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Time Domain Reflectometry Field Measurements of Soil Water Content and Electrical Conductivity[1]

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ABSTRACT

Simultaneous measurements of volumetric water content and bulk electrical conductivity were made using time domain reflectometry (TDR) with a single parallel transmission line (PTL) imbedded in the soil. Sixty PTL's were installed at five depths in 12 existing lysimeter plots, irrigated with different amounts of water at two salt concentrations (1.3 and 3.1 dS/m). The water content measurements obtained with TDR showed a good relationship to gravimetric determinations ($r^2 = 0.84$) and were comparable to neutron probe measurements. The TDR measurements of bulk soil electrical conductivity were similar to the measurements of the same soil physical property measured with the four-probe electrode technique. The relation between bulk soil electrical conductivity and the conductivity of the soil solution is discussed. The importance of measuring both soil water content and salinity in a nondestructive manner on the same sampling volume, enabling repeated in situ measurements is stressed.

Additional Index Words: **soil salinity, neutron scattering, spatial variability, soil solution conductivity, four-electrode probe.**

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THE CONVENTIONAL METHOD for measuring soil salinity is by taking soil samples and determining the electrical conductivity of the extract of a saturated soil paste (Rhoades, 1982). These measurements can be converted into soil solution salt concentration by correcting for the soil water content at the time of sampling. The soil solution can be sampled directly by porous suction cups. This method, however, is limited to a narrow range of soil moisture between (approximately) field capacity and saturation and the small sample volume tends to make the measurements variable (Broadbent, 1981). Soil water content can be measured by destructive sampling and gravimetric determination or by the in situ neutron scattering method which has the advantage of measuring soil water content on a volume basis. The limitations of the neutron method are its relatively large sampling volume, the inability to measure close to the soil surface, the radiation hazard involved, and the need for individual soil calibration (Graecen, 1981). The fact that water content and salinity are usually obtained from separate samples with different geometry introduces an additional error in soil salinity assessment.

Recently, Dalton et al. (1984) proposed the simultaneous measurement of both soil water content and salinity for studies on water and salt management, using time domain reflectometry (TDR). The relative dielectric constant of soil is primarily related to its water content. Measurement of the dielectric constant in the time domain, by measuring the propagation velocity of a voltage pulse was introduced by Fellner-Feldegg (1969).

Topp et al. (1980) showed a unique relationship between the relative dielectric constant ϵ and the volumetric water content θ for a large range of soils and soil-like materials. In later work, parallel transmission lines (PTL) constructed of metal rods were used to measure water content in the field with TDR (Topp et al., 1982). The relative dielectric constant ϵ is calculated from the measured transit time t of a voltage pulse through the length ℓ of soil material as given by the electrode length according to

$$\epsilon = [ct/2\ell] \qquad [1]$$

where c = velocity of light in free space (3×10^8 m/s). The empirical relationship between relative dielectric constant ϵ and soil volumetric water content θ was found to be (Topp et al., 1980)

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\epsilon - 5.5 \times 10^{-4}\epsilon^2 + 4.3 \times 10^{-6}\epsilon^3 . \qquad [2]$$

It was found that this relationship was nearly independent of soil texture, soil density, temperature and salt content. It was noted, however, that soil salinity did influence the TDR signal in the soil medium (Topp et al., 1980).

Dalton et al. (1984) in attempting to account for the signal attenuation which occurs in saline soils, used results from transmission line theory to calculate the electrical conductivity of moist soil. Figure 1 shows the assumed equivalent circuit of a differential length of the parallel transmission line. L and R are the inductance and series resistance of the electrodes. C and G are the equivalent shunting capacitance

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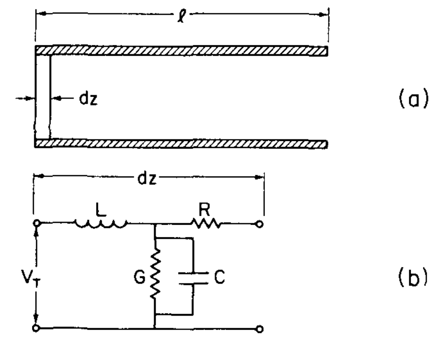

Fig. 1. (a) Parallel transmission line (PTL) of length *l* and (b) distributed inductance *L*, resistance *R* and shunting conductance *G* and capacitance *C* along a differential element of the PTL.

