Aust. J. Soil Res., 1995, **33**, 265–76

Use of Time Domain Reflectometry (TDR) to Measure the Water Content of Sandy Soils

Peter J. Gregory,[A,B] *Roland Poss,*[A,C] *Judy Eastham*[A,D] *and Shayne Micin*[A]

[A] Division of Plant Industry, CSIRO,
Private Bag, P.O.,Wembley, W.A. 6014.
[B] Present address: Department of Soil Science, The University of Reading,
Whiteknights, P.O. Box 233, Reading, RG6 2DW, U.K.
[C] On leave from ORSTOM, UR 2B, 213 Rue La Fayette, 75480,
Paris cedex 10, France.
[D] CRC for Soil and Land Management, Glen Osmond, S.A. 5064.

Abstract

We investigated the potential sources of error when using time domain reflectometry (TDR) to measure the water content of sandy soils and evaluated the technique as a means of measuring evaporation from columns of soil and changes in soil water storage beneath crops. Inaccurate depth location of the transmission lines or the development of a hole at the tip of the transmission lines introduced an error about 10 times larger than the errors associated with hardware and software. Calibration in two sandy soils gave a curve of similar shape to that found by others except for values of dielectric constant <6 when measured values of water content were less than those expected. Daily evaporation from soil columns measured by weighing and with TDR showed large differences between the two techniques (up to 32%) but compensating errors over time allowed cumulative evaporation to be estimated with TDR to within 6·6% of that determined by weighing over a 162 h period. Under field conditions, the agreement between TDR and neutron probe measures of changes in soil water storage in the upper 0·3 m was good and generally within 10% over both 14 day and longer periods.

Keywords: TDR, water content, neutron probe, sandy soils, time domain reflectometry.

Introduction

Since Topp *et al.* (1980) demonstrated that time domain reflectometry (TDR) could be used to determine the volumetric water content of soils, the technique has been applied to many soil physical problems including frozen soils (Stein and Kane 1983), saline soils (Dasberg and Dalton 1985) and unsaturated water flow (Malicki *et al.* 1992). Recent developments in the design of field probes has led to the introduction of multi-wire transmission lines which produce more reliable measurements by reducing unwanted electrical noise and information loss due to impedance and geometry mismatch between the transmission lines and connecting cable (Zegelin *et al.* 1989). Stainless steel rods can be inserted into the soil as transmission lines and left in permanent positions and read, when required, by placement of a detachable head over the ends of the rods.

Many soils in the wheatbelt of Western Australia are sands, especially at the surface, so that TDR is potentially an appropriate means of measuring their water content. However, preliminary observations suggested several practical

0004-9573/95/020265$05.00

problems that required attention before the technique could be used routinely. In particular, when making repeated measurements with a detachable head, it is possible to displace the rods from their true depth in the soil either by pushing them in or lifting them out slightly. This vertical movement of the transmission lines not only altered the length of the transmission line in the soil but also affected the contact between the transmission line and the soil.

Work by several authors has suggested that the empirical relation between water content and dielectric constant found by Topp *et al.* (1980) is applicable to a wide range of mineral soils although a separate calibration is required for organic soils (Roth *et al.* 1992). Zegelin *et al.* (1992) concluded that the 'universal' calibration of Topp *et al.* (1980) worked well in coarser, light textured soils but that at low water contents ($<0\cdot05$ m^3 m^{-3}) there might be systematic departure from the relation because the dielectric constant of individual soil components becomes important. Despite the attractiveness of the technique in terms of the rapidity and reliability of measurements, there have been few comparisons with other methods of measuring soil water content except gravimetrically. Zegelin *et al.* (1992) compared daily changes in stored soil water beneath a wheat crop measured by TDR with those measured in a weighing lysimeter over a 6 day wetting and drying period and a 16 day drying period. In both comparisons, the trends in soil water were similar for both techniques although TDR tended to underestimate losses in absolute terms by about 1·5 mm but with an average deviation of <10%.

The work reported in this paper had three main aims. First, to determine the relative importance of systematic sources of error including calibration and misplacement of the transmission lines. Second, to evaluate the use of TDR over short time periods as a means of measuring evaporation from sandy soils. Finally, to compare estimates of seasonal and periodic changes in stored soil water in the upper 0·3 m of two sandy soils measured with TDR and a neutron probe.

