

Time domain reflectometry measurement principles and applications

Scott B. Jones,^{1*} Jon M. Wraith² and Dani Or¹

¹ *Department of Plants, Soils and Biometeorology, Utah State University, Logan, UT 84322-4820, USA*

² *Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717-3120, USA*

*Correspondence to:
S. B. Jones, Department of Plants, Soils and Biometeorology, Utah State University, Logan, UT 84322-4820, USA.
E-mail: sjones@mendel.usu.edu

Abstract

Time domain reflectometry (TDR) is a highly accurate and automatable method for determination of porous media water content and electrical conductivity. Water content is inferred from the dielectric permittivity of the medium, whereas electrical conductivity is inferred from TDR signal attenuation. Empirical and dielectric mixing models are used to relate water content to measured dielectric permittivity. Clay and organic matter bind substantial amounts of water, such that measured bulk dielectric constant is reduced and the relationship with total water content requires individual calibration. A variety of TDR probe configurations provide users with site- and media-specific options. Advances in TDR technology and in other dielectric methods offer the promise not only for less expensive and more accurate tools for electrical determination of water and solute contents, but also a host of other properties such as specific surface area, and retention properties of porous media. Copyright © 2002 John Wiley & Sons, Ltd.

Key Words TDR; dielectric; permittivity; soil moisture; soil electrical conductivity

Introduction

Time domain reflectometry (TDR) is a relatively new method for measurement of soil water content and electrical conductivity. Each of these attributes has substantial utility in studying a variety of hydrologic processes. The first application of TDR to soil water measurements was reported by Topp *et al.* (1980). The main advantages of TDR over other soil water content measurement methods are: (i) superior accuracy to within 1 or 2% volumetric water content; (ii) calibration requirements are minimal—in many cases soil-specific calibration is not needed; (iii) lack of radiation hazard associated with neutron probe or gamma-attenuation techniques; (iv) TDR has excellent spatial and temporal resolution; and (v) measurements are simple to obtain, and the method is capable of providing continuous measurements through automation and multiplexing. A variety of TDR systems are available for water content determination in soil and other porous media (e.g. Figure 1). Many, but not all commercially available systems may also be used to measure soil electrical conductivity. Thus potential users should consider present and future measurement requirements before purchasing.

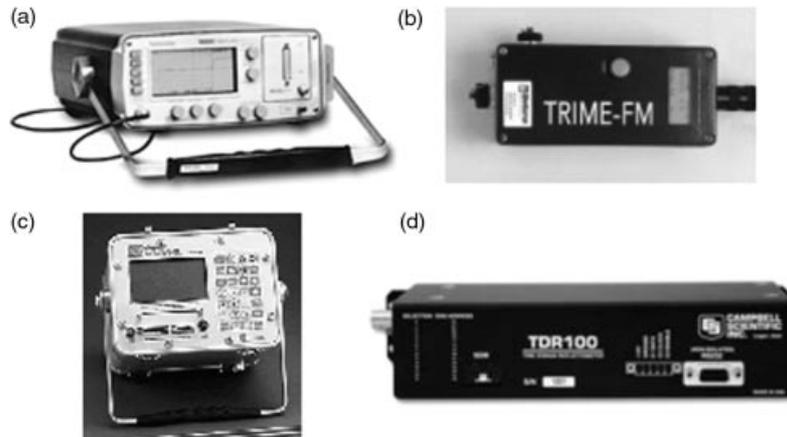


Figure 1. Different TDR devices shown are: (a) 1502C (Tektronix Inc., Beaverton, OR); (b) TRIME-FM (IMKO, Ettlingen, Germany); (c) TRASE System I (Soil Moisture Equipment Corp., Goleta, CA); (d) TDR100 (Campbell Scientific Inc., Logan, UT)

Basic principles

In the telecommunications industry TDR is used to identify locations of discontinuities in cables, hence the term ‘cable tester’ is a common name for general-purpose TDR instruments. The signal propagation velocity V_p (a function of the cable dielectric constant), along with a typical reflection at a point of discontinuity in a cable, allows the operator to determine locations of line breaks or other damage to cables using travel time analysis. Using similar principles, a waveguide or probe of known length L may be embedded in soil (Figure 2) and the travel time for a TDR-generated electromagnetic ramp to traverse the probe length may be determined. From the travel time analysis the soil’s bulk dielectric constant is computed (the terms dielectric constant and dielectric permittivity are synonymous), from which the volumetric water content is inferred. The bulk dielectric constant ϵ_b of soil surrounding the probe is a function of the propagation velocity ($v = 2L/t$) according to

$$\epsilon_b = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2 \quad (1)$$

where c is the speed of light (velocity of electromagnetic waves) in vacuum ($3 \times 10^8 \text{ m s}^{-1}$), and t is the travel time for the pulse to traverse the length of the embedded waveguide (down and back: $2L$). The travel time is evaluated based on the ‘apparent’ or electromagnetic length of the probe, which is characterized on the TDR output screen by diagnostic

changes in the waveform: x_1 marks the entry of the signal to the probe, and x_2 marks the reflection at the end of the probe (Figure 3). As shown in Figure 3, the apparent probe length ($x_2 - x_1$) increases as the water content (and dielectric constant) increases, a consequence of reduced propagation velocity. The relationship between locations of the two reflection points x_1 and x_2 , and the bulk dielectric constant is:

$$\epsilon_b = \left(\frac{x_2 - x_1}{V_p L}\right)^2 \quad (2)$$

where V_p is a user-selected relative propagation velocity, often set at $V_p = 0.99$.

