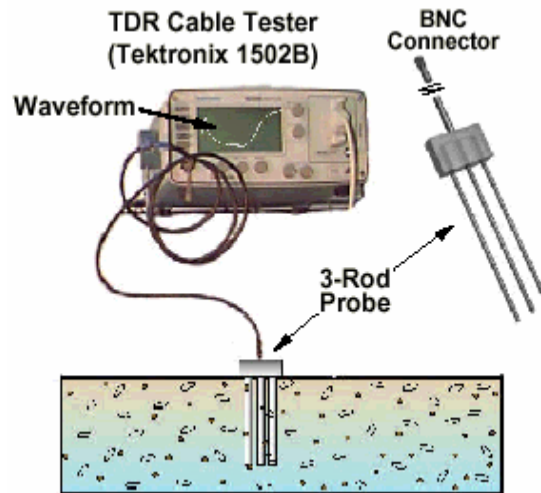


Chapter 9:

Principals of Time Domain Reflectometry

Time Domain Reflectometry

Time Domain Reflectometry (TDR) is a relatively new method for measurement of soil water content. Its first application to soil water measurements was reported by Topp et al. (1980). The main advantages of the TDR method over other methods for repetitive soil water content measurement (e.g., neutron probe) are superior accuracy to within 1 or 2% of volumetric water content; (ii) calibration requirements are minimal (in many cases soil-specific calibration is not needed); (iii) averts radiation hazards associated with neutron probe or gamma-attenuation techniques; (iv) excellent spatial and temporal resolution; and (v) measurements are simple to obtain, and the method is capable of providing continuous soil water measurements through automation and multiplexing.



The propagation velocity (v) of an electromagnetic wave along a transmission line (wave-guide) of length L embedded in the soil is determined from the time response of the system to a pulse generated by the TDR cable tester. The propagation velocity ($v=2L/t$) is a function of the soil bulk dielectric constant (ϵ_b) according to

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

where c is the velocity of electromagnetic waves in vacuum (3×10^8 m/s), and t is the travel time for the pulse to traverse the length of the embedded wave-guide (down and back). The definition of the dielectric constant is given in Eq. (1); it simply states that the dielectric of a medium is the ration squared of propagation velocity in vacuum relative to that in the medium. The soil bulk dielectric constant (ϵ_b) is governed by the dielectric of liquid water $\epsilon_w \approx 81$, 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 the dielectric constants makes the method relatively insensitive to soil composition and texture and thus a good method for liquid soil water measurement. Note that because the dielectric of frozen water is much lower than for liquid, the method may be used in combination with a neutron probe or other technique which senses total soil water content, to separately determine the volumetric liquid and frozen water contents in frozen or partially-frozen soils (Baker and Allmaras, 1990).

Two basic approaches have been used to establish the relationships between ϵ_b and volumetric soil water content (θ_v). The first approach is empirical, whereby

mathematical expressions are simply fitted to observed data without using any particular physical model. 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_v for multiple soils. The second approach uses a model of the dielectric constants and the volume fractions of each of the soil components to derive a relationship between the composite (bulk) dielectric constant and soil water (i.e., a specific component). Such a physically based approach, called a dielectric-mixing model, was adopted by Dobson et al. (1985) and by Roth et al. (1990).

TDR calibration establishes the relationship between ϵ_b and θ_v . For this discussion we assume that calibration is conducted in a fairly uniform soil without abrupt changes in soil water content along the wave-guide. The empirical relationship for mineral soils as proposed by Topp et al. (1980):

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

provides adequate description for the water content range < 0.5 (which covers the entire range of interest in most mineral soils), with an estimation error of about 0.013 for θ_v . However, Eq. (2) fails to adequately describe the ϵ_b - θ_v relationship for water contents exceeding 0.5, and for organic soils or mineral soils high in organic matter, mainly because Topp's calibration was based on experimental results for mineral soils and concentrated in the range of $\theta_v < 0.5$. Birchak et al., (1974) and Roth et al. (1990) proposed a physically based calibration model that considers dielectric mixing of the constituents and their geometric arrangement. According to this mixing model the bulk dielectric constant of a three-phase system may be expressed as:

$$\epsilon_b = [\theta_v \epsilon_w^\beta + (1-\eta) \epsilon_s^\beta + (\eta - \theta_v) \epsilon_a^\beta]^{1/\beta} \quad (3)$$

where η 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), $1-\eta$, θ_v and $\eta-\theta_v$ are the volume fraction and ϵ_s , ϵ_w , ϵ_a are the dielectric constants of the solid, aqueous and gaseous phases, respectively. Note that $\theta_v = V_w/V_t$, $(1-\eta) = V_s/V_t$, and $(\eta-\theta) = V_{air}/V_t$, so these components sum to unity. Rearranging Eq. (3) and solving for θ_v yields:

$$\theta_v = \frac{\epsilon_b^\beta - (1-\eta) \epsilon_s^\beta - \eta \epsilon_a^\beta}{\epsilon_w^\beta - \epsilon_a^\beta} \quad (4)$$

which determines the relationship between ϵ_b (measured by TDR) and θ_v . Many have used $\beta=0.5$ which is shown by Roth et al. (1990) to produce a calibration curve very similar to the third-order polynomial proposed by Topp for the water content range of $0 < \theta_v < 0.5$. If we introduced into (4) common values for the various constituents such as $\beta=0.5$, $\epsilon_w=81$, $\epsilon_s=4$, and $\epsilon_a=1$ we obtain the simplified form

$$\theta_v = \frac{\sqrt{\epsilon_b} - (2-\eta)}{8} \quad (5)$$

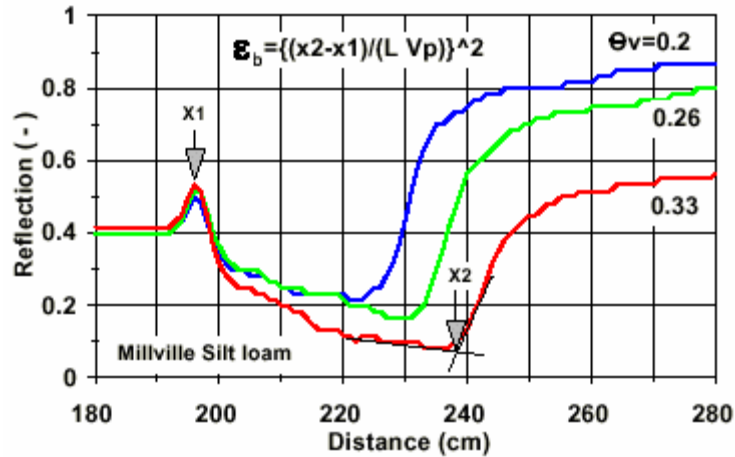


Figure 2: Sample TDR waveforms measured in Millville Silt loam using Tektronix 1502B TDR cable tester ($V_p=0.00$) and 3-rod probes ($L=0.1\text{m}$). The calculation of the bulk dielectric constant is based on $\epsilon_b = \left\{ \frac{(x_2 - x_1)}{(L V_p)} \right\}^2$ where V_p is the relative velocity of propagation (usually set as $V_p=0.99$). The TDR automatically considers half roundtrip of the signal.

Note that the soil's porosity must be known or estimated when using the mixing model approach. A comparison between Topp's expression (Eq. 2) and a calibration curve based on Eq. (5) with $n=0.5$ is depicted in Figure 3. Summarizing, Eq. (2) establishes an empirical relationship between bulk soil dielectric and volume water content while Eq. (3) and Eq. (4) are based on physical and geometric considerations. Eq. (5) is a simplified version of Eq. (4).

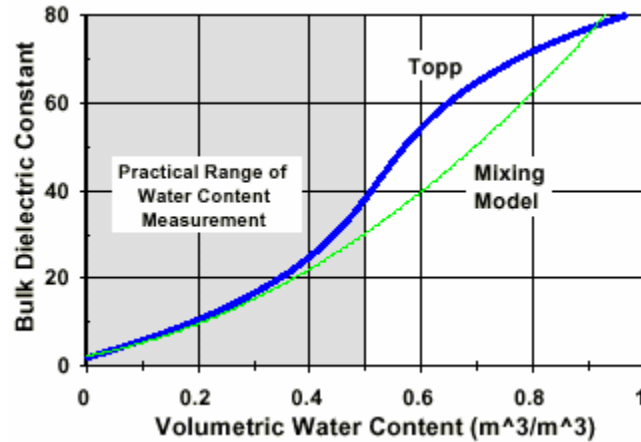


Figure 3: Relationships between bulk soil dielectric constant and θ_v expressed by two commonly used TDR calibration approaches.

