Measurement of Soil Water Content with a 50-MHz Soil Dielectric Sensor

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ABSTRACT

The Hydra Probe[1] is a relatively inexpensive and widely used soil water content (θ, m^3 m^{-3}) sensor. It measures both the real (ε_r) and imaginary (ε_i) components of the complex soil dielectric constant at 50 MHz. Our objectives were to: (i) determine the accuracy and precision of Hydra Probe dielectric measurements, (ii) establish an electrical conductivity limit for Hydra Probe measurements, (iii) document effects of soil type and temperature, and (iv) relate these results to much more thoroughly studied relationships established for time domain reflectometry (TDR). We evaluated Hydra Probe ε_r measurement precision and accuracy in air, ethanol, butanol, and water. Electrical conductivity effects were established in a series of aqueous KCl solutions. Effects of soil type on calibration were evaluated with four soils. Temperature sensitivity was tested in air, oven-dried, and nearly saturated soil. Each test was performed with three sensors. We found that, in fluids, the sensors were accurate (ε_r within 0.5), precise (coefficient of variation [CV] $< 1\%$), and that inter-sensor variability was generally low except in KCl solutions with electrical conductivities >0.142 S m^{-1} (0.01 *M*). There was a strong correlation between θ and ε_r for all soils tested but the θ–ε_r relationship varied with soil. Deviations of measured θ–ε_r from the Topp equation increased in magnitude with ε_i, which may be the key to more general calibrations. Temperature effects on ε_r were negligible in oven dry soils and different for each soil when nearly saturated. The largest temperature effect relative to 25°C was ± 0.03 m^3 m^{-3}. In general, it appears that differences between Hydra Probe and TDR measurements are related to differences in soil dielectric properties at the measurement frequencies of the two instruments.

KNOWLEDGE OF soil–water content (θ, m^3 m^{-3}) is critical for determination of local energy and water balance, transport of applied chemicals to plants and ground water, irrigation management, and precision farming. The traditional standard θ measurement technique is gravimetric sampling (Gardner, 1986), in which a sample of soil is physically removed, weighed in the field moist condition, and then weighed again after oven drying. Multiplication of the gravimetric water content by the bulk density gives θ. Alternative methods are desirable because gravimetric sampling is destructive, eventually altering the nature of the site, it is confounded by spatial variability and it requires an on-site visit to collect data. Several nondestructive methods have been devised to measure and monitor θ including neutron thermalization (Greacen, 1981), electrical resistance (Coleman and Hendrix, 1949; Spaans and Baker, 1992; Seyfried, 1993), TDR (Topp et al., 1980; Cassel et al., 1994), and electrical capacitance (Robinson and Dean, 1993; Nadler and Lapid, 1996; Seyfried and Murdock, 2001). The electronic techniques have the added advantage that data can be collected nearly continuously and either stored on site or transmitted to a computer via telephone or radio.

With TDR, the travel time of electromagnetic pulses traveling along a waveguide, which is directly related to the apparent soil dielectric constant (K_a), is measured. Since the dielectric constant of water (80 at room temperature) is very much greater than that of air (1) or soil solids (2–5), the measured composite K_a is primarily a function of θ. Intensive research of TDR (see Zegelin et al., 1992; Jones et al., 2002) has shown that K_a can be related to θ with reasonable accuracy for a wide variety of soils using a single calibration equation developed by Topp (Topp et al., 1980). Although application of the Topp equation to high clay content soils often leads to an underestimation of θ (e.g., Dirksen and Dasberg, 1993), TDR is generally regarded as the best available electronic technique for the measurement of θ.

The high cost of TDR has lead to the development of alternative soil water sensors that use the principle of measuring soil dielectric properties to determine θ. Probably the most widely used of these alternative sensors measure soil capacitance (Dean et al., 1987; Evett and Steiner, 1995; Paltineanu and Starr, 1997; Seyfried and Murdock, 2001). Briefly, the basis for the most common approach to measuring soil capacitance is that when a circuit with a capacitor is subjected to an oscillating signal, the resultant oscillation frequency is related to the circuit capacitance which, in turn, is directly related to its dielectric constant. Capacitance devices are designed to effectively make the soil of interest the primary dielectric material for a capacitor so that changes in θ result in changes in the circuit frequency. Empirical calibrations are used to relate θ to measured frequency (Whalley et al., 1992).

In this paper, we report results from the investigation of the Hydra Probe soil water sensor. The Hydra Probe differs from most other alternative sensors in that outputs from the sensor include bulk soil electrical conductivity and temperature (measured with a thermistor), in addition to θ. The Hydra Probe is better described as a soil dielectric sensor than a capacitance sensor because it measures both components of the complex dielectric constant. This allows for a more direct comparison with TDR than is possible with capacitance sensors.

The Hydra Probe is currently in widespread use (e.g., the Soil Climate Analysis Network of the Natural Resource Conservation Service) and is under active consideration for use in other soil water monitoring programs. It has proven to be robust under a variety of field condi-

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[1] Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the author or USDA.

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Abbreviations: CV, coefficient of variation; S1, sensor #1; S2, sensor #2; S3, sensor #3; TDR, time domain reflectometry.

tions. Like most of the alternative sensors, the Hydra Probe has received little independent evaluation. In a previous report, we presented data indicating that the standard calibration curves supplied by the manufacturer do not effectively describe measured data and that soil temperature effects may be substantial (Seyfried and Murdock, 2002). Our objectives in this paper are to: (i) determine the accuracy and precision of Hydra Probe dielectric measurements, (ii) establish an electrical conductivity limit for Hydra Probe measurements, (iii) document effects of soil type and temperature on dielectric measurement, and (iv) relate these results to much more thoroughly studied relationships established for TDR. We expect that results from this study will lead to better use of these sensors in future field monitoring programs and will facilitate interpretation of data currently being collected.

