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Accuracy and precision of soil water measurements by neutron, capacitance, and TDR methods

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Abstract

Accurate soil water content measurements are required for measurements of crop water use and of the hydraulic characteristics of soils. Although the soil moisture neutron probe (SMNP) has served this need well, increasing regulatory burdens, including the requirement that neutron probes not be left unattended, limit the usefulness of the method. Newer methods, which measure the electric properties of soils, typically allow data logging and unattended operation, but with uncertain precision and accuracy. We compared the Sentek EnviroSCAN[1] and Diviner 2000 capacitance devices, the Delta-T Profiler capacitance probe, the Trime T3 tube-probe, a prototype TDR tube-probe, and the SMNP. All the devices can be used in access tubes. Experiments were conducted in triplicate re-packed columns of three soils: 1) a silty clay loam (30% clay, 53% silt), 2) a clay (48% clay, 39% silt), and 3) a calcic clay loam (35% clay, 40% silt) containing 50% $CaCO_3$. Each 75 cm deep, 55 cm diameter column was weighed continuously to 50 g precision on a platform scale. Conventional time domain reflectometry (TDR) measurements of water content and thermocouple measurements of temperature were made at depths of 2, 5, 15, 25, 35, 45, 55, and 65-cm in each column every 30 min. Depth resolution of each device was investigated by lowering its probe from a height 30-cm above the soil surface and taking measurements at 2-cm increments until the probe was 30-cm below the soil surface. Comparisons of soil water content reported by the devices vs. soil temperature were made before the columns were wetted. The capacitance sensors were significantly sensitive to soil temperature (0.0005 to 0.0010 $m^3\ m^{-3}\ °C^{-1}$); but TDR and the SMNP were not. The Trime T3 device was most sensitive to temperature (0.009 $m^3\ m^{-3}\ °C^{-1}$). Measurement precision of the devices was investigated by repeated measures through time. Factory calibrations produced water contents ranging up to 0.09 $m^3\ m^{-3}$ larger than water content of the air-dry soil determined by mass balance. The Delta-T system was most inaccurate, followed by the Trime system, which gave water contents up to 0.06 $m^3\ m^{-3}$ larger than actual. The conventional TDR and EnviroSCAN systems were most accurate, giving readings within 0.02 $m^3\ m^{-3}$ of actual air-dry values. The capacitance systems and the Trime T3 generally were not sensitive to soil volumes outside of their respective sensor heights, indicating small measurement volumes generally, and suggesting that these systems may be susceptible to soil disturbance close to the access tube during installation.

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

Keywords: neutron scattering, profile water content, calibration, temperature, salinity, soil horizon

Introduction

Accurate soil water content measurements are required for measurements of crop water use and of the hydraulic characteristics of soils. For nearly 50 years, the neutron probe has served this need well. But, increasing regulatory burdens, including the requirement that neutron probes not be left unattended, limit the usefulness of the method, particularly for unattended, automated data acquisition. In many field experiments, these limitations prevent the method from being useful for capturing the depth of water added to the soil via irrigation or precipitation without confounding effects of crop water use and evaporation from the soil surface that occur between measurements. Since 1980, several methods have been researched that rely on measurements of soil electric properties as a surrogate for soil water content (Topp *et al*., 1980; Dean *et al*., 1987; Paltineanu and Starr, 1997). These electronic methods typically allow data logging and unattended operation, but with uncertain precision and accuracy (Baumhardt *et al*., 2000; Evett and Steiner, 1995). Our objective was to compare, in three different soil materials, the accuracy, precision, temperature sensitivity and sensing volume of several commercially available devices that could be used in access tubes to measure soil water content in the root zone and below. Comparisons were made vs. soil water content determined by mass balance in soil columns and by time domain reflectometry (TDR).

Materials and Methods

Three soils were acquired in fall 2000 at Bushland, Texas, air dried, crushed and sieved to 2-mm diameter. The soils were 1) a silty clay loam (30% clay, 53% silt), hereinafter referred to as A; 2) a clay (48% clay, 39% silt), hereinafter referred to as B; and 3) a clay loam (35% clay, 40% silt) containing 50% $CaCO_3$, hereinafter referred to as C. Soils A, B, and C were derived, respectively, from the A, Bt, and Btk horizons of a Pullman soil, which is a fine, mixed, superactive, thermic Torrertic Paleustoll with mixed clay mineralogy including a large proportion of montmorillonite. The difference in clay content from 30 to 48% between soils A and B should illuminate any texture dependence of measurement methods. The 50% $CaCO_3$ content of soil C should illuminate any effects of soil chemical composition on measurements.

