Symposium no. 59 Paper no. 1021 Presentation: poster

Neutron scattering, capacitance, and TDR soil water content measurements compared on four continents

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Abstract

Neutron scattering, capacitance, and time domain reflectometry (TDR) methods of soil water content measurement were compared in a wide variety of soils and environments. Comparisons aimed to establish the accuracy and precision of each method and particular device, the need for and amenability of the device to soil-specific calibration, the volume of measurement, and conditions of successful use. Measurements were made in a soil in Australia, three soils in Austria, five soils in France, two soils in Tunisia, and three soils in the United States. Except for conventional TDR, the devices were used in access tubes. Several experiments included gravimetric sampling. Devices tested included the soil moisture neutron probe (SMNP), Sentek EnviroSCAN and Diviner 2000 capacitance probes, the IMKO Trime tube probe, and conventional TDR systems from Soil Moisture Inc., Tektronix, Inc. and Dynamax, Inc. The Sentek, IMKO, Delta-T and SMNP devices all required soil-specific calibration. The conventional TDR systems were reasonably accurate without calibration. Due to their small measurement volume, installation of access tubes without soil disturbance outside of the tube was critical for success with the Sentek, IMKO, and Delta-T devices, but not for the SMNP. Successful tube installation was difficult with the smaller diameter devices (<30 mm), and was difficult in some soils for all devices except the SMNP. Access tubes available from the manufacturers for the Sentek, IMKO, and Delta-T devices were expensive compared with access tubes for the SMNP. Preliminary calibration vs. gravimetric sampling resulted in coefficients of determination (r^2) values of 0.42 and 0.53 in two Austrian soils for the Diviner. Also, the Trime system, using its standard factory calibration, did not compare well with SMNP, Diviner or EnviroSCAN measurements. Both the Diviner and EnviroSCAN devices were highly sensitive to the electrical conductivity of soil water, with a 5% change in water content caused by an EC increase of 5 dSm^{-1}. Tests in Australia showed the EnviroSCAN to overestimate water content near saturation and to underestimate near wilting point compared with the SMNP and laboratory determined water holding characteristics. Plant available water capacity measured by the EnviroSCAN system was twice that indicated by laboratory measures and the SMNP. In Tunisian, the Trime system was calibrated vs. the SMNP in a silty clay loam with r^2 of 0.60, but in a more clayey soil in France, calibration resulted in r^2 of 0.92. In Tunisia, comparison of the Trime device to gravimetric samples showed a generally linear relationship with data centered around the 1:1 line. However, for all soils in France and Tunisia, the Trime factory calibration was not suitable and calibration for different soil horizons was necessary. In the USA, devices were compared in soil columns. The EnviroSCAN and Diviner overestimated water content by 0.03 m^3 m^{-3} in dry soil, while the Trime overestimated water contents by 0.06 m^3 m^{-3}. Conventional TDR measurements were within 0.01 m^3 m^{-3} of values determined by mass balance.

Keywords: profile water content, TDR, neutron probe, calibration, capacitance, dielectric methods

Introduction

Measurement of the water content of soil profiles both within and below the root zone is necessary in many fields of agricultural, hydrological, environmental, and engineering science. In most cases, water content data are needed in units of volume per unit volume (e.g., m^3 m^{-3}). For example, such data are needed for physical descriptions of water, solute and heat fluxes, and for calculation of the water held in a particular depth of soil. The earliest methods of soil water measurement consisted of soil sampling, often by augering, and weighing of the sample before and after drying in an oven. The data resulting are in units of mass of water per unit mass of dry soil (e.g., g g^{-1}). This is still the standard method, against which all others are compared. Measurement of the soil's bulk density (g cm^{-3}), usually done by extracting cores of known volume, allows conversion of mass-based water contents to volumetric water contents. However, this introduces additional error due to the small-scale variability of bulk density. The most accurate volumetric water contents are obtained with thin-walled cylindrical tube samplers, which obtain a sample of known volume so that volumetric water content and bulk density can be calculated for each sample (Hignett and Evett, 2002). Whether done by augering or coring, soil sampling is destructive and time consuming; and is thus inappropriate in many studies.

