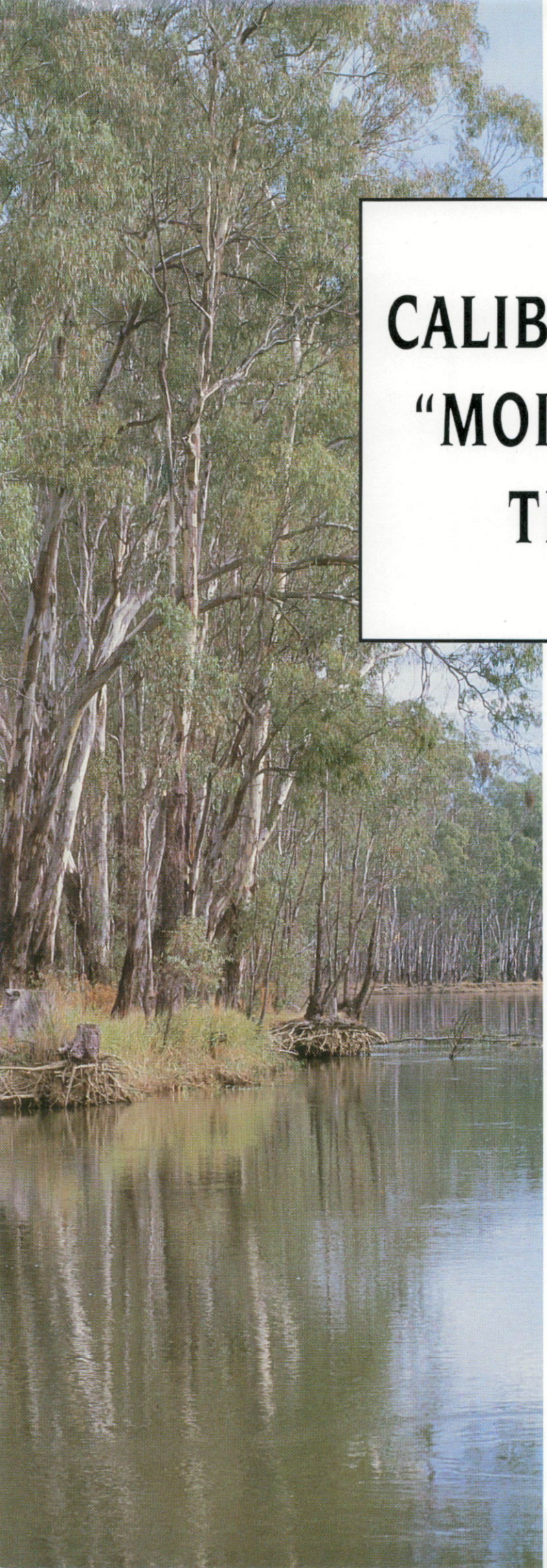


CALIBRATION OF THE "MOISTURE POINT" TDR SYSTEM

S. Dasberg
H. Alksnis
P. Daniel
J. D. Kalma
S. J. Zegelin

Report 95/4
June 1995

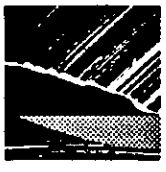
COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

CALIBRATION OF THE "MOISTURE POINT" TDR SYSTEM

S Dasberg
H Alksnis
P Daniel
J D Kalma
S J Zegelin

Report 95/4

June 1995



COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Dasberg, S (Sam) 1930 -
Calibration of the 'Moisture Point' TDR System

Bibliography.
ISBN 1 876006 02 1.

1. Time-domain reflectometry. 2. Soil moisture - Measurement.
3. Moisture meters - Calibration. I. Dasberg, Sam, 1930- .
II. Cooperative Research Centre for Catchment Hydrology.
(Series: Report (Cooperative Research Centre for Catchment Hydrology); 95/4)

631.432

Keywords

Soil/Water Systems
Time Domain Reflectometry
Probes
Water Content
Calibration
Soil (Types of)
Field Studies

ISSN 1039-7361

Preface

The material in this report is a contribution to one of the core research projects in the Cooperative Research Centre for Catchment Hydrology (CRCCH), entitled "Development and evaluation of predictive tools for water production in natural, disturbed and managed forests".

The project aims to synthesise our knowledge of forest water balance, to generate key experimental information on the factors that determine how water, soils, trees and landscapes interact. An important facet of this work is to study water movement in the forest soils; this requires that we use soil moisture measurement equipment.