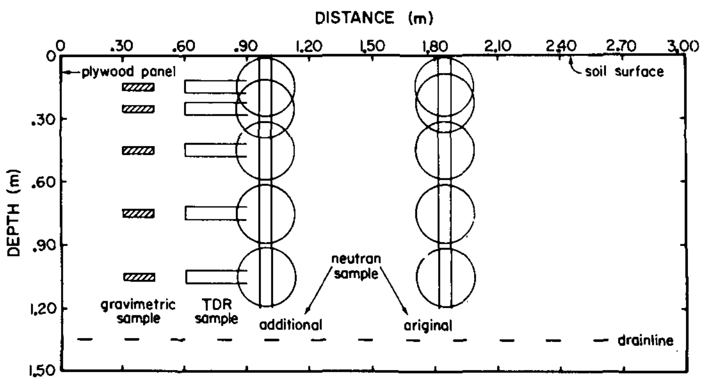

Fig. 2. Schematic cross section through lysimeter plot showing location and volume of soil samples.

and conductance between the electrodes respectively. There is no inherent frequency dependence assumed for the incremental conductance component in Fig. 1. It is this component of the equivalent circuit which is later compared to another method of measuring soil electrical conductivity. V_T is the input voltage to the line, but due to losses, the voltage along the line is assumed to decrease exponentially. The voltage at the end of the line is given by $V_L = V_T \exp(-\alpha L)$ where α is an attenuation coefficient. If perfect reflection at the end of the line is assumed, the voltage returning to the source will be

$$V_R = V_T \exp(-\alpha 2\ell)\,. \qquad [3]$$

For steady state sinusoidal conditions and for low loss lines an approximate expression for the attenuation coefficient is given from electromagnetic theory (Ramo and Whinnery, 1959) as

$$\alpha \approx R/[2(L/C)^{1/2}] + [G(L/C)^{1/2}]/2\,. \qquad [4]$$

Using values of L and C for parallel rod transmission line and assuming the skin resistance R to be negligible,

$$\alpha \approx 60\pi\sigma/(\epsilon)^{1/2} \qquad [5]$$

where σ is the bulk electrical conductivity. From Eq. [3] and [5], the bulk electrical conductivity is

$$\sigma \approx [(\epsilon)^{1/2}]/120\pi\ell \ln (V_T/V_R\,. \qquad [6]$$

This equation, developed by Dalton et al. (1984), in conjunction with Eq. [1] and [2], allows for the simultaneous determination of soil water content θ and soil electrical conductivity σ, based on the measured parameters t, V_T, and V_R.

The relationship between σ and θ was investigated by Rhoades et al. (1976) in their development of the four-electrode probe measurement of σ and was shown to be

$$\sigma = \sigma_w \theta\, T(\theta) + \sigma_s \qquad [7]$$

where σ_w is the electrical conductivity of the soil water, T is the transmission coefficient linearly dependent on θ and σ_s is the solid phase conductivity.

Dalton et al. (1984) conducted an experiment where the dielectric constant and electrical conductivity were measured in soil columns of equal water content, but highly varying salt content. The results showed a good linear relationship between TDR measured bulk electrical conductivity (Eq. [6]) and soil water electrical conductivity. Furthermore, these results were in close agreement to calculated σ values based on Eq. [7] using parameters from four-probe electrode calibrations.

These results form the basis of the following experimental study where we compare this TDR method under field conditions with the established methods: neutron and gravimetric methods for soil water content, four-electrode probe and soil water extraction methods for soil electrical conductivity.