MATERIALS AND METHODS

Sensor Description

The dielectric constant of a material is, in general, complex and proportional to the electrical permittivity of the material and the permittivity of free space such that

$$K = \frac{\varepsilon}{\varepsilon_0} \qquad [1]$$

and

$$K = \varepsilon_r + i\varepsilon_i, \qquad [2]$$

where K is the dimensionless complex dielectric constant, ε is the electrical permittivity, ε_0 is the permittivity in free space, ε_r is the real component of the complex dielectric constant, ε_i is the imaginary component of the complex dielectric constant and $i = (-1)^{1/2}$. The Hydra Probe measures both ε_r and ε_i. Heimovaara et al. (1994) and Or and Wraith (1999) showed that, in general, the K_a measured with TDR is effectively equal to ε_r, so that the Hydra Probe-measured ε_r values are used to calculate θ.

The effects of frequency dependent dielectric polarization and frequency independent electrical conductivity on Hydra Probe measurements are indistinguishable and related by the following expression:

$$\varepsilon_i = \frac{\sigma}{\omega\varepsilon_0} \qquad [3]$$

where σ is the electrical conductivity and ω is the angular frequency. Hydra Probe-calculated values of σ are based on Eq. [3]. Another critical parameter, the loss tangent ($\tan \delta$), is proportional to the energy dissipation experienced by the input voltage and defined as

$$\tan \delta = \varepsilon_i/\varepsilon_r. \qquad [4]$$

The Hydra Probe design is based on the work of Campbell (Campbell, 1988, 1990), who described the theory of operation. The instrument consists of a 4-cm diameter cylindrical head, which has four 0.3-cm diameter tines which protrude 5.8 cm. These are arranged such that a centrally located tine is surrounded by the other three tines in an equilateral triangle with 2.2-cm sides. A 50-MHz signal is generated in the head and transmitted via planar waveguides to the tines, which constitute a coaxial transmission line. The impedance of the probe depends on the electronic components and the K of the material between the tines (e.g., soil). The relationship is:

$$Z_p = \text{cotanh}\,\frac{(\omega L\,\sqrt{K})}{c}\,i \qquad [5]$$

where Z_p is the probe impedance, L is the electric length of the probe, and c is the speed of light (Campbell, 1990).

When a voltage is applied to the probe, the reflected signal is related to Z_p such that

$$\frac{Z_p}{Z_c} = \frac{1 + \Gamma}{1 - \Gamma} \qquad [6]$$

where Z_c is the characteristic impedance of the coaxial cable and Γ is the complex ratio of the reflected voltage to the incident voltage. The Hydra Probe uses measured Γ to determine Z_p that can, in turn, be used to determine K. Seven-conductor cable transmits analog DC voltages to a datalogger. Downloaded voltage data are then used to calculate ε_r, ε_i, and temperature. Calibration equations relating ε_r to θ are supplied by the manufacturer (Vitel Inc., 1994).

In this study we performed tests of the Hydra Probe in four fluids and four different soils. The soil tests included a wide range of water contents and temperatures. The fluids, which have a known ε_r, were used to establish the accuracy of ε_r measurements. A series of KCl solution concentrations was used to establish the limit of instrument operation in terms of σ. These data also provide information concerning instrument precision independent of any variability introduced by placing the sensors in the soil and having a variable degree of physical contact. The soil–ε_r relationships provide practical information concerning the calibration of these sensors, and, when compared with intensively studied high-frequency measurements of TDR, may lead to the development of more generalized calibration approaches. Temperature effects are also a practical consideration, particularly where large diurnal fluctuations are apparent. Temperature effects also add information concerning the nature of soil water and how low frequency corrections might be established.

Tests in Fluids

Sensor-measured ε_r in air, ethanol, butanol, distilled-deionized water, and a series of KCl solutions was used to determine measurement accuracy in known environments and to compare the variations of individual sensor response in a uniform media. For the ethanol and butanol measurements, each sensor was placed sequentially into the same media within a 15-min time frame and at least 10 measurements were made. All measurements were made at room temperature. For the measurements in air, each of the three sensors was suspended in air in an environmental chamber and the air temperature was varied slowly from 5 to 45°C. This provides an indication of sensor accuracy (ε_r in air is 1.0), variability among sensors and temperature effects on the electronic components. We used the following KCl solution molarities to establish the impact of solution conductivity on measured ε_r: 0 (distilled-deionized), 0.0005, 0.001, 0.005, 0.01, 0.02, 0.03, 0.04, 0.05, and 0.1 M. The electrical conductivity of each solution was measured using a conductivity electrode calibrated with standard solutions.

Tests in Soils

Four soils were used. Summit was collected from the top 30 cm of a Lolalita sandy loam soil (coarse-loamy, mixed, superactive nonacid, mesic Xeric Torriorthent), Sheep Creek was collected from the upper 30 cm of a Searla loam (loamy skeletal, mixed, superactive, frigid Calcic Argixeroll) and

Foothill was collected from the argillic horizon of a Larimer loam (fine loamy over sandy skeletal, mixed, mesic Xerollic Haplargid). These three soils are common at ongoing study sites. The fourth soil was construction sand with the following distribution of effective particle-size diameters: 16%, 1.0 to 2.0 mm; 55%, 0.5 to 1 mm; 22% 0.1 to 0.25 mm; and 7% 0.05 to 0.25 mm. The Summit, Sheep Creek and sand were used in a previous study of TDR calibration and application to frozen soil (Seyfried and Murdock, 1996).

These soils exhibit a range of properties (Table 1). Each was packed to a consistent, but different, bulk density, which was determined at the end of each measurement from knowledge of the oven-dry soil weight and the container volume (Table 1). Electrical conductivity of the saturated paste extract (Table 1) was measured for each of the soils according to Rhoades (1982).

Each soil was packed uniformly into a plexiglas Tempe cell 6.0 cm high with an inside diameter of 5.1 cm. At the lower boundary the ceramic plate was replaced with a plexiglas disk of equivalent thickness drilled with many fine holes and covered with filter paper. The sensor was placed vertically into the cell filled with soil. The surface was covered with parafilm to prevent evaporation. The soil was initially oven dry. Distilled, deaired, deionized water was added from below similar to the method described by Young et al. (1997). Soil water content was calculated from the known volume of water added within a given time increment. The amount of water added was determined by continuously monitoring the weight of water in the source flask, which was placed on a balance. Water was pumped into the high hydraulic conductivity sand and Summit soils, and siphoned into the low hydraulic conductivity Foothill and Sheep Creek soils. All data were collected and stored on a datalogger. Bulk density was determined at the end of each trial. This procedure was repeated three times for each soil using a different sensor for each trial.

