Published online November 16, 2005

Time Domain Reflectometry Laboratory Calibration in Travel Time, Bulk Electrical Conductivity, and Effective Frequency

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ABSTRACT

Accurate soil water content measurements to considerable depth are required for investigations of crop water use, water use efficiency, irrigation efficiency, and the hydraulic properties of soils. Although the soil moisture neutron probe has served this need well, it cannot be used unattended. Newer methods, which respond to the electrical properties of soils, typically allow data logging and unattended operation, but with uncertain precision, accuracy, and volume of sensitivity. In laboratory columns of three soils, we calibrated a conventional time domain reflectometry (TDR) system for use as a reference system for a companion study of water content sensors that are used in access tubes. Measurements were made before, during, and after wetting to saturation in triplicate repacked columns of three soils: (i) a silty clay loam (30% clay, 53% silt), (ii) a clay (48% clay, 39% silt), and (iii) 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 TDR measurements of water content and thermocouple measurements of temperature were made at eight depths in each column every 30 min. Accuracy of the TDR system was judged by the root mean squared difference (RMSD) between column mean water contents determined by mass balance and those determined using the Topp equation as a standard calibration. Smaller values of the RMSD metric indicated more accurate standard calibration. Although the TDR system exhibited RMSD <0.03 m^3 m^{-3} using the Topp equation, there were differences in accuracy between the three soils, and there was some temperature dependency at the saturated end, although not at the dry end. This paralleled the temperature dependency of the soil bulk electrical conductivity (BEC). Incorporation of bulk electrical conductivity and effective frequency of the TDR measurement into the calibration model reduced the calibration RMSE to <0.01 m^3 m^{-3} and practically eliminated temperature effects. Because the temperature effects on the TDR measurement are embedded in the BEC and effective frequency, a measurement of temperature is not needed to apply the calibration to these soils.

Accurate soil water content values from the surface to well below the root zone are required for determination of crop water use, water use efficiency, irrigation efficiency, and the hydraulic characteristics of soils. For nearly 50 yr, the profiling neutron moisture meter (NMM) has served this need well. Useful measurements with the NMM may be made in depth increments as small as 10 cm, from as shallow as 10 cm (Evett et al., 2003) to depths >30 m. But, increasing regulatory burdens, including the requirement that the NMM 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 determining 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 brought to the scientific market that rely on measurements of soil electrical properties as a surrogate for soil water content, including TDR (Topp et al., 1980) and capacitance methods (Dean et al., 1987; Paltineanu and Starr, 1997). In 2000, an international effort was begun under the auspices of the International Atomic Energy Agency (IAEA) to study the time domain reflectometry and capacitance methods of soil water sensing as compared with the NMM (IAEA, 2000). As part of this effort, we began laboratory soil column and field comparisons of conventional TDR, the NMM, the Sentek Diviner2000 and EnviroSCAN capacitance systems (Sentek Pty. Ltd., South Australia), the Delta-T PR1/6 capacitance system (Delta Devices Ltd., Cambridge, UK), and the Trime T3 tube probe TDR system (IMKO Micromodultechnik GmbH, Ettlingen, Germany).[1] All but the conventional TDR system were designed to sense the soil from within an access tube. Preliminary results have been reported elsewhere (Evett et al., 2002a, 2002b).

Conventional TDR systems are here defined as those that employ probes (usually bifilar or trifilar waveguides) that are inserted into or buried in the soil and are connected to a TDR instrument either directly or through a system of coaxial multiplexers, for the purpose of capturing a waveform that is analyzed to determine the travel time of the TDR pulse along that length of the probe rods that is in contact with the soil. Due to installation difficulties, these TDR systems are not well adapted for determination of water contents well below the root zone. However, a conventional TDR system was used in the soil column comparison study as a reference system because of its perceived relative immunity to temperature and bulk electrical conductivity interferences, with the intention of using water contents determined by TDR at multiple levels in each column to calibrate the other instruments. Calibration of the other systems depended on good accuracy with the TDR sys-

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Published in Vadose Zone Journal 4:1020–1029 (2005).
Special Section: Soil Water Sensing
doi:10.2136/vzj2005.0046

[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.

Abbreviations: BEC, bulk electrical conductivity; EM, electromagnetic; IAEA, International Atomic Energy Agency; NIST, U.S. National Institute of Standards and Technology; NMM, neutron moisture meter; RMSD, root mean squared difference; TDR, time domain reflectometry.

tem. Here we discuss calibration of the conventional TDR system.

The TDR method makes use of electrical theory for signals in wave guides. For a coaxial cable, the value of the propagation velocity, v, of an electronic pulse along the cable is inversely proportional to the permittivity, ε, of the dielectric (insulating medium, often plastic) between the inner and outer conductors of the cable:

$$v/c_o = (\varepsilon\mu)^{-0.5} \quad [1]$$

where c_o is the speed of light in a vacuum, and μ is the magnetic permeability of the dielectric material. For a TDR probe in a soil, the dielectric material between the probe rods is a complex mixture of air, water, and soil particles that exhibits a variable apparent permittivity, ε_a, which in turn affects the velocity of a pulse along the probe rods. The measured property in the TDR method is the travel time, t_t, of the electronic pulse along the length (L) of the probe rods that are exposed to the soil. The velocity of the pulse can be calculated as $v = 2L/t_t$. Assuming $\mu = 1$, one sees that an apparent permittivity, ε_a, may be determined for a probe of known length, L, by measuring t_t:

$$\varepsilon_a = [c_o t_t/(2L)]^2 \quad [2]$$

Topp et al. (1980) found that a single polynomial function described the relationship between volumetric water content, θ_v, and values of ε_a determined from Eq. [2] for four mineral soils.

$$\theta_v = (-530 + 292\varepsilon_a - 5.5\varepsilon_a^2 + 0.043\varepsilon_a^3)/10^4 \quad [3]$$

Since 1980, other researchers have shown that the relationship between θ_v and $t_t/(2L)$ is practically linear (e.g., Ledieu et al., 1986; Yu et al., 1997). Indeed, Topp and Reynolds (1998) found that Eq. [3] is equivalent to $\theta_v = 0.115(\varepsilon_a)^{0.5} - 0.176$. We note here that the apparent permittivity, as calculated from travel time using Eq. [2], contains any deviation from unity of μ. In addition, the value of ε_a increases with the bulk electrical conductivity, σ_a (S m^{-1}), of the soil (Wyseure et al., 1997; Robinson et al., 2003), particularly for σ_a >0.2 S m^{-1}. Also, the value of σ_a increases with soil water content (Rhoades et al., 1976; Mmolawa and Or, 2000). The value of ε_a may increase or decrease with temperature depending on the soil texture (Campbell, 1990; Pepin et al., 1995; Persson and Berndtsson, 1998; Wraith and Or, 1999) and increases as measurement frequency decreases (Campbell, 1990). The latter fact means that, for a broadband method such as TDR, there is a cable length effect because coaxial cable acts as a low pass filter—the longer the cable, the less signal energy is present in the higher frequencies. The TDR estimated value of ε_a increases with cable length (Hook and Livingston, 1995), particularly for high surface area soils (Logsdon, 2000). Topp et al. (2000) found that TDR signal dielectric loss is a function of σ_a, regardless of whether this conductivity arises from soil water solution conductivity or from clay type and content. Thus, TDR calibrations should take σ_a into account, and probably cable length as well.