The study described in this report was carried out by Dr Sam Dasberg of the Institute of Soils and Water in Israel while he was a visiting scientist at the Canberra laboratory CSIRO Division of Water Resources. Dr Dasberg's visit was funded jointly by CSIRO and the CRCCH.

This report summarises results of a calibration and testing program for the commercially-available "Moisture Point" Time Domain Reflectrometry system. It has been an important part of the CRCCH's experimental program as the device will be relied upon to yield estimates of soil moisture status across a range of different soil environments.

Dr Rob Vertessy
Deputy Director
Cooperative Research Centre for Catchment Hydrology

Abstract

The "Moisture Point" Time Domain Reflectrometry (TDR) system (manufactured by Environmental Sensors, Gabel Company) has several attractive features. These include the possibility to measure distinct layers of a soil profile by remotely switched shorting diodes, and low attenuation of the signal and retrievability of the probe. Measurements were carried out with this instrument in several soils at different water contents, both in the laboratory and in the field. These measurements were compared with the conventional three-rod TDR probes, with volumetric samples, and with neutron method measurements.

These calibrations have shown that the cylinder of measurement along the segment of the probe has a small diameter (less than 1 cm). In the laboratory, with uniformly mixed soil material, a linear relationship was obtained between the travel time of the signal and volumetric water content, with a high coefficient of determination ($r^2 = 0.98$). However, field measurements with the "Moisture Point" showed only an approximate relation to the data obtained from samples, and measurements with the neutron probe and three-rod probe. We believe that this poor relationship is due to the small sphere of influence of the TDR measurements and the great spatial variability that exists in field soil water content.

Acknowledgements

The senior author expresses his sincere thanks to the CSIRO Division of Water Resources and the CRC for Catchment Hydrology for financial support for his sabbatical stay in Canberra and for providing equipment for this investigation. Special thanks are due to Dr Rob Vertessy, who initiated and supported this study.

Author Affiliations

S. Dasberg

Institute of Soils and Water, Volcani Center, ARO, Bet Dagan, Israel

H. Alksnis

CSIRO Division of Water Resources, Canberra

P. Daniel

CSIRO Division of Water Resources, Canberra

J.D. Kalma

Department of Civil Engineering and Surveying, University of Newcastle

S.J. Zegelin

CSIRO Centre for Environmental Mechanics, Canberra

Contents

List of Figures

List of Tables

1. INTRODUCTION

Time Domain Reflectrometry (TDR) for the measurement of soil water content has come of age. It has been known that the dielectric properties of soil are dominated by its water content (θ). Water has a high dielectric constant (80 in the frequency range below 1 GHz) as compared to soil material. Topp et al. (1980) were the first to use TDR to measure the apparent dielectric constant (K_a) of soils. It is based on the measurement of the travel time (t) of an electromagnetic pulse in a transmission line or probe of length L according to

$$K_a = (ct/2L)^2 \qquad (1)$$

where c is the velocity of light. Topp et al., (1980) were able to show that the empirical $K_a(\theta)$ relationship

$$K_a = 3.03 + 9.3\,\theta + 146\,\theta^2 - 76.7\,\theta^3 \qquad (2)$$

is nearly independent of soil type, density, texture, temperature or salinity. This universal relationship has been applied successfully by other investigators, as for example Dalton and van Genuchten (1986), Zegelin et al. (1992), Heimovaara and Bouten (1990). Some exceptions to Equation (2) have been reported, however. Notably, the dielectric constant of ice is similar to that of the soils solid phase ($K_a = 3.2$) and this technique can therefore be used to determine the unfrozen water content of frozen soils (Patterson and Smith, 1981). Soils with high organic matter content show lower K_a than obtained by Equation (2) (Herkelrath et al., 1991). A similar effect was found in soils with high clay content by several investigators (Dasberg and Hopmans, 1991; Smith and Tice, 1988; Dirksen and Dasberg, 1993). This effect of soil texture has been known for some time in the remote sensing literature in the frequency range of 1-5 GHz (Dobson et al., 1985). A possible reason for this deviation from the universal relationship of Equation (2) could be that not all of the water in the soil behaves like free water, but some of the water is tightly bound to colloidal surfaces and its dielectric property is more like ice than like liquid water. This idea can be expressed as a four-component mixing model, containing soil (s), air (g), free water (fw) and bound water (bw), according to Birchak et al. (1974):

$$K_a^{\alpha} = (1-\varnothing)\,K_s^{\alpha} + (\varnothing - \theta)\,K_g^{\alpha} + (\varnothing - \theta_{bw})\,K_{fw}^{\alpha} + \theta_{bw}K_{bw}^{\alpha} \qquad (3)$$

where Ø stands for porosity and α, is a curve fitting parameter. The exponent α was found by several investigators to be close to the value α=0.5 (Roth et al., 1990; Dobson et al., 1985; Heimovaara, 1993; Dasberg and Hopmans, 1992; Dirksen and Dasberg, 1993).

