A COMPARISON OF LABORATORY AND FIELD CALIBRATION OF THE ECH2O EC-20 SOIL MOISTURE PROBE FOR SOILS IN THE MIDDLE RIO GRANDE VALLEY

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ABSTRACT

Throughout the American West irrigated agriculture has been targeted to increase water use efficiency. Soil moisture sensors offer a method to achieve efficiency improvements but have found limited use due primarily to high cost and lack of soil specific calibration equations. In this paper we examine the ECH2O EC-20 soil moisture sensor, a low cost capacitance sensor and develop a unique laboratory calibration method. Field and laboratory calibration equations were developed for 6 soil types in the Middle Rio Grande Valley. The average absolute error in volumetric water content for field calibration was 0.43 m^3/m^3, and 0.012 m^3/m^3 for the laboratory calibration. The factory calibration equation for the EC-20 was also evaluated and found to yield an average absolute error of 0.049 m^3/m^3. We found that the EC-20 is a reliable, cost effective, and accurate sensor, and recommend that the laboratory calibration method presented here be used to obtain maximum accuracy. We also recommend that the field calibration of the EC-20 soil moisture sensor be foregone, as this type of calibration exhibits large error rates. Additionally, it was found that the field calibration method was time consuming, covered a small range of moisture content values and was destructive to the area around installed sensors, which could lead to measurement errors.

INTRODUCTION

The Middle Rio Grande Valley in central New Mexico is a prime example of a region where agricultural water users have been targeted to increase water use efficiencies due to increasing demands, interstate compacts and instream flow requirements linked to federally listed endangered species. To improve water delivery efficiencies, the New Mexico Interstate Stream Commission and the Middle Rio Grande Conservancy District have developed a Decision Support System over the last several years. The Decision Support System monitors soil moisture levels and soil water depletion, and schedules irrigation according to crop demand which increases water delivery efficiencies (Oad et al. 2009; Gensler et al. 2009). In order to validate the moisture depletion calculated using

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∞ Nathi Manana passed away at his home in South Africa March 17, 2011. You will be missed “ungami wami.”
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the Decision Support System, it was necessary to deploy soil moisture sensors in several fields to determine actual depletions. To ensure that the data collected was as accurate as possible, both laboratory and field calibration equations for moisture sensors were developed throughout the Middle Rio Grande Valley.

An available probe that has found implementation is the ECH20 EC-20 (Decagon Devices, Pullman, WA, 2006b) dielectric probe from Decagon Devices, see Figure 1. The ECH2O EC-20, which offers a low cost alternative to other capacitance type meters (Kizito et al. 2008; Saito et al. 2008; Sakaki et al. 2008; Bandaranayake et al. 2007; Nemali et al. 2007; Plauborg et al. 2005), has been used to improve irrigation management for citrus plantations (Borhan et al. 2004) and the precision of the ECH20 EC-20 is such that it can be used for greenhouse operations and to schedule field irrigations (Nemali et al. 2007). The main benefit of the ECH2O sensor is that it is one of the most inexpensive probes available and therefore can be widely used and implemented (Christensen, 2005; Luedeling et al. 2005; Riley et al. 2006). EC-20 sensors allow for the measurement of water content associated with saturation, field capacity, and wilting point, along with the redistribution pattern of soil water and possible drainage below the root zone. This information can be used to decide the time and amount of irrigation (Bandaranayake et al. 2007).

Through previous research it has been found that dielectric sensors often require site specific calibration either through field methods or laboratory analyses. Inoue et al. (2008) and Topp et al. (2000) found that it was necessary to perform site specific calibrations for capacitance sensors to account for salinity concerns and Nemali et al. (2007) found that it was necessary to calibrate the ECH2O sensors because output was significantly affected by the electrical conductivity of the soil solution. Other studies have found that site specific corrections are required for mineral, organic, and volcanic soils (Paige and Keefer 2008; Bartoli et al. 2007; Regelado et al. 2007; Malicki et al. 1996). Despite the need for site specific calibration limited published data for ECH20 sensors are available and further studies on the EC-20 are needed (Saito et al. 2008; Sakaki et al. 2008; Bandaranayake et al. 2007; Norikane et al. 2005; Bosch, 2004).

Laboratory calibration of the EC-20 can be completed by performing a series of measurements on multiple soil samples with varying moisture content and developing regression equations from the collected data. This method has proven successful for the calibration of several dielectric instruments (Seyfried and Murdock 2004; Veldkamp and O'Brien 2000). Field calibration can be accomplished through regression with numerous gravimetric samples and is an approach that has been used in the calibration of capacitance probes and TDR sensors (Geesing et al. 2004; Walker et al. 2004; Kelleners et al., 2004; Morgan et al. 1999).

The objectives of this study were to:

- Perform a field calibration of the ECH20 EC-20 soil moisture sensor for various soil types in the Middle Rio Grande Valley

- Perform laboratory calibrations using a modified method for the ECH20 EC-20 soil moisture sensor for various soil types in the Middle Rio Grande Valley
- Compare the laboratory and field calibrations and evaluate the laboratory method and;
- To determine the difference displayed by both methods in regards to the manufacturer's generic calibration equation

The goal of this research was to provide irrigators and researchers with a precise laboratory calibration method, specific laboratory and field calibration equations, and an understanding of the accuracy that can be expected using various calibration methods for the ECH2O EC-20 soil moisture sensor. Although the focus of this research is related to irrigated agriculture, other users of soil moisture sensors in various applications could benefit from this research.

MATERIAL AND METHODS

Eight fields, irrigated using border and flood irrigation, within the Middle Rio Grande Valley were chosen for soil moisture monitoring using ECH2O EC-20 sensors. The EC-20 probe has a flat design for simple insertion and allows for continued monitoring at a user defined interval. The overall length of the sensor is 20.5 cm with a width of 3.1 cm, a blade thickness of 0.1 cm and a 6 cm sensor head length (Figure 1). The total sampling volume of the probe is between 128 and 256 cm^3 depending on soil water content (Bandaranayake et al. 2007). The ECH2O EC-20 soil probe measures the capacitance of the surrounding soil medium, which is related to dielectric permittivity of the medium (Kizito et al. 2008). The final output from the sensor is either in a voltage or a raw count value that can be converted to a volumetric water content using calibration equations (Kelleners et al. 2005).

Figure 1. ECH2O EC-20 Soil Moisture Sensor

Details on the EC-20 sensor measurement principle and function are reported by the manufacturer (Decagon Devices, 2006a).

