PERFORMANCE EVALUATION OF TDT SOIL WATER CONTENT AND WATERMARK SOIL WATER POTENTIAL SENSORS

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ABSTRACT

This study evaluated the performance of digitized Time Domain Transmissometry (TDT) soil water content sensors (Acclima, Inc., Meridian, ID) and resistance-based soil water potential sensors (Watermark 200, Irrometer Company, Inc., Riverside, CA) in two soils. The evaluation was performed by comparing volumetric water content (θ_v) data collected in the laboratory and in fields near Greeley, CO, with values measured by the sensors. Calibration equations of θ_v were then developed based on the laboratory and field data. Statistical targets to determine accuracy of the equations were ±0.015 $m^3\ m^{-3}$ mean bias error and a root mean square error of less than 0.020 $m^3\ m^{-3}$.

Under laboratory and field conditions, the factory-based calibrations of θ_v did not consistently achieve the required accuracy for either sensor. Field tests indicated that using the calibration equation developed in the laboratory to correct data obtained by TDT and Watermark sensors in the field at Site A (sandy clay loam) was not consistently accurate. Using the laboratory equations developed for the Watermark sensors at Site B (loamy sand) accurately measured θ_v.

Field tests found that a linear calibration of the TDT sensors (and a logarithmic calibration for the Watermark sensors) could accurately correct the factory calibration of θ_v in the range of permanent wilting point (PWP) to field capacity (FC). Furthermore, the van Genuchten (1980) equation was not significantly more accurate than the logarithmic equation, and the additional work of deriving the former equation did not seem worthwhile, within the range of soil water contents analyzed.

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 soil water content sensors to closely monitor a wide range of field soil water content conditions. These measurements can potentially be used

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to accurately determine irrigation amounts and timing. Most soil water content sensors are a simple, cost-effective way to closely monitor soil water conditions in the crop root zone. Using these sensors, an irrigation manager can determine irrigation timing and amount. Irrigations can then be scheduled whenever the soil water content is depleted to a management allowed level (previously-set critical level).

Soil water content sensors are gaining increased 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 potential sensors to farmers throughout rural Afghanistan (Kapinos, 2006). Yet Hignett and Evett (2008) 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 them in specific soil types.

This study evaluates the performance of digitized Time Domain Transmissometry (TDT) soil water content sensors (Acclima, Inc., Meridian, ID) and resistance-based (Watermark 200, Irrometer Company, Inc., Riverside, CA) soil water potential sensors. A handful of studies have been performed on these sensors, but few have been conducted for particular soils in the state of Colorado. Performance evaluations and specific calibrations have not been carried out on irrigated (surface and sprinkler) coarse-loamy to silty-clay soils in eastern Colorado. It is hypothesized that the accuracy of the sensors in these soils will be different than the results found by the sensor manufacturers. Hignett and Evett (2008) warn that 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.” In the field, though, factors such as rocks, roots, and variations in clay content, temperature and salinity may mean that “the manufacturer’s calibration is rarely applicable.”

Therefore, a thorough evaluation and the development of a family of soil-specific sensor calibration curves are highly desirable. These can improve farmers’ abilities to track soil water status and therefore improve irrigation water monitoring and irrigation scheduling. The result will translate into water savings, improved crop yields, and protection of groundwater from potential agro-chemical contamination.

MATERIALS AND METHODS

This study took place during the 2010 growing season and included soils from two agricultural fields in eastern Colorado. Laboratory and field tests were performed on the TDT soil water content and Watermark soil water potential sensors between mid-July and early-October, 2010. The first field was an experimental field cooperatively operated by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS), Regenesis Management Group, and Colorado State University (CSU). Corn was grown at this location and was irrigated using furrows. This field is located near the City of Greeley airport and is hereafter referred to as Site A. The second field was a commercially-operated alfalfa field near La Salle, with the research coordinated through the Central Colorado Water Conservation District (CCWCD). This field was irrigated using a center pivot sprinkler system and is hereafter referred to as Site B. Geographic coordinates, bulk density and soil texture for the soils at each site are presented in Table 1. Bulk density was obtained using a Madera Probe (Precision Machine, Inc., Lincoln, NE). The porosity was estimated using the sampled bulk density from each field and an assumed particle density of 2.65 g/cm^3. Soil textures were determined by a particle size analysis (Hydrometer Method; Gavlak, et al., 2003).