For most practical applications it suffices to consider the definition of the dielectric constant in Equation (1), which simply states that the dielectric constant of a porous medium is the ratio squared of the propagation velocity in vacuum relative to that in the medium. The soil’s bulk dielectric constant ϵ_b is dominated by the dielectric constant of liquid water $\epsilon_w = 81$ (20°C), as the dielectric constants of other soil constituents are much smaller; e.g. soil minerals $\epsilon_s = 3$ to 5 , frozen water (ice) $\epsilon_i = 4$, and air $\epsilon_a = 1$. This large disparity of dielectric constants makes the method relatively insensitive to soil composition and texture, and thus a good method for ‘liquid’ water measurement in soils. Note that, because the dielectric constant of ice is much lower than for liquid water, the method may be used in combination with a neutron probe or other techniques that sense total soil water content to determine separately the volumetric liquid

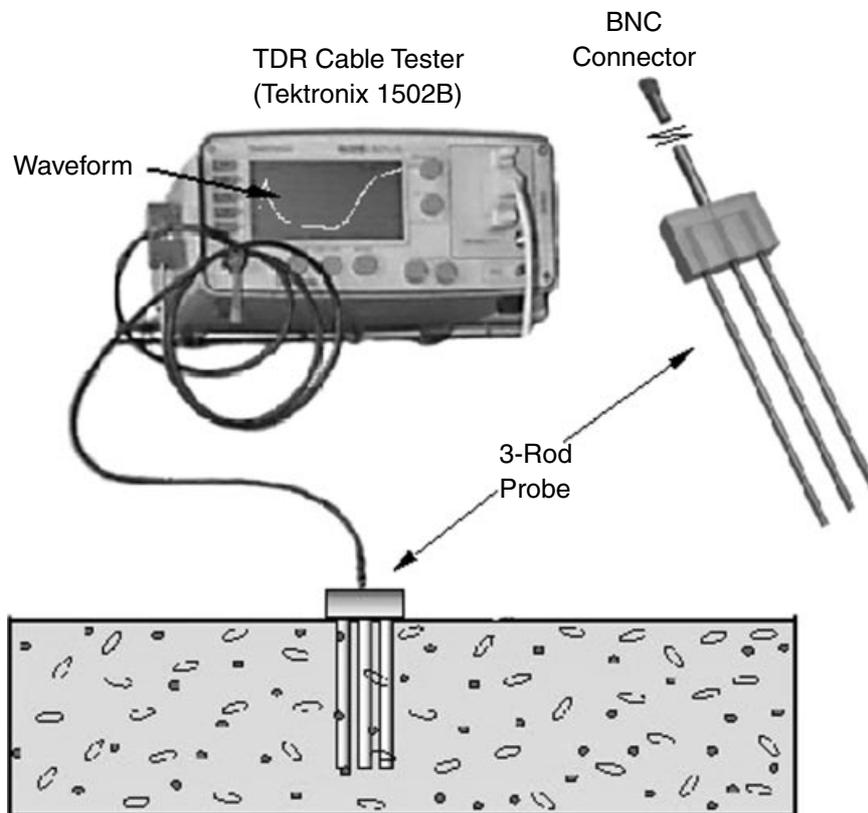


Figure 2. TDR cable tester with three-rod probe embedded vertically in surface soil layer

and frozen water contents in frozen or partially frozen soils (Baker and Allmaras, 1990). Several factors influence dielectric constant measurements, including soil porosity and bulk density, measurement frequency, temperature, water status (bound or free) and dipole moments induced by mineral, water, and air shapes. The need to relate water content to ϵ_b and to account for the factors just mentioned has resulted in a variety of empirical and 'dielectric mixing' models.

Empirical and dielectric mixing models

Two basic approaches have been used to establish the relationships between ϵ_b and volumetric soil water content θ . The empirical approach simply fits mathematical expressions to measured data, unique to the physical characteristics of the soil or porous medium. Such an approach was employed by Topp *et al.* (1980), who fitted a third-order polynomial to the observed relationships between ϵ_b and θ for multiple soils. The empirical relationship for mineral soils

proposed by Topp *et al.* (1980) of

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \epsilon_b - 5.5 \times 10^{-4} \epsilon_b^2 + 4.3 \times 10^{-6} \epsilon_b^3 \quad (3)$$

provides an adequate description for the water content range <0.5 , which covers the entire range of interest in most mineral soils, with a θ estimation error of about 0.013. However, Equation (3) fails to describe the $\epsilon_b - \theta$ relationship adequately for water contents exceeding 0.5, and for organic soils or mineral soils high in organic matter or clay content.

In its simplest form the dielectric mixing approach uses dielectric constants and volume fractions for each of the soil constituents (e.g. solid, water, air) to derive a relationship describing the composite (bulk) dielectric constant. Such a physically based approach was adopted by Birchak *et al.* (1974), Dobson *et al.* (1985), Roth *et al.* (1990), and Friedman (1998). According to Roth *et al.* (1990), the bulk dielectric