The standard Decagon calibration equation using millivolts for the EC-20 is given as:

$$\theta(m^3/m^3) = 0.000695(mV) + (-0.29) \quad (1)$$

For the Em5B Decagon logger output of rawcounts the equation is:

$$\theta(m^3/m^3) = 0.000424(\text{rawcount}) + (-0.29) \quad (2)$$

In some instances, such as the use of a datalogger other than the Decagon loggers it may be necessary to convert between millivolts and raw counts. If millivolt output is desired, the rawcounts can be converted for the Em5b datalogger using the following equation:

$$\text{mV} = [\text{rawcounts } (3000 \text{ (logger excitation voltage)})]/4096 \quad (3)$$

Two ECH20 EC-20 soil moisture probes were installed in each field at a depth of 20 cm and 61 cm. The Natural Resource Conservation Service (NRCS) recommends installing soil moisture sensors at 15-20 cm and 46-61 cm to obtain profiles in the Middle Rio Grande Valley. The sensors were installed 15 m into the field away from the border to minimize edge effects by digging a shallow trench into the field at a distance of one half the field lengths from the irrigated end. This ensured that the sensors would be obtaining a representative measurement while not impeding field trafficability. Once the sensors were installed the trench was refilled with soil and packed to prevent preferential flow during irrigation events.

This resulted in a total deployment of 16 ECH20 EC-20 sensors. During installation a four liter soil sample was obtained from each depth in order to determine soil type, electrical conductivity, and perform laboratory sensor calibrations. All probes were installed vertically using the factory recommended tools consisting of an auger, blade for making a pilot hole, and the ECH2O insertion tool. The insertion tool is critical for the installation of the EC-20 sensors as it prevents the sensor from being snapped while it is being inserted. The installed sensors were connected to an Em5b datalogger, mounted on a T-post at the edge of the field, which reads electrical rawcounts of the EC-20 sensor. The Em5B was set to record soil moisture every 60 minutes. Figure 2 displays the location of the fields instrumented with EC-20 sensors. Fields 1, 2, 3, and 6 were planted in alfalfa and fields 4, 5, 7, and 8 were planted in grass hay. At the beginning of the irrigation season in early March all fields were fertilized at rates between 110 and 168 kg/hectare.

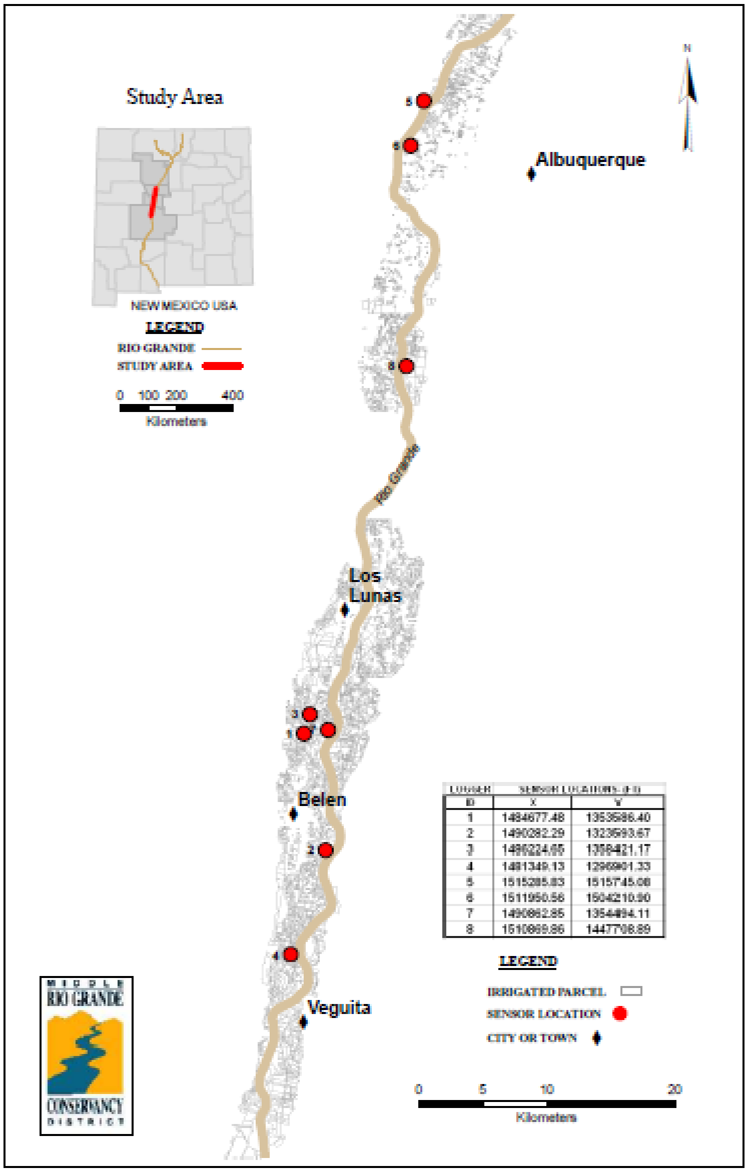

Figure 2. Soil Moisture Sensor Locations in the Middle Rio Grande Valley

In order to determine soil type for all 16 installation locations both sieve and hydrometer analyses were completed. In addition to this analysis electrical conductivity was determined for each soil using the 1:1(V:V) soil: water extract method and a HATCH HQ 40d electrical conductivity sensor.

Analysis on soil temperature was not conducted as previous research has shown that temperature effects on ECH20 sensors are minimal (Kizito et al. 2008; Norikane et al. 2005; Campbell, 2002). Specifically, (Bandaranayake et al. 2007) showed that temperature changes of 30 degrees Celsius resulted in a 0.047 m^3/m^3 change in water content for the EC-20 soil moisture sensor. Other researchers have also found that changes in EC-20 measured water content are minimal with 0.0022m^3/m^3 changes per degree C (Nemali et al. 2007).

To address concerns related to soil salinity influencing field measurements, analysis was conducted on collected data to determine if large spikes in sensor output existed. Bandaranayake et al (2007), found that salinity due to fertilization increased sensor output by 200mV which corresponds to .14 m^3/m^3 and that salinity effects could be determined graphically. Using the hourly data collected by the sensors in the field it was possible to determine if spikes in sensor output existed that did not correspond to an irrigation event.

Field Calibration

Throughout the irrigation season, gravimetric samples were taken for each of the 16 deployed sensors at the exact depth of the sensor installation (either 20 or 61 cm) and in close proximity (less than 60 cm) to the sensor. It was not feasible to collect samples closer to the sensor due to possible damage to the sensor and sensor cables. Therefore, field samples were not directly co-located with the sensor but this was deemed appropriate due to limited spatial soil variability in the monitored fields. Similar sampling techniques used by other researchers have been effective at developing field calibration equations (Bandaranayake et al. 2007; Kaleita et al. 2005). The collection of the samples was timed to account for pre and post irrigation soil moisture levels. Overall, five measurements with two replicates per measurement were collected for each sensor installation. These two replicates were averaged to determine volumetric water content and field bulk density. The samples were collected using an Oakfield Soil Sampling Auger and stored in airtight soil moisture tins. These samples were weighed and oven dried at 105^0C for 24 hrs and reweighed to determine volumetric water content and the field bulk density of each sample. This volumetric water content from the two samples was correlated to a rawcount reading from the Em5b datalogger for the hour during which the sample was taken.