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

Soil	Lat. (N)	Long. (W)	ρ_b (g/cm^3)	φ (%)	Sand (%)	Silt (%)	Clay (%)	Class
A	40°26’	104°38’	1.46	45	65	10	25	Sandy clay loam
B	40°15’	104°40’	1.68	37	85	3	12	Loamy sand

Factory Calibrations

The TDT soil water content sensor is pre-calibrated by the sensor manufacturer, which enables it to give a direct reading of volumetric soil water content (θ_v), soil temperature (°C), and electrical conductivity (EC, dS/m). The Acclima (2010) states volumetric water content accuracy of ±1% (full scale) under temperature conditions of 0.5 to 50 °C and bulk EC of 0 to 3 dS/m. Laboratory and field tests were conducted to test this claim of accuracy.

The Watermark sensor directly measures voltage excitation (in mV) which is converted to electrical resistance (in kOhms) through the datalogger’s internal program (Campbell Scientific, 2009). Soil water potential (SWP, kPa) is then estimated using the electrical resistance through another internal correction. The equations used in the dataloggers in Site A are shown in Equations 1 and 2.

$$R_s = V_r / (1 + V_r) \tag{1}$$

$$SWP = 7.407 * R_s / (1 - 0.018 * (T - 21)) - 3.704 \tag{2}$$

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 measured by the TDT sensor, and SWP (kPa) is the soil water potential. SWP is directly related to θ_v through water retention (or release) curves, which vary by soil type. The manufacturer of the Watermark sensor recommended relating the SWP 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, and Ley et al. (1994) noted that specific soils will deviate from these generalized relations.) This curve was generalized using equation 3.

$$\theta_v = \alpha X^{\beta} \tag{3}$$

where α and β are coefficients and X is the sensor-based soil water potential (millibars, mb). The α and β coefficients for the soil in Site A are 104.63 and -0.19, respectively, and coefficients for the soil at Site B were 38.14 and -0.14, respectively.

Laboratory Calibrations

Laboratory calibrations were performed using soil samples collected from the upper 0-30 cm layer from sites A and B from the locations shown in Figure 1.

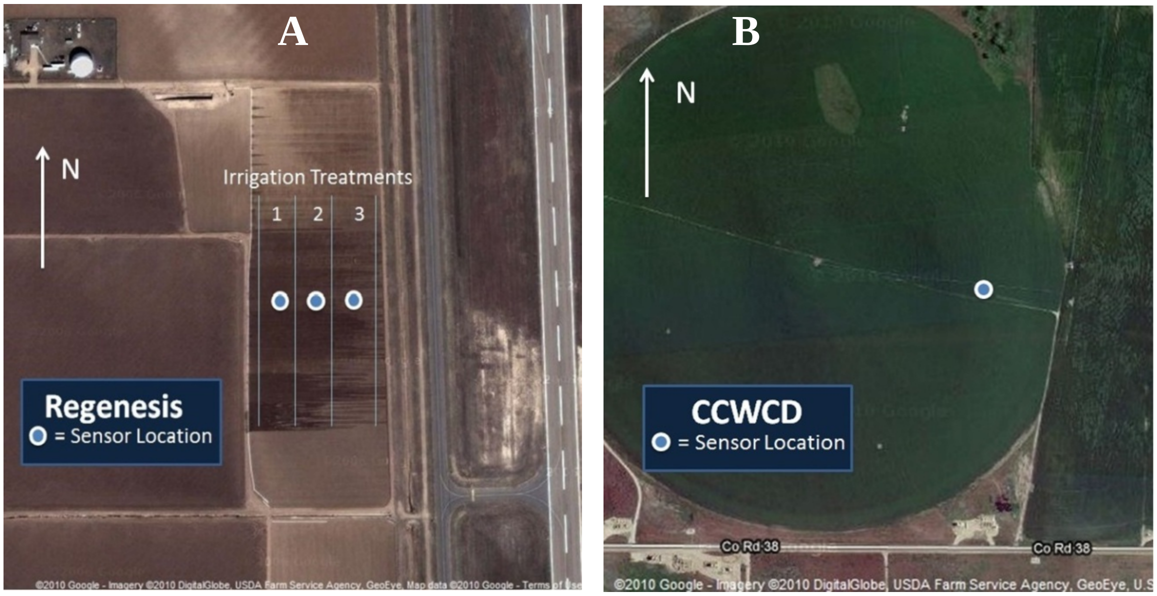

Figure 1. a) Approximate Locations of Sensors at Site A. (This field, near Greeley, CO, was split into three sections that received water in different amounts and frequencies.) b) Approximate Location of Sensors at Site B (La Salle, CO)

The laboratory calibration for the TDT sensor was based on the procedure proposed by Starr and Paltineanu (2002) and Cobos (2009). Soil collected from each field was air-dried until it could pass through a 2-mm sieve. It was then packed in a 19 L container to approximate field bulk density. The sensor was then inserted vertically into the soil, and several sensor readings were taken over an interval of at least 20 minutes. After each sensor was read, gravimetric samples were taken from the container 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. 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 reached saturation.

