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Soil Physics

Field Performance of Five Soil Moisture Instruments in Heavy Clay Soils

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The increased use of soil moisture retrieval from satellites has heightened the need for improved accuracy of point measurements that are used to validate remotely sensed soil moisture products. A wide range of devices can be installed for operational monitoring of soil moisture; however, many of these devices have not been tested in situ in soils with a very high reactive clay content. The objective of this study was to evaluate the accuracy in field performance of five soil moisture sensors: the EnviroSCAN probe, the Diviner 2000 (both from Sentek Technologies), the Hydra Probe soil sensor (Stevens Water Monitoring Systems), the ThetaProbe ML2x (Delta-T Devices), and the ECH$_2$O EC-5 (Decagon Devices) in soils that had about 71% clay content. The instruments' default calibrations were tested against observed soil moisture from core samples using the thermogravimetric method. New calibration equations were developed for each device, which were evaluated using an independent data set. The ThetaProbe had the lowest root mean square error (RMSE) of 0.025 m^3 m^{-3} and mean bias error (MBE) of 0.002 m^3 m^{-3} in the precalibration analysis. Although the Hydra Probe showed the highest precalibration errors, the instrument made the greatest improvement in post-calibration analysis, with an RMSE of 0.129 m^3 m^{-3} using the default equation reduced to 0.014 m^3 m^{-3} using in situ calibration, and the 0.110 m^3 m^{-3} MBE was reduced to 0 after applying in situ calibration.

Abbreviations: MBE, mean bias error; NRMSE, normalized root mean square error.

Water plays a very significant role in nearly all earth processes, and one of the most anthropogenically significant aspects of the water cycle is soil moisture. The variability of weather parameters, especially precipitation, is a major meteorological driver that influences soil-water dynamics. The location and timing of extreme weather events such as hailstorms and tornadoes have even been linked to variability in soil moisture (Hanesiak et al., 2004). Drought and flood risks are strongly impacted by variations in antecedent soil moisture. Crop yields in semiarid regions are highly correlated to adequate soil moisture levels (Walker, 1989; Raddatz et al., 1994). Likewise, crop disease and insect pressure are strongly impacted by variations in soil moisture (Bom and Boland, 2000; Todd et al., 2002; Matheron and Porchas, 2005).

The complexity of land topography and the heterogeneity of soil create significant spatial variability in soil moisture levels, which is a challenge for the determination of soil moisture on a large spatial scale. Point measurements of soil moisture with a high level of absolute accuracy are essential for developing meaningful measures of soil moisture at a broad scale. Many different devices can be installed for operational monitoring of soil moisture at specific points, including devices that monitor the soil moisture temporal variability every few seconds.

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However, they do not measure soil moisture directly but determine a soil property, e.g., soil dielectric permittivity, which can be related to the moisture content of the soil. The choice of soil moisture monitoring technique is dependent on the data application. Considerations such as long or short term, continuous or occasional, surface or soil profile monitoring, as well as available resources in terms of cost, installation technicality, field accessibility, data collection frequency, sensor durability and ruggedness under field conditions like stoniness and salinity, adaptability under various weather conditions, as well as the range of output parameters are important for designing any soil moisture monitoring network. Farmers may be more concerned about the cost of the device than the absolute soil moisture value. However, researchers tend to be more critical about the choice of a device that will provide an accurate absolute value.

The behavior of water coupled with a complex pore space geometry in clay soils often constitutes a major challenge that affects the electromagnetic property of the soil being sensed. Dielectric permittivity sensors operating at frequencies <100 MHz tend to be sensitive to temperature and electrical conductivity due to the polarization effect (Chen and Or, 2006; Assouline et al., 2010). Studying the effect of temperature on the complex permittivity of 19 soils using a 50-MHz frequency Hydra Probe, Seyfried and Grant (2007), observed a ± 0.028 m^3 m^{-3} change in volumetric water content as a result of the positive and negative effect of the real dielectric permittivity in a 40°C temperature change (5–45°C). The imaginary component of the dielectric permittivity was found to be about six times more sensitive to temperature change than the real component. Kelleners et al. (2005) observed that the overestimation of permittivity values was due to dielectric dispersion and ionic conductivity. They suggested that by increasing the operating frequency of sensors from <175 MHz to >1 GHz, the performance of reflectometers may be enhanced because at higher frequencies, sensors are less sensitive to dielectric dispersion and ionic conductivity.

Several studies have investigated the performance of soil moisture instruments. Huang et al. (2004) compared the performance of five water sensors including the ThetaProbe, Aqua-Tel, Profile Probe, Watermark, and Aquaterr to determine if the factory calibrations of these devices can be used in the field. They observed that using the factory-recommended parameters, the Profile Probe (r^2 = 0.987, RMSE = 0.018 m^3 m^{-3}) and the ThetaProbe (r^2 = 0.983, RMSE = 0.037 m^3 m^{-3}) were more accurate than other soil moisture sensors when tested in the laboratory. However, when the Profile Probe laboratory-derived calibration was evaluated under field conditions, it overestimated soil moisture, especially at depth. Their study and others such as those of Lukanu and Savage (2006), Logsdon (2009), and Ojo (2012) have shown that soil moisture instrument calibrations developed by the manufacturers using laboratory procedures are not always adaptable for use under field conditions. Field calibration of the sensors should be developed using different soil types. Paige and Keefer (2008) evaluated three soil moisture sensors installed in a shrub-covered, semiarid watershed in Arizona and reported that each sensor responded differently to precipitation events and soil variability. Chow et al. (2009) compared the field performance of nine soil moisture sensors in sandy loam in the maritime region of Canada. They observed that the sensor with the best factory calibration had a relative RMSE of 15.78% with an r^2 of 0.75.

