Time-Domain Reflectometry Measurements of Surface Soil Water Content

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D.C. Nielsen
United States Department of Agriculture

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677 South Segoe Rd., Madison, WI 53711 USA

TIME-DOMAIN REFLECTOMETRY MEASUREMENTS OF SURFACE SOIL WATER CONTENT

D. C. NIELSEN,* H. J. LAGAE, AND R. L. ANDERSON

Abstract

Surface soil water content is an important parameter influencing such processes as residue decomposition, nutrient cycling, microbial activity, and weed seed germination and emergence. This experiment was conducted to determine if time-domain reflectometry (TDR) could be used to measure water content in the 0- to 50-mm soil layer. Wave guides were installed horizontally at a depth of 25 mm below the soil surface in field plots differing in current crop-tillage history. The TDR system was interrogated hourly by a data logger. Daily average soil water contents from TDR were computed and compared with water contents obtained from gravimetric soil sampling. The TDR values were linearly related ($r^2 = 0.84$) with gravimetric samples of soil water content when wave guides were at a depth of 25 mm, but not when wave guides were at a depth of 13 mm. Continuous measurements of surface soil water content can be obtained from an automated TDR system.

SOIL WATER CONTENT in the surface layer (0–50 mm) strongly affects processes such as residue decomposition, microbial activity, nutrient cycling, and weed seed germination and emergence. Computer models that simulate these processes require surface soil water contents as a boundary condition. The daily measuring of surface soil water content can be tedious and difficult. Recently, water balance models (Ritchie et al., 1986) have been used to estimate soil water content in surface soils as a controlling parameter for models of such processes as N mineralization of crop residues (Vigil et al., 1991). However, the predictive accuracy of soil water models for near-surface (0–50 mm) conditions has not been validated.

Gravimetric sampling requires an intrusive measurement and is time consuming and labor intensive, and does not allow the same site to be monitored over time. Neutron scattering is not accurate in the surface layer because of the escape of neutrons to the atmosphere. Soil moisture blocks are not accurate at the low water contents typically found in this layer as soils dry. Time-domain reflectometry, when automated, offers potential for obtaining accurate measurements of surface soil water content on a nearly continuous basis, providing data for water balance model validation.

Detailed descriptions of TDR principles, techniques, and designs have been previously given (Topp et al., 1980; Dalton and van Genuchten, 1986; Topp and Davis, 1985; Zegelin et al., 1992). Briefly, the basic principle of operation is that two metal rods inserted into the soil act as a wave guide for the propagation of an electromagnetic pulse from a cable tester. When the pulse encounters a discontinuity, such as the end of the wave guide, a portion of the energy is reflected back to the cable tester. The dielectric constant of the soil affects the travel time of the pulse. The major factor affecting the dielectric constant of mineral soils is the water content.

Knight (1992) showed that the volume of soil sampled by a TDR system employing a parallel wire wave guide was dependent on the spacing of the two parallel rods. He also showed that for parallel-rod wave guides, most of the measurement sensitivity is close to the rods if the rod diameter is small compared with the spacing between them, which could cause significant errors if an air gap developed close to the rods. To minimize this "skin effect", Knight (1992) recommended that the ratio of rod diameter to rod spacing be not less than 0.1.

Baker and Lascano (1989) performed a thorough laboratory study of TDR spatial sensitivity employing water- or air-filled glass tubes and wave guide rods (diam. = 3.175 mm) spaced 50 mm apart. They found the volume of soil sensed by the two-rod TDR probe was slightly larger than a cylinder having a diameter equal to the rod separation distance. They concluded that with this diameter rod and wave guide spacing, it should be possible to horizontally place wave guides as close to the soil surface as 20 mm with little loss in accuracy. This study gathered observational data regarding the accuracy of an automated TDR system to measure soil water content in the 0- to 50-mm surface soil layer.