A total of sixty data points (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 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. 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% (by volume) for Site A and 7 to 16% for Site B. Using these estimates, the range of water contents in the laboratory studies fully covered the PWP to FC range for each soil, but in no soil was saturation achieved.

A linear calibration equation was developed for each soil by plotting the probes' readings versus the volumetric water content derived from the gravimetric method. These equations were developed using Microsoft Excel® Regression Analysis, based on the sensor-based θ_v. They take the form of equation (4, below.

$$\theta_v = \alpha_0 X + \alpha_1 \tag{4}$$

where *α* is a coefficient and *X* is the sensor-based θ_v (dimensionless). During these tests, the TDT sensor registered bulk EC in the range of 0.00 - 1.60 dS/m (0.69 dS/m average) in the soil from Site A and never registered a bulk EC reading in the soil from Site B. The soil temperature was nearly constant (~21 °C) throughout the entire study.

The laboratory calibration procedure using the Watermark sensor was different from that of the TDT because water tension 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 buckets of different water contents. One Watermark sensor was placed in each bucket and left for an average of three days to equilibrate with the soil. Gravimetric samples were then taken from each bucket, 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 and three samples (n=3) were used in the analysis of the soil from Site B.

Two types of calibration equations were developed by plotting θ_v versus the SWP sensor output. The logarithmic equation is shown in equation 5 below.

$$\theta_v = \alpha \ln|X| + \delta \tag{5}$$

where *α* and *δ* are coefficients and *X* is the sensor-based soil water tension (millibars, mb).

The van Genuchten (1980) equation was also used to relate the sensor-based SWP to measured θ_v, shown in equation 6.

$$\theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^{1-\frac{1}{n}}} \tag{6}$$

where θ_s is the saturated soil water content, θ_r is the residual soil water content, *h* is the absolute value of the soil water tension (cm H_2O), and *α* (cm^{-1}) and *n* 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 assumed porosity at each location.

However, θ_r was assumed for each soil using the values recommended by Schaap & Leij (1998): 0.063 and 0.079 for the sandy clay loam (Site A) and loamy sand (Site B), 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-sampled θ_v.

Field Calibration

During the summer of 2010, TDT and Watermark sensors were installed at Site A. This site had three differing irrigation treatments, as shown in Figure 1. Each treatment contained one TDT sensor and treatment 1 had one Watermark sensor. The sensors were installed under the crop row, roughly 0.2 m apart from each other, at a uniform depth of 10 cm below the average elevation of the row height and the furrow bottom. These sensors were installed by digging a shallow trench and inserting the sensors horizontally into the wall, then backfilling the trench. Data collection for the sensors began in mid-July.

At Site B, one Watermark sensor was placed at 61 cm and another at 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 thermocouple was installed 30 cm beneath the surface to monitor soil temperature (°C). The Watermark and temperature sensors came into service in the end of July of 2010.

From the time of installation until the first week of October, 2010, automated sensor readings were recorded at Site A every five minutes. At Site B automated readings were recorded every eight hours, until the third week of October, 2010. Readings were compared with periodic gravimetric measurements, totaling eleven from each irrigation treatment in Site A and five at each depth from Site B.

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 ranged from 15 - 22 °C in irrigation treatment 1, 15 - 24 °C in treatment 2, and 16 - 30 °C in treatment 3. Bulk 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.

Sensor-specific linear calibration equations were developed for the TDT sensors based on the θ_v read by the sensor. This equation is shown in equation 4, above. For the Watermark sensors, the logarithmic and van Genuchten (1980) equations (shown in equations 5 and 6, above) were derived.