Materials and Methods

Instrumentation

The TDR equipment comprised a Tektronix 1502C Metallic TDR Cable Tester modified to communicate with a DOS portable computer with PYELAB TDR SYSTEM software (CSIRO Aust. 1992). The probes used were the three-wire type described by Zegelin *et al.* (1989) with stainless steel rods 6·35 mm in diameter, length as appropriate, set 50 mm apart; the rods were installed vertically. The software allows control of scanning, scaling and analysis of the trace from the computer keyboard while in the field, and storage of the traces and the resulting measurements. The rods were carefully inserted into the soil using a former to keep them at the correct lateral spacing and a metal block with holes to encase the rods as a driver to ensure they did not penetrate the soil too deeply (Fig. 1). Soil samples of known volume were used to calibrate the transmission lines separately for readings taken at 0–0·1, 0–0·2 and 0–0·3 m.

The neutron probe used was a Campbell Pacific instrument which was calibrated separately for readings taken at 0·1, 0·2 and 0·3 m depth using soil samples of known volume that were dried in an oven.

Sites and Soils

Most of the work reported was conducted at the joint Western Australian Department of Agriculture/CSIRO research annex at East Beverley (32° 08′ S.; 117° 10′ E.). The soil is a shallow, yellow duplex [(Northcote (1979) Dy 2·82; USDA, Typic Natrixeralf)] comprising a layer of sand some 0·3–0·4 m deep overlying deeply weathered kaolinite clay. This paper is concerned only with the sand layer and some physical properties are given in Table 1; further soil properties for deeper profiles are given by Tennant *et al.* (1992). Some work was also undertaken at Trefort's Farm, Narrogin (33° 54′ S.; 117° 13′ E.), on a duplex soil on a site with a slope of about 3%, which forms part of the Malebelling land surface (Mulcahy and Hingston 1961); physical properties of the upper 0·3 m are also given in Table 1.

Table 1. Some physical properties of the soils used

Site	Depth (cm)	Clay <2 μm	Silt 2–53 μm (g kg^{-1})	Sand 53–2000 μm	Bulk density (Mg m^{-3})
East Beverley	0–10	39	38	923	1·57
	10–20	45	37	918	1·75
	20–30	41	32	927	1·73
Narrogin	0–10	117	123	760	1·34
	10–20	118	109	773	1·66
	20–30	152	97	751	1·66

Sources of Error and Calibration

Sources of error were studied at the East Beverley site. The effect of the number of traces averaged to produce the analysed reading was studied using 0·2 m long transmission lines. Ten successive measurements were made at the same spot averaging 1, 2, 4, 8, 16 and 32 traces to produce the analysed reading. The accuracy of the 'standardized' technique of using four traces was also determined by making ten successive measurements at the same place for 0·1, 0·2 and 0·3 m long transmission lines.

The effect of incorrect depth location of the transmission lines was studied by pushing 0·1, 0·2 and 0·3 m long transmission lines into the soil but leaving them 25 mm too proud, then pushing them gently to 20 mm too deep in 5 mm steps; four measurements were made for each depth. Another common practical problem found in sandy soils was that, once the rods were pushed in, they could be drawn up again using the detachable head. This left a small hole underneath the rod and reduced rod/soil contact throughout its length. The influence of this hole was examined by pushing transmission lines 0·1, 0·2 and 0·3 m long up to 20 mm too deep and then pulling them back to their correct position (Fig. 1).

Comparison of TDR and soil water content determined by drying samples of moist soil was undertaken six times (nine sites) at East Beverley and five times (six sites) at Narrogin. On each occasion, three analyses of each TDR reading (each reading is the mean of four traces) were taken at each depth interval (0–0·1, 0–0·2 and 0–0·3 m) and three samples of soil in 0–0·1, 0·1–0·2 and 0·2–0·3 m intervals were collected in stainless steel cylinders 98 mm long and 60·1 mm diameter.

