THESIS

PERFORMANCE EVALUATIONS AND CALIBRATIONS OF SOIL WATER CONTENT/POTENTIAL SENSORS FOR AGRICULTURAL SOILS IN EASTERN COLORADO

Submitted by

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ABSTRACT

PERFORMANCE EVALUATIONS AND CALIBRATIONS OF SOIL WATER CONTENT/POTENTIAL SENSORS FOR AGRICULTURAL SOILS IN EASTERN COLORADO

Due to competition for water from expanding urban and industrial demands, irrigated agriculture needs to improve its water management methods. One technique is closely monitoring volumetric soil water content (θ_v; m^3 m^{-3}) in the crop root zone to accurately determine irrigation timing and amount. Numerous soil water content sensors are available, and they vary widely in operating principles and accuracy. However, the performance of these sensors in sandy clay loam, clay loam and loamy sand soil types in irrigated agricultural fields in eastern Colorado is largely unknown.

This study evaluated the performance of three soil water content sensors (CS616/625, Campbell Scientific, Inc., Logan, UT; TDT, Acclima, Inc., Meridian, ID; 5TE, Decagon Devices, Inc., Pullman, WA) and a soil water potential sensor (Watermark 200SS, Irrometer Company, Inc., Riverside, CA) in the soils mentioned above. The evaluation was performed using θ_v data collected in the laboratory and in fields near Greeley, CO. Soil water content/potential values measured by the sensors were compared with corresponding values derived from gravimetric samples, ranging from the

approximate permanent wilting point (PWP) to field capacity (FC) volumetric water contents. Calibration equations of sensor-measured θ_v were developed based on the laboratory and field data, and were compared with the factory-recommended calibrations. In addition, laboratory tests using an additional salt (calcium chloride dihydrate) concentration with varying soil water content were carried out to determine the effects of the soil bulk electrical conductivity on CS616, TDT, and 5TE sensor readings.

Evaluation of Sensor performance was based on statistical targets for these tests. The target, or maximum, allowed errors were a mean bias error (MBE) of ±0.020 $m^3\ m^{-3}$ and a root mean square error (RMSE) of less than 0.035 $m^3\ m^{-3}$. Inspections were also made to analyze the capacity of each sensor to accurately read the full range of moisture contents from near PWP to saturation. Additionally, the sensors in the field were placed horizontally at a shallow (10-cm) depth to capture wide fluctuations in soil temperature and examine its effect on sensor readings. Careful installation measures were taken to ensure that air gaps did not exist between the sensor rods and the soil by inserting the sensors when the soil was fairly moist and workable.

Under laboratory and field conditions, the factory-based calibrations of θ_v did not consistently achieve the required accuracy for any sensor. The MBE of the factory calibrations of θ_v for the CS616 sensors ranged from 0.032 to 0.337 $m^3\ m^{-3}$ in the three soils. The factory calibration for the TDT sensors produced MBE values in the range of 0.007 to 0.061 $m^3\ m^{-3}$ in the three soils. The MBE of the factory calibrations of θ_v for the 5TE sensors ranged from 0.004 to 0.024 $m^3\ m^{-3}$ in the three soils. The factory calibration for the Watermark sensors produced MBE values in the range of 0.082 to 0.200 $m^3\ m^{-3}$ in the three soils.

Additional salt (calcium chloride dihydrate) concentrations in the laboratory caused the CS616 to give an error reading. Also, the higher concentrations increased the MBE of the factory calibration of the TDT sensor by 0.026 $m^3\ m^{-3}$ in the sandy clay loam (Site A), and 0.066 $m^3\ m^{-3}$ in the clay loam (Site C), and increased the MBE of the 5TE sensors in the soils from Sites A and C by 0.172 $m^3\ m^{-3}$ and 0.162 $m^3\ m^{-3}$, respectively.

Field tests indicated that using the calibration equation developed in the laboratory to correct the data obtained by CS616, TDT, 5TE and Watermark sensors in the field at Site A were not consistently accurate in every treatment. However, they were more accurate than the factory calibration equations. Applying the laboratory-derived calibration equation developed for the CS625 sensors at Site B (loamy sand) was accurate at the 30- and 61-cm depths. However, using this equation resulted in an overestimation of θ_v by 0.032 $m^3\ m^{-3}$ at the 91-cm depth. Using the laboratory equations developed for the Watermark sensors at Site B accurately measured θ_v at the 61- and 91-cm depths (RMSE = 0.014 and 0.024 $m^3\ m^{-3}$, respectively).

Results from field tests at Sites A and B indicated that a linear calibration of the TDT and 5TE sensors (and a logarithmic calibration for the Watermark sensors) could reduce the errors of the factory calibration of θ_v to 0.020±0.035 $m^3\ m^{-3}$ (2±3.5%). These tests also confirmed that each individual sensor needed a unique calibration equation for every soil type and location in the field. Furthermore, the calibrated van Genuchten (1980) equation was not significantly more accurate than the calibrated logarithmic equation.

Analysis of the θ_v graphs from the field data indicated that the CS616, 5TE and Watermark sensor readings were influenced by diurnal fluctuations in soil temperature, while the TDT was not influenced. Therefore, the TDT sensor was overall the most robust of the four sensors that were evaluated. Additionally, it is recommended that the soil temperature be considered in the calibration process of the CS616, 5TE, and Watermark sensors through either a correction equation or taking readings from the sensors during times that the soil temperature is similar (for example, every day at noon).

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INTRODUCTION AND BACKGROUND

Due to competition for water from urban growth, drought and changing climate conditions, irrigated agriculture needs to improve its water management methods (Cooley et al., 2009). One technique uses buriable-type soil water content sensors to closely monitor a wide range of field volumetric soil water content (θ_v; units of $m^3\ m^{-3}$, expressed as a %) conditions. Knowing periodic soil water contents enables an irrigation manager to determine optimum irrigation timing and amount (Morgan et al., 2001). Irrigations can then be scheduled whenever the soil water content is depleted to a management allowed level (previously-set critical level). Alternatively, a soil water potential sensor can be used to schedule irrigations whenever the soil water potential reaches a previously-set threshold.

The use of soil water content sensors is gaining vast federal support. The U.S. Department of Agriculture recently awarded the White River Irrigation District in Arkansas $4.45 million to install water measurement and monitoring technology, which includes soil water content sensors (NRCS, 2009). Furthermore, since 2006 the U.S. Air Force has been introducing Watermark soil water content sensors to farmers throughout rural Afghanistan (Kapinos, 2006). Yet Hignett and Evett (2008a) warn that some soil water content sensors are being used in applications for which they are not suited, producing results that have little relation to actual field conditions. These and other examples indicate that soil water content sensors are achieving widespread use and swift measures should be taken to assess their performance in specific soil types.

This study evaluated the performance of three soil water content sensors (CS616/625, Campbell Scientific, Inc., Logan, UT; digital TDT, Acclima, Inc., Meridian, ID; 5TE, Decagon Devices, Inc., Pullman, WA) and a soil water potential sensor (Watermark 200SS, Irrometer Company, Inc., Riverside, CA). Campbell (2011) refers to the CS616/625 sensors' performances synonymously because "the CS625 is a modified CS616 for use with the Campbell Scientific CR200 series [wireless] dataloggers".

Several studies have been performed on these instruments, but few have been conducted for particular soils in the state of Colorado. Several researchers found that the CS616/625 is sensitive to fluctuations in soil temperature (Seyfried and Murdock, 2001; Western and Seyfried, 2005; Benson and Wang, 2006; Logsdon and Hornbuckle, 2006; Ruelle and Laurent, 2008; Logsdon, 2009; Evett et al., 2010). Benson and Wang (2006) found that daily changes in soil temperature caused the sensor's θ_v output to vary by 0.10 $m^3\ m^{-3}$ in highly-electrically conductive soils. Therefore they presented a soil-specific six-step procedure (with two regressions) to correct the CS616 sensor for temperature fluctuations. They found that this procedure removed most of the daily temperature-induced fluctuations of the sensor's θ_v output, but not all. Chandler et al. (2004) found that CS615 sensors (a previous version of the CS616) could be linearly calibrated using θ_v measurements with a TDR (with errors near ±1% θ_v, relative to TDR), and this calibration varied with soil type. Kelleners et al. (2009) noted that the relatively low operating frequency (<175 MHz) of the CS625 caused it to have errors in measuring dielectric permittivity in different soils (particularly in highly conductive soils), while the TDR sensor had small differences between soils due to its high operating frequency (>1 GHz). Logsdon (2009) compared laboratory and field calibrations of the CS616 sensor and found that "field calibrations would be recommended over laboratory calibrations for the CS616 sensor, at least for field monitoring." Logsdon also concluded that "a temperature correction should be considered and included when needed."

Blonquist et al. (2005a) compared the TDT with two TDR instruments and found that the "TDRs and the TDT operated within ±3 permittivity units of each other across the permittivity range of 9 - 80", and the TDT had an operating frequency similar to the TDR instruments. This leads to the assumption that the performance of the TDT sensors should be similar to that of the TDR instruments in soils of different textures, given proper insertion in the soil.

Rosenbaum et al. (2010) analyzed the 5TE sensor in dielectric liquids and found that "the sensor-to-sensor variability was significantly larger than the measurement noise". Furthermore, they indicated that "an improvement in accuracy of nearly 0.1 cm^3 cm^{-3} can be reached in the high-permittivity range" (18-35) through individual calibrations.

Leib and Matthews (1999) compared eight soil moisture sensors installed in field plots and found that Watermark sensors "followed soil moisture trends in a fairly stable manner and could [be] used as a marker of when to start and stop irrigation", though they indicated that a site calibration is needed to improve sensor accuracy.

Performance evaluations and specific calibrations have not been carried out on irrigated (surface and sprinkler) soils in eastern Colorado. It is hypothesized that the accuracy of the sensors in these soils will be different than the accuracy specified by the sensor manufacturers. Hignett and Evett (2008a) warn:

> 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 produces a very precise and accurate calibration for the conditions tested.

However, factors in the field, such as rocks, roots, variations in clay content, temperature, soil compaction, and salinity, often result in the manufacturer's calibration not being applicable (Hignett and Evett, 2008a). Therefore, a thorough evaluation of sensor performance and the development of a family of soil-specific sensor calibration curves are highly desirable.

Applications for Accurate Soil Water Content/Potential Sensors

The ideal application for monitoring soil water content is determining irrigation timing and amounts. During the crop growing season, a maximum value for the soil moisture deficit is determined by a number of changing variables, such as crop type, growth stage, root depth, soil type, and soil layers. This value is termed the Management Allowed Depletion (MAD), and it is the amount of water depleted (below the field capacity) from the root zone. Field capacity (FC) is "the water content in a field soil after the drainage rate has become small and it estimates the net amount of water stored in the soil profile for plant use" (Fangmeier et al., 2006). MAD can also be expressed in terms of volumetric water content ($\theta_{v\text{-critical}}$), where irrigations are triggered once the θ_v sensor readings approach the critical value.

Irrigation amounts can be calculated using the θ_v sensor readings: the depth of water required is the $\theta_{v\text{-critical}}$ subtracted from the field-capacity, multiplied by the root zone depth, and divided by an irrigation efficiency (which is typically dependent on irrigation system and management). A more detailed explanation of the use of the sensors in irrigation management can be found in Varble and Chávez (2011) and Fangmeier et al. (2006). A sensor that measures soil water potential (or tension) can be used in scheduling irrigation timing by setting a critical soil water tension value to trigger an irrigation event, but this method cannot be used to determine irrigation amounts unless the soil water potential is related to θ_v using a calibration equation.

Cooley et al. (2009) gave a roadmap of necessary changes for California agriculture to achieve a sustainable future through the efficient use of water. They reported three overarching categories: efficient irrigation technologies, improved irrigation scheduling, or regulated deficit irrigation. The first category involves switching to typically more-efficient irrigation techniques (such as from flood irrigation to sprinkler or drip). With the second category, the irrigation manager applies water according to crop water needs, based on soil and climate monitoring; this is the area with the greatest potential for water savings. Furthermore, improvements in irrigation scheduling translate into energy savings, improved crop yields, and protection of groundwater from potential agro-chemical contamination (Morgan et al. 2001). The third category (regulated deficit irrigation) saves water by reducing ET demands by allowing the soil moisture deficit to increase during crop growth stages that are drought-tolerant. Efficiencies with the latter two categories are increased substantially with the accurate monitoring of soil water content because water use by the crops changes through the season. However, an inaccurate sensor is unacceptable in these situations because it will over-irrigate if it underestimates θ_v, and cause crop damage if it overestimates θ_v. In extreme situations, if the sensor never reads a previously-set $\theta_{v\text{-critical}}$, the crop will never be irrigated and will perish. Therefore, in instances where water conservation is critical and where crop production is to be optimized, a soil water content/potential sensor that reliably makes accurate readings of θ_v is required.

Sensor Principles of Operation

The CS616/625, TDT and 5TE sensors (Figure 1) are electromagnetic sensors that do not directly measure water content (Acclima, 2008; Ruelle and Laurent, 2008; Decagon, 2010; Campbell, 2011), but instead make another measurement (discussed later) that is influenced by the dielectric permittivity (ε_a) of the soil. The permittivity of water is much greater than permittivity of other components in the soil, so small changes in soil water content cause large variations in the soil's ε_a (Ruelle and Laurent, 2008). Campbell (2011) states:

> Since water is the only soil constituent that (1) has a high value for dielectric permittivity and (2) is the only component other than air that changes in concentration, a device sensitive to dielectric permittivity can be used to estimate volumetric water content.

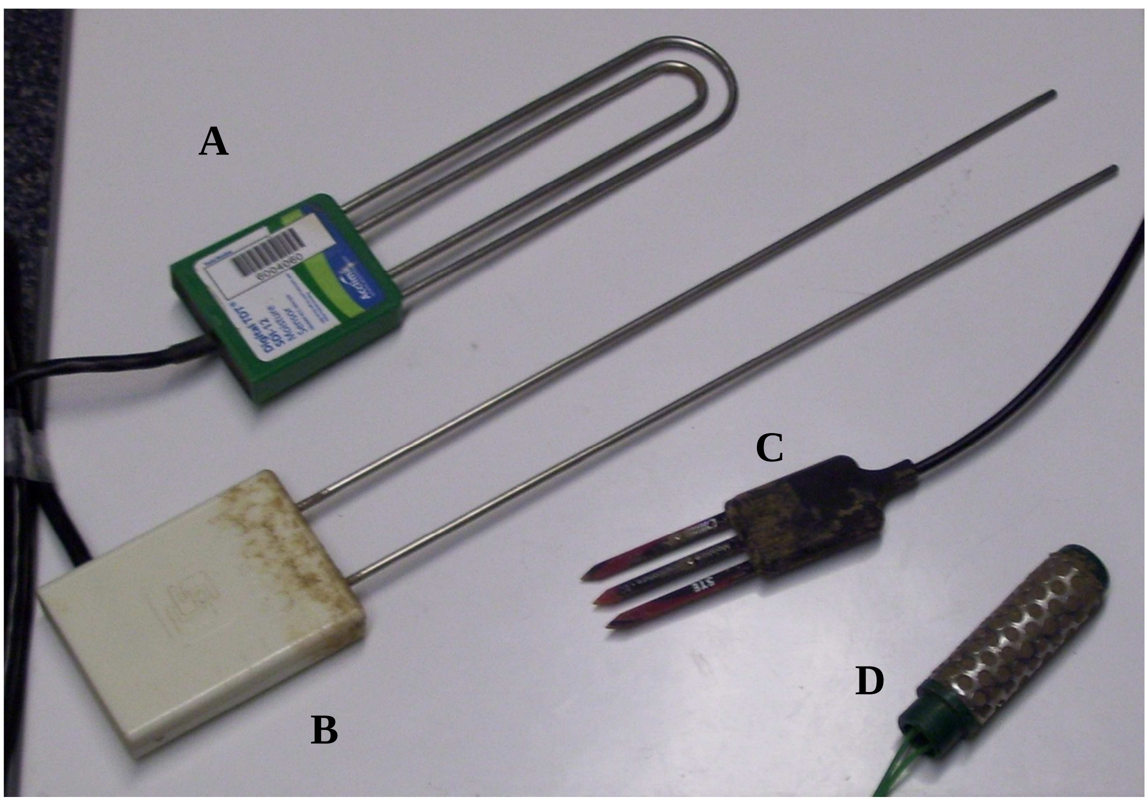

Figure 1. The Four Sensors Evaluated in this Study: a) Acclima TDT, b) Campbell Scientific CS616, c) Decagon Devices 5TE, d) Watermark 200SS

The CS616/625 sensor operates by sending an electromagnetic pulse along its rods that, once it reaches the end of the rods, is reflected back to the probe head. 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 μs). The soil's dielectric permittivity influences the velocity of the electromagnetic pulse, which in turn influences the period. The probe then relays this data to a Campbell Scientific, Inc., datalogger. A calibration equation (discussed later) then relates the probe's output period to soil water content (Campbell, 2011; Ruelle and Laurent, 2008).

The TDT sensor operates by measuring "the permittivity of soils by determining the propagation time of an electromagnetic wave transmitted along a waveguide [rods] through the soil" (Acclima, 2008). This computation takes place inside the TDT's probe head, and the equation for permittivity is shown in Equation 1, below (Blonquist et al., 2005b).

$$\varepsilon_a = \left(\frac{ct}{L}\right)^2 \qquad 1$$

where c is the speed of light in a vacuum ($3*10^8$ m s^{-1}), t (s) is the electromagnetic wave travel time along the rods, and L (m) is the length of the probe. The TDT then internally computes θ_v (m^3 m^{-3}) using the Topp equation (Topp et al. 1980), shown in equation 2. This value is then communicated with a datalogger using the SDI-12 interface.

$$\theta_v = 4.3*10^{-6}\varepsilon_a^3 - 5.5*10^{-4}\varepsilon_a^2 + 2.92*10^{-2}\varepsilon_a - 5.3*10^{-2} \qquad 2$$

The 5TE sensor measures ε_a by supplying "a 70 MHz oscillating wave to the sensor prongs … [and] the stored charge is proportional to [the] soil dielectric" (Decagon, 2010). In SDI-12 communication mode, the 5TE reports ε_a to the datalogger. The ε_a values in turn can be converted to θ_v automatically within the datalogger or manually by the user. The standard calibration equation recommended by Decagon (2010) is the previously-mentioned Topp equation (Equation 2).

The Watermark sensor (Figure 1) estimates soil water potential (expressed as tension; units: kPa, mb) by measuring the voltage excitation (mV) between a pair of electrodes embedded in a porous body that equilibrates with the surrounding soil water. The voltage excitation is then converted (using Equations 3) to electrical resistance (in kOhms) through the datalogger's internal program (Campbell Scientific, 2009). As water content in the sensor body increases, the resistance between the electrodes decreases (Hignett and Evett, 2008b; Irrometer, 2009). The relationship between resistance (ohm) and soil water potential (SWP; kPa) is constant, and programmed into the datalogger using Equation 4.

$$R_s = V_r / (1 + V_r) \qquad 3$$

$$SWP = 7.407*R_s / (1 - 0.018*(T - 21)) - 3.704 \qquad 4$$

where V_r (mV) is the ratio of the measured voltage divided by the excitation voltage, R_s (kOhms) is the measured resistance, T (°C) is the soil temperature (which was measured by the TDT sensor in this study), and SWP (kPa) is the soil water potential (or tension). Soil water tension is directly related to θ_v through a water retention (or release) curve, which varies by soil type (discussed later).

Placement of Sensors

The location of sensor installation should be representative of the field (Heng and Evett, 2008). However, several variables in the soil may exist on the field-scale, including variation in soil texture, effects of ponding, proximity to trees, and distribution of irrigated water (Hignett and Evett, 2008a). Local (<1 m^3) variables, such as bulk density, water content, and proximity of plant roots, are also often present (Hignett and Evett, 2008a). Therefore, Heng and Evett (2008) advise that "banks or pairs of [sensors] be installed in at least three locations within a field." To get a more accurate number of samples required, Hignett and Evett (2008a) suggest using Equation 5 to determine the mean water content within a plot.

$$N = \left(\frac{u_{\alpha/2} S}{d}\right)^2 \qquad 5$$

where N is the sample size, $u_{\alpha/2}$ is the (1 – α) probability level standard normal distribution, d is the target value about the mean, and S is the standard deviation. Additionally, more sensor groups may be needed based on soil variability so that each installation site "represents the field in terms of water application patterns, soil types, slopes and exposure". Heng and Evett (2008) also advise that the sensors "should be located directly in the active rooting zone of the growing plant," and at least two sensors should be "placed just below the bottom of the root zone to check for overirrigation".

Gravimetric Sampling

The most accurate method of measuring water content is direct gravimetric sampling of the soil. This method involves measuring the soil bulk density, then collecting soil samples to be placed in a convective oven at 105 °C for 24 hours. Topp and Ferré (2002) report that this method has an error limit of 0.3% water content.

However, this method has obvious drawbacks: the samples are destructive, time-consuming, and can only be used in steady-state situations. Furthermore, the problem of the minimum necessary representative elementary volume (REV) arises. Evett (2008) exemplifies that the measurement errors decrease as the REV increases. However, Evett (2008) and Hillel (1998) also caution that the REV has an upper-bound that is based on the spatial variability in the soil. If a soil varies systematically in a particular direction, then “increasing the size of the sample measured may not produce a consistent value at all” (Hillel, 1998). The problems are further compounded by the fact that, in order to maintain the same precision, the REV must increase as the volumetric water content decreases; thus, “no simple statement of the desired sample volume can be given” (Evett, 2008).

MATERIALS AND METHODS

This study took place during the 2010 crop growing season and included soils from three agricultural fields in eastern Colorado. Laboratory and field tests were performed on the CS616/625, TDT and 5TE soil water content and Watermark soil water potential sensors between mid-July and early-October, 2010. The first soil in the study was from a research field operated by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS). This field of furrow-irrigated corn was located near the City of Greeley airport and is hereafter referred to as Site A. The second soil was from a commercially-operated alfalfa field near La Salle, with the research coordinated through the Central Colorado Water Conservancy District (CCWCD). This field was irrigated using a center pivot sprinkler and is hereafter referred to as Site B. Figure 2 shows the irrigation systems and crop types used at Sites A and B. The third soil was from a research field operated by Colorado State University's Arkansas Valley Research Center (CSU-AVRC), located near Rocky Ford. This location of furrow irrigated alfalfa is hereafter referred to as Site C.