Materials and Methods

The study was conducted during the 1992 growing season at the USDA Central Great Plains Research Station, 6.4 km east of Akron, CO. The soil type at this location is a Rago silt loam (fine, montmorillonitic, mesic Pachic Argiustoll). The plot area was fertilized on 27 Mar. 1992 with 67 kg N ha^{-1} broadcast as NH_4NO_3. Total precipitation of 58 mm between fertilization and the first sampling date should have eliminated any potential effects of high soil electrical conductivity on TDR measurements in the surface soil layer. The TDR system used consisted of a Tektronix 1502B cable tester interfaced to a Campbell Scientific 21X data logger equipped with a TDR PROM[1] (Campbell Scientific, Logan, UT). Wave guides consisted of pairs of 30-cm stainless steel soil rods (rod diam. = 5 mm). Wave guides were buried horizontally by making a narrow trench in the soil surface to a depth of 25 mm, laying the wave guide in the trench, and then covering with the removed soil. No special precautions were taken to maintain intimate soil contact with wave guides. The measurement site was visually inspected every 2 to 3 d for signs of soil cracking or physical disturbance of the soil surface. On six dates during the growing season (nonuniform intervals between dates), the depth of the wave guides below the soil surface was checked by inserting a thin-bladed putty knife into the soil until it contacted the wave guide and then measuring the insertion depth. Spacing between the steel rods comprising one set of wave guides was 50 mm.

A single pair of wave guides was placed in each of six plots that varied in prior tillage condition and current crop. The six plots were barley (*Hordeum vulgare* L.)–no till, proso millet

USDA-ARS Central Great Plains Res. Stn., P.O. Box 400, Akron, CO 80720. Received 28 Oct. 1993. *Corresponding author (dnielsen*lamar.colostate.edu).

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[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA.

(*Panicum miliaceum* L.)-till, proso millet-no till, corn (*Zea mays* L.)-no till, corn-till, and fallow-till.

Soil water content was measured with the TDR system every hour and daily average volumetric water contents were computed. Gravimetric soil samples were taken on 12 dates from 1 May to 29 Oct. 1992 in the same plots as TDR measurements were taken, but in a location that varied from 2 to 4 m from the wave guide location. At each sampling date, three soil cores of the 0- to 25- and 25- to 50-mm depths were taken and composited into one sample for each depth. The diameter of the soil core was 19 mm. Bulk density was calculated for each sample after drying at 105°C for 48 h. Gravimetric soil water content was converted to volumetric water content using the calculated bulk density.

Results and Discussion

The comparison of water content by gravimetric soil probing (0–50 mm) vs. water content by TDR (wave guides at 25 mm) shows good agreement between methods across a wide range of water contents (Fig. 1). Linear regression ($P = 0.0001$) indicated that the TDR measurements systematically underestimated the soil water content relative to the gravimetric readings (mean difference between TDR and probe measurements = -0.008 m^3 m^{-3}; paired t-test = 2.675 [Table 1]). This was particularly noticeable in the barley–no till and corn–till plots. This could result from soil compaction and overestimated bulk density for soil cores. But if soil compaction occurred during the probing process, we would have expected to see a systematic error in all plots sampled, and we did not. Additionally, accounting for the higher probed water contents in the barley–no till plots compared with TDR readings would require a compaction error of 15 to 25% in determining bulk density. Our visual observations during soil sampling would not support this degree of compaction. Another possible explanation for the underestimation of soil water content by TDR is that wave guide position was slightly nearer to the soil surface than planned due to soil settling after installation.

