International soil moisture sensor comparison

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A four-year effort to compare and test soil moisture sensors is drawing to a close. The cooperative research project was sponsored by the International Atomic Energy Agency (IAEA) and included scientists from Australia, Austria, France, Tunisia, and the United States. The laboratory and field comparisons were desired by the IAEA to find if technologies existed that could replace the neutron thermalisation method for soil profile water content estimation. Neutron thermalisation measurements are done with the neutron moisture meter (NMM), a device invented 50 years ago for measurements at any depth desired within an access tube placed vertically in the soil. Accurate profile water content measurements are crucial to determining crop water use and irrigation infiltration, and thus are key to studies of crop water use efficiency and irrigation efficiency. These are two important elements in the goal of producing more crop per drop in our increasingly water-short world. Soon after its invention the NMM was shown to be superior to standard gravimetric sampling because of its repeatability and large soil volume measured.

Devices studied included those measuring frequency domain (capacitance) and time domain responses to changes in soil water content, most of which operated within plastic access tubes. Tests conducted at Bushland included several devices that worked within access tubes: the NMM (model 503DR1.5, Campbell Pacific Nuclear International[1]), the Sentek EnviroScan and Diviner2000, the Trime T3 tube probe, and the Delta-T PR1/6.

The Sentek and Delta-T devices measure the frequency of oscillation of an electronic circuit including a capacitor that is coupled with the soil outside the access tube. The oscillation frequency decreases as soil water content increases. Thus, these are capacitance devices, also known as frequency domain devices. The Trime T3 device attempts to measure the travel time of an electronic pulse along wave guides that are placed in contact with the inside wall of a plastic access tube. Thus, it is a sort of time domain reflectometry device.

These sensors were compared with a conventional time domain reflectometry (TDR) system in large soil columns (three replicates each of three soils important in the Southern High Plains) placed on scales so that column mean water content was determined independently by mass balance to better than 0.01 $m^3 m^{-3}$ (see Figure 43). Tests of sensitivity to soil temperature and sensitivity to the soil-air interface were conducted in these columns.

Figure 43. Soil columns on scales. Columns were 55 cm in diameter and contained a soil depth of 75 cm. Sides of columns were covered with aluminum foil to reflect radiant energy. Columns were covered with plastic sheeting after saturation. In foreground is the Delta-T PR1/6 capacitance probe.

[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.

In a winter wheat field, transects of ten access tubes for each device were installed with a spacing of 10 m to study the devices' ability to accurately portray the spatial variability of soil profile water content. The soil was a Pullman silty clay loam, a fine, mixed, superactive, thermic Torrertic Paleustoll with mixed clay mineralogy including large proportions of illite and montmorillonite (Soil Survey Staff, 2004). This soil has an A horizon containing 35% clay, a strong Bt horizon containing 50% clay, and a Btk horizon containing up to 50% $CaCO_3$; from which horizons, the A, B, and C soils, respectively, were derived for packing the soil columns. Measurements were taken over several months, beginning in a relatively dry soil profile and continuing as rain and evapotranspiration wetted and dried the field, and as one half of the field was irrigated periodically.

Soil column tests showed that factory calibrations were not accurate for the devices used in access tubes, all of which would require soil-specific calibrations to yield more accurate results (see Table 12). The three soils varied most in clay content, which was of mixed mineralogy (largely illitic and montmorillonitic), and in calcium carbonate content.

Using manufacturer calibrations, conventional TDR, which used a Tektronix cable tester (model 1502C) and three-rod probes (20 cm long) buried in the soil, was at least twice as accurate as any of the devices used in access tubes, being within ± 0.024 $m^3\ m^{-3}$ of mass balance water content on average in saturated soil. Only the NMM and conventional TDR were not significantly sensitive to soil temperature (see Table 13).

Temperature sensitivity of both Sentek devices was small enough not to be problematic in field studies; but sensitivities of the Delta-T PR1/6 and Trime T3 were problematic, particularly in wet soil. Tests of response to nearness to the soil-air interface revealed that the soil volume measured by all the devices used in access tubes decreased as water content increased, except for the Trime T3 probe. Only the NMM and Delta-T PR1/6 had volumes larger than the sensor height in wet soil.

Table 12. Saturated column mean volumetric water contents (VWC) by mass balance, and device errors ($m^3\ m^{-3}$).

