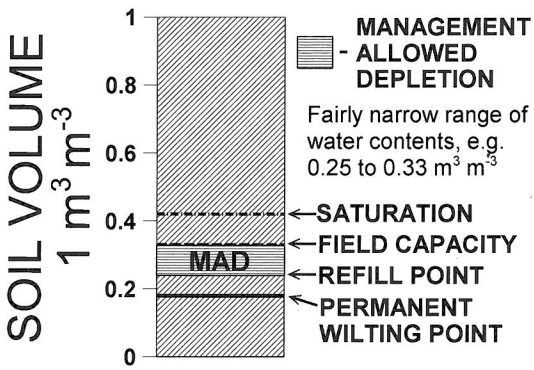

Fig. 1. Illustration of the soil profile indicating fractions of the total soil volume (here represented by unity) that are occupied by water at four key levels of soil water content. For this silty clay loam, the soil is full of water at saturation (0.42 $m^3\ m^{-3}$), drains easily to field capacity (0.33 $m^3\ m^{-3}$), and reaches the permanent wilting point (1.5 MPa) at 0.18 $m^3\ m^{-3}$ water content. For corn, irrigations are scheduled when the soil water content reaches or is projected to reach 0.25 $m^3\ m^{-3}$, the value of θ_{MAD} for this soil and crop.

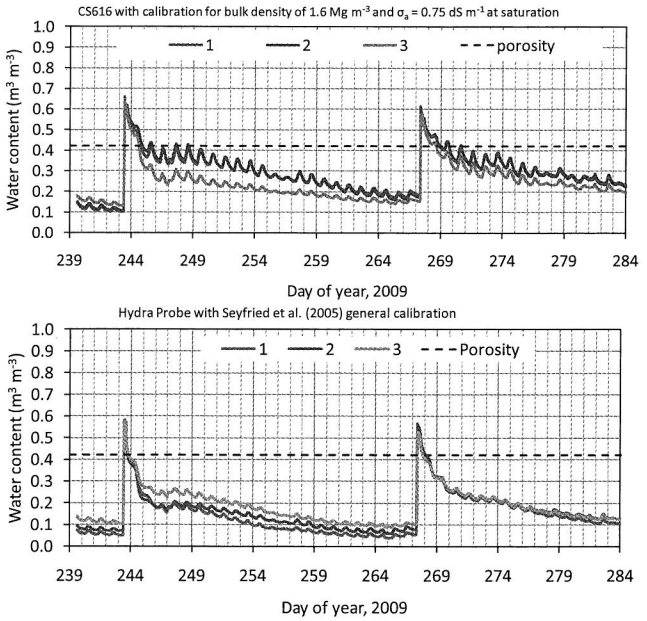

Fig. 2. CS616 water contents from calibration for sandy clay loam, ρ_b of 1.6 Mg m^{-3} and σ_a = 0.75 dS m^{-1} at saturation (top); and Hydra Probe water contents using Seyfried et al. (2005) general calibration (bottom).

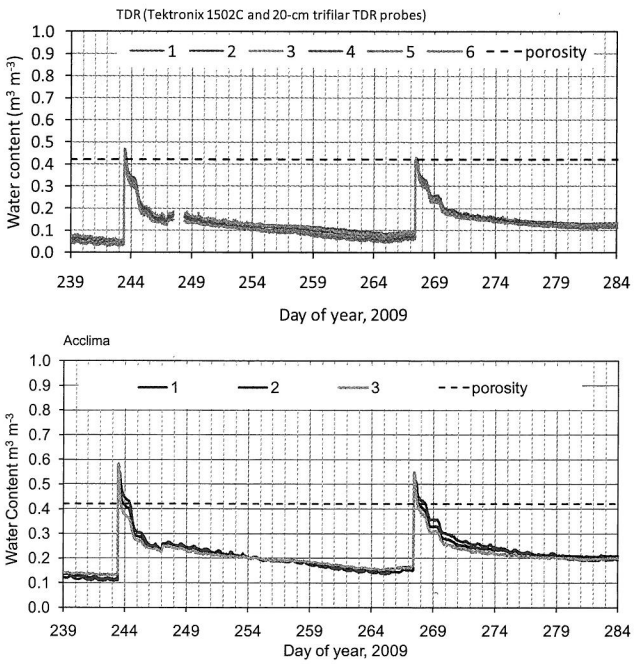

Fig. 3. Conventional time domain reflectometry (TDR) water contents using soil-specific calibration (top); and Acclima sensor water contents (bottom).

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