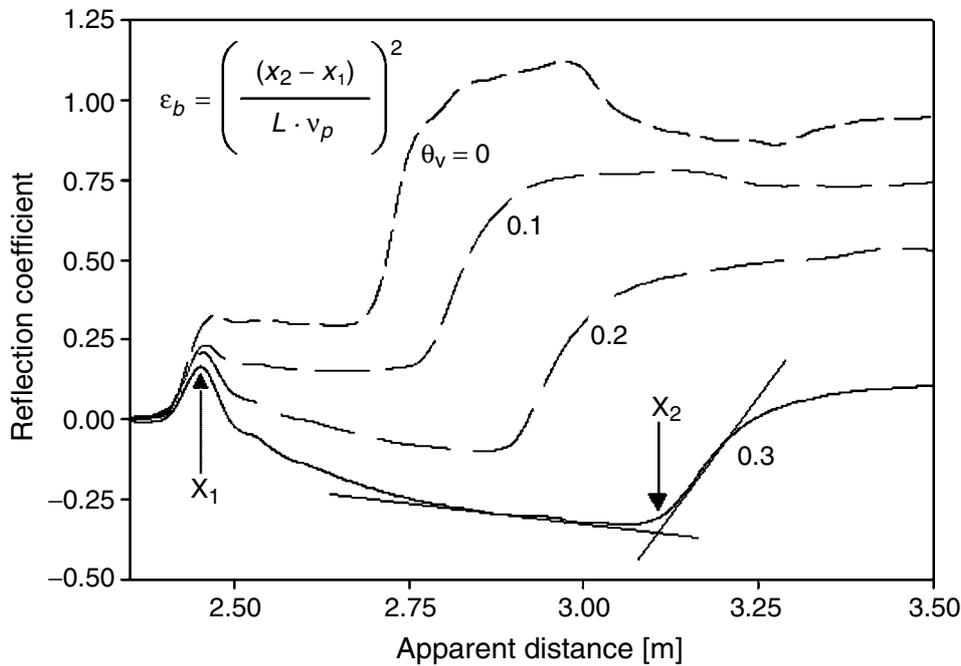


Figure 3. Sample TDR waveforms measured in Millville silt loam soil using the Tektronix 1502B TDR cable tester and three-rod probes (length $L = 0.15$ m). The calculation of the bulk dielectric constant is based on $\epsilon_b = [(x_2 - x_1)/(LV_p)]^2$, where V_p is the relative velocity of propagation (usually set at 0.99)

constant of a three-phase system may be expressed as

$$\epsilon_b = [\theta \epsilon_w^\beta + (1 - n) \epsilon_s^\beta + (n - \theta) \epsilon_a^\beta]^{1/\beta} \quad (4)$$

where n is the soil's porosity, $-1 < \beta < 1$ summarizes the geometry of the medium in relation to the axial direction of the wave guide ($\beta = 1$ for an electric field parallel to soil layering, $\beta = -1$ for a perpendicular electrical field, and $\beta = 0.5$ for an isotropic two-phase mixed medium); $1 - n$, θ and $n - \theta$ are the volume fractions and ϵ_s , ϵ_w and ϵ_a are the dielectric constants of the solid, water and air phases respectively. Note that the summed volumetric contribution of each phase relative to the total volume is unity. Rearranging Equation (4) and solving for θ yields

$$\theta = \frac{\epsilon_b^\beta - (1 - n) \epsilon_s^\beta - n \epsilon_a^\beta}{\epsilon_w^\beta - \epsilon_a^\beta} \quad (5)$$

which determines the relationship between θ and ϵ_b measured by TDR. Many have used $\beta = 0.5$, which was shown by Roth *et al.* (1990) to produce a calibration curve very similar to the third-order

polynomial proposed by Topp *et al.* (1980) for the water content range $0 < \theta < 0.5$. If we introduce into Equation (5) common values for the various constituents, such as $\beta = 0.5$, $\epsilon_w = 81$, $\epsilon_s = 4$, and $\epsilon_a = 1$, we obtain an approximate simplified form:

$$\theta = \frac{\sqrt{\epsilon_b} - (2 - n)}{8} \quad (6)$$

Note that the soil's porosity must be known or estimated when using the mixing model approach. A comparison between the Topp *et al.* (1980) expression [Equation (3)] and a calibration curve based on Equation (5) with $n = 0.5$ and $\beta = 0.5$ is depicted in Figure 4.

Soils having high clay or organic matter content often require soil-specific calibration. The presence of high porosity combined with large amounts of 'bound' water fraction produces substantial differences between the dielectric signature of typical mineral versus organic soils. This is illustrated (Figure 4) by comparing an empirical expression of Schaap *et al.* (1996) fitted to 505 TDR measurements in organic

