Measurement of Soil Water Content using Time-domain Reflectrometry (TDR): A Field Evaluation[1]

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ABSTRACT

For measurement of water content using TDR, parallel wire transmission lines varying in length from 0.125 to 1 m were installed vertically at planting time at three sites in a corn field. At one of the sites horizontal lines and additional vertical transmission lines with electrical impedance discontinuities were installed for comparison. Measurements of water content using a portable TDR cable tester were made periodically during the growing season. Comparisons of water contents by TDR with those from gravimetric samples showed that generally both were the same values. Standard deviations of differences between TDR and gravimetric values were ± 0.02 m^3m^{-3} when measured locations were the same but increased to ± 0.06 m^3m^{-3} when measured locations were different. Repeated measurements at the same location were highly correlated, one with another, over the season. Analysis of variance showed that all transmission line types were yielding equivalent values and that the horizontal transmission lines gave the minimum standard error of the mean. Data from transmission lines with impedance discontinuities gave water content profiles from a single measurement but the analyses of the TDR data curves were more complex than for the lines wihtout impedance discontinuities. The variety of transmission line configurations for use in TDR measurement allows considerable flexibility of choice in relation to one's application.

***Additional Index Words:* gravimetric sampling, transmission lines.**

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CONSIDERABLE PROGRESS has been made in the application of time-domain reflectrometry, (TDR) to measurement of soil water content. Using coaxial lines where sample boundaries are unambiguously specified, Topp et. al., (1980) showed that water content was the factor mainly determining the dielectric constant of soil material. Factors such as temperature, soil type, density of sample, and salt content had essentially insignificant effects. In further studies, an empirical equation relating measured dielectric constant and water content was found to apply not only for coaxial transmission lines but also for parallel pair transmission lines placed in the soil (Topp et al., 1982a, b). The parallel lines provided a good measure of water content regardless of the distribution of the water along the line. TDR also gave a profile of water content when lines with discontinuities were used. The parallel line geometry was favored for field use and was used successfully in two types of infiltration experiments (Topp and Davis, 1981; Topp et al., 1983). In 1982, we presented a review of progress in measurement of water content by TDR (Topp and Davis 1982).

This paper evaluates three variations of parallel pair transmission lines at three sites under a silage corn crop. TDR measured water contents are compared to values obtained by gravimetric sampling. Details of design and installation of transmission lines are given and discussed in relation to the improvements which are required.

MATERIALS AND METHODS

Field evaluation of TDR was conducted under a crop of silage corn (*Zea mays* L.) where measurements were taken from seeding time, on 1 June to harvest on 19 Sept. Three sites with differing soil and landscape characteristics were chosen. Site no. 1, which was more intensively instrumented than the other two, was on a flat location of the Dalhousie soil association (Typic Haplaquolls) with a clay loam texture. Site no. 2, was a similar soil but in a depressional area. Site no. 3, of the Manotick soil association (Aquic Dystrochepts) had about 0.85 m of sandy loam soil underlain by clay.

Types of Transmission Lines

Parallel pair transmission lines were installed in triplicate with both vertical and horizontal orientation in the soil. Those installed vertically were of two types, those with and without electrical discontinuities. The lines without discontinuities, (i.e. continuous lines) installed at all three sites were made from 12.7-m diam brass rods used in pairs with rods 50 mm apart. The lengths of the lines in each set were 0.25, 0.50, 0.75, and 1.00 m. At each site, three complete sets of four pairs of different lengths were installed in adjacent corn rows. Each pair was spaced about 1 m from the adjacent pairs as shown in Fig. 1. Thus, each set spanned a 4 m length of corn row. Measurements of the surface 0.125 m were accomplished with the hand probe described by Topp et al., (1984) with 0.125 m probes in it. Consequently a new location was chosen at the time of each measurement. The other lines remained in place from 1 June until 19 Sept.