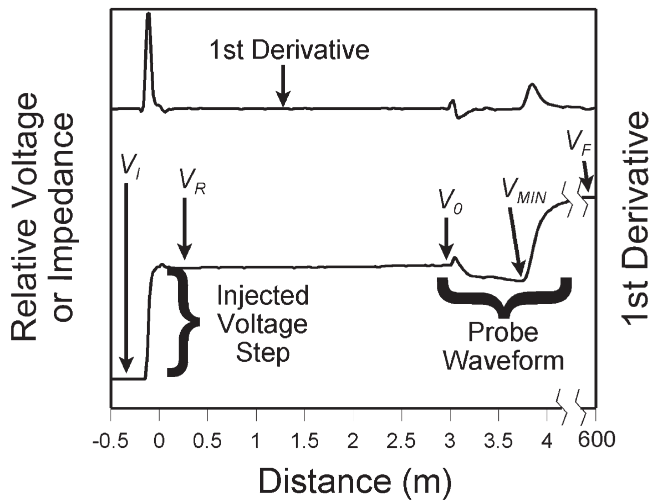

Fig. 1. Plot of a waveform and its first derivative from a Tektronix 1502C TDR cable tester set to begin at −0.5 m (inside the cable tester). The voltage step is shown to be injected just before the zero point (BNC connector on instrument front panel). At 3 m from the instrument, a TDR probe is connected to the cable. The relative voltage levels, V_I, V_{min}, V_o, and V_F are used in calculations of the bulk electrical conductivity of the medium in which the probe is inserted and in determination of the probe characteristic impedance. Waveform positions for determining values of these parameters are described numerically in Evett (2000a, 2000c), where V_o here is denoted V_{o2}.

Fortunately, conventional TDR may be used to assess σ_a (Wraith, 2002)

$$\sigma_a = \frac{\varepsilon_o c_o}{L}\frac{Z_o}{Z_u}\left[\frac{2(V_o - V_I)}{V_F - V_I} - 1\right] \quad [4]$$

where ε_o is the permittivity of free space (8.854×10^{-12} F m^{-1}), c_o is the speed of light in a vacuum (299 792 458 m s^{-1}), L is the probe length (m), V_o, V_F, and V_I are relative voltages measured from the wave form (Fig. 1), Z_o is characteristic impedance of the probe (Ω), and Z_u is the characteristic impedance of the cable tester (Ω). Topp et al. (2000) and others found that Eq. [4] accurately provides the soil BEC. Thus, it should be possible to include the important effects of temperature-dependent σ_a in a soil specific TDR calibration.

HYPOTHESIS DEVELOPMENT

For a signal at a single angular frequency, ω, the effect of direct current electrical conductivity, σ_{dc}, on the apparent permittivity can be represented by (Robinson et al., 2003)

$$\varepsilon_a = \frac{\mu\varepsilon'}{2}\left(1 + \left\{1 + \left[\left(\varepsilon''_{relax} + \frac{\sigma_{dc}}{\omega\varepsilon_o}\right)\Big/\varepsilon'\right]^2\right\}^{0.5}\right) \quad [5]$$

where ε' is the real component of the complex dielectric permittivity, ε''_{relax} is the increase in permittivity due to relaxation losses, and the other terms are as defined above. Although Eq. [5] is for a single frequency, it includes the effects that are important interferences to the TDR method. As the signal frequency decreases (longer cables), the value of σ_{dc}/ω increases, leading to larger values of ε_a. As conductivity increases (soils with larger BEC), the value of ε_a increases, more so at lower frequencies. As relaxation losses increase (e.g., bound water effects), the value of ε_a increases. For broad band signals such as that of TDR, the angular frequency may be replaced by $2\pi f$, where f is an effective frequency (Robinson et al., 2003), which previously has been calculated for TDR in at least two different ways (Or and Rasmussen, 1999; Topp et al., 2000).

Parallel with the increase of travel time with the square root of permittivity (Eq. [2]), Eq. [5] suggests that travel time will increase with the square root of conductivity. Assuming that relaxation losses are not large, we hypothesize that, for situations in which the effective frequency is unvarying, a useful calibration model will be

$$\theta_v = a + b[c_o t_t/(2L)] + c(\sigma_a)^{0.5} \quad [6]$$

where the coefficient c is likely to be negative. This is similar to the model suggested by Wyseure et al. (1997).

The effective frequency will decrease for longer cables and in dispersive soils. Also, the degree of dispersion may increase with water content (Dirksen and Dasberg, 1993; Robinson et al., 2003), leading to a decrease in the effective frequency as water content increases. Not all clay soils are dispersive, as was illustrated by Evett (2000b), who contrasted TDR waveforms across a range of water contents for the nondispersive, kaolinitic Cecil clay vs. the dispersive Pullman soil. Equation [5] also suggests that travel time will vary as the square root of $1/f$. We hypothesize that in dispersive and conductive soils, or in systems with varying cable lengths, a useful calibration model will be

$$\theta_v = a + b[c_o t_t/(2L)] + c[\sigma_a/(2\pi f_{vi}\varepsilon_o)]^{0.5} \quad [7]$$

where we define an effective frequency, f_{vi}, primarily by the slope of the second rising limb of the waveform (a method to determine f_{vi} is given in the next section). Note that neither Eq. [6] nor [7] includes explicitly any variation in ε''_{relax}, the increase in permittivity due to relaxation losses.

