PROGRESS REPORT

IAEA Research Contract Number: 11186/FAO

Title: Accuracy and Precision of Neutron Scattering, TDR, and Capacitance Methods of Soil Water Measurement

Institute: USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas

Chief Investigator: Steven R. Evett, Ph.D.

Period: April 1, 2001 through March 31, 2002

The project compares five profiling water content measurement systems with the neutron probe. Funding from the IAEA was combined with funding from three Groundwater Conservation Districts in the Texas Panhandle.

Probe Comparison in Soil Columns

Three soils were acquired, air dried, crushed and sieved to 2-mm diameter (Fig. 1). The soils were A) a silty clay loam derived from the A horizon of a Pullman soil (30% clay, 53% silt), B) a clay derived from the Bt horizon of a Pullman soil (48% clay, 39% silt), and C) a clay loam (35% clay, 40% silt) derived from the Bk horizon of a Pullman soil containing 50% $CaCO_3$. The Pullman soil 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 1 and 2 should cause any texture dependence of measurement methods to show up. The 50% $CaCO_3$ content of soil C should cause any effects of soil chemical composition on measurements to show up.

Fig. 1. Three soils after crushing and sieving (left). Soil A (clay) is in the back. Soil B (silty clay loam) is in the foreground. Soil C (50% $CaCO_3$) appears to be nearly white. Nine deck scales and data logger for soil column mass measurement (right).

Soil was packed uniformly into three replicate columns for each soil. 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 (Fig. 2). Horizontal, trifilar TDR probes (20-cm length) 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 water content were obtained every two layers. Column sides were covered with reflective aluminum foil to minimize diurnal 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., model CR7, Logan, Utah) connected to the paralleled output of the four load cells in each deck scale (WeighTronix, Inc.), using a six-wire bridge configuration to minimize temperature induced errors. Mean values were output every 30 min. Calibration with test masses traceable to NIST resulted in a precision of approx. 50 g (Fig. 3).

Fig. 2. Access tubes fixed in place prior to soil packing (left), and soil column with access tubes and cables for TDR and thermocouples after packing.

Measurements of soil water content with the 63 20-cm trifilar TDR probes were made every 30 min using the TACQ program (Evett, 2000ab) running a system composed of an embedded computer (IBM PC/AT compatible), cable tester (Tektronix, model 1502C), and five coaxial multiplexers (Evett, 1998).

Three capacitance type soil water measurement systems were used (Sentek Environmental Technologies, Kent Town, South Australia, models EnviroScan and Diviner 2000; Delta-T Devices Ltd., Cambridge, UK, model PR1/6 Profile Probe). 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 (Fig. 4). 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). The Delta-T probe has sensors in fixed positions on a plastic rod. We made readings every other day in two columns of each soil with the Diviner 2000 at the same depths as for the EnviroScan.

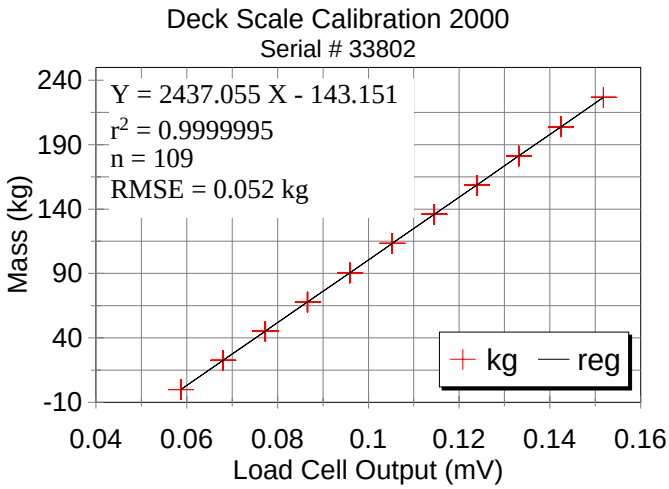

Fig. 3. Example of calibration results for deck scales used to measure soil column mass.