Each soil was packed uniformly into three replicate columns. Soil in each column was 75-cm deep and 55-cm in diameter, and rested on a 5-cm deep drainage bed of fine pure silica sand in which was embedded a ceramic filter tube specified at 100 kPa air entry potential. Soil was packed in 5-cm layers around access tubes, which were held in place with a jig so that tube positions would be identical in each column. Horizontal, trifilar TDR probes (20-cm length, Dynamax[2], Inc., Houston, model TR-100) were installed at 2, 5, 15, 25, 35, 45, 55, and 65-cm depths in each column to measure soil water content, and thermocouples were installed at the same depths to measure soil temperature. Samples for initial gravimetric water content were obtained every two layers. Column sides were covered with reflective aluminum foil to minimize diel

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heating and cooling on the sides. Column soil surfaces were left exposed to solar radiation and air temperature variations in the green house that housed the experiment.

Column mass was measured every 6 s using a data logger (Campbell Scientific, Inc., Logan, Utah, model CR7) connected to the paralleled output of the four load cells in each deck scale (Weigh-Tronix, Inc., Fairmount, MN, model DS3040-10K), using a six-wire bridge configuration to minimize temperature-induced errors. Mean values were output every 5 min. Calibration with test masses traceable to NIST resulted in a precision of approx. 50 g. Initial volumetric water content of each column was computed from the mass of soil added, the volume of the column, and the water contained in the soil as determined from the gravimetric samples.

Measurements of soil water content with the 72 20-cm trifilar TDR probes were made every 30 min using the TACQ program (Evett, 2000ab) running a system comprising an embedded computer (IBM PC/AT compatible), cable tester (Tektronix Inc. Redmond, OR, model 1502C), and five coaxial multiplexers (Evett, 1998).

Three capacitance type soil water measurement systems were used (Delta-T Devices Ltd., Cambridge, UK, model PR1/6 Profile Probe; and Sentek Environmental Technologies, Kent Town, South Australia, models EnviroSCAN and Diviner 2000). The EnviroSCAN system features a string of sensors placed every 10 cm on a plastic backbone through which a communications cable runs to the sensor string head. Sensors were placed to measure 10-cm high intervals centered at 5, 15, 25, 35, 45, 55, and 65 cm. One string of sensors was placed in one column of each soil and logged continuously every 30 min. The Diviner 2000 consists of a single sensor, similar to that used in the EnviroSCAN, fitted to a square rod that allows the sensor to be lowered to 1.6-m depth in an access tube. The same size PVC plastic access tube is used for both Sentek systems (5.1-cm inside diameter, 5.6-cm outside diameter). We made readings every other day in two columns of each soil with the Diviner 2000 at the same depths as for the EnviroSCAN. The PR1/6 probe has six capacitance sensors on fixed spacing on a monolithic round rod. The sensor centers of measurement are at depths of 10, 20, 30, 40, 60, and 100 cm. In use, the rod is lowered into a fiberglass access tube (inside diameter of 26 mm, outside diameter of 28 mm).

A prototype trifilar TDR probe called a sheathed probe (Environmental Sensors Inc., Victoria, BC, Canada) was used in three parallel and coplanar access tubes. The center access tube was 25-mm diameter thinwall PVC. The outside two tubes were galvanized steel water pipe. The sensing element was a copper cylinder 20-cm in height. We made daily measurements at 20-cm depth intervals with the top-most measurement centered at 10 cm below the soil surface.

Finally, we used the Trime T3 tube probe, which is a cylindrical probe with two waveguides oriented vertically on opposite sides of a cylindrical plastic body (IMKO Micromodultechnik, GmbH, Ettlingen, Germany, model TRIME-T3 Tube Access Probe). The measurement length of the T3 probe is 17.5 cm. The probe is suspended from a cable and lowered to any desired depth in the polycarbonate plastic access tube (41-mm inside diameter, 44-mm outside diameter). We made measurements at 17.5-cm depth intervals with the top-most measurement centered at 8.75 cm below the soil surface. Daily measurements were made. With both the sheathed and Trime probe, a measurement was also made with the probe resting against the bottom of the access tube.