A second type of vertical transmission line, used only at site no. 1, had electrical impedance discontinuities filled with

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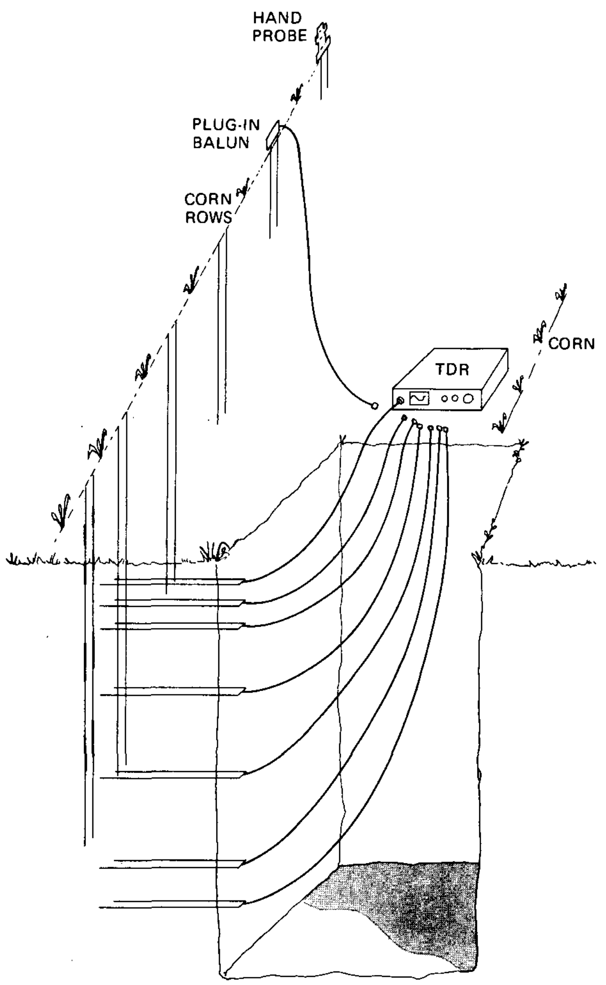

Fig. 1—A diagramatic representation of TDR transmission line installations at site no. 1.

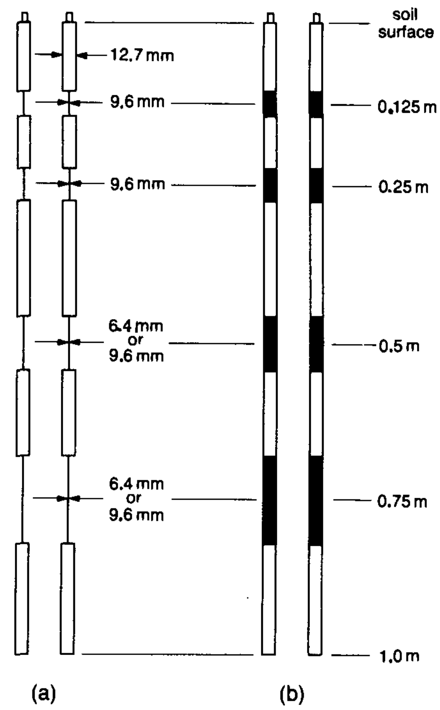

Fig. 2—A vertical transmission line having discontinuities. 2(a) shows the diameters and mid-point depths of cut-away portions of the brass before adding dielectric in the discontinuities, as shown in 2(b).

a dielectric material as described by Topp et al., (1982b) and as shown in Fig. 2. Preliminary investigation of the data showed that measureable reflection of signal from those discontinuities deeper in the soil (0.50 and 0.75 m) were obtained only for those lines where diameters were reduced to 6.4 mm before adding the dielectric as shown in Fig. 2(b). Triplicate installations of the dielectric filled transmission lines were made at site no. 1, within the corn rows (Fig. 1).

The third type of transmission line tested as site no. 1 was also of the parallel pair type but installed horizontally in the soil. These transmission lines consisted of a pair of 1.6 mm diam stainless steel rods, 0.4 m long, separated by 50 mm. They were placed at depths of 0.065, 0.185, 0.375, 0.625, 0.875, and 1.00 m in the soil. Except for the 1.00 m depth, these depths corresponded to the mid-point of the depth intervals monitored by the vertical transmission lines.