Measurement of Evaporation

Irregularities in the soil surface may prevent uniform contact of the connecting head with the soil surface so that the length of transmission line in the soil is not the same for all rods. Eight undisturbed cores, 0·35 m long and 0·15 m diameter, were collected from East Beverley, by pushing Vaseline-coated, polyvinyl chloride cylinders into wet soil, and brought to the laboratory. Four columns had 0·20 m long rods inserted to 0·2 m depth, while in the remaining four, the rods were installed 10 mm too shallow (i.e. 0·19 m length in the soil). Movement of the rods during the experiment was prevented by sealing small rubber washers to the rods with silicone cement at the soil surface.

To achieve an initial volumetric water content (θ_v) >0·20, 400 cm^3 of water was added to each column after protecting the surface with a filter paper. The columns were sealed at the base and placed in a ventilated, constant temperature room (22·5±0·5°C). The columns were weighed daily on a balance and their water content was determined with TDR. From the second day, four columns (two with rods of correct length, two with rods too short) were placed in front of a fan to increase the evaporative demand while the remaining four were left at some distance. The potential evaporation at the two locations was estimated by weighing three containers of water with dimensions similar to those of the soil columns.

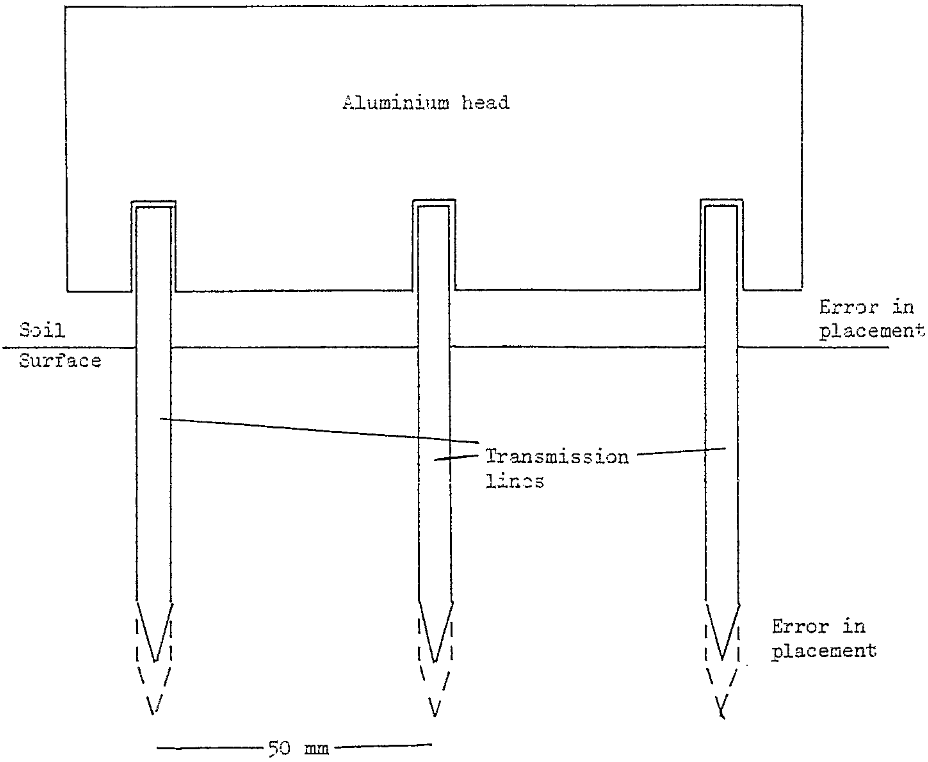

Fig. 1. Diagrammatic representation of the placement and misplacement of transmission lines. The dashed lines indicates the correct placement when the aluminium head would be on the soil surface.

Comparison of TDR and Neutron Probe

The neutron probe has been used widely to determine the changes in soil water storage in profiles, although separate calibrations are necessary near the soil surface because of losses of neutrons to the air. While the spatial resolution of the neutron probe and TDR are different [see de Vries and King (1961) and Bell (1976) for the neutron probe and Zegelin *et al.* (1989, 1992) for TDR], sufficient replication of measurements should ensure that both techniques produce similar estimates of changes in water storage. Measurements of soil water content with both TDR and neutron probe were made at about 14 day intervals during the growth of early- and late-sown lupin and wheat crops at East Beverley in 1991. Each crop was replicated six times and each plot contained a neutron probe access tube and TDR transmission lines 0·1, 0·2 and 0·3 m long sited within 1·5 m of the access tubes. Neutron probe readings were taken at 0·1, 0·2 and 0·3 m, and the separate calibrations were applied to determine the water content at each depth. In calculating the water balance of the surface 0·3 m, the readings at 0·1, 0·2 and 0·3 m were assumed to correspond to the depth intervals 0–0·15, 0·15–0·25 and 0·25–0·30 m.