In the 1950's the soil moisture neutron probe (SMNP) was introduced and quickly became a widely accepted non-destructive method of soil profile water content measurement (Evett, 2001). The SMNP uses a cylindrical access tube that is usually inserted vertically into the soil allowing measurement to many meters depth. The probe is suspended inside the tube by a cable so that measurements may be made at any depth increment. Typically, depth increments range from 10 to 20 cm. Theory, and methods of calibration and use are given by Hignett and Evett (2002), who show that calibration against multiple volumetric soil samples taken at each depth increment will repeatedly result in coefficients of determination (r^2) values > 0.9 and root mean squared errors (RMSE) of calibration < 0.01 m^3 m^{-3}.

Alternatives to the neutron probe have been investigated, but often rejected due to insufficiently accurate calibrations using standard methods (e.g., Evett and Steiner, 1995). However, these alternatives, which employ methods of measuring the soil dielectric permittivity, are attractive because they are not radioactive, and so may be used remotely and unattended, and with a minimum of regulatory burden and expense. Several such devices were introduced in the later 1980s and 1990s; and in 1998 the

International Atomic Energy Agency (IAEA) convened a meeting of five consultants to review these developments, resulting in an IAEA TECDOC on "Comparison of soil water measurement using the neutron scattering, time domain reflectometry (TDR) and capacitance methods". This report demonstrated the lack of good scientific comparisons of these devices; and so, the IAEA awarded four research contracts for comparisons of the SMNP, TDR and capacitance methods. This interim report covers the first year of a three-year project comparing several devices.

Materials and Methods

Studies took place at several locations in Australia, Austria, France, Tunisia, and the United States on several soils (Table 1), and used two or more devices at each location (Table 2). The Sentek Enviroscan and Diviner 2000, and the Delta-T Profile Probe employ capacitance technologies. The Campbell Pacific Nuclear (CPN), Troxler 4300, and Nardieux Humisol Solo models 25 and 40 are SMNP devices employing neutron thermalization. The manufacturer (IMKO) of the Trime tube probe describes the technology as TDR. However, the time measurement is described as a "pseudo-transit time"; and it is done using a voltage comparator to tell when the reflected waveform has reached a particular (unspecified) voltage. This is fundamentally different from the TDR method as reported by Topp *et al.* (1980) and Evett (2000), and introduces problems that will be discussed later. The Soil Moisture Trase and Dynamax Vadose TDR systems employ conventional TDR methods using trifilar probes. Except for the conventional TDR systems, all the devices were designed to be used in access tubes to acquire data at several depths; and so, all were evaluated in light of their being possible replacements for the SMNP. The access tubes were all some sort of plastic. The conventional TDR systems were used primarily as checks on data from the other systems.

The Sentek Enviroscan system employs capacitance sensors that may be fixed at 10-cm depth increments on a backbone that is semi-permanently placed in a plastic access tube installed in the ground for long term measurement at user-chosen time intervals. The Diviner 2000 employs a single sensor, similar to those used in the Enviroscan, that is moved up and down in a like access tube, and which records readings at 10-cm depth increments utilizing an automatic depth recorder. Its use is similar to that of the SMNP in that the device is moved around the field from access tube to access tube, with data being collected in a data logger for later download to a computer in the laboratory. The Delta-T Profile Probe is similar to the Enviroscan in that intervals between measurement depths are fixed, but more limited in that only four or six measurements may be made in a single access tube and no adjustment of the depth increments is possible (the probe is monolithic, and two lengths are available). However, the Delta-T may be moved from access tube to access tube quickly as is done with the Diviner 2000. Operation and calibration of the SMNP devices is well described in Hignett and Evett (2002). The Solo instruments employ an automatic mechanism for lowering the probe and taking readings at set depth increments. The Trime tube probe can be lowered inside an access tube to take readings at any depth desired by the user up to the cable length.

In all cases, access tubes were installed according to manufacturer's recommendations and in some cases, with manufacturer assistance. Instruments were operated according to instructions in their respective manuals.

Table 1 Locations, lead researchers and soils.