Installation of Transmission Lines

The vertically installed transmission lines, (rods of 12.7 mm diam) were pushed or hammered into 9.6-mm diam pilot holes (Topp and Davis, 1981; Topp et al., 1982a and b). The pilot holes were drilled using a portable electric drill. The drill bit was a wood bit, 0.30 m long, 9.6 mm diameter, welded to a 6.4-mm diam steel rod. A wooden guide 30 cm high mounted on a 1 m by 1 m plywood base was used to align the drill bit, giving 50-mm spacing between pilot holes and preventing oversized holes by wobble of the drill bits. A small amount of water was added to stabilize the cultivated surface soil when installations were made prior to any rainfall.

The horizontal lines were installed from a soil pit dug to about 1.1 m deep (Fig. 1). The paired 1.6-mm diam rods making up one transmission line were mounted in a guide with parallel grooves along which the rods were pushed into the face of the pit which was parallel to the corn row. Connections were made by soldering the shield braid of a 3 m, 50-ohm coaxial cable to one rod and the center conductor to the other rod. The other end of the coaxial cable extended to the soil surface for connection to the TDR cable tester. The soil pit was back-filled. Three sets of installations were made at site no. 1 separated by about 8 m along one row of corn.

Measurement of Soil Water Content

The soil water content registered by each transmission line was determined by measuring the dielectric constant of the soil. The TDR trace given by a cable tester (Tektronix Model 1502) was photographed. The dielectric constant was determined from the photograph by the procedure described by Topp et al. (1982a). The empirical Eq. [7] given by Topp et al., (1980) was used to convert the dielectric constants to volumetric water contents.

Measurements were made by connecting the portable cable tester to each transmission line in turn. A balun, consisting of an RF pulse transformer mounted on a fiber glass board, was used to make the connection between the balanced parallel vertical lines in the soil to the coaxial cable from the cable tester. The balun was plugged into holes drilled in each rod end of the lines. The TDR measurements were made at 7-d to 3.5-d intervals depending on the weather conditions. Measurements were made more frequently when rain occurred. At selected times during the growing season soil samples for gravimetric determination of water content were taken and sectioned into depth increments to allow paired comparison with the TDR values.

Figure 3 shows examples of TDR traces which were ob-

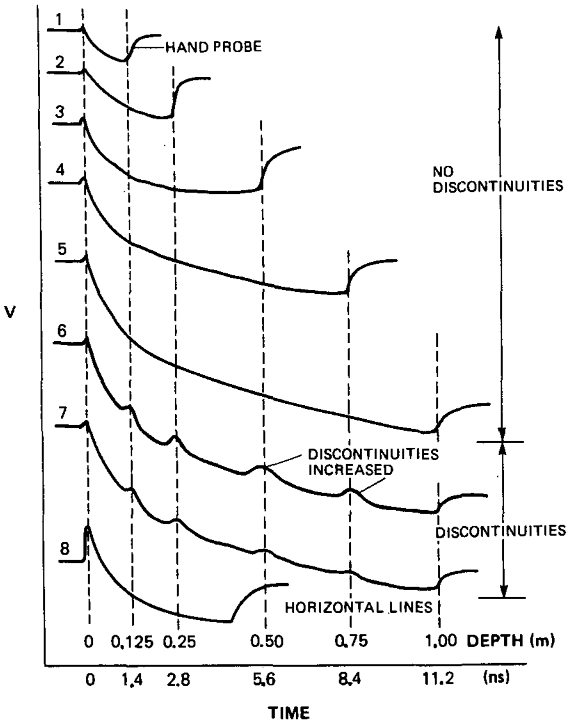

Fig. 3—Typical TDR data traces to determine travel times for calculation of various volumetric water contents. The vertical axis "V", is measured as a voltage of the reflected signal.