The electromagnetic (EM) methods (time domain and capacitance or frequency domain) of soil moisture sensing typically allow data logging and unattended operation, but with uncertain precision and accuracy in soils of the U.S. southern Great Plains (Baumhardt et al., 2000; Evett and Steiner, 1995). U.S. agricultural soils in the Great Plains and further west often exhibit three important horizons differing in texture and/or chemical composition: (i) a well mixed Ap horizon, (ii) an illuvial clay horizon below that featuring larger clay content, and (iii) a horizon of carbonate accumulation below that, sometimes containing 50% or more $CaCO_3$ along with some $CaSO_4$. These contrasts in texture and chemical composition could potentially affect the calibrations of soil water content sensors. Our objective was to calibrate conventional TDR in three soil materials representing one instance of these important horizons, determining the accuracy, differences among soils, and sensitivity to temperature, bulk electrical conductivity, and cable length. Comparisons were made vs. soil water content determined by mass balance in soil columns. If accurately calibrated, TDR determined water contents would be used to cross-calibrate the other sensors in our larger study.

MATERIALS AND METHODS

Three soils were acquired in Fall 2000 at Bushland, TX, air dried, crushed, and sieved to <2-mm diameter. The soils were (i) a silty clay loam (30% clay, 53% silt), referred to as Soil A; (ii) a clay (48% clay, 39% silt), referred to as Soil B; and (iii) a clay loam (35% clay, 40% silt) containing 50% $CaCO_3$, referred to as Soil C. On a total mass basis, the C soil contained only 17% clay. Soils A, B, and C were derived, respectively, from the A, Bt, and Btk horizons of a Pullman soil, a fine, mixed, superactive, thermic Torrertic Paleustoll with mixed clay mineralogy, including large proportions of illite and montmorillonite (Soil Survey Staff, 2004). The difference in clay content from 30 to 48% between Soils A and B should illuminate any texture dependence of the measurement methods. The 50% $CaCO_3$ content of Soil C should illuminate effects of this soil chemical composition on measurements.

Each soil was packed uniformly in 5-cm lifts 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 a ceramic filter tube specified at 100-kPa air entry potential was embedded. Soil was packed around access tubes for other sensors, which were held in place with a jig so the tube positions would be identical in each column. For the conventional TDR systems, horizontal, trifilar TDR probes (model TR-100, 20-cm length, Dynamax, Inc., Houston, TX) were installed at depths of 2, 5, 15, 25, 35, 45, 55, and 65 cm in each column, and thermocouples were installed at the same depths to measure soil temperature. Three samples for initial gravimetric water content were obtained every two layers. Column sides were covered with reflective aluminum foil to minimize diel heating and cooling on the sides. Column soil surfaces were left exposed to solar radiation and air temperature variations in the greenhouse that housed the experiment. For measurements at the saturated end, the soil surface was temporarily covered with a sheet of polyethylene after excess water was suctioned from above the surface so the measured mass would not be increased by water standing on the surface.

Column mass was measured every 6 s using a data logger (model CR7, Campbell Scientific, Inc., Logan, UT) connected to the paralleled output of the four load cells in each deck scale (model DS3040-10K, Weigh-Tronix, Inc., Fairmount, MN), using a six-wire bridge configuration to minimize temperature-induced errors. Mean values were output every 5 min. Calibration with test masses traceable to the U.S. National Institute of Standards and Technology (NIST) resulted in RMSE values of linear regression ≤50 g for all scales. 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. The CR7 data logger was also used to acquire soil temperature data from the thermocouples. After an initial period during which data at the air-dry end were collected, the columns were infused with CO_2 through the filters in the bottom of each column, followed by slow wetting through the filters under a hydraulic head of 2.2 m. It required several months to fully saturate all the columns. Because there was some soil swelling, the height of each soil column was measured periodically, and volume adjustments were made accordingly.

Measurements of travel time in the 72 20-cm trifilar TDR probes were made every 30 min using the TACQ program

Table 1. Total TDR coaxial cable lengths from Tektronix 1502C cable tester through primary and secondary multiplexers (Mux) to probe.

Column	Soil	Mux address	Primary Mux to cable tester length (m)	Primary Mux to secondary Mux length	Cable on probe length	Total length
			m			
1	C	1	1.5	1.9	3	6.4
4	B	1	1.5	1.9	3	6.4
2	B	3	1.5	4.4	3	8.9
3	A	3	1.5	4.4	3	8.9
5	A	2	1.5	3.2	3	7.7
7	B	2	1.5	3.2	3	7.7
6	C	4	1.5	4.1	3	8.6
8	A	4	1.5	4.1	3	8.6
9	C	5	1.5	5.5	3	10

(Evett, 2000a, 2000b) running under DOS and controlling a conventional TDR system comprising an embedded computer (IBM PC/AT compatible), cable tester (model 1502C, Tektronix Inc., Redmond, OR), and five coaxial multiplexers arranged in a star configuration with one primary and the others secondary (Evett, 1998). Travel times were determined automatically by TACQ using the default waveform interpretation algorithms. Apparent dielectric constant was calculated using Eq. [2]. Total coaxial cable length varied among columns from 6.4 to 10.0 m, such that no one soil type had a preponderance of shorter or longer cables (Table 1). Bulk electrical conductivity was calculated from Eq. [4], using relative voltage values V_o and V_f determined using the waveform positions described in Evett (2000a, 2000c) (Fig. 1). For BEC calculations, the mean probe characteristic impedance for three probes was determined from repeated ($n = 8$) measurements of V_o and V_{min} in deionized water using (Wraith, 2002)

$$Z_o = Z_u \varepsilon_w^{0.5} \frac{V_{min}}{2V_o - V_{min}} \qquad [8]$$

where ε_w is the permittivity of water, and V_o and V_{min} are as in Fig. 1. Water temperature was measured using a thermometer traceable to NIST, and water permittivity was calculated according to Weast (1971, p. E-61). Probe characteristic impedance measurements were repeated for each total cable length reported in Table 1, and with multiplexers included in the circuit.

An effective frequency was calculated from the slope, ΔV_t, of the second rising limb of the waveform, which represents the reflection of the TDR pulse at the end of the probe rods, and from the magnitude of the initial voltage step (TDR pulse height). The TACQ program was modified to output the slope value and the time base, t_b (ns per unit), of the waveform (version TACQbeta available at http://www.cprl.ars.usda.gov/programs/, verified 18 Aug. 2005), and the magnitude of the initial voltage step was calculated as $V_0 - V_I$ from the BEC data output by TACQ (Evett, 2000a, 2000c) (Fig. 1). This differs from the procedure used by Topp et al. (2000), which relied on finding the maximum value of the second rising limb to fit a horizontal line tangent to it. Finding this maximum value may be difficult due to multiple reflections in the waveform. Also, this maximum value decreases as BEC increases, leading to a reduction in the reflected pulse magnitude. The resulting reduced rise time causes the effective frequency determined by the method to Topp et al. (2000) to be larger than that determined by our method, in effect confounding the effect of BEC on frequency (slope of the reflection) with the effect that BEC has on the magnitude of the reflected pulse (a conduction effect).