Location	Researcher	Site	Soil
Keith, South Australia	C.T. Hignett	1	Sand (0-20 cm), Medium clay (20-40 cm), $CaCO_3$ below 40 cm
Grosse-Enzerdorf, Austria	P. Cepuder	1	Silt loam (0-60 cm), Silty clay loam (60-100 cm), Silt loam to silty clay loam (100-120 cm), Silty clay loam (120-135 cm)
		2	Silt loam (0-140 cm)
		3	Silt loam (0-80 cm), Silt (80-100 cm), Silt loam (100-140 cm)
Grenoble, France	J.-P. Laurent	1	Sandy loam with low electrical conductivity
Montpellier		2	Clay loam with $CaCO_3$
Avignon		3	Silt loam with $CaCO_3$
Champenoux		4	Silty clay loam with clay horizon, hydromorphic
St. Laurent de la Prée		5	Nearly 100% chlorite clay
Cherfech, Tunisia		6	Silty clay loam, 45% $CaCO_3$, EC = 0.96-2.6 dSm^{-1}
Bushland, Texas, United States	S.R. Evett	1	Silty clay loam (30% clay, 53% silt, 17% sand)
		2	Clay (48% clay, 39% silt, 13% sand)
		3	Clay loam (35% clay, 40% silt, 25% sand) with 50% $CaCO_3$

Table 2 Locations, devices used, and technologies.

Location	Device	Technology
Keith, South Australia	Sentek Enviroscan	Capacitance,
	SMNP	Neutron scattering
Grosse-Enzerdorf, Austria	Sentek Enviroscan	Capacitance
	Sentek Diviner 2000	Capacitance
	Nardieux Humisol Solo 40	Neutron scattering
	Soil Moisture Trase	Time domain reflectometry
	Trime-T3 tube probe	Step pulse and voltage comparator
Grenoble, France	Troxler 4300	Neutron scattering
	Trime-T3 tube probe	Step pulse and voltage comparator
Montpelier	Nardieux Humisol Solo 25	Neutron scatterings
	Trime-T3 tube probe	Step pulse and voltage comparator
Avignon, Champenoux	SMNP (unspecified)	Neutron scatterings
and St. L. de la Prée	Trime-T3 tube probe	Step pulse and voltage comparator
Bushland, Texas, USA	CPN 503DR	SMNP
	Trime-T3 tube probe	Step pulse and voltage comparator
	Sentek Enviroscan	Capacitance
	Sentek Diviner 2000	Capacitance
	Delta-T PR1/6	Capacitance
	Dynamax Vadose	Time domain reflectometry

Results and Discussion

Sentek EnviroSCAN and Diviner 2000. Comparison between the EnviroSCAN and the SMNP took place on a duplex soil with three distinct horizons in Australia. Field capacity and wilting point values of volumetric water content (VWC) were measured in the laboratory for each soil horizon for later comparison with maximum and minimum field-measured VWC values. Four access tubes for each device were installed in replicated plots that were flood irrigated. Data from day of year (DOY) 148, when the most dry soil profile occurred, and DOY 204, two days after an irrigation, were plotted, illustrating the much greater scatter in the data from the EnviroSCAN as compared with the SMNP (Figure 1). Greater scatter is expected with the capacitance method due to the much smaller volume of soil that is measured, which allows the method to measure small-scale heterogeneity in VWC. Unfortunately, the smaller measured volume also makes this method susceptible to errors caused by soil disturbance during access tube installation, or due to macropores, cracks, or other soil heterogeneities. The greater scatter from the capacitance device implies that a greater number of access tubes would be necessary to measure a field-average profile water content to a given precision than would be needed for the SMNP. A more serious problem is the over estimation of water contents evidenced for the capacitance device, which reported water contents as much as 0.337 m^3 m^{-3} larger than field capacity at 20-cm depth and 0.189 m^3 m^{-3} larger at 30-cm depth (Figure 1, Table 3). The EnviroSCAN and Diviner use the same technology; and both are sensitive to the electrical conductivity (EC) of the soil solution (Figure 2). Evidently, the EC of the soil solution should be reported along with other soil data pertinent to any calibration done on these instruments. These capacitance probes are also sensitive to soil temperature, with a 10ºC change in temperature causing a 0.009 m^3 m^{-3} change in reported water content in a dry soil (Figure 3).