Periodic measurements were made over at least two days in the dry soil columns with a sensor of each device centered at 25-cm depth for comparison with measurements of temperatures at that depth. The extent to which each sensor was sensitive to soil outside of its own height was tested by lowering each sensor in 2-cm increments from a height well above the soil surface to a depth well below the soil surface (high enough and low enough, respectively, so that readings did not change with vertical position).

Results and Discussion

After packing, the soil columns had mean initial water contents of 0.051, 0.056, and 0.041 $m^3\ m^{-3}$ for soils A, B, and C, respectively, and mean bulk densities of 1.48, 1.47, and 1.40 Mg m^{-3}, respectively.

Temperature effects

Temperatures in the soil columns varied diurnally by up to 16ºC due to solar radiation in the green house. Temperature variations decreased with depth, indicating that the reflective shielding was effective in preventing heat loading on the sides of the columns. Corresponding soil column mass measurements indicated that temperature effects on water content derived from mass measurements were < 0.01 $m^3\ m^{-3}$. Water content reported by each device was linearly regressed vs. temperature. Soil type did not influence the relationship between reported water content and soil temperature of the EnviroSCAN system (Figure 1), for which a 10ºC change in temperature would cause a 0.009 $m^3\ m^{-3}$ change in reported water content as shown by linear regression (Table 1). For the Delta-T Profiler, the sensitivity was 0.01 $m^3\ m^{-3}$ per 10ºC. The Diviner was less sensitive, with a 10ºC change in temperature causing a 0.005 $m^3\ m^{-3}$ change in reported water content. However, a 10ºC change in temperature would cause a 0.09 $m^3\ m^{-3}$ change in water content reported by the Trime T-3 probe. All regressions were significant at the P = 0.001 level, with slopes significantly different from zero. Tests were performed in air dry soils (~0.05 $m^3\ m^{-3}$). Water content values from the SMNP and the Dynamax TDR system were not significantly dependent on soil temperature.

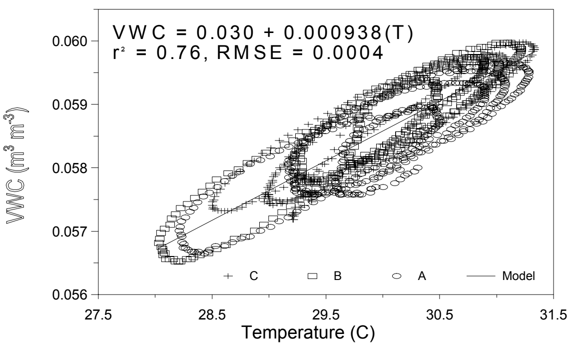

Figure 1 As an example, the relationship between volumetric water content (VWC) reported by the EnviroSCAN and soil temperature was significant at P<0.0001.

Table 1 Temperature sensitivity[1] of the devices[2].

Instrument	Slope, (m^3 m^{-3}) °C^{-1}	r^2	RMSE (m^3 m^{-3})
Delta-T PR1/6	0.0010	0.73	0.0013
Diviner	0.0005	0.65	0.0003
EnviroSCAN	0.0009	0.76	0.0004
Trime T3	0.0090	0.52	0.0050

[1] Measured at 25-cm depth.
[2] Regressions and regression slopes were not significant for TDR and neutron probe.

Reported water contents in dry soil

The factory calibration for each system was used to calculate reported water contents from raw measurements. Water content values from the Trime tube probe ranged from 0.032 to 0.055 m^3 m^{-3} larger than water content calculated from mass balance (Table 2 and Figure 2). The Diviner reported mean water contents ranging from 0.016 to 0.034 m^3 m^{-3} larger than actual values. The EnviroSCAN was more accurate, reporting mean water contents ranging from zero to 0.021 m^3 m^{-3} larger than actual. The Delta-T probe was most inaccurate, reporting mean water contents ranging from 0.081 to 0.091 m^3 m^{-3} larger than actual. The conventional TDR performed as well as the EnviroSCAN, giving readings quite close to those determined on the air dry soil during packing. Water contents from the prototype sheathed probe were obviously incorrect due to lack of calibration. The range of readings was as large as that from the Trime system. The increase of water content values with depth may be due to incorrect cable lengths in the prototype and is not reported here. Neutron probe water contents were only approximately correct because the soil columns were not large enough to represent an equivalent infinite volume, and because of the nearness of other access tubes.