At Narrogin, a barley crop was grown in 1991 and soil water content was measured at about 14 day intervals at ten locations over a 100 m transect by using the neutron probe, and at three locations (top, middle and bottom of the transect) by using the TDR with transmission lines 0·1, 0·2 and 0·3 m long.

Results

Sources of Error and Calibration

Three sources of error are involved in TDR measurement of water content: the instrument error, the placement of the transmission lines in the soil, and the choice of the appropriate calibration curve. The number of traces averaged to produce the reading that was analysed had little effect on the accuracy of the measurement except if only one trace was used. For a soil with θ_v of $0 \cdot 099\ m^3\ m^{-3}$, the standard deviation of the measurement decreased from $0 \cdot 0020\ m^3\ m^{-3}$ for one trace to 0·0011 for two and four traces, to 0·0010 for eight traces, and to 0·0008 for sixteen and thirty-two traces. In all subsequent studies, four traces were used as the standard measurement procedure.

The standard deviation of the water content determinations (including the deviation due to the electronics and software) was $<0 \cdot 0021\ m^3\ m^{-3}$ for all three lengths of rod studied. At the 95% level of probability, the error involved in a single determination was $<0 \cdot 0044\ m^3\ m^{-3}$; this result is in agreement with other estimates (CSIRO Aust. 1992).

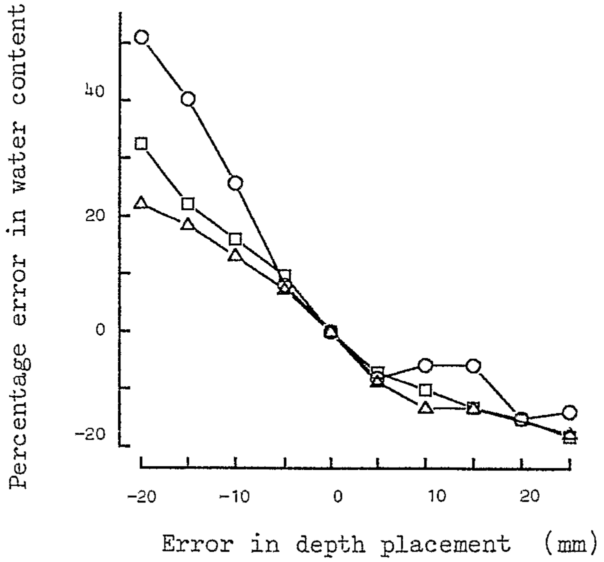

Fig. 2. The relative error in water content resulting from an error in the depth of placement of the transmission lines; positive values of depth are lines placed too shallow (○, 0·10 m lines; □, 0·20 m lines, △, 0·30 m lines). The values of water content with transmission lines at the correct depth were 0·086 for 0–0·1 m, 0·099 for 0–0·2 m, and 0·113 for 0–0·3 m.

Fig. 2 shows the effect of misplacement of transmission lines on the estimate of water content. Water contents were overestimated when transmission lines were too deep and underestimated when they were too shallow. As expected, rods that were too deep had a greater influence on measured water content than those that were too shallow because of the marked difference in dielectric constant between air and soil. When transmission lines were pushed in too deep, an error in depth location of only 5 mm produced an error in water content of about 10% equivalent to almost 0·01 m^3 m^{-3}. When the error in the depth of placement was >5 mm, the error in water content was consistently largest for 0·1 m and smallest for 0·3 m transmission lines. This was because the error was a greater proportion of the length of the shorter transmission lines.

