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USING SOIL WATER SENSORS TO IMPROVE IRRIGATION MANAGEMENT

José L. Chávez
Assistant Professor
Civil & Environ. Engineering Dept.
Colorado State University
Fort Collins, Colorado
Voice: 970-491-6095
Fax: 970-491-7727
Jose.Chavez@colostate.edu

Steven R. Evett
Research Soil Scientist
Soil & Water Management Research
USDA-ARS[1]
Bushland, Texas
Voice: 806-356-5775
Fax: 803-356-5750
Steve.Evett@ars.usda.gov

ABSTRACT

Irrigation water management has to do with the appropriate application of water to soils, in terms of amounts, rates, and timing to satisfy crop water demands while protecting the soil and water resources from degradation. In this regard, sensors can be used to monitor the soil water status; and some can be used to calculate irrigation amounts and to decide when to optimally irrigate. This article consists of two parts: 1) presentation of different soil water sensor technologies, and 2) accuracy assessment of selected sensors. The selected sensors included the Acclima[2] (ACC) time domain transmissometer (Acclima, Inc., Meridian, ID), the CS616 and CS655 water content reflectometers (Campbell Scientific, Inc., Logan, UT), the Hydra Probe (Stevens Water Monitoring Systems, Inc., Portland, OR), and the 5TE (Decagon Devices, Inc., Pullman, WA). Sensed soil water content values, in a sandy clay loam soil and a silty clay loam soil, were compared with corresponding values derived from gravimetric samples and TDR readings. Factory based calibrations performed well for the ACC and CS655, but not for the other sensors. The ACC and CS655 sensors were promising for irrigation management, although proper installation is important. Evaluations indicated that a linear calibration for the ACC and the CS616 sensors could improve the water content readings.

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INTRODUCTION

Nowadays we live in a scenario of climate change and population growth that challenges farmers to be more efficient with their water resources; i.e. to obtain a larger yield with the same or with less water. Improvements in water use efficiency can be achieved utilizing soil water sensors to track the daily soil water content status.

Many methods of determining soil water content have been developed, from simple manual gravimetric sampling to sophisticated neutron probe (NP) and time domain reflectometry (TDR) sensors. One common technique is to measure the soil dielectric permittivity, that is, the capacitive and conductive parts of a soil's electrical response. If the dielectric permittivity is determined at a sensor effective frequency in the range where permittivity is not frequency dependent and if it is determined using a time domain measurement, then the permittivity measurement can be directly related to soil volumetric water content through the use of an appropriate calibration curve (Topp et al. 1980; Evett et al., 2012). However, there are several different types of sensors commercially available that operate at different effective frequencies and that use either time domain or frequency domain measurement methods. These present different levels of soil water content/potential reading accuracy. Hignett and Evett (2008) indicated the following: *"in general, a manufacturer's calibration is commonly performed in a temperature controlled room, with distilled water and in easy to manage homogeneous soil materials (loams or sands) which are uniformly packed around the sensor. This calibration procedure produces a very precise and accurate calibration for the conditions tested. However, in field conditions variations in clay content, temperature, and salinity may affect the manufacturer's calibration."* Therefore, the accuracy of sensors needs to be assessed for a proper utilization of the sensors' measurements in irrigation water management.

Evett et al. (2010) reported field studies of soil water sensors that could be buried or inserted into the soil or that could be used from within plastic access tubes inserted into the soil. Since then, new sensors have been put on the market. In this article, the following is presented: a) a description of an array of selected soil water content sensor technologies, and b) an assessment of the accuracy of selected soil water content sensors, including those not reported on earlier.

MATERIALS AND METHODS

Part 1. Description of important soil water content sensor types

Neutron Probe (NP)

Neutron probes use a radioactive, non-directional, neutron emitting source along with a detector of slow neutrons. The hydrogen in water molecules slows down (thermalizes) the fast (high energy) neutrons, and the slow neutrons randomly return to the detector where they are counted (Evett, 2008). Because it can be used with a cable of practically any length, measurements with the NP can be made at depths ranging from 4 in (10 cm) to >10 ft (>3 m) below the soil surface. The typical soil volume radius sampled by the probe ranges from 6 to 20 in (15 to 50 cm) depending on the soil water content (larger radius for drier soil conditions).