The effective frequency (radians) used in the present study, with subscript "vi" to indicate that it was based on the initial voltage step, was

$$f_{vi} = \varepsilon_o 2\pi \times 10^9 \times \Delta V_t/[t_b(V_0 - V_I)] \qquad [9]$$

Equation [9] embodies the essential information about effective frequency changes without relying on fitting a tangent line horizontal to a part of the waveform that may be poorly defined due to multiple reflections.

Assuming that calibrations of TDR travel time vs. water content are practically linear, an accurate two-point calibration should be possible if conductivity and temperature effects are minimal. Thus, the TDR system was calibrated vs. the column mean water contents for each soil using data from the air-dry state and the saturated state. In addition, calibrations were conducted with both travel time and conductivity as independent variables as in Eq. [6], and with travel time, conductivity, and effective frequency as independent variables as in Eq. [7].

RESULTS AND DISCUSSION

After packing, the soil columns had mean initial water contents of approximately 0.05 $m^3\ m^{-3}$ (Table 2), and mean bulk densities of 1.48, 1.47, and 1.40 Mg m^{-3} for Soils A, B, and C, respectively. Saturated water contents varied, with Soils B and C having larger saturated water contents due to swelling and the resultant increases in porosity. Column mean water contents estimated from TDR using Eq. [3] from Topp et al. (1980) differed by as much as 0.042 $m^3\ m^{-3}$ from mass balance values.

TDR Calibrations in Terms of Travel Time

Although the square root of the apparent permittivity has been identified as linear with water content, permittivity is not a measured but a calculated quantity. Therefore, the linear regressions reported here are for θ_v vs. $c_o t_t/(2L)$, where t_t and L are measured. Combining data for the three soils, TDR calibration was highly significant (Table 3), with slope and intercept close to the values reported by Topp and Reynolds (1998), but with a slightly smaller slope value than those reported by Yu et al. (1997). The RMSE of regression value of 0.02 $m^3\ m^{-3}$ is comparable to the $\pm$0.02 $m^3\ m^{-3}$ accuracy

Table 2. Air-dry and saturated column mean volumetric water contents (VWC) by mass balance, and errors in TDR water content ($m^3\ m^{-3}$) estimated using Eq. [3].

Soil	VWC by mass balance		TDR difference from VWC by mass balance	
	Air dry	Saturated	Air dry	Saturated
A	0.053	0.433	−0.015	0.002
B	0.056	0.474	−0.009	0.004
C	0.041	0.481	−0.001	−0.042
RMSD†			0.010	0.024

† Root mean squared difference.

Table 3. Linear calibration equations of θ_v vs. $c_o t_t/(2L)$ for conventional time domain reflectometry in three soils (3879 observations for each soil).

Soil	Intercept	Slope	r^2†	RMSE
				$m^3\,m^{-3}$
Combined data	−0.156	0.1121	0.988	0.0196
A	−0.146 a‡	0.1095 b	0.997	0.0085
B	−0.148 b	0.1071 c	0.997	0.0097
C	−0.184 c	0.1223 a	0.999	0.0058
Topp and Reynolds (1998)	−0.176	0.115	-	0.013§
Ledieu et al. (1986)	−0.176	0.114	0.97	0.013¶
Yu et al. (1997) silt loam	−0.180	0.122	0.989	0.0114
Yu et al. (1997) sand	−0.142	0.114	0.999	0.0043
Yu et al. (1997) sandy loam	−0.200	0.122	0.988	0.0104

† Value is adjusted coefficient of determination.
‡ Values followed by different letters are significantly different at the 0.001 probability level.
§ From Topp et al. (1980) reported as standard error of estimate.
¶ Reported as residual standard deviation.

typically claimed for TDR. Moreover, multiple comparisons of intercepts and slopes (SAS, 2004) showed that these were significantly different for the three soils. Accuracy for the individual soil calibrations was better than 0.01 $m^3\,m^{-3}$ as indicated by the RMSE of regression. For the clay-rich A and B soils, calibration equation slopes were smaller than that reported by Topp and Reynolds (1998), which was based on the four mineral soils studied by Topp et al. (1980), three of which had clay contents in the range of the A and B soils studied here. The difference is probably attributable to differences in clay mineralogy, the clay in our soils being rich in smectitic clay (montmorillonite), which is known to be electrically more lossy than clays with smaller ion exchange capacities and surface areas. The smaller slopes for our A and B soils would mean that a given measured travel time would result in an overestimate of water content (for large water contents) if the Topp and Reynolds (1998) equation were used. However, errors that would occur for measurements in our Soils A and B using the equation of Topp et al. (1980) rather than our calibration equations are within ±0.02 $m^3\,m^{-3}$ for the range of water contents studied (≈0.05–0.49 $m^3\,m^{-3}$). For our Soil C, use of the Topp et al. (1980) equation would underestimate water content by 0.042 $m^3\,m^{-3}$ at saturation, but by only 0.001 $m^3\,m^{-3}$ at air-dry water contents.

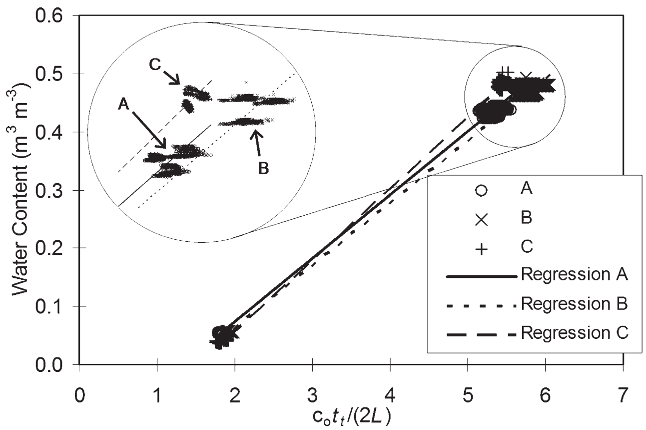

Fig. 2. Calibration equations for conventional time domain reflectometry in terms of column mean water content vs. column mean travel time for three soils (A, B, and C), disregarding effects of temperature and coaxial cable length. Inset shows horizontal jitter for Soils A and B.