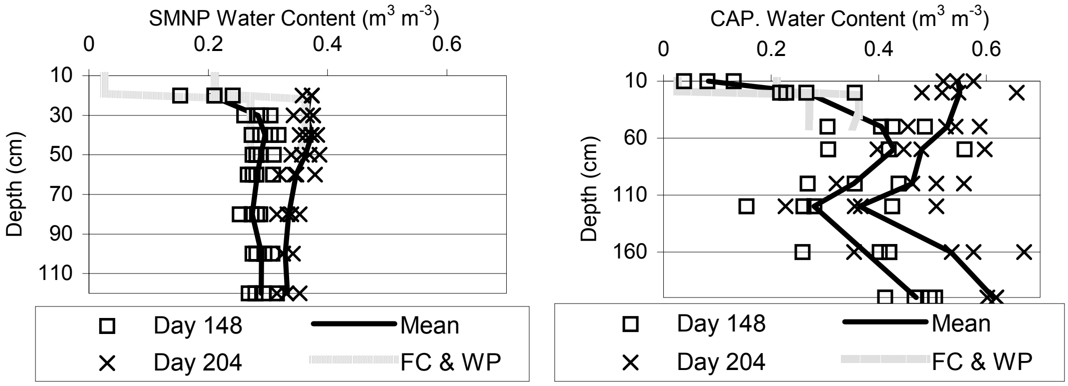

Figure 1 Soil moisture as measured by the SMNP (left) and the EnviroSCAN (right, CAP.) in S. Australia on the day with the driest profile measured (148) and on the second day after an irrigation (204). The field capacity (FC) and wilting point (WP) water contents are plotted as gray lines for depths from 10 to 50 cm.

There is ample evidence that the Sentek capacitance systems should be calibrated for individual soils (Baumhardt *et al.,* 2000). The Diviner was calibrated vs. gravimetric soil samples taken with a percussion drill to 1-m depth at different times of the year to obtain a range of samples (Figure 4) at two sites in Austria. In order to avoid disturbance of ongoing data collection, samples were not taken in close proximity to the access tubes. Water contents were converted to volumetric using the mean bulk density at each depth. The root mean squared error (RMSE) of prediction was large (0.038 and 0.046 m^3 m^{-3}), reflecting the large scatter in the data. The calibration for site 1 was more nearly of the form of the factory calibration (concave upward); but neither calibration was close to those obtained in Texas, California, and Beltsville in the United States, or in Australia (Baumhardt et al., 2000; Paltineanu and Starr, 1997). The calibrations may improve when destructive sampling close to the access tubes is performed at the experiment's end. Water contents from the Diviner were similar to those from the SMNP (Figure 5), although both were approx. 0.04 m^3 m^{-3} larger than gravimetrically determined values.

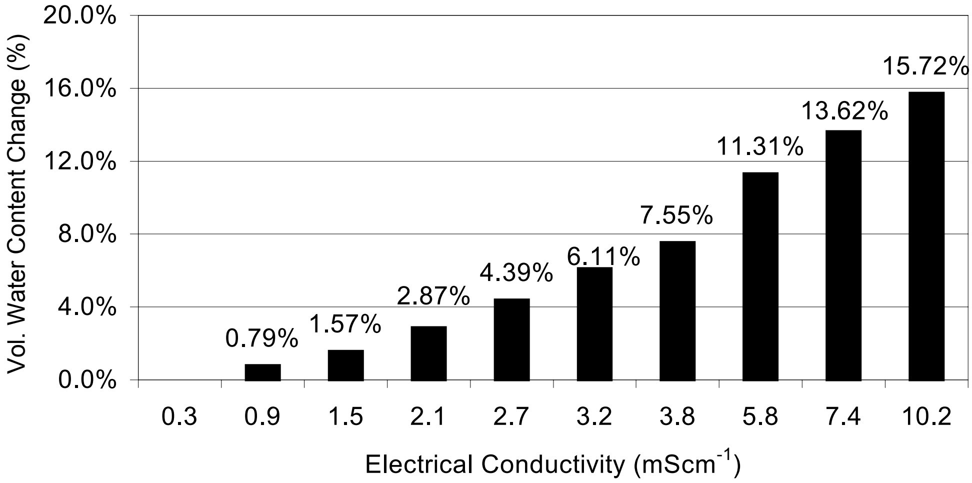

Figure 2 Relationship between electrical conductivity ($mScm^{-1}$) and percent change in the volumetric water content (m^3 m^{-3}) reported by the Diviner 2000.