Limitations or disadvantages of the TDR method include relatively high equipment expense, potential limited applicability under highly saline conditions due to signal attenuation, and the fact that soil-specific calibration may be required for soils having large amounts of bound water or high organic matter contents.

EXAMPLE 2-1: Inference of Bulk soil Dielectric Using a Mixing Model

What is ϵ_b of a soil having $\theta_v=0.2$ and bulk density of 1.325 Mg/m^3 ? What if the soil contained the same volume fraction of ethanol rather than water?

Solution: We estimate the porosity for this soil as $1-1.32/2.65 = 0.5$, where 2.65 is the particle density for most soils. (i) Using Eq. (3) we find: $\epsilon_b = [0.2*81^{0.5} + (1-0.5)*4^{0.5} + (0.5-0.2)*1^{0.5}]^{1/0.5} = [1.8+1.0+0.3]^2 = 9.61$.

(ii) For ethanol (and assuming 25°C) we substitute the appropriate dielectric from the following table to arrive at an answer of $\epsilon_b = [0.986+1.0+0.3]^2 = 5.226$.

Note that because ethanol undergoes relaxation (a change in dielectric constant) within the TDR frequency bandwidth, the apparent dielectric $\epsilon_{\text{ethanol}}$ as measure using TDR is closer to 16. This means that some caution is required in attempting to model the apparent bulk dielectric of soils or other complex mixtures based on tabular values of the component dielectric constants.

Material (Fluids)	Dielectric Constant (20-25°C)	Material (Solids)	Dielectric Constant (20-25°C)
Water	80.4 – 78.5	Ice (-12°C)	4.1 – 3.7
Ethanol	24.3	Fused Quartz (SiO ₂)	3.78
Ammonia	16.9	Sandy Soil (dry)	2.55
Benzene	2.29	Loamy Soil (dry)	2.51
Acetone	20.7	PVC	2.89
Air	1.0	Polyethylene	2.25
CO ₂ (liquid)	1.6	Teflon	2.1
CO ₂ (gas)	1.001	Wood (Douglas Fir)	1.90 – 1.95

Sources: CRC Handbook of Chemistry and Physics (1993), von-Hippel (1955).

There are several other methods for soil water measurement, including: (i) methods based on electrical resistance or capacitance of a pair of electrodes embedded in porous media (e.g., gypsum or fiberglass) and brought to equilibrium with soil water; (ii) gamma ray attenuation methods including dual-probe apparatus for bulk density and water content, or x-ray computed tomography; and (iii) miscellaneous methods including fiber optics, nuclear magnetic resonance (NMR), and geophysical methods (ground-penetrating radar and electrical resistivity sounding).

Electrical Conductivity Measurement using Time-Domain Reflectometry (TDR)

As surface waves (known as transverse electromagnetic waves – TEM) 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 serves as a basis for the simultaneous measurement of bulk soil electrical conductivity (EC) and volumetric water content (Section 1.6.2) using TDR. Application of TDR to measure soil EC was recognized by Dalton et al. (1984) who proposed a “lumped circuit load” transmission line analogy for EC measurement by TDR. The soil-probe system (e.g., see Dalton 1992) is assumed to comprise a lumped circuit having a load impedance Z_L at the end of the transmission line (i.e., typically a coaxial cable) of known

characteristic impedance Z_c (the cable impedance is typically 50Ω). A reflection coefficient, ρ , may be defined in terms of the cable and load (i.e., soil-probe) impedances as:

$$\rho = \left(\frac{Z_L - Z_C}{Z_L + Z_C} \right) \quad (6)$$

There are two main approaches to determining EC from TDR measurements: *The Cell Constant Approach*: When ρ is known (measured from TDR cable tester, or as computed from impedance, and final and initial voltages: $\rho = [(V_f - V_0)/V_0]$, Z_L may be found by rearranging Eq. (6) as:

$$Z_L = \left(\frac{Z_C(1 + \rho)}{1 - \rho} \right) \quad (7)$$

where ρ is determined after multiple reflections have died out (i.e., at relatively long distances along the waveform). Following the approach of Dalton et al. (1990) and Nadler et al. (1991), an experimentally obtained probe constant (K) may be used to relate the EC to its measure load impedance:

$$EC = K / Z_L \quad (8)$$

The probe constant, K, may be determined by immersing the probe in one or (preferably) more solution of known EC, and using:

$$K = EC_{ref} Z_L / f_T \quad (9)$$

Where EC_{ref} is electrical conductivity of the reference (known) solution and f_T is a temperature correction coefficient (e.g., U.S. Salinity Laboratory Staff, 1954) 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, and using $25 \text{ }^\circ\text{C}$ as the standard temperature.

The Thin-Section Approach: Originally proposed by Giese and Tiemann (1975), this has been shown to be a particularly effective means of quantifying the soil apparent bulk EC (EC_a). The Giese and Tiemann equation may be written as:

$$EC = \left(\frac{\epsilon_0 c}{L} \right) \left(\frac{Z_0}{Z_u} \right) \left(\frac{2V_0}{V_f} - 1 \right) \quad (\text{dS/m}) \quad (10)$$

where ϵ_0 is the permittivity of free space ($8.9 \times 10^{-12} \text{ F m}^{-1}$), c is the speed of light in vacuum ($3 \times 10^8 \text{ m s}^{-1}$), L is probe length (m), Z_0 is characteristic probe impedance (Ω), Z_u is the TDR cable tester output impedance (generally 50Ω), V_0 is the incident pulse voltage (Figure 4), and V_f is the return pulse voltage after multiple reflections have died out.

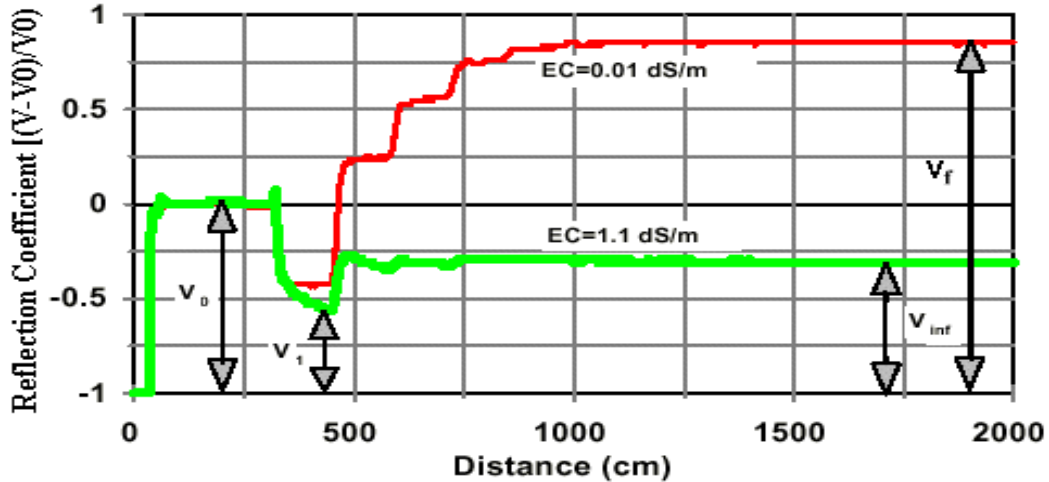


Figure 4: TDR waveforms at two measured bulk soil electrical conductivity levels. Arrows and corresponding labels indicate voltage locations used to calculate EC and/or determine probe impedance (see relevant equations in text).