The NP is somewhat expensive and, by regulation, must be operated by a trained and licensed person since using the NP involves manipulating a radiation source. Therefore the NP is mainly used in research and to evaluate other sensors. The NP sensor can be very accurate when field calibrated and provides quick readings. However, the NP needs to be calibrated for the soil and access tube. The calibration is a linear relationship between neutron count ratio (neutron count in soil divided by standard neutron count in shield) readings and soil volumetric water content (ft/ft or m^3/m^3) obtained with the gravimetric/volumetric sampling method. By regulation, the NP cannot be used unattended, so automatic, unattended datalogging is not possible.

Porous Blocks (Resistance)

These sensors consist of blocks made of gypsum, nylon, granular matrix, or fiberglass. Embedded in the blocks are electrodes that measure the resistance (Ohms) between these electrodes. The resistance changes as a function of soil water tension (matric potential), which is related to the soil water content. Watermark sensors (e.g., 200SS, Irrometer Company, Inc., Riverside, CA) are of the resistance block type sensors. These sensors have their electrodes covered by a synthetic porous membrane housed in a perforated plastic casing. The Watermark is a low cost sensor that works in most soils. It contains a gypsum tablet that helps in buffering soil salinity. As a resistance sensor its readings are in "Ohms." A calibration equation (e.g., Shock et al., 1998) is used to convert the "Ohms" or rather "kOhms" to soil matric potential or suction (kPa, mb, or cb). The sensor operating range is said to be 0-200 kPa. In contrast, blocks made of gypsum such as the GB-1 (Delmhorst Instrument CO., Towaco, NJ) allegedly read the resistance in the soil over a wider range (10-1,500 kPa or 0.1-15 b). With a resistance based sensor one obtains the tension at which the water is being held in the soil. To convert soil matric potential to soil volumetric water content (VWC or θ_v) one uses a soil characteristic curve (or soil water release/retention curve), which is specific for each soil and each soil layer, and which changes with soil bulk density (compaction).

Measurements Related to Soil Dielectric Permittivity

There are several sensor types that respond to changes in the soil dielectric permittivity (also known as the dielectric constant, although it is not a constant in soils). The permittivity increases with soil water content, but depending on the measurement method and effective frequency, the permittivity may also be strongly dependent on bulk electrical conductivity (which is affected by clay content and type and by soil salinity and temperature), bound water (water held tightly to clay surfaces, the permittivity of which is temperature dependent), and even by the effective frequency of the electronic signal used. The major classes of methods are those that work 1) in the time domain, measuring the time it takes an electronic pulse to travel through an electrode buried in the soil, and 2) in the frequency domain, measuring the resonant frequency of an oscillating electronic circuit, part of which is coupled with the soil through electrodes buried in the soil or contained in a plastic access tube inserted into the soil.

Time Domain Methods

A basic conventional time domain reflectometry (TDR) instrument consists of a fast oscilloscope and a pulse generator. The instrument is used in a TDR system, which typically consists of, at minimum, the instrument, a computer or datalogger to control the instrument and interpret data, and a TDR probe consisting of rigid electrodes that are inserted into the soil (length varies, but 4 to 8 inches are common). A fast rise time electromagnetic pulse is sent through the electrodes (two or three). The pulse is reflected from the ends of the electrodes and returned to the instrument, which captures a waveform showing the pulse relative voltage as it passes through the electrodes. The speed of the pulse is inversely proportional to the soil VWC.

The TDR system interprets the waveform to find the travel time of the pulse. The system can be calibrated using a linear equation relating VWC to travel time. Or, the system can calculate the soil dielectric permittivity (which is inversely and non-linearly related to the velocity of the electromagnetic pulse). Then, an equation like Topp’s equation (Topp et al., 1980) can be used to convert the permittivity readings to VWC. Conventional TDR systems are very accurate, expensive, used mainly in research, and provide an integrated/average soil water content along the depth/length of the probe. Soil-specific calibrations are needed in some soils or if high accuracy is needed; but a single calibration can be used in many soils because TDR readings are relatively independent of soil texture, bound water, salinity, density, or temperature. Highly accurate calibration methods used for science applications may use ancillary measurements of soil temperature and bulk electrical conductivity. Most conventional TDR systems can accurately measure the bulk EC, which not only is useful for enhanced calibration equations but is useful for irrigation management, including leaching, to deal with saline soils.