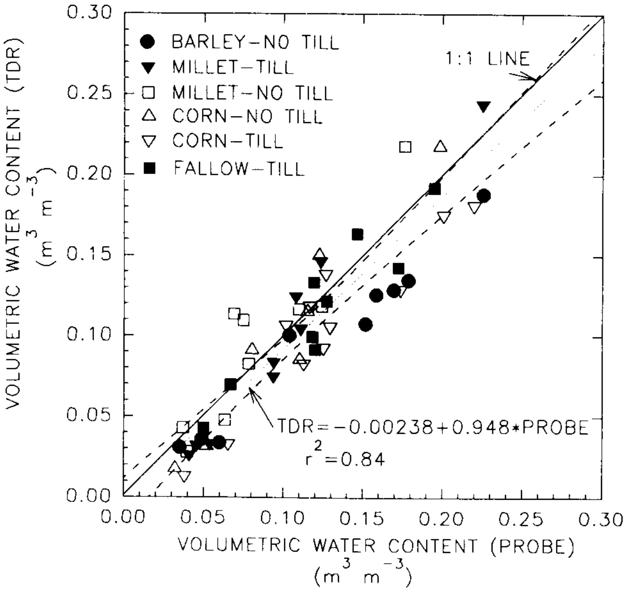

Fig. 1. Comparison of surface soil water content measured gravimetrically (PROBE) (0–50 mm) vs. time-domain reflectometry (TDR) (wave guides at 25 mm) under six cropping–tillage combinations. (Solid line is 1:1 line; short dashed line is regression line, long dashed lines are 95% confidence interval for regression line.)

Table 1. Summary of results from paired t-test comparing volumetric water contents from gravimetric probing (θ_{probe}) and time-domain reflectometry (θ_{TDR}).

n†	Mean (θ_{probe}) − (θ_{TDR})	SD‡	SE§	t	P
	m^3 m^{-3}				
54	−0.008	0.022	0.003	2.675	0.0099

† n = number of paired observations.
‡ SD = standard deviation of differences.
§ SE = standard error.

The scatter about the 1:1 line can be mainly attributed to spatial variation in soil water content across a plot, and to inaccuracies in determining bulk density from the small gravimetric soil cores. As stated above, the physical location of the gravimetric samples was at times up to 4 m away from the TDR sampling sites. One other potential source of variability could be our use of the daily average water content by TDR instead of the water content by TDR at the time of gravimetric sampling. Daily changes in surface soil water content ranged in magnitude from 0.003 to 0.030 m^3 m^{-3}, depending on environmental conditions and crop cover, but averaged ≈0.015 m^3 m^{-3} for the data reported here. Water content measured with the TDR at the time of gravimetric sampling (≈ 15:00 h) was typically only 0.003 m^3 m^{-3} higher than the daily average water content by TDR. Therefore use of the daily average water content by TDR, as opposed to the hourly TDR reading at the time of gravimetric sampling, did not greatly increase the variability in the data plotted in Fig. 1. The level of variability shown in Fig. 1 is similar to that reported by Topp and Davis (1985) when comparing water contents of horizontally installed wave guides at depths ranging from 65 to 1000 mm.

Our field data confirm the laboratory results of Baker and Lascano (1989) regarding depth sensitivity of TDR. Figure 2 shows two sets of points taken in the proso millet-till plot: the solid circles were taken prior to checking the depth placement of the wave guides, and the open triangles were taken after repositioning the wave guides at 25 mm below the soil surface. Apparently some soil settling or erosion had occurred after the initial installation of the TDR wave guides so that they were actually at a depth of 13 mm below the soil surface instead of the planned 25-mm depth. At this shallow depth, the TDR measurements severely underestimated the soil water content compared with the gravimetric measurements, with the difference most pronounced for the wettest measurements. When the TDR readings for this plot are compared with gravimetrically sampled soil water content in the 0- to 25-mm layer only, the agreement improves for water contents <0.15 m^3 m^{-3}, but is still greatly underestimated by TDR for wetter soil conditions (Fig. 3). It is possible that these low values are a result of air gaps developing around the wave guides as the soil dried. An alternative explanation