Most soil moisture sensor calibration and inter-sensor comparison studies have been performed on coarse- and/or medium-textured soils (Fares and Alva, 2000; McMichael and Lascano, 2003; Chandler et al., 2004; Geesing et al., 2004; Plauborg et al., 2005; Polyakov et al., 2005; Evett et al., 2006; Lukanu and Savage, 2006; Paige and Keefer, 2008; Kelleners et al., 2009; Chow et al., 2009; Gabriel et al., 2010; Sakaki et al., 2011; Paraskevas et al., 2012; Mittelbach et al., 2012). None of the literature reviewed had reported an in situ calibration or inter-sensor comparison study in soils with >65% clay content.

The thermogravimetric method is the standard method for quantifying soil moisture; it involves oven drying a known volume of moist soil and determining the weight loss to give the gravimetric water content, which can be multiplied by the bulk density to obtain the volumetric water content (Topp et al., 2008). This method has significant limitations because it is a relatively slow process that requires intensive labor and the sampled soil cannot be used for repeated measurement. Despite these limitations, this method is very important for calibrating soil moisture sensors (Robock et al., 2000; Walker et al., 2004; Robinson et al., 2008). Robinson et al. (2008) and Dobriyal et al. (2012) published comprehensive reviews on the various soil physical properties and the corresponding soil sensing instrumentation used in determining soil moisture.

In this study, five widely used sensors were evaluated: the EnviroSCAN probe, the Diviner 2000 (both from Sentek Technologies), the Hydra Probe soil sensor (Stevens Water Monitoring Systems), the ThetaProbe ML2x (Delta-T Devices), and the ECH$_2$O EC-5 (Decagon Devices). The objectives of this study were to evaluate the accuracy in field performance of these five soil moisture instruments in heavy clay soil by comparing the soil moisture output from their factory default calibration with the volumetric water content determined using the thermogravimetric method and to assess the improvements in accuracy made from new in situ calibration equations developed for each sensor.

MATERIALS AND METHODS

Site Description

The experiment was conducted at the Regional Operation Center of Agriculture and Agri-Food Canada in Winnipeg in the fall of 2013 and spring of 2014. The study area, being vertisolic, is characterized by heavy clay soil with a surface (0–15-cm) texture ranging from 67 to 76% clay and a sand content ranging from 5 to 7% with 7.8% organic matter; the subsurface texture (15–30 cm) contained 69 to 74% clay and 5 to 6% sand with 5.5% organic matter. The cation exchange capacity ranged between 36.3 and 45.1 and between 42.9 and

47.8 cmol kg^{-1} of soil in the surface and subsurface layers, respectively. The site elevation is 233 m above sea level and lies within the Osborne soil series, which is a poorly drained Rego Humic Gleysol developed on a moderately to strongly calcareous, fine-textured lacustrine deposit.

About 8% of the Canadian Prairie farmland is vertisolic soils with clayey (>60% clay content) glacio-lacustrine parent materials and is characterized by high soil water holding capacity and low hydraulic conductivity. At low soil moisture contents, these soils shrink, which results in the formation of large cracks. At high soil moisture contents, the soil swells because of the dominance of smectitic clay minerals (Anderson, 2010). Vertisolic soils occur in the Manitoba Red River Valley, which is a highly productive agricultural area. Due to its low hydraulic conductivity, this soil type contributes to spring flooding from snowmelt, which sometimes results in delayed seeding. In situ soil moisture monitoring networks have been established in this region by Agriculture and Agri-Food Canada as well as Manitoba Agriculture Food and Rural Development to assist in flood and drought monitoring and forecasting. The evaluation of the accuracy of various soil moisture instruments and their adaptability to the heavy clay soils in this region is critical to ensure the accuracy of the soil moisture measurements for many hydrologic and agronomic applications.

Soil Moisture Instruments

The EnviroSCAN probe and the Diviner 2000 are multidepth instruments. Both devices require the installation of an access tube in the ground, and the soil volume measured is mostly within a 10-cm diameter of the tube (Schwank et al., 2006; Sentek Technologies, 2011). The ECH_2O EC-5, Hydra Probe, and ThetaProbe soil moisture devices are prong based, with tines protruding out of the probe head. Table 1 provides information on the frequency and output of the five soil moisture instruments as well as some literature that provides detailed sensor descriptions, calibration studies, and research applications.