Two assumptions are critical to this measurement approach. The first is that the dielectric properties measured by the Hydra Probe represent the arithmetic average of soil water in the measurement volume. This assumption was supported during preliminary method testing in sands and with pure water in which we could accurately predict sensor response and is consistent with the short column length relative to measurement wavelength (Chan and Knight, 1999). The other assumption was that soil water equilibrated rapidly. This was supported during method testing when we moistened samples at very different rates and obtained similar results.

Soil water content was calculated from the measured ε_r using different calibration equations. The manufacturer provides three calibration equations labeled “sand,” “silt,” and “clay” to be used in soils dominated by those particle sizes (Vitel Inc., 1994). We evaluated the accuracy of all three in each of the soils along with the universal equation for TDR proposed by Topp et al. (1980).

Temperature effects on sensor response were determined in air, in the oven-dry soil prior to each calibration trial, and in nearly saturated soil after each trial. Each temperature test consisted of placing the samples in an environmental chamber, which was equilibrated sequentially to temperatures of 45, 35, 25, 15, and 5°C. For each temperature test, an additional soil sample of similar water content was included that recorded temperature using a calibrated thermocouple.

Table 1. Properties of soils tested.

Soil	Sand	Clay	Bulk density	Electrical conductivity
	kg kg^{-1}		kg m^{-3}	S m^{-1}
Sheep Creek	0.23	0.19	1280	0.774
Summit	0.69	0.05	1670	0.253
Foothill	0.31	0.29	1510	0.145
Sand	0.97	<0.1	1640	0.0000568

RESULTS

Measurements in Fluids

The average measured ε_r at 25°C in air, with the 99% confidence interval in parenthesis, for Sensor 1 (S1), Sensor 2 (S2), and Sensor 3 (S3) were 1.52 ($\pm$0.01), 1.39 ($\pm$0.01), and 1.38 ($\pm$0.02), respectively. Although S1 was significantly different from S2 and S3, all three sensors were highly precise and had a small absolute error relative to the known value of 1.0 for air. All three sensors had a highly linear response to temperature in air ($R^2 = 0.97$ for all three) with nearly identical slopes resulting in an ε_r change of about 0.00768 ε_r per °C. For a 40°C temperature change, this corresponds to an apparent θ change of about 0.01 m^3 m^{-3}, which is negligible for most applications. There was a significant difference in regressed ε_r values at 0°C (y intercept) between S1 and the other two sensors, which resulted in an ε_r about 0.11 greater for S1 over the entire temperature range. From this data it appears that the sensors themselves have a statistically significant but practically negligible temperature sensitivity.

There was no significant ($\alpha = 0.01$) difference in ε_r measured in ethanol among the three sensors tested. The overall average ε_r was 24.5 $\pm$ 0.15, which is very close to the handbook value of 24.3 at 25°C (Weast, 1986). The overall average ε_r measured in butanol was 16.40 $\pm$ 0.12, which is slightly lower than the value of 16.8 reported by Fellner-Feldegg (1969). These data indicate that, at moderately high ε_r values (an ε_r of 24 corresponds to a θ of about 0.39 m^3 m^{-3} and an ε_r of 16.8 corresponds to a θ of about 0.30 m^3 m^{-3}), the sensor differences apparent in air had disappeared and that ε_r was measured accurately with high precision.

The measured ε_r and 99% confidence interval in deionized, distilled water, corrected to 25°C, was 80.11 ($\pm$0.02) for S1, 79.93 ($\pm$0.01) for S2, and 79.87 ($\pm$0.02) for S3. These are slightly high compared with the handbook value of 78.57 (Weast, 1986). Although there were statistically significant differences among sensors and between the sensors and the standard value, those differences were small and represent excellent agreement. Sensor precision was again excellent.

Increasing solution σ from 1.55×10^{-4} S m^{-1} (distilled-deionized water) to 0.073 S m^{-1} (0.005 M) had no effect on the average ε_r measured with all three sensors, which was close to that of pure water (Fig. 1a). At an electrical conductivity of 0.142 S m^{-1}, (0.01 M), there was a small decrease in average ε_r to 76.6. The increase in electrical conductivity to 0.277 S m^{-1} (0.02 M) resulted in a noticeable ε_r decrease measured for all three sensors. Further increases in electrical conductivity resulted in unrealistic ε_r values. In addition, agreement among the three sensors declined when concentrations were >0.02 M. Corresponding ε_i values indicate that a substantial change in ε_r occurred when ε_i is >50 and tan δ is about 1.45. It is noteworthy that Topp et al. (1988)

found that TDR-measured K_a was constant and equal to that of pure water over this range of KCl solution concentrations, which is consistent with other measurements of ε_r in solution (Stogryn, 1971). They also concluded that ε_i was much lower than ε_r in those solutions when measured with TDR (Topp et al., 1988).

The effect of solution σ on measured inter-sensor variability of ε_i was similar to that observed for ε_r (Fig. 1). We have no independent measure to determine the accuracy of Hydra Probe ε_i measurements, but Hydra Probe-calculated σ is directly proportional to the measured ε_i (Eq. [3]). Comparison of Hydra Probe-measured σ with independent measurements shows a pattern of accuracy deterioration with increasing solution σ (and concentration) similar to that of ε_r. Assuming that an accurate calculation of σ implies an accurate ε_i measurement, this indicates that ε_i and ε_r accuracy are similarly affected by solution σ.

Soil Water Calibration

For the Summit and sand soils, all three sensors responded almost identically to changes in water content (Fig. 2a,b). In the Foothill and Sheep Creek soils, S1 and S2 were in close agreement but S3 consistently measured different ε_r values, corresponding to a θ about 0.03 to 0.05 $m^3\ m^{-3}$ greater than the other two sensors (Fig. 2c,d). Despite these discrepancies, it is apparent that there is a strong correlation between the measured ε_r and θ and that a reasonably good calibration equation could be determined for each of the four soils.

