Proceedings of the 23rd Annual Central Plains Irrigation Conference, Burlington, CO., February 22-23, 2011
Available from CPIA, 760 N. Thompson, Colby, Kansas

PERFORMANCE EVALUATION OF SELECTED SOIL MOISTURE SENSORS

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

Jordan L. Varble
Research Assistant
Colorado State University
Fort Collins, Colorado
Voice: 970-491-1470
Fax: 970-491-7727
Jordan.varble@colostate.edu

Allan A. Andales
Assistant Professor
Colorado State University
Fort Collins, Colorado
Voice: 970-491-6516
Fax: 970-491-0564
Allan.Andales@colostate.edu

ABSTRACT

Irrigation water management practices could greatly benefit from using soil moisture sensors that accurately measure soil water content or potential. Therefore, an assessment on soil moisture sensor reading accuracy is important. In this study, a performance evaluation of selected sensor calibration was performed considering factory- laboratory- and field-based calibrations. The selected sensors included: the Digitized Time Domain Transmissometry (TDT, Acclima, Inc., Meridian, ID) which is a volumetric soil water content sensor, and a resistance-based soil water potential sensor (Watermark 200, Irrometer Company, Inc., Riverside, CA). Measured soil water content/potential values, on a sandy clay loam soil, were compared with corresponding values derived from gravimetric samples. Under laboratory and field conditions, the factory-based calibrations for the TDT sensor accurately measured volumetric soil water content. Therefore, the use of the TDT sensor for irrigation water management seems very promising. Laboratory tests indicated that a linear calibration for the TDT sensor and a logarithmic calibration for the watermark sensor improved the factory calibration. In the case of the watermark, a longer set of field data is needed to properly establish its accuracy and reliability.

INTRODUCTION

Soil moisture is an important factor used in irrigated agriculture to make decisions regarding irrigation scheduling and for land managers making decisions concerning livestock grazing patterns, crop planting, and soil stability for agricultural machinery operations. Many methods of determining soil moisture have been developed, from simple manual gravimetric sampling to more sophisticated remote sensing and Time Domain Reflectometery (TDR) measurements. One common technique is to measure dielectric constant, that is, the capacitive and conductive parts of a soil’s electrical response. Through the use of appropriate calibration curves, the dielectric constant measurement can be directly related to soil moisture (Topp et al. 1980). However, there are several different types of sensors commercially available which present different levels of soil water content/potential readings' accuracy. Hignett and Evett (2008) indicated the following: *"in general, a manufacturer's calibration is commonly performed in a temperature controlled room, with distilled water and in easy to manage homogeneous soil materials (loams or sands) which are uniformly packed around the sensor. This calibration procedure produces a very precise and accurate calibration for the conditions tested. However, in field conditions variations in clay content, temperature, and salinity may affect the manufacturer's calibration."*

Sensor accuracy needs to be assessed in order to do a better job managing water and to realize the reliability of the sensor. In addition, appropriate sensor calibration curves can be developed during the sensor evaluation process.

This study evaluates the performance of a Digitized Time Domain Transmissometry (TDT) soil water content sensor developed by Acclima, Inc. (Meridian, ID), and of a resistance-based (Watermark 200, Irrometer Company, Inc., Riverside, CA) soil water potential sensor on a sandy clay loam soil from an agricultural field near Greeley, CO.

MATERIALS AND METHODS

This study took place during the 2010 corn growing season in eastern Colorado. The field was an experimental field cooperatively operated by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) and Colorado State University (CSU) near the City of Greeley, CO. Corn was grown at this location and was irrigated using furrows. Geographic coordinates, dry bulk density, porosity and soil texture of the soil can be found in Table 1. Bulk density was obtained using a Madera Probe (Precision Machine, Inc., Lincoln, NE). The porosity was estimated using the sampled bulk density from each field and an assumed particle density of 2.65 g/cm^3. Soil textures were determined in the Laboratory by a particle size analysis (Hydrometer Method; Gavlak, et al., 2003).

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

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

Factory Calibrations

The TDT soil water content sensor is provided with a calibration by the sensor manufacturer, which enables the sensor to give a direct reading of volumetric soil water content (θ_v), soil temperature (°C), and electrical conductivity (EC, dS/m). According to the Cut Sheet TDT soil moisture sensor (2010), the volumetric water content accuracy of the sensor is ±1% (full scale) under temperature conditions of 0.5 to 50 °C and 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 are shown as Equations 1 and 2.

$$R_s = V_r / (1 + V_r) \quad (1)$$

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

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 volumetric water content through curves for general soil types published by Ley et al. (2004). This curve was generalized using equation 3.

$$\theta_v = \alpha X^{\beta} \quad (3)$$

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 this study are 104.63 and -0.19, respectively.

