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In-Soil and Down-Hole Soil Water Sensors: Characteristics for Irrigation Management

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Abstract. *The past use of soil water sensors for irrigation management was variously hampered by high cost, onerous regulations in the case of the neutron probe (NP), difficulty of installation or maintenance, and poor accuracy. Although many sensors are now available, questions of their utility still abound. This study examined down-hole (access tube type) and insertion or burial type sensors for their ability to deliver volumetric water content data accurately enough for effective irrigation scheduling by the management allowed depletion (MAD) method. Down-hole sensors were compared with data from gravimetric sampling and field-calibrated neutron probe measurements. Insertion and burial type sensors were compared with a time domain reflectometry (TDR) system that was calibrated specifically for the soil; and temperature and bulk electrical conductivity measurements were also made to help elucidate sensor problems. The capacitance type down-hole sensors were inaccurate using factory calibrations, and soil-specific calibrations were not useful in a Central Valley California soil and a Great Plains soil. In both soils, these sensors exhibited spatial variability that did not exist at the scale of gravimetric and NP measurements or of irrigation management, resulting in errors too large for the MAD approach. Except for one, the point sensors that could be buried or inserted into the soil gave water contents larger than saturation using factory calibrations. The exception was also the least temperature sensitive, the others exhibiting daily water content variations due to temperature of >= 0.05* $m^3\ m^{-3}$ *water content. Errors were related to bulk electrical conductivity of this non-saline but clayey soil.*

Keywords. Soil water content, Irrigation scheduling, Irrigation Management, Sensors, Temperature.

Introduction

For many years it has been feasible to sense soil volumetric water content (θ_v, $m^3\ m^{-3}$) using electromagnetic (EM) sensors that respond to the large change in soil bulk dielectric permittivity, ε_a (nondimensional), that results from changes in θ_v (e.g., Kuráž et al., 1970; Matthews, 1963; Thomas, 1966), though not accurately. With the successful introduction of time domain reflectometry (TDR) for sensing θ_v in the early 1980s (e.g., Topp et al., 1980; Dalton et al., 1984), it became possible to accurately estimate soil water content using an EM sensor. Most TDR instruments operate in a ~1 GHz frequency range in which interference from 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. Evett et al. (2005) and Schwartz et al. (2009) showed how σ_a measurements, easily made with TDR, and temperature measurements could be combined to correct these relatively minor interferences with TDR measurements. But lower cost alternatives 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, there is increasing evidence that the EM fields of capacitance sensors do not evenly permeate the soil volume, which results in sensed ε_a and θ_v not being representative of the soil water content variation (Evett et al. 2009). Evett et al. (2006, 2009) evaluated several down-hole soil water sensors used in access tubes to determine the soil profile water content and change in storage and found that the capacitance type sensors were too inaccurate to be useful. However, sensors used in access tubes are not directly in contact with the soil, which likely impacts negatively the performance of these EM sensors.

The management allowed depletion (MAD, %) is the percentage depletion of plant available soil water content (PAWC = FC – PWP, where FC is field capacity and PWP is permanent wilting point, both in $m^3\ m^{-3}$) 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 percentages according to crop, soil, crop water use rate, rooting depth, salinity, drainage, irrigation practice, soil fertility, etc. Because soils rapidly drain to FC 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). The MAD percentage may be chosen such that the soil never becomes dry enough to limit plant growth and yield, or it may be a larger percentage that allows some plant stress to develop. For irrigation scheduling using the management allowed depletion (MAD) concept, irrigation is initiated when soil water has decreased to a level $\theta_{IRR} = \theta_{FC} - \theta_{MAD}$. It is common to irrigate at some value of θ_v, θ_{IRR+}, that is larger than θ_{IRR}. 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_I. Minimizing the difference, $d = \theta_{I+} - \theta_I$, requires more accurate θ_v sensing, but it allows the 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 – α) 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

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

With these results in mind, our objective was to compare the accuracy and variability of the previously studied down-hole soil water sensors with those of five soil water sensors made for direct burial or insertion under conditions that ensured spatially uniform θ_v subject to large temporal variations of θ_v, temperature (*T*, °C) and σ_a.