Statistical Analysis

Four statistical measures were computed to compare and evaluate each model-predicted (*P*) equation 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 7), root mean square error (RMSE; Equation 8), and index of agreement (κ; Equation 9) as defined by Willmott (1982).

$$\mathrm{MBE} = n^{-1} \sum_{i=1}^{n} (P_i - O_i) \tag{7}$$

$$\mathrm{RSME} = \left[n^{-1} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{0.5} \tag{8}$$

$$\kappa = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)}{\sum_{i=1}^{n} \left(|P'_i| - |O'_i| \right)^2} \right] \tag{9}$$

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

Hignett and Evett (2008) 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 MBE under 2.0% and RMSE less than 3.5% fit this criterion. 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. The statistical values (see Table 2) 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), and overestimated by 6% in the loamy sand (Site B). However, the RMSE was greater than 3.5% in all soils, so the factory calibration did not meet the criteria for any soil. These less-favorable values may be attributed to a lower number of samples or problems with the sandy soil not packing correctly around the sensor's metal loop. Under no laboratory tests did the Watermark sensors achieve the required accuracy.

Table 2. Comparison of the Factory Calibration-Based θ_v (%) with Laboratory Measurements of θ_v (%) for the Different Soils in the Study

Soil Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT					
Sandy clay loam	60	0.94	-1.2	3.9	0.95
Loamy sand	6	0.98	6.1	6.7	0.75
Watermark					
Sandy clay loam	7	0.93	20.5	21.1	0.32
Loamy sand	3	0.65	8.2	8.8	0.61

In the field tests, the MBE and RMSE of applying the factory calibration to the data from the TDT sensor in treatment 2 were within the limits (0.7% and 2.3%, respectively), but the MBE's in treatments 1 and 3 were 2.7% and $^{-}$2.2%, respectively. The Watermark's factory calibration overestimated θ_v in the three treatments at Site A by 11.2% and at both depths at Site B by 10% (Table 3).

Table 3. Comparison of the Factory Calibration-based θ_v (%) with Field Measurements of θ_v (%) at Sites A and B

Soil Type	Location / Depth (cm)	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT						
Sandy clay loam (A)	1	11	0.73	2.1	3.0	0.85
	2	11	0.83	1.8	2.9	0.92
	3	12	0.77	-1.8	3.3	0.90
Watermark						
Sandy clay loam (A)	1	15	0.87	11.2	12.6	0.48
Loamy sand (B)	61	5	0.85	10.5	10.5	0.27
	91	5	0.33	10.4	10.6	0.32

Laboratory Calibration Evaluation

Soil-specific calibration equations developed in the laboratory yielded high levels of accuracy, well within the targeted statistical parameters, for both sensors. The MBE, RMSE and κ parameters, shown in Table 4, were each better than the parameters representing the factory calibrations. In both soils, the logarithmic and van Genuchten (1980) equations developed for the Watermark sensor produced similar levels of accuracy. In the soil from Site B, both equations developed for the Watermark sensor had higher RMSE values than in the soil from Site A, most likely due to the smaller sample size.

Table 4. Comparison of the Laboratory-based Calibration of θ_v (%) versus Laboratory Measurements of θ_v (%)

Soil Type	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT						
Sandy clay loam	Linear	60	0.94	0.0	1.9	0.98
Loamy sand	Linear	6	0.98	0.0	0.7	0.99
Watermark						
Sandy clay loam	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

Table 5 displays the results of comparing the use of the laboratory-derived calibration equations with field-measurements of θ_v (%). The large MBE (> ±2.0%) and RMSE (> 3.5%) values indicated that the laboratory-derived calibration equations for the both sensors were not consistently accurate. 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. The laboratory equations for the Watermark sensor at Site A 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. 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. 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 5. Comparison of the Laboratory-based Calibration of θ_v (%) versus Field Measurements of θ_v (%) at Sites A and B

Soil Type	Location / Depth (cm)	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT							
Sandy clay loam (A)	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
Watermark							
Sandy clay loam (A)	1	Logarithmic	15	0.81	-3.0	3.6	0.82
		van Genuchten	15	0.90	-2.6	2.8	0.87
Loamy sand (B)	61	Logarithmic	5	0.83	1.3	1.5	0.87
		van Genuchten	5	0.88	1.2	1.6	0.78
	91	Logarithmic	5	0.30	0.6	2.4	0.73
		van Genuchten	5	0.38	1.6	2.4	0.61

Field Calibration Evaluation

The field-based calibration equations developed for both sensors, within the PWP to FC range of water contents, showed higher levels of accuracy than the factory- or laboratory-derived equations. As shown in Table 6, the RMSE values were consistently low (and κ values high) for both sensors in both fields, and well within the ideal statistical targets. This also agrees with research conducted by Dr. Steve Evett (Personal Communication, 2010), that “a linear soil-specific calibration would suffice to correct [the TDT] to be useful in scheduling [irrigations] according to” management allowed depletion. When comparing the complex van Genuchten (1980) equation with the simpler logarithmic equations, it appears that the van Genuchten (1980) calibration equation is trivially more accurate (RMSE decrease by 0.5%) than the logarithmic calibration equation.