Our Soil C is approximately 50% $CaCO_3$, far from the kind of mineral soils studied by Topp et al. (1980).

Temperature Dependency

The calibrations shown in Table 3 are highly significant, explain >99% of the variability in the data, and exhibit low RMSE values. However, there was some horizontal jitter in the data from Soils A and B at the saturated end (Fig. 2, inset). This variation in travel time for essentially constant water content could be due to a temperature effect that was not observed in our earlier experiments (Evett et al., 2002a, 2002b). To investigate this, we regressed water content, derived from TDR travel time measurements using the calibrations in Table 1, vs. soil temperature, both sensed at 15-cm depth in all columns. For Soils A and C, the regressions explained <9% of the variability in the data ($r^2 < 0.09$), and regression slopes showed <0.01 $m^3\,m^{-3}$ variation in water content with a 10°C variation in temperature. However, for Soil B, the regression explained 49% of the variability in water content with a slope of 0.0039 $m^3\,m^{-3}\,°C^{-1}$ (Fig. 3).

Because there seemed to be some trend in the data

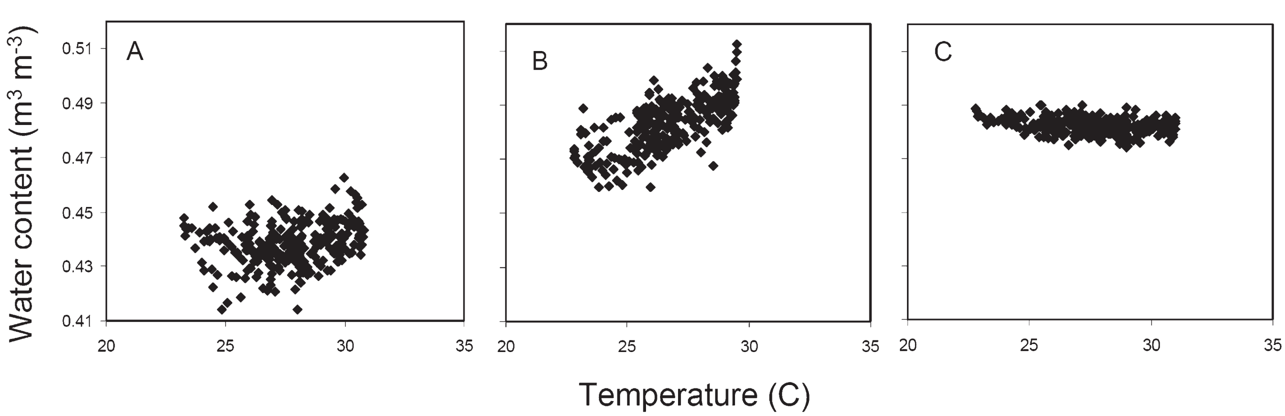

Fig. 3. Water content from TDR measurements at 15-cm depth in all columns vs. soil temperature at the same depth for Soils A, B, and C. Water content data for the second and third column of each soil were adjusted to match the mean of the water content for the first column so that the data would overlap despite small differences in column water contents, allowing any temperature dependency to be apparent.

Table 4. Linear regression equations of column mean water content, θ_v ($m^3 m^{-3}$) vs. column mean temperature (°C) for conventional time domain reflectometry in three saturated soils (992 observations).

Soil	Intercept	Slope	r^2†	RMSE
				$m^3 m^{-3}$
A	0.375	0.00173	0.337	0.00364
B	0.398	0.00323	0.609	0.00353
C	0.470	0.00024	0.035	0.00187

† Value is adjusted coefficient of determination.

from the 15-cm depth for Soils A and C, we then regressed the column mean travel times vs. the column mean temperatures in an effort to reduce the signal/noise ratio by essentially averaging out the noise through the combined use of data from the eight TDR probes in each column vs. the use of data from one probe at 15 cm in each column. All three regressions were significant, but the regression for the C soil explained only 3.5% of the variation in water content and, with its small slope, is not considered important. Regressions for both Soils A and B explained important amounts of the variation in water content, and the slopes indicated that temperature induced errors could be as large as 0.017 $m^3 m^{-3}$ per 10°C for Soil A and 0.032 $m^3 m^{-3}$ per 10°C for Soil B (Table 4, Fig. 4). The increase in the percentage of water content variation that is explained for Soils A and B is due to the improved signal/noise ratio resulting from the combination of data from eight probes for each column. This partially explains why in our earlier work (Evett et al., 2002b) we did not see an important effect of temperature in water content data from conventional TDR when using data from only one depth. It also explains why some total profile water content data from TDR shows temperature dependency when this dependency is not observed in data from individual probes.

Temperature dependency of TDR measurements is partially linked to loss of high frequency components of the TDR pulse in lossy media. Soils A and B in our study are examples of lossy media, with the 50% clay Soil B being considerably more lossy. As measurement frequency decreases temperature dependence increases. This is predicted by Eq. [5] where the quantity σ_{dc}/ω becomes larger as ω becomes smaller. Temperature dependency also increases with the BEC of the soil, which in turn increases with soil water content. This explains why, in the air-dry state when BEC was smallest and effective frequency was largest, none of our three soils exhibited any temperature dependency for TDR.

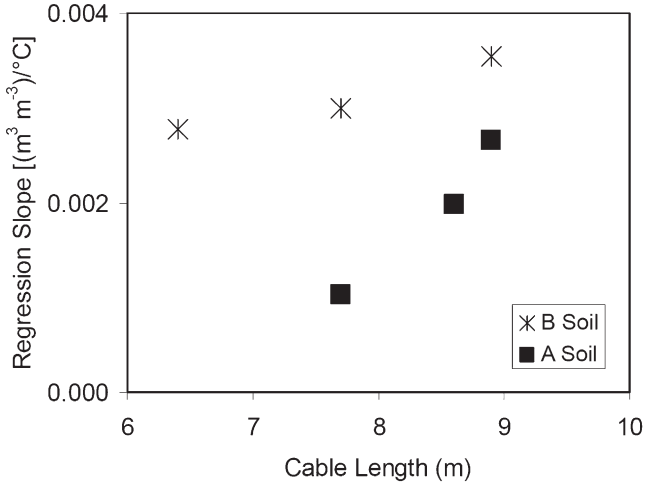

Fig. 5. Temperature dependency (regression slope) vs. total coaxial cable length for Soils A and B. Regression slope is for column mean water content vs. column mean temperature.