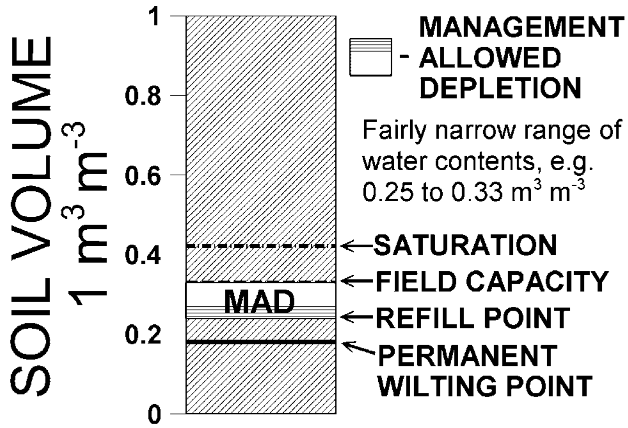

Figure 1. Illustration of the soil profile indicating fractions of the total soil volume (here represented by unity) that are occupied by water at four key levels of soil water content. For this silty clay loam, the soil is full of water at saturation (0.42 $m^3\ m^{-3}$), drains easily to field capacity (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_{IRR} for this soil and crop.

Table 1. Example calculation† using management allowed depletion percentage to calculate the allowable water content change (θ_{MAD}, $m^3\ m^{-3}$) in three soils with widely different textures.

Horizon	θ_{FC}	-	θ_{PWP}	=	θ_{PAWC}	×	MAD/100	=	θ_{MAD}
	--------------------		$m^3\ m^{-3}$		----------------		fraction		$m^3\ m^{-3}$
silt loam	0.295	-	0.086	=	0.209	×	0.6	=	0.126
loamy sand	0.103	-	0.066	=	0.037	×	0.6	=	0.022
clay	0.332	-	0.190	=	0.142	×	0.6	=	0.085

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

Methods

A 1-m by 2-m field area was prepared by installing straight, parallel rails leveled end to end and side to side. The soil was scraped away between the rails to a depth of 5.4 cm using a purpose-built tool, leaving a firm surface. Sensors were installed horizontally on this surface, after which soil was manually packed over the sensors, and brought to the top surface of the rails so that all sensors were buried at 5.4 cm depth. The soil was a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) at the USDA-ARS, Conservation & Production Research Laboratory, Bushland, Texas (35° 11' N, 102° 06' W, 1170 m elev. above MSL). Sensors included six TDR probes (20-cm, planar trifilar), as described by Evett (2000a) except that RG6 cable was used to reduce attenuation by low-pass filtering; six water content reflectometers (model CS616[1], Campbell Scientific Inc., Logan, UT, USA); three Acclima sensors (model ACC-SEN-TDT, Acclima, Inc., Meridian, ID, USA), which are described as digital time domain transmissivity sensors; and three Hydra Probes (Stevens Water Monitoring Systems, Inc., Portland, OR, USA), which report values of the real (ε_r) and imaginary (ε_i) components of permittivity, T and σ_a; ; six 5TE sensors (Part # 40557, model 5TE, Decagon Devices, Pullman, WA, USA), which report θ_v, T and σ_a values; 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). The TDR system thus served as the control. Dataloggers were used to measure sensor and thermocouple outputs (model CR3000, CSI, Logan, UT, USA in the case of Hydra Probe, CS616 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. Sensors 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

The EM devices for use in access tubes produced larger *s* values than did the NP and gravimetric samplings of profile water content, and numbers of access tubes needed to obtain

[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.

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 apparent 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.

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	Irrigated	0.0045	≤1	≤1

push tube	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)
¶ Analytically, the value is ≤1, but realistically there must be at least one access tube.