Data Collection

Three areas were established and categorized as "wet," "moist," and "dry." Each area had several sampling sites established. The wet area was flooded a few days before sampling, and rain shelters were placed above the dry area a few weeks before sampling. The wet, moist, and dry calibration areas were expected to contain >0.40, 0.30 to 0.40, and <0.30 $m^3\ m^{-3}$ water content, respectively. The Sentek tubes were installed to the 60-cm depth, and 15 and 35 cm were the depths from which the observed soil moisture was compared with the sensor readings. On the sampling days, the soil moisture content was first determined using the multidepth instruments. Immediately after taking the readings, three soil cores (7-cm length and 7.2-cm diameter) were taken very close to each tube at 11 to 18 cm to represent the 15-cm depth and at 31 to 38 cm for the 35-cm depth. Each core was assigned to one of three pronged instruments—the Hydra Probe, ThetaProbe, or ECH_2O EC-5—to determine the instruments' soil moisture reading before using the thermogravimetric method to determine the volumetric water content. The observed volumetric water content for each core as determined with a specific instrument was used to calibrate that instrument. However, the mean value from all three cores was used in calibrating the EnviroSCAN and Diviner 2000. Volumetric water content sensed by the instruments in a heterogeneous medium such as soil is influenced by soil properties like bulk density and environmental conditions like temperature (Evett et al., 2006; Fares et al., 2007). The effect of these factors on the instruments' soil moisture readings was not analyzed in this study because the data collection, using all five instruments, was performed under the same conditions (e.g., bulk density and temperature).

Calibration and Statistical Analysis

Soil moisture instruments relate measureable soil properties such as changes in frequency or dielectric permittivity to the volumetric water contents. Table 1 shows the preset factory calibration equations used by the instruments. However, to achieve bet-

Table 1. Information on the soil moisture instruments tested in this study.

Instrument	Operating frequency	Default calibration†	Sensor output	Literature
	MHz			
EnviroSCAN	100‡	$\theta = (5.11SF - 0.1456)^{2.475}$	scaled frequency	Paltineanu and Starr (1997), Nachabe et al. (2004), Kelleners et al. (2004), Schwank et al. (2006), Starr and Rowland (2007), Holcomb et al. (2011)
Diviner 2000	100‡	$\theta = (3.642SF)^{3.0175}$	scaled frequency	Groves and Rose (2004), Evett et al. (2006), Ma et al. (2007), Egea et al. (2009, 2010), Sentek Technologies (2011), Paraskevas et al. (2012)
ECH_2O EC-5	70	$\theta = 0.00085RAW - 0.48$	raw count	Rosenbaum et al. (2010), Sakaki et al. (2011), Decagon Devices (2012), Durigon et al. (2012)
Hydra Probe	50	$\theta = 0.109\sqrt{(\varepsilon)} - 0.179$	real dielectric	Cosh et al. (2004), Seyfried et al. (2005), Bellingham (2007), Logsdon et al. (2010), Rowlandson et al. (2013), Vaz et al. (2013)
ThetaProbe ML2x	100	$\theta = 0.542V - 0.06$	voltage (mV)	Delta-T Devices (1999), Koyama et al. (2010), Sakaki et al. (2011), Kulasekera et al. (2011), Adams et al. (2013)

† Default calibration equations show the relationship between volumetric water content θ and the sensor output.

‡ Frequency varies with the soil permittivity within a range of approximately 100 MHz in water to 150 MHz in air (Schwank et al., 2006).

ter accuracy, user-specific calibration that relates the instruments' raw output to the observed soil moisture is important. The volumetric water contents from the soil cores were related to the raw data from the instruments to develop new coefficients. A general calibration equation was developed for each of the five instruments using the entire data collected, and the generated calibration for the multidepth instruments was compared with other published calibration equations. After this, the data were divided into two halves; one half was used to develop a new calibration equation and the other half was used to evaluate the newly developed equation. Statistical indicators such as the coefficient of determination (r^2), the root mean square error (RMSE):

$$\mathrm{RMSE}=\left[\frac{\sum\left(D_i-\mathrm{Obs}_i\right)^2}{n}\right]^{0.5} \quad [1]$$

normalized root mean square error (NRMSE):

$$\mathrm{NRMSE}=\frac{1}{\overline{\mathrm{Obs}}}\sqrt{\frac{\sum\left(D_i-\mathrm{Obs}_i\right)^2}{n}}\times 100 \quad [2]$$

and the mean bias error (MBE):

$$\mathrm{MBE}=\frac{1}{n}\sum_{i=1}^{N}\left(D_i-\mathrm{Obs}_i\right) \quad [3]$$

were used to compare the devices' output (D_i) to the observed soil moisture (Obs_i). Part of the measurement requirement of some missions, such as the Soil Moisture Active Passive (SMAP) and Soil Moisture and Ocean Salinity (SMOS), was to obtain the volumetric soil moisture with an accuracy within 0.04 $m^3\ m^{-3}$ (Entekhabi et al., 2010; Kerr et al., 2010). The NRMSE gives the relative difference between the default and the observed values. If the NRMSE is <10%, the default value can be considered excellent, good if between 10 and 20%, fair if within the 20 to 30% range, but poor if >30% (Raes et al., 2012).