MATERIALS AND METHODS

Twelve of the 24 rhizotron plots established in 1981 at the U.S. Salinity Laboratory for measuring the influence of irrigation frequency on the leaching requirement of alfalfa were used for evaluation of the TDR method. These plots were described previously in detail (Hoffman et al., 1983). Each plot has dimensions of 3 by 3 by 1.5 m and included one neutron probe access tube, and four-electrode burial probes installed horizontally at five depths. The profile of each plot is horizontally accessible by plywood panels. The soil is Pachappa fine-sand loam topsoil (coarse, loamy, mixed, thermic Mollic Haploxeralfs). Transmission lines were installed at five depths in four experimental treatments replicated three times; all irrigated twice per cutting as follows:

1. With water of 1.3 dS/m, at 0.12 leaching fraction
2. With water of 1.3 dS/m, at 0.06 leaching fraction
3. With water of 3.1 dS/m, at 0.24 leaching fraction
4. With water of 3.1 dS/m, at 0.12 leaching fraction

The transmission lines were constructed from 0.32-cm diameter parallel brass rods 5 cm apart at lengths of 20 cm for the high salinity plots or 30 cm for the low salinity plots. Shielded TV wire embedded in 70-cm-long 2.16-cm od PVC tubing, which served as a handle, provided the connection by means of an impendance matching transformer to a TDR measuring unit, consisting of oscilloscope, pulse generator and sampling head (Tectronics model 7603).

Horizontal holes, 6.35-cm in diameter and 60 cm long, were made at depths of 15, 25, 45, 75 and 105 cm from the soil surface through the side panels of 12 plots. Prior to installation of the transmission lines, in situ electrical conductivity was measured with a hand-held four-electrode probe instrument (Rhoades and van Schilfgaarde, 1976) at 30 cm distance from the side panels. Soil samples were taken at this location. From half of each sample soil solution was extracted by centrifuge and the electrical conductivity was determined. The gravimetric water content was determined by oven drying the other half of each sample and θ was calculated using the known bulk density of the soil (1.57 Mg m^{-3}). The electrical conductivity of the saturated extract was determined after adding 25% of water by weight (approximately SP) to a dry soil sample and extracting by vacuum (Rhoades, 1982).

The transmission lines were installed carefully in order to ensure good soil contact. The hole was backfilled with the original soil and TDR readings were taken one day after installation, measuring transit time t, transmitted voltage V_T and reflected voltage V_R. From these measurements, θ and σ were calculated using Eq. [1], [2], and [3]. Neutron measurements were taken at corresponding depths in existing access tubes, located about 1 m from the wave guides (see

Table 1. Water balance obtained during irrigation of experimental plots by water metering and by soil water content measurements before and after irrigation with neutron and TDR methods (mm/1.20 m soil depth).

Water quality, dS/m	Leaching fraction	Plot	Water applied†	Original neutron	Additional neutron	TDR
1.3	0.06	2	110.2	159.5	167.2	121.5
		13	108.0	111.0	--	64.8
		20	110.4	118.7	--	--
		Avg	111.2	129.7	167.2	93.2
1.3	0.12	8	135.0	114.6	157.9	128.5
		17	134.8	82.2	117.9	-
		19	133.3	116.4	--	109.5
		Avg	134.4	104.4	137.7	119.0
3.1	0.12	1	134.6	121.3	127.5	112.1
		10	136.1	119.9	-	128.2
		22	136.7	161.5	-	128.0
		Avg	135.8	134.2	127.5	122.8
3.1	0.24	6	158.7	125.7	172.0	-
		16	155.3	142.2	150.5	127.8
		21	159.7	111.1	--	174.5
		Avg	157.9	126.3	161.3	151.2

† Corrected for drainage and evapotranspiration.