Laboratory Calibration

Laboratory calibrations were performed using a modified approach to the manufacturer's suggested calibration method (Decagon, 2006b). For the laboratory calibration of ECH2O EC-20 sensors a 15 cm diameter piece of PVC pipe was used as a calibration cylinder (volume 2100 cm^3). Before calibration began the soil samples were oven dried for a period of 24 hrs at 105^o C. Subsequently the cylinder was packed to the exact bulk density measured in the field, which was accomplished by packing the soil into the cylinder by sections. Once the oven dry soil was packed into the cylinder at field bulk density, the EC-20 sensor was inserted using the manufacturer recommended insertion tool. The probe was allowed to equilibrate, which involved taking readings every 30 seconds until the readings did not change. Then the final equilibrated reading of the raw counts was recorded using an Em5b datalogger, and the probe was removed from the calibration cylinder

After removing the probe from the cylinder, it was necessary to obtain a volumetric sample to determine soil moisture content for a given sensor output. This was accomplished by using two small cylinders constructed out of copper water pipe with volumes of 23.40 and 23.73 cm^3 respectively. To decrease the effect of compacting the soil in the measurement cylinder, the edges of the copper cylinders were beveled to a thin, sharp edge using a metal file. The cylinder and the volume of soil contained in it were then extracted from the test cylinder. The samples were trimmed from the top and bottom edges of the cylinder to ensure accuracy in the volume measurements and emptied into soil moisture sampling tins and weighted. The samples were then placed in an oven at 105^0 C for 24 hours and re-weighted thereafter. Volumetric water content was then calculated for each of the soil samples. Bulk density was also determined and used to verify that the field bulk density was indeed replicated in the calibration cylinder.

This procedure was completed for each of the 16 soil types by subsequently adding 100 ml of water to the soil to increase the moisture content and develop calibration curves. Once readings were obtained from the oven dry sample, the soil inside the calibration cylinder was placed in a pan where 100 ml of water were added. The sample was then mixed for a period of 10 minutes to ensure uniform distribution of the water throughout the soil. Once mixing was complete the soil was packed back into the calibration cylinder at the field bulk density. The EC-20 probe was inserted again, the equilibrated raw count recorded, and two volumetric samples were removed to determine the water content. This process was repeated until the water content of the soil reached saturation which was determined through laboratory analysis. In most cases this resulted in at least 7 measurements consisting of a raw count and a soil moisture content. A more detailed explanation of calibrating capacitance probes can be found in Starr and Palineanu (2002) and Polyakov et al. (2005).

From the collected field and laboratory data it was possible to develop predictive regression equations relating raw count to volumetric water content. Based on the work of several researchers (Bandaranayake et al. 2007; Mitsuishi and Mizoguchi, 2007; Kaleita et al. 2005; Plauborg et al. 2005; Fares et al. 2004; Paltineanu and Starr, 1997; Gaudo et al. 1993) and advice from Decagon Devices (Gaylon Campbell – personnel communication) linear and polynomial regression equations are most appropriate for capacitance type sensor calibration. Both linear and polynomial equations were developed for each soil type and the best fit for each soil type was utilized in subsequent analysis. The best fit regression equation for each soil type was selected based on the highest coefficient of determination.

In order to determine the accuracy of the factory, and developed field, and laboratory calibration equations, the absolute error in water content between the predicted volumetric water content and the actual measured water content was calculated using the following equation:

$$\text{ABS Error} = (\text{Sum ABS } [\theta_{\text{Equation}} - \theta_{\text{Actual}}])/ N \qquad (4)$$

Where N is the number of observations.

The absolute error in water content was selected as being appropriate based on the preliminary findings that several of the field calibration equations exhibited both over and under prediction for the same soil type.

RESULTS

From the soil analysis it was determined that the 16 installation sites were characterized by six soil textures consisting of sand, sandy loam, silt loam, loam, clay loam, and clay. The field bulk densities varied from 1.4 to 1.6 g/cm^3. The EC analysis revealed variations from 2.0 dS/m to 6.29 dS/m. No sample exceeded 8 dS/m where capacitance sensors experience distortion. Table 1 displays the results of the soil analyses.

Table 1. Soil Characteristics for Monitored Fields in the Middle Rio Grande Valley

Soil Class	Field	Depth (cm)	% Sand (> .05mm)	% Silt (.002 to .05mm)	% Clay (< .002mm)	Field Bulk Density (g/cm^3)	pH 1:1	EC (ds/m) 1:1
Sand	3	61	90.0	5.0	5.0	1.59	7.80	4.29
Sand	5	61	96.0	2.0	2.0	1.52	7.93	3.14
Sand	8	61	96.0	2.0	2.0	1.60	7.58	2.89
Sandy Loam	3	20	76.0	14.0	10.0	1.54	7.79	3.07
Sandy Loam	4	61	78.0	16.0	6.0	1.68	8.07	2.00
Sandy Loam	7	61	60.0	29.0	11.0	1.51	7.75	2.90
Sandy Loam	8	20	67.0	19.0	14.0	1.48	6.95	1.73
Silt Loam	1	61	23.0	52.0	25.0	1.62	7.71	2.71
Loam	2	61	44.0	48.5	7.5	1.56	7.85	4.39
Loam	4	20	43.0	31.0	26.0	1.47	7.62	3.80
Loam	5	20	36.0	48.0	16.0	1.37	7.41	6.29
Loam	7	20	43.0	35.0	22.0	1.54	7.72	3.20
Clay Loam	1	20	40.0	27.5	32.5	1.42	8.03	3.51
Clay Loam	6	20	23.0	50.0	27.0	1.47	7.75	4.00
Clay Loam	6	61	23.0	47.0	30.0	1.52	7.87	3.60
Clay	2	20	20.0	27.5	52.5	1.41	7.85	5.23

Analysis of collected data did not show the significant spikes in output associated with salinity described by Bandaranayake et al. 2007 which exhibited changes of 0.14 m^3/m^3. Figure 3 displays the soil moisture depletion measured throughout the 2008 irrigation season for the 20 cm sensor installation on field 5 which is a loam soil and the 20cm sensor installation on field 6 which is a clay loam soil. The other 14 installations exhibited similar depletion and irrigation patterns without spikes associated with salinity with soil moisture depletion ranging from 0.05 m^3/m^{3}for clay and clay loam soils to 0.15 m^3/m^3 for loam and sandy loam soils. A major reason that salinity did not affect the sensor installations is that the irrigation practices in the Middle Rio Grande Valley are flood irrigation with the average applications being 15 cm per irrigation event for the monitored fields (Kinzli, 2010). This amounts to 138 cm per year on average for the monitored fields (Kinzli, 2010). The large amounts of water applied insured adequate flushing of salts and kept the salinity values low during the irrigation season (Kinzli, 2010). Additionally, the farmers on the monitored fields did not fertilize during the irrigation season.