RESULTS AND DISCUSSION

Instrument Default vs. Thermogravimetric Water Content

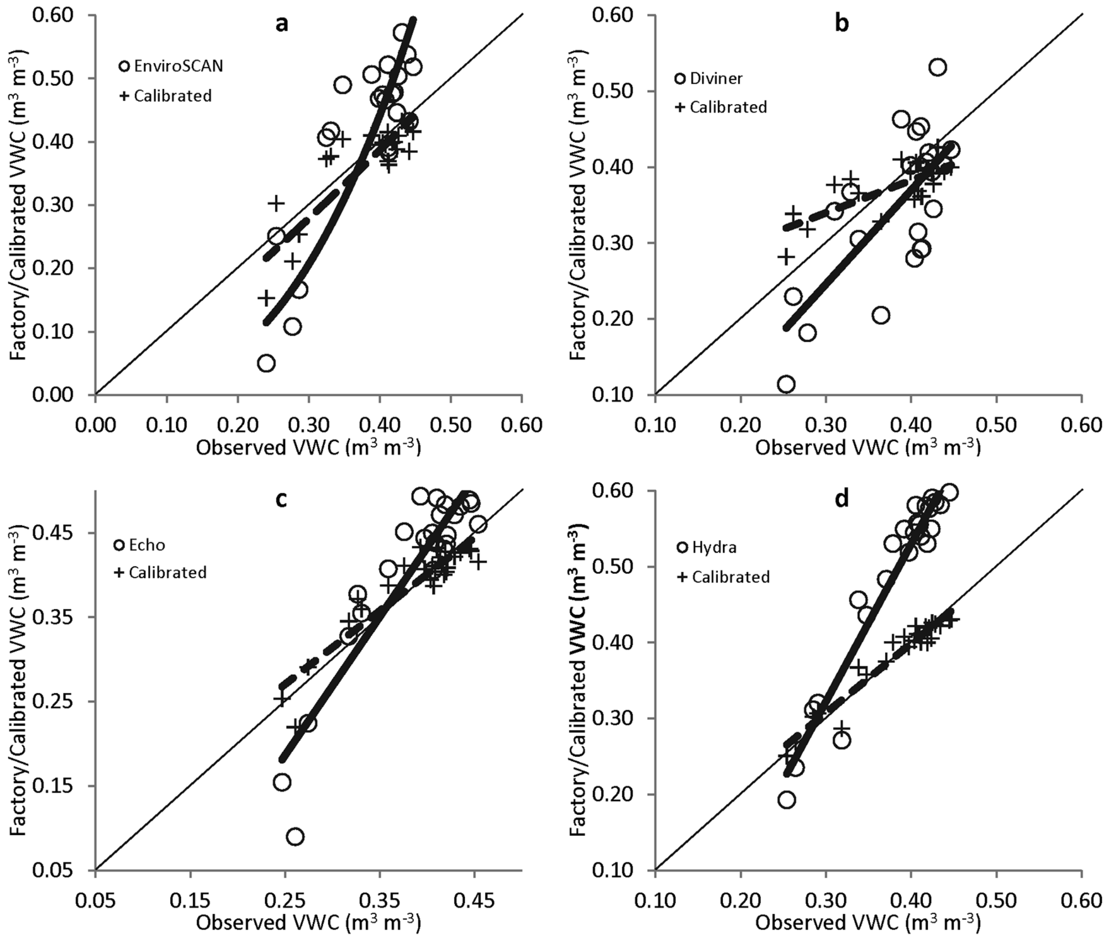
The outputs of all five instruments using their default settings were compared with the volumetric water content from thermogravimetric analysis. The observed soil moisture ranged from near the permanent wilting point at 0.20 $m^3\ m^{-3}$ to slightly above field capacity at 0.46 $m^3\ m^{-3}$; this range covers most of the soil moisture conditions expected during the growing season. The volumetric water contents in the moist category (as described above) were observed to be close to or within the wet category in 45% of the cases. Thus, there were more data points close to field capacity than to the permanent wilting point. Data analysis (not shown) did not indicate any observable difference in the instruments' sensing of the soil moisture at the two depths considered: 15 and 35 cm. Therefore, all of the data collected were analyzed together, and no depth-related comparison is reported.

The results in Table 2 show that the two multidepth instruments (EnviroSCAN and Diviner 2000) had lower R^2 values of 0.80 and 0.62, respectively, when compared with the three pronged sensors, which had R^2 values ranging from 0.89 to 0.95. This may be due to the presence of cracks within the soil sensing volume of the multidepth instruments leading to greater underestimation at low soil moisture content (Fig. 1a–1b). During core sampling, these cracks were avoided. Thus, the observed moisture content from core samples may not be entirely ideal for calibrating the multidepth instruments at low moisture content. In smectitic clays, the shrinking of the soil at low moisture content creates cracks with water molecules adhering to the soil matrix and potentially creating an air pocket with a very low dielectric constant in contact with the probe. Campbell (1990) observed that the degree of bonding of water molecules to soil particles influences the dielectric permittivity of the medium (cf. Schwartz et al., 2009). The underestimation at low soil moisture contents was less in the three pronged sensors because cracks were avoided in the core samples used in calibrating these sensors.

The Hydra Probe had the highest R^2 of 0.95. However, despite having the best R^2, the performance of the Hydra Probe using the default setting was generally poor, with RMSE, NRMSE, and MBE values of 0.131 $m^3\ m^{-3}$, 36.6%, and 0.108 $m^3\ m^{-3}$, respectively. The sensor grossly overestimated the soil moisture content near field capacity. This is consistent with studies such as that of Seyfried and Murdock (2004), who observed that the Hydra Probe clay calibration equation gave unrealistic readings at high water contents. Logsdon and Hornbuckle (2006) compared three sensors and reported that the Hydra Probe had the highest RMSE and suggested that this may be due to its lower operating frequency, which is sensitive to electrical conductivity. Of all the instruments compared in this study, the Hydra Probe has the lowest operating frequency (Table 1). The Diviner 2000 showed a slightly negative MBE, but a positive bias was observed in all other sensors. Overall, the default setting of the ThetaProbe had the best performance, with an RMSE of 0.025 $m^3\ m^{-3}$ and 0.2% MBE. At low soil moisture content, all the instruments underestimated soil moisture (Fig. 1). At the high end, however, the EnviroSCAN, ECH_2O EC-5, and Hydra Probe overestimated soil moisture. This result reinforces the need to calibrate the sensors to local conditions to enhance the accuracy of the output.