Geographic coordinates and soil texture for the soils at each site are presented in Table 1. The soil textures were determined by a particle size analysis (Hydrometer Method; Gavlak, et al., 2003). At all fields, the soil collected for use in the laboratory was removed from the upper 10- to 30-cm layer.

Table 1. Site Name, Geographic Coordinates and Soil Texture

Soil	Lat. (N)	Long. (W)	- - - Texture - - -			
			Sand (%)	Silt (%)	Clay (%)	Class
A	40°26’	104°38’	65	10	25	Sandy Clay Loam
B	40°15’	104°40’	85	3	12	Loamy Sand
C	38°02’	103°41’	37	23	40	Clay Loam

Bulk density and porosity of the soils at each site are presented in Table 2. Bulk density was measured using a Madera Probe (Precision Machine, Inc., Lincoln, NE). The porosity was estimated using the sampled bulk density from each field and an assumed particle density of 2.65 g/cm^3.

Table 2. Site Name, Dry Soil Bulk Density (ρ_b) and Soil Porosity (φ)

Soil	Treatment / Depth	ρ_b (g/cm^3)	φ (%)
A	1	1.42	47
	2	1.54	42
	3	1.52	43
	Avg.	1.49	44
B	30 cm	1.61	39
	61 cm	1.74	34
	91 cm	1.67	37
	Avg.	1.68	37
C	n/a	1.33	50

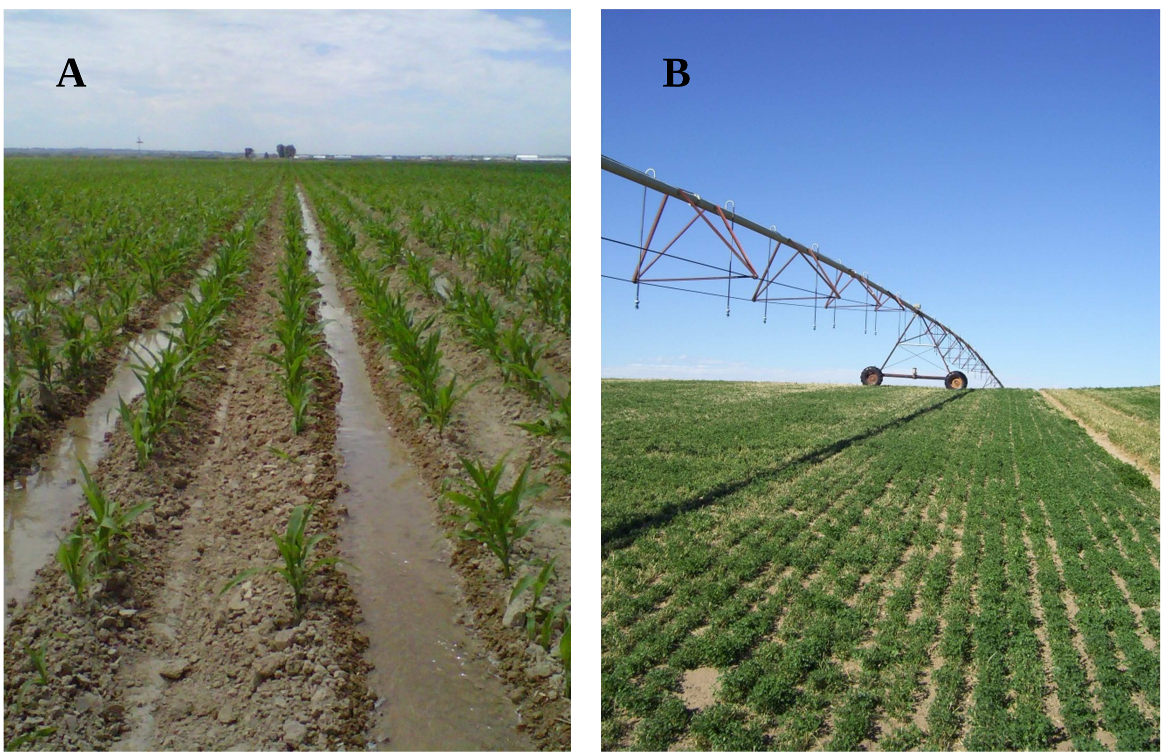

Figure 2. Irrigation Techniques and Crop Types Used at A) Site A and B) Site B

Factory Calibrations

The CS616/625 and TDT soil water content sensors are pre-calibrated by the sensor manufacturers, which enables them to give a direct reading of volumetric soil water content (θ_v). This calibration is hereafter referred to as the 'factory calibration' of θ_v. The standard (or factory) calibration recommended by Decagon (2010) for the 5TE is equation 2, which was manually computed by the user. Additionally, the TDT and 5TE sensors measure soil temperature (°C) and bulk soil electrical conductivity (EC, dS/m).

Campbell (2011) stated that the CS616/625's standard (factory) calibration of θ_v has an accuracy of ±0.025 $m^3\ m^{-3}$ when the bulk soil EC is < 0.5 dS/m. Acclima (2010) stated that the TDT factory calibrated measurement of volumetric water content has an accuracy of ±0.01 $m^3\ m^{-3}$ under temperature conditions of 0.5 to 50 °C and EC of 0 to 3 dS/m. The 5TE's operator's manual (Decagon Devices, 2010) asserts that the factory calibration of θ_v is accurate to ±0.03 $m^3\ m^{-3}$ in mineral soils "that have solution [EC] < 10 dS/m." Laboratory and field tests were conducted to test these claims of accuracy.

The manufacturer of the Watermark sensor recommended relating the SWP (previously-discussed) to θ_v through soil water release curves for general soil types similar to those presented by Ley et al. (1994). (These are generalized soil water release curves originally published by the NRCS; Ley et al. (1994) noted that specific soils will deviate from these generalized relations.) This curve was generalized using equation 6.

$$\theta_v = \alpha X^\beta \qquad 6$$

where θ_v is in $m^3\ m^{-3}$, α and β are coefficients and X is the sensor-based soil water tension (millibars, mb). The soils at Sites A and C had the same α and β coefficients of 104.63 and -0.19, respectively, and coefficients for the soil at Site B were 38.14 and -0.14, respectively. Laboratory pressure chamber tests using re-packed soil samples from each site were conducted to test the applicability of these generalized soil water release curves. Graphs showing the results of these tests can be found in APPENDIX B - Supplementary Graphs (Figures B-5 to B-7).

CS616, TDT, and 5TE Laboratory Procedure

Laboratory calibrations were performed using soil samples collected from the upper 0-30 cm layer from sites A, B, and C from locations shown in Figure 3, Figure 4, and Figure 5, respectively.

The laboratory calibration for the CS616, TDT, and 5TE sensors was based on the procedure proposed by Starr and Paltineanu (2002) and Cobos and Chambers (2010). Soil collected from each field was air-dried and passed through a 2-mm sieve. It was then packed in a 19 L container to approximate soil bulk density in the field. One at a time, each sensor was inserted vertically into the soil (Figure 6). Several sensor readings were taken, and then averaged, over an interval of at least 20 minutes. After each sensor was read, gravimetric samples were taken from the soil core and oven-dried at 105 °C for 24 hours.

The volumetric water content was then computed by multiplying the gravimetric water content by the soil bulk density obtained from the field, divided by the density of water. The soil from the container was then wetted with 500 mL of water and mixed thoroughly. The above procedure was repeated, each time repacking the container, taking multiple sensor readings, and adding another 500 mL of water until the soil water content was greater than field capacity.

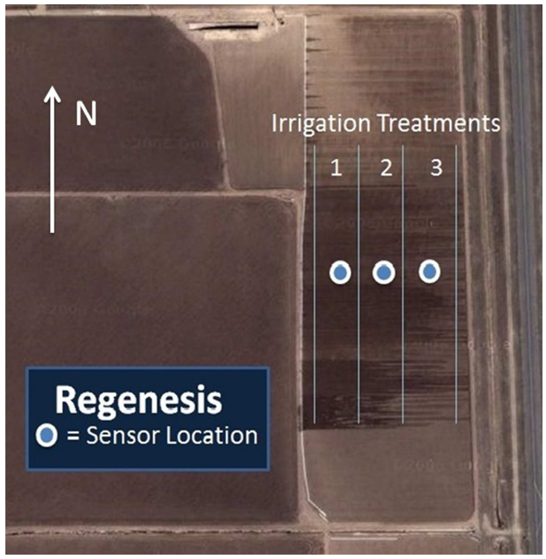

Figure 3. Approximate Locations of Sensors at Site A. (This field, near Greeley, CO, was split into three sections (or treatments) that received water in different amounts and frequencies.)

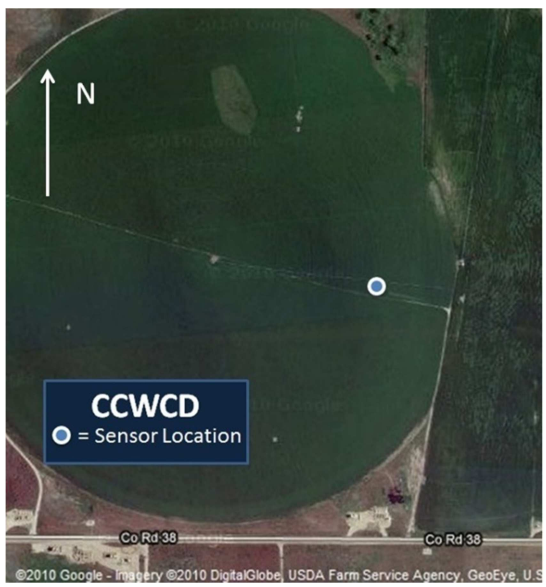

Figure 4. Approximate Location of Sensors at Site B (La Salle, CO)

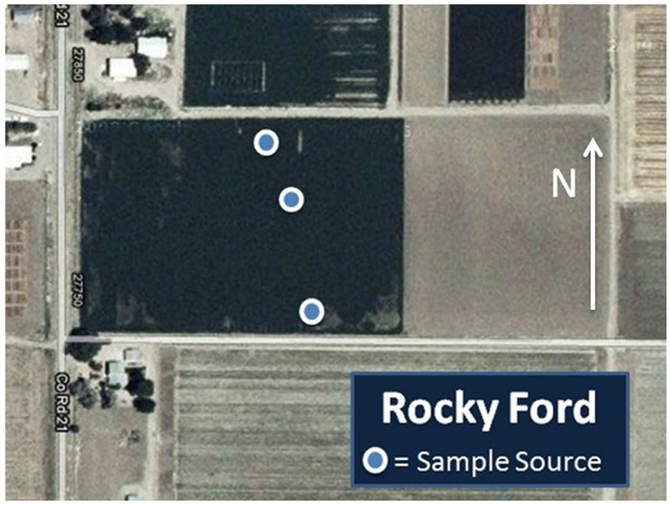

Figure 5. Approximate Locations of Samples Collected from Site C (Rocky Ford, CO)

Figure 6. TDT, CS616, and 5TE Sensors Inserted Into Repacked Soil Cores from the Three Soils Used in the Laboratory

A total of sixty gravimetric soil samples (n=60) were used in the analysis of the soil from Site A, and volumetric water contents ranged from 10.7 to 35.9%. Six gravimetric soil samples (n=6) that ranged in θ_v from 9.3 to 23.2% were used in the analysis of the soil from Site B. In the soil from Site C, fifty-six gravimetric soil samples (n=56) were used, with θ_v ranging from 17.3 to 38.1%. Fangmeier et al. (2006) reported permanent wilting points (PWP) and field capacities (FC) for soils that were in the same textural groups as those tested in the laboratory as 16 to 26% for Site A, 7 to 16% for Site B, and 20 to 34% for Site C. Laboratory pressure chamber tests using re-packed soil samples from each site (Figures B-5 to B-7; APPENDIX B - Supplementary Graphs) found that the PWP and FC were 33.5 to 30.5% for Site A, 8.3 to 6.2% for Site B, and 35.2 to 26.8% for Site C. Using these estimates, the water contents in the laboratory studies approximately ranged from PWP to FC for each soil, but in no soil was complete saturation achieved.

CS616, TDT, and 5TE Laboratory Calibration Equations

A linear calibration equation (hereafter referred to as the 'laboratory calibration' of θ_v) was developed for each sensor by plotting the probes' readings versus the volumetric water content derived from the gravimetric method. The equations were developed using the Microsoft Excel® Regression Analysis, and took the form of equation 7.

$$\theta_v = \alpha_0 X + \alpha_1 \qquad 7$$

where θ_v is expressed in %, α_0 and α_1 are coefficients, and X is the sensor-based factory calibration of θ_v (dimensionless; %). The temperature of the soil in the laboratory tests was relatively constant (~21°C) throughout the entire study. During these tests the TDT sensor registered bulk soil EC in the range of 0.00-1.60 dS/m (0.69 dS/m average) in the soil from Site A, 0.00 in the soil from Site B, and 0.00-3.07 dS/m (1.37 dS/m average) in the soil from Site C.

Watermark Laboratory Calibrations

The laboratory calibration procedure using the Watermark sensor was different from that of the other sensors because the energy state of the water in the Watermark sensor must equilibrate with that of the surrounding soil before an accurate reading could be taken. Therefore the sieved soils from the previous tests were separated into multiple smaller containers of different water contents. One Watermark sensor was placed in each container and left for an average of three days to equilibrate with the matric potential of the soil water. Gravimetric samples were then taken from each container, oven-dried and converted into θ_v using the dry soil bulk density obtained from field samples. A total of seven samples (n=7) were used in the analysis of the soil from Site A, three in the analysis of the soil from Site B, and four in the analysis of the soil from Site C.

Two types of calibration equations were developed for the Watermark sensor to relate soil water tension to θ_v ($m^3\ m^{-3}$; %) by plotting the measured θ_v versus the soil water tension sensor output. The logarithmic equation (equation 8) is a simple, straight-forward equation that did not require assumed coefficients.

$$\theta_v = \alpha \ln|X| + \delta \qquad 8$$

where θ_v is expressed in %, α and δ are coefficients, and X is the soil water tension sensor-based value (millibars, mb).

However, the logarithmic equation is not capable of representing water contents in the range near saturation (Hillel, 1998). Therefore, van Genuchten (1980) proposed an equation that could represent the entire soil water retention curve (equation 9). This equation was also used in this research to relate the sensor-based soil water tension to θ_v ($m^3\ m^{-3}$), based on its greater capabilities and wide acceptance in the literature (Butters, 2010).

$$\theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^{1-1/n}} \qquad 9$$

where θ_v is expressed in %, θ_s is the saturated soil water content ($m^3\ m^{-3}$), θ_r is the residual soil water content ($m^3\ m^{-3}$), h is the absolute value of the soil water tension (cm H_2O), and α (cm^{-1}) and n (dimensionless) are soil-specific coefficients. When fitting the van Genuchten (1980) equation to the laboratory and field data, θ_s was estimated for each soil using the estimated porosity at each location. However, θ_r was estimated for each soil using the values recommended by Schaap and Leij (1998): 0.063, 0.079, and 0.049 for the sandy clay loam (Site A), the loamy sand (Site B), and the clay loam (Site C), respectively. The α and n coefficients were then derived using Microsoft Excel® Solver.

To analyze the accuracy of the calibration equations obtained from the laboratory procedure, the 'laboratory equations' were applied to the field sensors' readings and results were compared with the field-measured θ_v.

Laboratory Salinity Tests

Subsequent to testing the Watermark sensors, the previous testing procedures on the water content sensors were repeated on the TDT and 5TE sensors, with varying levels of water content (19-33% in the soil from Site A; 15-33% in the soil from Site C) and a one-time addition of salts to the soils from Sites A and C. The aim was to increase the salt concentrations until the TDT sensor measured bulk soil EC of slightly under 6 dS/m in each soil. To accomplish this, 97 g of calcium chloride dihydrate were dissolved in 350 mL deionized water and mixed thoroughly with the soil from Site A, and 86 g was dissolved in 700 mL deionized water and mixed thoroughly with the soil from Site C. Tests on the soils were then conducted in the manner previously mentioned (see CS616, TDT, and 5TE Laboratory Procedure); each time 500 mL of water was added between tests. This procedure produced bulk soil EC readings by the TDT sensor in the range of 0.88-5.79 dS/m (3.79 dS/m average) in soil from Site A and 1.65-5.92 dS/m (4.37 dS/m average) in the soil from Site C. A total of eight samples per soil type were used to measure the amount of bias that the higher salt concentrations introduced in the factory calibration of θ_v.

The CS616 sensor gave an error reading at the higher bulk EC concentrations (>3 dS/m), so it could not be included in this part of the study. The Watermark sensors were not used in this part of the study because they have "an internal gypsum tablet [that] buffers against the salinity levels found in irrigated soils" (Campbell, 2009). This, in theory, means that the sensors' sensitivity to bulk soil EC is minimal when the sensors are new, but increases as the sensors age (and the internal tablet dissolves).

Field Calibration

During the summer of 2010, CS616, TDT, 5TE and Watermark sensors were installed at Site A. This site had three differing irrigation treatments, and each treatment contained one of each sensor (with the exception that treatments 2 and 3 did not have a Watermark sensor installed). In each irrigation treatment the sensors were installed under the crop row, roughly 25-30 cm apart from each other, at a uniform depth of 10 cm below the average height ($h \approx 4$ cm) of the top of the row and the bottom of the furrow (Figure 7).

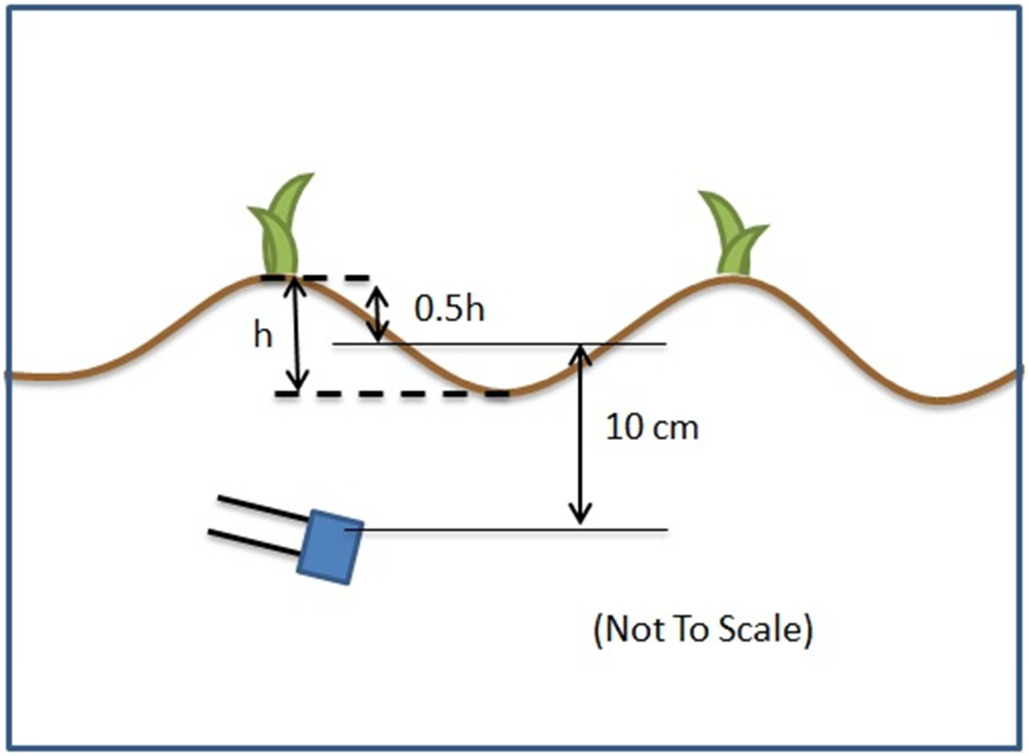

Figure 7. Depth of Sensor Placement at Site A.

These sensors were installed by digging a shallow trench and inserting the sensors horizontally into the wall, then backfilling the trench (Figure 8). Data collection for the sensors began in mid-July.

Figure 8. 5TE, TDT and CS616 sensors at 10 cm depth at Site A.

At Site B, three CS625 sensors were placed 30, 61, and 91 cm below the surface by digging a trench, inserting the sensors horizontally, then backfilling the trench. Approximately 3 m from these sensors, two Watermark sensors were placed at 61 cm and 91 cm below the surface. These sensors were installed by creating a small vertical hole with a soil auger, then lowering the sensor to the desired depth. Also at this location, a CS109-L thermocouple (Campbell Scientific, Inc., Logan, UT) was installed 30 cm beneath the surface to monitor soil temperature (°C). Data collection from sensors began in the end of July of 2010. From the time of installation until first week of October, 2010, sensor readings were taken automatically at Site A every five minutes. At Site B readings were taken every eight hours, until the third week of October, 2010. Readings were compared with periodic gravimetric soil water content measurements, totaling eleven from each irrigation treatment in Site A and five at each depth from Site B.

Figure 9. CS625 Sensors Installed at Depths of 30-, 61-, and 91-cm.

The gravimetric samples were taken using a soil auger approximately 1-2 meters away from each sensor location. These samples were immediately placed in sealed containers inside a cooler and taken directly to a laboratory to be weighed, oven-dried, and weighed again. The gravimetric samples were then converted into θ_v using the dry soil bulk density field values. During the times of gravimetric field sampling at Site A, soil temperatures at the sensor depth ranged from 15-22 °C in irrigation treatment 1, 15-24 °C in treatment 2, and 16-30 °C in treatment 3. EC ranged from 0-1.23 dS/m in treatment 1, 0-1.31 dS/m in treatment 2, and 0-2.12 dS/m in treatment 3. At Site B, soil temperatures ranged from 13-20 °C, and EC was not measured.

A few times in the field 3-4 samples were taken at the same location to observe gravimetric measurement variability, which ranged from 0.003 to 0.016 $m^3\ m^{-3}$ (during the remainder of the field visits multiple samples were taken and composited into one can). Multiple gravimetric samples were also taken in the laboratory, and variability ranged from 0.003 to 0.01 m^3 m^{-3}.