Several sensors employ time domain transmissometry, which is similar to TDR but measures transmission time in a loop circuit and does not rely on a reflection. These include the Acclima ACC, the ESI Gro-Point, and the Aquaflex SE200. These time domain transmission (TDT) sensors vary in the way in which they determine the pulse travel time. Of the three mentioned, only the Acclima ACC captures and interprets a waveform to determine travel time as accurately as a conventional TDR system. The TDT sensors all have the electronics embedded in a plastic sensor head, so that the expensive TDR instrument is avoided. We studied the ACC (Acclima, Inc., Meridian, ID) sensor, which has a waveguide consisting of two looping rods 8 in (20.3 cm) long. Besides providing readings of VWC (by Topp's equation), the sensor also provides soil temperature and soil bulk electric conductivity (EC_b, dS/m). This sensor communicates with a datalogger using the SDI-12 interface which is "Serial Data Interface at 1200 Baud". SDI-12 is an asynchronous, ASCII, serial communications protocol.

Other time domain methods attempt to measure travel time of a reflected pulse using electronics embedded in sensor heads, but do not capture a waveform. Although these may be called TDR sensors, the ways in which they determine pulse travel time may have limited accuracy due to strong effects of soil bulk electrical conductivity and temperature. We studied the CS616 and CS655 "water content reflectometers" (Campbell Scientific, Inc., Logan, UT), which employ two electrode rods (lengths of 4 to 12 in). An electronic pulse is sent from the probe head and reflected from the ends of the rods. Once the probe head detects the return of the pulse, another pulse is sent. The probe then records the frequency of these pulses and reports the inverse of the frequency (also called a period, with units of micro seconds or µs). The soil's dielectric permittivity influences the velocity of the electromagnetic pulse, which in turn influences the period. The probe then relays the data sensed to a datalogger. A calibration equation (provided by the manufacturer), that can be coded in the datalogger program, then relates the probe's output period to volumetric soil water content (Campbell, 2011; Ruelle and Laurent, 2008).

Frequency Domain Methods (Capacitance Sensors)

The capacitance sensors (e.g., Diviner 2000 and EnviroScan, Sentek Sensor Technologies, Stepney SA, Australia) are based on the varying frequency of oscillation of an electromagnetic field in the soil. An oscillating current is induced in a circuit, part of which is a capacitor that is arranged so that the soil becomes part of the dielectric medium affected by the electromagnetic field between the capacitor's electrodes. Varying soil VWC influences the dielectric permittivity of the soil, which in turn affects the capacitance, causing the frequency of oscillation to shift. These sensors are referred to as Frequency Domain sensors. The manufacturer provides a calibration equation (embedded in the sensor electronics or applied separately) relating readings from the sensor to VWC. According to Evett et al. (2008), in general the manufacturer calibration may not perform well in field conditions due to temporal variation of soil bulk electrical conductivity and due to the small scale spatial variability of soil water content and bulk EC.

We studied the 5TE capacitance sensor (Decagon Devices, Inc., Pullman, WA). This sensor measures the relative permittivity of the soil by supplying "a 70 MHz oscillating wave to the sensor prongs … [and the resulting] stored electric charge [in the prongs] is proportional to [the] soil dielectric properties." In SDI-12 communication mode, the 5TE reports the relative permittivity to the datalogger. The relative permittivity values in turn can be converted to VWC automatically within the datalogger. The standard calibration equation recommended by the manufacturer is the previously-mentioned Topp's equation.

We also studied the Hydra Probe, which reports values of the real (ε_r) and imaginary (ε_i) components of permittivity, the temperature (T) and bulk electric conductivity (σ_a).

Part 2. Selected soil water content sensors accuracy assessment

Two different sensor evaluation studies were carried out. One in Greeley, Colorado evaluated CS616 and ACC sensors while the other study in Bushland, Texas evaluated CS616, CS655, ACC, Hydra Probe, and 5TE sensors.