Fig. 2). At a later stage, an additional neutron access tube was installed in each plot and soil samples and four-probe measurements were taken during installation (Fig. 2), using the procedure described previously. During irrigation of the experimental plots, TDR and neutron measurements were taken for all depths 1 d before irrigation and 2 d after irrigation. The amount of water applied to each plot was measured and corrected for drainage during that time period and for evapotranspiration as estimated by measuring pan evaporation. This was compared to the change in soil water content as measured by both TDR and neutron methods.

RESULTS AND DISCUSSION

Water Content Measurement

Figure 3a shows the relationship between TDR and the gravimetrically determined water contents obtained from subsamples taken while installing the PTL and the additional neutron access tubes. Figure 2b shows the relationship between the two sets of neutron probe readings and the same gravimetric water contents as above. The calculated regression equations and coefficients of determination (r^2) of θ_{TDR} and θ_{neutr} θ_{grav} for 102 data points are as follows:

$$\theta_{TDR} = 1.02\ \theta_{grav} - 0.023\ r^2 = 0.84$$

$$\theta_{neutr} = 0.86\ \theta_{grav} + 0.031\ r^2 = 0.82$$

$$\theta_{TDR}\ \text{vs.}\ \theta_{neut}\ r^2 = 0.79$$

These data show that the correlation between TDR and gravimetric determination is similar to that between neutron and gravimetric determination, but it is somewhat closer to a 1:1 relationship.

The lower than expected correlation coefficient between $\theta_{neutron}$ and θ_{grav} may be due to spatial variability in the horizontal plane containing the sampling and measuring volumes. This may also be true for the $\theta_{TDR} - \theta_{grav}$ correlation. Some indication for this is found in the following. Additional neutron probes were installed in the plots as close to the TDR probes as possible (Fig. 2). The comparison between these neutron probe and gravimetric determinations of water content increased the correlation coefficient to $r^2 = 0.92$ for 56 data points.

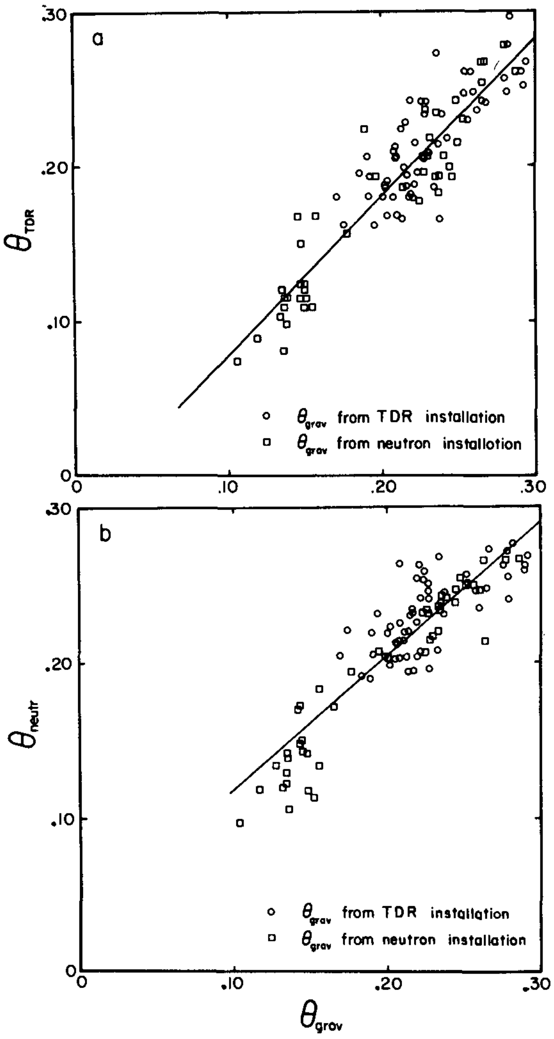

Fig. 3. (a) Soil water content as measured by TDR vs. gravimetric determination and (b) water content as measured by neutron scattering vs. gravimetric determination.