Table 2 Difference between column mean water content (VWC, m^3 m^{-3}) reported by each instrument and mass balance water content (VWC_M) in air-dried soils (SD in parentheses).

VWC_M	Soil A	Soil B	Soil C
	0.051 (0.0024)	0.056 (0.0010)	0.041 (0.0035)
Instrument		$VWC - VWC_M$	
Delta-T PR1/6	0.088 (0.0036)	0.091 (0.0063)	0.081 (0.0047)
Diviner	0.016 (0.010)	0.021 (0.0009)	0.034 (0.0042)
EnviroSCAN	0.000 (0.0059)	0.021 (0.0084)	0.016 (0.0064)
TDR	-0.020 (0.0017)	-0.014 (0.0056)	-0.005 (0.0058)
Trime T3	0.032 (0.0020)	0.049 (0.0045)	0.055 (0.0051)

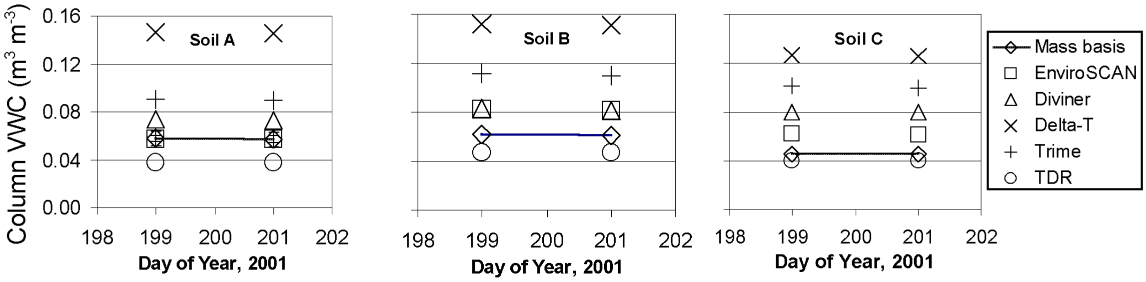

Figure 2 Mean column water contents, determined by mass balance for soil A, B, and C, compared with mean column water contents reported by each sensor.

Sensitivity to the soil-air interface

The height of a 90% response window was calculated for each sensor by determining the sensor elevation above or below the soil surface at which the reported water content differed by 5% from the smallest and largest water contents, respectively (Figure 3). The SMNP had a 90% response window of 28-cm, as expected, more than twice its detector tube length of 13.2 cm. The response window was centered at 6.0 cm below the soil surface; a result that was not unexpected because the radioactive source is located just below the detector tube. The Delta-T probe 90% response window was centered at 0.4 cm, just above the soil surface, and had a height of 8.0 cm, almost twice the sensor height (bottom sensor). However, the 2-cm depth increment used between measurements may not have been small enough to obtain good precision with this probe, which had the smallest height. The Diviner had a 90% response window of 6.0 cm, almost the same as the 6.2-cm sensor height. The sensor response was centered at 1.5 cm below the soil surface. The EnviroSCAN sensor is very similar to that of the Diviner, but is difficult to move within the access tube. For these reasons, we did not test soil-air interface sensitivity of the EnviroSCAN sensor. The Trime probe, with a sensor height of 17.5 cm, achieved 90% response over an 18-cm high window. Sensor response was centered at 1.75 cm above the soil surface. This was the only sensor that had an asymmetrical response (Figure 3). Of the electronic methods, only the Delta-T appeared to be sensitive to changes in the sensed medium above and below the active elements of the sensor. Table 3 evice sensitivity to the soil-air interface[1].