The quantity of $\epsilon_0 c/L$ in Eq. (10) may be simplified to $1/(120\pi L)$, the values of V_0 and V_f are easily acquired from the cable tester output signal, and the probe impedance (Ω) may be determined by immersion in de-ionized water at known dielectric ϵ (i.e., tabular temperature-dependent dielectric values) according to:

$$Z_0 = Z_u \sqrt{\epsilon} \left(\frac{V_1}{2V_0 - V_1} \right) \quad (11)$$

where the required signal voltages (V_0, V_1) are illustrated in Figure 4. Alternatively, for specific probe geometries (e.g., true coaxial, two-rod balanced design), Z_0 may be calculated with formulae found in electronics textbooks. It should be also noted that $\epsilon_0 c Z_0/L = Z_0/120\pi L$ may be lumped into a geometric probe constant equivalent to K in Eq. (9). EC may thereby be estimated using Eq. (10) as:

$$EC = \left(\frac{K}{Z_u} \right) \left(\frac{2V_0}{V_f} - 1 \right) \quad (12)$$

with K either calculated using Eq. (9) and the relevant physical quantities (ϵ_0 , c , L), or empirically determined by immersion in known solutions as outlined previously. Figure 5 illustrates the typically excellent agreement found between EC measured using TDR (Eq. 12) and with and EC electrode.

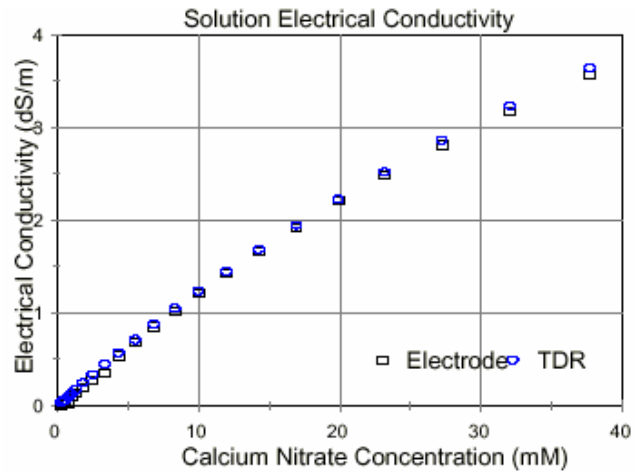
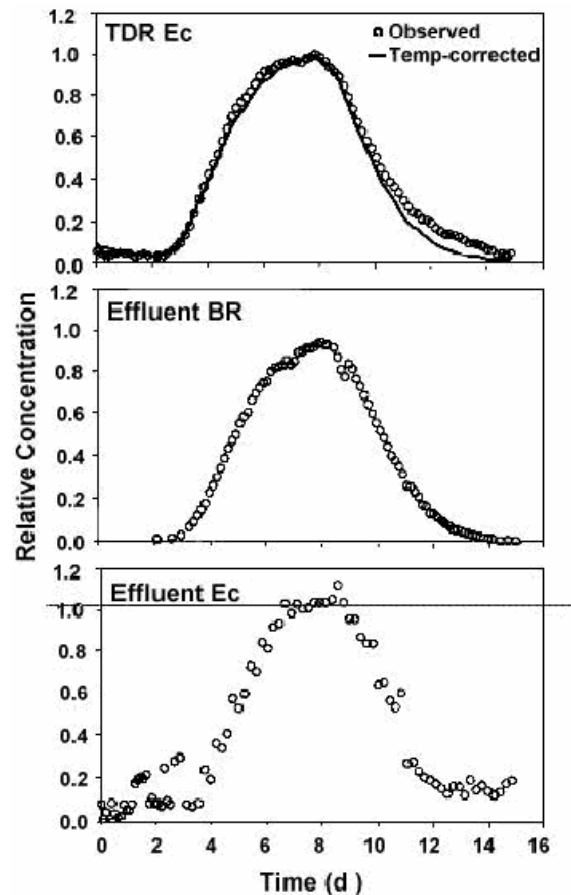


Figure 5: Comparison of TDR and electrode measurements of EC for a range of $\text{Ca}(\text{NO}_3)_2$ solutions. Solutions were continuously stirred and maintained at 25 °C.