		Difference from VWC by mass balance					
SOIL	VWC BY MASS BALANCE	DELTA-T PR1/6	DIVINER-2000	ENVIRO-SCAN	TRIME T3	NEUTRON[1]	TDR
A	0.433	1.339	0.084	-0.037	0.064	0.000	0.002
B	0.474	1.312	0.001	-0.062	0.088	-0.016	0.004
C	0.481	1.244	-0.037	-0.104	0.055	-0.014	-0.042
RMSD[2]		1.299	0.053	0.073	0.070	0.012	0.024

[1] The neutron moisture meter was field calibrated.

[2] Root mean squared difference from VWC by mass balance.

Table 13. Temperature sensitivity[1] in saturated soil[2].

INSTRUMENT	SLOPE ($M^3\ M^{-3}$) °C-1	R2	RMSE ($M^3\ M^{-3}$)
Trime T3	0.0204	0.75	0.0012
Delta-T PR1/6	0.0250	0.94	0.0002
EnviroSCAN	0.0010	0.88	0.00001
Diviner2000	0.0019	0.77	0.0001

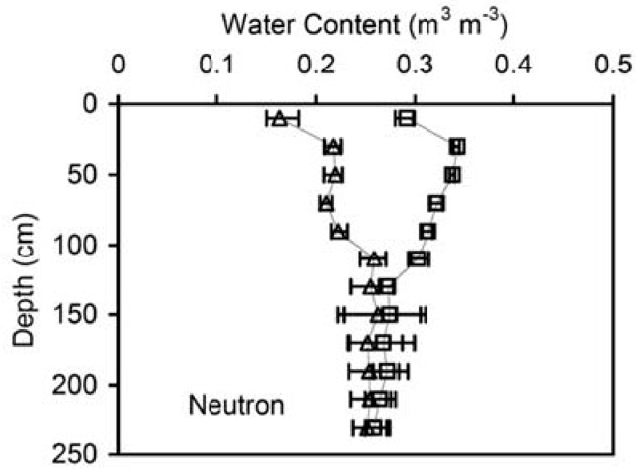
[1] Measured at 25 cm depth.

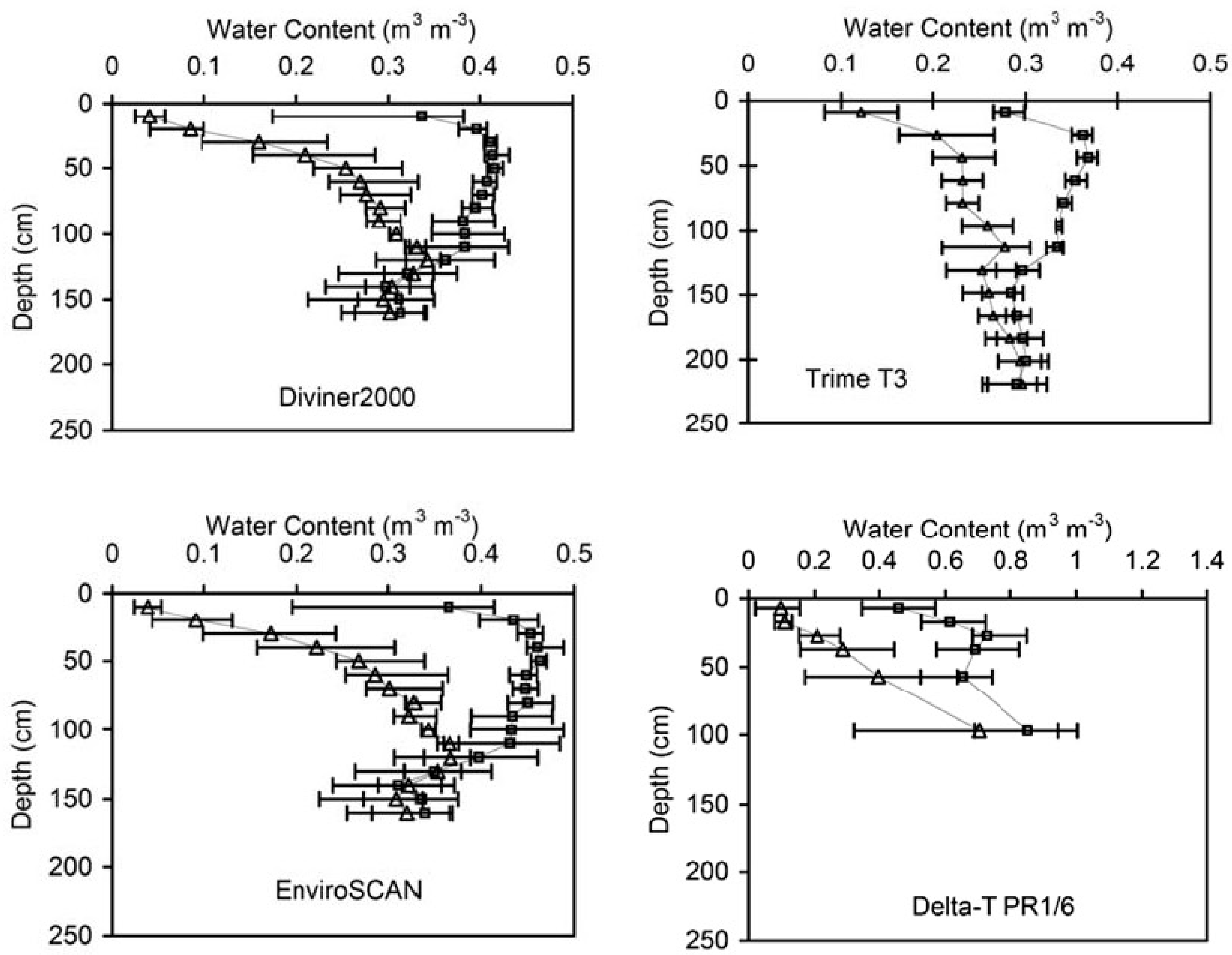
[2] Regressions and regression slopes were not significant for conventional TDR and the neutron moisture meter.