Colorado Study

This study took place during the 2011 corn growing season in eastern Colorado. The field was an experimental field cooperatively operated by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) and Colorado State University (CSU) near the City of Greeley, CO. Corn was grown at this location and was irrigated using furrows. Geographic coordinates, dry bulk density, porosity and texture of the soil can be found in Table 1. Bulk density was obtained using a Madera Probe (Precision Machine, Inc., Lincoln, NE). The porosity was estimated using the sampled bulk density and an assumed particle density of 2.65 g/cm^3. Soil textures were determined in the Laboratory by a particle size analysis (Hydrometer Method; Gavlak, et al., 2003).

Table 1. Site Name, Geographic Coordinates, Dry Soil Bulk Density (ρ_b), Porosity (φ), and Soil Texture in the 10 - 30 cm soil layer.

Site	Lat. (N)	Long. (W)	ρ_b (g/cm^3)	φ (%)	Sand (%)	Silt (%)	Clay (%)	Class
Greeley, CO	40°26'	104°38'	1.46	45	65	10	25	Sandy clay loam

The ACC soil water content sensor is provided with a calibration by the sensor manufacturer, which enables the sensor to give a direct reading of volumetric soil water content (VWC), soil temperature (°C), and bulk electrical conductivity (σ_a, dS/m). According to Acclima (2010), the volumetric water content accuracy of the sensor is ±1% (full scale) under temperature conditions of 0.5 to 50°C and σ_a of 0 to 3 dS/m.

During August of 2011, ACC and CS616 sensors were installed at the study site. Three sensors of each type were installed, at different locations 45 m apart, one ACC and one CS616 were installed at each site under the corn bed, roughly 0.3 m (1 ft) away from each other, at a depth of approximately 1-5 inches (2-12 cm) (slanted) below the average level of the corn beds. Sensor readings were recorded every fifteen minutes using an automatic datalogger (CR1000, Campbell Scientific, Inc., Logan, UT). Sensor evaluation was performed using the data collected in 2011.

The VWC from the sensors were compared with VWC measurements obtained with a portable TDR sensor (MiniTrase kit, Soil Moisture Equipment Corp., Santa Barbara, CA), in the 0-6 in (0-15 cm) surface layer. Ten VWC readings were taken with the TDR sensor during the month of August in 2011 at a location approximately 1 m from the location of the ACC and CS616 sensors. The TDR system used incorporated a calibration defined by the manufacturer.

Texas Study

The study was done at the USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas in the plow layer (Ap horizon) of the Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll). A 40 in by 80 in (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 2 in (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 the same depth. Sensors were placed so that the six sensors of each type were intermixed in position with the six sensors of the other types. All measurements were made every 0.5 h for two years. The plot area was surrounded by a low berm and flooded by irrigation after sensor installation, then flooded by irrigation or wetted by precipitation periodically during the testing period. Minor soil settling occurred after the 1st flooding, indicating that the pre-flooding bulk density (ρ_b, Mg m^{-3}) was <1.54, the target ρ_b to achieve a porosity of 0.42 $m^3\ m^{-3}$; so soil was added to the plot and leveled between the rails to achieve the target depth of 5.4 cm and bulk density of 1.54. The bulk density was confirmed by volumetric sampling. This meant that the water content could not exceed the soil porosity of 0.42 $m^3\ m^{-3}$, which allowed over estimation of water content by any sensor to be easily confirmed. The plot was kept bare of vegetation. In contrast with the Colorado study, the Texas study was designed so that all sensors would be subjected to the same conditions of soil texture, air-filled porosity, water content, temperature and bulk electrical conductivity so that comparisons could be made between each sensor type and the TDR system and between sensors of the same type (to assess inter-sensor variation).

Sensors included six CS616 sensors (Campbell Scientific Inc., Logan, UT, USA); six ACC sensors (model ACC-SEN-TDT, Acclima, Inc., Meridian, ID, USA); six Hydra Probes (Stevens Water Monitoring Systems, Inc., Portland, OR, USA); and six type-T thermocouples (hand made). Later in the study, the CS616 sensors were exchanged for CS655 sensors, also from Campbell Scientific, Inc., and six 5TE sensors (Decagon, Inc., Pullman, WA) were included.