Table 6. Comparison of the Field-based Calibration of θ_v (%) versus Field Measurements of θ_v (%) at Sites A and B

Soil Type	Location / Depth (cm)	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT							
Sandy clay loam (A)	1	Linear	11	0.73	0.0	1.9	0.91
	2	Linear	11	0.83	0.0	1.9	0.95
	3	Linear	12	0.74	0.0	2.4	0.93
Watermark							
Sandy clay loam (A)	1	Logarithmic	15	0.81	0.0	1.6	0.94
		van Genuchten	15	0.86	0.0	1.4	0.96
Loamy sand (B)	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

An analysis of the factory-, laboratory-, and field-derived calibrations of θ_v (%) is not complete without a visual inspection of the data in graphical form. In Figure 2, the derived equations are applied to the TDT sensor in treatment 1 at Site A. This field was surface irrigated with application times exceeding 12 hours, so it is assumed that the soil around the sensors reached saturation. Assuming a porosity of 45%, the TDT's factory calibration measured impossible levels of water content, while the laboratory- and field-derived equations indicated saturation. It is evident in Figure 2 that the TDT responded well to small amounts of rainfall (for example, ≈3 mm on August 19th), and all equations measured water content levels similar to the gravimetric field measurements.

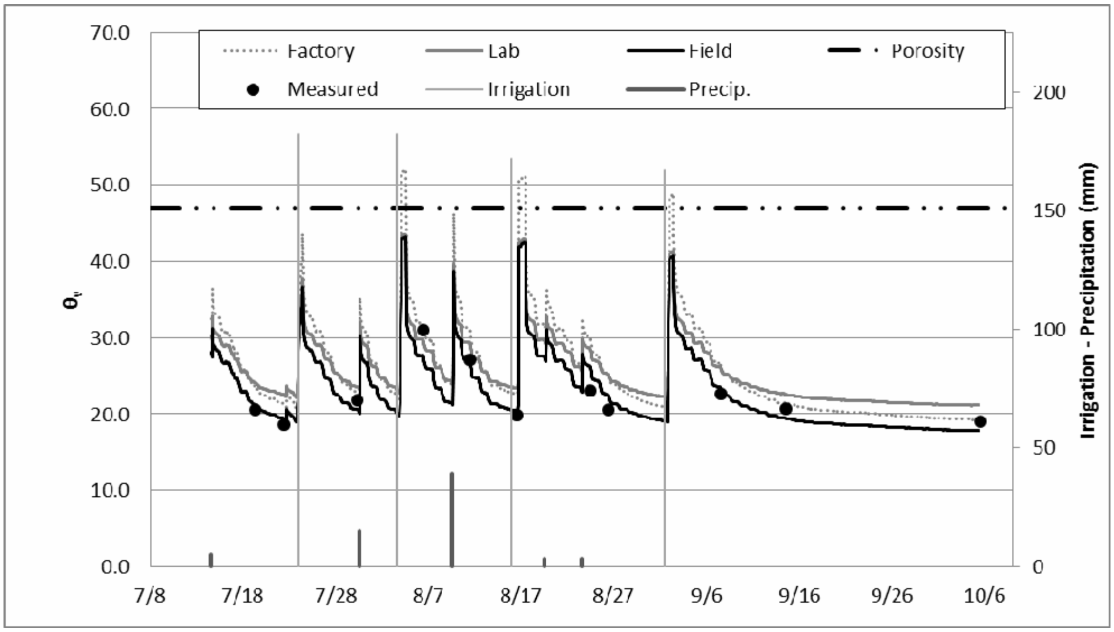

Figure 2. TDT Calibration Equations for Site A, Treatment 1

In Figure 3, it is clear that none of the Watermark's calibration equations adequately represented the full range of water contents. The Watermark's factory calibration reported water contents much greater than porosity, and the other equations did not report saturation during irrigations. It is assumed that if gravimetric measurements would have been made immediately after irrigations ended, the derived equations also would have reported saturated conditions. The field measurements in Figure 3 show that the field-derived van Genuchten (1980) equation was the best in measuring water contents in the ranged of PWP to FC. This coincides with the data presented in the previous tables.