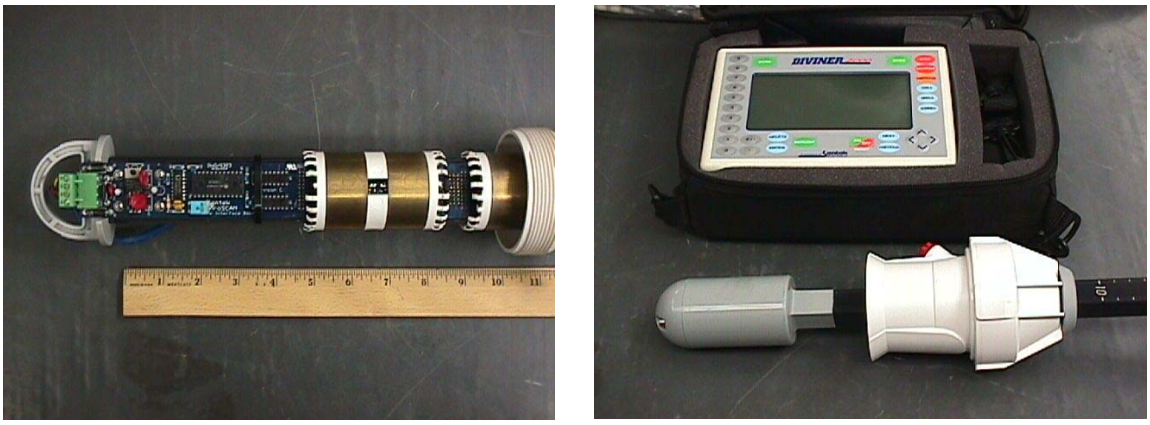

Fig. 4. Sentek EnviroScan sensor string partially removed from access tube (left). The communications circuit is visible just to the right of the green connector on the left. One complete sensor is shown with two brass rings separated by white plastic and with white plastic fingers on either end. The Sentek Diviner 2000 probe is in a gray plastic housing (right). A square rod passes through the white head, which rests on top of the access tube during use. Sensors in the rod signal the portable data logger (top right) as to the depth of the probe as the probe is moved up and down in the access tube.

Two profiling TDR systems were used. One was a cylindrical probe with two opposing waveguides oriented vertically along the cylindrical body (Fig. 5) (IMKO Micromodultechnik, GmbH, Ettlingen, Germany, model TRIME-T3 Tube Access Probe). The measurement length of the tube probe is 17.5 cm. 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. The other was a prototype trifilar probe design from ESI called a sheathed probe (Fig. 6). The sheathed probe has a 20-cm measurement length. We made daily measurements at 20-cm depth intervals with the top-most measurement centered at 10 cm below the soil surface. With both systems, a measurement was also made with the probe resting against the bottom of the access tube.

Measurements were made in air dry soil, while the columns were wetting (from the bottom) and when the columns were saturated.