Linear calibration equations (hereafter referred to as the 'field calibration' of θ_v) were developed for the CS616/625, TDT, and 5TE sensors, using the same methodology as the laboratory experiments (equation 7, above). For the Watermark sensors, two types of calibration equations were used. The logarithmic equation (shown in equation 8 above) and the van Genuchten (1980) equation (shown in equation 9 above) were used at both sites. Calibration equations to account for a soil temperature correction were also developed for the CS616/625, 5TE, and Watermark sensors. These equations took the form of equation 10 (CS616/625, 5TE) and equation 11 (Watermark).

$$\theta_v = \alpha X + \beta T + \delta \qquad 10$$

$$\theta_v = \alpha \ln|X| + \beta T + \delta \qquad 11$$

where θ_v is expressed in %, α, β, and δ are coefficients, X is the sensor-based θ_v (dimensionless; %), and T is the sensor-based soil temperature (°C). For the CS616 and Watermark sensors, T was measured using the TDT sensors at Site A and the CS109-L sensor at Site B.

Statistical Analysis

Four statistical measures were computed to compare and evaluate each equation-predicted (P) value with the observed (O) gravimetric samples taken from the field and laboratory soils. These include the coefficient of determination (R^2), mean bias error (MBE; Equation 12), root mean square error (RMSE; Equation 13), and the index of agreement (κ; Equation 14) defined by Willmott (1982).

$$\mathrm{MBE} = n^{-1}\sum_{i=1}^{n}(P_i - O_i) \qquad 12$$

$$\mathrm{RSME} = [n^{-1}\sum_{i=1}^{n}(P_i - O_i)^2]^{0.5} \qquad 13$$

$$\kappa = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)}{\sum_{i=1}^{n}(|P_i'| - |O_i'|)^2}\right] \qquad 14$$

where *n* is the sample size, $P'_i = P_i - \bar{O}$, $O'_i = O_i - \bar{O}$, and $\bar{O}$ is the average observed value. The units for MBE and RMSE are volumetric water content (m^3 m^{-3}; expressed as a %), and κ is dimensionless.

Hignett and Evett (2008a) point out that in most agricultural and research applications the measurement accuracy needs to be within 0.01 to 0.02 m^3 m^{-3}. Therefore, statistical goals of MBE of ±2.0% volumetric water content and RMSE less than 3.5% volumetric water content were formulated to deem a particular calibration equation ‘accurate’ or not. The scale of κ ranges between 0-1, with higher numbers representing greater correlation between the model prediction and observations.

RESULTS AND DISCUSSION

Factory Calibration Evaluation

This study found that, under laboratory and field conditions, the factory-based calibrations of θ_v did not achieve the required accuracy within the PWP to FC range of water content for any sensor. This was not unexpected for the CS616/625 or 5TE sensors because the respective user manuals say that the factory calibration of θ_v is accurate to ±2.5% and ±3% (Campbell Scientific, 2011; Decagon Devices, 2010), which are already greater than the goal of 1-2%. (Full calibration equations can be found in APPENDIX A - Calibration Equations.)

The MBE values for the CS616's factory calibration in Table 3 show that, in the laboratory, this sensor overestimated θ_v by an average of 10% in the sandy clay loam (Site A), 3% in the loamy sand (Site B), and 24% in the clay loam (Site C). The statistical values for the TDT sensor indicate that, in the laboratory, the factory calibration underestimated θ_v by 1.5% in the sandy clay loam (Site A), overestimated by 6% in the loamy sand (Site B), and underestimated by 2.5% in the clay loam (Site C). However, the RMSE was greater than 3.5% in all soils; thus the TDT factory calibration did not meet the criteria for any soil. The factory calibration of θ_v of the 5TE sensor was accurate in the sandy clay loam. However, the 5TE's factory calibration was not accurate in the loamy sand (MBE = 2.5%) or the clay loam (RMSE = 3.8%). The MBE values for the Watermark's factory calibration in the laboratory tests show that this sensor overestimated θ_v by 20%, 8%, and 17% in the sandy clay loam, loamy sand, and clay loam soils, respectively. During these tests the TDT sensor registered EC in the range of

0.00-1.60 dS/m (0.69 dS/m average) in the soil from Site A, 0.00 in the soil from Site B, and 0.00-3.07 dS/m (1.37 dS/m average) in the soil from Site C.

Table 3. Comparison of the Factory Calibration-Based θ_v (%) with Laboratory Measurements of θ_v (%) for the Different Sensors and Soils

Soil Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS616					
Sandy clay loam	60	0.92	10.4	14.7	0.70
Loamy sand	6	0.99	3.2	3.4	0.90
Clay loam	56	0.88	24.3	28.9	0.38
TDT					
Sandy clay loam	60	0.94	-1.5	4.1	0.95
Loamy sand	6	0.98	6.1	6.7	0.75
Clay loam	56	0.95	-2.6	4.7	0.91
5TE					
Sandy clay loam	60	0.92	-0.7	2.2	0.97
Loamy sand	6	0.98	2.4	2.5	0.92
Clay loam	56	0.74	0.4	3.8	0.92
Watermark					
Sandy clay loam	7	0.82	20.0	20.8	0.33
Loamy sand	3	0.65	8.2	8.8	0.61
Clay loam	4	0.75	17.3	21.2	0.37

Graphs of the laboratory-obtained θ_v data offer a good illustration that a linear calibration equation would be sufficient to correct the data collected from the sensors. Figure 10 showed that the factory calibration of θ_v for the CS616 sensor in the laboratory on the sandy clay loam was accurate at the lower water contents (11-20%), but not at the higher water contents (25-36%). Figure 11 indicated that the factory calibration of θ_v for the TDT sensor slightly underestimated θ_v at the lower water contents (11-23%) in the sandy clay loam and slightly overestimated θ_v at the higher water contents (27-36%). Figure 12 showed that the factory calibration of θ_v for the 5TE sensor closely matched the one-to-one line. This suggested an accurate calibration for the sandy clay loam, with some scatter at the higher water contents (32-36%). This is in agreement with the data presented in Table 3. Figure 13 showed that the factory calibration of θ_v for the

Watermark sensor overestimated θ_v at all water contents, with the magnitude of errors greater with the higher water contents.

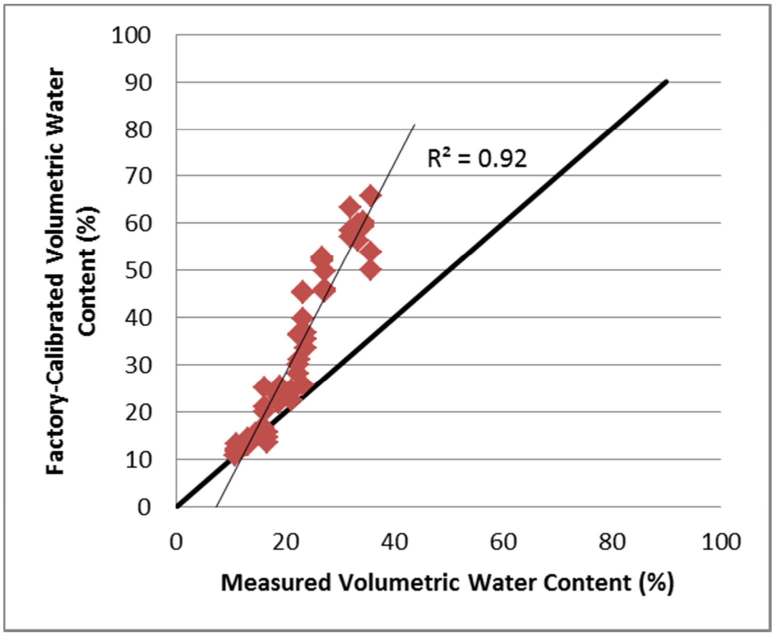

Figure 10. Graphical comparison of the Factory-Calibrated Measurement of θ_v by the CS616 Sensor in the Laboratory vs. Gravimetric Measurements of θ_v in the sandy clay loam (Site A)

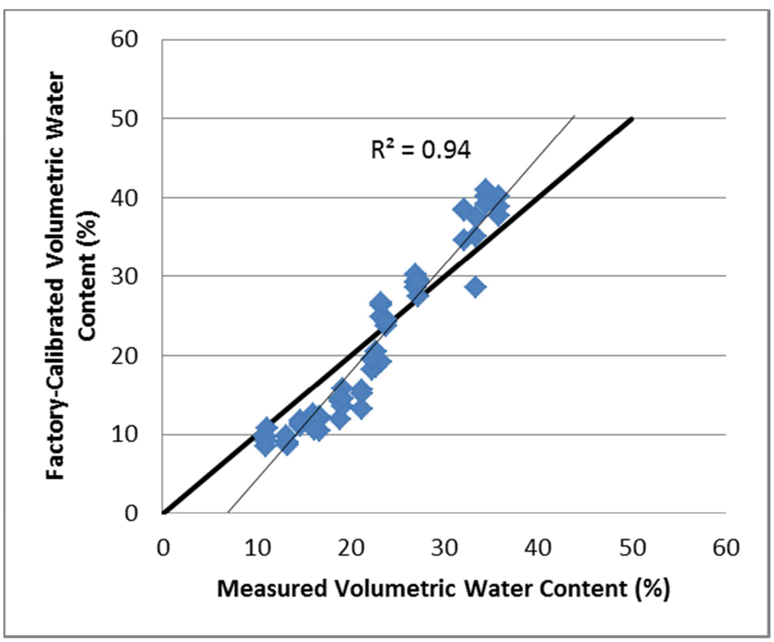

Figure 11. Graphical comparison of the Factory-Calibrated Measurement of θ_v by the TDT Sensor in the Laboratory vs. Gravimetric Measurements of θ_v in the sandy clay loam (Site A)

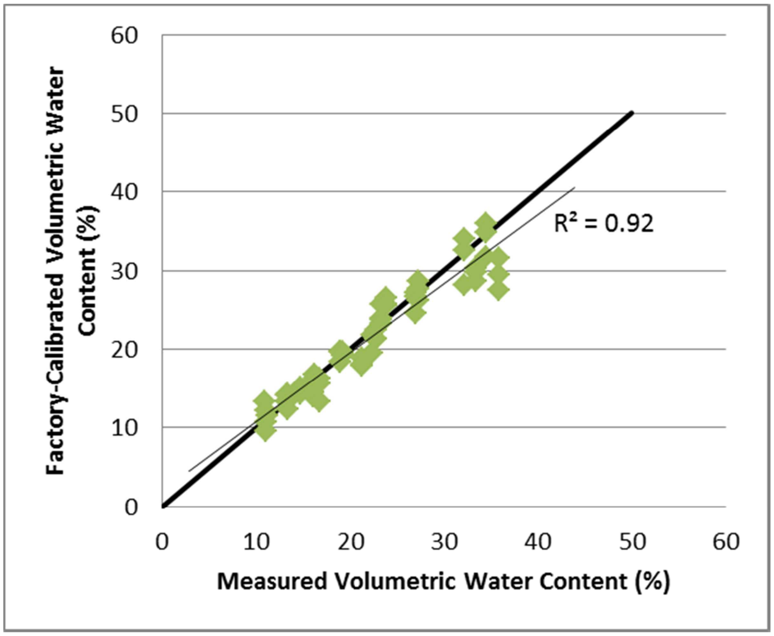

Figure 12. Graphical comparison of the Factory-Calibrated Measurement of θ_v by the 5TE Sensor in the Laboratory vs. Gravimetric Measurements of θ_v in the sandy clay loam (Site A)

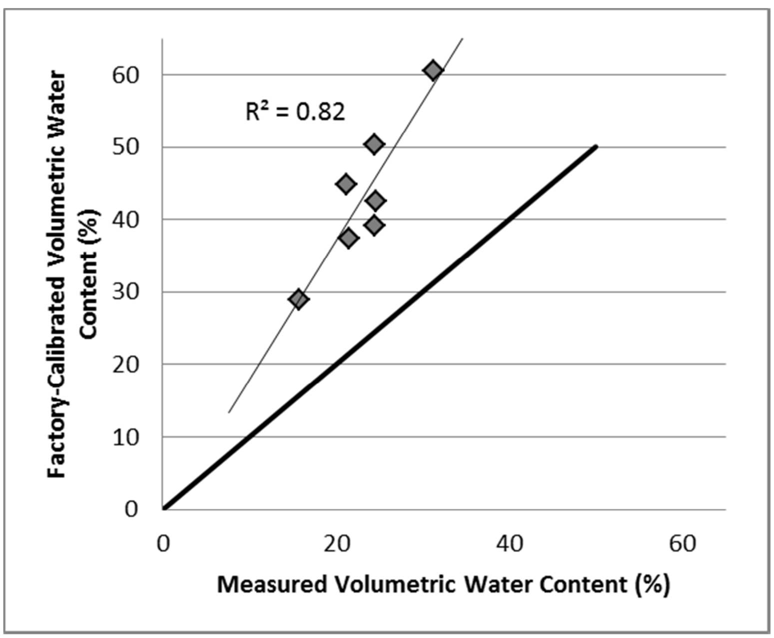

Figure 13. Graphical comparison of the Factory-Calibrated Measurement of θ_v by the Watermark Sensor in the Laboratory vs. Gravimetric Measurements of θ_v in the sandy clay loam (Site A)

In the field tests, the factory calibrations of θ_v for the CS616 sensor at Site A overestimated (MBE) θ_v by 19% in treatment 1, 32% in treatment 2, and 28% in treatment 3. The MBE and RMSE of applying the factory calibration to the data from the TDT sensor in treatment 2 were within the limits (i.e., 0.7% and 2.3%, respectively) However, the MBE in treatments 1 and 3 were 2.7% and -2.2%, respectively. The factory calibration applied to the data collected from the 5TE sensors installed at Site A underestimated θ_v by 2.4% in treatment 1, and resulted in an RMSE of 3.7% in treatment 3. However, the MBE and RMSE for the 5TE were within the allowable limits in treatment 2 (1.0% and 2.8%, respectively). The Watermark's factory calibration overestimated θ_v in treatment 1 at Site A by 11.2%, which is roughly half of the error found in the laboratory.

Table 4. Comparison of the Factory Calibration-based θ_v (%) with Field Measurements of θ_v (%) for the Different Sensors at Site A (sandy clay loam)

Irrigation Treatment	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS616					
1	11	0.86	18.8	19.2	0.31
2	11	0.53	32.1	33.7	0.24
3	12	0.56	28.0	29.2	0.30
TDT					
1	11	0.76	2.7	3.3	0.82
2	11	0.83	0.7	2.3	0.94
3	12	0.74	-2.2	3.8	0.89
5TE					
1	11	0.63	2.4	3.5	0.68
2	11	0.74	1.0	2.8	0.85
3	12	0.67	-1.1	3.7	0.82
Watermark					
1	11	0.87	11.2	12.6	0.48

When inspecting the data from each treatment at Site A, it was clear that none of the sensors' factory calibrations performed satisfactory. In Figure 14, it was clear that the factory calibration of θ_v for the CS616 sensors overestimated θ_v at all water contents, with the magnitude of errors greater with the higher water contents. This implies that the factory calibration for the CS616 sensor cannot be used in irrigation scheduling for reasons twofold: the overestimation of θ_v means that the irrigations will be timed later than needed and the high slope means the depths of water applied will be greater than needed. Figure 15 showed that the factory calibration of θ_v for the TDT sensors closely matched the one-to-one line, suggesting an accurate calibration. In Figure 16, the factory calibration of θ_v for the 5TE sensors overestimated θ_v at the higher water contents, and underestimated θ_v at the lower water contents. The data in these figures represented the combined data from the three sensors that were installed in the field. The large amount of scatter in the figures (shown by the low R^2 values) suggested that each sensor needs to be calibrated individually. Figure 17 showed that the calibration of θ_v for the Watermark sensor overestimated θ_v at all water contents, with the magnitude of errors greater with the higher water contents.

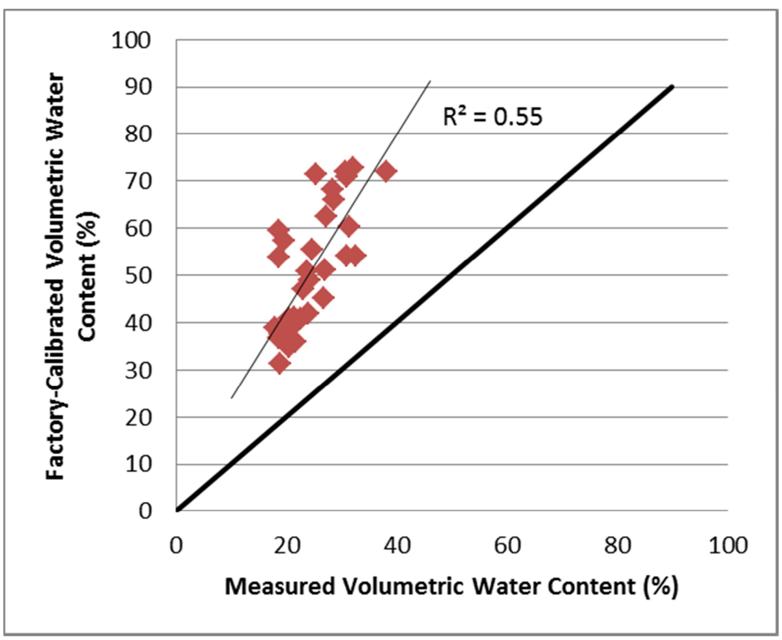

Figure 14. Graphical Comparison of the Factory-Calibrated Measurement of θ_v by the CS616 Sensors in the Field (sandy clay loam; Site A) vs. Gravimetric Measurements of θ_v

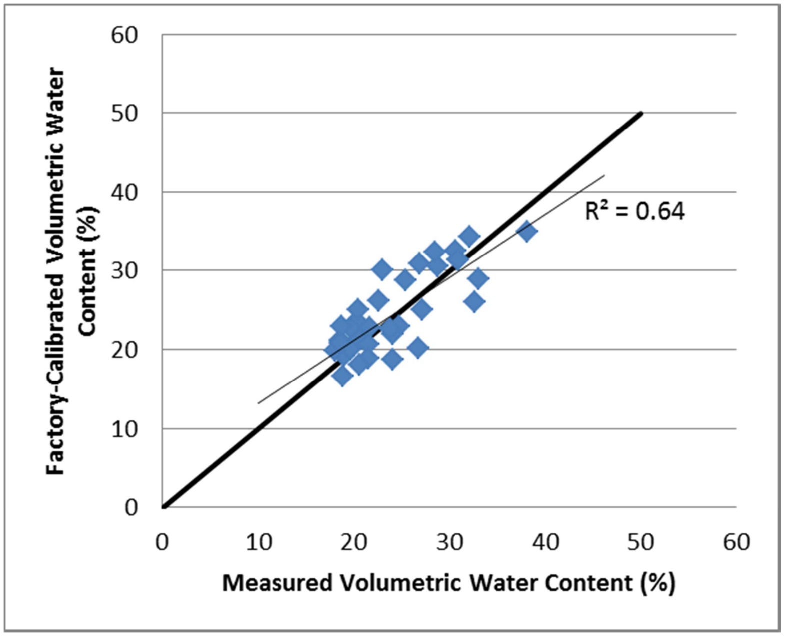

Figure 15. Graphical Comparison of the Factory-Calibrated Measurement of θ_v by the TDT Sensors in the field (sandy clay loam; Site A) vs. Gravimetric Measurements of θ_v

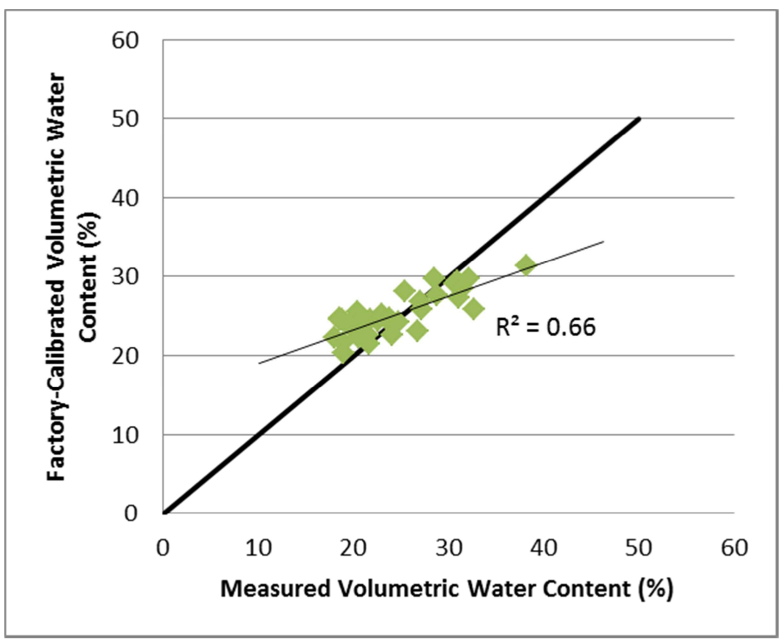

Figure 16. Graphical Comparison of the Factory-Calibrated Measurement of θ_v by the 5TE Sensors in the field (sandy clay loam; Site A) vs. Gravimetric Measurements of θ_v

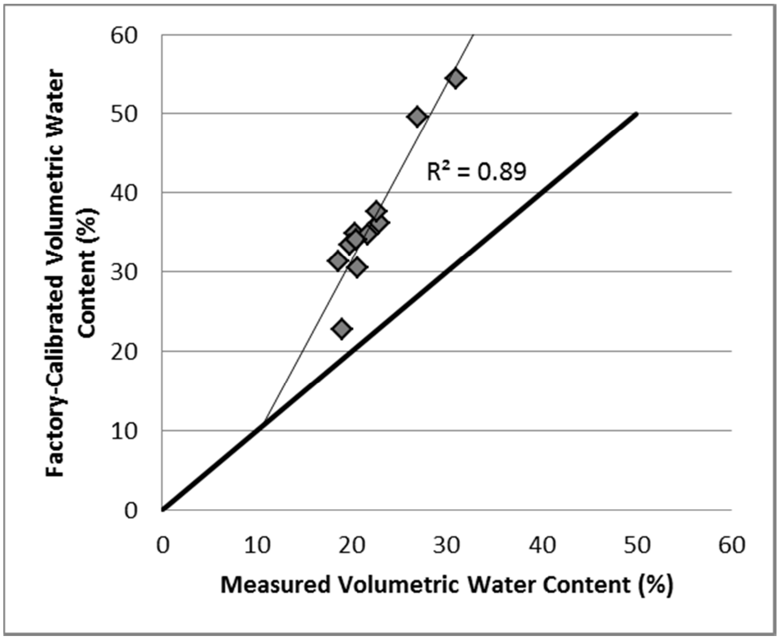

Figure 17. Graphical Comparison of the Factory-Calibrated Measurement of θ_v by the Watermark Sensors in the field (sandy clay loam; Site A) vs. Gravimetric Measurements of θ_v

Figure 18 is another form to express of the data presented in the previous graphs. This figure shows the results of applying the factory calibrations to the four sensors in treatment 1 at Site A (additional graphs can be found in APPENDIX B - Supplementary Graphs; Figures B-1 and B-2). Given the estimated porosities in treatments 1, 2, and 3 of 47%, 42%, and 43%, respectively, the factory calibrations for the CS616 and Watermark (and to a lesser degree the TDT) sensors measured impossible levels of water content (greater than porosity) in each treatment during irrigations. Furthermore, the factory calibration applied to the 5TE sensor in Treatment 1 did not measure saturation during irrigations (Site A was surface irrigated with application times exceeding 12 hours; thus it is assumed that during irrigation events the soil around the sensors reached saturation. This leads to similar conclusions reported by several researchers that the CS616 (Seyfried and Murdock, 2001; Chandler et al., 2004; Walker et al., 2004; Czarnomski et al., 2005; Plauborg et al., 2005; Western and Seyfried, 2005; Benson and Wang, 2006; Logsdon and Hornbuckle, 2006; Ruelle and Laurent, 2008; Logsdon, 2009; Evett et al., 2010), TDT (Evett et al., 2010), 5TE (Evett et al., 2010), and Watermark (Hignett and Evett, 2008b) sensors require soil-specific calibration.