TDR thus seems an attractive method for soil water content measurement. It is non-destructive, a universal calibration curve is valid for many soils, there is no radiation hazard and the measurements can be recorded and multiplexed. The main disadvantage is that, in order to measure water content changes in a soil profile, the probes have to be buried at the relevant depths for each soil layer. Another disadvantage is that, in saline soil, the signal is attenuated completely and no measurements are possible (at $Ec_e > 5$ **dSm**$^{-1}$ approximately, depending on probe geometry). The high price of the measuring equipment is also a disadvantage of the current TDR technique.

Recently, a new TDR instrument has come to the market (Moisture Point from Environmental Sensors) which has several attractive features:

1. The possibility to measure (θ) in distinct layers of a soil profile by remotely switched shorting diodes, placed at known distances along the probe.
2. The probe is retrievable and can be repeatedly inserted into the soil.
3. The effect of attenuation of the signal by salinity and by long cables is reduced by the use of diodes.
4. The price of the equipment, if used as a routine monitoring device, is much lower than traditional TDR equipment. It consists of probes with several segments and a measuring instrument which displays volumetric water contents.

These features of the "Moisture Point" (MP) equipment seem very attractive for use in soil water measurements. The ideas on which the design of this instrument are based were published by Hook et al. (1992). However, some aspects need to be investigated before extensive field use of the equipment can be recommended.

1. The instrument should be calibrated in the laboratory with at least two different soil types and compared with the "conventional" three-rod probe equipment (TRP) as well as with other methods of soil water determination (volumetric sampling, neutron probe).

2. The sphere of influence of the MP probe should be established. Since the distance between the two probe electrodes is small (1.9 cm), the sphere of influence should also be quite small (Knight, 1992).

3. The compaction of the soil caused by the insertion of the probe could cause problems. Several authors have shown the great sensitivity of the TDR method to soil bulk density (Dirksen and Dasberg, 1993, Zegelin et al, 1992).

The purpose of this investigation is:

1. To calibrate the MP instrument

2. To compare the MP with the TRP instrument and other measurements

3. To establish the volume of measurement

4. To evaluate the performance of the MP equipment in the field.

2. CHARACTERISTICS OF THE MP PROBE

An MP probe consists of two stainless steel bars, with diode connections every 15 cm, a coaxial cable for the transmission of the electromagnetic pulse, and a cable connecting the diodes to a switch box. This is all embedded in epoxy between the two steel bars. The signals reflected from the segments were measured by a cable tester (Tektronix 1502B) and not by the measuring instrument provided by the manufacturer (Environmental Sensors). The travel time of the electromagnetic pulse generated in the cable tester to a certain point along the probe can be measured by activating a specific diode on the probe. The travel time of the pulse along a segment of the probe can be measured by subtracting the travel times to the beginning and the end of this segment.

It has been shown that there exists a linear relationship between the volumetric water content of the soil and the travel time as measured by TDR (Whalley, 1993), based on both theoretical and experimental findings. However, the travel time measured along a segment of the MP probe is not only based on the water content of the soil in which it is embedded, but also on the epoxy material between the electrodes and the wiring contained in this material. Therefore, the measured travel time (T_m) has to be converted into the corrected travel time (T_c), which is a measure of the soil water content by

$$T_c = \frac{T_m}{B} - \frac{A}{B} \qquad (4)$$

(see Hook et al., 1992). Each segment has distinct calibration coefficients **A** and **B** because of the non-uniformity of the epoxy and the wiring. This calibration can be achieved by measuring travel time in materials of known relative dielectric constant, for example water (K_a = 80.4 at 20°C) and air (K_a = 1).

3. EXPERIMENTAL PROCEDURES

1. The calibration coefficients **A** and **B** of each segment were calculated from measurements of the travel time along each segment in air and in water. For the measurements in water, the probes were immersed in a water column of 24 cm diameter. **A** and **B** were calculated for each segment using Equation (4) while the travel times in water and air were the theoretical values at the temperature of measurement.