In the local sensor study, values of σ_a determined by the TDR system 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. The TDR probes exhibited similar θ_v values, reaching a peak of 0.48 m^3 m^{-3} during the 1st flooding, which indicated an initial ρ_b of 1.39 Mg m^{-3} (Fig. 1). After settling, the peak θ_v was 0.42 m^3 m^{-3}, which is a typical porosity for the Pullman clay loam. Temperature interference was < 0.01 m^3 m^{-3} diurnally. Values of θ_v were similar over the small plot area.

The Acclima sensor performed similarly to the TDR system, exhibiting similar small temperature interference and slightly more difference in θ_v among the three sensors (Figure 1). Overestimation of θ_v was linked to overestimation of ε_a (Table 3). Since the relationship between ε_a from the Acclima to ε_a from the TDR system was highly linear and temperature interference was minimal in both systems, a soil-specific calibration is easily achieved for the Acclima by applying a linear correction to ε_a.

Comparison of the point sensors at 5.4-cm depth revealed inter-sensor variability of up to 0.08 m^3 m^{-3} for both the Hydra Probe and CS616 (Figure 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. Over the duration of the experiment, standard deviations of water content were 0.009, 0.011, 0.012, and 0.022 m^3 m^{-3} for the TDR, Acclima, CS616 and HydrProbe sensors, respectively.

The Hydra Probe overestimated ε_a more than did the Acclima (Table 3), but its θ_v estimates were comparable to those of the Acclima (Figures 1-2) except that it was more temperature sensitive, with diurnal variations up to 0.02 m^3 m^{-3}. Possibly because of this, the relationship between Hydra Probe ε_a and that from the TDR system was not as linear as for the Acclima. Given the range of σ_a measured by TDR, a CS616 calibration from the manufacturer for ρ_b of 1.6 Mg m^{-3} and σ_a = 0.75 dS m^{-1} at saturation was used. Even so, the CS616 overestimated θ_v more than the Acclima or Hydra Probe and was more temperature dependent, with diurnal variations due to temperature of up to 0.05 m^3 m^{-3}. Unlike the Acclima and Hydra Probe, the CS616 does not report T or σ_a, so temperature correction will require additional measurements. Differences in θ_v between sensors were also larger for the CS616.

Table 3. Linear regressions comparing Acclima apparent permittivity, ε_a, and Hydra Probe real permittivity, ε_r, to that from the TDR system.

Sensor	Intercept (-)	slope	r^2
Acclima	2.30	1.108	0.997
Hydra Probe	-1.51	1.451	0.961