tained from the different types of transmission lines used at site no. 1. Curves such as 1 to 5 were also obtained from sites no. 2 and no. 3. A brief discussion of how these types of curves were used and interpreted is in order. Vertical lines without discontinuities resulted in simple curves from which it was relatively easy to get the total water in the soil within the depth interval spanned by the transmission line (Topp et al., 1982a). To get the vertical distribution of water from lines without discontinuities we used lines of different lengths as described above. The water content at a particular depth increment, say 0.25 to 0.50 m, was obtained by subtraction of travel times measured from curves 3 and 2 in Fig. 3. (The distances given above the horizontal axis in Fig. 3 are for reader reference and do not imply a fixed relationship between distance and travel time). Thus a profile of water content to the depth of 1 m required data from five vertical lines without discontinuities.

The TDR curves from the horizontally installed lines (curve 8 in Fig. 3) were easily measured using only one scale setting of the cable tester. As above, however, five lines were required to give a full profile of water content. From a single installation of a vertical line with discontinuities, it was possible to get water content information equivalent to five vertical lines without discontinuities or five horizontal lines (i.e. curve 6 or 7 in Fig. 3 contains information comparable to curves 1 through 5 or five curves such as in 8).

At the end of the season (Sept. 19) a detailed sampling was carried out for determination of both gravimetric water content and bulk density. Cylindrical samples 20 mm in diam were taken from within each vertical transmission line. The bulk density was obtained from these samples by assuming each sample had a cross-sectional area equal to the inner open area of the sampler and the lengths were cut precisely to the desired length. Below the 0.25-m depth this sampling procedure resulted in no measurable compaction. In about 30% of the samples from the upper 0.25 m, compaction, varying from 5 to 25%, occurred. Such compaction was assumed to be evenly distributed and the upper sample

Table 1. Summary of results from paired t-test comparing gravimetric, θ_{vg}, and TDR, θ_T, water contents.

Site no.	Transmission line type	n†	Mean $(\theta_T - \theta_{vg})$	SD†	SE†	t*	Significance of difference
			(a) During the season				
1	Horizontal	39	0.008	0.042	0.007	1.3	ns
1	Continuous	30	0.021	0.061	0.011	1.9	s
1	Discontinuity	30	0.041	0.053	0.010	4.2	s
2	Continuous	19	−0.021	0.065	0.015	1.3	ns
3	Continuous	19	0.012	0.064	0.015	0.8	ns
			(b) End of the season				
1 & 2	Continuous	26	−0.002	0.021	0.004	0.5	ns
1	Discontinuity	36	0.019	0.074	0.012	1.6	ns
3	Continuous	14	0.027	0.024	0.006	4.4	s

* $t > 1.7$ indicates mean differences are significant at the 5% level.
† n = number of paired observations, SD = standard deviation of differences, SE = standard error.

was divided into two equal portions, each corresponding to a 0.125-m length. The depths for sampling and sectioning of the samples were at 0.125, 0.25, 0.50, 0.75, and 1.00 m as was used for the TDR measurements.

RESULTS AND DISCUSSION

Comparisons of TDR and Gravimetric Measurements

A paired t-test generally showed no significant difference at the 5% level between the TDR and gravimetric-measured water contents during the season (Table 1a). The major exception was from the vertical lines with discontinuities at site no. 1 which showed a mean difference of 0.041. An explanation for why these lines measured high θ_T values (θ_T = water content by TDR) was not apparent, even though about half of this difference is explained below. The mean difference of 0.021 between θ_T and θ_{vg} (θ_{vg} = volumetric water content from gravimetric samples) for the continuous lines is barely significant at the 5% level (t = 1.9 vs. 1.7).