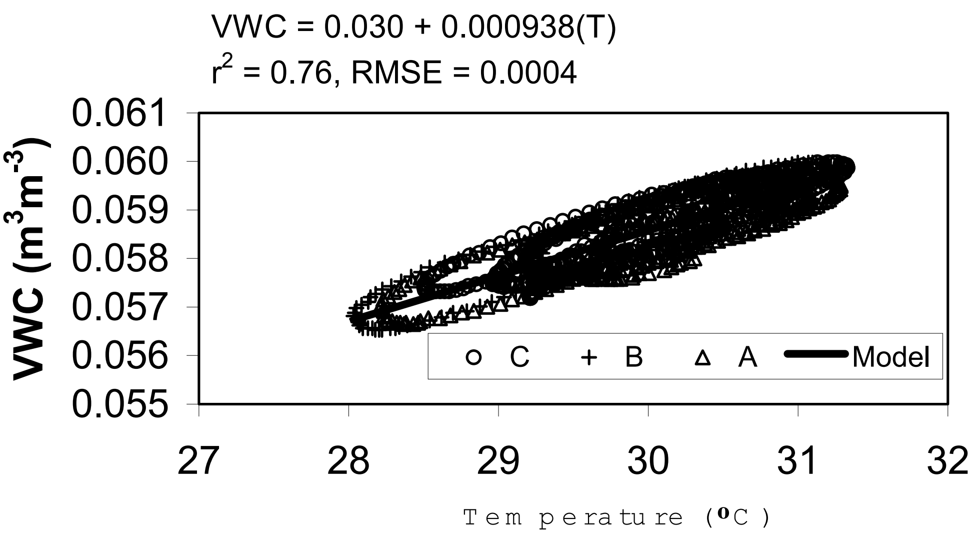

Figure 3 Dependence of water content (VWC) on temperature for the Sentek EnviroSCAN in three soils at Bushland, Texas.

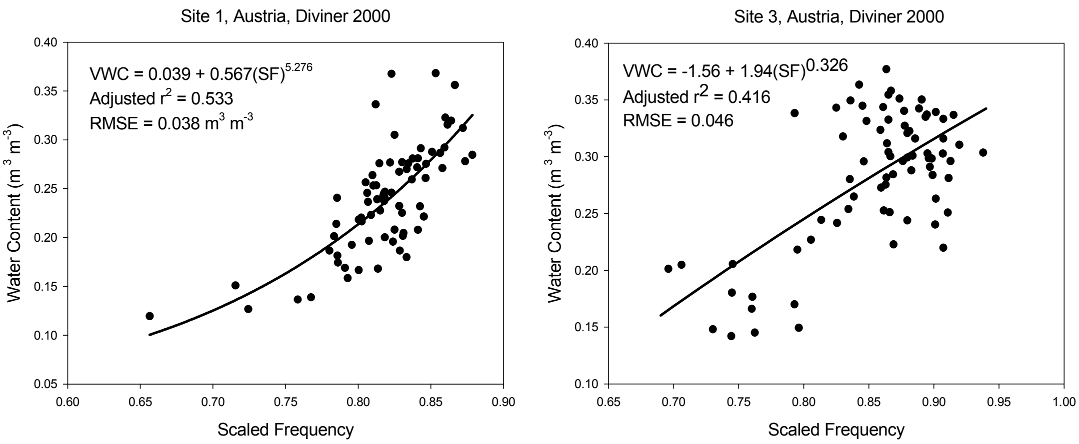

Figure 4 Calibrations of the Diviner 2000 for sites 1 and 3, Austria.