The Topp equation was included in Fig. 2a through 2d to provide a basis for comparison among soils and for comparison with TDR. In general, values from the Topp equation were roughly parallel with those measured, but displaced upward, usually overestimating θ. For oven-dry water contents in all four soils, the Topp equation overestimated θ by 0.02 to 0.03 $m^3\ m^{-3}$. This is because the Topp equation θ for an ε_r of 2.8 is 0.025 $m^3\ m^{-3}$. An ε_r value of 2.8 is close to what was measured for all the oven-dry soils and also a reasonable number for mineral soil. In the sand, the Topp-estimated and measured θ values converged as θ increased and were generally in close agreement. For the Summit soil, measured and Topp-estimated values diverged slightly as θ increased, with the discrepancy increasing from about 0.03 $m^3\ m^{-3}$ at oven-dry to about 0.05 $m^3\ m^{-3}$ near saturation. For the Sheep Creek soil, measured values were about 0.10 $m^3\ m^{-3}$ less than the Topp-estimated values for most of the measurement range and converged to about 0.05 $m^3\ m^{-3}$ at high θ values. The Foothill samples were consistently more than 0.10 $m^3\ m^{-3}$ less than the Topp-estimated values after the initial, much smaller difference. The different responses relative to the Topp equation demonstrate the need for individual soil calibration equations.

We evaluated the three calibration equations supplied by the manufacturer in terms of the average difference (absolute value) between the measured and instrument-derived estimate of θ for all soils (Table 2). The shapes of the three curves are shown in Fig. 3 relative to the Topp equation. For θ values between 0 and about 0.33 $m^3\ m^{-3}$, the "silt" and "sand" calibration equations are fairly close and somewhat below the Topp equation, making them closer to the measured values for all soils except the sand. At higher water contents, the two curves take unrealistic and divergent trends, with the "silt" approaching a maximum at $\theta = 0.41$ $m^3\ m^{-3}$ and the "sand" steeply increasing. The "clay" calibration provided greater estimates of θ than the Topp equation over most of the range and has an unrealistic shape at high water contents.

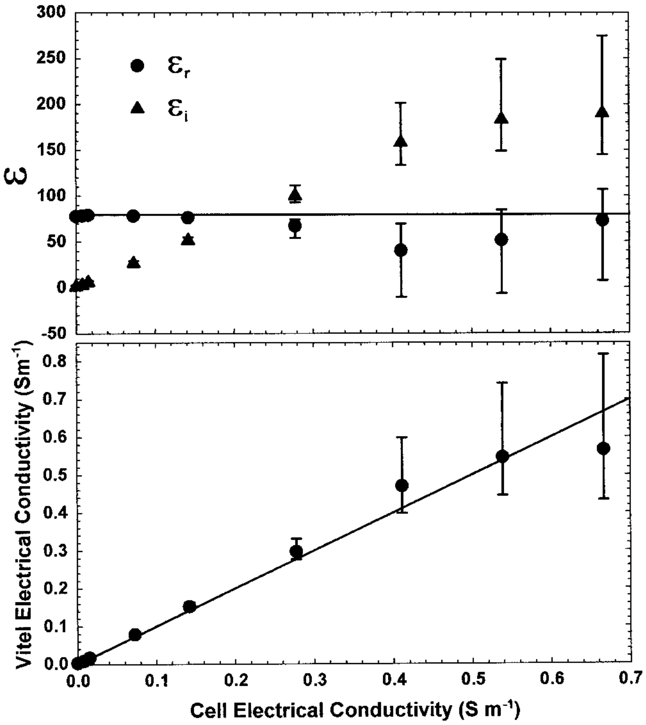

Fig. 1. Real (ε_r) and imaginary (ε_i) components of the complex dielectric constant for different KCl solution concentrations. The HP label refers to Hydra Probe. Each point represents the average of the three sensors. Error bars data indicate the measurement range among the three sensors. Individual response remained precise relative to sensor differences. Deviations were more extreme at concentrations >0.05 *M*.

The "sand" equation described the sand and Summit soils reasonably well but did poorly with the other soils (Table 2). This is due to the rapid rise of the curve at high water contents, which had numerous measurements above 0.33 $m^3\ m^{-3}$. The "silt" equation was closest overall to the measured data. This is somewhat misleading because it overestimated θ at low values and underestimated them at high values. The "clay" curve was the worst overall for every soil. The degree of fit was poor and the shape of the curve was unrealistic. In general, the "sand" calibration is probably the best choice for θ's ranging from 0 to 0.33 $m^3\ m^{-3}$ and the silt is best if the range of θ's increases much beyond that. If an average difference of 0.03 $m^3\ m^{-3}$ is regarded as reasonably good agreement, only the sand and Summit soils were well calibrated using any of the tested calibration curves.