2. The volume of measurement in water was determined by measuring travel times along each segment of these probes immersed in water in PVC cylinders of 24, 15, 10, 7.5, 6.2, 5, 4.2 and 2.8 cm diameter, respectively.

   Measurements in air were carried out while the probes were suspended in air, and in cylinders of 4 cm and 2.8 cm diameter, surrounded with water in a 24 cm diameter cylinder.

3. Laboratory calibration in soil with changing water content was carried out using Bungendore sand (Zegelin et al., 1992). The soil was gradually wetted by thorough mixing with small amounts of water in the range from air dry to saturation. At each wetness, the soil was packed in containers of different diameter (24, 15, 10 and 6 cm) and travel times along one segment of each probe were determined. In the 24 and 15 cm containers, measurements with the TRP probes were carried out using the Pye lab software developed in CSIRO Centre for Environmental Mechanics. Volumetric water content was determined at each wetness using 209 cm^3 sampling rings.

4. A similar calibration was carried out using Bungendore sand mixed with 4% by weight of graphite, in 24 cm cylinders only.

5. Field evaluation of the method was carried out in the Lockyersleigh catchment at three sites, utilising neutron moisture meter (NMM) access tubes inserted and calibrated eight years ago (Alksnis et al., 1990). A 70 cm diameter ring of galvanized iron was placed around the NMM tube and measurements were taken with the neutron probe and with the MP probe at three stages: dry; after saturation with water to a depth of 1 m approximately; and after redistribution of 20-24 hrs. In the last stage, volumetric samples were taken at four depths (5-10, 20-25, 35-40 and 50-55

cm) using 209 cm^3 sampling rings. Unfortunately, measurements with the TRP probes could not be carried out on this occasion because of equipment failure.

Another field calibration was carried out at one of the previous sites, using TRP probes buried and inserted horizontally at depths of 5, 20, 35, 50 and 65 cm. Samples were collected both at the dry stage and after redistribution of soil water.

Finally, another laboratory calibration was carried out using soil material from the Lockyersleigh site.

4. RESULTS

Table 1 shows the calibration coefficients of each segment in four different MP probes, calculated from travel time determinations in air and in water. One should note the large differences between the segments caused by the heterogeneity of the epoxy material. These coefficients are built into the software supplied by the manufacturer. However, the coefficients provided by the manufacturer were different from those we obtained.

The approximate cylinder of influence around each segment can be deduced from the data in Tables 2 and 3. With readings in water, an almost 10% reduction in travel time was obtained at a diameter of 4 cm, whereas at 2.8 cm a 25% reduction occurred. However, when the readings were taken in air, the effect of surrounding water was only measurable at a diameter of 2.8 cm. One should take into account the wall thickness of the PVC cylinder (approximately 2 mm), the dielectric constant of which is more similar to air than to water. It therefore seems that the maximum radius of influence does not exceed 2 cm. Taking into account the dimensions of the probe itself (1.3 x 1.9 cm), one can safely assume that the cylinder of measurement around the probe has an approximate radius of 1 cm.

Table 1. Measured corrected travel times in air and in water at 20°C in all probe segments and calculated coefficients **A** and **B**.

Probe	Segment	Measured travel times (n sec)		Calculated coefficients	
		air	water	A	B
78DDC4	1	1.502	6.427	1.436	0.6167
	2	1.253	6.208	1.019	0.6205
	3	1.448	6.773	1.171	0.6669
	4	1.455	6.497	1.304	0.6314
$927D_{qg}$	1	1.468	6.460	1.348	0.6252
	2	1.300	6.092	1.167	0.6001
	3	1.461	6.494	1.318	0.6303
	4	1.421	6.500	1.234	0.6361
$78E_{249}$	1	1.380	6.399	1.196	0.6285
	2	1.636	6.490	1.692	0.6076
	3	1.327	6.458	1.065	0.6426
	4	1.522	6.953	1.238	0.6801
	5	1.468	6.617	1.277	0.6448

Table 2. Effect of diameter of water cylinder on relative travel time (24cm = 1.0) Data shown are averages of all segments of each probe.

Diameter (cm)	24	15	10	7.5	6.2	5	4.2	2.8
Probe								
$28E_{249}$	1.00	1.01	1.01	1.01	1.01	.96	.92	.77
$927D_{92}$	1.00	.98	1.00	.98	1.00	.94	.89	.75
78DDC4	1.00	.98	1.01	.97	.97	.94	.88	.74

Table 3. Effect of diameter of air cylinder on relative travel time (travel time in free air =1.0).