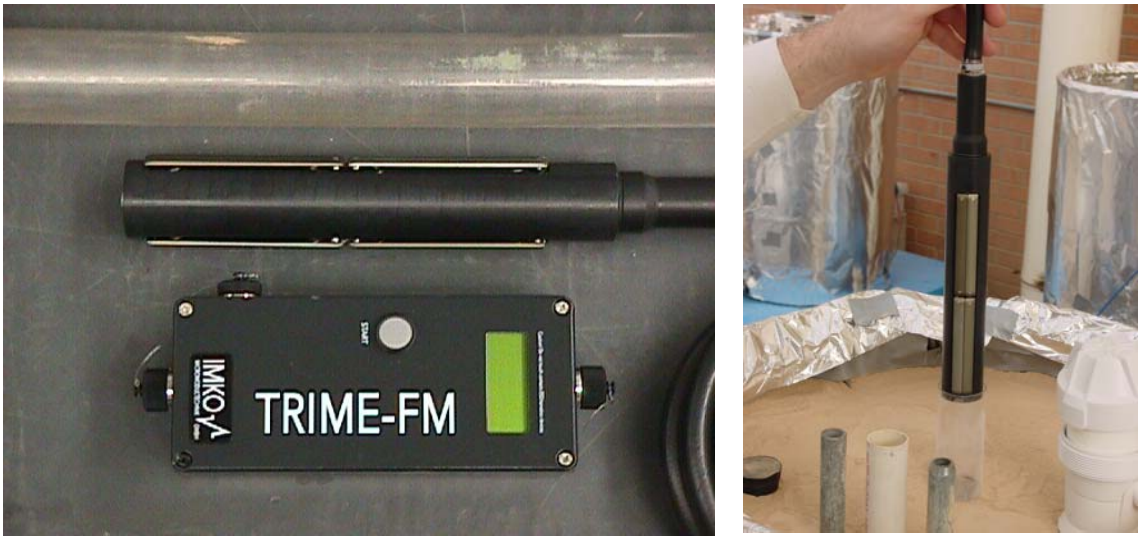

Fig. 5. The Trime tube probe and readout with an access tube (left). The tube probe being inserted into an access tube prior to a measurement (right).

Results to Date

After packing, the soil columns had mean initial water contents of 0.051, 0.056, and 0.041 m3 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 showed that temperature effects on water content derived from mass measurements were <0.01 m^3 m^{-3}. Tests were performed in air dry soils (~0.05 m^3 m^{-3}) and after the columns were saturated with water. 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 (Fig. 7), for which a 10ºC change in

temperature would cause a 0.009 or 0.010 m^3 m^{-3} change in reported water content when the soil is dry or wet, respectively, as shown by linear regression (Table 1).