Field Calibration

The data from the field calibration showed that a significant amount of scatter existed with regard to the factory calibration equation. The data points from the field calibration were clustered together and covered a minimal range of volumetric water contents compared to the laboratory calibration. This is the case because the finer soils exhibited a minimal variation in volumetric water content throughout the irrigation season with maximum changes being around 0.05 m^3/m^3 (Figure 3). The curvature of the collected points can be explained using linear equations (Figures 4 and 5). The slope of data points collected from the fields was in most cases significantly different from the factory equation slope.

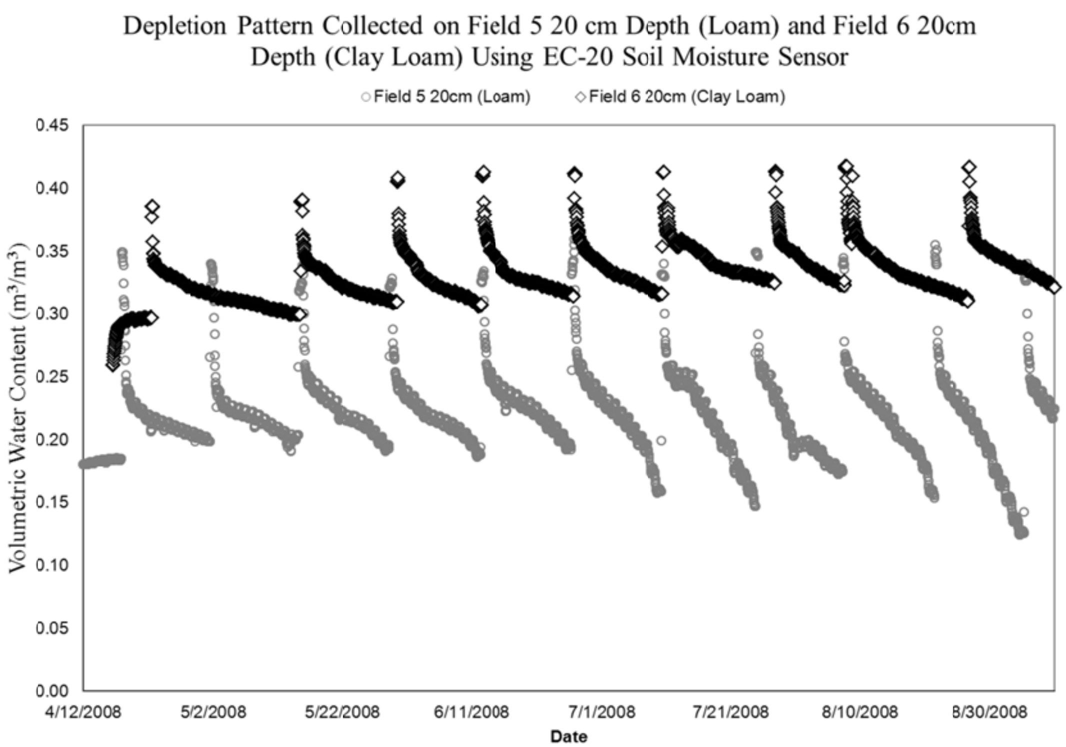

Figure 3. Depletion Pattern Collected on Field 5 20 cm Depth (Loam) and Field 6 20cm Depth (Clay Loam) Using EC-20 Soil Moisture Sensor

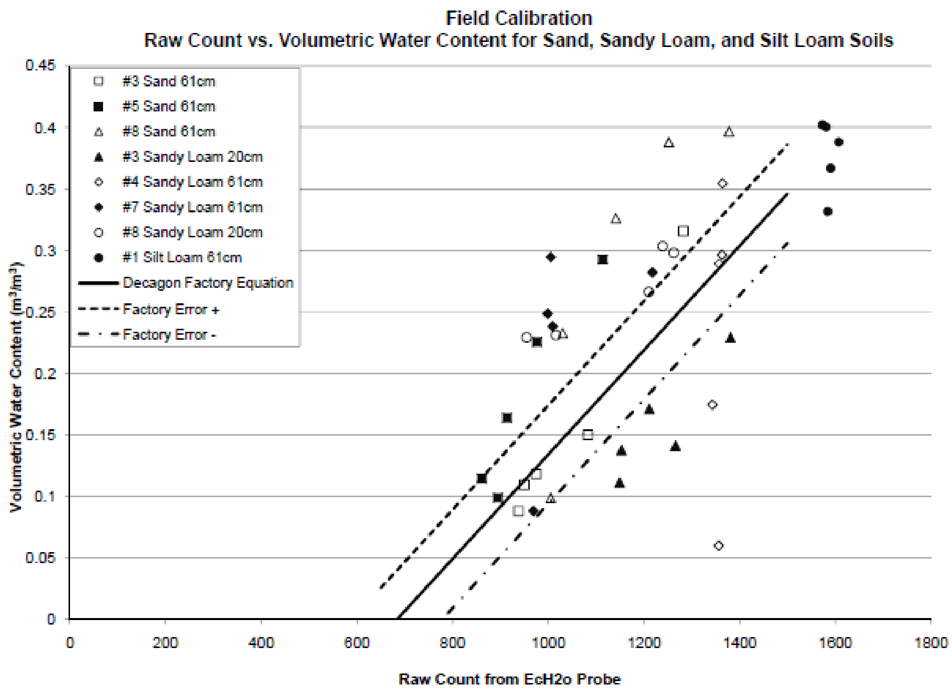

Figure 4. Field Calibration Compared to Factory Calibration Curve for Sand, Sandy Loam, and Silt Loam Soils