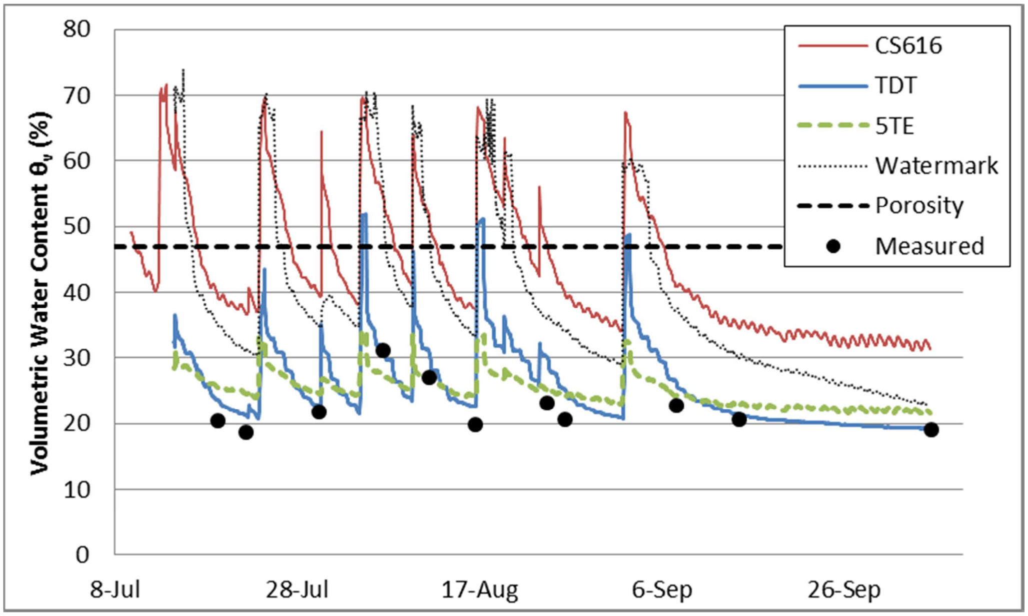

Figure 18. Graphical comparison of the Factory-based Calibration of θ_v (%) for the CS616 (red), TDT (blue), 5TE (green) and Watermark (black dotted) Sensors in Treatment 1, Site A (sandy clay loam)

The factory calibrations of the CS625 and Watermark sensors in Site B did not achieve sufficient accuracy (Table 5). Here, the overestimation of θ_v (CS625 MBE of 5% and Watermark MBE of 10%) and poor indices of agreement of all sensors particularly stand out.

Table 5. Comparison of the Factory Calibration-Based θ_v (%) versus Field Measurements of θ_v (%) for the Different Sensors at Site B (loamy sand)

Depth (cm)	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS625					
30	5	0.99	4.4	4.9	0.73
61	5	0.99	4.2	5.0	0.59
91	5	0.35	5.6	6.9	0.42
Watermark					
61	5	0.85	10.6	10.7	0.27
91	5	0.33	10.8	11.0	0.31

An analysis of the data confirmed that the factory calibrations of the CS625 and Watermark sensors in Site B overestimated θ_v at every depth. Figure 19 showed that the factory calibration of θ_v for the three CS625 sensors overestimated θ_v at all water contents, with the magnitude of errors equal at the different water contents. Figure 20 showed that the factory calibration of θ_v for the two Watermark sensors overestimated θ_v at all water contents, with the magnitude of errors greater with the higher water contents. Figure 21 also showed that the factory calibration of θ_v applied to the CS625 and Watermark sensors at the 61-cm depth overestimated θ_v at all water contents (additional graphs can be found in APPENDIX B - Supplementary Graphs; Figures B-3 and B-4).

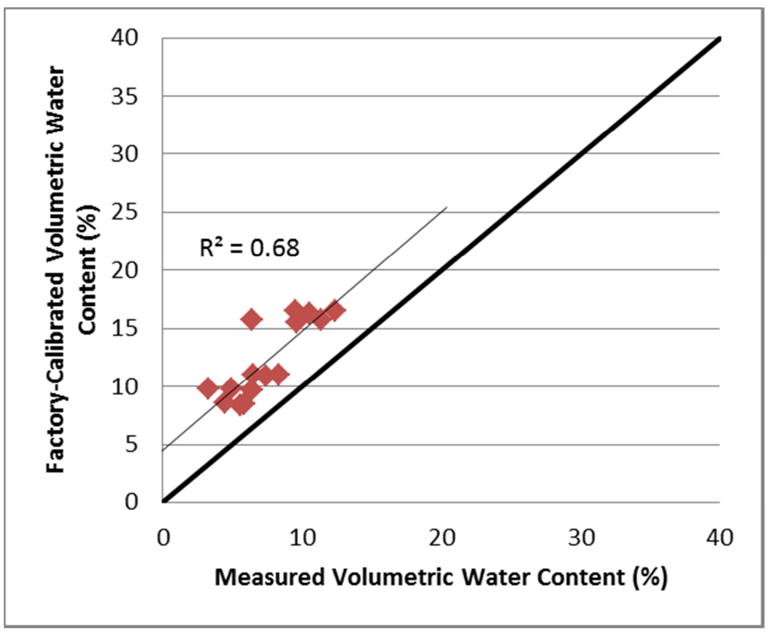

Figure 19. Graphical Comparison of the Factory-Calibrated Measurement of θ_v by the CS625 Sensors in the field (loamy sand; Site B) vs. Gravimetric Measurements of θ_v

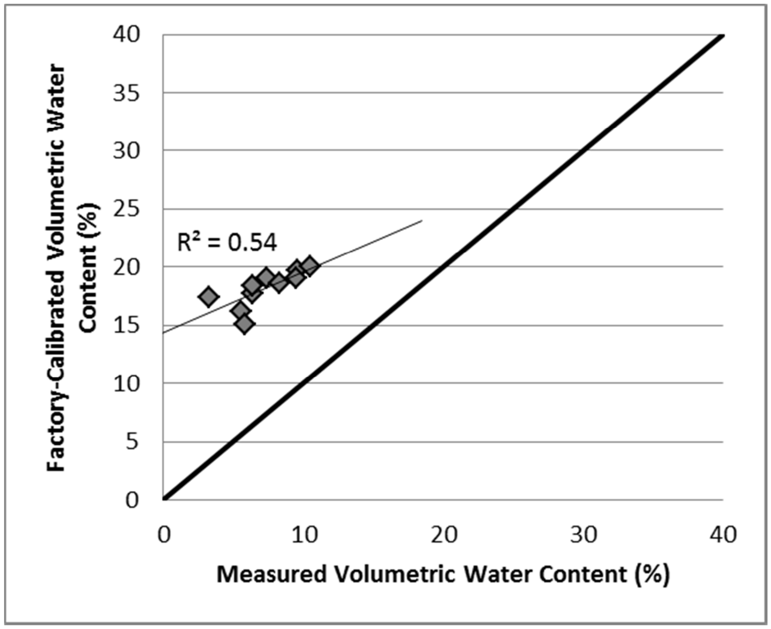

Figure 20. Graphical Comparison of the Factory-Calibrated Measurement of θ_v by the Watermark Sensors in the field (loamy sand; Site B) vs. Gravimetric Measurements of θ_v

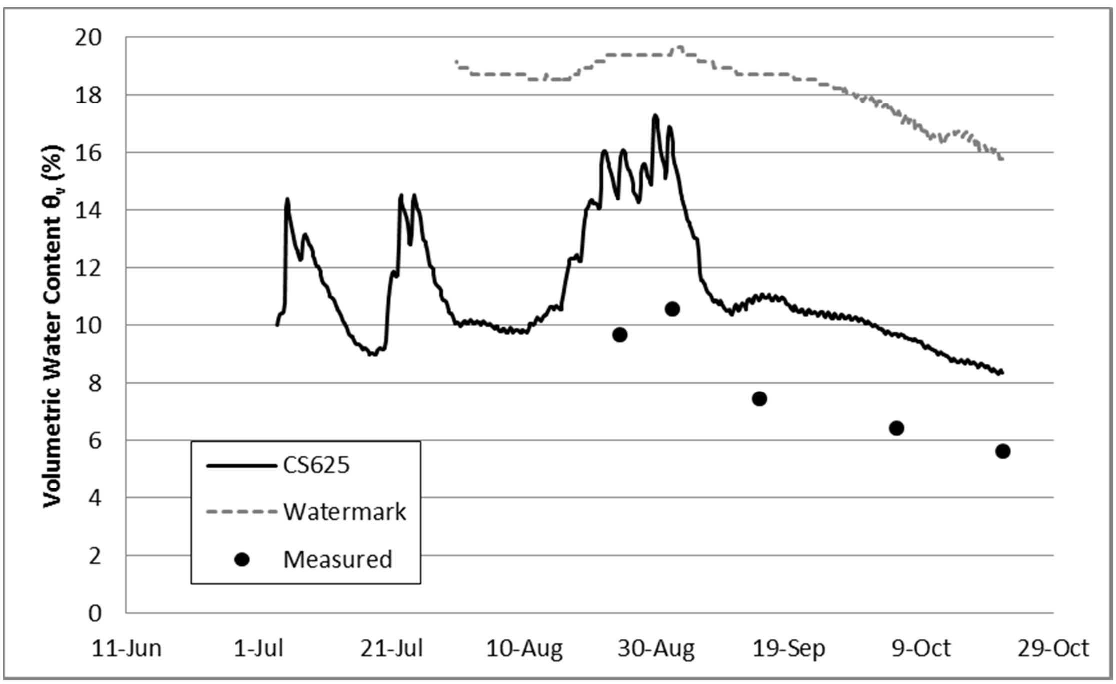

Figure 21. Graphical comparison of the Factory-based Calibration of θ_v (%) for the CS625 (black) and Watermark (gray) Sensors at Site B (loamy sand), at the 61-cm Depth

<u>Sensor Sensitivity to Soil Salinity</u>

Bulk soil electrical conductivity depends both on the concentration of salts in the soil and the volumetric water content: the bulk EC increases as θ_v increases, as shown in

Figure 22. Therefore, a one-time addition of salts to the soil in the laboratory (at multiple θ_v) was sufficient to observe the TDT and 5TE sensors' θ_v responses to multiple values of bulk EC. Additional graphs of bulk EC vs. θ_v are located in APPENDIX B - Supplementary Graphs (Figures B-8 to B-10).

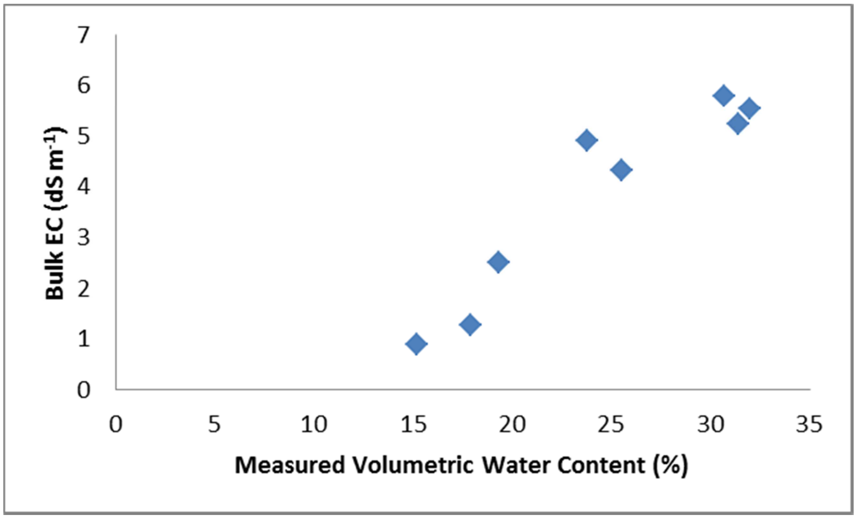

Figure 22. Bulk Soil EC Measured by the TDT sensor vs. Volumetric Water Content of the Sandy Clay Loam (Site A) in the Laboratory

Higher salt concentrations (in the range of 0.9-5.9 dS/m) in the sandy clay loam (Site A) increased the TDT's θ_v MBE by 2.6% (Table 6), and in the clay loam (Site C) the higher salt concentrations (in the range of 1.7-5.9 dS/m) increased the TDT's MBE by 6.6%. Also in these tests, the θ_v MBE of the 5TE increased by 18% in the sandy clay loam (Site A) and 17% in the clay loam (Site C).

Table 6. Comparison of the Factory Calibration-Based θ_v (%) with Laboratory Measurements of θ_v (%) for the Different Sensors and Soils with Increased Salt Concentrations

Soil Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT					
Sandy clay loam	8	0.94	1.1	3.8	0.94
Clay loam	9	0.72	4.0	6.8	0.72
5TE					
Sandy clay loam	8	0.88	16.9	19.8	0.49
Clay loam	8	0.77	17.3	18.2	0.36

It is clear from Figure 23 that the increased bulk soil EC in the laboratory (caused by increasing the salt concentration and water contents) introduced errors in the TDT and 5TE sensors. This error was larger in the 5TE than the TDT, and larger in the soil with higher clay content (clay loam; Site C). This similarly reflects the data in Table 6.

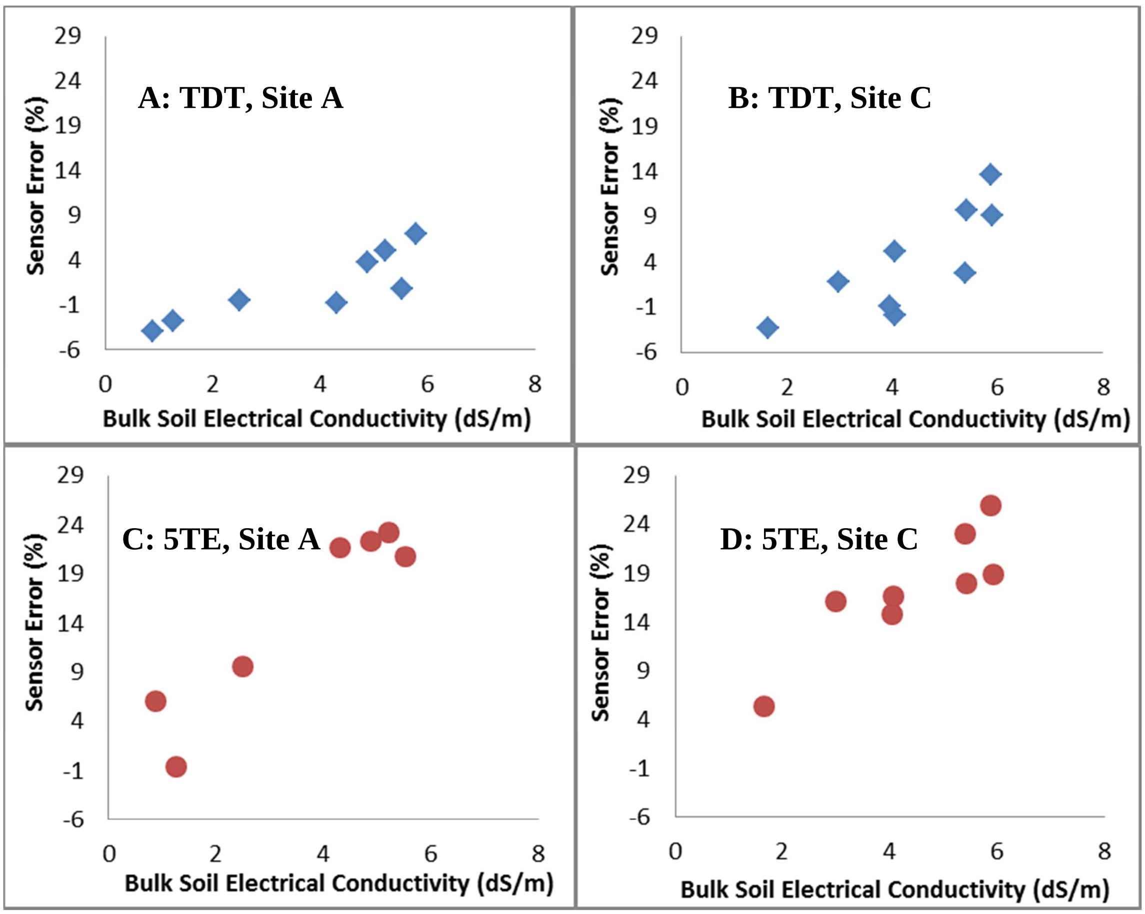

Figure 23. Graphical Representation of the Errors Introduced by Increased Bulk Soil EC in the Laboratory on: a) the TDT Sensor in the Sandy Clay Loam; b) the TDT Sensor in the Clay Loam; c) the 5TE sensor in the Sandy Clay Loam; d) the 5TE sensor in the Clay Loam. (EC was read by the TDT Sensor.)

Sensor Sensitivity to Soil Temperature Fluctuations

Close inspection of the output predicted by factory calibrations of the four sensors in treatment 1 at Site A (Figure 24) showed that diurnal oscillations of θ_v were evident in the CS616, 5TE, and Watermark sensors, while the TDT had virtually none. This result indicated that the CS616, 5TE, and Watermark sensors were strongly influenced by changes in soil temperature, while the TDT was not. This is in agreement with previous research on the CS616/625 (Seyfried and Murdock, 2001; Western and Seyfried, 2005; Benson and Wang, 2006; Logsdon and Hornbuckle, 2006; Ruelle and Laurent, 2008; Logsdon, 2009; Evett et al., 2010), TDT (Evett et al., 2010), and Watermark (Hignett and Evett, 2008b). The diurnal oscillations of θ_v also indicated that the Watermark's factory calibration that included a soil temperature correction was not able to fully remove the effect of soil temperature on sensor performance.

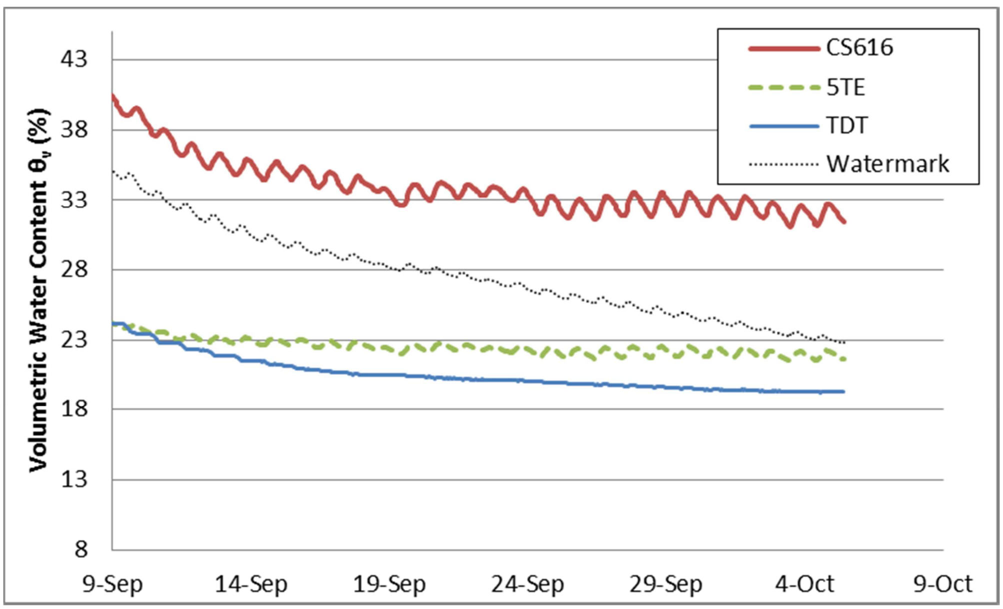

Figure 24. Graphical Comparison of the Factory-Based Calibration of θ_v (%) for the CS616 (red), TDT (blue), 5TE (green) and Watermark (black dotted) Sensors Installed in Treatment 1 at Site A (sandy clay loam), Exhibiting Temperature-Induced Diurnal Oscillations in Three Sensors

The linear regressions performed on the CS616, 5TE, and Watermark sensors' measured θ_v to correct for temperature effects were able to improve the MBE and RMSE values for each sensor (full equations are located in APPENDIX A - Calibration Equations). However, graphs of the data proved that these equations introduced additional noise in the data for the Watermark (±1%; Figure 25), CS616 (±4%; Figure

26) and 5TE (±2%; Figure 27) sensors. Therefore, this method of correcting for temperature effects is not recommended for the CS616, 5TE, or Watermark sensors.