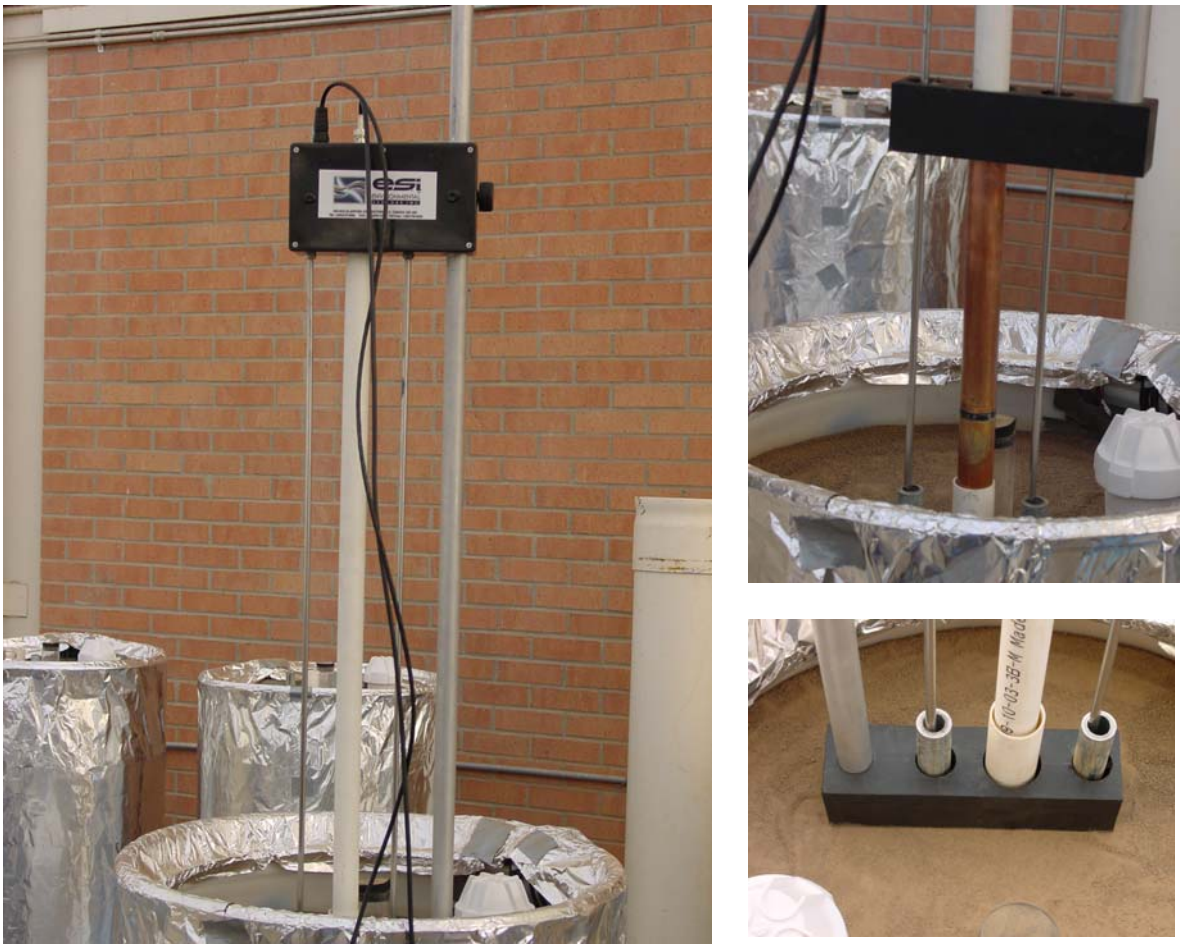

Fig. 6. Prototype sheathed TDR probe inserted to second depth range (20-40 cm) (left). Black knob on right side of head is for depth adjustment. Prototype sheathed TDR probe being inserted into three access tubes (top right). The surface reference shoe is visible at the top of the picture. The waveguide consists of the copper tubing visible entering the middle, white plastic tube; and the ground rods entering the two steel tubes on either side. When inserted for the first reading, the shoe rests on the soil surface with the three access tubes protruding above it (right bottom). The aluminum tube on the left side is fixed permanently to the shoe and slides up and down within the probe head.

For the Delta-T Profiler, the sensitivity was 0.01 m^3 m^{-3} per 10ºC for dry soil, increasing to 0.25 m^3 m^{-3} per 10ºC for saturated soil. The Diviner was less sensitive, with a 10ºC change in temperature causing a 0.005 m^3 m^{-3} change in reported water content for dry soil, increasing to 0.019 m^3 m^{-3} per 10ºC for saturated soil. 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 in dry soil, increasing to 0.20 m^3 m^{-3} per 10ºC for saturated soil. All regressions were significant at the P = 0.001 level, with slopes significantly different from zero. Water

content values from the SMNP and the Dynamax TDR system were not significantly dependent on soil temperature.

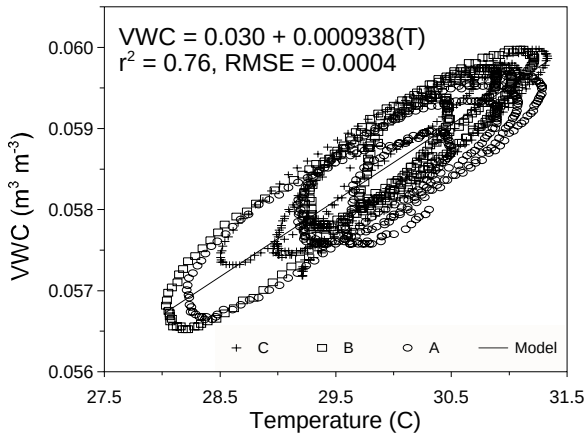

Figure 7. As an example, the relationship between volumetric water content (VWC) reported by the EnviroSCAN and soil temperature was significant at P < 0.0001 for air dry soils.