Field tests revealed that variability across the ten access tubes was smallest for the NMM, followed by the Trime T3, both Sentek devices, and the Delta-T PR1/6 in increasing order of variability (see Figure 44). Variability in transects of gravimetric moisture measurements, accomplished with a hydraulically pushed sampling tube, was close to that of the NMM, but was widely variable from one date to the next because of the destructive nature of gravimetric sampling, which required that sampling locations be changed at each sampling date.

The ability to accurately sense changes in profile water content due to irrigation was best for the NMM and Trime T3 devices, and worst for the Delta-T PR1/6. The larger variability of the capacitance devices (Sentek and Delta-T) was probably due to the much smaller soil volumes sensed by capacitance methods, which renders these devices more sensitive to both small scale variability of soil water content in volumes smaller than the representative elemental volume, and sensitive to any soil disturbance or air voids that might be created during access tube installation (all access tubes were installed according to manufacturer recommendations and with extreme care, sometimes requiring several hours to a day to install one plastic access tube).

Figure 44. Plots of field profile soil water content as reported by five moisture sensing devices discussed in the text using the factory calibrations, except for the neutron probe for which a field calibration had been previously accomplished. Data are from transects of ten access tubes for each device, spaced at 10 intervals across a winter wheat field, one half of which was irrigated. Plots are for the mean of five access tubes in each half of the field on 19 November 2003. Error bars around the mean values represent the maximum and minimum readings. Note the expanded scale for the Delta-T PR1/6 plot.





In general, the comparison studies revealed that there is not yet a suitable replacement for the NMM for soil water balance studies. Some alternative devices are too sensitive to soil temperature. Most measure such small volumes that they produce highly variable readings in the field, probably because they are sensing volumes smaller than the representative elemental volume for soil water content. Similarly, they are rendered sensitive to soil disturbance or voids caused by access tube installation. Also, the alternative devices are difficult to field calibrate for two reasons. First, they measure volumes that are too small to allow volumetric soil sampling within the device-measured volume surrounding an access tube. Second, unlike the NMM and conventional TDR, their measurand is nonlinearly related to water content, requiring at least three widely different water contents in the field to be measured to establish a calibration curve. Only the Trime T3 tube probe and the NMM allowed measurements deep enough to completely assess changes in profile water content due to crop water extraction and infiltration of irrigation and rain in all foreseeable circumstances. This is deeper than 2.5 m to even 3 m.

Studies at other locations produced results similar to those described here, but differed in soil environments, sensors compared, experimental methods and other aspects. The final Consultants' Meeting on "Comparison of Soil Moisture Sensors between Neutron Probe, Time Domain Reflectometry, and Capacitance Probes," was held March 24-28, 2003 at IAEA Headquarters in Vienna, Austria. Research reports detailing the studies are expected to be published in a special issue of the *Vadose Zone Journal* in 2005.

References

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