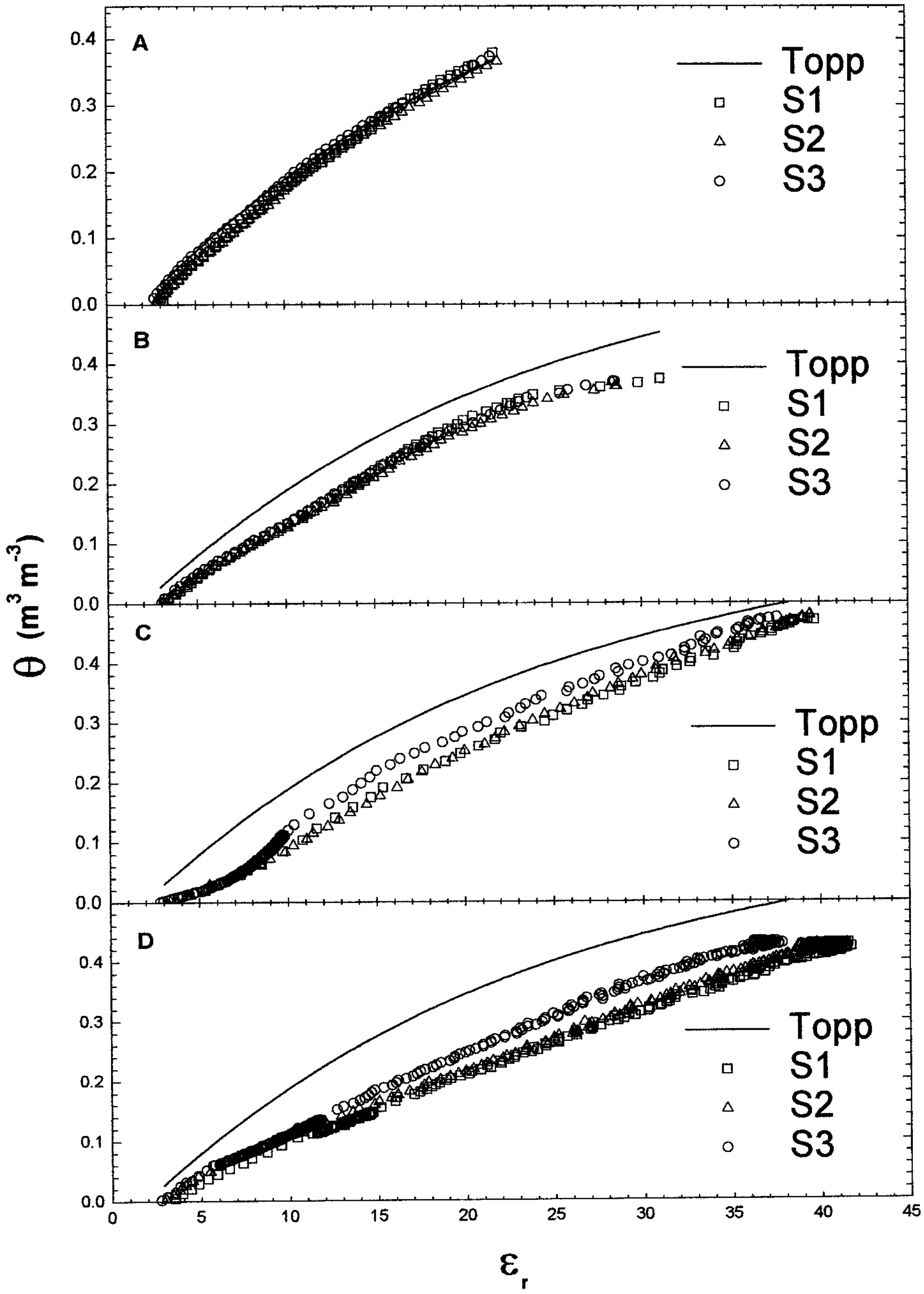

Fig. 2. The measured real dielectric constant (ε_r) using three Hydra Probe sensors (S1, S2, and S3) compared with the Topp equation as affected by soil water content for (a) the sand soil, (b) Summit soil, (c) Sheep Creek soil, and (d) Foothill soil.

Temperature Effects

The effect of temperature on measured ε_r in oven-dry soil was positive, just slightly greater than that observed in air and about the same for all soils (Fig. 4a–d). The 25°C ε_r values varied slightly among soils, ranging from 2.7 to 3.2, and are consistent with reasonable values of ε_r of 4 to 5 for mineral soils.

Table 2. Average difference between θ measured gravimetrically and estimated with different calibration equations.

Soil	Topp	Sand	Silt	Clay
	$m^3\ m^{-3}$			
Sand	**0.011**	**0.020**	**0.012**	**0.046**
Summit	**0.050**	**0.024**	**0.034**	**0.078**
Sheep Creek	**0.070**	**0.089**	**0.054**	**0.088**
Foothill	**0.093**	**0.202**	**0.037**	**0.125**

In nearly saturated soil, there was considerable variation in temperature response among soils. For the sand, the temperature response was slightly negative. The temperature response in the Sheep Creek soil was very slight excepting S3. In the Summit and Foothill soils, there was a distinct, roughly linear increase with temperature. The ε_r change in the Summit soil over the 40°C temperature change was about 4.5, corresponding to an estimated θ change of about 0.04 $m^3\ m^{-3}$ and the ε_r change in the Foothill soil was about 6.5, corresponding to an estimated θ change of about 0.06 $m^3\ m^{-3}$.

Individual sensor precision was high, as indicated by

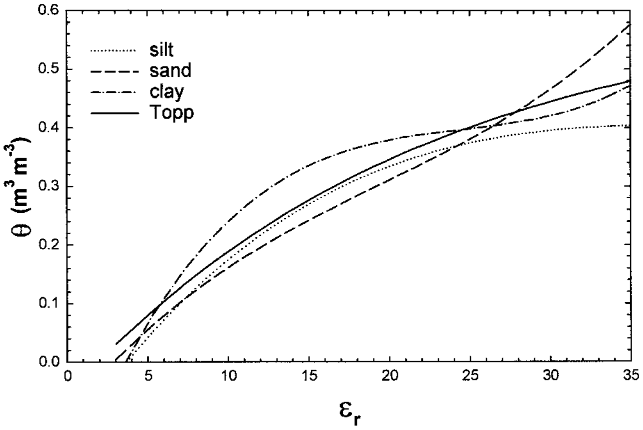

Fig. 3. Comparison of manufacturer supplied calibration curves, labeled sand, silt, clay, and the Topp equation.

the narrow range of measured values, for all conditions except the Foothill and Sheep Creek soils at temperatures >35°C. All three sensors responded practically identically in the sand and Summit soils. In the Sheep Creek soil, S3 was substantially lower than the other two. In the Foothill soil, there was a distinct ranking of sensors with S1 > S2 > S3.

DISCUSSION

These results show that there is a distinct instrument sensitivity to soil type among the four soils tested, indicating a need for individual soil calibration. In addition, measured ε_r for three of the four soils tested deviated considerably from the Topp equation. In a previous study, we found that the TDR-measured K_a–θ relationship for the Sheep Creek, Summit, and sand soils was in good agreement with the Topp equation (Seyfried and Murdock, 1996). Although no measurements were made on the Foothill soil in that study, other TDR data collected in relatively high clay content soils (e.g., Dirksen and Dasberg, 1993) indicate that deviations from the Topp equation are generally smaller and in the opposite direction from what we observed (i.e., for a given ε_r, the actual θ would be greater than the Topp equation value). Thus, although both the Hydra Probe and TDR measure soil dielectric properties, they appear to measure considerably different values for these soils except the sand.