Table 2. Accuracy of soil moisture output from each sensor using their respective default calibration equations as determined by the R^2, RMSE, normalized root mean square error (NRMSE), and mean bias error (MBE).

Instrument	n	R^2	RMSE	NRMSE	MBE
			$m^3\ m^{-3}$	%	$m^3\ m^{-3}$
EnviroSCAN	43	0.80	0.100	26.3	0.047
Diviner 2000	44	0.62	0.075	19.7	−0.008
ECH_2O EC-5	50	0.89	0.058	15.1	0.014
Hydra Probe	50	0.95	0.131	36.6	0.108
ThetaProbe ML2x	48	0.91	0.025	6.5	0.002



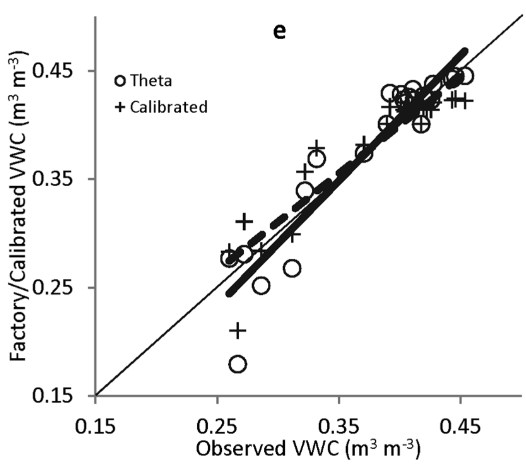


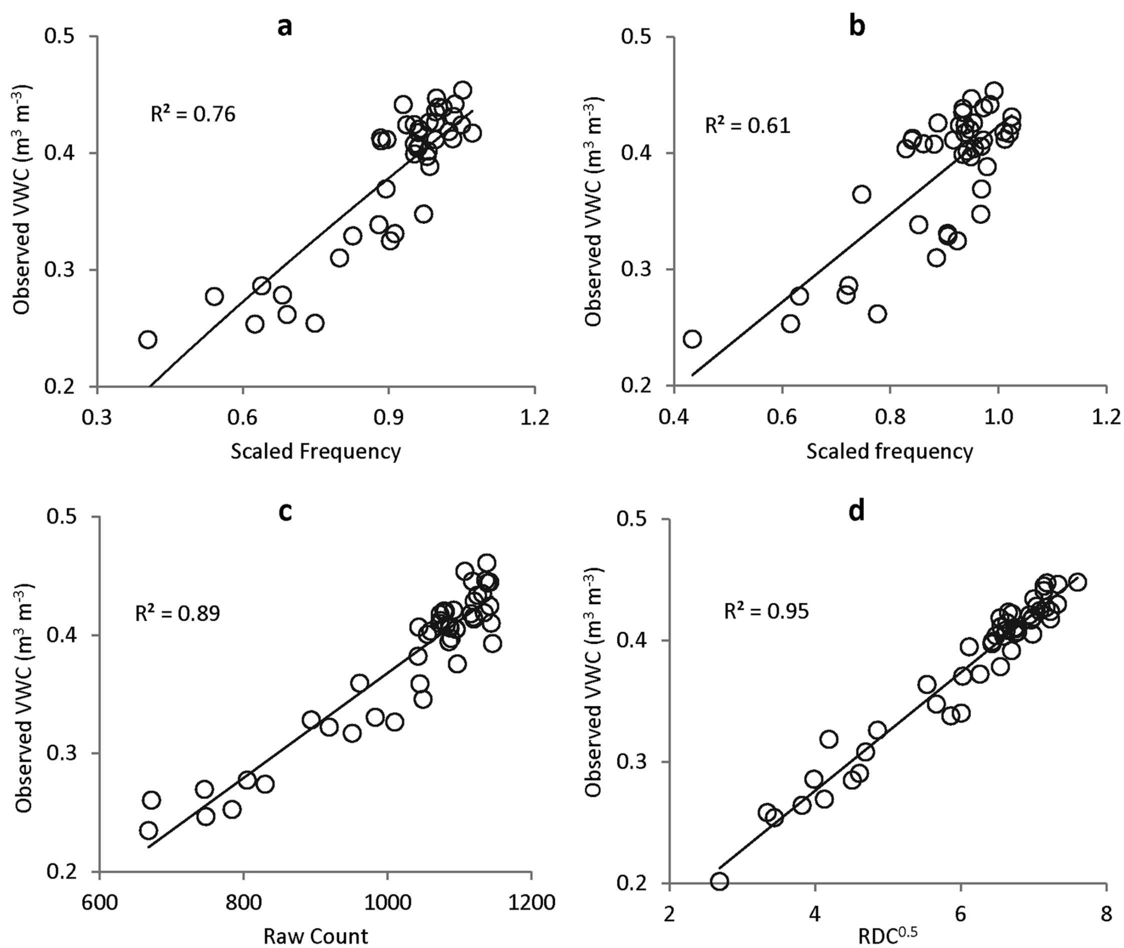
Fig. 1. A 1:1 comparison of observed moisture content with the factory-derived moisture content (○) and calibrated volumetric water content (VWC) (+) for (a) the EnviroSCAN probe, (b) the Diviner 2000, (c) the ECH_2O EC-5, (d) the Hydra Probe, and (e) the ThetaProbe ML2x. The thin solid line is the 1:1 line, the thick solid line is the factory-derived trend line, and the thick dashed line is the calibration equation trend line.