Probe	Segment	Reading in free air	4.2cm	2.8cm
$28\ E_{249}$	1	1.00	.97	1.01
	2	1.00	.92	1.04
	3	1.00	1.06	1.14
	4	1.00	1.04	1.10
	5	1.00	.99	1.09
$927D_{q2}$	1	1.00	1.00	1.04
	2	1.00	.94	1.03
	3	1.00	.95	1.10
	4	1.00	1.04	1.16
$28DDC_4$	1	1.00	1.06	.98
	2	1.00	1.00	1.10
	3	1.00	1.03	1.10
	4	1.00	1.02	1.12
Average		1.00	1.00	1.08

The results of the calibration experiments with Bungendore sand are shown in Figure 1. These data show that the TRP measurements in sand without graphite coincide with the previously published relationship (White et al., 1994). The points for 4% graphite do not fall on the published line. This could be due to the fact that it is difficult to mix the very fine powdered graphite with the dry sand and the added percentage is therefore not identical in both cases. However, the data for the (MP) can not be described by the same relation as for the TRP. The θ travel time relations are linear and calibration of the device seems feasible. The introduction of the calibration coefficients **A** and **B** (see Table 1) should have converted the travel times to values comparable to those obtained with the TRP and equivalent to $\sqrt{\mathbf{K}_a}$ ($\mathbf{K}_a$ is the apparent dielectric constant). The consistently

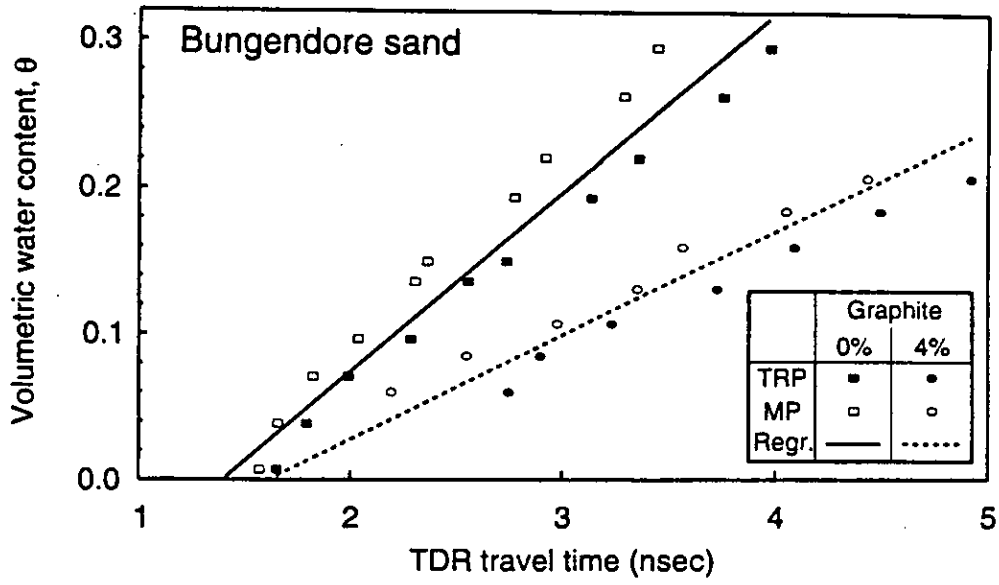


Figure 1. The relation between volumetric water content (θ) and travel time (nsec) for Bungendore sand, measured with MP and TRP as compared to the published data (White et al., 1994).

higher values obtained by the MP relative to the TRP from the same water contents and from the same soil samples can partly be explained by the effect of the epoxy between the electrodes in this device.

The results of the first field experiment at Lockyersleigh are shown in Figure 2. At the dry stage, there seems to be a reasonable correspondence between the NMM data and the MP data. The travel times along each segment of the MP probes were converted to θ using the calibration obtained in the laboratory for Bungendore sand. At saturation, the readings obtained with the MP were sometimes higher than the total pore space and are not presented. At the drained stage, after redistribution of the water, the MP estimates of θ at site C12b corresponded with the neutron data, whereas at the other sites the values were much too high. On the other hand, the duplicate volumetric soil samples gave values of θ similar to the NMM data. We thought that, since the MP rods were inserted at the dry stage after first making a hole with the dummy rod, a preferential pathway was created which caused accumulation of water close to the probes during the flooding of the sites. This could explain the very high water contents measured with the MP during saturation and also after redistribution.