Given the accuracy of Hydra Probe measurements in fluids, it is likely that measured differences between the Hydra Probe and TDR reflect differences in soil dielectric properties at the measurement frequencies of the two instruments. The effective TDR measurement frequency, assuming minimal attachments and cable length (Logsdon, 2000) is about 1 GHz (Or and Wraith, 1999), which is much greater than the measurement frequency of the Hydra Probe (50 MHz) or other alternative electronic sensors. The ε_r of water is essentially constant between 50 MHz and 5 GHz, suggesting that measurements made within that frequency range should yield the same result. However, the limited soil dielectric data collected in that frequency range indicate that the ε_r of soil, and therefore presumably of soil water, may vary considerably between 50 MHz and 1 GHz (Peplinski et al., 1995; Wensink, 1993; Saarenketo, 1998).

Saarenketo (1998), for example, measured ε_r at frequencies ranging from 50 MHz to 3 GHz on four different clay samples. In all cases, ε_r decreased with measurement frequency between 50 MHz and 1 GHz. The greatest change was for a sample of Beaumont clay (smectitic mineralogy), which, at $\theta = 0.5$ m^3 m^{-3}, decreased from about 64 at 50 MHz to 29 at 1.01 GHz. The smallest ε_r decrease was for a kaolinte sample, which decreased from about 27 at 50 MHz to about 24 at 1.01 GHz at the same θ. Campbell (1990) measured substantial reductions in ε_r as measurement frequency was increased from 1 to 50 MHz for some soils. Trends in the data indicated that the decrease in ε_r extends beyond 50 MHz. Exceptions were two sands he measured, which appeared to be near a minimum at 50 MHz.

Consistent with Debye theory of dielectric relaxation (Or and Wraith, 1999; Hoekstra and Delaney, 1974 for application to soils), observed decreases in ε_r with increasing measurement frequency, sometimes referred to as dispersion (Campbell, 1990), are closely associated with relatively high values of ε_i and tan δ. Campbell (1990) showed that dispersion between 1 and 50 MHz was a nonlinear (positive) function of ε_i for six of the seven soils he investigated. Wensink (1993) also found a strong dependency of ε_r on ε_i, which he called effective conductivity. In the Saarenketo (1998) data, the Beaumont clay, which had the greatest dispersion between 50 MHz and 1.01 GHz, also had the highest ε_i, which was 67 at 120 MHz with tan δ > 1 (50 MHz ε_i was not measured). The kaolinte sample, which had the least dispersion, had the lowest ε_i (17) and tan δ (0.6) at 120 MHz among the four samples measured. In all cases, ε_i decreased substantially with measurement frequency and tan δ was <0.5 at 1.01 GHz.

Some generalizations that may be drawn from these investigations are that: (i) ε_r measured at 50 MHz is greater than or equal to that measured at 1 GHz, (ii) ε_r measured at 50 MHz is more sensitive to variations in soil properties such as clay content and clay type than at 1 GHz, and (iii) high ε_i and tan δ are associated with high dispersion. The implications for Hydra Probe measurements are that they will tend to overestimate θ if the Topp equation is used, calibrations will be more sensitive to soil type than TDR, and that deviation from the Topp equation will be greatest in soils with high ε_i and tan δ.

These generalizations are consistent with our soil calibration results (Fig. 2a–d). The tan δ data shown in Fig. 5 were generated by fitting polynomial equations to the results from all three sensors to obtain a single ε_r–θ and ε_i–θ relationship, which was then used to calculate tan δ. The generally slight change in tan δ with water content except at very low θ values was similar to that observed by Campbell (1990). The Hydra Probe ε_r data collected at 50 MHz exceed Topp equation values considerably for the Foothill and Sheep Creek soils, which had relatively high tan δ (>1). Hydra Probe-measured ε_r values were in slight excess of Topp values for the Summit soil, which had moderately high tan δ