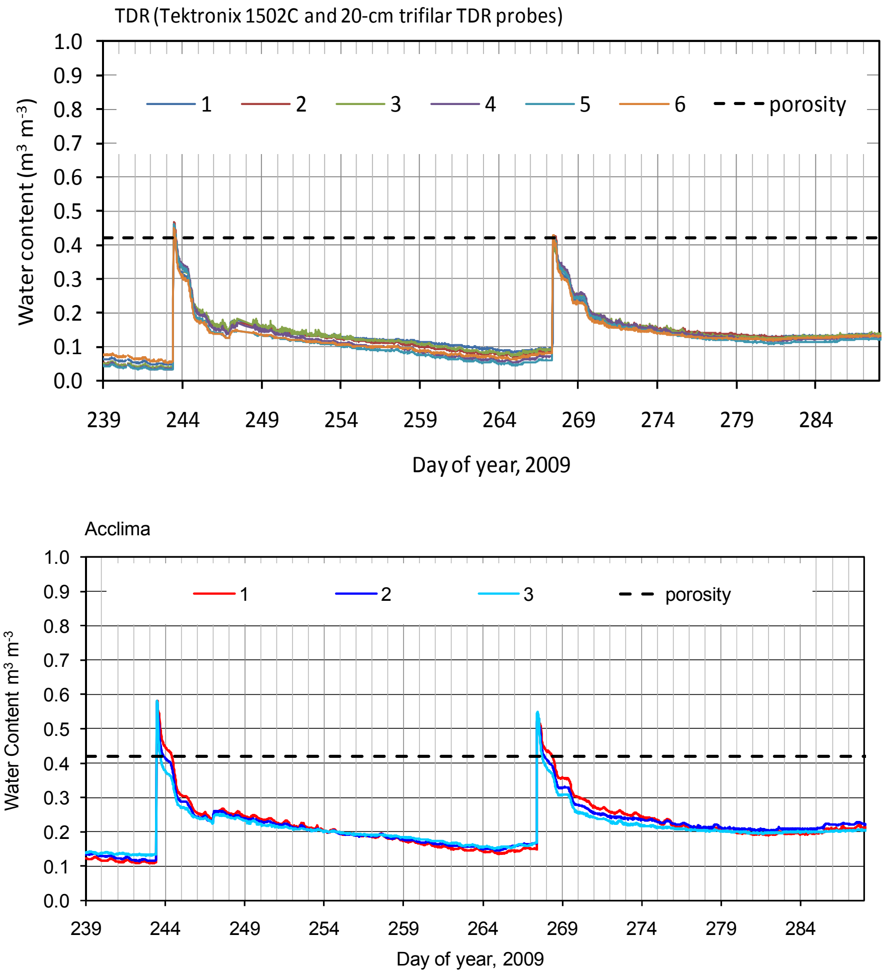

Figure 1. Conventional time domain reflectometry (TDR) water contents using soil-specific calibration (top); and Acclima sensor water contents (bottom).

The Acclima overestimated σ_a by nearly 100% (Table 4), but had a more linear relationship with that determined by TDR than did the Hydra Probe. The Hydra Probe exhibited a less linear relationship with σ_a values from TDR, particularly for the "temperature corrected" values from the Hydra Probe, which exhibited hysteresis in the relationship with σ_a from TDR due to temperature interference with the Hydra Probe values. Temperature was determined accurately by the Acclima; but the Hydra Probe exhibited a positive offset of 2.9°C (Table 5). This may have been due to the large sensor head of the Hydra Probe, which could have influenced the temperature measurement by heat conduction from above. Due to the diurnal variation of *T*, conduction of heat in the sensor head would also explain the more scattered relationship with thermocouple-measured *T* for the Hydra Probe.

Table 4. Linear regression relationships comparing Acclima and Hydra Probe bulk electrical conductivity, σ_a, to that from the TDR system.

Sensor	Intercept (S/m)	slope	r^2
Acclima	-0.022	1.985	0.953
Hydra Probe	-0.017	0.865	0.920
Hydra Probe (temperature corrected)	-0.018	0.908	0.884