__Laboratory Calibrations__

Laboratory calibrations were performed using soil samples collected from the upper 0-30 cm layer.
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 soil water content readings were taken every 20 minutes. After each sensor reading, soil gravimetric samples were taken from the container and were 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 field core soil samples (undisturbed soil structure). The soil from the container was then wetted with 500 mL of water and was mixed thoroughly. The above procedure was repeated several times, each time repacking the container, taking multiple readings and adding another 500 mL of water.

A total of sixty data points (n=60) were used in the analysis of the soil moisture. The volumetric water contents of the soil moisture samples ranged from 10.7 to 35.9%. Fangmeier et al. (2006) reported values of permanent wilting point (PWP) and field capacity (FC) for the same type of soil as the one used in this study as being 16 to 26% (by volume). Therefore, the range of soil water content sampled in the laboratory covered the PWP to FC range.

A linear calibration equation was developed by plotting the sensor probes' readings (θ_v_s) versus the volumetric water content derived from the gravimetric method (θ_v_g). The linear regression equations were developed using Microsoft Excel® Regression Analysis. The equations take the form of equation 4, below.

$$\theta_v\_g = \alpha_0 \, \theta_v\_s + \alpha_1 \qquad 4$$

where α_o is the slope of the of the curve while α_1 is the intercept of the curve with the Y-axis. θ_v_s is the sensor-based θ_v (dimensionless). During these tests, the average EC recorded by the TDT sensor was 0.69 dS/m. 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 can 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 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.

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

$$\theta_v\_g = \alpha \ln|X| + \delta \qquad 5$$

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

To assess the accuracy of the developed calibration equation 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.

<u>Field Calibration</u>

During July of 2010 TDT and Watermark sensors were installed at the study site. This site had three differing irrigation treatments and each treatment contained one TDT sensor and one Watermark sensor. In each irrigation treatment the sensors were installed under the crop row/bed, roughly 0.25 m apart from each other, at a depth of 10-12 cm below the average level of the corn beds. These sensors were installed by digging a shallow trench and inserting the sensors horizontally into the wall, then backfilling the trench. Data collection for each TDT sensor began in the mid July. Data collection for the Watermark sensor in treatment 1 also began in mid-July, while the sensors in treatments 2 and 3 began operating in the middle of September.

From the time of installation until the first week of October, 2010, automated sensor readings were recorded every five minutes. Readings were compared with periodic gravimetric measurements, totaling eleven from each irrigation treatment. Since the Watermark sensors in treatments 2 and 3 did not begin operating until September, only two gravimetric samples were collected for each treatment for these sensors.

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 (wet), oven-dried, and weighed again (dry). The gravimetric samples were then converted into θ_v using the dry soil bulk density field value. During the times of gravimetric field sampling, soil temperatures 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.

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 equation (equation 5) was derived. Generalized equations were developed to incorporate the readings from all of the Watermark sensors in that field.

<u>Statistical Analysis</u>

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 6), root mean square error (RMSE; Equation 7), and index of agreement (κ; Equation 8) as defined by Willmott (1982).

$$\mathrm{MBE} = n^{-1}\sum_{i=1}^{n}(P_i - O_i) \qquad 6$$

$$\mathrm{RSME} = [n^{-1}\sum_{i=1}^{n}(P_i - O_i)^2]^{0.5} \qquad 7$$

$$\kappa = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)}{\sum_{i=1}^{n}(|P_i'| - |O_i'|)^2}\right] \qquad 8$$

where n is the sample size, $P'_i = P_i - \bar{O}$, and $O'_i = O_i - \bar{O}$. 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 2.5% and RMSE less than 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

In general, under laboratory and field conditions, the factory-based calibrations of θ_v did not consistently achieve the required accuracy within the PWP to FC range of water contents. For the TDT sensor, the factory calibration performed well in most cases. For the Watermark sensors, on all tests the sensor did not achieve the required accuracy.

Table 2 and Table 3 show low MBE and RMSE and high κ values for the TDT sensor. This result indicates that the TDT's factory calibration was within the previously-described limits and thus performed very well. The MBE values for the Watermark's factory calibration in Table 2 show that this sensor overestimated measured θ_v in average 20.5±21.1% in the laboratory test. This is a large overestimation and in part it may be due to lack of appropiate equilibrium of water tension between the the sensor cap and soil during the three days that the probe was left in the container at a given soil water level.

Table 2. Comparison of the Factory Calibration-Based θ_v (θ_{v}_s, %) with Laboratory Measurements of θ_v (θ_{v}_g, %).