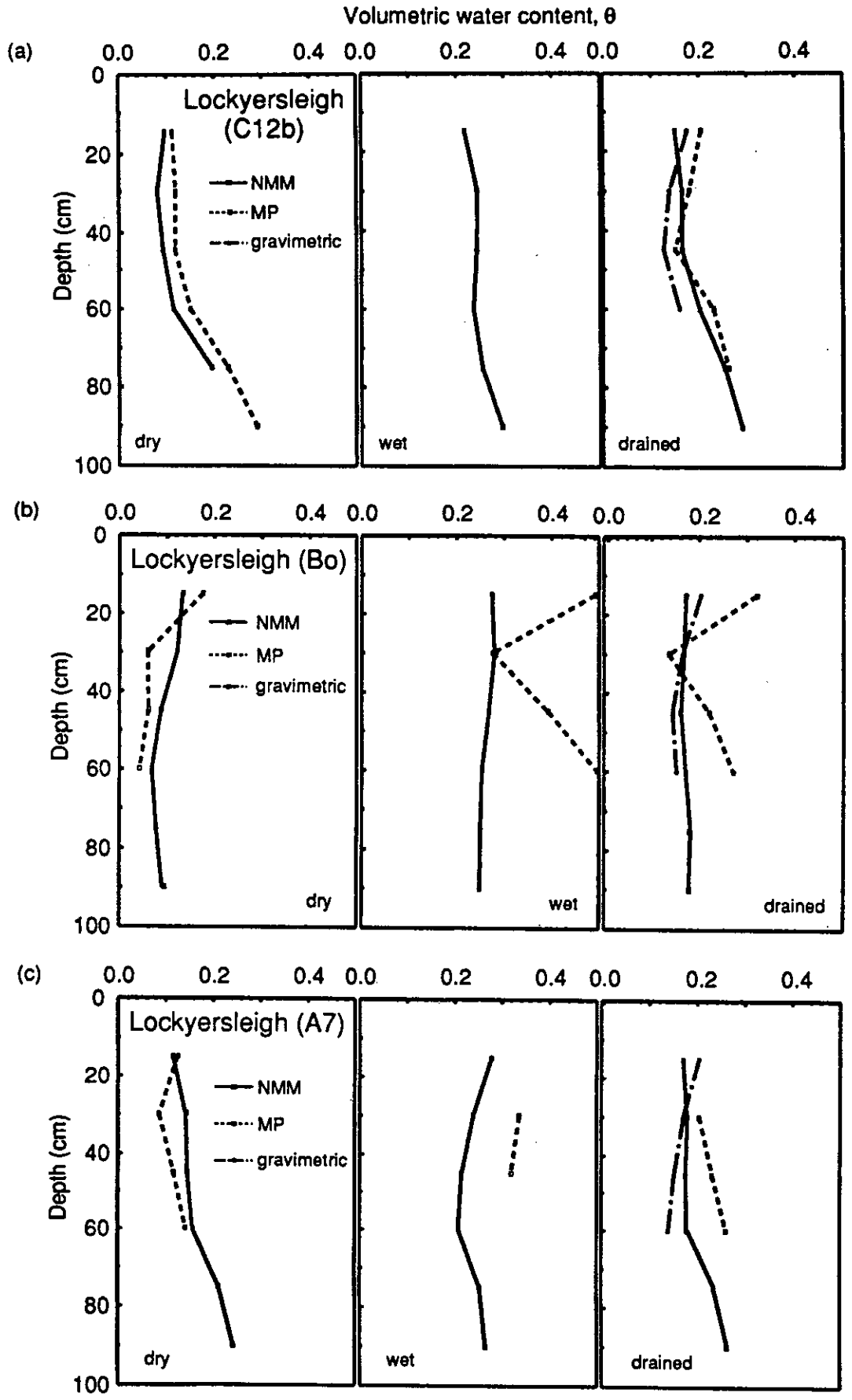


Figure 2. Distribution with depth of water content, measured at three sites at Lockyersleigh, at three stages (wet, dry and drained), with three methods: neutron moisture meter (NMM), moisture point (MP) and volumetric sampling.

Accordingly, another set of measurements was carried out at Lockyersleigh, this time with addition of the TRP probes, inserted horizontally at the appropriate depths before wetting the plot. Samples were taken at the initial and at the final stage. Three MP rods were inserted: one as in the first experiment, one sealed with bentonite after insertion and a third was inserted after soil saturation had been attained. The results of this experiment are shown in Figure 3. Again, the best agreement between the four methods was obtained at the dry stage. The TRP data were in good agreement with the NMM data at all stages. The MP data again showed high values at saturation and after drainage. The mode of insertion of the rods did not have any effect on the readings; the rod inserted after wetting the soil showed over-saturation in the 0-15 cm layer both at the wet and at the drained stage. The MP data in Figure 3 were obtained using the calibration of Bungendore sand.