Comparisons were made with data from six conventional TDR probes (20-cm, planar trifilar), built as described by Evett (2000a) except that RG6 cable was used to reduce attenuation. 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). Because it employed a soil-specfiic calibration and could determine dielectric permittivity, bulk electrical conductivity and water content with high accuracy (Evett et al., 2005), the TDR system served as the control in this study. 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 ACC sensors). 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. Thermocouple measurements of temperature were used as the control or standard against which temperatures from the other sensors were compared.

Statistical Analysis

Statistical measures were computed to compare and evaluate each model-predicted (*P*) VWC with the observed (*O*) VWC values ($m^3\ m^{-3}$) taken from the field. These include the mean bias error (*MBE*; Equation 1), and the root mean square error (RMSE; Equation 2), as defined by Willmott (1982).

$$\mathrm{MBE} = \mathrm{n}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{P_i} - \mathrm{O_i}) \tag{1}$$

$$\mathrm{RSME} = [\mathrm{n}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{n}}(P_i - O_i)^2]^{0.5} \tag{2}$$

where *n* is the sample size. The units for MBE and RMSE are absolute volumetric water content errors ($m^3\ m^{-3}$).

RESULTS AND DISCUSSION

Colorado Study

The factory calibration was evaluated with the 2011 VWC measured data collected with the TDR sensor. The absolute errors were -0.049±0.059 $m^3\ m^{-3}$, and 0.314±0.062 $m^3\ m^{-3}$, for the ACC and CS616 sensors, respectively. This result shows that the CS616 sensor is not reliable and indeed needs site specific (soil/sensor) calibration; while the ACC sensor showed much less error. One issue with the ACC sensor might be the difficulty of installing it properly in drier soils due to the nature of the looping probes that may prevent full contact of the soil with the probe (air voids). Figure 1 show the graphical representation of the comparison of the sensors' VWC data.

Texas study

All 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. 2). After settling, the peak θ_v was 0.42 $m^3\ m^{-3}$, which is a typical porosity for the Pullman clay loam Ap horizon after consolidation. Temperature interference was < 0.01 $m^3\ m^{-3}$ diurnally. Importantly, values of θ_v were quite similar over the small plot area. Values of σ_a ranged from 0.2 to 1.3 dS m^{-1} over the course of the study. The ACC sensor performed similarly to the TDR system, exhibiting similar small temperature interference and slightly more difference in θ_v among the sensors (Fig. 2). Since the relationship between ε_a from the ACC to ε_a from the TDR system was highly linear (Table 2) and temperature interference was minimal in both systems, a soil-specific calibration can be easily achieved for the Acclima by applying a linear correction to ε_a.

The Hydra Probe overestimated ε_a more than did the ACC (Table 2), but its θ_v estimates were similar in magnitude to those of the ACC (Figures 2-3). However, it was more temperature sensitive, with diurnal variations up to 0.02 $m^3\ m^{-3}$, and it exhibited larger inter-sensor variation, up to 0.08 $m^3\ m^{-3}$. The temperature sensitivity may have been why the relationship between Hydra Probe ε_a and that from the TDR system was not as linear as for the ACC. The CS616 does not directly report T, ε_a or σ_a. The 5TE underestimated ε_a and exhibited the largest error and smallest r^2 value, the latter of which indicates a lack of linearity in response. This was due to soil temperature effects that caused hysteresis in the response. Such temperature effects are common with capacitance based sensors. The CS655 overestimated ε_a by about 30%, but with the second smallest error (after the ACC) and high linearity, indicated that a simple linear correction would be effective in correcting its output in the Pullman soil.

Table 2. Linear regressions comparing Acclima ACC, 5TE and CS655 apparent permittivity, ε_a, and Hydra Probe real permittivity, ε_r, to that from the TDR system.

Sensor	Intercept (-)	slope	RMSE (-)	r^2
ACC	2.00	1.088	0.40	0.988
Hydra Probe	0.88	1.328	0.85	0.965
5TE	4.76	0.815	1.004	0.877
CS655	0.03	1.334	0.541	0.985

Knowing the soil bulk electrical conductivity is important since high conductivities can affect plant growth and indicate the need for leaching. The Acclima greatly overestimated σ_a (Table 3), but had a more linear relationship with σ_a determined by TDR than did the Hydra Probe and so could be easily corrected with a linear calibration. However, the great overestimation of σ_a by the ACC indicates a problem with the algorithm by which σ_a is computed in that sensor. 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 incorrect compensation for temperature interference in the Hydra Probe sensor. The 5TE underestimated σ_a by about 35% and exhibited by far the largest error. Its response was also not linear (r^2=0.58), indicating that a correction is not practical. The CS655 estimated σ_a very well with nearly perfect 1:1 correlation.