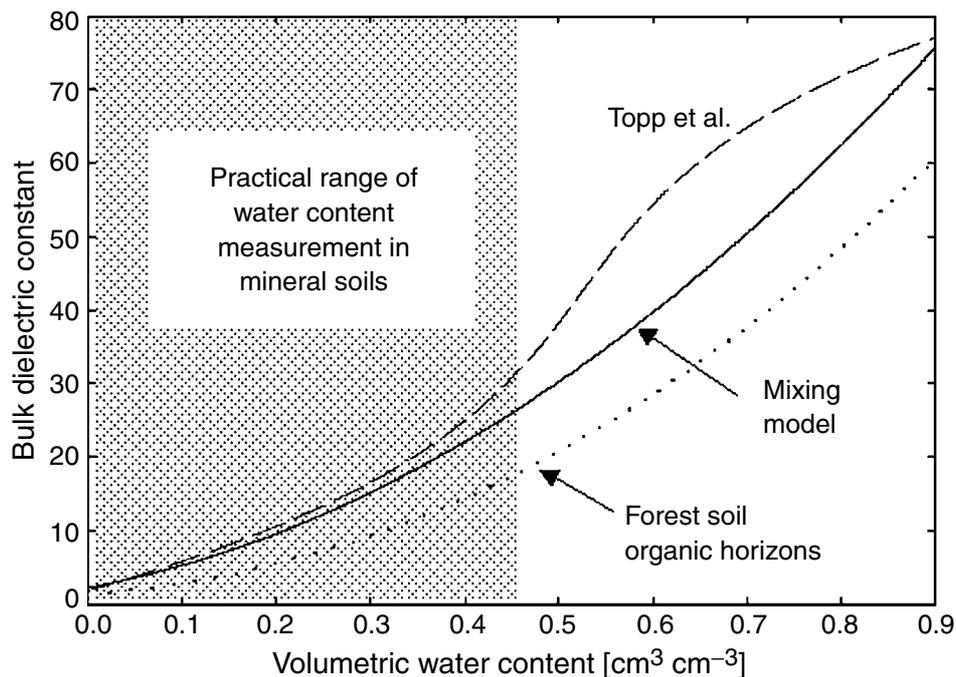


Figure 4. Relationships between bulk soil dielectric constant and θ expressed using the Topp *et al.* (1980) empirical equation for mineral soils and for the Birchak *et al.* (1974) mixing model using a porosity of 0.5. Higher porosities and bound water in forest soil organic horizons exhibit a reduced dielectric signature by comparison (Schaap *et al.*, 1996)

horizons of eight forest floor soils given as

$$\theta = (0.133\sqrt{\varepsilon_b} - 0.146)^{0.885} \quad (7)$$

Media with large porosities, such as horticultural planting media ($n \approx 0.95$) and clays, are susceptible to large variations in bulk density and porosity. Independent measurements of bulk density should improve calibration, but the bound water influences, which are generally correlated to surface area, may be more difficult to account for.

Bound water and temperature effects

Water molecules within the vicinity of solid surfaces are subjected to interfacial forces that constrain their movement, rendering them rotationally hindered. Consequently, both their ability to follow the alternating electric field, and their dielectric constant are reduced. High surface-area porous media (e.g. clays, peats, some forest soils) bind a substantial fraction of the water phase, resulting in reduced bulk dielectric constant measurements relative to low surface-area materials (e.g. sandy soils) when compared at

similar water contents. The amount of bound water is related to the specific surface area and the thickness of the affected (bound) layer. Estimates of the dielectric constant values for the first, second and third monolayers of water are available (Thorpe, 1959; Bockris *et al.*, 1963). Or and Wraith (1999) developed a model for the temperature-dependent thickness of the bound water phase. For media with large surface areas it was found that TDR-measured water content increased with increasing temperature due to reduction of the bound water layer thickness, without any changes in the total mass of water (an example is depicted in Figure 5). This phenomenon has important implications for interpretation of near-soil-surface measurements using TDR (e.g. infiltration or evaporation studies), where the measurement artefact must be filtered out. Interestingly, measurements of the dielectric response of wetted porous media under changing temperature may be useful in estimating the specific surface area ($\text{m}^2 \text{kg}^{-1}$), because of the fundamental relationship between bound water and solid surface area (Wraith and Or, 1998). Expressions have been derived for describing the combined bound- plus

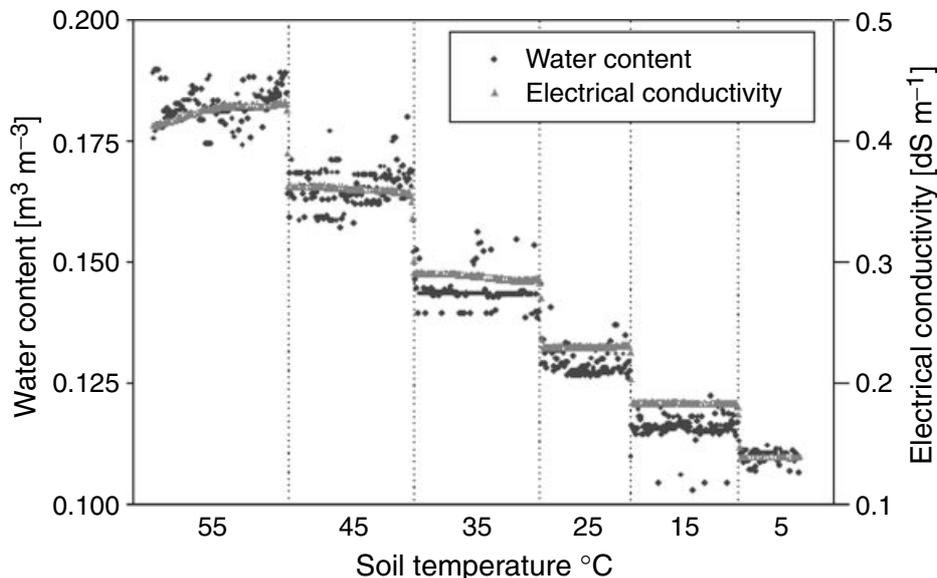


Figure 5. Measured volume water content and bulk soil electrical conductivity within sealed soil containers under imposed temperature changes. Soil temperatures are indicated; actual water content did not change. Modified from Wraith and Or (1999), copyright 1999 by the American Geophysical Union

free-water dielectric constant based on surface area and bulk density (Friedman, 1998) and including the temperature dependence (Jones and Or, 2001).