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

	Slope, (m^3 m^{-3}) °C^{-1}		r^2		RMSE (m^3 m^{-3})	
Instrument	Dry	Saturated	Dry	Saturated	Dry	Saturated
Delta-T PR1/6	0.0010	0.0250	0.73	0.94	0.0013	0.00024
Diviner	0.0005	0.0019	0.65	0.77	0.0003	0.0001
EnviroSCAN	0.0009	0.0010	0.76	0.88	0.0004	0.000012
Trime T3	0.0090	0.0204	0.52	0.75	0.0050	0.0012

[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, Fig. 8). 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.

Reported Water Contents in Saturated Soils. The Diviner, EnviroSCAN, and conventional TDR all reported water contents within 0.04 m^3 m^{-3} of those calculated by mass balance for the saturated soil columns (data not shown). The Delta-T reported water contents ranging from 1.55 to 1.85 m^3 m^{-3}, clearly unrealistic. The Trime probe reported water contents exceeding 0.6 m^3 m^{-3}, also unrealistic.

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).

	Soil A	Soil B	Soil C
VWC_M	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)

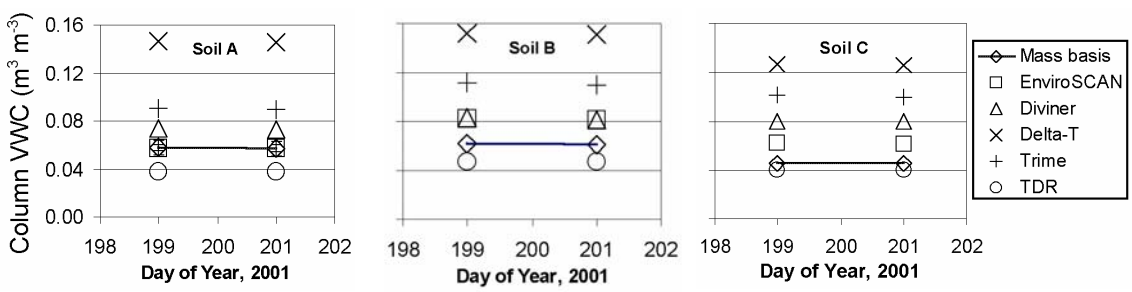

Figure 8. Mean column water contents, determined by mass balance for soil A, B, and C, compared with mean column water contents reported by each sensor.

Sensitivity to the Soil-Air Interface for Air Dry Soil. 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 (Table 3, Fig. 9). 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 (Fig. 9). 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. Device sensitivity to the soil-air interface[1].

Instrument	Sensor Element Height (cm)	Height of 90% Response Window		Ratio of Response to Sensor Heights	
		Dry	Saturated	Dry	Saturated
Delta-T PR1/6	4.8	8	5	1.67	1.04
Diviner	6.2	6	6	0.97	0.97
ESI sheath probe	15.0	20	NA[2]	1.33	NA
Neutron probe	13.2	28	20	2.12	1.52
Trime T3	17.5	18	18	1.03	1.03

[1] Measured in 2-cm increments from >30 above the soil to >30 below the surface.
[2] Not Yet Available.