Table 3. Linear regression relationships comparing Acclima ACC and Hydra Probe bulk electrical conductivity, σ_a, to that from the TDR system.

Sensor	Intercept (S/m)	slope	RMSE (S/m)	r^2
ACC	-0.014	2.347	0.009	0.950
Hydra Probe	0.000	0.850	0.004	0.924
Hydra Probe (temperature corrected)	0.013	0.706	0.010	0.584
5TE	0.005	0.650	0.009	0.588
CS655	-0.008	1.007	0.001	0.993

Knowing soil temperature is important early in the season to guide planting and also in order to apply temperature corrections to water content data. Temperature was determined with sufficient accuracy by all the sensors as shown by nearly 1:1 responses that were highly linear with errors <1°C (Table 4). An earlier report of overestimation of temperature by the Hydra Probe (Evett et al., 2010) was found to be related to continuous reading of the sensor, which apparently caused self heating. Turning off the sensor between half-hourly readings resolved this problem.

Table 4. Linear regression relationships comparing Acclima ACC and Hydra Probe temperatures, *T*, to that from the six thermocouples.

Sensor	Intercept (°C)	slope	RMSE (°C)	r^2
ACC	0.10	1.008	0.62	0.997
Hydra Probe	0.48	0.989	0.80	0.995
5TE	0.11	0.992	0.85	0.994
CS655	-0.19	1.000	0.95	0.992

Most producers and irrigators will not take the time to do soil-specific calibration of sensors, so it is important to know how well each sensor estimates water content using the best factory or otherwise known calibration. 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 ACC or Hydra Probe and was more temperature dependent (Figs. 2-3, not shown in Table 5), with diurnal variations due to temperature of up to 0.05 m^3 m^{-3}. Unlike the ACC and Hydra Probe, the CS616 does not report *T* or σ_a, so temperature correction would require additional measurements. Differences in θ_v between sensors were also larger for the CS616, up to 0.12 m^3 m^{-3}. In contrast, the newer CS655 performed much better; it was well correlated with water content, with a slope of close to unity and root mean square error (RMSE) of 0.01 m^3 m^{-3}. The ACC exhibited the smallest root mean square error and was the most well correlated with water content, probably due to the fact that it captures and interprets a waveform for pulse travel time, as does a conventional TDR system. The Hydra Probe was less well correlated with water content than the ACC or CS655 and exhibited a larger root mean squared error of 0.015 m^3 m^{-3}; both problems are related to it sensitivity to σ_a interference, which is influenced by temperature changes. The 5TE was the worst performing sensor using the factory calibration. It was the least well correlated with water content (smallest r^2), and had the largest error, largest intercept and slope furthest from unity.

Table 5. Linear regression relationships comparing estimated water contents from the Acclima ACC, Hydra Probe, 5TE, CS616 and CS655 to data from the TDR system.

Sensor	Intercept (m^3 m^{-3})	slope	RMSE (m^3 m^{-3})	r^2
ACC	0.05	0.932	0.004	0.994
Hydra Probe	0.02	1.027	0.015	0.938
5TE	0.10	0.687	0.018	0.820
CS655	0.04	1.037	0.010	0.973

CONCLUSIONS

This article presents several soil water content sensor technologies along with an assessment of the performance of selected soil water content sensors. The ACC, Hydra Probe, 5TE, CS655 and CS616 sensors were evaluated in the field. The sensor measurements of soil water content were compared with corresponding values derived from gravimetric samples and with values from a TDR system. Linear calibration equations could be developed easily for the ACC and CS655 sensors based on volumetric soil water content data obtained in the field by gravimetric/volumetric sampling or with a calibrated TDR system. According to evaluations, the ACC and CS655 sensors seem to be more robust and accurate sensors overall. The Acclima algorithm for finding the travel time makes it an accurate time domain method (Anderson 2003) and thus suitably accurate for irrigation scheduling. However, the nature of its looping probes may hinder the correct installation of the sensor and therefore the appropriate use of the resulting data. The CS655 was easily installed since it could be pushed into the soil. Regarding the CS616 sensor, it showed a very large error if used with the factory calibration and was overly temperature sensitive. However the sensor needs a better calibration, perhaps incorporating the effect of soil temperature and salinity in order to lower its error to around 0.03 m^3 m^{-3}. Unfortunately, it measures neither. The authors can recommend the ACC and CS655 sensors for irrigation scheduling. The results found in this study are encouraging in that some of the studied soil water content sensors have the potential to be used in irrigation water management schemes.