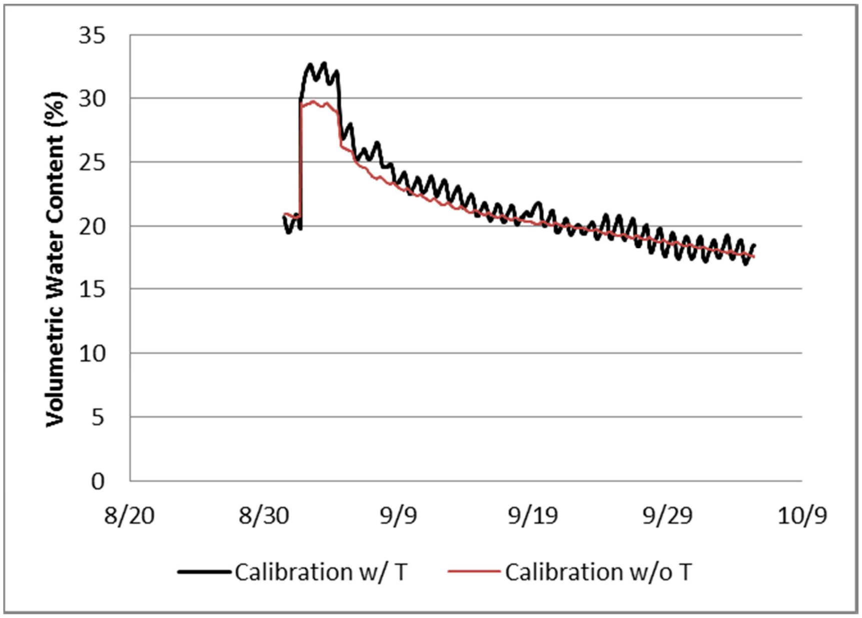

Figure 25. Graphical Representation of the Field-Based Calibrations of θ_v (%) that Included a Temperature Correction (black) and did not Include a Temperature Correction (red) for the Watermark Sensor Installed in Treatment 1 at Site A (sandy clay loam)

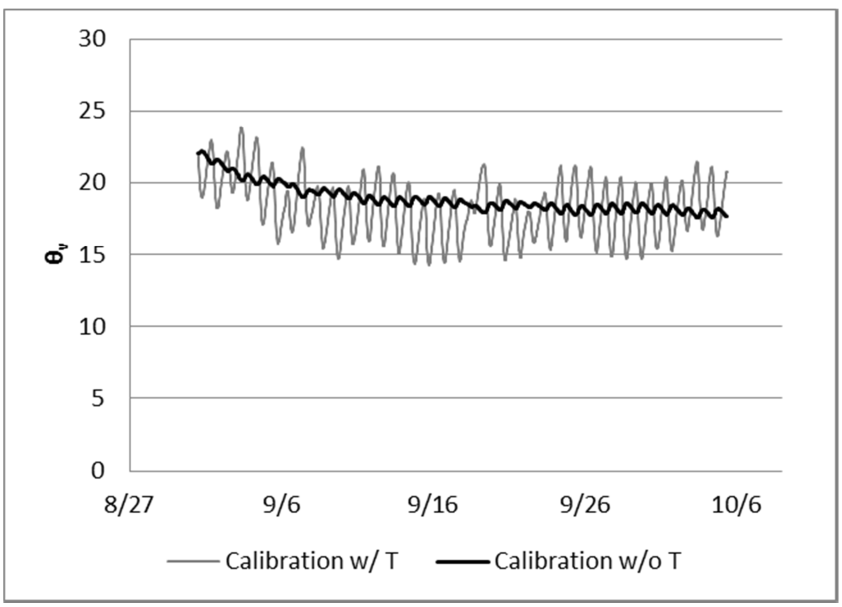

Figure 26. Graphical Representation of the Field-Based Calibration of θ_v (%) that Included a Temperature Correction (gray) and did not Include a Temperature Correction (black) for the CS616 Sensor Installed in Treatment 2 at Site A (sandy clay loam)

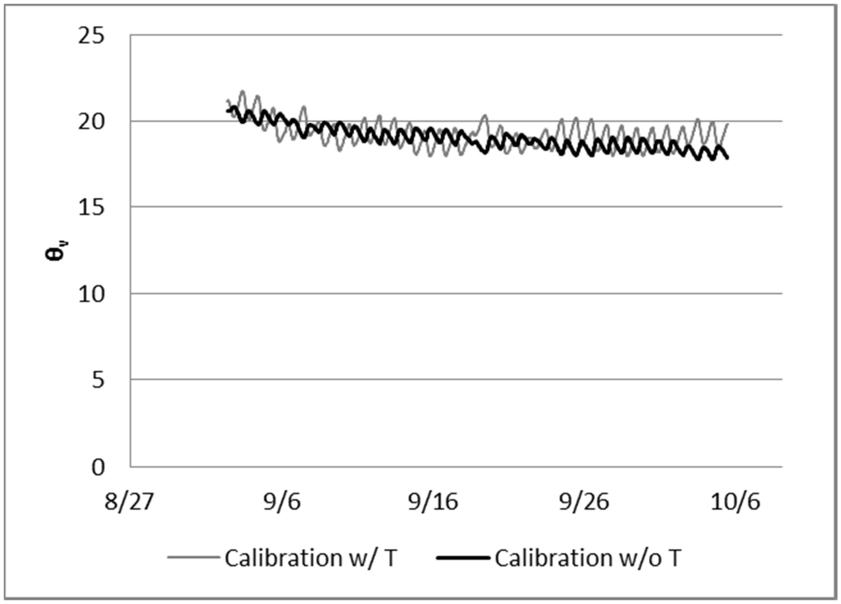

Figure 27. Graphical Representation of the Field-Based Calibration of θ_v (%) that Included a Temperature Correction (gray) and did not Include a Temperature Correction (black) for the 5TE Sensor Installed in Treatment 2 at Site A (sandy clay loam)

Laboratory Calibration Evaluation

Soil-specific calibration equations developed for the CS616, TDT, 5TE, and Watermark sensors in the laboratory yielded high levels of accuracy, as shown in Table 7. (Full calibration equations can be found in APPENDIX A - Calibration Equations.) These calibrations were unique for each soil, and the MBE, RMSE errors were smaller (and κ parameters larger) than the factory calibrations. The RMSE parameters were within the statistical targets in every test. Also shown in this table, new calibration equations developed for the TDT and 5TE sensors after the introduction of salts for the soils from Sites A and C again resulted in small RMSE values. This leads to the conclusion that the calibrations applied to each sensor sufficiently improved readings of volumetric water content using data from laboratory tests, given that the pore water EC remains relatively constant. In all soils, the logarithmic and van Genuchten (1980) equations produced similar levels of accuracy for the Watermark sensor. Therefore, the van Genuchten (1980) equation was not significantly more accurate than the logarithmic equation, and the additional work of deriving the parameters for the former equation did not seem worthwhile, within the range of soil water contents analyzed.

Table 7. Comparison of the Laboratory-based Calibration of θ_v (%) versus Laboratory Measurements of θ_v (%) for the Different Sensors and Soils

Soil Type	Add'l Salts	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS616							
Sandy clay loam	N	Linear	60	0.92	0.0	2.1	0.98
Loamy sand		Linear	6	0.99	0.0	0.4	1.00
Clay loam		Linear	56	0.88	0.0	2.1	0.97
TDT							
Sandy clay loam	N	Linear	60	0.94	0.0	1.9	0.98
	Y	Linear	8	0.94	0.0	1.5	0.98
Loamy sand	N	Linear	6	0.98	0.0	0.7	0.99
Clay loam	N	Linear	56	0.95	0.0	1.4	0.99
	Y	Linear	9	0.72	0.0	2.1	0.91
5TE							
Sandy clay loam	N	Linear	60	0.92	0.0	2.1	0.98
	Y	Linear	8	0.88	0.0	2.1	0.97
Loamy sand	N	Linear	6	0.98	0.0	0.7	0.99
Clay loam	N	Linear	56	0.78	0.0	2.8	0.93
	Y	Linear	8	0.77	0.0	2.1	0.93
Watermark							
Sandy clay loam	N	Logarithmic	7	0.94	0.0	1.1	0.98
		van Genuchten	7	0.93	0.0	1.2	0.98
Loamy sand		Logarithmic	3	0.60	0.0	3.3	0.86
		van Genuchten	3	0.75	-0.2	2.6	0.93
Clay loam		Logarithmic	4	0.76	0.0	2.0	0.93
		van Genuchten	4	0.76	0.0	2.0	0.93

Table 8 displays the results of using the soil-specific calibration equations developed in the laboratory on the CS616, TDT, 5TE and Watermark sensors installed in the field at Site A. The approximate range of field-measured θ_v was PWP to FC. The large MBE (> ±2.0%) and RMSE (> 3.5%) values indicated that the laboratory-derived calibration equations for the CS616, TDT, 5TE, and Watermark sensors were not consistently accurate. However, the laboratory equation for the CS616 was more accurate than the factory calibration, reducing the MBE to 3.3, 7.7, and 4.4% in treatments 1, 2, and 3, respectively. When compared with the TDT's factory calibration, the TDT's laboratory calibration yielded comparable MBE and RMSE values, and was accurate only in treatment 2. Applying the laboratory-derived calibration to the data collected from the 5TE sensors in the field produced accurate estimates of θ_v in treatments 2 and 3 (MBE of 2.0% and -0.2%, respectively), but not for treatment 1 (MBE of 3.3%). Also, applying the 5TE's laboratory calibration was slightly less accurate overall than using the 5TE's factory calibration. The laboratory equations for the Watermark sensor were less inaccurate than the factory calibration, and the accuracy of the laboratory-derived van Genuchten (1980) calibration equation was similar to the accuracy of the laboratory-derived logarithmic equation. This is evidence again that the van Genuchten (1980) equation was not significantly more accurate than the logarithmic equation for this application, and that the additional work of deriving the parameters for the former equation did not seem worthwhile, within the range of soil water contents analyzed.

Table 8. Comparison of the Laboratory-based Calibration of θ_v (%) versus Site A (sandy clay loam) Field Measurements of θ_v (%) for the Different Sensors

Location	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS616						
1	Linear	11	0.86	3.3	3.6	0.77
2	Linear	11	0.53	7.7	8.6	0.59
3	Linear	12	0.56	4.4	5.9	0.73
TDT						
1	Linear	11	0.76	2.8	3.3	0.78
2	Linear	11	0.83	0.8	2.1	0.93
3	Linear	12	0.74	-2.0	3.7	0.86
5TE						
1	Linear	11	0.63	3.3	4.2	0.64
2	Linear	11	0.74	2.0	3.2	0.82
3	Linear	12	0.67	-0.2	3.5	0.84
Watermark						
1	Logarithmic	11	0.81	-3.0	3.6	0.82
	van Genuchten	11	0.90	-2.6	2.8	0.87

Figure 28 and Figure 29 show the results of using the laboratory equations on the field data collected by the CS616, TDT, 5TE and Watermark sensors at Site A. The graphs confirmed that the field data from the CS616, TDT, 5TE and Watermark sensors, calibrated with equations developed in the laboratory, were not always accurate in measuring θ_v. Also, it is clear that the TDT sensor in treatment 3 measured impossible levels of water content (above porosity).

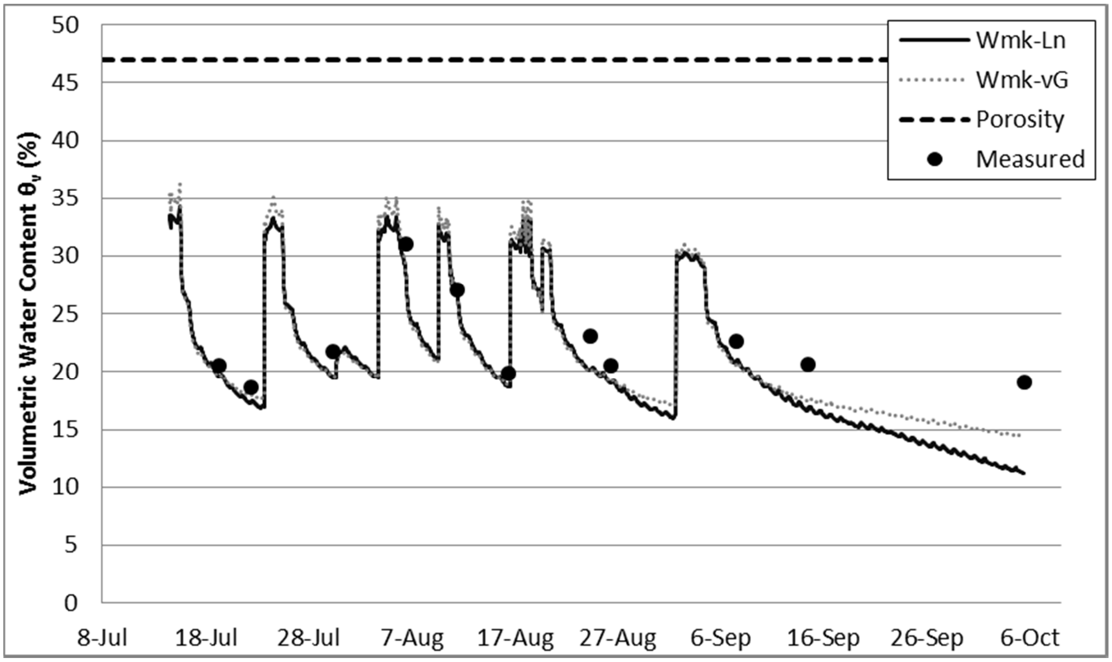

Figure 28. Graphical Comparison of the Laboratory-Based Calibration of θ_v (%) for the Watermark Sensor Installed in Treatment 1 at Site A (sandy clay loam)

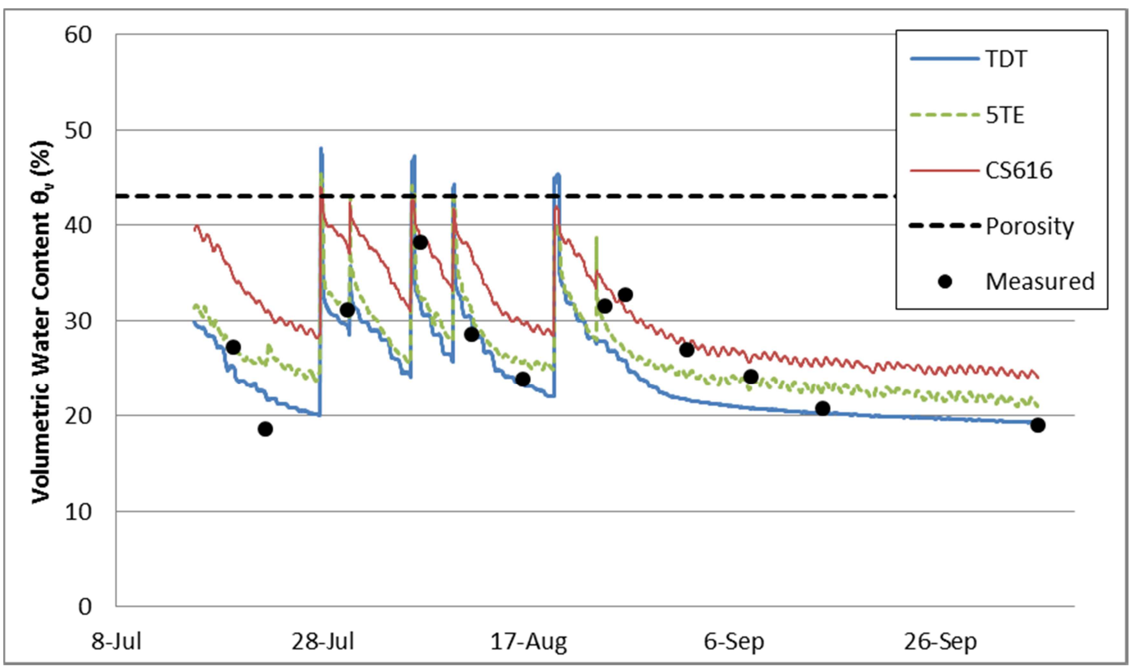

Figure 29. Graphical Comparison of the Laboratory-Based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green) Sensors Installed in Treatment 3 at Site A (sandy clay loam)

Applying the laboratory-derived calibration equation developed for the CS625 sensors at Site B was accurate at the 30- and 61-cm depths. However, using this equation resulted in an overestimation of θ_v (MBE; Table 9) by 3.2% at the 91-cm depth. At the deepest depth, the poor MBE and RMSE values could be due to the small number of samples or the difficulty of obtaining an accurate measurement from that depth. The laboratory equations developed for the Watermark sensors at Site B accurately predicted θ_v at the 61- and 91-cm depths (RMSE = 1.4% and 2.4, respectively). At both depths, the laboratory-derived van Genuchten (1980) calibration equation performed nearly identically to the laboratory-derived logarithmic equation.

Table 9. Comparison of the Laboratory-based Calibration of θ_v (%) versus Field Measurements of θ_v (%) at Site B (loamy sand) for the Different Sensors

Depth (cm)	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS625						
30	Linear	5	0.99	2.0	2.4	0.89
61	Linear	5	0.99	1.9	2.3	0.83
91	Linear	5	0.35	3.2	4.4	0.54
Watermark						
61	Logarithmic	5	0.83	1.0	1.3	0.90
	van Genuchten	5	0.89	1.0	1.4	0.82
91	Logarithmic	5	0.30	0.6	2.4	0.73
	van Genuchten	5	0.36	1.6	2.4	0.60

Figure 30 shows that the laboratory equations for the CS625 and Watermark sensors improved the accuracy of the measured θ_v at the 61-cm depth. Additional graphs can be found in APPENDIX B - Supplementary Graphs (B-11 to B-14).

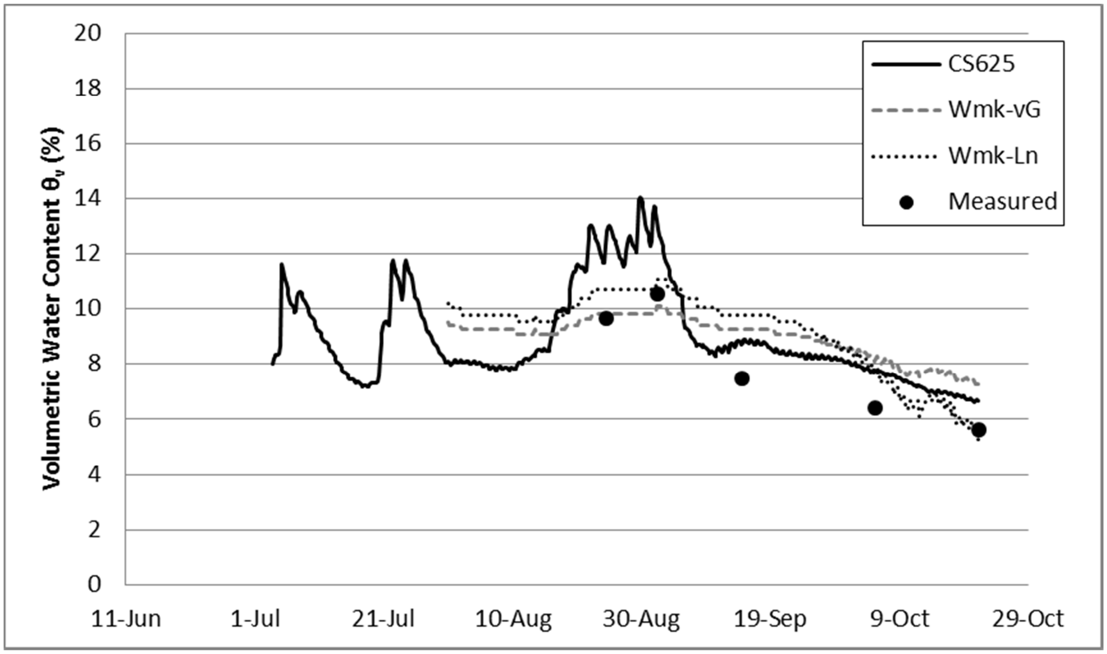

Figure 30. Graphical comparison of the Laboratory-based Calibration of θ_v (%) for the CS625 (black) and Watermark (gray-solid and black-dotted) Sensors at Site B (loamy sand), at the 61-cm Depth

Field Calibration Evaluation

The sensor-specific calibrations performed on the four sensors installed in the field at Site A showed higher levels of accuracy than the factory- or laboratory-derived equations, as shown in Table 10. The calibration equations for the CS616 sensors were accurate in treatments 1 and 2 (RMSE = 1.3% and 3.1%, respectively), but not in treatment 3 (RMSE = 3.8%). This result agrees with findings made by Logsdon (2009) that "field calibrations would be recommended over laboratory calibrations for the CS616 sensor, at least for field monitoring." The field-derived calibration equations for the TDT sensors were accurate in treatments 1, 2, and 3 (RMSE of 1.7%, 1.9%, and 2.9%, respectively). The field-derived calibration equations for the 5TE sensors were also accurate in treatments 1, 2, and 3 (RMSE of 2.2%, 2.3%, and 3.3%, respectively). The field-derived logarithmic and van Genuchten (1980) calibration equations for the Watermark sensor were also accurate in treatment 1 (RMSE of 1.6% and 1.2%, respectively). When comparing the complex van Genuchten (1980) equation with the simpler logarithmic equation for the Watermark sensors, it is not clear that either performed better than the other. This result is indicated through the fact that both equations had similar RMSE and κ values. Once again, it was evident that the van Genuchten (1980) equation was not significantly more accurate than the logarithmic equation, and that the additional work of deriving the parameters for the former equation did not seem worthwhile, within the range of soil water contents analyzed.

Table 10. Comparison of the Field-based Calibration of θ_v (%) versus Site A (sandy clay loam) Field Measurements of θ_v (%) for the Different Sensors

Location	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS616						
1	Linear	11	0.86	0.0	1.3	0.96
2	Linear	11	0.53	0.0	3.1	0.82
3	Linear	12	0.56	0.0	3.8	0.83
TDT						
1	Linear	11	0.76	0.0	1.7	0.93
2	Linear	11	0.83	0.0	1.9	0.95
3	Linear	12	0.74	0.0	2.9	0.92
5TE						
1	Linear	11	0.63	0.0	2.2	0.88
2	Linear	11	0.74	0.0	2.3	0.92
3	Linear	12	0.67	0.0	3.3	0.89
Watermark						
1	Logarithmic	11	0.81	0.0	1.6	0.94
	van Genuchten	11	0.89	0.0	1.2	0.97

Graphs of the sensors at Site A (shown in Figure 32; additional graphs found in APPENDIX B - Supplementary Graphs; Figures B-15 to B-18) show that, similar to the laboratory equations, in each treatment the field calibrations for the CS616 incorrectly reported θ_v at saturation. This result indicated that a higher-order polynomial calibration equation was necessary for using the CS616 to measure the full range of PWP to saturation. The Watermark sensors in treatment 1 also did not measure saturation appropriately. This result is most likely due to the fact that field measurements of θ_v were not taken immediately following an irrigation event, and the field drained before a measurement could be made. In treatments 2 and 3, the TDT and 5TE sensors briefly measured impossibly large (greater than porosity) θ_v. The data shown in these graphs agreed with research conducted by Evett et al. (2010), where they stated that "a linear soil-specific calibration would suffice to correct [the TDT] to be useful in scheduling [irrigations] according to" management allowed depletion. However, the TDT and 5TE sensors are not recommended for studies that rely on accurate measurements of saturation (such as water balance studies), unless gravimetric measurements can be made at a time when the soil is saturated.