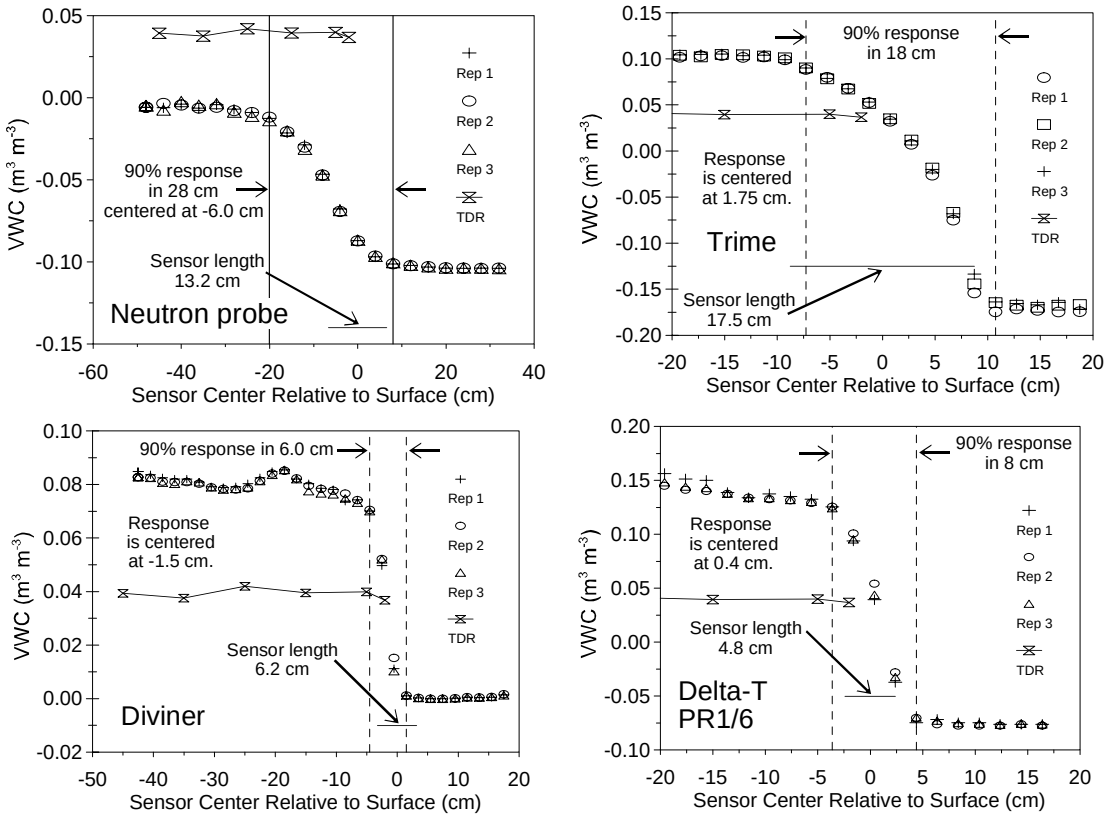

Figure 9. Response to nearness to the soil surface for the SMNP (upper left), the Trime tube probe (upper right), the Diviner 2000 (lower left), and the Delta-T PR1/6 (lower right) in soils A and B.

Sensitivity to the Soil-Air Interface for Saturated Soil. The height of the 90% response window was within 0.5 cm or 4% of the height of the sensor for the Delta-T, Trime, and

Diviner probes when the soil was saturated (Table 3), leading to the conclusion that these probes have a very limited field of influence beyond the sensor body in saturated soils. The neutron probe demonstrated a 90% response window, 52% larger than its height, indicating a field extending approximately 3.4 cm above and below the sensor body. Data for the sheath probe are not yet available.

Conclusions

It is clear that, without additional calibration, the conventional TDR system, the EnviroSCAN, and the Diviner systems have been the most accurate so far. These systems are either insensitive (TDR) or only moderately sensitive (EnviroSCAN and Diviner) to soil temperature fluctuations. All three systems report water contents within 0.05 m^3 m^{-3} of that measured by mass balance across the entire range of soil water content. The Delta-T and Trime were both more inaccurate at the dry end, and quite inaccurate at the saturated end; and both were quite sensitive to soil temperature fluctuations. It is certainly possible that the Delta-T and Trime probes could be calibrated for a specific soil, but their temperature sensitivity leads to the conclusion that they cannot be recommended for field work in soil water content measurement. The small measurement volumes of the Delta-T, Diviner (and thus EnviroSCAN), and Trime probes will make them sensitive to small scale variations in soil water content and bulk density close to the access tube, and sensitive to any soil disturbance during access tube installation. The small measurement volumes also mean that field calibrations will be impractical in most soils because the volume of soil sensed by these probes is too small to allow sampling with existing volumetric soil sampling equipment. The neutron probe was insensitive to soil temperature and had a measurement volume extending axially from 3.4 cm (dry) to 7.4 cm (saturated) beyond the probe. Because of its larger measurement volume it will be less sensitive to small scale variations in soil properties and to soil disturbance caused during access tube installation. For these reasons, and because we know that the neutron probe can be accurately field calibrated (Hignett and Evett, 2002), it remains the recommended probe for profile soil water content measurements from within access tubes.