TDR probe configurations

Modelled after a coaxial design, Campbell (1990) and Heimovaara (1994) used seven-wire probes to measure the dielectric constant of soils and liquids. A number of different geometrical configurations have been proposed, which have a single central conductor and from one to six outer conducting rods (Figure 6). The two-wire probe has the advantage of minimal soil disturbance, but produces an unbalanced signal, leading to unwanted noise and signal loss (White and Zegelin, 1995). This problem may be minimized using a balun (balancing transformer) embedded in the probe head to reduce signal and information loss (Spaans and Baker, 1993). The three- or more-rod probes provide a balanced signal, avoiding the balun requirement at the expense of some additional soil disturbance [see Zegelin *et al.* (1989) for a comparison]. Though not commonly used in soils, the parallel plate probe was shown by Robinson and Friedman (2000) to provide a highly uniform electrical field between plates. The highly concentrated electrical field converging on the central conductor

of the multi-wire probes (see Figure 6), more heavily weights the dielectric constant of constituents within this region. Ferre *et al.* (1998) found that two-rod probes have a larger sample area compared with three-rod probes, and that thin rod coatings (for reducing conductive losses) for any probes will reduce the sampling area of the probe. Measurement error increases, for example, as air gaps develop when probes are repeatedly inserted and removed, or in shrink–swell soils.

For all conventional probe designs, water content is often assumed to be uniformly integrated along the probe's longitudinal axis. A recent study by Chan and Knight (1999) cautions against the accepted notion that, if water is evenly distributed along the rods or concentrated in one or more 'pockets', the same measured mean dielectric constant results. Their analysis is based on the wavelength λ to layer (heterogeneity) thickness t ratio λ/t . For $\lambda/t > 10$ the dielectric constant of the soil is computed as an arithmetic average (effective medium theory) of the layers, whereas for $\lambda/t < 1$ the geometric average (Ray theory) of the soil layers is used to compute the soil dielectric constant. Scattering effects that occur within the transition zone, $1 < \lambda/t < 10$, may cause measurement difficulties, and the propagation direction of the

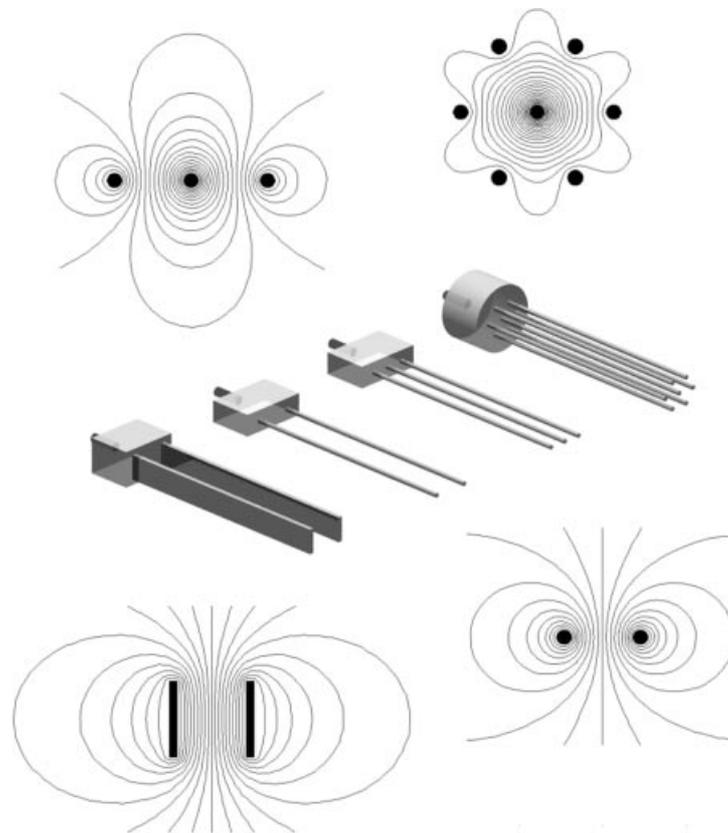


Figure 6. Various TDR soil moisture probe designs have been proposed, such as the multi-wire and parallel plate configurations shown here. Electrical field lines generated for different probe configurations are also shown, where closer line spacing is associated with a more concentrated field (i.e. greater influence on permittivity)

electromagnetic wave relative to the layering is also an important factor.

The particular spatial sensitivities of different probe configurations can be used to one's advantage in specific research applications. For example, a two- or three-rod probe placed horizontally serves as an effective point (plane) measurement for water or solute fronts moving vertically through soil profiles. Seven-rod or parallel plate designs, on the other hand, sample a larger effective volume of soil, which may be desired for routine measurements. Other TDR probe applications have been developed that provide soil matric potential measurements (e.g. Wraith and Or, 2001). These may be used separately, or may be paired with conventional probe designs to obtain simultaneous *in situ* measurements of θ and matric potential h from which the soil water characteristic relationship $\theta(h)$ may be elucidated.

TDR measurements are easily automated using a computer or datalogger, and analysis of waveforms is commonly completed during measurement, or may be analysed later if waveforms are saved. Automated measurement of θ requires only a few seconds for each probe. As many as 8 or even 16 probes may be attached to a single multiplexer, and several multiplexers may be connected in series to provide a large array of spatially distributed measurements. However, owing to signal deterioration with cable length, practical distances from the probe to TDR unit are typically limited to 20 to 30 m. Longer cable lengths may provide reliable readings where soil salinity and clay content are low. The ability to obtain high-resolution time series measurements at multiple locations (e.g. depths) using automated and multiplexed TDR is a particularly useful research and management tool.