For the end-of-season measurements, sites no. 1 and no. 2 showed an excellent 1:1 correspondence between gravimetric and TDR measurements on the vertical lines without discontinuities (Fig. 4). A paired t-analysis (Table 1b) showed the mean difference $(\theta_T - \theta_{vg})$ was only -0.002 m^3m^{-3} with a standard deviation of 0.021 m^3m^{-3}. For site no. 3 the TDR gave slightly higher values which were, on average, 0.027m^3m^{-3} greater than those from the gravimetric samples. There was some evidence that this discrepancy resulted from water collected around the top of the rods for each transmission line in the sandy soil at site no. 3. Small (about 1 mm) annular gaps had formed at the top of the rods. At the time of sampling, immediately after a rain, these gaps had filled with water or silt. The TDR measured the water thus accumulated but this was not part of the gravimetric samples. Thus water in such gaps might have caused the TDR to measure higher at site no. 3 at the time of the last sampling.

For the lines with discontinuities, at site no. 1, a closer examination showed that TDR measured values of water content for the 0 to 0.125-m depth tended to be consistently high. In an effort to see if these differences resulted from water in gaps at the top of

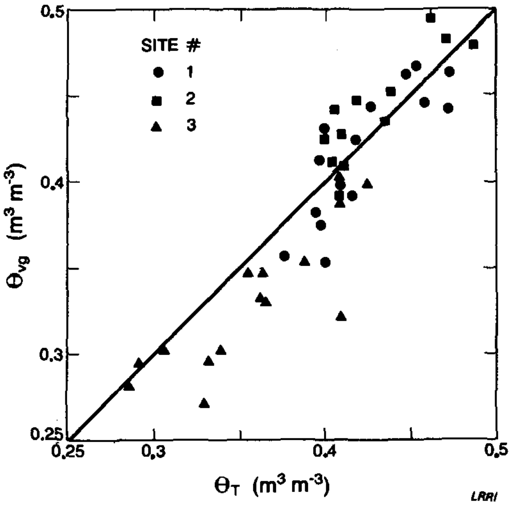

Fig. 4—The gravimetric water content, θ_{vg}, (on a volume basis) vs. TDR water content, θ_T, at the three sites at the time of sampling 18 Sept. and 19.

the rods, we excluded data collected < 2 d after rainfall events > 10 mm. Repeating the paired t-analysis with this more restricted data set gave a mean ($\theta_T - \theta_{vg}$) reduced by 0.02 m^{3}m^{-3}. The mean difference for these lines with discontinuities still remained significant but at about half of the value reported in Table 1a.

For the lines without discontinuities (continuous) at all three sites, the SD of differences for the data taken during the season was >0.06 m$^{3-3}$ (Table 1a). For the data taken at the end of the season the SD was reduced to just over 0.02 m$^{3-3}$ (Table 1b). Variance in measurement made in the field arises from both spatial variability and instrument precision. In general, these two sources cannot be separated. The gravimetric and TDR measured water contents, of necessity were from different places during the season in order that the gravimetric sampling did not disturb the soil measured by TDR. At the end of the season, however, the soil measured by the TDR was sampled for gravimetric water content. Thus the SD of difference between θ_T and θ_{vg} of 0.02 m^{3}m^{-3} obtained when both techniques measured the same soil would have the lesser contribution from spatial variability, whereas

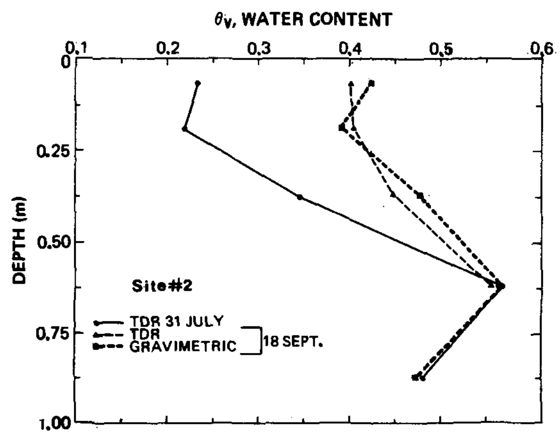

Fig. 6—Water content profiles at site no. 2 for two dates comparing data from TDR lines and gravimetric samples.