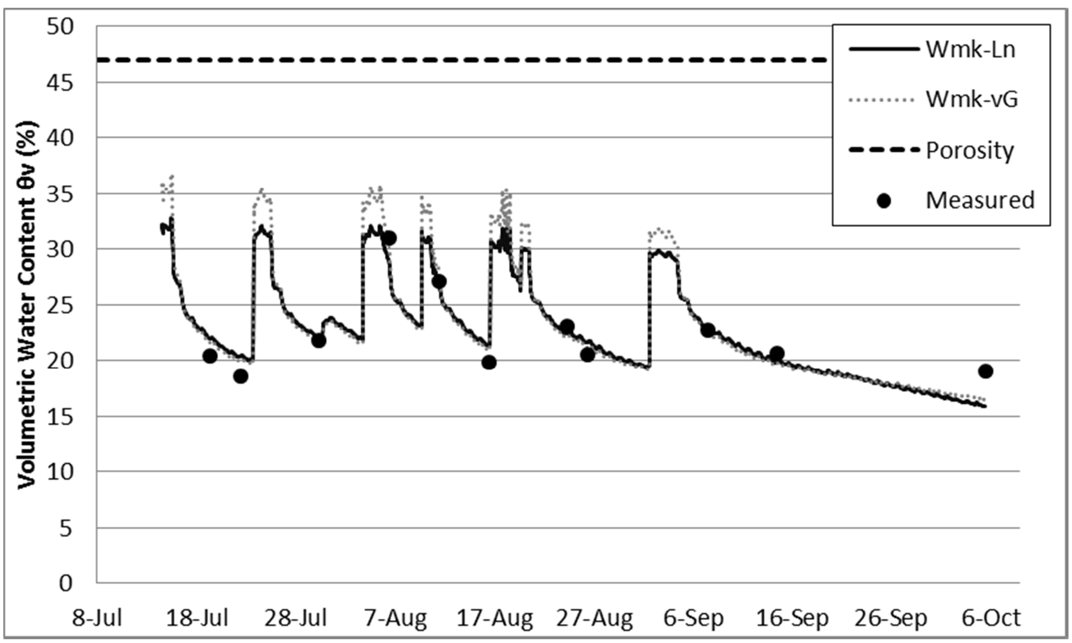

Figure 31. Graphical Comparison of the Field-Based Calibration of θ_v (%) for the Watermark Sensor Installed in Treatment 1 at Site A (sandy clay loam)

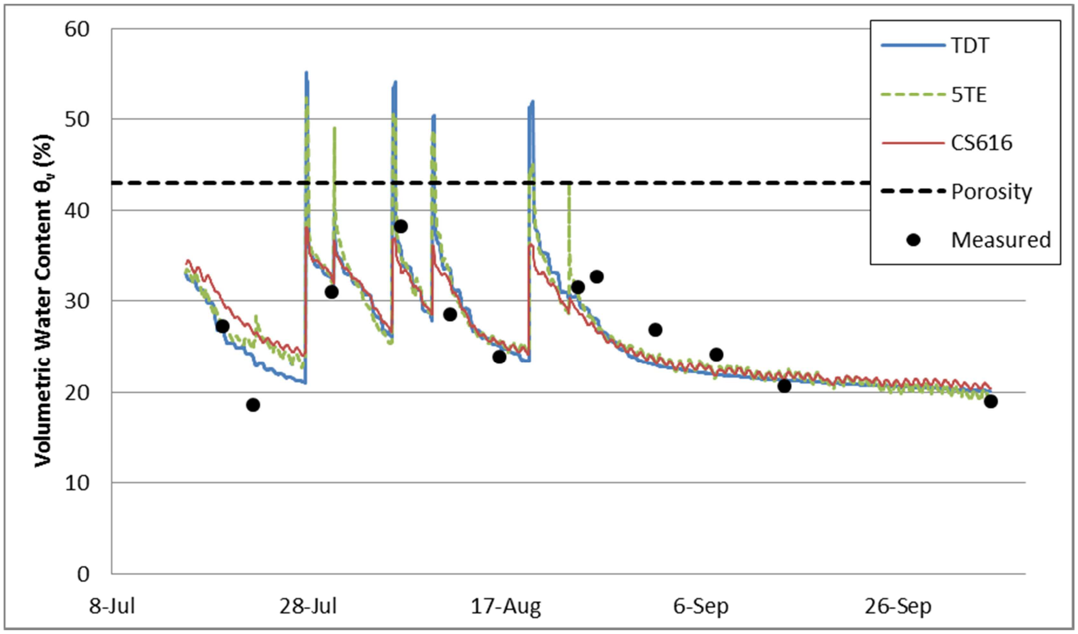

Figure 32. Graphical Comparison of the Field-Based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green)Sensors Installed in Treatment 3 at Site A (sandy clay loam)

The sensor-specific calibrations performed on the CS625 and Watermark sensors installed in the field at Site B showed higher levels of accuracy than the factory- or laboratory-derived equations, as shown in Table 11. The RMSE and κ values were all within the goals for both sensors at each depth. When comparing the complex van Genuchten (1980) equation with the simpler logarithmic equation for the Watermark sensors, the former equation was slightly more accurate than the latter, as shown by the smaller RMSE (0.5 to 0.8%) values and the more-representative curve at the 91-cm depth.

Table 11. Comparison of the Field-based Calibration of θ_v (%) versus Field Measurements of θ_v (%) at Site B (loamy sand) for the Different Sensors

Depth (cm)	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
CS625						
30	Linear	5	0.99	0.0	0.3	1.00
61	Linear	5	0.99	0.0	0.2	1.00
91	Linear	5	0.35	0.0	2.0	0.71
Watermark						
61	Logarithmic	5	0.83	0.0	0.8	0.95
	van Genuchten	5	0.97	-0.1	0.3	0.99
91	Logarithmic	5	0.26	0.0	1.9	0.59
	van Genuchten	5	0.73	0.1	1.1	0.91

Figure 33 confirms the results of the previous table that the field-derived calibration equations for the CS625 and Watermark sensors accurately measured θ_v at Site B.

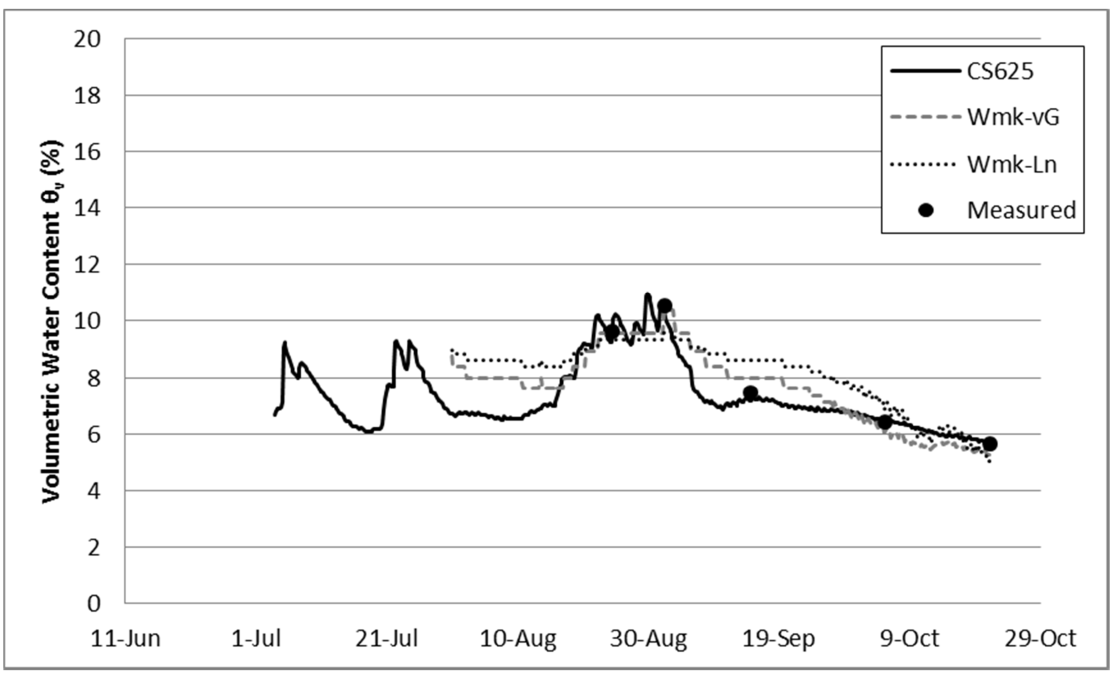

Figure 33. Graphical comparison of the Field-based Calibration of θ_v (%) for the CS625 (black) and Watermark (gray-solid and black-dotted) Sensors at Site B (loamy sand), at the 61-cm Depth

Possible Sources of Errors

Accurate sensor readings "depend on the absence of air gap between the [sensor] rods and soil" (Ruelle and Laurent, 2008; Heng and Evett, 2008). The air gaps "may occur during installation or subsequently as the soil tends to shrink upon drying" (Hillel, 1998), thus, care must be taken during installation. To avoid these air gaps, the CS616, TDT, and 5TE sensors were installed when the soil was moist and easily workable. Due to the TDT's metal loops, however, all air gaps could not be avoided with this insertion technique, and are a source of possible errors with this sensor. The Watermark sensors were installed by creating a hole with a soil auger slightly less than the diameter of the sensor. The sensor was then coated with a slurry of the removed soil and inserted into the hole. The hole was then backfilled with the remaining slurry.

The relationship between water content and matric potential in the soil is hysteretic (Hillel, 1998). This means that the same value of matric potential can represent two different water contents, depending on whether the soil is "wetting" or "drying". Therefore all tests on the Watermark sensor took place while the soil was drying, and none of the developed equations for this sensor are applicable for soil that is wetting (which occurs only briefly during irrigation or precipitation events).

Recommendations

For applications requiring the highest levels of accuracy, such as research or irrigation scheduling according to Management Allowed Depletion, all sensors evaluated in this study require unique sensor- and soil- specific field calibrations. A linear, field-based calibration equation is satisfactory to achieve the required accuracy of the TDT and 5TE sensors. The linear field-based calibration of the CS616/625 sensors did not perfectly reduce the errors of the factory calibration of θ_v to 0.020 ±0.035 m^3 m^{-3}, but the calibrations were near these tolerances and the sensor can be used as long as the operator understands that some errors (±0.04 m^3 m^{-3}) may exist. The factory calibrations of the TDT and 5TE sensors are acceptable in applications for which high accuracy is not important. Field-derived logarithmic and van Genuchten (1980) equations were equally accurate calibrations for estimating volumetric water content with the Watermark sensor readings.

The CS616, TDT, and 5TE sensors experienced errors in reporting volumetric water content with increased bulk soil EC (dS m^{-1}). This is in agreement with Campbell (2011) that the CS616/625 is not accurate above 0.5 dS m^{-1}, and with Acclima (2010) that the TDT is not accurate above 3 dS m^{-1}. In addition, the magnitude of the sensitivity to increased bulk soil EC was greatest in the 5TE sensor and was greater for all sensors in the soil with higher clay content. Changes in soil temperature influenced the reporting of volumetric water content by the CS616/625, 5TE and Watermark sensors, but not the TDT sensor. Therefore, it is recommended that the soil temperature be considered in the calibration process through either a correction equation or taking readings from the sensors during times that the soil temperature is similar (for example, every day at noon).

The TDT sensor had the lowest cost (US $115) of the sensors used in this study. The Watermark sensor (model 157-L, Campbell Scientific, Inc., Logan, UT; this model was selected because of its ability to connect to a datalogger capable of an internal, user-defined calibration) had the same cost (US $115), however the acquisition of a separate sensor for measuring soil temperature is needed for proper sensor calibration and operation. The cost of the CS616/625 was 60% greater (US $185) than the TDT, and the cost of the 5TE was 90% greater (US $220) than the TDT.

Update

Campbell (2010) stated that it will release improved versions of the CS616/625. These newer sensors will be capable of communicating in the SDI-12 interface, measuring soil temperature and bulk electrical conductivity, and operate in soils with bulk electrical conductivity of 0-3.7 dS m^{-1}.

SUMMARY AND CONCLUSIONS

This research evaluated the performance of CS616/625, TDT and 5TE soil water content and Watermark soil water potential sensors, within the PWP to FC range of water contents, under laboratory and field conditions. Volumetric soil water content/potential values measured by the sensors were compared with corresponding values measured by gravimetric samples. Linear calibration equations were developed for the CS616/625, TDT and 5TE sensors. For the Watermark sensor, calibration equations taking the form of van Genuchten (1980) and of the logarithmic form were developed. The derived equations were compared against each other and with factory-recommended calibrations. Acceptable sensor errors for these tests were ±2.0% (units in θ_v expressed as a %) MBE and less than 3.5% (units in θ_v expressed as a %) RMSE.

In the laboratory tests, it was found that the CS616 sensor's factory-recommended calibration overestimated θ_v by an average of 10% in the sandy clay loam (Site A), 3% in the loamy sand (Site B), and 24% in the clay loam (Site C). Laboratory tests on the TDT sensor showed that the factory calibration was somewhat inaccurate in every soil (RMSE 4.1-6.7%). The factory calibration for the 5TE sensor was accurate in the sandy clay loam, but not the loamy sand (MBE = 2.5%) or the clay loam (RMSE = 3.8%). Also in the laboratory, the factory calibration for the Watermark sensor overestimated θ_v by an average of 20%, 8%, and 17% in the soils from Sites A, B, and C, respectively. The data developed in the laboratory was used to develop 'laboratory equations' to be applied to the sensors installed in the fields.

Salt (calcium chloride dihydrate) was added to the soils from Sites A and C until the TDT measured the soil bulk EC of 5.79 dS/m in the Site A soil and 5.92 dS/m in the

Site B soil. The increases in salt concentrations caused the CS616 to give an error reading, indicating that this sensor is very sensitive to soil salinity and therefore not recommended to read θ_v in soils affected by salinity. The bias of the TDT sensor was increased by 2.6% at Site A, and 6.6% at Site C. The errors associated with the TDT sensor increased at higher levels of bulk EC, which is in agreement with Acclima (2010) that the TDT is no longer accurate above 3 dS m^{-1}. Meanwhile, the bias of the 5TE sensor was increased by 18% at Site A and 17% at Site C when salts were added to the soil. The errors associated with the 5TE sensor also increased as bulk EC increased. Graphical representation of the data confirmed that the increased bulk soil EC in the laboratory introduced greater errors on the 5TE sensor than the TDT, and both sensors experienced greater MBE errors in the soil with higher clay contents.

During the summer of 2010, CS616/625, TDT, 5TE and Watermark sensors were installed in irrigated agricultural fields near Greeley, CO. The factory-recommended and laboratory-derived calibration equations were applied to these sensors, and compared with periodic gravimetric samples. At Site A, the factory calibrations of θ_v for the CS616 sensor at Site A overestimated (MBE) θ_v by 19%, 32%, and 28% in treatments 1, 2, and 3, respectively. The factory calibration for the TDT sensor was accurate in treatment 2, but not treatments 1 and 3 (MBE of 2.7% and $^{-}$2.2%, respectively). The factory calibration applied to the 5TE sensor was also accurate in treatment 2, but not treatment 1 (MBE of 2.4%) or treatment 3 (RMSE = 3.7%). The factory calibration for the Watermark sensor overestimated θ_v by 11%. Also at Site A, the laboratory calibrations for the CS616, TDT, 5TE, and Watermark sensors were not consistently accurate in every treatment.

The factory calibrations of the CS625 and Watermark sensors in Site B did not achieve sufficient accuracy at any depth. Applying the laboratory-derived calibration equation developed for the CS625 sensors at Site B was accurate at the 30- and 61-cm depths. However, using this equation resulted in an overestimation of θ_v by 3.2% at the 91-cm depth. Using the laboratory equations developed for the Watermark sensors at Site B accurately measured θ_v at the 61- and 91-cm depths (RMSE = 1.4% and 2.4, respectively).

Field-derived calibration equations developed for all sensors in both fields returned higher accuracy than the factory- or laboratory-derived equations, and were all within the desired limits in the approximate range of PWP to FC. This implies that a unique field-derived calibration equation is necessary for every sensor and soil type, if the sensors are to be used in irrigation scheduling to determine the irrigation timing and amounts. However, only the TDT and 5TE sensors reported appropriate θ_v values near saturation during irrigation events. Furthermore, it was evident that the van Genuchten (1980) equation was not significantly more accurate than the logarithmic equation, and that the additional work of deriving the parameters for the former equation did not seem worthwhile, within the range of soil water contents analyzed. Visual inspection of the graphs from the field data suggest that the CS616/625, 5TE and Watermark sensors were strongly influenced by fluctuations in soil temperature, while the TDT sensor was not influenced. Therefore, it is recommended that the soil temperature be considered in the calibration process of the CS616, 5TE, and Watermark sensors through either a correction equation or taking readings from the sensors during times that the soil temperature is similar (for example, every day at noon). Furthermore, quality control checks should be performed to monitor the bulk EC levels in the soil and, if needed, re-calibrate the sensors to account for the increased bulk EC.

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APPENDIX A - Calibration Equations

The complete calibration equations used for the sensors in this study are below:

CS616/625

Table A - 1. Calibration Equations Used for the CS616/625 Sensors

Eq. Type	Soil Type	Location / Depth (cm)	Equation
Factory	n/a	n/a	$\theta_{vi} = 0.0007*P^2 - 0.0063*P - 0.0663$
Laboratory	Sandy clay loam	n/a	$\theta_v = 0.41*\theta_{vi} + 8.56$
	Loamy sand	n/a	$\theta_v = 0.83*\theta_{vi} -0.25$
	Clay loam	n/a	$\theta_v = 0.27*\theta_{vi} + 13.36$
Field	Sandy clay loam	1	$\theta_v = 0.5*\theta_{vi} + 1.78$
			$\theta_v = 0.52*\theta_{vi} - 0.25*T + 5.49$
		2	$\theta_v = 0.26*\theta_{vi} + 9.75$
			$\theta_v = 0.36*\theta_{vi} - 1.23*T + 27.85$
		3	$\theta_v = 0.37*\theta_{vi} + 6.62$
			$\theta_v = 0.45*\theta_{vi} - 0.85*T + 20.70$
	Loamy sand	30	$\theta_v = 1.02*\theta_{vi} - 4.63$
			$\theta_v = 1.06*\theta_{vi} - 0.12*T - 3.12$
		61	$\theta_v = 0.59*\theta_{vi} + 0.79$
			$\theta_v = 0.58*\theta_{vi} + 0.02*T + 0.48$
		91	$\theta_v = 0.39*\theta_{vi} +1.84$
			$\theta_v = 0.43*\theta_{vi} - 0.09*T + 3.04$

θ_{vi} = Factory-Calibrated θ_v
P = Probe Output Period
T = TDT Probe Output Soil Temperature (°C)

TDT

Table A - 2. Calibration Equations Used for the TDT Sensors

Eq. Type	Soil Type	Add'l Salts	Location	Equation
Factory	n/a	n/a	n/a	θ_{vi} = Topp et al. (1980)*
Laboratory	Sandy clay loam	N	n/a	$\theta_v = 0.69*\theta_{vi} + 7.89$
		Y	n/a	$\theta_v = 0.63*\theta_{vi} + 7.87$
	Loamy sand	N	n/a	$\theta_v = 0.64*\theta_{vi} + 1.07$
	Clay loam	N	n/a	$\theta_v = 0.61*\theta_{vi} + 12.13$
		Y	n/a	$\theta_v = 0.41*\theta_{vi} + 13.43$
Field	Sandy clay loam	n/a	1	$\theta_v = 0.78*\theta_{vi} + 2.87$
		n/a	2	$\theta_v = 0.78*\theta_{vi} + 4.8$
		n/a	3	$\theta_v = 0.83*\theta_{vi} + 6.28$

*Computed internally by the probe

θ_{vi} = Factory-Calibrated θ_v
Topp et al. (1980): $\theta_v = 4.3*10^{-6}\varepsilon_a^3 - 5.5*10^{-4}\varepsilon_a^2 + 2.92*10^{-2}\varepsilon_a - 5.3*10^{-2}$

5TE

Table A - 3. Calibration Equations Used for the 5TE Sensors

Eq. Type	Soil Type	Add'l Salts	Location	Equation
Factory	n/a	n/a	n/a	θ_{vi} = Topp et al. (1980)*
Laboratory	Sandy clay loam	N	n/a	$\theta_v = 1.05*\theta_{vi} - 0.24$
		Y	n/a	$\theta_v = 0.36*\theta_{vi} + 9.39$
	Loamy sand	N	n/a	$\theta_v = 1.10*\theta_{vi} - 4.05$
	Clay loam	N	n/a	$\theta_v = 0.68*\theta_{vi} + 8.43$
		Y	n/a	$\theta_v = 0.41*\theta_{vi} + 7.68$
Field	Sandy clay loam	n/a	1	$\theta_v = 1.83*\theta_{vi} - 22.85$
				$\theta_v = 2.48*\theta_{vi} - 0.79*T - 23.78$
		n/a	2	$\theta_v = 1.44*\theta_{vi} - 12.01$
				$\theta_v = 1.58*\theta_{vi} - 0.72*T - 1.24$
		n/a	3	$\theta_v = 1.42*\theta_{vi} - 9.73$
				$\theta_v = 1.65*\theta_{vi} - 0.96*T + 4.70$

*Computed by the user, as recommended by Decagon (2010)

ε_a = Computed Internally by the Probe
θ_{vi} = Factory-Calibrated θ_v
T = Probe Output Soil Temperature (°C)