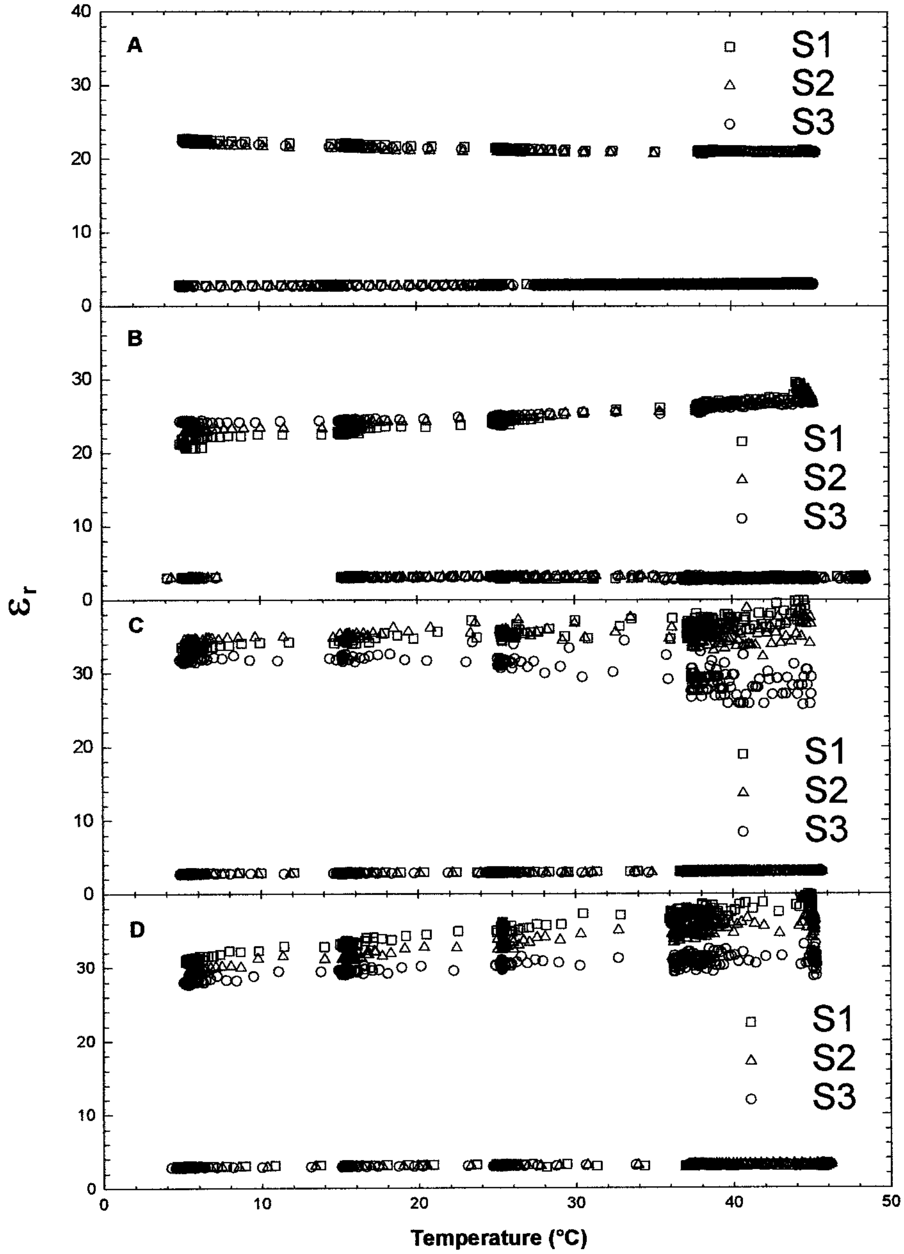

Fig. 4. Effect of temperature on measured real dielectric constant (ε_r) for the three sensors tested (S1, S2, and S3), in oven-dry (dry) and near saturated (wet) soil conditions for (a) sand soil, (b) Summit soil, (c) Sheep Creek soil, and (d) Foothill soil. Dense concentrations of points occur where the rate of temperature change was slow.

values, and the sand, which had very low tan δ values, agreed with the Topp equation very closely. Thus it appears that, in soils with very low ε_i and tan δ, soil water has dielectric properties close to those of pure water, there is little dispersion, and the Topp equation applies for a wide frequency range. In soils with high ε_i and tan δ, soil water has dielectric properties different from those of pure water, experiences significant dispersion in ε_r between 50 MHz and 1 GHz, and therefore deviates from the Topp equation. This would suggest that it might be possible to correct ε_r for loss effects using measured ε_i.

At this point we have collected insufficient data to establish a quantitative relationship between ε_i and the amount of calibration deviation from the Topp equation. However, it is important to note that, with the Hydra Probe, measured values of ε_i result from frequency independent ionic conductivity and frequency dependent dielectric relaxation. The two processes influencing ε_i measurements with the Hydra Probe may have very different effects on ε_r (White et al., 1994). This issue must be addressed if ε_i or tan δ measurements can be used to correct the θ–ε_r relationship.

Temperature Effects

In general, temperature effects on soil dielectric properties are complex and related to soil properties such as the amount of bound water, clay mineralogy, and ion

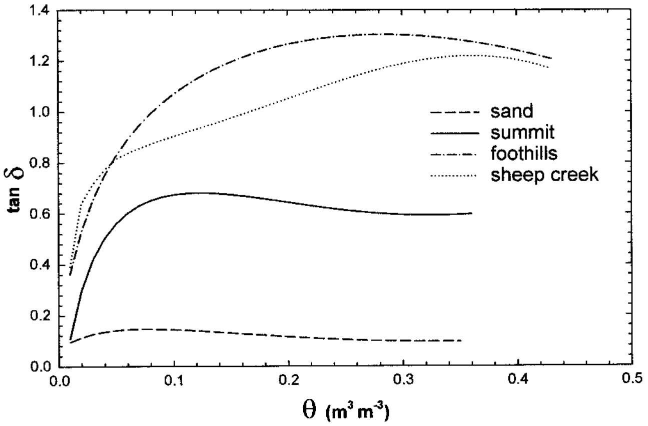

Fig. 5. Loss tangent (tan δ) of four soils as a function of soil water content. Curves were generated from best-fit polynomial equations of ε_r and ε_i for each soil.

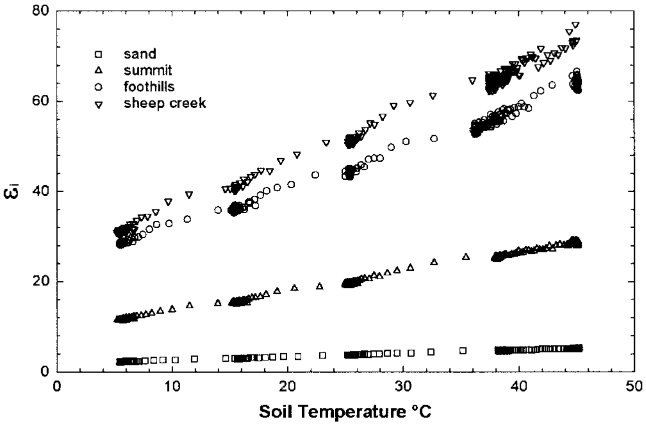

Fig. 6. Effect of temperature on ε_i for the four soils measured at nearly saturated soil water contents with Sensor S2.

valence. These effects are poorly understood, even for TDR, and a mechanistic description is beyond the scope of this paper. However, some observations can be made that may improve the interpretation of Hydra Probe data.

The decline in ε_r with temperature observed with the sand is consistent with the known decline in ε_r of pure water (Weast, 1986). Pepin et al. (1995) and others have shown that in sands, TDR measured ε_r declines with temperature can be described using the following simple mixing model attributed to Birchak et al. (1974):

$$K_a^{0.5} = (1 - P)K_s^{0.5} + (P - \theta)K_g^{0.5} + \theta[K_\omega^{0.5}(T)]^{0.5} \quad [7]$$

where the subscripts s, g and w denote the dielectric constants of the solid, gas, and water phases in soil, respectively, P is the porosity and T denotes temperature. It is implicitly assumed that TDR is primarily a measurement of ε_r. The functional relationship $K_w(T)$ is defined by Weast (1986) as used by others (e.g., Roth et al., 1990; Pepin et al., 1995; Seyfried and Murdock, 1996).