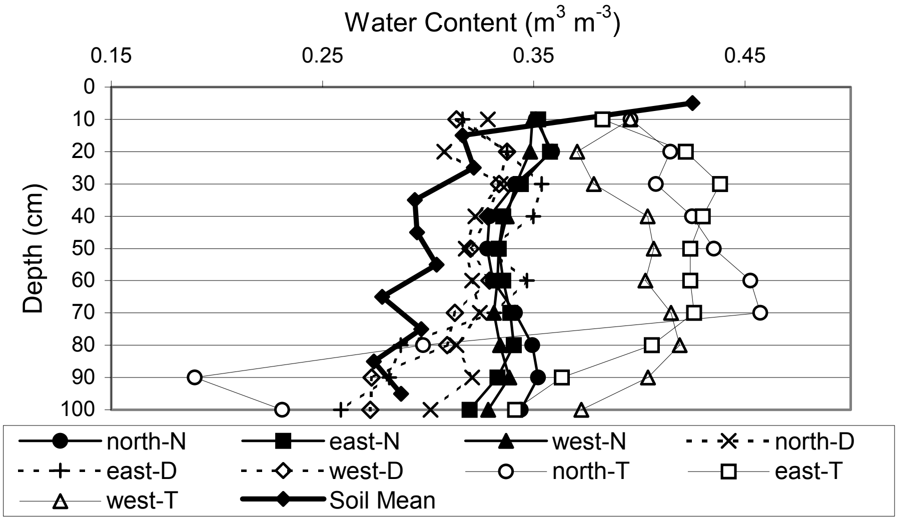

Figure 5 Comparison of SMNP (N), Diviner (D), and Trime tube probe (T) measurements vs. the mean of gravimetric soil water (SD <= 0.02 $m^3 m^{-3}$ at all depths) for 2 June 2001 at site 1 in Austria (three access tubes for each device).

Trime tube probe

Evaluation of the Trime probe vs. the Diviner and SMNP demonstrated that the former produced larger deviations in the Austrian data; and it over estimated water content by > 0.10 $m^3 m^{-3}$ using the factory calibration (Figure 5). In three dry (0.04 $m^3 m^{-3}$) Texas soils, the Trime over estimated by >0.06 $m^3 m^{-3}$. As with the other devices, the Trime probe must be calibrated for the specific soil in which it will be used. At locations in France and Tunisia, linear regression of Trime readings vs. SMNP and gravimetrically determined water contents resulted in r^2 values of 0.92 and 0.60, respectively (Figure 6). The regression slopes were far from unity, indicating a need for soil-specific calibration. As with the Austrian data, the Trime over estimated water contents when using the factory calibration. Soil moisture profiles that corresponded well to results from SMNP devices were obtained at Montpelier and Grenoble by applying a linear correction to data from the Trime system, using the data from previously site-calibrated SMNP devices as reference values. Soils at St. Laurent de la Prée and Champenoux were more problematic. At the former site, a nonlinear relationship was necessary to correct water contents above approx. 0.4 $m^3\ m^{-3}$, which were otherwise over estimated by as much as 100% in the heavy clay soil. At the latter site, the Trime system returned erratic values and often displayed "salinity too high", despite the fact that the soil was not saline. The soil at Champenoux contained 45% clay, of a type that caused attenuation of the wave form (measured with a Trase TDR system connected to the Trime T-3 probe, Figure 7). It should be noted that these wave forms could have been interpreted correctly using a conventional TDR system.

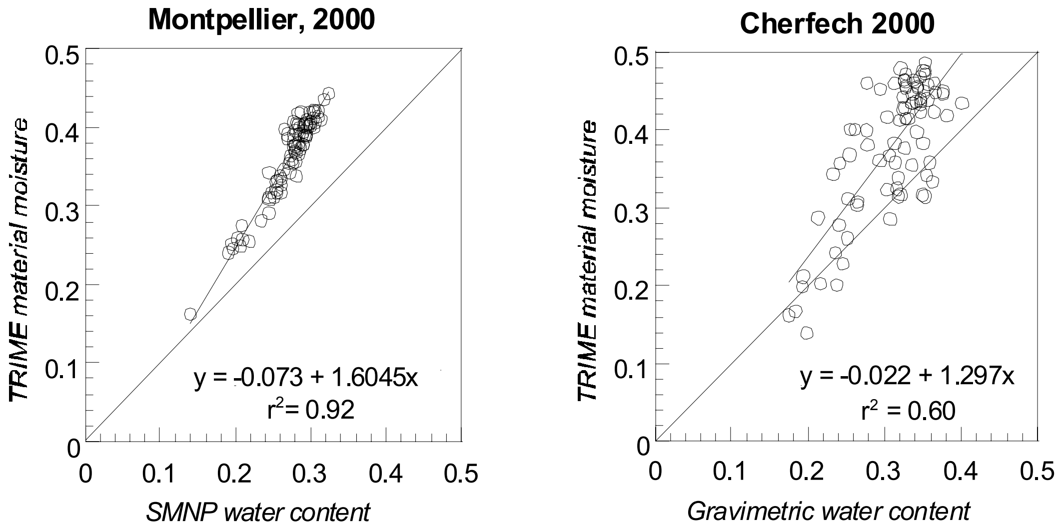

Figure 6 Comparison of Trime readings with SMNP and gravimetric data for locations in France and Tunisia for several dates and depths. Water contents are in $m^3\ m^{-3}$.