Watermark

Table A - 4. Calibration Equations Used for the Watermark Sensors

Eq. Type	Soil Type	Loc. / Depth (cm)	Eq. Type	Equation
Factory	Sandy clay loam	n/a	n/a	$\theta_v = 104.63*SWP_{mBar}^{-0.19}$
	Loamy sand	n/a	n/a	$\theta_v = 38.14*SWP_{mBar}^{-0.14}$
	Clay loam	n/a	n/a	$\theta_v = 104.63*SWP_{mBar}^{-0.19}$
Laboratory	Sandy clay loam	n/a	Log	$\theta_v = -3.63*\ln(SWP_{cm}) + 41.12$
			vG*	$\theta_s = 0.440$; $\theta_r = 0.063$; $\alpha = 0.332$; $n = 1.21$
	Loamy sand	n/a	Log	$\theta_v = -3.78*\ln(SWP_{cm}) + 28.48$
			vG*	$\theta_s = 0.370$; $\theta_r = 0.049$; $\alpha = 0.331$; $n = 1.52$
	Clay loam	n/a	Log	$\theta_v = -1.90*\ln(SWP_{cm}) + 32.39$
			vG*	$\theta_s = 0.500$; $\theta_r = 0.079$; $\alpha = 37.384$; $n = 1.12$
Field	Sandy clay loam	1	Log	$\theta_v = -2.65*\ln(SWP_{cm}) + 37.75$
				$\theta_v = -2.89*\ln(SWP_{cm}) - 0.37*T + 45.99$
			vG*	$\theta_s = 0.470$; $\theta_r = 0.063$; $\alpha = 0.678$; $n = 1.18$
	Loamy sand	61	Log	$\theta_v = -3.02*\ln(SWP_{cm}) + 23.55$
				$\theta_v = -4.88*\ln(SWP_{cm}) - 0.55*T + 42.61$
			vG*	$\theta_s = 0.370$; $\theta_r = 0.049$; $\alpha = 0.026$; $n = 2.78$
		91	Log	$\theta_v = -1.83*\ln(SWP_{cm}) + 16.75$
				$\theta_v = -5.23*\ln(SWP_{cm}) - 0.99*T + 52.63$
			vG	$\theta_s = 0.370$; $\theta_r = 0.049$; $\alpha = 0.011$; $n = 5.36$

*van Genuchten (1980): $$\theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^{1-1/n}}$$

T = Soil Temperature (°C)

SWP_{mBar} = Soil Water Potential (expressed as tension) measured by the sensor, in units of millibars

SWP_{cm} = Soil Water Potential (expressed as tension) measured by the sensor, in units of centimeters of H_2O

APPENDIX B - Supplementary Graphs

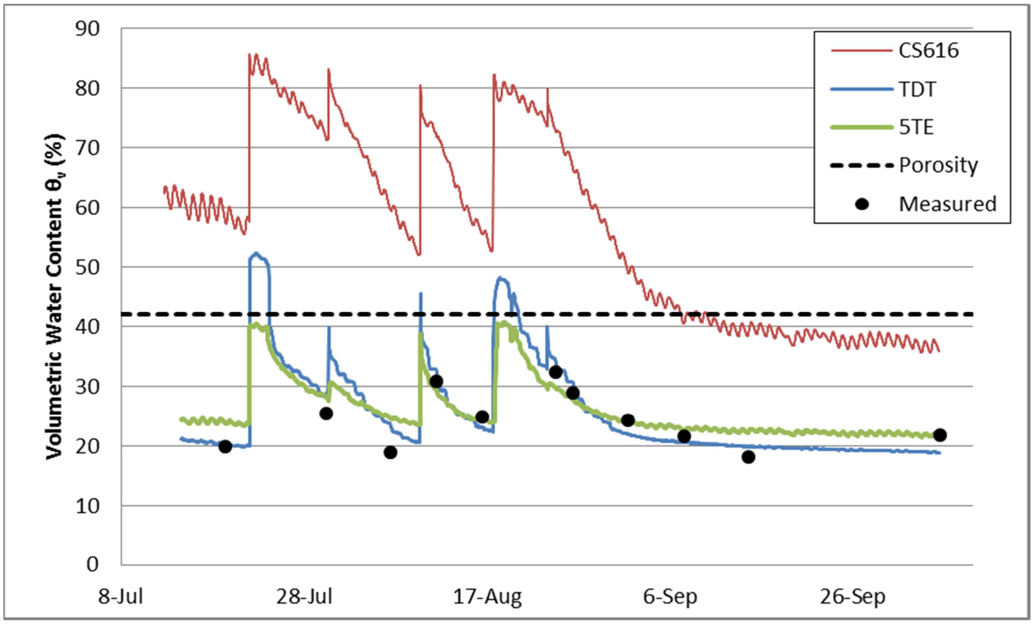

Figure B - 1. Graphical comparison of the Factory-based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green) Sensors in Treatment 2, Site A (sandy clay loam)

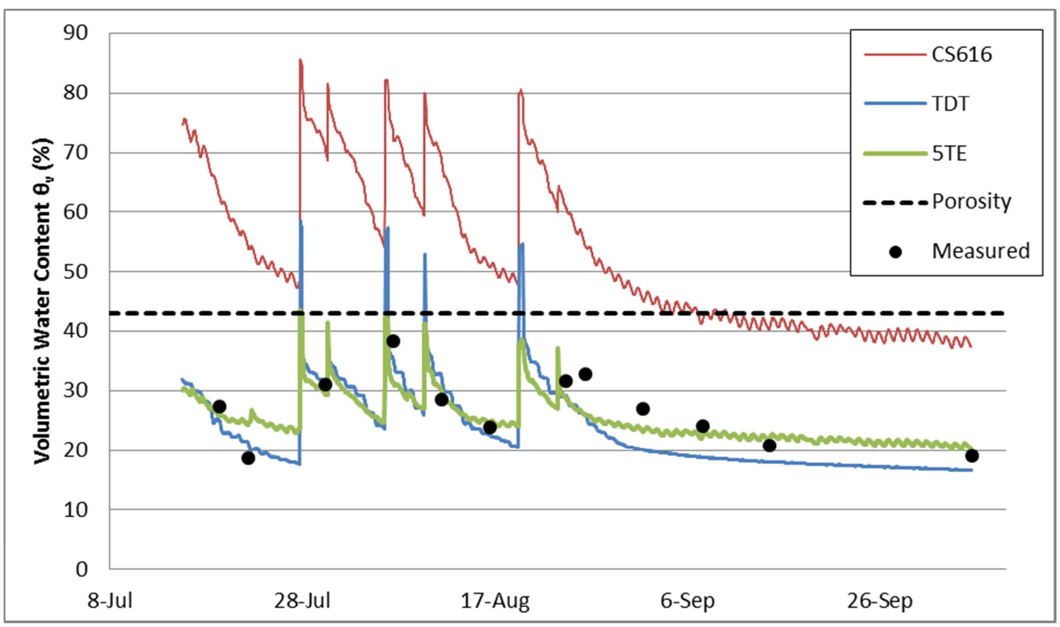

Figure B - 2. Graphical comparison of the Factory-based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green)Sensors in Treatment 3, Site A (sandy clay loam)

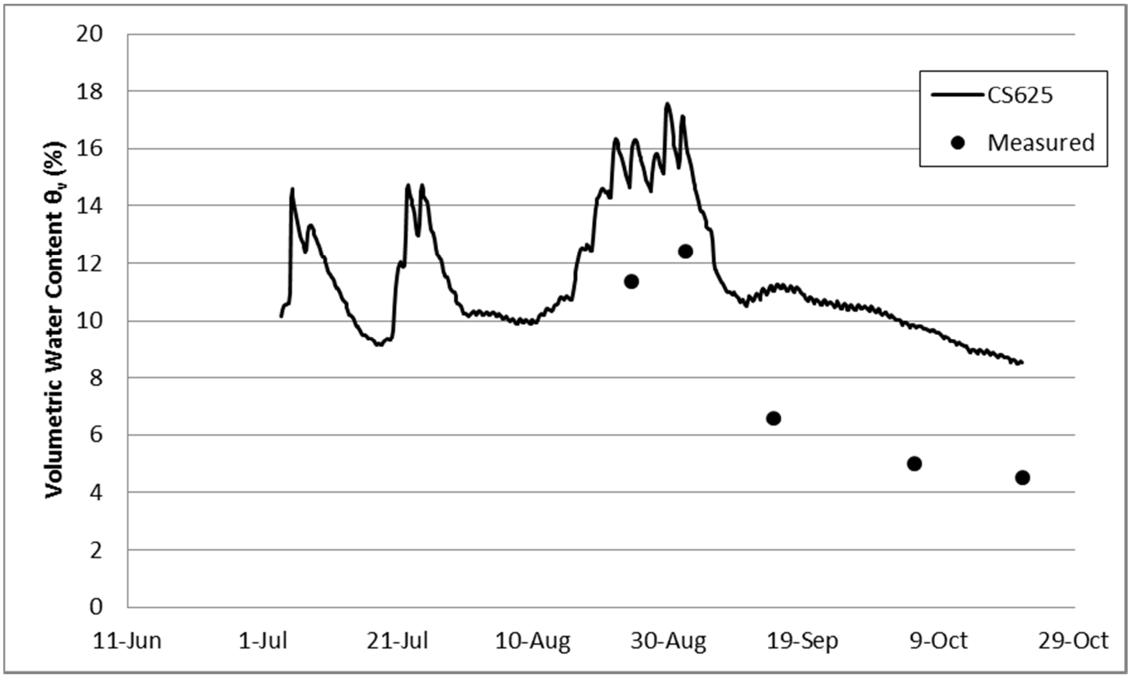

Figure B - 3. Graphical comparison of the Factory-based Calibration of θ_v (%) for the CS625 Sensor at Site B (loamy sand), at the 30-cm Depth

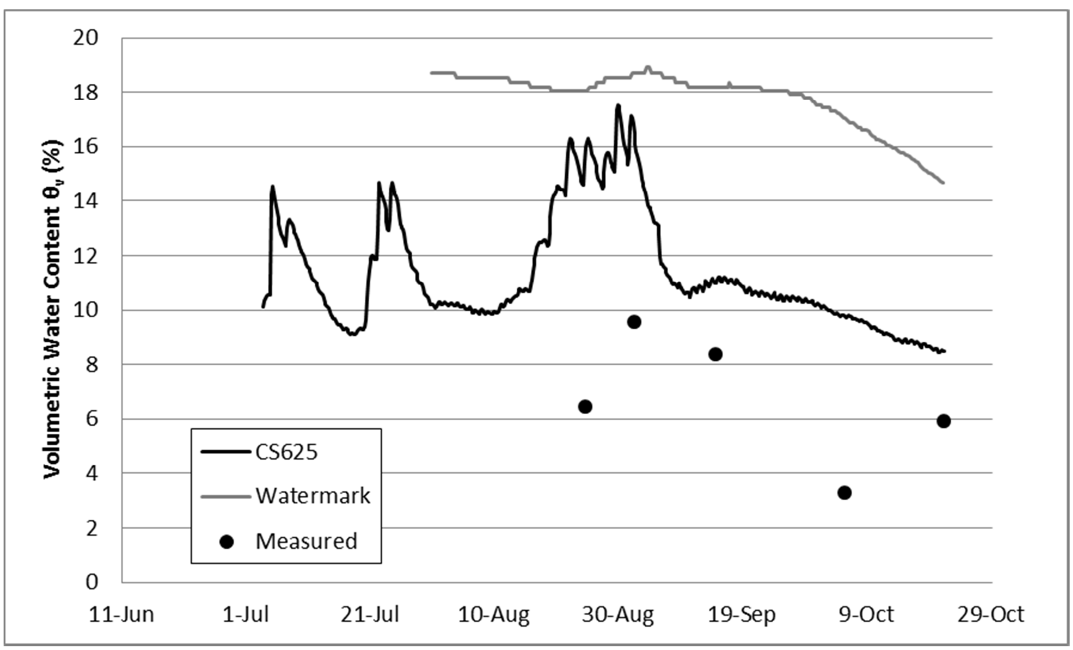

Figure B - 4. Graphical comparison of the Factory-based Calibration of θ_v (%) for the CS625 (black) and Watermark (gray) Sensors at Site B (loamy sand), at the 91-cm Depth

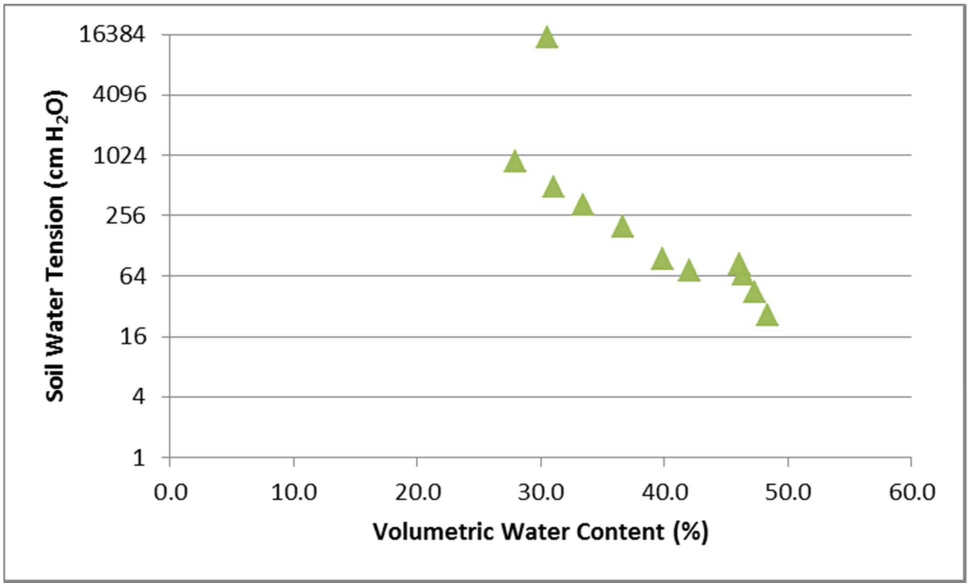

Figure B - 5. Soil Water Release Curves Developed from Laboratory Pressure Chamber Tests using Repacked Soil Cores from Site A (sandy clay loam)

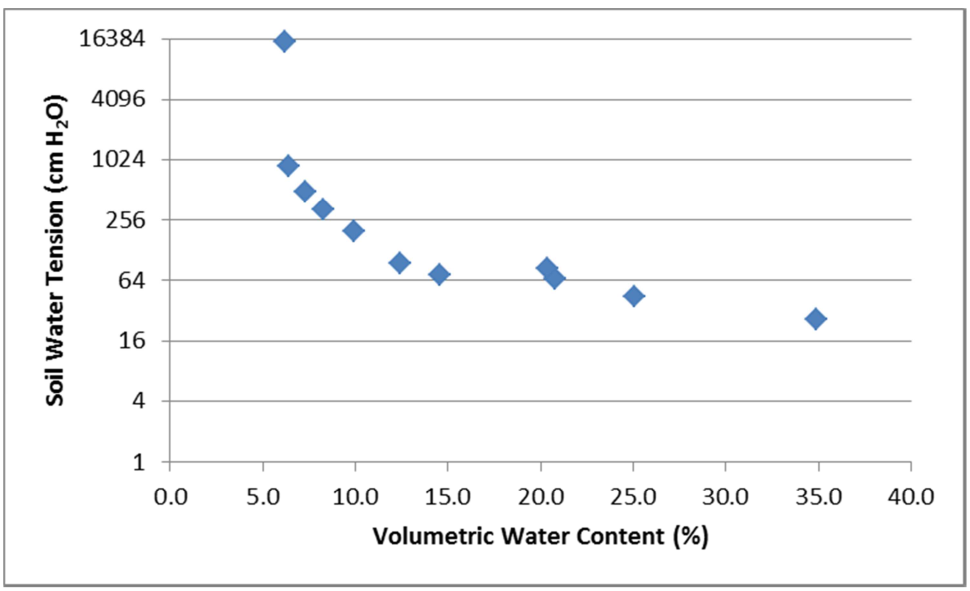

Figure B - 6. Soil Water Release Curves Developed from Laboratory Pressure Chamber Tests using Repacked Soil Cores from Site B (loamy sand)

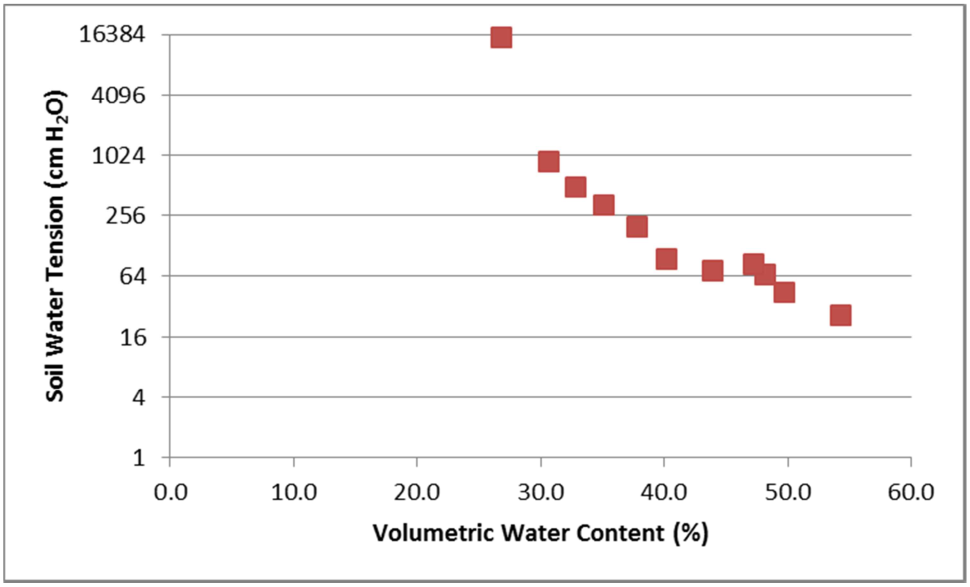

Figure B - 7. Soil Water Release Curves Developed from Laboratory Pressure Chamber Tests using Repacked Soil Cores from Site C (clay loam)

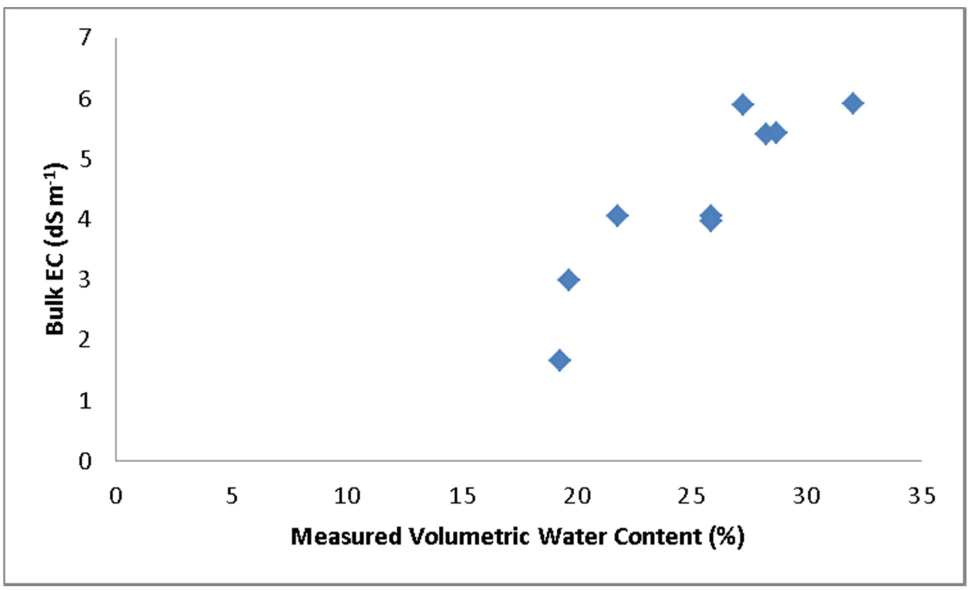

Figure B - 8. Bulk Soil EC Measured by the TDT sensor vs. Volumetric Water Content of the Clay Loam (Site C) in the Laboratory

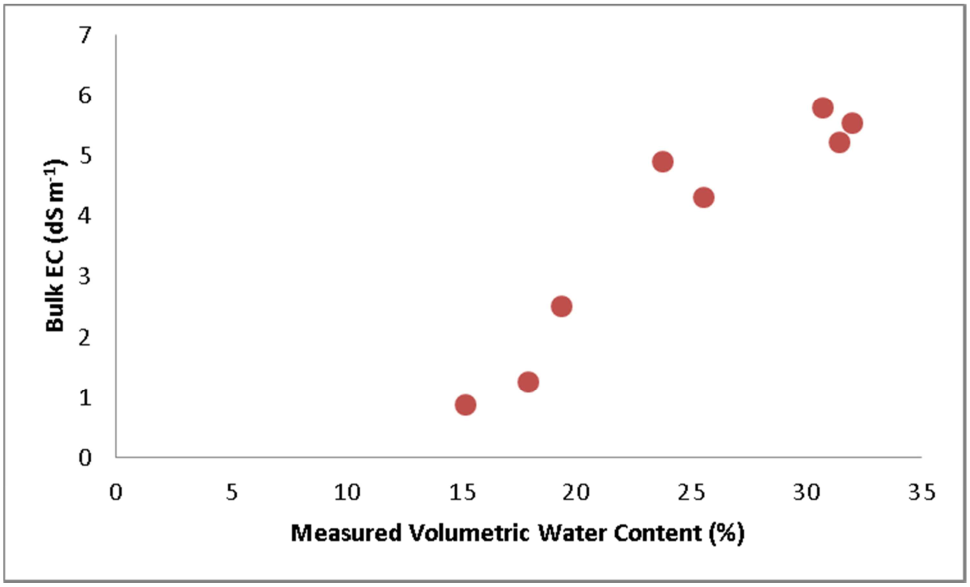

Figure B - 9. Bulk Soil EC Measured by the 5TE sensor vs. Volumetric Water Content of the Sandy Clay Loam (Site A) in the Laboratory