In order to rule out the possibility that the soil material from Lockyersleigh had a different calibration than Bungendore sand, we ran another calibration experiment with soil material from the Lockyersleigh site. The results given in Figure 4, show that both calibrations coincide. The standard deviations of the travel time at each water content are also shown, along with the regression line as calibrated for the Bungendore sand. The r^2 value of 0.96 for the Lockyersleigh data compares favourably with the value of 0.99 obtained for the Bungedore data. Looking at the relation between the water content and the travel time for all the individual data obtained at site B_o in Lockyersleigh, (see Figure 5) the spread of the data seems

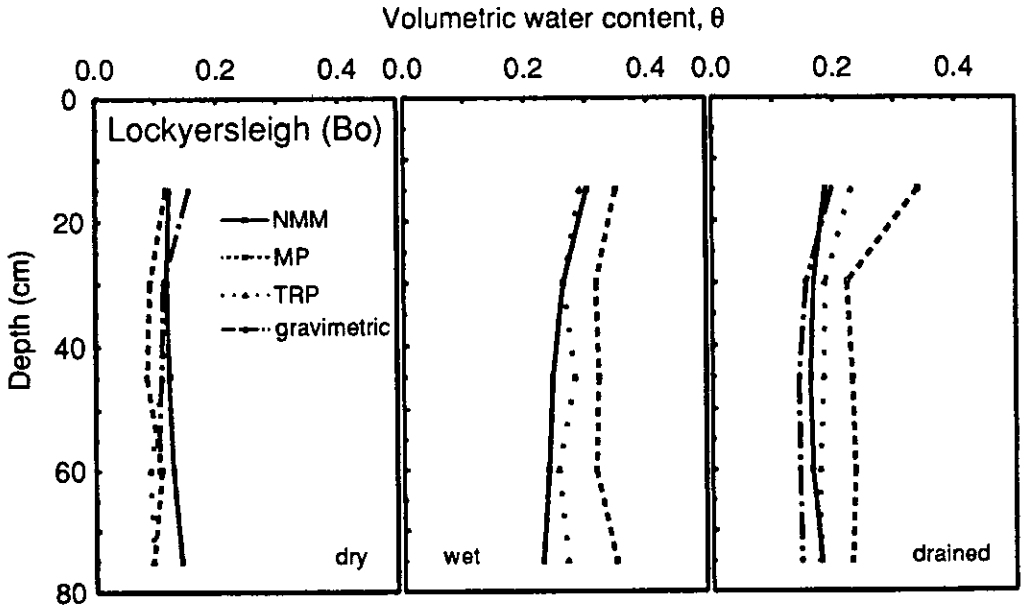


Figure 3. Distribution with depth of water content at site B_o at Lockyersleigh, at three stages (dry, wet and drained), with four methods (NMM, MP, TRP and sampling).

much greater and they do not coincide with the laboratory calibration. The regression lines for the MP probes have r^2 values ranging between 0.69 and 0.83. We do not yet have a satisfactory explanation for this phenomenon, except for the fact that the field soil has greater variability than the well-mixed laboratory samples. Even in the laboratory samples some variability occurred.