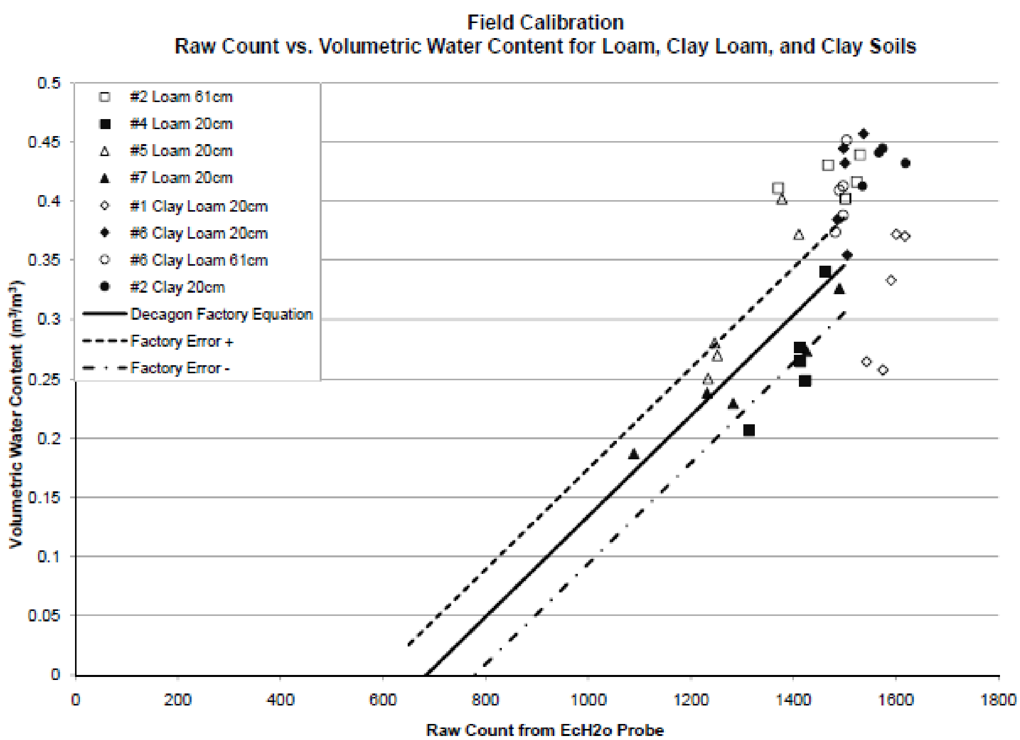

Figure 5. Field Calibration Compared to Factory Calibration Curve for Loam, Clay Loam, and Clay Soils

The field calibrations were most successful for sand soils (Figure 4) where a larger range of moisture contents was obtained from the field measurements. In the other five soil textures the data collected from the field sampling was bunched together in tight clusters at higher volumetric water content values. This is the case because during the irrigation season the variation in soil moisture is reduced as percent of fine material in the soil increases. For sandy loam the field calibration showed extreme variation and for loam, silt loam, clay loam, and clay (Figure 5), the field calibration resulted in a cluster of points located at the upper end of the volumetric content range.

The development of calibration equations from the field data resulted in linear equations for all 16 sensors. The results for the field calibration are displayed in Table 2. The absolute error ranged from 0.036 m^3/m^3 to 3.18 m^3/m^3 with an average absolute error of 0.43 m^3/m^3 for the 16 developed equations. The adjusted coefficient of determination varied between -0.26 and 0.95 with an average value of 0.56. The equations developed for sand collectively showed the lowest average absolute error of 0.076 m^3/m^3 with an average adjusted coefficient of determination of 0.85. The average absolute errors and adjusted coefficients of determination by soil texture for sandy loam, loam, and clay loam were 0.939 m^3/m^3 (0.54), 0.128 m^3/m^3 (0.57) and 0.514 m^3/m^3 (0.40) respectively. For silty loam and clay only one sample was collected and the absolute error and adjusted coefficient of determination for these was 0.702 m^3/m^3 (0.76) and 0.160 m^3/m^3 (-0.04) respectively. The equations that exhibited the largest absolute error were Field 4 61 cm with 3.18 m^3/m^3, Field 1 61 cm with 0.702 m^3/m^3, Field 1 20 cm with 0.687 m^3/m^3, and Field 6 61 cm with 0.686 m^3/m^3.

Table 2. Results of Field Calibration for EC-20 Soil Moisture Sensor

Soil Class	Field	Depth (cm)	Regression Equation (x =raw count)	Adjusted R^2	Range in volumetric Water Content	Abs Error (m^3/m^3)
Sand	3	61	7.68E-04x - 5.52E^{-01}	0.880	0.09-0.29	0.06
Sand	5	61	6.26E-04x - 4.98E^{-01}	0.950	0.08-0.32	0.06
Sand	8	61	7.06E-04x - 5.32E^{-01}	0.710	0.10 -0.40	0.11
Sandy Loam	3	20	4.14E-04x - 3.52E^{-01}	0.690	0.11-0.23	0.06
Sandy Loam	4	61	7.46E-03x - 9.84E^{+00}	0.880	0.06-0.35	3.19
Sandy Loam	7	61	1.01E-04x + 1.59E^{-01}	-0.260	0.09-0.29	0.26
Sandy Loam	8	20	2.37E-04x - 3.73E^{-03}	0.850	0.23 -0.30	0.26
Silt Loam	1	61	2.19E-03x - 3.13E^{+00}	0.760	0.33-0.40	0.70
Loam	2	61	7.44E-05x + 3.10E^{-01}	-0.180	0.40-0.44	0.13
Loam	4	20	7.81E-04x - 8.30E^{-01}	0.710	0.21-0.34	0.22
Loam	5	20	7.70E-04x - 6.90E^{-01}	0.870	0.25-0.40	0.13
Loam	7	20	3.15E-04x - 1.60E^{-01}	0.890	0.19-0.33	0.04
Clay Loam	1	20	1.71E-03x - 2.38E^{+00}	0.680	0.26-0.37	0.69
Clay Loam	6	20	1.13E-03x - 1.29E^{+00}	0.000	0.35-0.46	0.17
Clay Loam	6	61	2.85E-03x - 3.86E^{+00}	0.530	0.37-0.45	0.69
Clay	2	20	1.93E-04x + 1.28E^{-01}	-0.040	0.41-0.44	0.16

Laboratory Calibration

The data from the laboratory calibration showed much less scatter than the developed field calibration equations. The data from the lab calibration exhibited exclusively linear and polynomial relationships which covered a large range of volumetric water contents (Figures 6 and 7). The slope of data points collected during the laboratory calibration was similar to the factory equation.