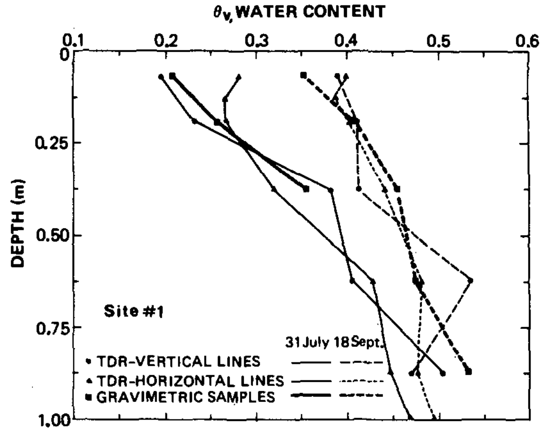

Fig. 5—Water content profiles at site no. 1 comparing data from horizontal and vertical TDR lines with those from gravimetric sampling on two dates.

the standard deviation value of 0.06 m^{3}m^{-3} obtained during the season would include a larger component resulting from spatial variability.

Comparisons of Different Line Types

An analysis of variance was carried out for four dates of measurements representing the wet and dry extremes (driest 24 and 31 July, wettest 11 and 18 Sept.). The three variables considered were line type, depth interval and replication. As expected, the water contents measured for the various depth intervals was significantly different (at 1% level) on all dates. In general, the variance attributable to line type was not significant. There were, however, three of the 20 examples where line type differences were significant at the 1% level and all three lines were reading differently (0-0.25 m on 31 July and 0-0.125 m and 0-0.5 m on 18 Sept.). The horizontal lines gave values significantly different (5% level) from the two types of vertical lines only for the 0 to 1.0-m depth on 31 July and 11 and 18 Sept. The individual replicates were not found to be a factor contributing significantly to the observed variance.

Figure 5 shows water content vs. depth profiles for site no. 1 on the driest observation date, 31 July and on one of the wettest dates, 18 Sept. The two types of TDR lines, vertical without discontinuities and horizontal, compare well with each other as shown by the analysis of variance above. Both compare favorably with the gravimetric samples. Near the surface the horizontal TDR lines gave water contents which tended to be high. These lines averaged the water content from midway between corn rows to the corn row. The vertical TDR lines and gravimetric samples were within the corn row. Thus the observed differences, may reflect differences in rainfall distribution under the corn canopy on 18 Sept., or in distribution of root extractions of water on 31 July. The different types and orientations of transmission lines used at site no. 1 all gave reliable measurements of water content. Later discussion will give consideration to choosing transmission lines for specific applications.

Figures 6 and 7 show a TDR measured profile for 31 July and profiles resulting from both TDR and gra-

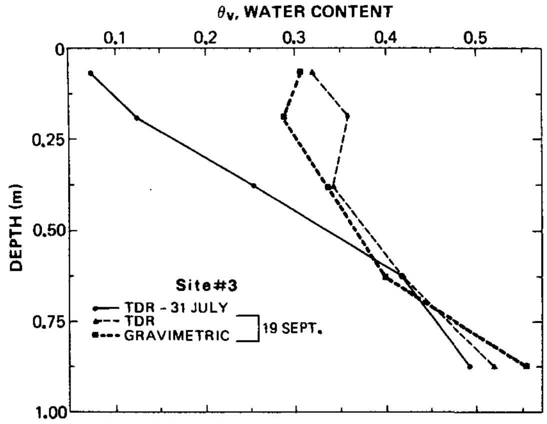

Fig. 7—As in Fig. 6 for site no. 3.

vimetric samples of 18 and 19 Sept. for sites no. 2 and no. 3, respectively. There is good agreement between gravimetric and TDR measured data of these profiles as shown earlier in Table 1 except for the one pair of points at 0.18 m in Fig. 7. We believe this discrepancy reflects the accumulation of water around the top of the rods which was measured by TDR but not by gravimetric samples and discussed above. The difference between measurements on the driest date, 31 July, and those on 18 and 19 Sept., show that only the top 0.5 m of soil actually dried during this season at sites no. 2 and no. 3. Figure 5 indicates that some drying had occurred to 1 m deep at site no. 1.