Another test of the validity of the TDR determined water content measurements was carried out during irrigation of the experimental plots. The water balance for all plots was calculated using TDR, neutron measurements and applied water (see Table 1). The discrepancy between the water actually applied and that measured by TDR and neutron probe seem to reflect soil variability. In many cases the differences between the two neutron sites per plot are as great or greater than the differences between TDR and neutron measurements. Both measurements seem to give a true estimate of water content for their sampling volume, and no conclusion can be drawn which method gives a better estimate of water content. More rigorous testing is needed to reach such a conclusion.

Salinity Measurement

The relationship between σ_{TDR} and σ(4-pr) is given in Fig. 4. These are two independent estimates of the same physical property, based on completely different measurement principles. Although the correlation be-

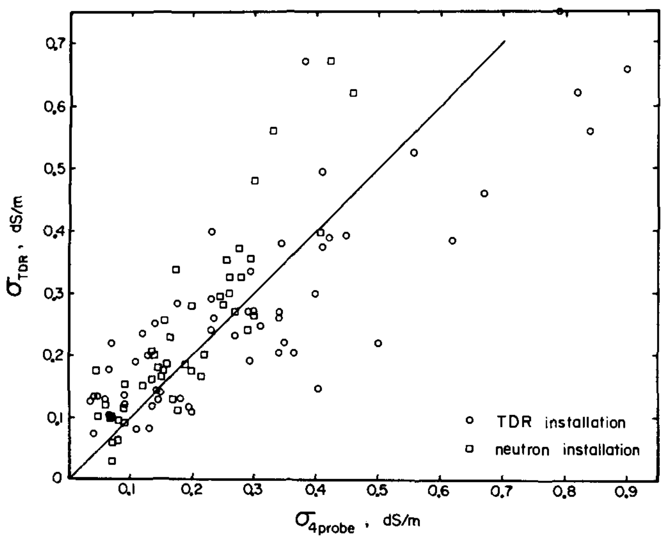

Fig. 4. Bulk soil electrical conductivity measured by TDR vs. measurement with four-electrode probe and 1:1 line.

tween the two is high (r^2 = 0.68 for 102 data points) many points are not close to the 1:1 line. The question therefore remains, which of the two measurements gives a better estimate of the bulk soil electrical conductivity?

The purpose of measuring σ is to obtain an estimate of σ_w, the electrical conductivity of the soil solution. An estimate of σ_w was obtained in our experiment by centrifuging the soil samples obtained during installation of the transmission lines and measuring the electrical conductivity of the filtrate, σ_{ex}. Since according to Eq. [4] the relation between σ and σ_w is dependent on the water content θ, we normalized our σ_{ex} data by calculating $\sigma_{sat} = \sigma_{ex}(\theta/\theta_{sat})$, taking θ_{sat} = 0.40 (SP $\times$ bulk density). This procedure is preferable to the determination of σ_w on the saturated extract, since by drying the soil and adding distilled water, ion exchange and solution of additional salts occur. Comparisons between σ and σ_{sat} are shown in Fig. 5a when σ is measured by TDR and in Fig. 5b when σ is measured by four-electrode probe. In each case the data consists of those taken while installing the transmission lines and later while installing additional neutron