Measurement of salinity and ionic solutes

Dalton *et al.* (1984) also first demonstrated the utility of TDR to measure the apparent bulk soil electrical conductivity. This unique ability to measure both soil water content θ and apparent soil electrical conductivity EC_a using the same instrumentation and probes, and in the same soil volumes, provided new opportunities to investigate salinity and the behaviour of ionic solutes in soils. The most critical frequencies for measurement of dielectric constant based on TDR travel-time are near 1 GHz, whereas TDR EC_a measurement relies on the lowest frequencies available (low kilohertz range), as close to direct current (DC) as feasible. Measurement of electrical conductivity using TDR is based on attenuation of the applied signal voltage as it traverses the medium of interest. As the transverse electromagnetic waves propagate along TDR probes buried in soil, the signal energy is attenuated in proportion to the electrical conductivity along the travel path. This proportional reduction in signal voltage is accurately related to the bulk soil electrical conductivity. Comparisons between the electrical conductivity measured in solutions using both TDR

and standard methods have repeatedly demonstrated the potential accuracy and precision of TDR measurements (e.g. Spaans and Baker, 1993; Heimovaara *et al.*, 1995; Mallants *et al.*, 1996; Reece, 1998). TDR electrical conductivity measurements may also be easily automated and multiplexed in the same manner as for θ . However, some commercially available TDR equipment does not include provision to measure electrical conductivity.

Originally proposed by Giese and Tiemann (1975), the thin-section approach has been shown to be a particularly effective means of quantifying EC_a using TDR. The Giese and Tiemann equation may be written as:

$$EC(S\ m^{-1}) = \frac{\epsilon_0 c Z_0}{L Z_c} \left(\frac{2V_0}{V_f} - 1 \right) \quad (8)$$

where ϵ_0 is the dielectric permittivity of free space ($8.9 \times 10^{-12}\ F\ m^{-1}$), c is the speed of light in vacuum ($3 \times 10^8\ m\ s^{-1}$), L (m) is probe length, Z_0 (Ω) is the characteristic probe impedance, Z_c is the TDR cable tester output impedance (typically $50\ \Omega$), V_0 is the incident pulse voltage and V_f is the return pulse voltage after multiple reflections have died out

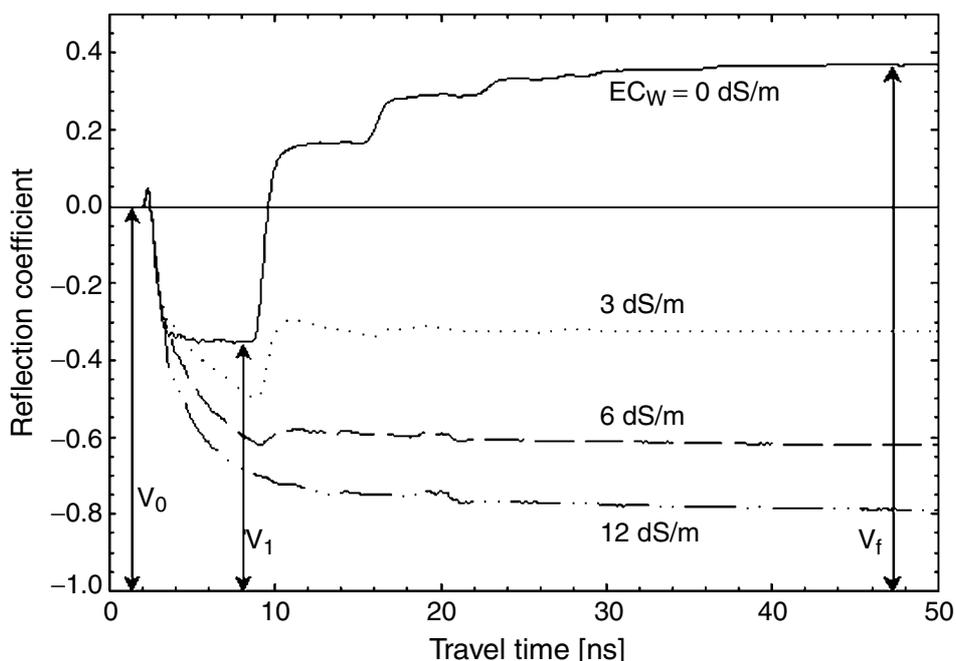


Figure 7. Attenuation of the TDR signal due to increasing soil solution electrical conductivity results in a reduced reflection coefficient at large distances (i.e. low frequency). The end-of-probe reflection is indistinguishable above about $6\ dS\ m^{-1}$, where time domain analysis for soil water content determination fails

(Figure 7). The quantity $\varepsilon_0 c/L$ in Equation (8) may be simplified to $1/(120\pi L)$, and the values of V_0 and V_f are easily acquired from the TDR output signal. A separate calibration procedure is required to determine the probe characteristic impedance Z_0 . This may be determined by immersion of the probe in deionized water with known (e.g. Weast, 1986) dielectric constant ε according to:

$$Z_0 = Z_c \sqrt{\varepsilon} \left(\frac{V_1}{2V_0 - V_1} \right) \quad (9)$$

where the required signal voltages V_0 and V_1 are illustrated in Figure 7. For specific probe geometries (e.g. true coaxial, two-rod balanced design), Z_0 may be calculated with formulae found in electronics textbooks, but because of inconsistencies in probe manufacture we prefer to use the simple deionized water calibration procedure. Finally, $\varepsilon_0 c Z_0/L = Z_0/120\pi L$ may also be lumped into a geometric probe constant K , and EC may thereby be estimated using Equation (8) as

$$EC = \frac{K}{Z_c} \left(\frac{2V_0}{V_f} - 1 \right) \quad (10)$$

with K either calculated using Equation (8) and the relevant physical quantities (ε_0 , c , L), or empirically determined by immersing the probe in one or (preferably) more solutions of known EC, and using

$$K = EC_{\text{ref}} \frac{Z_L}{f_T} \quad (11)$$

with EC_{ref} the known electrical conductivity of the reference solution, Z_L as the measured resistive load impedance across the probe [$Z_L = Z_c/(2V_0/V_f - 1)$] and f_T a temperature correction coefficient to relate the measured reference solution to a desired standard temperature. Heimovaara *et al.* (1995) found that the relationship $f_T = 1/[1 + 0.019(T - 25)]$ was appropriate for a variety of saline solutions, using 25 °C as the standard temperature.