Table 2. The effect of a cavity at the tip of the TDR transmission lines on the measured water content

The results are the water content (m^3 m^{-3}) relative to the water content in the absence of a cavity

Length of transmission lines (m)	Length of cavity (mm) 5	10	15	20
0·10	−0·004	−0·011	−0·012	−0·011
0·20	−0·010	−0·014	−0·012	−0·016
0·30	−0·005	−0·011	−0·010	−0·010

The presence of a cavity in the soil at the tip of the rods (induced by withdrawing the rods from the soil) resulted in a reduced estimate of the water content (Table 2). The error in water content increased with the length of hole up to 10 mm and remained almost constant thereafter. The reduced estimate of water content may have arisen because of both field lines extending beyond the tip of the probe into the air gap (although this effect has not been documented in other literature) and the annular gap around the tapered ends of the transmission lines together with any disturbance caused during movement of the transmission lines [see Baker and Lascano (1989) and Knight (1992) for details of the radial sensitivity of TDR].

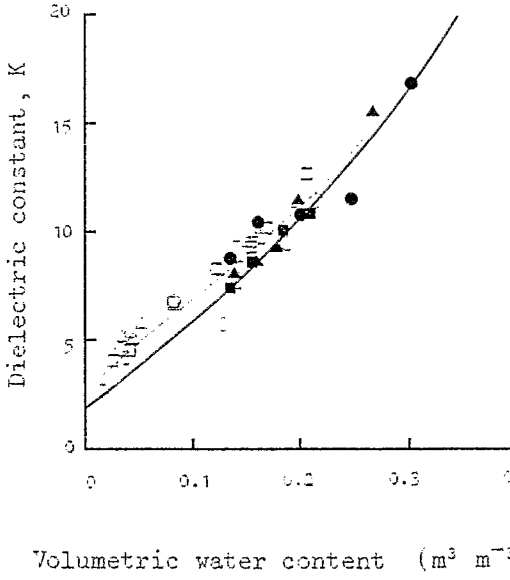

Fig. 3. The relationship between measured dielectric constant (K) and volumetric water content for 0–0·10 m (circles), 0–0·20 m (squares) and 0–0·30 m (triangles) at East Beverley (open symbols) and Narrogin (closed symbols). The solid line is equation (1) and the dashed line is the best fit to the data (equation 2).

The overall shape of the calibration (Fig. 3) agreed with the empirical, third-order polynomial proposed by Topp *et al.* (1980):

$$\theta_V = (-5{\cdot}3 \times 10^{-2}) + (2{\cdot}92 \times 10^{-2}K) - (5{\cdot}5 \times 10^{-4}K^2) + (4{\cdot}3 \times 10^{-6}K^3), \quad (1)$$

where θ_V is the volumetric water content and K is the apparent dielectric constant. The equation that best fitted the data was

$$\theta_V = (-5{\cdot}44 \times 10^{-2}) + (1{\cdot}79 \times 10^{-2}K) + (9{\cdot}96 \times 10^{-4}K^2) - (4{\cdot}97 \times 10^{-5}K^3). \quad (2)$$

Use of the 'universal' calibration of Topp *et al.* (1980) consistently overestimated θ_V by about 0·02, particularly at water contents $<0{\cdot}1\ \mathrm{m^3\ m^{-3}}$. Although equation (2) is necessary to determine the absolute values of θ_V, where changes in stored soil water are required, equation (1) produces acceptable estimates. For example, change in K from 10·00 to 5·00 (the range of most interest on these sandy soils) equates to a change in θ_V of $0{\cdot}109\ \mathrm{m^3\ m^{-3}}$ using equation (1) and $0{\cdot}113\ \mathrm{m^3\ m^{-3}}$ using equation (2).

Measurement of Evaporation

Over the first 25 h, the TDR overestimated the rate of evaporation, as compared with weighing, by $0{\cdot}027\ \mathrm{mm\ h^{-1}}$ with transmission lines installed to the correct depth, and by $0{\cdot}034\ \mathrm{mm\ h^{-1}}$ when transmission lines were 10 mm too shallow (Table 3). Thereafter, the rates of evaporation measured by both techniques were similar and the cumulative evaporation measured was similar until about 114·5 h. As the study continued, the TDR progressively underestimated evaporation, presumably because of upward movement from the soil below 0·2 m, beyond the depth of the transmission lines.