Calibration Results

Table 3 shows the field calibration equations that were developed by relating the raw output from the sensors to the observed volumetric water content from soil cores using all the data collected. The two multidepth sensors showed lower R^2 values of 0.76 and 0.61 for the EnviroSCAN and Diviner 2000, respectively, compared with the prong-based sensors with R^2 values of 0.89, 0.95, and 0.89 for the ECH_2O EC-5, Hydra Probe, and ThetaProbe, respectively (Fig. 2). Evett et al. (2006) compared the factory calibration of several soil moisture sensors, including the EnviroSCAN and Diviner 2000, with the observed soil moisture in silty clay loam, clay, and clay loam soils. The calibration equations developed in the laboratory for the silty clay loam and clay had R^2 values of 0.993 and 0.992 for the EnviroSCAN and Diviner 2000, respectively. Similarly, Groves and Rose (2004) obtained an R^2 value of 0.93 for laboratory calibration of

Table 3. Field calibration equations for volumetric soil moisture content (θ) developed for each sensor using all data points.

Instrument	n	R^2	Equation	x input
EnviroSCAN	43	0.76	$\theta = 0.4121x^{0.8088}$	scaled frequency
Diviner 2000	44	0.61	$\theta = 0.3781x + 0.0452$	scaled frequency
ECH_2O EC-5	50	0.89	$\theta = 0.0004x - 0.0752$	raw count
Hydra Probe	50	0.95	$\theta = 0.0487x + 0.0816$	(real dielectric)$^{0.5}$
ThetaProbe ML2x	48	0.89	$\theta = 0.0985x - 0.0956$	(real dielectric)$^{0.5}$



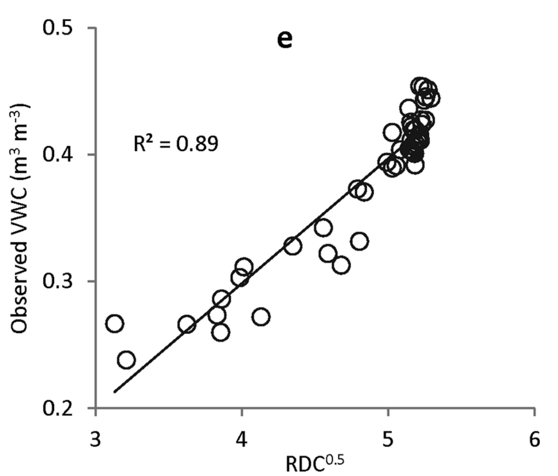


Fig. 2. General field calibration of volumetric water content (VWC) vs. real dielectric constant (RDC) for (a) the EnviroSCAN probe, (b) the Diviner 2000, (c) the ECH_2O EC-5, (d) the Hydra Probe, and (e) the ThetaProbe ML2x.

the Diviner 2000 in a clay soil. The R^2 values obtained by these researchers were higher than the values obtained in our study. This can be explained by the controlled environment the laboratory provided in their study compared with field calibration.

Sentek Technologies (2011) conducted EnviroSCAN field calibration experiments in cracking clay soils at various sites in Australia and reported an R^2 of 0.58. In contrast, Fares et al. (2004) observed an R^2 value of 0.89 for a shrink–swell clay soil (35–100-cm depth) in South Australia using the EnviroSCAN. It should be noted that the manufacturer of these multidepth devices, Sentek Technologies (2011), used power functions for the default calibration but reported many studies that have found and used linear functions. The equations that we developed in this study use soil moisture (*y* axis) as a function of the instruments' output—in this case, scaled frequency (*x* axis). This is different from the suggested equation format, which uses scaled frequency as a function of soil moisture.

The calibration equations developed for the three pronged sensors had R^2 values of 0.89, 0.95, and 0.89 for the ECH_2O EC-5, Hydra Probe, and ThetaProbe, respectively. The ThetaProbe R^2 of 0.89 is higher than the R^2 value of 0.77 observed by Kaleita et al. (2005), who used the ThetaProbe for field calibration of soils with clay contents ranging from 16 to 26%. The ECH_2O EC-5 probe R^2 value of 0.89 is slightly higher than the R^2 of 0.87

found by Odubanjo et al. (2013). Overall, the Hydra Probe had the best R^2 of 0.95. This value is higher than the field calibration R^2 value of 0.81 obtained by Rowlandson et al. (2013) for the surface layer of soils with >40% clay content across 25 fields in Manitoba, Canada.