Water Content vs. Time

Figure 8 shows the pattern of wetting and drying of the upper 0.25 m recorded during the latter part of the season at site no. 3. The data from each line maintained the same relative value with respect to the other two. Graphs of the data from the other lines and the other sites had patterns very similar to that shown in Fig. 8. It appeared that on any day the observed readings had a large contribution to variance which was location dependent. We reasoned that since all the locations were subjected to similar rainfall and evapotranspiration conditions the water content values from comparable depth intervals should be highly correlated with each other over the season. To test this hypothesis we have calculated within class correlation coefficients for each transmission line type and depth interval as described by Steel and Torrie (1960). All of the within class correlation coefficients given in Table 2 are significant at the 1% level, showing that for

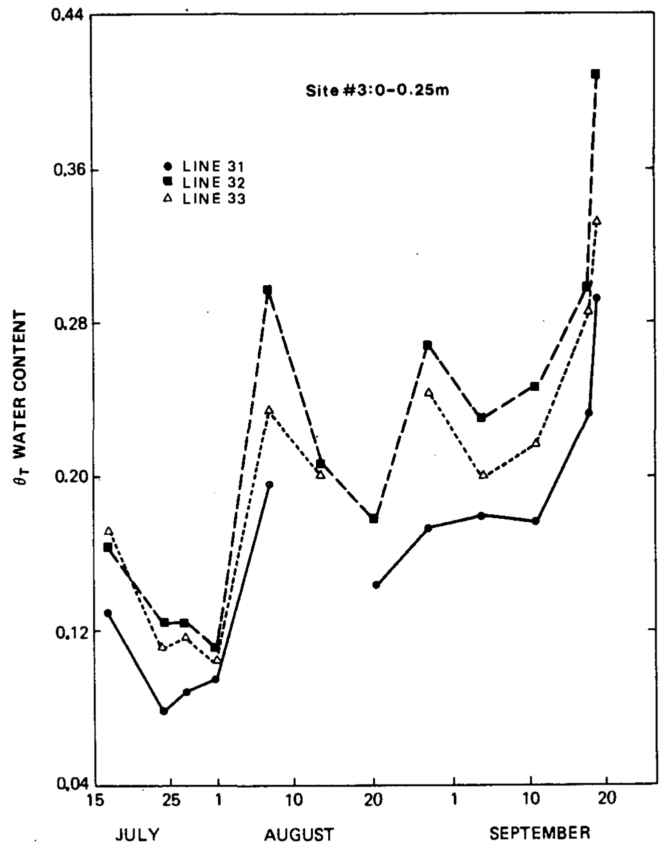

Fig. 8—The TDR measured water content for the upper 0.25 m at site no. 3. The measurements were made repeatedly on three lines from 17 July to 19 Sept.

all of the line types and depth intervals the TDR measured water content values remained parallel in time. This strong correlation within a particular line type and depth indicates that the variance found for any set of measurements did not arise from random sources. This is advantageous when considering changes in water content from one time to another. The errors or deviations associated with the difference is less than the sum of the errors of each measurement. From the analysis of variance necessary to calculate the within class correlation coefficients above, it was possible to determine the standard error of the mean for each line type and depth given in Table 3.

The standard error values are, in general, low, indicating good reproducibility of the TDR measurements. There are, however, some depth, location and

Table 2. Within class correlation coefficients where one class includes the data from one transmission line type and one depth measured during the season.

	Site no. 1				2	3
Depth, m	Horizontal lines	Depth, m	Vertical continuous	Vertical discontinuity	Vertical continuous	Vertical continuous
0.063	0.63	0-0.125	0.60	0.62	0.71	0.87
0.125	0.83	0-0.25	0.94	0.83	0.84	0.93
0.185	0.89	0-0.50	0.93	0.72	0.80	0.91
0.375	0.77	0-0.75	0.93	0.53	0.70	0.85
0.625	0.86	0-1.00	0.85	0.84	--	0.88
0.875	0.81					
1.000	0.51					

Table 3. Standard error of the mean† for each line type and depth interval for the season.