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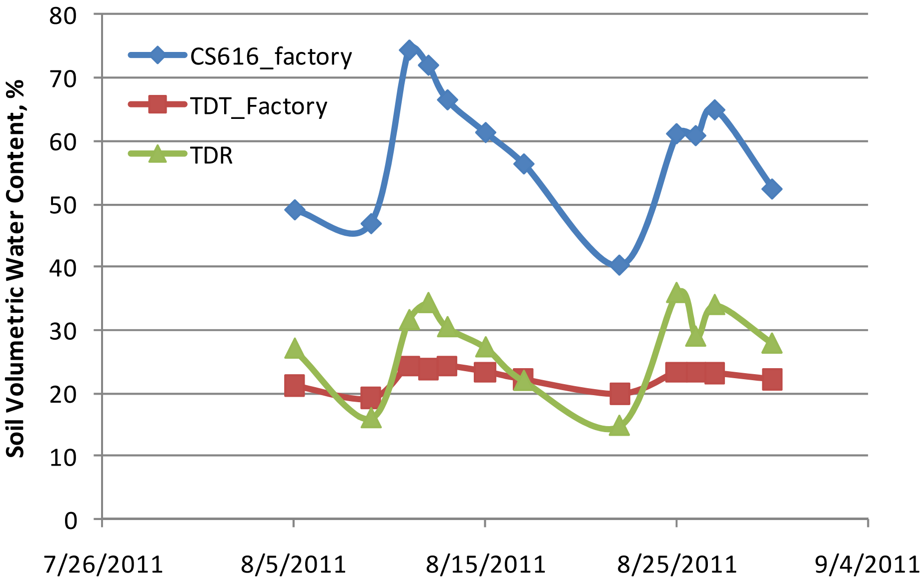

Figure 1. Comparison of the VWC of the CS616 and ACC (TDT) factory calibration readings with TDR VWC values in Colorado.