Multidepth Instruments' Calibration Comparisons

Calibration equations derived for the multidepth sensors in this study were compared with several published calibrations determined in clay soil (Table 4). Although there are quite a number of published calibrations for the multidepth instruments, very few of these calibrations have been conducted in soils with >35% clay. Groves and Rose (2004) and Evett et al. (2006) developed calibration equations in the laboratory for clay soils using the multidepth instruments. Fares et al. (2004), Sentek Technologies (2011), and our study developed field-based calibrations in clay soils. Figure 3 compares the equations using both the Diviner 2000 and the EnviroSCAN. The two laboratory-derived equations, using the Diviner 2000, had almost the same air-dry and saturation points but different pathways. The calibration equation of Groves and Rose (2004) showed higher volumetric water content than that of Evett et al. (2006) at the same scaled frequency. The Evett et al. (2006) laboratory-derived calibration using the EnviroSCAN was higher than the two laboratory-derived calibrations using the Diviner 2000. A similar trend was observed between the laboratory-derived equations and the calibration of Fares et al. (2004) in clay at <0.40 $m^3\ m^{-3}$ volumetric water content.

The field-derived calibration from Sentek Technologies (2011) using the EnviroSCAN was perfectly aligned with the Diviner 2000 calibration derived from this study. This perfect alignment is reflected in the RMSE of both calibrations, which was 0.036 $m^3\ m^{-3}$ (Table 4). The EnviroSCAN calibration equation derived in this study showed slightly higher volumetric water contents at low scaled frequencies and slightly lower water contents at high scaled frequencies than the Diviner 2000 calibration equation. The two equations derived in our study for the two multidepth instruments were not significantly different from each other ($p = 0.48$) within the observed soil moisture range, which could be a result of both devices operating at similar frequencies. At volumetric water contents <0.40 $m^3\ m^{-3}$, the laboratory-derived calibrations and those of Fares et al. (2004) had lower soil moisture than the calibration equation from this study. Haberland et al. (2014) conducted both laboratory and field calibrations using the Diviner 2000 in clay loam and clay soils. They observed that the manufacturer's default equation gave satisfactory results in the laboratory but underestimated the water content in both soils under field conditions.

Table 4. Comparison of published calibration equations for the multidepth sensors.

Instrument	Clay/silt contents	Equation†	RMSE
	%		$m^3\ m^{-3}$
EnviroSCAN			
This study	71/24	$\theta = 0.4121SF^{0.8088}$	0.030
Evett et al. (2006)‡	39/46	$\theta = 0.605SF^{3.812} + 0.024$	0.178
Sentek Technologies (2011)	cracking clay	$100\theta = (0.073 + SF)/0.0254$	0.029
Fares et al. (2004)§	62/11	$\theta = 1.605SF^{0.552} - 1.186$	0.072
Diviner 2000			
This study	71/24	$\theta = 0.3781SF + 0.0452$	0.036
Evett et al. (2006)	39/46	$\theta = 0.457SF^{5.421} + 0.034$	0.116
Sentek Technologies (2011)¶	cracking clay	$100\theta = (0.073 + SF)/0.0254$	0.036
Groves and Rose (2004)	44/19	$100\theta = (SF/0.3107)^{3.3715}$	0.090

† θ, volumetric water content ($m^3\ m^{-3}$); SF, scaled frequency.

‡ Single calibration equation developed from a silty clay loam with 30% clay and 53% silt and a clay soil with 48% clay and 39% silt.

§ Calibration equation and texture represents lower soil profile of 35–100-cm depth.

¶ Clay calibration equation derived using the EnviroSCAN but applied for use with the Diviner 2000 for comparison; 0.073 is the average of the *C* constant for the top 30-cm depth.

Evaluation Results

The data set was divided in half, and new field calibration equations were developed for each device using one-half of the data. This was done to assess the improvements made over the default equation using independent data sets (the other half) that were not included in developing the calibration equations. Kaleita et al. (2005) conducted a ThetaProbe field calibration study of different medium-textured soils in Iowa and recommended that about 20 sample points be used for developing a valid field calibration equation. Both our calibration and evaluation data sets consisted of >20 sample points. Table 5 shows that all the sensors had improved RMSE, NRMSE, and MBE values with the in situ calibration equations compared with the default in the evaluation data set. The two multidepth sensors had slight negative biases and the three pronged sensors were almost bias neutral.

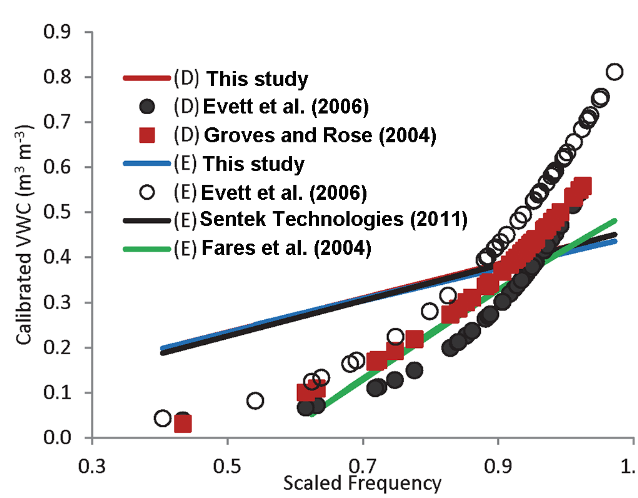


Fig. 3. The comparison of several volumetric water content (VWC) calibration equations for the Diviner 2000 (D) and EnviroSCAN (E). The lines are field-based calibrations and symbols are laboratory-based calibrations.