Evaporation exhibited three distinct stages as found by several workers. Both techniques demonstrated linear relations between cumulative evaporation and the square root of time for a prolonged period (between about 2 and 9 days). The bulk soil water content at which evaporation changed from first to second stage was between 0·16 and $0{\cdot}18\ \mathrm{m^3\ m^{-3}}$, irrespective of the potential evaporative demand which ranged from 3·2 to $6{\cdot}6\ \mathrm{mm\ day^{-1}}$ for the high rate and 1·7 to $3{\cdot}6\ \mathrm{mm\ day^{-1}}$ for the low rate (Fig. 4).

Table 3. The rate of evaporation ($\mathrm{mm\ h^{-1}}$) from columns of soil measured with a balance and with TDR transmission lines inserted *0·20* or *0·19 m* into the soil

Time (h)	Balance	TDR: 0·20 m	Balance	TDR: 0·19 m
0–25	0·082	0·109	0·090	0·124
25–51	0·093	0·103	0·082	0·052
51–72	0·123	0·122	0·107	0·114
72–87·5	0·156	0·135	0·127	0·110
87·5–114·5	0·093	0·066	0·074	0·049
114·5–137	0·103	0·083	0·092	0·062
137–162	0·083	0·063	0·072	0·048
162–185·8	0·078	0·057	0·069	0·045
185·8–213·8	0·057	0·052	0·049	0·041

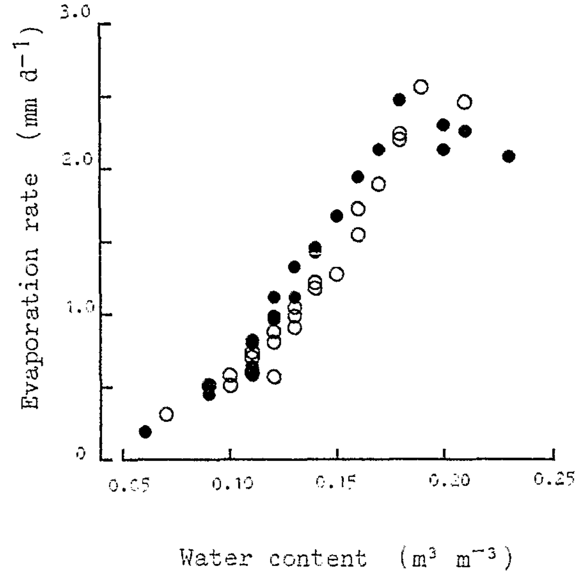

Fig. 4. Relation between the rate of evaporation determined by TDR and water content of the bulk soil at high (○) and low (●) rates of potential evaporation.

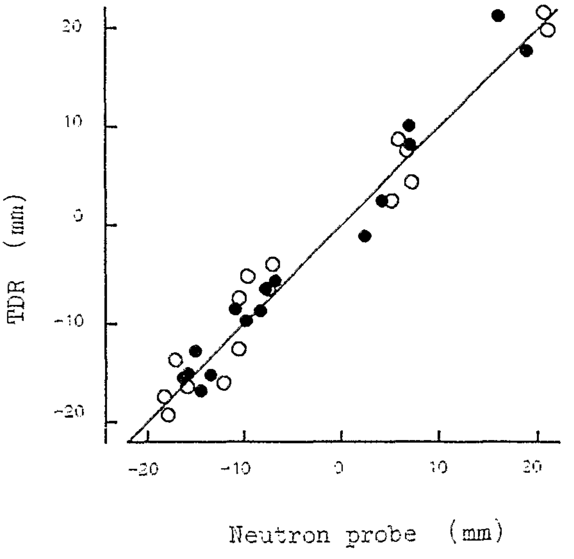

Fig. 5. Comparison of changes in stored soil water measured with TDR and neutron probe for crops of lupin (○) and wheat (●) at East Beverley. The line shown is the 1:1 line; regression $y = 0 \cdot 999x + 0 \cdot 429$, $r^2 = 0 \cdot 963$.