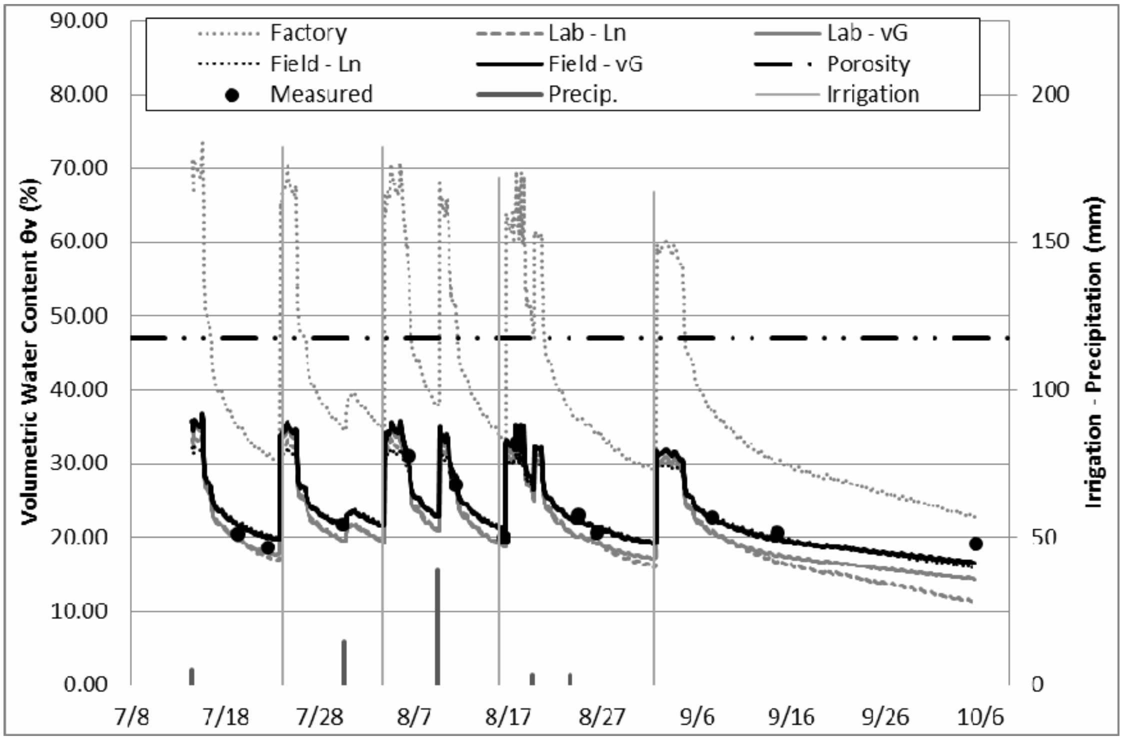

Figure 3. Watermark Calibration Equations for Site A, Treatment 1

CONCLUSIONS

This research evaluated the performance of Watermark soil water potential and TDT soil water content sensors under laboratory and field conditions in sandy clay loam and loamy sand soils. Measured soil water content/potential values were compared with corresponding values derived from gravimetric samples, ranging in water content from permanent wilting point (PWP) to field capacity (FC). Linear calibration equations were developed for the TDT sensor. For the Watermark sensor, calibration equations taking the form of van Genuchten (1980) and logarithmic calibration equations were developed. These equations were compared against each other and with factory-recommended calibrations. Statistical targets for these tests were ±2% (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 on the soils from Sites A and B, we found that the TDT's factory-recommended calibration was not suitable for either soil. Laboratory tests on the same soils also found that the Watermark's factory-recommended calibration overestimated θ_v by 10-11%, for both soils. The laboratory data was used to develop various calibration equations that improved the accuracy of the factory calibrations, and all equations reached the required statistical parameters.

During the summer of 2010, TDT 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 against periodic gravimetric samples. At Site A, 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 laboratory calibrations for the TDT sensors were not consistently accurate in every treatment. At Sites A and B, the Watermark's factory-recommended equations overestimated θ_v by 10-11%. The Watermark's laboratory-derived equations underestimated the field-measured θ_v (MBE: -3.8%) at Site A, but at Site B, the laboratory-derived equations applied to the Watermark sensors were within the statistical goals.

Field-derived calibration equations developed for both sensors in the fields returned higher accuracy than the factory- or laboratory-derived equations. The RMSE for the TDT sensors at Site A were ≈2% and for the Watermark sensors RMSE ranged from 0.5% to 2.2% at both sites.

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