Mindful that coaxial cables act as low pass filters and that increasing cable length will lead to loss of high frequency components of the TDR pulse, we regressed column mean water contents for each column vs. column mean temperatures and plotted the slopes vs. total cable length for each column (Fig. 5). There is an apparent nonlinearly increasing temperature dependency with cable length. Thus, for Soils A and B it appears that a complete TDR calibration should account for the effects of both soil temperature and cable length. Since the effect of soil temperature is tied to the temperature dependency of BEC, and since the cable length effect is tied to the fact that cables act as low pass filters, then Eq. [6] and [7] may be useful calibration models.

Bulk Electrical Conductivity

The characteristic impedance of our TDR probes increased linearly with cable length, ranging from 260 to 267 Ω for cable lengths ranging from 6.4 to 10.0 m,

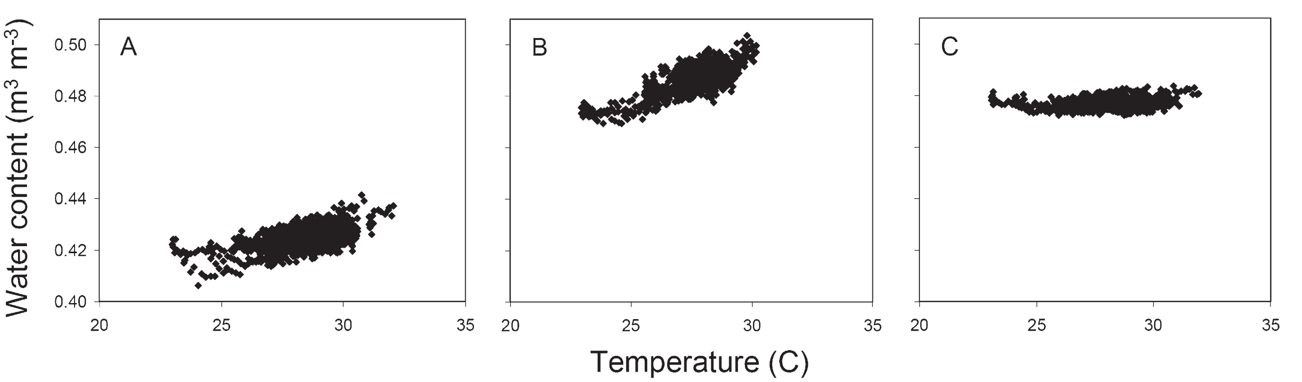

Fig. 4. Column mean water content from TDR measurements in all columns vs. column mean soil temperature for Soils A, B, and C. Water content data for the second and third column of each soil were adjusted to match the mean of the water content for the first column so the data would overlap despite small differences in column water contents.

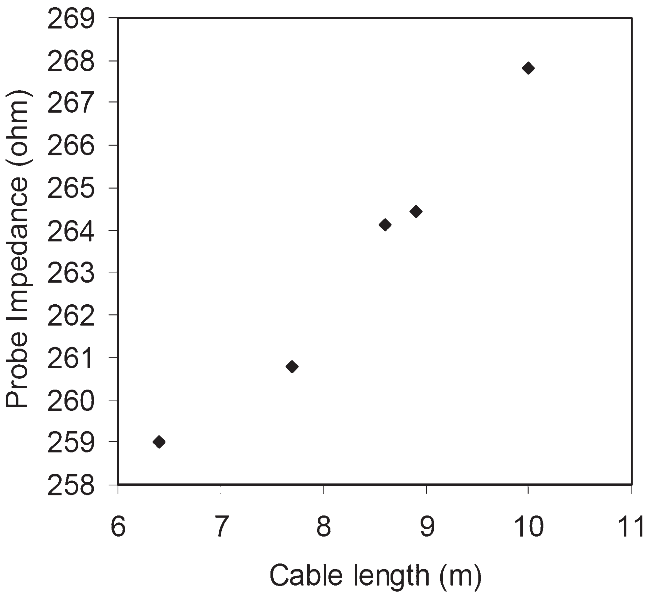

Fig. 6. Relationship between probe characteristic impedance and cable length for 50-Ω type RG58 coaxial cable (Alpha Wire Co., part no. 9058C).

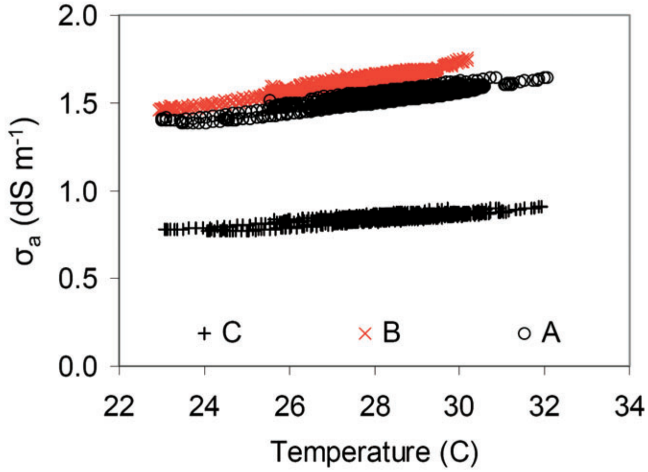

Fig. 7. Relationship between bulk electrical conductivity, σ_a, and soil temperature for the saturated A, B, and C soils.

respectively (Fig. 6). For the same five cable lengths, impedance standard deviations ranged from 1.7 to 2.8 Ω, in no particular order, indicating good repeatability among probes. In air-dry soil, relationships between σ_a and temperature were significant but weak (Table 5). Linear regression slopes were less than -1.15×10^{-4} and regressions explained less than 26% of the variation in σ_a. While the coefficients of determination were small, there was very little scatter in the data, as shown by the small values of RMSE. Mean values of σ_a were <0.042 dS m^{-1}, and σ_a increased with increasing clay content, in agreement with the results of Rhoades (1981), who found that soil matrix conductivity increased with clay content.