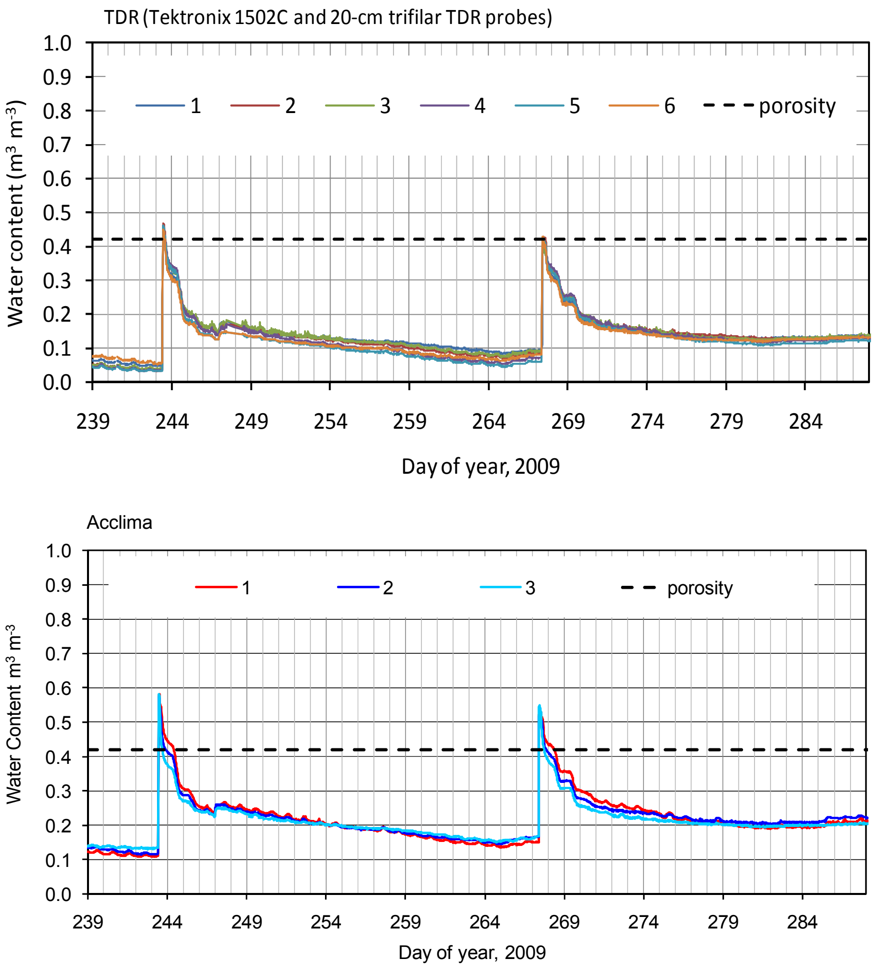

Figure 2. Conventional time domain reflectometry (TDR) water contents using soil-specific calibration (top) and Acclima sensor water contents (bottom) during the first two plot flooding and dry down periods, in Texas.

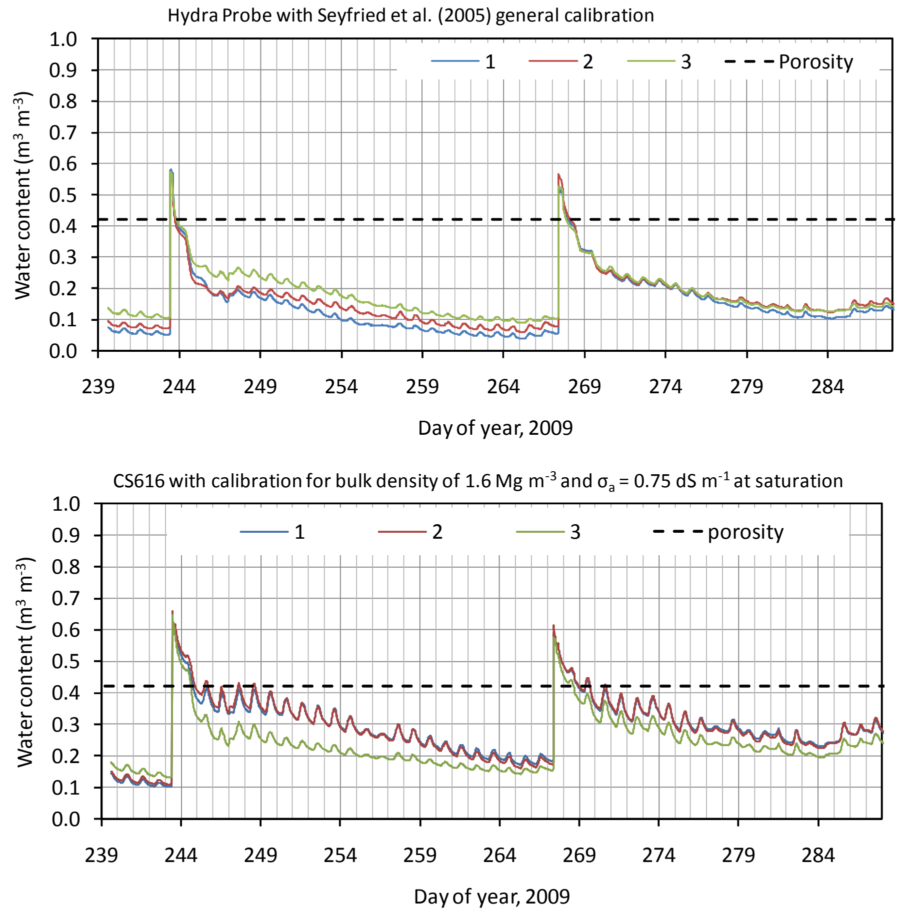

Figure 3. Hydra Probe water contents using Seyfried et al. (2005) general calibration (top); and CS616 water contents from calibration for sandy clay loam, ρ_b of 1.6 Mg m^{-3} and σ_a = 0.75 dS m^{-1} at saturation (bottom) for the first two flooding and dry down periods, in Texas.