The unique ability of TDR to measure both θ and EC provides many opportunities for research. For example, it has been used to measure transport properties for ionic solutes under steady and non-steady flow conditions in soils, to monitor water and nitrogen status in the root zone, and to characterize the distribution of water and fertilizers around drippers. Figure 8 illustrates bromide concentrations

and electrical conductivity measurements in effluent fractions from a soil column compared with EC_a measurements using TDR a few centimeters above the column base. The results in Figure 8 are plotted as relative 'concentrations' consistent with conventional breakthrough curve format. The excellent correlation of EC_a and soil solution EC_w shown for this saturated system degenerates under partially saturated conditions, where enhanced tortuosity, variable liquid configuration, and hysteresis complicate the measurement. Calibration models are, therefore, needed to relate measured EC_a to the EC or ionic concentration of soil solution because of the dependence of EC on water content as well as on ionic strength and soil geometry. Examples of such models and their application may be found in various papers, including those by Risler *et al.* (1996), Mallants *et al.* (1996), Das *et al.* (1999) and others.

Alternative frequency domain analyses

Although TDR offers simultaneous and accurate water content and electrical conductivity determination in soils and other porous media, waveform reflections necessary for dielectric constant measurements can be totally attenuated in lossy materials. Factors such as soil texture, salinity, cable length, probe geometry and water content all influence signal attenuation. Attenuated waveforms of varying degree, resulting from a range of solution electrical conductivities, are illustrated in Figure 7. Nadler *et al.* (1999) found that at field capacity water content in sandy and loamy soils, TDR could be safely used for θ measurements up to EC_a of approximately 2 dS m⁻¹. TDR applications are, therefore, limited to soils with moderate to low salinity, unless measures are taken to preserve the waveform reflection occurring at the end of the waveguide. Rod coatings have been used successfully to reduce signal attenuation and preserve information needed to evaluate the dielectric constant in highly saline soils. Since these coatings significantly influence the resulting permittivity ε_b , specific $\theta - \varepsilon_b$ calibration is required for measurements using coated rods, making this a less appealing method (Mojid *et al.*, 1998). Coated rods also make measurement of EC extremely difficult (i.e. requiring extensive calibration over a range of conditions) or ineffective.

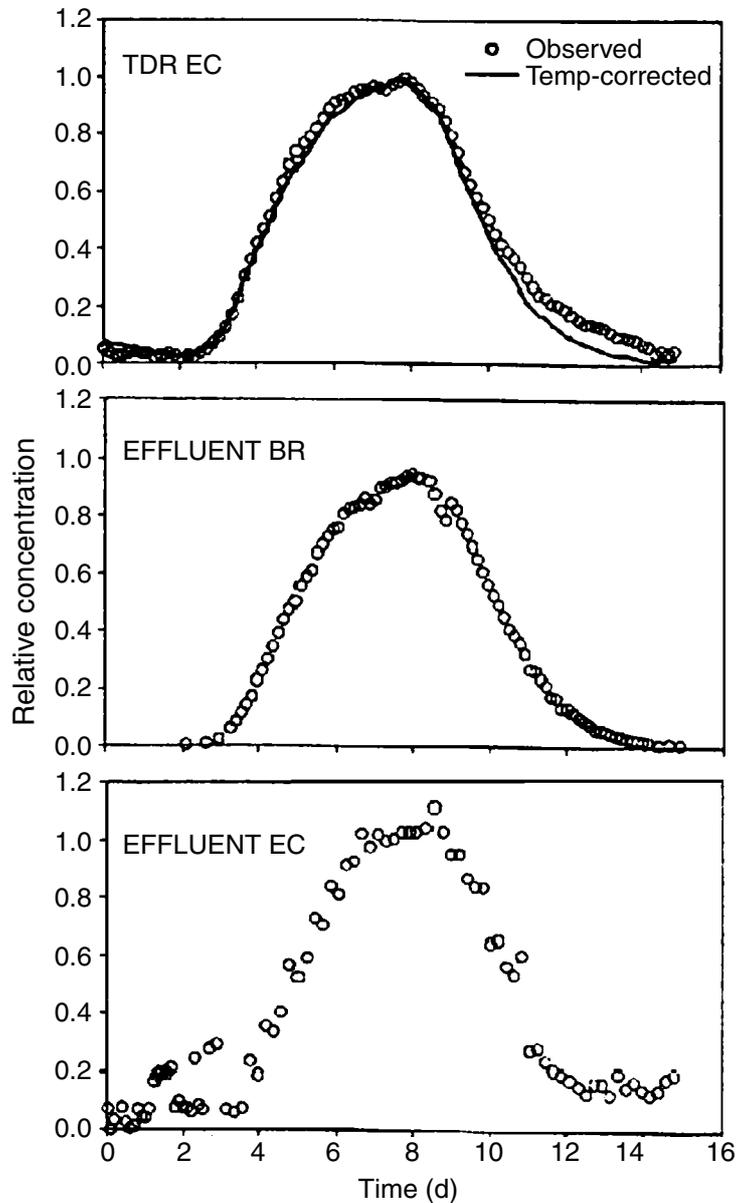


Figure 8. Relative EC measured using TDR during steady flow compared with relative bromide concentration and EC in the column effluent fractions. Source: Wraith *et al.* (1993). Reproduced by permission of Soil Science Society of America

The potential benefits of a combination of shorter TDR probes combined with waveform transformations for improving dielectric constant determination at higher levels of electrical conductivity are illustrated in Figure 9. Travel-time analysis provided reliable ϵ_b measurement for 10 and 15 cm probes up to $EC_w \approx 6 \text{ dS m}^{-1}$, whereas, for frequency domain

analysis, shorter 2 and 3 cm probes extended ϵ_b determination by a factor of four to five, up to 24 dS m^{-1} , as shown for a silt loam soil.