For the saturated soils, mean values of σ_a were an order of magnitude larger, in agreement with the well known positive relationship between σ_a and water content (Gupta and Hanks, 1972; Rhoades et al., 1976; Bohn et al., 1982). Also, σ_a linearly increased with temperature for the saturated A and B soils, with linear regressions explaining 82% of the variation in σ_a (Table 5). The larger mean value of σ_a and larger slope for Soil B were expected due to this soil's greater clay content. The values found for Soils A and B are similar in magnitude to those found by Persson and Berndtsson (1998) for a mix of montmorillonite clay and sand and for a clayey moraine soil. Although the relationship between σ_a and temperature was apparently linear for Soil C (Fig. 7), the coefficient of determination and slope were both smaller than for Soils A and B. The values of σ_a were also approximately twice as large for Soils A and B as for Soil C at any given temperature. These results explain both the results on the temperature dependency of travel times (apparent water contents) and the results of the calibrations. The latter showed lower calibration slopes (greater sensitivity of t_t to changing water content) for Soils A and B, corresponding to the larger BEC values and greater temperature dependency of BEC for these soils. Note that the slopes for saturated soils in Table 5 are larger for Soils A and B than the well-established relationship between electrolytic conductivity and temperature of 0.019 dS m^{-1} °C^{-1} (Rhoades et al., 1999). Similar slopes have been measured by others (e.g., Persson and Berndtsson, 1998) for clay soils. Also, there is no reason to think that bulk electrical conductivity in saturated clayey soils is wholly determined by the electrolytic conductivity of the bulk soil water.

Table 5. Linear regression equations of column mean bulk electrical conductivity (dS m^{-1}) vs. column mean temperature (°C) for conventional time domain reflectometry in three air-dry and saturated soils (714 observations for air-dry soil, 992 observations for saturated soil).

Soil	Intercept	Slope	r^2†	RMSE
	dS m^{-1}	dS m^{-1} °C^{-1}		dS m^{-1}
		Air dry		
A	0.040	-9.47×10^{-5}	0.241	0.00016
B	0.042	-1.15×10^{-4}	0.262	0.00018
C	0.035	-8.57×10^{-5}	0.178	0.00019
		Saturated		
A	0.520	0.0336	0.823	0.0234
B	0.563	0.0363	0.826	0.0228
C	0.346	0.0163	0.348	0.0338

† Value is adjusted coefficient of determination.

Calibration with σ_a and Effective Frequency as Covariates

Effective frequencies calculated using Eq. [9] averaged 0.229, 0.215, and 0.189 GHz for the air-dry Soils A, B, and C, respectively, similar to those found by Topp et al. (2000) for dry soils. When the soils were saturated, effective frequencies decreased to averages of 0.0159, 0.0130, and 0.0432 GHz for Soils A, B, and C, respectively, probably due to the impact of increasing BEC with wetness. The latter values were somewhat smaller than those found by Topp et al. (2000), probably because our soils were wetter (saturated), but also because of the differences in our method in calculating

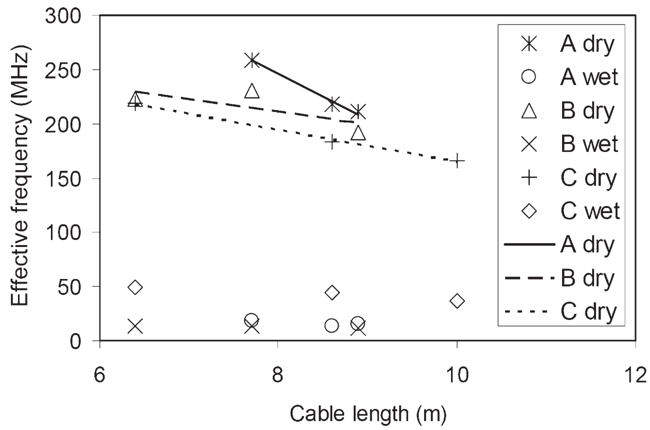

Fig. 8. Effective frequency calculated using Eq. [9] vs. cable length for saturated and air-dry soils.

effective frequency. The effective frequency was largely dependent on soil wetness, decreasing for wetter soils, but also decreased for longer cable lengths (Fig. 8), more so when the soil was air dry. The smallest value of effective frequency was for the saturated Soil B, which we expected to be the most electrically lossy soil due to its larger clay content and the illitic and montmorillonitic clay types. Effective frequency was also temperature dependent, much more so in air-dry soil than in saturated soil (Table 6). This behavior was similar to the effect of cable length, which was much stronger for air-dry soils.

For the combined data from all soils, inclusion of σ_a in the calibration model (Eq. [6]) resulted in some improvement (decrease) in the RMSE of regression (Table 7) compared with that for the model including only travel time (Table 3). The regression coefficient *c* was significant ($P < 0.0001$) and negative, in accordance with the theory (embodied in Eq. [5]) that increases in σ_a result in corresponding increases in apparent permittivity that are not related to increases in water content. All coefficients were significant ($P < 0.0001$) for individual soil calibrations as well, but contrary to theory, the *c* coefficient was positive for Soil B, and it was twice as large as that for Soil A. Also, the *b* coefficient for this soil was much smaller than those found by Topp and Reynolds (1998), by Ledieu et al. (1986), and from our own data (Table 3).

Inclusion of both σ_a and the effective frequency, f_{vi},

Table 6. Linear regression equations of effective frequency, f_{vi} (MHz), vs. temperature (°C) for the A, B, and C soils under air-dry and saturated conditions. Intercepts and slopes were significant ($P = 0.0001$).

Soil	Intercept	Slope	r^2†	RMSE
				$m^3\ m^{-3}$
		Air-dry		
A	330	−2.87	0.28	4.31
B	321	−3.07	0.40	3.55
C	257	−1.96	0.24	3.47
		Saturated		
A	42	−0.94	0.65	1.03
B	38	−0.92	0.70	0.82
C	80	−1.30	0.60	1.58

† Value is adjusted coefficient of determination.

in the calibration model (Eq. [7]) resulted in greater improvement in the RMSE of regression for the combined data, reducing it by one-half, even though no additional coefficient was fitted. Although RMSE values for Soils B and C were not reduced over those obtained with the Eq. [6] model, the *c* coefficients were all negative, in agreement with theory. Also, the *b* coefficients were similar in value for the combined data and for the individual soils, indicating that the Eq. [7] model encompassed the important physical effects of bulk electrical conductivity and signal frequency loss for the three soils and the TDR systems with varying cable lengths.

Surprisingly, inclusion of σ_a effects in Eq. [6] did not result in an overall decrease in the temperature dependency of estimated water contents (Table 8). Compared with estimates of water content from the Topp et al. (1980) equation, the calibrations based on Eq. [6] resulted in decreased temperature dependency for Soil A, but increased dependency for Soils B and C. Because of the large temperature dependency of σ_a, this was not expected. However, inclusion of both σ_a and effective frequency in the Eq. [7] model resulted in calibrations that exhibited uniformly small temperature dependencies, all $<0.0006\ m^3\ m^{-3}\ °C^{-1}$ temperature change. We conclude that the full model (Eq. [7]) is more physically realistic.