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Instrument	Sensor element height (cm)	Height of 90% response window	Ratio of response to sensor heights
Delta-T PR1/6	4.8	8	1.67
Diviner	6.2	6	0.97
ESI sheath probe	15.0	20	1.33
Neutron probe	13.2	28	2.12
Trime T3	17.5	18	1.03

[1] Measured in 2-cm increments from >30 above the soil to >30 below the surface.

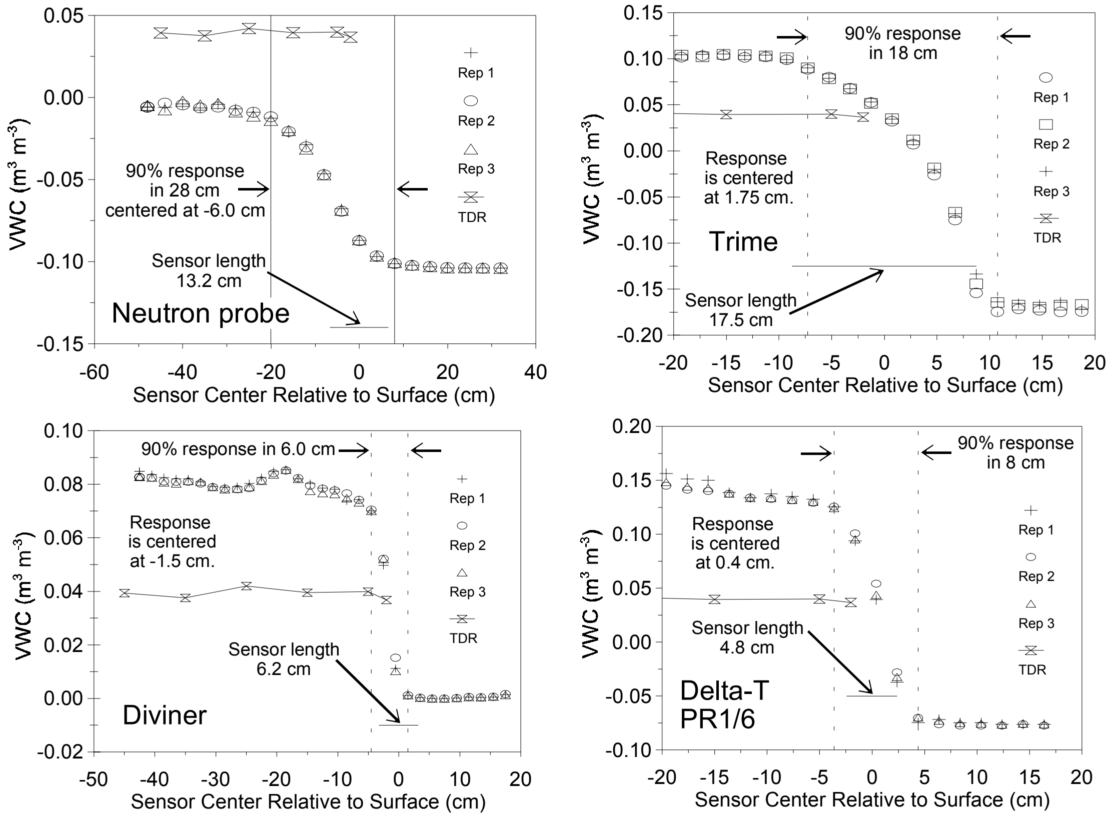

Figure 3 Response to nearness to the soil surface for the SMNP (upper left), the Trime tube probe (upper right), the Diviner 2000 (lower left), and the Delta-T PR1/6 (lower right) in soils A and B.

Conclusions

It is still too early to draw conclusions from this study, although it is clear that, without additional calibration, the conventional TDR and EnviroSCAN systems have been the most accurate so far. Experiments now taking place include wetting the columns slowly from the bottom while measurements continue. Once the columns are saturated with water, experiments on the sensitivity of the instruments to the soil-air interface will be repeated, followed by experiments determining the temperature effect at saturation. Columns will then be drained, first by gravity, followed by suction at 100 kPa, while measurements continue. A late summer wheat or rye crop will be planted to further dry the columns as measurements continue. After harvest, the columns will be re-saturated and experiments on soil water salinity experiments will be performed.

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