Papers and Presentations Related to Project 11186

Evett, S.R. Measuring soil water by time domain reflectometry. Accepted for publication In The Encyclopedia of Water Science, Dekker.

Evett, S.R. Measuring soil water by neutron thermalization. Accepted for publication In The Encyclopedia of Water Science, Dekker.

Evett, S.R., J.A. Tolk, and T.A. Howell. Sensors for soil profile moisture measurement compared. Submitted to Agron. Abstr. 2002.

Evett, S.R., B.B. Ruthardt, S.T. Kottkamp, J.A. Tolk, and T.A. Howell. Profiling soil water probes compared in three soils. Agron. Abstr. 2001. (CD-ROM)

Evett, S.R., B.B. Ruthardt, S.T. Kottkamp, T.A. Howell, A.D. Schneider, and J.A. Tolk. Accuracy and Precision of Soil Water Measurements by Neutron, Capacitance, and TDR Methods. 17th World Congress of Soil Science, August 14-21, 2002, Bangkok, Thailand, Transactions, pp. 318-1 - 318-8. (CD-ROM)

Evett, Steven, Jean-Paul Laurent, Peter Cepuder, and Clifford Hignett. Neutron Scattering, Capacitance, and TDR Soil Water Content Measurements Compared on Four Continents. 17th World Congress of Soil Science, August 14-21, 2002, Bangkok, Thailand, Transactions, pp. 1021-1 - 1021-10. (CD-ROM)

Evett, S.R., N. Ibragimov, B. Kamilov, Y. Esanbekov, M. Sarimsakov, J. Shadmanov, R. Mirhashimov, R. Musaev, T. Radjabov, and B. Muhammadiev. Soil moisture neutron probe calibration and use in five soils of Uzbekistan. 17th World Congress of Soil Science, August 14-21, 2002, Bangkok, Thailand, Transactions, pp. 839-1 - 839-10. (CD-ROM)

Hignett, C., and S.R. Evett. 2002. Neutron Thermalization. Section 3.1.3.10 In G. Clarke Topp and Jacob Dane (eds.) Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 3rd Edition. AGRONOMY Monograph Number 9. (in press)

Kamilov, B., N. Ibragimov, S. Evett, and L. Heng. Use of neutron probe for investigations of winter wheat irrigation scheduling in automorphic and semi-hydromorphic soils of Uzbekistan. Accepted for publication In Proc. International Workshop on Conservation Agriculture for Sustainable Wheat Production in Rotation with Cotton in Limited Water Resource Areas, October 13-18, 2002, Tashkent, Uzbekistan. 2002.

References

Evett, S.R. 1998. Coaxial multiplexer for time domain reflectometry measurement of soil water content and bulk electrical conductivity. Trans. ASAE 41(2):361-369. (Available at http://www.cprl.ars.usda.gov/programs/)

Evett, S.R. 2000a. The TACQ Program for Automatic Time Domain Reflectometry Measurements: I. Design and Operating Characteristics. Trans. ASAE vol. 43(6):1939-1946. (Available at http://www.cprl.ars.usda.gov/programs/)

Evett, S.R. 2000b. The TACQ Program for Automatic Time Domain Reflectometry Measurements: II. Waveform Interpretation Methods. Trans. ASAE vol. 43(6):1947-1956. (Available at http://www.cprl.ars.usda.gov/programs/)

Hignett, C., and S.R. Evett. 2002. Neutron Thermalization. Section 3.1.3.10 In G. Clarke Topp and Jacob Dane (eds.) Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 3rd Edition. AGRONOMY Monograph Number 9. (in press)