DISCUSSION AND CONCLUSIONS

For the three soils, ranging from 17 to 48% clay, inclusion of both bulk electrical conductivity and an effective frequency in the calibration model (Eq. [7]) resulted in a common calibration equation with an accuracy of $0.01\ m^3\ m^{-3}$ and a temperature sensitivity of $<0.0006\ m^3\ m^{-3}\ °C^{-1}$, a factor of six smaller than that for a soil specific calibration done using only travel time as an independent variable. The accuracy was improved twofold over that for a common calibration using only travel time. Extending the results of Wyseure et al. (1997), we found that the model including effective frequency, in addition to travel time and bulk electrical conductivity, was capable of correcting the temperature dependency of TDR derived water contents.

The success of the Eq. [7] calibration model contradicts the analysis of Wraith and Or (1999) that argued for a negligible effect of the loss tangent, which includes $\sigma_a/(2\pi f_{vi}\varepsilon_o)$, for soil water with a conductivity of 0.075 $S\ m^{-1}$. That analysis used a conductivity that was too small to reflect conditions of our study. Soil BEC may be a factor of from 5 to 18 times smaller than soil solution EC (Rhoades et al., 1999). If the factor is 10 for our soils, then our BEC values ranging up to 0.2 $S\ m^{-1}$ would reflect an equivalent soil solution EC of approximately 2 $S\ m^{-1}$, much larger than the value supposed by Wraith and Or (1999). Moreover, it is important to note that our soil was wetted with water of low conductivity; the soil BEC is largely a result of clay content, clay type, and water content, but not the conductivity of the bulk soil solution per se. Analysis based on the loss tangent of soil water would not necessarily apply. We also note that the effective frequencies we measured for saturated

Table 7. Linear calibration equations including bulk electrical conductivity, σ_a, and effective frequency, f_{vi}, terms for conventional time domain reflectometry in three soils (3879 observations for each soil). All coefficients were significant ($P = 0.0001$).

Soil	a	b	c	r^2†	RMSE
					m³ m⁻³
		$\theta_v = a + b[c_o t_t/(2L)] + c(\sigma_a)^{0.5}$			
Combined data	−0.186	0.1386	−0.3223	0.994	0.0140
A	−0.155	0.1169	−0.0780	0.997	0.0085
B	−0.112	0.0771	0.3441	0.997	0.0090
C	−0.208	0.1471	−0.3804	0.999	0.0053
		$\theta_v = a + b[c_o t_t/(2L)] + c[\sigma_a/(2\pi f_{vi}\varepsilon_o)]^{0.5}$			
Combined data	−0.182	0.1271	−0.004933	0.997	0.0100
A	−0.183	0.1311	−0.005855	0.999	0.0061
B	−0.158	0.1127	−0.001480	0.997	0.0095
C	−0.196	0.1299	−0.005008	0.999	0.0053
Topp and Reynolds (1998)	−0.176	0.115	-	-	0.013‡
Ledieu et al. (1986)	−0.176	0.114	-	0.97	0.013§

† Value is adjusted coefficient of determination.
‡ From Topp et al. (1980) reported as standard error of estimate.
§ Reported as residual standard deviation.

soils were on the order of 0.1 GHz, well into the dispersive range for clay soils with large surface area and ion exchange capacity, such as bentonite (Robinson et al., 2003).

The full model (Eq. [7]) still does not include relaxation effects on the imaginary permittivity, ε''. Relaxation effects may explain the slightly smaller values of coefficients b and c for Soil B, which was the most lossy soil. However, the success of the full model using combined data from three soils indicates that relaxation effects are minor in these soils.

The inclusion of effective frequency in the calibration model allowed both the low-pass filtering effect of longer cables and the decrease of effective frequency with temperature increase to be accounted for, practically eliminating both the tendency of the TDR system to overestimate water contents from probes attached to longer cables and the temperature dependency of TDR readings.

The Eq. [7] calibration model, including bulk electrical conductivity and effective frequency properties as independent variables, can be applied easily using data collected by the TACQ TDR data acquisition program. Modification of other TDR data acquisition systems to output the required slope data, which is already internally computed in these systems, should be easy. Most TDR systems already provide the needed data for BEC calculations. An important result of this study is that soil temperature need not be measured. Its effects are embedded in the behavior of BEC and effective frequency. The Eq. [7] model should be tested on a wider variety of soils; temperature, soil solution EC, and wetness ranges; and cable lengths and types. The fact that it does not explicitly include relaxation effects may not be important, as these may be inherent in the effective frequency reduction.

Table 8. Temperature dependency (m³ m⁻³ °C⁻¹) of water contents estimated from data measured in saturated columns using Eq. [3] (Topp et al., 1980), Eq. [6] that includes σ_a, and Eq. [7] that includes both σ_a and effective frequency. The coefficients for Eq. [6] and [7] were those generated using the combined data for all three soils (Table 7).

Soil	Eq. [3]	Eq. [6]	Eq. [7]
A	0.00141 b†	0.00106 b	−0.00036 b
B	0.00239 a	0.00270 a	0.00054 a
C	0.00017 c	−0.00050 c	−0.00041 b

† Values followed by different letters are significantly different at the 0.001 probability level.

More problematic for wide adoption is the proposed calibration model's inability to predict a decrease in permittivity with temperature, a phenomenon reported by Wraith and Or (1999) and others for some soils. If the decrease is due to the decline of the permittivity of bulk water as temperature increases, then it may be that a summed effect will suffice to extend the proposed model to these soils. Such an effect would easily explain the decline in bulk soil permittivity reported by Wraith and Or (1999) for the 0 to 65°C temperature range and for the water contents in their study. Because we did not study a soil that behaved in this manner, study of the problem is beyond the scope of our investigation.

The fact that the proposed calibration model (Eq. [7]) does not reflect a complete physical analysis of the soil water system (e.g., does not explicitly account for relaxation losses, temperature effects on permittivity of bulk water) may cause it to be inappropriate for some soils. However, we believe that for many soils, it includes the important effects of frequency loss (whether due to cable length or soil dielectric) and bulk electrical conductivity. It will be interesting to see if calibrations in other soils using this model result in similar model parameters.

ACKNOWLEDGMENTS

This work was supported in part by International Atomic Energy Agency research contract number 11186/FAO. The authors wish to thank Mr. Brice Ruthardt for his conscientious and long-term effort in preparing the soil columns, installing sensors and data logging equipment, calibrating the scales, and collecting and processing data for this and the companion experiment.

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