Soil Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	60	0.94	-1.2	3.9	0.95
Watermark	7	0.93	20.5	21.1	0.32

Table 3. Comparison of the Factory Calibration-based θ_v (θ_{v}_s, %) with Field Measurements of θ_v (θ_{v}_g, %).

Soil Type	Location	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	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	Composite*	15	0.87	11.2	12.6	0.48

*One equation represented readings from all field sensors.

However, in the field, the Watermark's factory calibration overestimation of θ_v was much less, i.e. 11.2±12.6% (Table 3). This seems to confirm that the Watermark sensor needed a longer time to attain equilibrium of soil water tension under laboratory conditions.

Laboratory Calibration

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.

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

Soil Type	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	Linear	60	0.94	0.0	1.8	0.98
Watermark	Logarithmic	7	0.94	0.0	1.1	0.98

Table 5 displays the results of comparing the use of the laboratory-derived calibration equations with field-measurements of θ_v (θ_v_g, %). For both sensors, applying the laboratory-derived equations to the field sensors' data yielded larger MBE, RMSE, and smaller κ values than when compared to measured data at the laboratory (in Table 4). With respect to the TDT sensor, the laboratory equations resulted in levels of accuracy that were very similar to the factory calibrations. However, applying the soil-specific calibration equation developed in the laboratory to the Watermark sensor installed in the field resulted in an average underestimation of 4.3±5.0% (Table 5).

Table 5. Comparison of the Laboratory-based Calibration of θ_v (θ_v_s, %) versus Field Measurements of θ_v (θ_v_g, %)

Soil Type	Location	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	1	Linear	11	0.73	2.0	2.8	0.83
	2	Linear	11	0.83	1.8	2.6	0.90
	3	Linear	12	0.77	-1.8	3.1	0.89
Watermark	Composite*	Logarithmic	15	0.79	-4.3	5.0	0.73

*One equation represented measurements from all field sensors.

Field Calibration

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 and errors well within the ideal statistical targets.

Table 6. Comparison of the Field-based Calibration of θ_v (%) versus Field Measurements of θ_v (%).

Soil Type	Location / Depth (cm)	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	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	Composite*	Logarithmic	15	0.81	0.0	1.6	0.94

*One equation represented measurements taken with all field sensors.

The different derived equations were applied to the field data from the TDT sensor in treatment 1, results are shown in Figure 1. This treatment was fully irrigated (no crop water stress). It is assumed that right after irrigation the soil around the soil moisture sensors reached complete saturation. Considering a porosity of 45%, the TDT's factory calibration measured levels of water content that were larger than porosity while the laboratory- and field-derived equations indicated complete saturation. It is evident in Figure 1 that the TDT responded well to small amounts of rainfall (≈3 mm on August 19th), and all calibration equations resulted in water content levels similar to values derived from gravimetric field measurements.