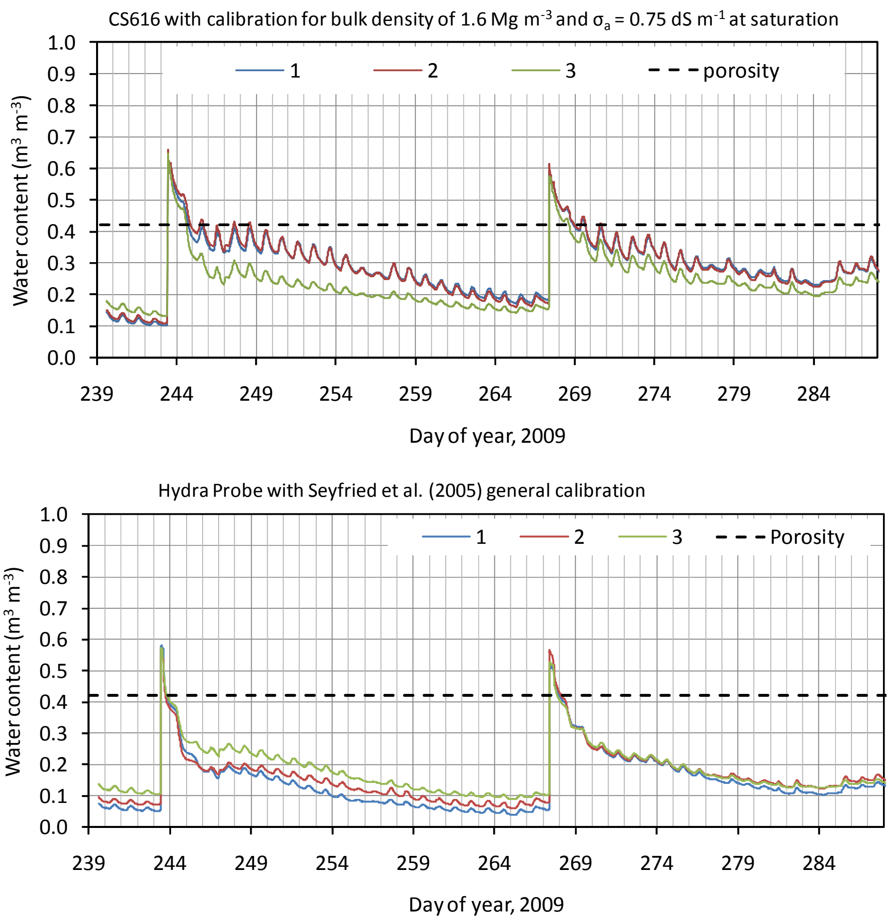

Figure 2. CS616 water contents from calibration for sandy clay loam, ρ_b of 1.6 Mg m^{-3} and σ_a = 0.75 dS m^{-1} at saturation (top); and Hydra Probe water contents using Seyfried et al. (2005) general calibration (bottom).

As sensor effective frequency, f_{eff}, decreases, ε_a typically becomes larger due to increased contributions from σ_a and dielectric relaxation to the imaginary component of permittivity. This was apparent in our results since the Acclima sensor had the largest f_{eff}. The CS616 has a larger f_{eff} than the Hydra Probe, but estimates ε_a, while the Hydra Probe estimates ε_r, which is less sensitive to σ_a. Overestimation of σ_a by the Acclima is related to the fact that σ_a is related to f_{eff}, which makes it a high frequency measurement and susceptible to relaxation effects (Topp et al. 2000). The Acclima algorithm for finding the travel time makes it a simplified TDR method (Anderson 2003) and suitable for irrigation scheduling and with calibration research uses.

Table 5. Linear regression relationships comparing Acclima and Hydra Probe temperatures, T, to that from the six thermocouples.

Sensor	Intercept (°C)	slope	r^2
Acclima	-0.190	1.007	0.996
Hydra Probe	2.87	1.011	0.987

Conclusion

Both the Hydra Probe and CS616 exhibited inter-sensor variability and temperature sensitivity of estimated θ_v that made them unsuitable for most field studies and model tests of infiltration, soil water redistribution and plant water uptake, and which may make them unsuitable for irrigation scheduling as well. The Acclima exhibited small inter-sensor variability and temperature dependency, similar to that of the TDR system. It may easily be calibrated as a useful tool in scientific studies and water management for disturbed soils (e.g., the plow layer). Because it must be buried rather than inserted into the soil, it may not be useful for deeper installations where the soil structure should not be disturbed, though this may not be a great concern for irrigation scheduling.

The local sensor study was set up to minimize variation in soil properties, including water content and those properties such as temperature and bulk electrical conductivity that could cause sensor-to-sensor variations in reported water content. The soil was repacked around the sensors and natural soil structure was destroyed. Therefore, sensor-to-sensor variability was relatively small for each type of local sensor compared to what might be seen in a typical installation for irrigation scheduling and control. Nevertheless, variability was greater than that from neutron probe and gravimetric water contents measured in an earlier study, probably because of the small sampling volume of the local sensors and also due to the fact that the neutron probe and gravimetric water contents were averages over depth. The performance of the local sensors in an irrigation scheduling context should be further evaluated.

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