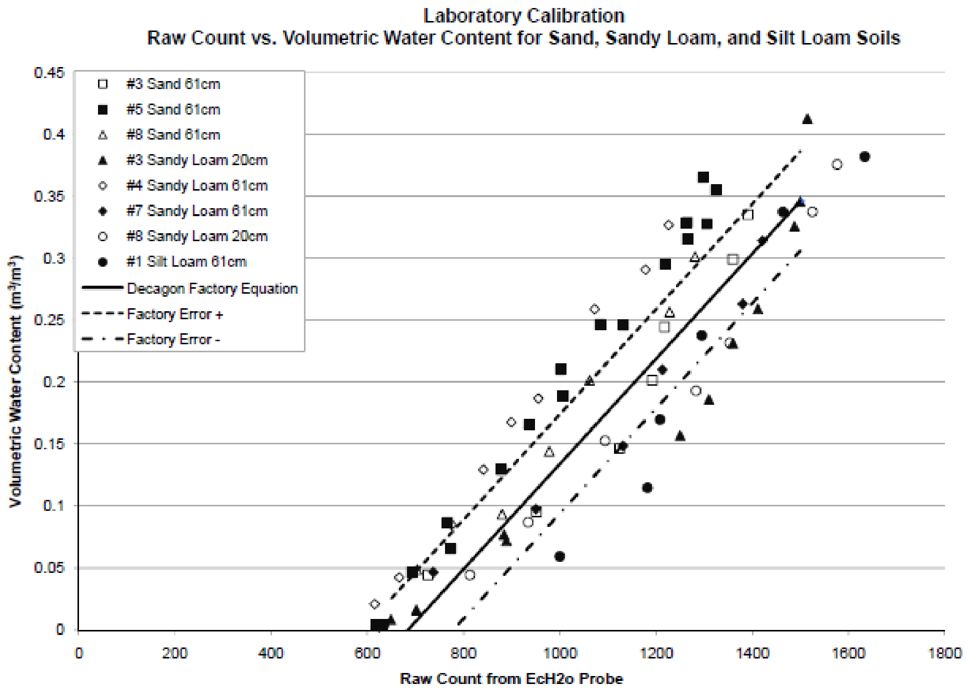

Figure 6. Laboratory Calibration Compared to Factory Calibration Curve for Sand, Sandy Loam, and Silt Loam Soils

The laboratory calibrations were successful for all 16 soils. The laboratory calibration allowed for precise management of bulk density and water content and therefore a large range of moisture contents was obtained for developing equations. For all 16 soil types, the variation in obtained data was minimal which resulted in accurate calibration equations.

The development of calibration equations from the laboratory data resulted in mostly polynomial equations. The results from the laboratory calibration effort are displayed in Table 3. The absolute error ranged from 0.00053 to 0.031 m^3/m^3 with an average absolute error of 0.012 m^3/m^3 for the 16 developed equations. The adjusted coefficient of determination varied between 0.880 and 0.998 with an average value of 0.979. The equations developed for loam collectively showed the lowest average absolute error of 0.0072 m^3/m^3 with an average adjusted coefficient of determination of 0.995. The average absolute errors and coefficients of determination by soil texture for sand, sandy loam, and clay loam were 0.014 m^3/m^3 (0.973), 0.012 m^3/m^3 (0.981) and 0.012 m^3/m^3 (0.988) respectively. For silt loam and clay only one sample of the soil texture was collected and the absolute error and coefficient of determination for these was 0.031 m^3/m^3 (0.880) and 0.011 m^3/m^3 (0.992) respectively. The equations that exhibited the largest absolute error were Field 1 61 cm with 0.031 m^3/m^3, Field 3 20 cm with 0.019 m^3/m^3, Field 5 61 cm with 0.017 m^3/m^3, and Field 8 61 cm with 0.017 m^3/m^3.

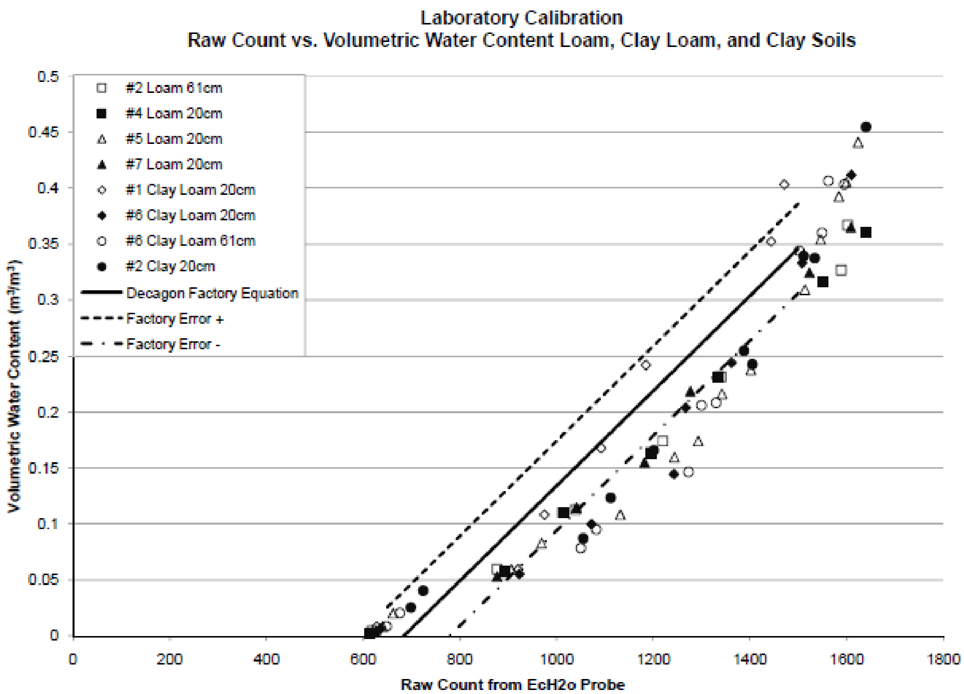

Figure 7. Laboratory Calibration Compared to Factory Calibration Curve for Loam, Clay Loam, and Clay Soils

Overall, it was found that in cases where a polynomial equation exhibited a higher coefficient of determination the use of the polynomial over a linear equation was warranted. The absolute error rates were significantly higher for linear equations when compared to polynomial equations and overall the absolute error rate was .029 m^3/m^3 less for the polynomial equations. This was tested using an F-Test-two sample for variance analysis at an α level of 0.05 for the 12 developed polynomial equations. The F-test resulted in an F statistic value of 0.017 with a significance limit of 0.355 which indicates a statistically significant difference between the use of linear and polynomial equations. The F test value indicates that the polynomial equations display less variance and are therefore a better fit for the data. Table 4 presents the comparison of polynomial and linear error rates for the 12 developed polynomial equations.