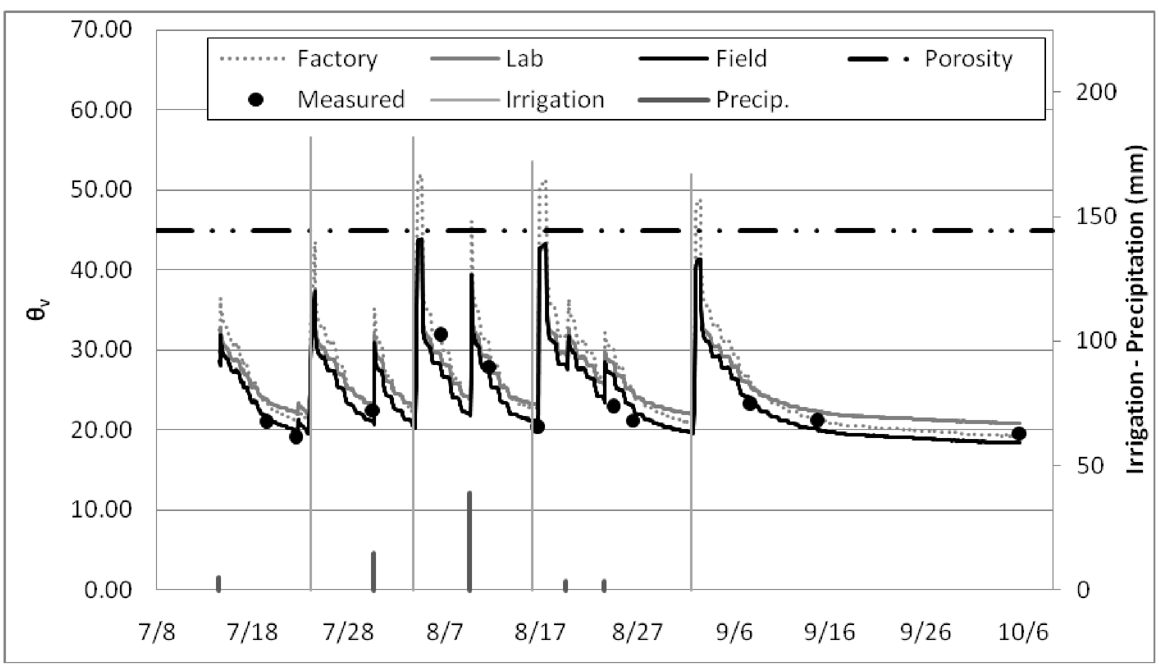

Figure 1. TDT soil water content sensor calibration curves for Treatment 1.

CONCLUSIONS

This research evaluated the performance of Watermark soil water potential and TDT soil water content sensors under laboratory and field conditions in a sandy clay loam soil. Sensor measured soil water content values were compared with corresponding values derived from gravimetric samples. Soil potential (tension) values from the watermark were converted to volumetric soil water content for the evaluation. Linear calibration equations were developed for the TDT sensor while a logarithmic calibration equation was developed for the Watermark sensor. According to laboratory tests, the TDT's factory-recommended calibration performed very well with errors less than 1.2±3.9%. In the case of the Watermark sensor, the factory-recommended equation, evaluated with measured soil water content from a corn irrigated field, in average overestimated soil water content by 11.2±12.6%.
Finally, field-derived calibration equations developed for both sensors resulted in higher accuracy than the factory- or laboratory-derived equations. The resulting mean bias error (MBE) and root mean square error (RMSE) for the TDT sensor was 1.8±2.6% and for the Watermark sensor -4.3±5.0%, respectively.
These results indicate that the TDT soil water content sensor was accurate and consistent in measuring soil moisture. In the case of the watermark sensor the accuracy was less than expected. However, more field data still are needed to further conclude on the accuracy and reliability of the watermark sensor.

REFERENCES

Campbell Scientific. 2011. Instruction Manual: Models 253-L and 257-L (Watermark 200) Soil Matric Potential Sensors. Revision 3/09. Also available at http://www.campbellsci.com/documents/manuals/253-257.pdf

Cobos, D.R., 2009. Calibrating ECH2O Soil Moisture Sensors. Application Note. Decagon Devices, Inc.

TDT Soil Moisture Sensor, 2010. TDT Soil Moisture Sensor. Cutsheet, Acclima, Inc., Meridian, ID. Also available at http://acclima.com/wd/acclimadocs/MoistureSensor/TDT%20Moisture%20Sensor%20Cut%20Sheet.pdf

Fangmeier, D.D., J.E. William, S.R. Workman, R.L. Huffman, G.O. Schwab, 2006. Soil and Water Conservation Engineering, 5th Ed. Thomson Delmar Learning, Clifton Park, NY. p. 337.

Gavlak, R.G., D.A. Horneck, and R.O. Miller, 2003. Plant, Soil and Water Reference Methods for the Western Region, 2nd ed. WREP 125.

Hignett, C., and S. Evett, 2008. Direct and Surrogate Measures of Soil Water Content. In: Evett, S.R., L.K. Heng, P. Moutonnet, and M.L. Nguyen, editors. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018-5518. p. 107-109.

Kapinos, J. 2006. Irrigation Sensors Benefit Afghanistan Farmers. United States Air Force, 455th Air Expeditionary Wing Public Affairs, Camp Cunningham, Bagram Airfield, Afghanistan.

Ley, T.W., R.G. Stevens, R.R. Topielec, and W.H. Neibling, 2004. Soil Water Monitoring and Measurement. PNW 475, a Pacific Northwest Publication. Washington State University, Pullman, WA.

National Resource Conservation Service (NRCS). 2009. Agricultural Water Enhancement Program Project Proposals Approved for Fiscal Year 2009. U.S. Department of Agriculture, Washington, DC.

Starr, J.L., and I.C. Paltineanu. 2002. Methods for Measurement of Soil Water Content: Capacitance Devices. p. 463-474. In J.H.Dane, and G.C.Topp (ed.) Methods of Soil Analysis: Part 4 Physical Methods. Soil Science Society of America, Inc., Soil Science Society of America, Inc.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. Water Resources Research 16(3):574-582.

Willmott, C.J. 1982. Some Comments on the Evaluation of Model Performance. Bull. of Am. Meteorol. Soc., 63, 1309-1313.