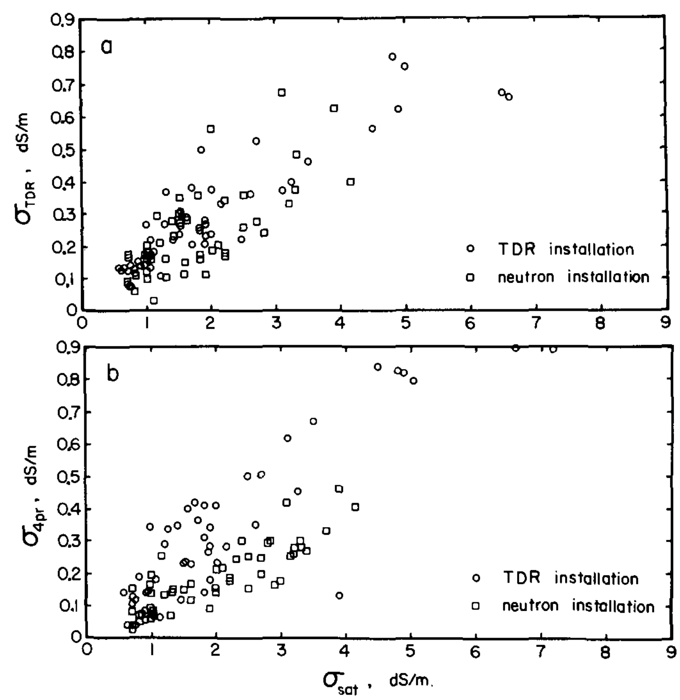

Fig. 5. Relationship between electrical conductivity of soil solution at saturation and bulk soil electrical conductivity measured (a) by TDR or (b) by four-electrode probe method.

access tubes. Again no conclusion can be drawn on which measurement gives a better relationship between σ and σ_{sat}. The TDR measured value of σ can also be compared with the calculated value of σ according to equation (4). Previously published parameters for Pachappa fsl (Rhoades et al., 1976) were used for this calculation: σ_s = 0.18 dS/m, $T = 1.382\theta - 0.093$). Figure 6 shows this comparison. According to equation (4), no σ values below σ_s were possible. However with both types of measurement of σ we obtained values < 0.18 dS/m. This is in accordance with the conclusions of Shainberg et al. (1980) and Nadler and Frenkel (1980) who showed the non-linearity of the σ/σ_w relationship in the low range of soil salinity.

The preliminary conclusion reached by Dalton et al. (1984) that "time domain reflectometry, in conjunction with known relationships between relative electrical conductivity and soil water conductivity, provides a new and powerful tool in soil water research in that a single measurement can yield both the soil water content and the soil water salinity"—has been borne out by the data presented in this paper. The water content measurements obtained with TDR show a good relationship to the standard gravimetric method and are comparable to the neutron measurements, as has been demonstrated previously by Topp (1980). The simplicity of the measurement and the reported universal calibrations, independent of soil density, temperature and salinity are additional advantages. But the main advantage of the method is that on the same sampling volume an estimate of the bulk soil electrical conductivity can be obtained. The results of this measurement seem to be comparable to the data obtained with the four-electrode probe method. Traditionally, soil salinity is evaluated by the electrical conductivity of the saturation extract. "Ide-

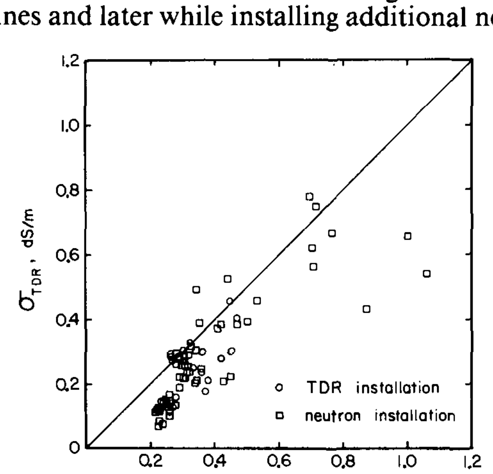

Fig. 6. Bulk soil electrical conductivity measured by TDR as compared to same calculated from centrifuge extract electrical conductivity.

ally, it would be desirable to know the solute concentration in the soil water over the entire range of field water contents and to obtain this information directly in the field, without need for collection of soil samples or laboratory analysis" (Rhoades, 1982). The proposed measurement of σ, together with the measurement of θ at the time of sampling, may pave the way in that direction. There seems to be no valid reason why guides to crop tolerance and salinity management could not be developed based on σ measurements rather than on determinations of the conductivity of the saturated extracts. More research is needed to evaluate the effects of environmental conditions on the σ measurements and to develop less expensive measuring instruments.

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