Table 5. Impact of field calibration on the accuracy of soil moisture measurement by each sensor as indicated by the R^2, RMSE, normalized root mean square error (NRMSE), and mean bias error (MBE).

Instrument	Equation	*n*	R^2	RMSE	NRMSE	MBE
				$m^3\ m^{-3}$	%	$m^3\ m^{-3}$
EnviroSCAN	default	22	0.71	0.096	25.3	0.033
	calibrated			0.040	10.5	−0.012
Diviner 2000	default	22	0.51	0.080	21.0	−0.035
	calibrated			0.040	10.6	−0.006
ECH_2O EC-5	default	25	0.84	0.060	15.6	0.023
	calibrated			0.023	6.0	0.003
Hydra Probe	default	25	0.94	0.129	33.9	0.110
	calibrated			0.014	3.8	0.000
ThetaProbe ML2x	default	24	0.88	0.027	7.1	0.003
	calibrated			0.023	6.0	0.002

Figure 1a shows that the EnviroSCAN calibration equation line is very close to the 1:1 line. At low soil moisture contents, it had a slight underestimation, but this gap was smaller at high moisture contents. Although a power function was used in the calibration, the line behaved like a linear regression line within the range of observed moisture content. The NRMSE was reduced from 25.3 to 10.5%. Figure 1b shows that the default equation consistently underestimated soil moisture. On the other hand, the calibration trend line crossed the 1:1 trend line at about 0.37 $m^3\ m^{-3}$ and showed overestimation at low soil moisture content and underestimation at high soil moisture content. Thus, depending on the evaluation data set, the developed calibration equation for the Diviner 2000 may result in very minimal improvement over the default equation. The calibration analysis of both the ECH_2O EC-5 and the ThetaProbe showed that the calibrated soil moisture data had a slight overestimation at low soil moisture contents, which disappeared as the moisture content increased (Fig. 2c and 2e). As discussed above, the ThetaProbe gave the best result during the pre-calibration analysis, and this can be observed in the close fit of the default trend line to the 1:1 line. Calibration resulted in minimal improvements.

Of all the sensors compared, the Hydra Probe showed the greatest improvement with field calibration. The RMSE of 0.129 $m^3\ m^{-3}$ using the default equation was reduced to 0.014 $m^3\ m^{-3}$ using the in situ calibration. The 11% overestimation bias was nonexistent using the calibration equation, i.e., on average, no overestimation or underestimation occurred. Figure 1d shows that the Hydra Probe calibration trend line (dashed lines) are almost perfectly aligned with the 1:1 line. Thus, using the square root of the Hydra Probe's real dielectric constant, we observed a nearly perfect absolute accuracy with the observed volumetric water content, which shows the absolute necessity of in situ calibration before using the instrument in heavy clay soils.

The effect of soil temperature on volumetric water measurement by capacitance sensors has been well documented (Schwank and Green, 2007; Fares et al., 2007; Seyfried and Grant, 2007). Analysis conducted in this study did not include any correction for temperature. Data collection was performed at soil temperatures between 10 and 20°C, and all the instruments were used under similar conditions. Therefore, temperature correction for the instruments used in this study is not expected to lead to a significant difference in the results of this instrument performance study. It should be noted that beyond the soil texture and temperature, other factors such as salinity, cation exchange capacity, clay mineralogy, and the amount of bound water can influence how soil moisture is sensed by the instruments (Schwartz et al., 2009). The calibration equations developed in this study should be evaluated at other heavy clay sites across the Prairies to determine their adaptability.

CONCLUSIONS

The field performance of five instruments that monitor soil moisture was compared in heavy clay soil, and in situ calibration equations were generated. Two of these instruments had simultaneous multidepth sensing capability and the other three instruments were prong-based, single-depth sensors. Soil moisture was monitored at the 15- and 35-cm depths, and core samples were collected to calibrate the instruments. Regardless of the instrument used, in situ calibration improved the performance of the instruments. The Hydra Probe had the greatest improvement, resulting in reduced RMSE from 0.129 to 0.014 $m^3\ m^{-3}$ in the evaluation data set, which underscores the importance of developing in situ calibration before using the instrument, especially in heavy clay soils. This study showed that the ThetaProbe did not need to be calibrated because the improvement observed with calibration was minimal.

Linear regression was used to describe the relationship between the raw output from the instrument and the observed volumetric water content for all the sensors except the EnviroSCAN, for which a power function was used. The two multidepth instruments showed similar post-calibration performance, with an RMSE of 0.04 $m^3\ m^{-3}$. The calibration equations generated for the two instruments were not significantly different from each other. However, using the default calibration equation, the Diviner 2000 had a better performance RMSE of 0.08 $m^3\ m^{-3}$ compared with an RMSE of 0.096 $m^3\ m^{-3}$ for the EnviroSCAN. The performance of both multidepth instruments was lower than that of the three pronged instruments because the multidepth instruments underestimated the observed soil moisture at low moisture contents. This was probably due to the presence of some cracks within the sensing volume of the dry clay soil. These cracks were avoided in taking core samples used for calibration of the pronged sensors. Some might argue that the calibration procedure was not an accurate depiction of the soil matrix under dry conditions. However, it must be remembered that when these sensors are deployed in heavy clay soils, cracking is a normal occurrence.

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