Comparison of TDR and Neutron Probe

Fig. 5 compares changes in stored soil water in the upper 0·3 m by using TDR (equation 1) and the neutron probe beneath four crops grown at East Beverley. The agreement between the two techniques is good for periods of both depletion and accretion (slope = 0·999; $r^2 = 0 \cdot 96$). When considered over the whole growing season, the agreement between the two techniques was generally within 10% except for the early-sown wheat crop (Table 4). During the period when the profile was drying (30 July to 8 October), the agreement between the estimates was extremely good (average within 5·5%), although there was a consistent tendency for the TDR to underestimate the depletion compared with the neutron probe by between 1·4 and 6·6 mm depending on the crop.

At Narrogin, the soil water balance measured by both techniques was in close agreement for the months of July, August and September, recording a total loss of water for the period of 0·5 mm by neutron probe and 2·3 mm by TDR. Similarly, for the period from the wettest profile (25 July) until 24 September, the depletion of water recorded by both techniques was close at 22·2 mm for the neutron probe and 26·5 mm by TDR.

Table 4. Comparison of the seasonal depletion, and depletion of soil water during the drying period estimated for 0–0·30 m soil depth by TDR and neutron probe techniques

The estimates (in mm) were obtained beneath four crops grown at East Beverley, Western Australia

Technique	Early-sown lupin	Late-sown lupin	Early-sown wheat	Late-sown wheat
	Seasonal: 18 June–19 November			
TDR	20·2	25·6	20·0	26·4
Neutron probe	23·2	23·4	30·0	28·1
	Drying period: 30 July–8 October			
TDR	58·2	60·2	56·9	57·6
Neutron probe	64·8	62·8	60·1	59·0

Table 5. Estimation of the errors in water content using TDR measurements

Source of error	Error (m^3 m^{-3})
Electronics and software	±0·0022
Transmission lines too shallow (10 mm)	−0·010
Transmission lines too deep (10 mm)	+0·016
Cavity at tip (10 mm)	−0·012

Discussion

The magnitude of the errors associated with water contents determined by TDR is summarized in Table 5. The errors introduced by averaging traces and electronics and software were similar in value to those described by CSIRO Aust. (1992) and about 10 times smaller than those introduced by inaccurate location of the transmission lines or the development of a hole at their tip. The relative importance of the measured errors agrees with that estimated by calculation. The apparent dielectric constant of the soil (K) can be estimated from the individual dielectric constants of the three soil components (mineral particles K_m, water K_w and air K_a) using a mixing model (Tinga *et al.* 1973):

$$K^{\alpha} = (1-f)K_{\mathrm{m}}^{\alpha} + \theta_{\mathrm{v}} K_{\mathrm{w}}^{\alpha} + (f-\theta_{\mathrm{v}}) K_{\mathrm{a}}^{\alpha}\,, \tag{3}$$

where f is the soil porosity and α is a constant whose value has been demonstrated to depend on the spatial arrangement of the soil components and the orientation of the mixture in the imposed field. For a homogeneous mixture with equally weighted dielectric constants, it has been demonstrated theoretically (Whalley 1993) that α has a value of 0·5. Roth *et al.* (1990) found a best fit of 0·46 for a range of soils, although bound water may change this value substantially. By assuming values of 5, 80 and 1 for K_m, K_w and K_a respectively, then K for a soil with a bulk density of 1·6 Mg m^{-3} and θ_v of 0·15 (properties similar to the soils used in this study) is 8·58. The effect of pushing in the transmission lines too deeply can be calculated using the equation

$$K = (ct/2L)^2 , \tag{4}$$

where c is the velocity of light in a vacuum (3×10^8 m s^{-1}), t is the travel time of the step pulse, and L is the length of the transmission line. If transmission lines were 0·21 m instead of the correct 0·2 m, K would be 9·47 (i.e. 10·3% greater than the true value). For transmission lines 0·2 m long incorrectly located with only 0·19 m in the soil, there is a homogeneous soil layer 0·19 m thick ($K = 8{\cdot}58$) and a layer of air of length 0·01 m ($K_a = 1$). The measured K would then be 8·36 (i.e. 2·6% smaller than the true value). Thus, as shown in Fig. 2, when rods are located too deeply a greater error is introduced compared with a location which is too shallow.