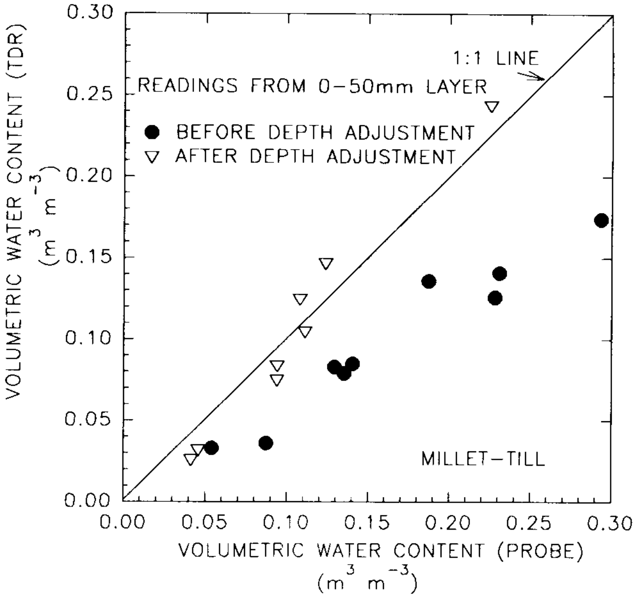

Fig. 2. Comparison of surface soil water content measured gravimetrically (PROBE) vs. time-domain reflectometry (TDR) before (wave guides at 13 mm) and after depth adjustments of wave guides to 25 mm in the proso millet-till plot. Gravimetric samples taken from the 0- to 50-mm layer.

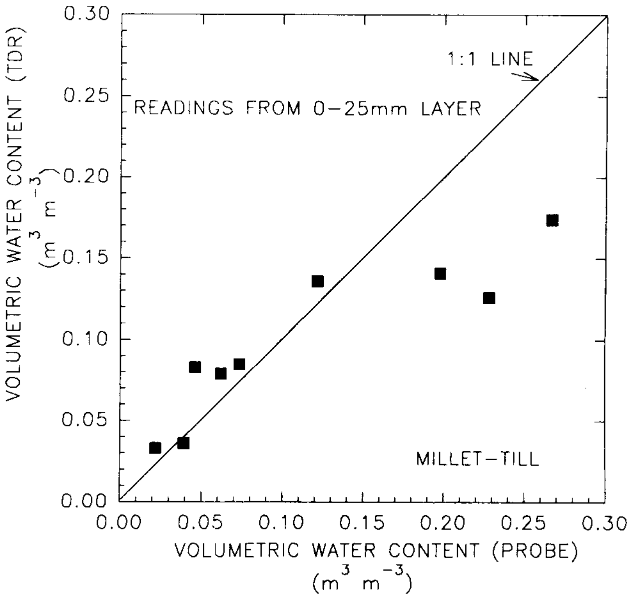

Fig. 3. Comparison of surface soil water content measured gravimetrically (PROBE) vs. time-domain reflectometry (TDR) in the proso millet-till plot where wave guides were at a depth of 13 mm due to soil settling and erosion. Gravimetric samples taken from the 0- to 25-mm layer.

is that with a wave guide spacing of 50 mm, the volume sensed by wave guides at a depth of 13 mm includes air above the soil surface, and the error becomes larger as the soil being sampled becomes wetter.

These results point out the importance of correct depth placement of the wave guides for accurate surface soil water measurements. Correct depth placement can be difficult in the dry, loose surface soil layer immediately following a tillage or planting operation. Depth placement should be checked periodically following wave guide installation to determine if soil settling has occurred, which could leave the wave guides too near the soil surface.

Summary and Conclusions

An automated TDR system can be used to accurately quantify daily surface soil water content in the 0- to 50-mm layer using wave guides of 5-mm diam. spaced 50 mm apart. Wave guide depth placement should be checked periodically to determine if the depth is sufficient to ensure that measurements are being made of the soil condition and not the air above the soil. Based on the results of this study, we would caution against wave guide placement <25 mm below the soil surface when using a wave guide spacing of 50 mm. Shallower wave guide placement could perhaps be used with narrower wave guide spacing, but this reduces the volume of soil being sampled. Continuous measurements of surface soil water content by automated TDR systems will be valuable for verifying models of water content that influence important processes such as residue decomposition, nutrient cycling, and weed emergence.

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