A straightforward application of Eq. [7] using values of 4 for K_s, 1 for K_g, 0.426 for P, and 0.385 for θ, yields values of ε_r which are in close agreement with those measured with the Hydra Probe in nearly saturated sand. For example, calculated values of 22.7 at 5°, 21.5 at 20°, and 20.5 at 35° all agree with those in Fig. 4a closely. Thus, temperature effects in sand measured with TDR and the Hydra Probe are similar indicating that soil water in sand has dielectric properties similar to those of pure water. This is consistent with the calibration results and may be a general feature of soils with low ε_r and tan δ.

The ε_r of the other soils did not decline with temperature. This has been observed in high clay content soils with TDR (Wraith and Or, 1999). One explanation is that increasing temperature releases bound water, which has a relatively low ε_r, thus producing an increased bulk ε_r (Pepin et al., 1995). For this explanation, it is assumed that there is no dispersion at the measurement frequency, which may be true at 1 GHz, but, as we have seen, may not be true at 50 MHz. Samples with considerable dispersion may experience increases in ε_r with temperature without liberation of bound water. Either or both of these mechanisms may have affected the temperature response for the Sheep Creek and Foothill soils, which had relatively high clay contents (therefore potentially high bound water contents) and relatively high dispersion. Neither mechanism would appear to apply to the Summit soil, which has low clay content and relatively low dispersion.

Another explanation is that increases in ε_r are due to the effects of σ. Recall that Hydra Probe-measured ε_i includes both electrical conductivity and dielectric polarization effects. Campbell (1990) showed that increasing σ can effectively increase the measured ε_r. Electrical conductivity is strongly effected by temperature, increasing approximately 2% per °C (Fenn, 1987). The Summit, Sheep Creek, and Foothill soils experienced dramatic increases in measured ε_i with temperature, while the sand did not (Fig. 6). This could explain the observed increase in ε_r with temperature for the Summit soil and Foothill soils and is consistent with the negative temperature effect in the sand. On the other hand, by this reasoning the Sheep Creek soil should have increased most with temperature and did not.

A final consideration when evaluating these data is the instrument accuracy and precision. Recall that results in KCl solutions indicated that sensor performance in terms of accuracy and precision deteriorated when solution ε_i exceeded about 50 and tan δ was greater than about 1.45. For both the Sheep Creek and Foothill soils those criteria were exceeded at about 35°C. In both soils, we also noted a considerable decrease in measurement precision, as indicated by the scatter of data points under those conditions (Fig. 4c,d). Thus, it is likely that measurement accuracy in those soils deteriorated somewhat at the higher temperatures.

There does not appear to be a single, simple explanation for the observed Hydra Probe temperature response in moist soil. Different processes acting simultaneously with contradictory effects on ε_r can produce variable effects for different soils. Although temperature effects must always be acknowledged, they should be viewed in the context of the intended application. For example, θ calculations based on a calibration performed at 25° for the most temperature sensitive soil we tested (Foothill) would result in theta estimation errors of $+0.03\ m^3\ m^{-3}$ at 5° and $-0.03\ m^3\ m^{-3}$ at 45°C. These errors may be acceptable for many applications and would be smaller for the other soils we tested.

CONCLUSIONS

The fluid tests conducted in air, water, and ethanol indicate that Hydra Probe ε_r measurements are accurate and precise and that there is good agreement among sensors over a wide range of ε_i and temperature for solution concentrations producing an $\varepsilon_i < 50$ and tan $\delta < 1.45$. Soil ε_r and θ were highly correlated for each of the four soils tested, but ε_r–θ relationship (calibration) varied among soils. None of the three calibration equations supplied by the manufacturer effectively described the measured data. However, the sand ε_r–θ relationship was well described by the Topp equation, as it was with TDR in a previous study (Seyfried and Murdock, 1996). For the other three soils, measured ε_r was greater than that predicted by the Topp equation for a given θ. Deviations from the Topp equation increased with measured ε_i and tan δ. These deviations probably reflect the differences in soil dielectric properties measured at 50 MHz with the Hydra Probe and those measured at approximately 1 GHz with TDR. This implies that soil water in sand has dielectric properties similar to pure water, which has no dispersion between 50 MHz and 1 GHz, resulting in a frequency independent ε_r–θ relationship. In addition, it appears that soil water in the other soils has dielectric properties different from pure water, as evidenced by high ε_i and tan δ, undergoes dispersion between 50 MHz and 1 GHz, and therefore has a frequency dependent ε_r–θ relationship. It may be possible to relate the amount of dispersion to ε_i and tan δ, but this requires further study.

The effect of temperature on measured ε_r was very slightly positive for all oven dry soils, consistent with the small temperature effect on the sensors and low temperature dependence of ε_r for solid soil constituents. The negative effect of temperature on the nearly saturated sand is similar to that expected with TDR and consistent with sand soil water having pure water dielectric properties. The lack of negative response in the other three soils may be due to bound water, dispersion and/or ionic conductivity effects. Interpretation of the high temperature Sheep Creek and Foothill soil should be tempered considering the effects of high ε_i and tan δ, on instrument accuracy and precision.

In general, we expect that the Hydra Probe measured-ε_r will be well correlated to θ for most soils. The calibration will be more sensitive to soil type and temperature than TDR. We expect that similar trends will be evident with other alternative soil water sensors, diminishing as the measurement frequency increases. Although few data of the type reported in this paper exist for other sensors, those expectations are borne out somewhat by data we collected with a different sensor, which uses a lower (variable) measurement frequency (Seyfried and Murdock, 2001). In that study we found those sensors to be more sensitive to soil type and temperature than the Hydra Probe for these soils. Other factors, such as cost, durability, ease of use, measurement volume, installation type (e.g., down-hole vs. wave guide) may be as important as laboratory tests of accuracy and precision. These data, should, however, provide valuable insight into the performance of the Hydra Probe sensor.

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