	Site no. 1				2	3
Depth, m	Horizontal lines	Depth, m	Vertical continuous	Vertical discontinuity	Vertical continuous	Vertical continuous
0.063	0.013	0-0.125	0.030	0.034	0.024	0.016
0.125	0.010	0-0.25	0.011	0.014	0.019	0.012
0.185	0.008	0-0.50	0.007	0.014	0.013	0.009
0.375	0.010	0-0.75	0.005	0.013	0.008	0.008
0.625	0.008	0-1.00	0.007	0.007	0.020	0.005
0.875	0.010					
1.000	0.006					

† SE of the mean ($m^3 m^{-3}$).

line type effects which relate to performance of the different lines. The highest standard error values for the shallowest depth probably resulted from the greater variability at or near the surface resulting from the variable spatial distribution of the rain falling through the corn canopy. The horizontal lines (col. 2, Table 3) resulted in the lowest standard errors. At site no. 1 the vertical lines with discontinuities showed the highest standard error compared to the other two types of lines. If one compares the standard errors for continuous lines at the three sites, sites no. 1 and 3 have comparable values but no. 2 has higher values, in general. The higher values at site no. 2 may have resulted from the fact that site no. 2, in a depressional area, was wetter. Measurements are somewhat more difficult in wetter soils because the wetter soil, being more conductive, attenuates more of the signal.

Some Considerations for TDR Installations

The current field study has demonstrated the applicability of the TDR technique to measure field water contents. Equivalent results were obtained using gravimetric sampling or the TDR technique which has the advantage of not disrupting the site after installation of the transmission lines. Although the current study used 12.7-mm diam rods for the vertical transmission lines, we have since found it was unnecessary to use pilot holes for the vertical installations if rods of smaller diameter are used. Accordingly we are now using 3-mm or 6-mm diam, rods in pairs for both the vertical and horizontal transmission lines. The 3-mm diam rods are used for lines up to 0.5 m long and 6-mm diam rods are used for lengths > 0.5 m. We have found that the direct insertion of the transmission lines caused little disturbance to the soil. It is possible to have flexibility in orientation and length of transmission lines so TDR measurements can be tailored to many specific applications.

Lines installed vertically have advantages: easy installation and removal, and measurement of total water within the depth spanned by the line. Horizontally placed lines better integrate or average the spatial variability in the horizontal directions. The major disadvantage of the horizontal lines was the need to dig a pit for installation. The associated interferences on water contents measured near a recently back-filled soil pit were not ascertained in this study.

Although the single vertical line with discontinuities offered as much water content information as five lines of the other two types, there were some difficulties encountered in using these lines in the field. The peaks on the TDR trace (curve 7, Fig. 3) which corresponded to the 0.50- and 0.75-m discontinuities were not always detectable. Attempts to increase these discontinuities resulted in some improvements as portrayed in curve 6 (Fig. 3). Inhomogenieties in the soil sometimes resulted in portions of such curves which could not be interpreted for the 0.5- and 0.75-m depths. In addition, the construction of lines with the discontinuities filled with dielectric material was labor intensive and time-consuming. We are of the opinion that the use of lines with discontinuities requires more research before their potential can be effectively realized in the field.

CONCLUSIONS

The current study has demonstrated that with a battery-powered instrument, the TDR technique is an accurate method for measuring soil water content in the field. The accuracy found was comparable to that of gravimetric samples. In both cases, the limit of accuracy appeared dependent upon the variability of the soil. When both methods used the same soil, as occurred at the end of the season, standard deviations of differences were as low as 0.02 $m^3\ m^{-3}$. When TDR and gravimetric samples measured noncoincident samples, the standard deviation increased to 0.06 $m^3 m^{-3}$. Both horizontally and vertically installed lines gave satisfactory measurements of water content. The horizontally installed lines, measuring over a larger horizontal cross-sectional, area showed less variation than vertical lines. The variety of transmission line configurations which have been evaluated provide considerable flexibility in choice of transmission lines to yield the desired water content information.

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