Conversion of the TDR waveform to the frequency domain provides the frequency-dependent dielectric constant, in addition, other information, such as electrical conductivity, relaxation frequency, and static

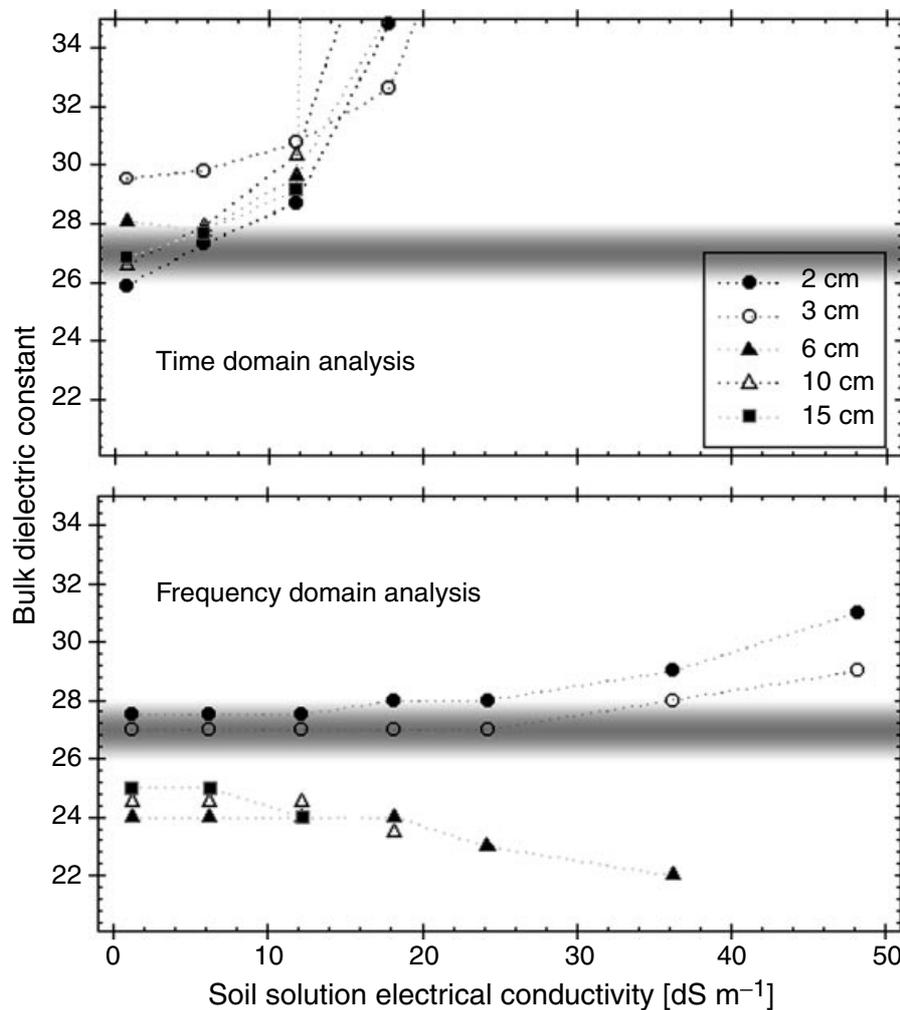


Figure 9. Bulk permittivity determined using time domain analysis and frequency domain analysis as a function of probe length and soil solution electrical conductivity. The shaded region indicates the 'true' bulk permittivity of the saturated Millville silt loam soil used

and high-frequency permittivities, may be extracted using optimization procedures (Heimovaara, 1994; Friel and Or, 1999). Despite the laborious nature of this approach, including fast Fourier transformation of the waveform and fitting of an appropriate model to the transformed scatter function, the procedure has the potential to be automated to make it more amenable to real-time measurements.

Outlook

In such a short review there are many inevitable omissions of details and complexities of the theory behind TDR. Nevertheless, we have attempted to provide

potential practitioners with essential elements and an overview of the state-of-practice using TDR. A particularly important advantage of TDR, relative to other methods, is the ability to provide intensive time series measurements, at multiple locations, which are critical to resolution of many hydrologic processes. Concurrent measurement of both θ and EC has also provided new research and management opportunities. Since its introduction in the early 1980s, the TDR method has stimulated increased interest in other electromagnetic methods based on different principles ranging from capacitance to frequency-shift sensors. This trend will undoubtedly continue with advances



in technology and with reduction in costs of electronic components; there are already available several stand-alone and relatively inexpensive sensors for water content measurement based on dielectric properties. Many of these inexpensive sensors currently have substantial measurement limitations relative to true TDR, however. The TDR method is maturing, as evidenced by the introduction of devices (e.g. Figure 1) specifically designed for hydrological applications. Moreover, the application of alternative methods of analysis, such as frequency domain techniques, provides a means to extend the useful range of utility as well as a potential for extraction of supplementary information concerning water and its interactions with porous media. Some potentially useful applications derived directly from the TDR method include measurement of specific surface area, and *in situ* determination of water retention properties of field soils.

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