Table 3. Results of Laboratory Calibration for EC-20 Soil Moisture Sensor

Soil Class	Field	Depth (cm)	Regression Equation (x = raw counts)	Adjusted R^2	Range in Volumetric Water Content	Abs Error (m^3/m^3)
Sand	3	61	$4.97E\text{-}04x - 3.04E^{-01}$	0.992	0.004-0.36	0.009
Sand	5	61	$4.14E\text{-}04x - 2.73E^{-01}$	0.940	0.004-0.34	0.017
Sand	8	61	$4.38E\text{-}04x - 2.73E^{-01}$	0.986	0.004-0.30	0.017
Sandy Loam	3	20	$5.23E^{-07}x2 - 7.51E^{-04}x + 2.97E^{-01}$	0.950	0.008 - 0.41	0.019
Sandy Loam	4	61	$Neg\ (8.72E^{-09}x2 + 5.21E^{-04}x - 3.01E^{-01})$	0.995	0.02-0.33	0.006
Sandy Loam	7	61	$2.17E\text{-}07x2 - 7.98E^{-05}x - 2.44E^{-02}$	0.987	0.002-0.31	0.011
Sandy Loam	8	20	$2.30E^{-07}x2 - 1.31E^{-04}x + 1.58E^{-03}$	0.991	0.004-0.38	0.010
Silt Loam	1	61	$4.13E^{-04}x - 3.10E^{-01}$	0.880	0.004-0.38	0.031
Loam	2	61	$4.57E^{-07}x2 - 6.31E^{-04}x + 2.40E^{-01}$	0.991	0.004-0.37	0.011
Loam	4	20	$1.73E^{-07}x2 - 3.05E^{-05}x - 4.42E^{-02}$	0.994	0.002-0.36	0.007
Loam	5	20	$1.43E^{-07}x2 + 3.21E^{-05}x - 7.47E^{-02}$	0.998	0.008-0.44	0.005
Loam	7	20	$1.87E^{-07}x2 - 4.27E^{-05}x - 4.59E^{-02}$	0.996	0.004-0.37	0.006
Clay Loam	1	20	$2.99E^{-07}x2 - 1.60E^{-04}x - 1.73E^{-02}$	0.982	0.008-0.40	0.015
Clay Loam	6	20	$3.88E^{-07}x2 - 4.58E^{-04}x + 1.42E^{-01}$	0.991	0.006-0.41	0.008
Clay Loam	6	61	$5.05E^{-07}x2 - 7.12E^{-04}x + 2.65E^{-01}$	0.991	0.008-0.41	0.012
Clay	2	20	$4.49E^{-07}x2 - 6.21E^{-04}x + 2.48E^{-01}$	0.992	0.03-0.45	0.011

Table 4. Comparison of Accuracy for Linear and Polynomial Equations

Soil Class	Calibration	Field	Depth (cm)	Abs Error (m^3/m^3) Polynomial Eq	Abs Error (m^3/m^3) Linear Eq
Sandy Loam	Lab	3	20	0.019	0.033
Sandy Loam	Lab	4	61	0.006	0.006
Sandy Loam	Lab	7	61	0.011	0.015
Sandy Loam	Lab	8	20	0.010	0.020
Loam	Lab	2	61	0.011	0.044
Loam	Lab	4	20	0.007	0.132
Loam	Lab	5	20	0.005	0.040
Loam	Lab	7	20	0.006	0.036
Clay Loam	Lab	1	20	0.015	0.030
Clay Loam	Lab	6	20	0.008	0.034
Clay Loam	Lab	6	61	0.012	0.048
Clay	Lab	2	20	0.011	0.035

Factory Equation

When applied to the laboratory data the standard factory equation resulted in significantly less error than the field calibration equations but more error than the laboratory calibration equations. Table 5 displays the results of applying the factory calibration equation to the lab data. Figure 4 through 7 display the factory calibration applied to the field and lab data respectively. The field calibration data exhibited a significant spread

(Figures 4 and 5) with extremely high errors when compared to the factory equation and therefore the factory equation was applied to the laboratory data.

Table 5. Results of Factory Calibration Equation for EC-20 Soil Moisture Sensor

Soil Class	Field	Depth (cm)	Abs Error (m^3/m^3)
Sand	3	61	0.059
Sand	5	61	0.044
Sand	8	61	0.045
Sandy Loam	3	20	0.036
Sandy Loam	4	61	0.070
Sandy Loam	7	61	0.104
Sandy Loam	8	20	0.067
Silt Loam	1	61	0.043
Loam	2	61	0.045
Loam	4	20	0.039
Loam	5	20	0.041
Loam	7	20	0.035
Clay Loam	1	20	0.032
Clay Loam	6	20	0.044
Clay Loam	6	61	0.044
Clay	2	20	0.042

The absolute error between the factory equation and lab results ranged from 0.032 to 0.104 m^3/m^3 with an average absolute error of 0.049 m^3/m^3 for the 16 soil samples. For loam the factory equation collectively showed the lowest average absolute error of 0.039 m^3/m^3. The average absolute errors by soil texture for sand, sandy loam, and clay loam were 0.049 m^3/m^3, 0.069 m^3/m^3, and 0.040 m^3/m^3. For silt loam and clay only one sample of the soil texture was collected and the absolute error for these was 0.043 m^3/m^3 and 0.042 m^3/m^3 respectively. The four equations that exhibited the largest absolute error were Field 7 61 cm with 0.104 m^3/m^3, Field 4 61 cm with 0.070 m^3/m^3, Field 8 20 cm with 0.067 m^3/m^3 and Field 3 61 cm with 0.059 m^3/m^3. The factory equation on average under predicted for sand soil by 0.037 m^3/m^3 and 0.0061 m^3/m^3 for sandy loam soils. For silt loam, loam, clay loam, and clay the factory equation on average over predicted the soil moisture content by 0.033, 0.029, 0.015, and 0.023 m^3/m^3 respectively.

DISCUSSION

The results obtained during this study provide insight into the two calibration methods and the differences to the standard factory calibration equation. Field calibration of the EC-20 sensor is the least desired calibration method and exhibits the largest error rates and scatter in data. The fact that significant scatter was observed can be attributed to the field calibration techniques. It was found that field calibration of the EC-20 sensor is limited due to variations in sampling locations which are caused by voids and varying root densities, even though the soil type was similar. Even though the sampling locations were adjacent to the EC-20 probe this is not the same as being co-located. Other limitations for field calibration which were observed during this study and by Kaleita et al (2005) were organic residues such as roots, worm holes, variations in field bulk density and the destructive and time consuming nature of the gravimetric sampling. The average adjusted r^2 values for the field calibration of 0.558 agree well with average values of 0.77, 0.69 and 0.74 obtained by Kaleita et al. (2005), Polyakov et al. (2005), and Leib et al. (2003) for field calibrations. Although none of the fields exhibited an EC higher than 5.23 dS/m there is the possibility that the field calibrations were influenced by variations in salinity during the irrigation season and this issue merits further investigation. It was also found that probe failure in the field led to collected gravimetric data that could not be correlated to a probe output, which limited the amount of data available for developing field calibration equations. On several occasions sensors failed due to water intrusion on the circuit boards and gophers gnawing on the cables, and shorting them out which reduced available data.