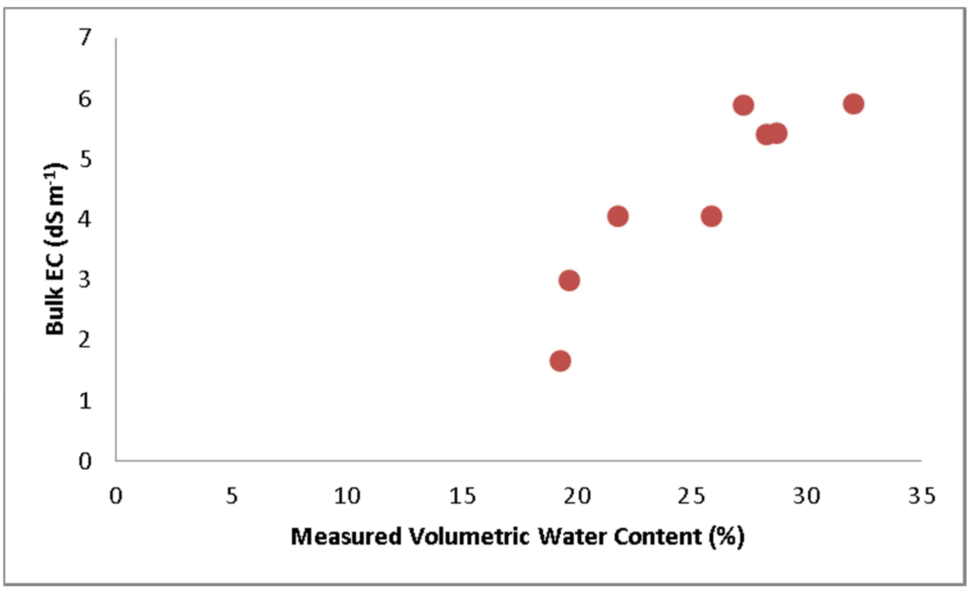

Figure B - 10. Bulk Soil EC Measured by the 5TE sensor vs. Volumetric Water Content of the Clay Loam (Site C) in the Laboratory

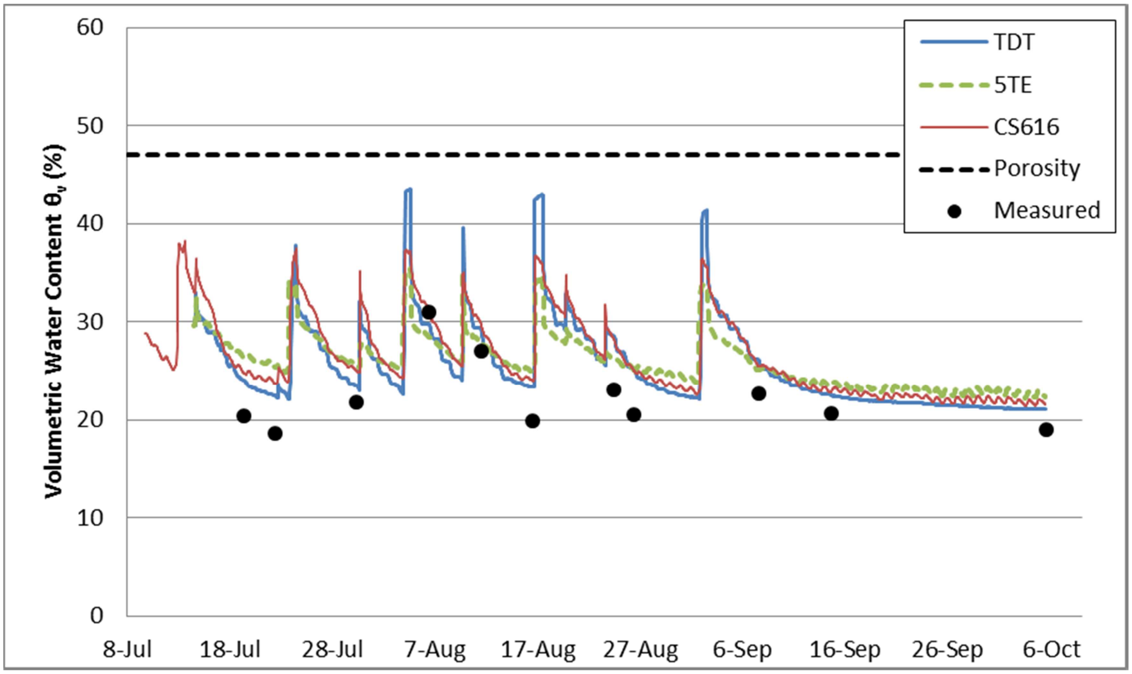

Figure B - 11. Graphical Comparison of the Laboratory-Based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green) Sensors Installed in Treatment 1 at Site A (sandy clay loam)

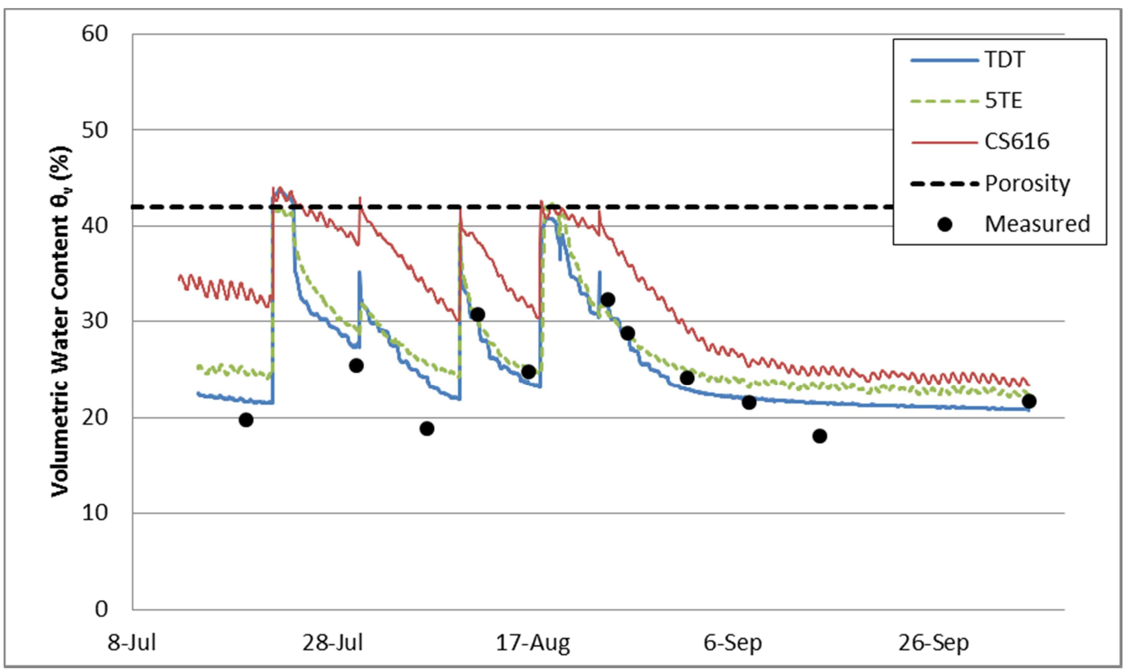

Figure B - 12. Graphical Comparison of the Laboratory-Based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green) Sensors Installed in Treatment 2 at Site A (sandy clay loam)

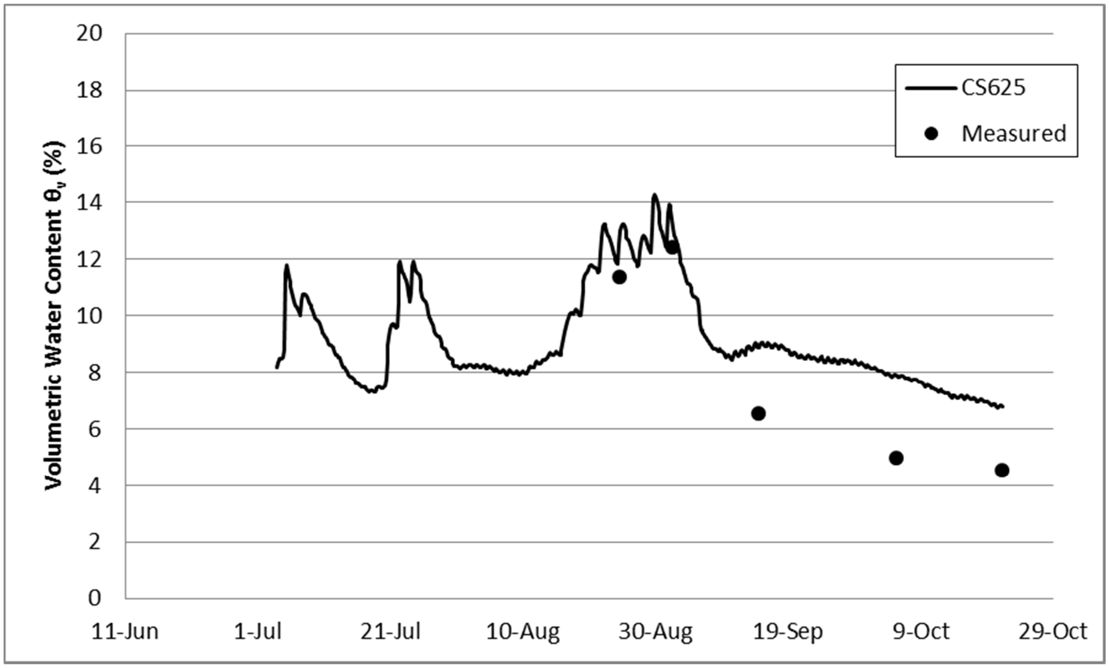

Figure B - 13. Graphical comparison of the Laboratory-based Calibration of θ_v (%) for the CS625 Sensor at Site B (loamy sand), at the 30-cm Depth

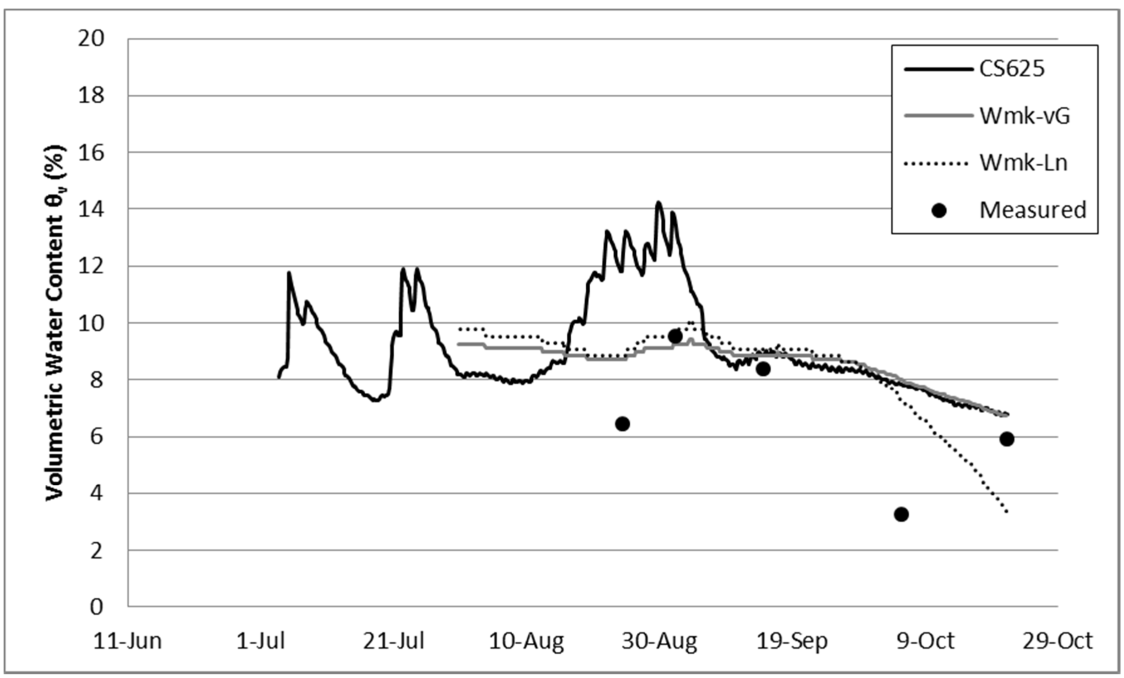

Figure B - 14. Graphical comparison of the Laboratory-based Calibration of θ_v (%) for the CS625 (black) and Watermark (gray-solid and black-dotted) Sensors at Site B (loamy sand), at the 91-cm Depth

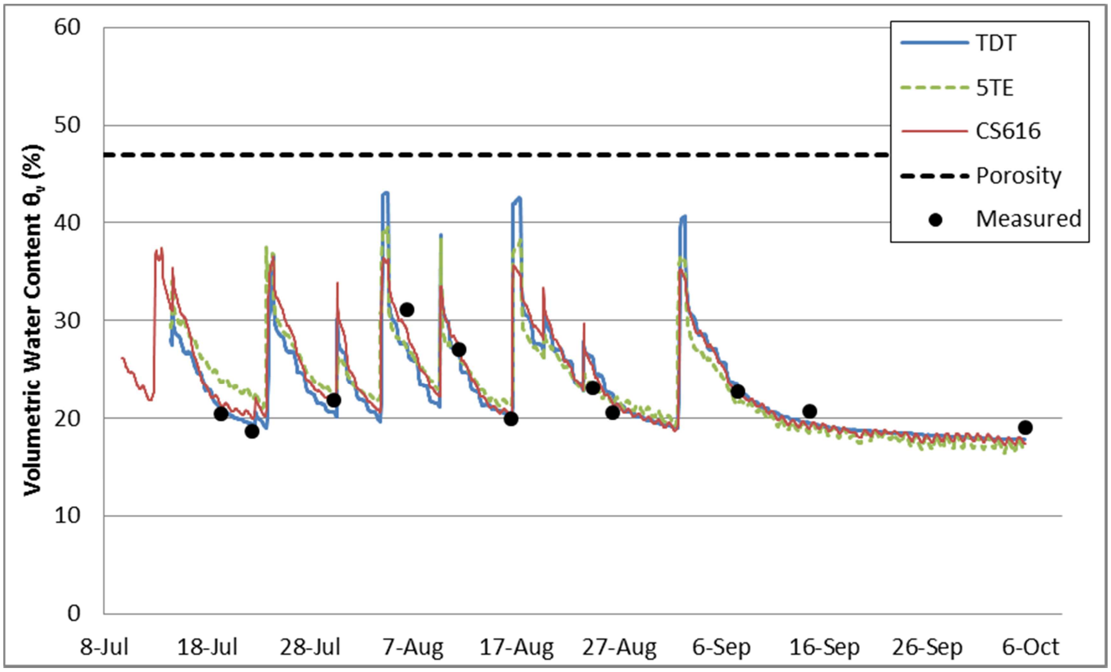

Figure B - 15. Graphical Comparison of the Field-Based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green)Sensors Installed in Treatment 1 at Site A (sandy clay loam)

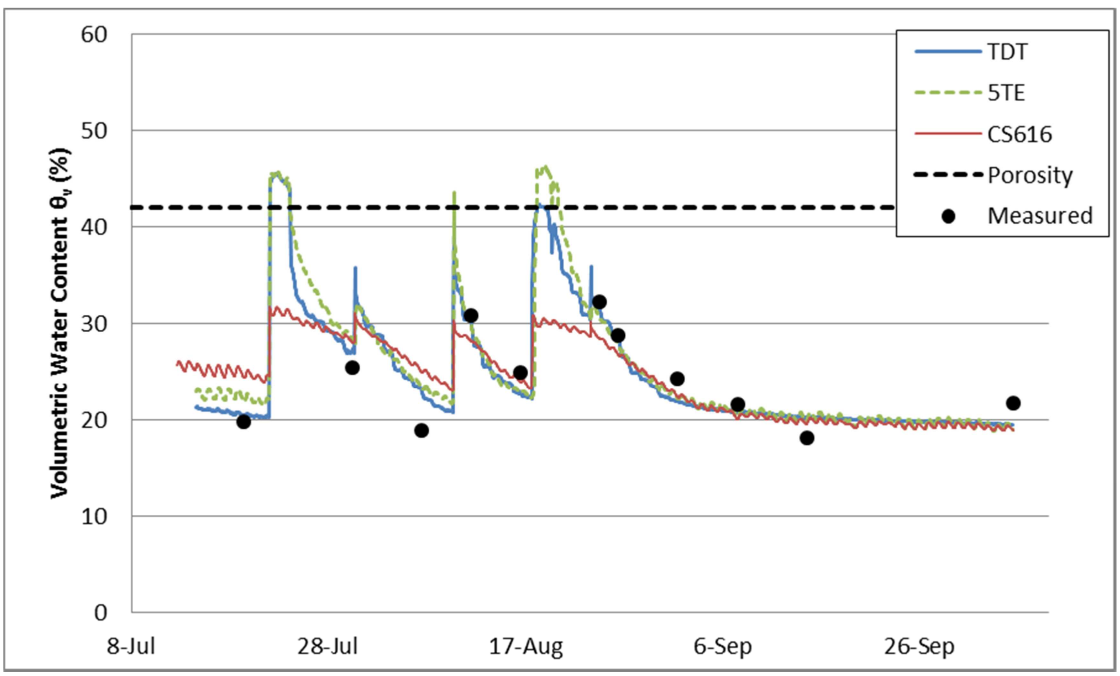

Figure B - 16. Graphical Comparison of the Field-Based Calibration of θ_v (%) for the CS616 (red), TDT (blue), and 5TE (green)Sensors Installed in Treatment 2 at Site A (sandy clay loam)

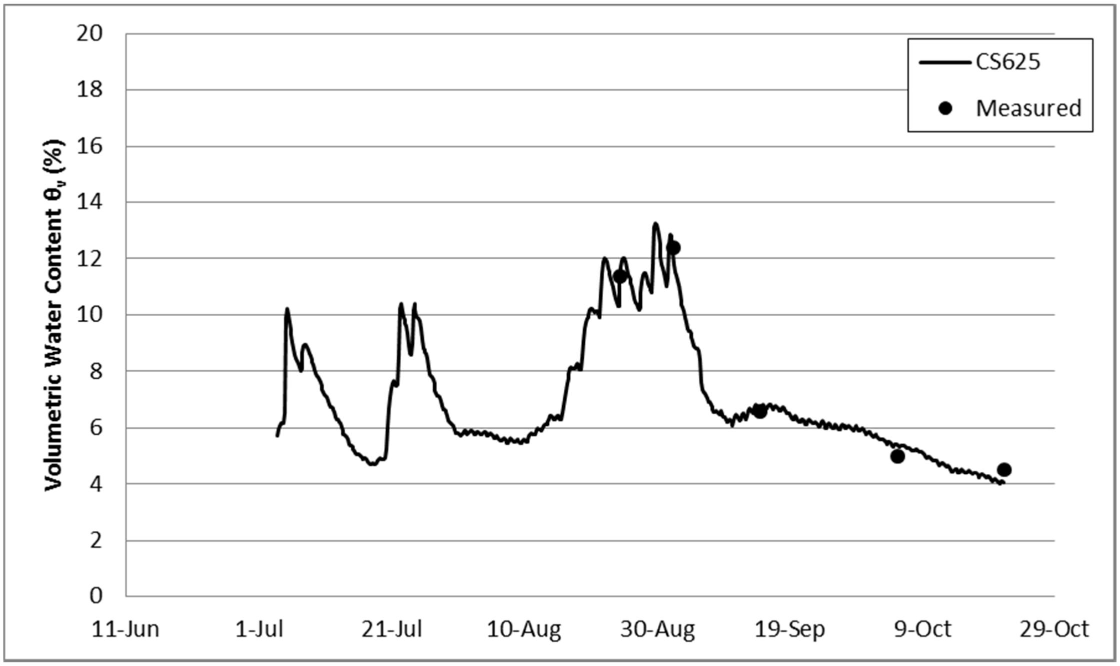

Figure B - 17. Graphical comparison of the Field-based Calibration of θ_v (%) for the CS625 Sensor at Site B (loamy sand), at the 30-cm Depth

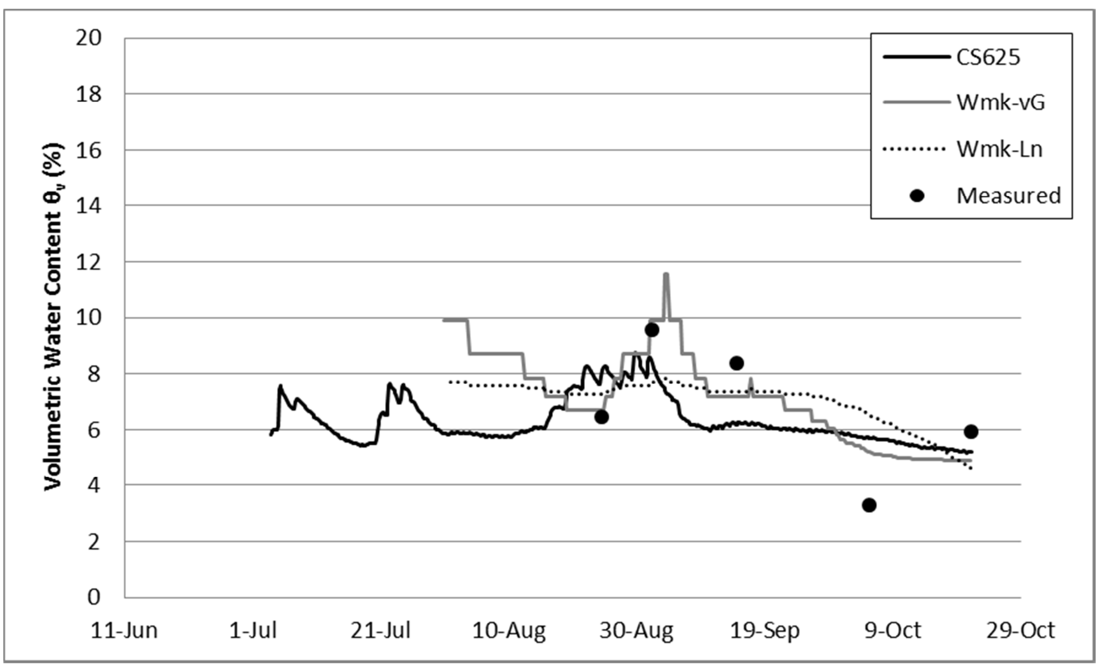

Figure B - 18. Graphical comparison of the Field-based Calibration of θ_v (%) for the CS625 (black) and Watermark (gray-solid and black-dotted) Sensors at Site B (loamy sand), at the 91-cm Depth