To leave the head attached to the transmission lines is rarely an option in field studies, both because of the cost and because the large block of metal may influence evaporation from the soil surface. In practical terms, if repeated measurements are required at the same location and the replacement of the head results in the transmission lines being pushed into the soil, then the water content measured will be an overestimate of the true value. This error may be reduced by pulling the transmission lines out to their true position, but this will cause a hole at the tip and an annular gap around the line, resulting in substantial errors (Whalley 1993). Thus it appears best in such circumstances to allow the transmission lines to remain too deep and to correct for the increased length of line rather than attempt to pull them out. Alternatively, for long-term studies, the use of a two-wire probe should be considered because this obviates the need for a connecting head and the transmission wires can be left undisturbed.

The measured calibration was similar in form to that determined by Topp *et al.* (1980) and Roth *et al.* (1992). Zegelin *et al.* (1989) determined that the calibration for a fine sand agreed well with the equation of Topp *et al.* except for values of θ_v <0·05 m^3 m^{-3} when measured values of K exceeded those expected. Our calibration, which at low values of θ_v was dominated by values from the dense sandy soil at East Beverley, suggests that K may differ between soils so that for accurate measurements of θ_v a separate calibration is required. However, we concur with the conclusion of Zegelin *et al.* (1992) that, for the estimation of a change in water content, the use of the calibration derived by Topp *et al.* (1980), even at low values of θ_v, will introduce only a small error (3·7% as K changes from 10·00 to 5·00). Whalley (1993) suggested that use of the refractive index ($K^{0\cdot5}$) is preferable to the use of K for calibration purposes. A plot of $K^{0\cdot5}$ against θ_v gave an intercept of 1·882, a slope of 7·255, and a regression coefficient of 0·96. Whalley (1993) hypothesized that the slope should be 7·94 if soil water has the same refractive index as free water; his soils had values that were all slightly greater than this.

Zegelin *et al.* (1992) concluded that TDR gave changes in stored soil water to an accuracy of about 10% for daily measurements. Our results under laboratory conditions showed greater variation than this over individual 24 h periods (up to 32%), but compensating errors over time allowed cumulative evaporation to be estimated to within 6·6% over a 162 h period. A partial explanation for the discrepancy, particularly in the later measurements, is that depletion of water may have occurred beneath the 0·2 m transmission lines; in Zegelin's study the transmission lines traversed the full profile. A feature of evaporation from this soil was that it proceeded at a substantial rate even after the formation of a dry surface. Like many sandy soils in Western Australia, this soil is hard-setting (Mullins *et al.* 1990) and a consequence of this behaviour is that hydraulic continuity is maintained as drying proceeds so that evaporative losses are not restricted to a shallow surface layer.

Under field conditions, the agreement between TDR and neutron probe estimates of changes in soil water storage was generally within 10% over both 14 day and longer periods. The much smaller volume of soil contributing to the measurement of water content by TDR had no deleterious effects on the estimation of changes in soil water storage when compared with the neutron probe. Given the more rapid times of measurement and the ability to use a single calibration for most mineral soils (Roth *et al.* 1992), TDR has advantages over the neutron probe technique for assessing seasonal changes in soil water storage.

Conclusions

Errors from instrumentation were small compared with those introduced by inaccurate location of transmission lines. On sandy soils where the repeated use of detachable heads may lead to misplacement of the transmission lines, it appears best to correct for the increased length of line rather than pull them out to their true location.

On the two soils studied, the measured calibration was similar to that determined by Topp *et al.* (1980) except for values of $\theta_v < 0 \cdot 05$ when measured values of K exceeded those expected. Despite the different volumes of soil sampled by the neutron probe and TDR techniques, estimates of changes in soil water storage were generally within 10% over both 14-day and longer periods of up to 5 months. We conclude that with careful placement and management of the transmission lines, TDR is an appropriate technique for assessing changes in soil water storage on these sandy soils.

Acknowledgments

We are grateful to the Grains Research and Development Corporation of Western Australia (formerly the Wheat Research Committee) for financial support for this research. We thank Dr D. Tennant (W.A. Department of Agriculture) for unpublished results of neutron probe readings at Narrogin, and Mr S. J. Zegelin and Dr K. R. J. Smettem for improvements to an earlier draft.

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Manuscript received 28 July 1994, accepted 21 October 1994