The error rates obtained using the field calibration methods are extremely high and it would not be possible to accurately measure the amount of water added or depleted using the field calibration equations. Although we attempted to schedule field sampling to cover a wide range of moisture contents, it was not possible to collect data at saturation or wilting point due to farmer irrigation practices. We therefore advise against using field calibrations for the EC-20 sensor and suggest performing the laboratory calibration presented here.

Our findings support that laboratory calibration is an accurate method to calibrate the EC-20 soil moisture sensor. The average adjusted r^2 value for the laboratory equations of 0.979 is significantly higher than the average adjusted r^2 value of 0.558 obtained from the field calibration. A high coefficient of determination indicates that the variability in the data is being explained adequately and our results for adjusted r^2 using the laboratory method compare favorably to the results of other researchers performing laboratory calibration equations for capacitance sensors. Kaleita et al. (2005) were able to obtain r^2 values of 0.85 and Polyakov et al. (2005) obtained values of 0.96 using laboratory calibration on capacitance sensors. The limited studies specific to the EC-20 have resulted in similar r^2 values with Nemali et al. (2007) finding r^2 values of 0.95 for 9 soilless substrates. Using a similar sensor, the ECH2O EC-5, Sakaki et al. (2008) were able to obtain r^2 values of 0.97.

The error rate observed indicates that the development of laboratory calibration equations can result in accurate measurement of soil moisture content. Our error rates agree well with Bosch (2004), who found that using laboratory equations, error rates for the EC-10 and EC-20 in sandy coastal soil were $0.05m^3/m^3$. Polyakov et al. (2005) found that the error rates were greatly reduced using laboratory calibrations in favor of field calibrations. Our findings also corroborate the results of Paltineanu and Starr (1997) that the most accurate calibration is achieved in the laboratory.

The method of using a calibration cylinder results in accurate laboratory equations due to the ability to replicate field bulk density. The use of a single probe in the laboratory calibration to represent the behavior of other probes is also appropriate. Statistical analysis has shown that there is no significant difference in the measurements of individual ECH20 Probes (Kizito et al. 2008; Sakaki et al. 2008; Nemali et al. 2007), and therefore probe specific calibrations were not required. We recommend that laboratory calibrations of capacitance sensors be completed using the procedure outlined here as replicating bulk density in the lab to bulk density found in the field is crucial to developing accurate equations (Mitsuishi and Mizoguchi, 2007; Starr and Palineanu, 2002). In addition to ensuring accuracy the method acceptably replicates field conditions so that minimal distortion occurs and the developed equations can be applied to collected field data.

The results obtained during this study indicate that the factory equation accuracy is dependent on soil type. The underprediction of soil moisture content in sand and sandy loam soils we observed was also found by Plauborg et al. (2005) for a different capacitance sensor. In one of the few studies done using the EC-20, Bosch (2004) found that the factory calibration equation consistently underpredicted the soil water content in three sandy coastal soils as well. For loam, silt loam, clay loam and clay the overprediction using the factory equation corresponds with results found by Inoue et al. (2008) and Polyakov et al. (2005). Both of these studies found that the manufacturer's equations overestimated the actual water content of dielectric soil moisture sensors.

The fact that the factory equation underestimates for sandy soils and overestimates for loam and clay soils indicates that the equation is designed to be used for general applications and is not soil specific. Additionally, the factory equation is linear. We found that the behavior of the EC-20 probe in sandy soils was explained by a linear equation but that for loam, silt loam, clay loam, and clay the behavior was characterized by second order polynomial curves. This is consistent with the finding of other researchers (Bandaranayake et al. 2007; Kaleita et al. 2005; Plauborg et al. 2005; Fares et al. 2004; Paltineanu and Starr, 1997; Gaudo et al. 1993). Although the factory equation is general we found that the accuracy of 0.04 m^3/m^3 without calibration suggested by the manufacturer was replicated in our study. Based on this finding, we suggest using the factory calibration equation in studies where extremely low error rates are not required. For all other studies such as precision irrigation, we recommend completing a laboratory calibration in favor of a field calibration due to the reasons mentioned previously.

During the installation of the EC-20 probes and the subsequent monitoring and data collection, much information was gained that will be useful to other researchers using similar equipment. We found that the installation of the Em5B datalogger on a T-post should be carried out using wire and not the factory supplied zip ties. Due to the extreme sunlight present in New Mexico, the zip ties were exposed to UV and became brittle and snapped in as little as two months. We also found that it was critical to use the factory supplied installation toolkit to ensure that sensors were not damaged during installation. Additionally, using the factory supplied auger was also crucial as the hole created is small and limits the amount of root damage. We recommend that the EC-20 sensors should be sealed at the interface between the probe and the lead wire with an extra layer of silicone before being installed to prevent water intrusion. If sensors are deployed away from the border of the field and longer cables are necessary, we suggest purchasing the correct length already set from the factory. This eliminates having a wire junction buried in the field which can lead to water instruction, electrical shorts, and erroneous sensor outputs. Finally, the sensors locations should be monitored and data downloaded continuously due to failure caused by gophers chewing on cables, other animals, and possible mechanical damage to dataloggers during normal field operations. Being diligent about monitoring the installation sites will prevent the loss of valuable data. One option that has recently become available for downloading data is the use of radio telementry and this offers the ability to remotely monitor installation sites. Although costly, this approach provides real time data that can be used for precise irrigation scheduling and warrants future study and implementation.

CONCLUSION

The study of the ECH2O EC-20 soil moisture probe in soils of the Middle Rio Grande Valley has shown that field calibration of the probe should be substituted for a laboratory calibration method. Through the completed study, it was possible to develop 16 accurate laboratory calibration equations for the ECH2O EC-20 soil moisture sensor. The modified laboratory calibration method used in the equation development provides researchers with a method that manages the bulk density to replicate field conditions and develops accurate equations. It is our hope that the laboratory calibration method presented here assists researchers in obtaining more precise calibration equations. Additionally, calibration equations for 16 EC-20 installations are presented which can be used by researchers in the Middle Rio Grande Valley and elsewhere with similar soil textures.

Through the use of lab calibrated EC-20 soil moisture sensors, it will become possible to precisely schedule irrigation events based on crop water requirements, which can reduce water use by up to 40% (Oad et al. 2009; Oad and Kullman 2006). In the Middle Rio Grande this is extremely crucial. The use of these sensors offers the ability and opportunity to increase water use efficiency through irrigation scheduling and ensure the sustainability of agriculture in the Middle Rio Grande Valley as interstate compacts and Endangered Species Act issues limit water available to agriculture during drought.

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