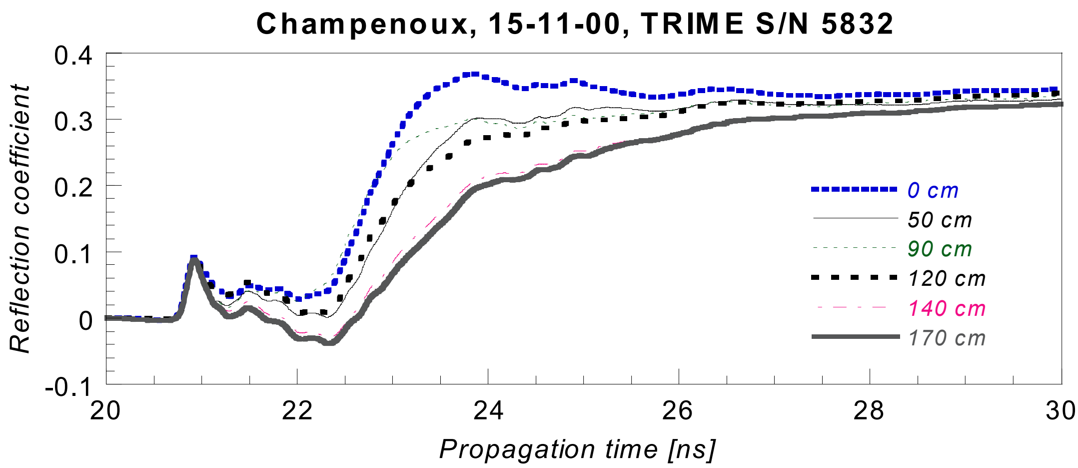

Figure 7 Examples of TDR-waveforms acquired on the Trime T3-probe in a tube in the Champenoux forest.

Temperature Sensitivity

Measurements in Texas showed that 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 (r^2 = 0.52, RMSE = 0.005 m^3 m^{-3}). Soil type did not influence the relationship between reported water content and soil temperature of the EnviroSCAN system in three Texas soils, where a 10ºC change in temperature would cause a 0.009 m^3 m^{-3} change in reported water content (r^2 = 0.76, RMSE = 0.0004 m^3 m^{-3}). For the Delta-T Profiler, the sensitivity was 0.01 m^3 m^{-3} per 10ºC (r^2 = 0.73, RMSE = 0.0013 m^3 m^{-3}). The Diviner was less sensitive, with a 10ºC change in temperature causing a 0.005 m^3 m^{-3} change in reported water content (r^2 = 0.65, RMSE = 0.0003 m^3 m^{-3}). All regressions were significant at the P = 0.001 level, with slopes significantly different from zero. Tests were performed in dry soils (0.04 m^3 m^{-3}) at 25-cm depth. Water content values from the SMNP and the Dynamax TDR system were not significantly dependent on soil temperature.

Conclusion

While these studies are ongoing, it appears that the SMNP is still the most practical device for field measurements of soil profile water content. All the systems required calibration, except for the conventional TDR systems. The Trime tube probe performed well in some situations, but not in others and was the most temperature sensitive (0.09 m^3 m^{-3} per 10ºC). Without calibration, it over estimated water contents more than the other systems based on measurement of soil electrical permittivity. The Sentek, Delta-T and Trime systems generally reported values that were more erratic than those reported by the SMNP. This may have been due, in part, to the smaller volume of soil measured by these devices. But, it may also have been due to undesired sensitivity to soil disturbance during access tube installation and to variations in soil macroporosity.

Acknowledgements

We gratefully acknowledge funding from the International Atomic Energy Agency for our individual research projects as well as the support of our parent organizations.

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