The unique ability of TDR to simultaneously measure θ and EC_a in the same soil volume has let to recent applications for monitoring or quantifying the behavior of salts or ionic solutes in the soil environment. The electrical conductivity of the bulk soil, EC_a , is of course strongly related to the EC of the soil solution (EC_w), but is dependent as well on the contributions of the ionic species on the solid particle exchange sites and on the tortuosity of the electrical current flow path. The latter attribute is a function of the liquid-solid-air phase geometry, and thus changes in response to θ and alteration of the particle or pore arrangement. Under constant θ (e.g., static, or steady flow) conditions, EC_a is highly correlated to the concentration of ionic species in the soil solution. This facilitates estimation of ionic solute (e.g., conservative tracer salt) transport through soil columns or profiles (Kachanoski et al., 1992; Wraith et al.,



1993; Mallants et al., 1994). Figure 6 provides a comparison of EC_a measured using TDR under steady flow conditions with electrical conductivity (EC electrode) and bromide concentration (ion chromatograph) in the soil column effluent.

Figure 6: Relative EC measure using TDR during steady flow compared with relative bromide concentration and EC in the column effluent fractions. Source: Wraith et al., 1993. See Fig. 14 for schematic.

Soil scientists, geochemists or geohydrologists, geophysicists, and others have developed a number of conceptual models for the dependence of EC_a on EC_w . One such model was presented by Rhoades et al. (1976):

$$EC_a = (T\theta EC_w + EC_s) \quad (13)$$

where T and EC_s are the soil-specific tortuosity factor and surface conductance, respectively. With θ and EC_a easily measured using TDR, the solution electrical conductivity may be estimated using Eq. (13) as:

$$EC_w = \frac{(EC_a - EC_s)}{T\theta} \quad (14)$$

This as well as somewhat more sophisticated approaches were evaluated relative to monitoring transport of ionic solutes through soil columns under non-steady water flow conditions by Risler et al. (1996) (Figure 7). Their results suggest the potential to monitor representative concentrations of ionic soil solutes under transient flow conditions. Advantages of automated TDR over time-consuming soil solution analyses include its non-destructive nature, the ability to provide highly detailed breakthrough curves (BTCs), and the capability for continuous and unattended operation. However, TDR measures the effect of total ionic solute concentration and cannot characterize the soil solution constituents.

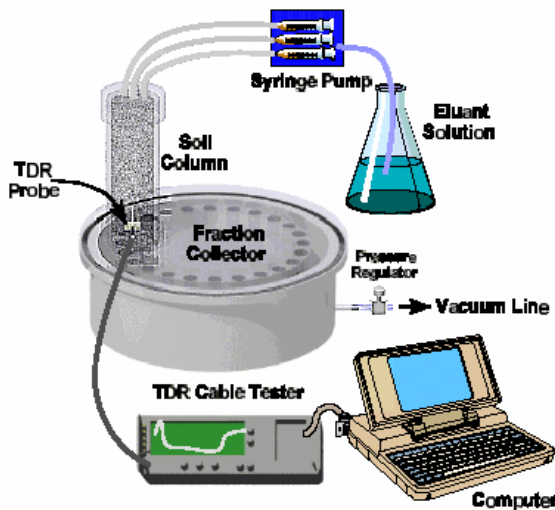


Figure 7: Schematic of computer-controlled TDR acquisition and analysis

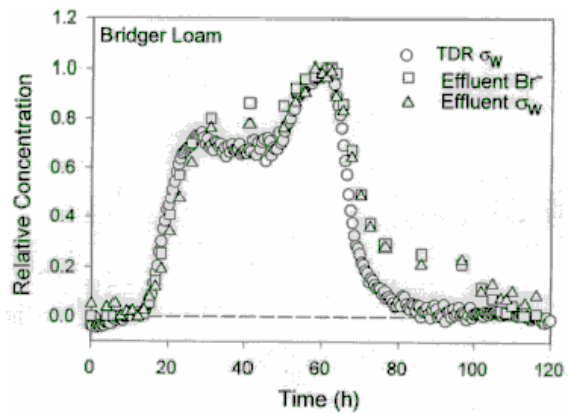


Figure 8: Relative soil solution EC (σ_w) as estimated using TDR with Eq. (14), and

system for monitoring ionic solute transport through unsaturated soil columns. Modified from Wraith et al., 1993.

measured in the column effluent using an electrode, under transient water flow conditions. Also shown are relative effluent fraction bromide concentrations. Source: Risler et al., 1996.