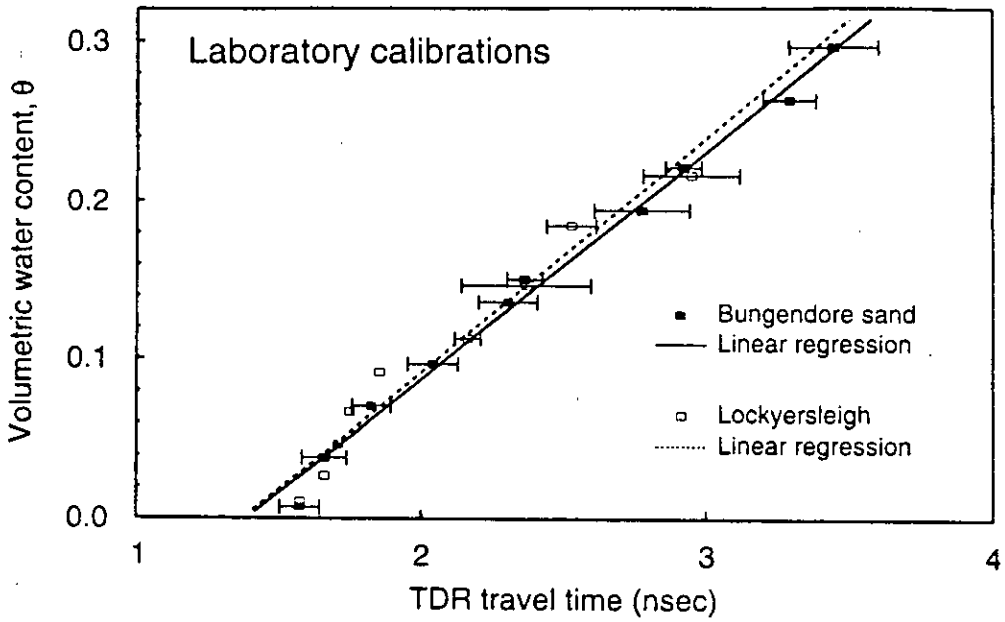


Figure 4. The relation between volumetric water content (θ) and travel time (nsec) for Bungendore sand and for Lockyersleigh soil material as measured with MP, showing standard deviations of travel time and the calculated regression line for the Bungendore sand data.

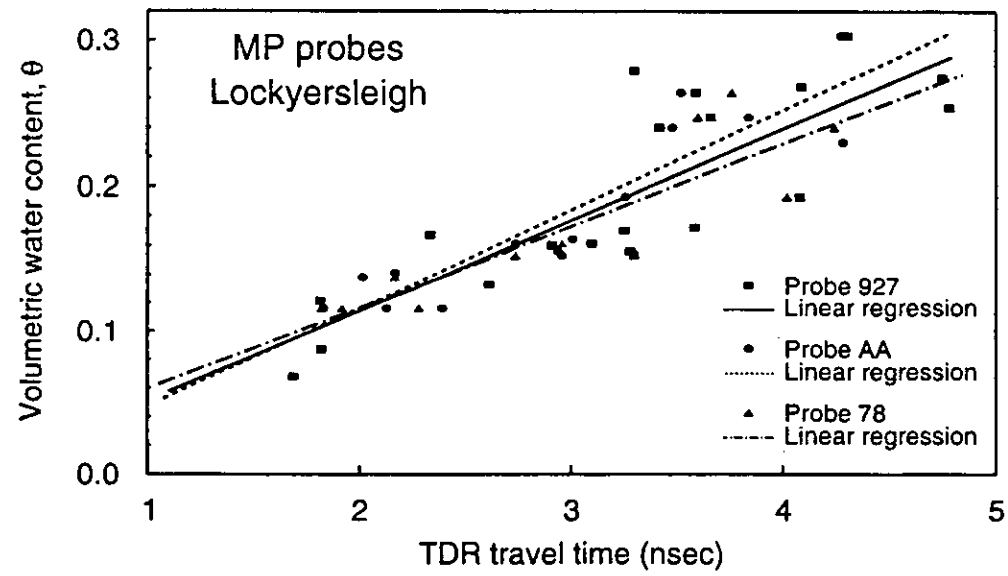


Figure 5. The relation between volumetric water content (θ) and travel time (nsec) for all field determinations obtained at site B_o in Lockyersleigh, with three probes in five layers.

5. CONCLUSIONS

Time Domain Reflectometry has become an established method to monitor soil water content. It has been shown that there exists a general relationship between the apparent dielectric constant and the volumetric water content of many soils. Only soils with a high clay content or with a large fraction of organic material deviate from this relationship. The two major disadvantages of this method are that for each soil layer, a separate probe is needed and that the technique is limited to soils with low salinity. These disadvantages can be overcome by the use of the Moisture Point (MP) probe, which has built-in diodes enabling the measurement of signal travel time along segments of the probe, which also lessen the attenuation of the signal caused by soil salinity.

Our calibration of the MP has shown that the cylinder of measurement around the probe has a diameter of less than 1 cm. In uniformly mixed soil material, a linear relationship between travel time of the signal and volumetric soil water content was obtained with a high coefficient of determination (r^2=0.98). However, the slope of the line is larger than that obtained with the conventional TRP measurement, since not only the soil surrounding the probe is measured, but also the epoxy material embedded in the probe. Field measurements taken with the MP showed only an approximate relation with the data obtained with neutron probe, sampling and TRP. The relation between travel time and water content for the field data showed a large spread, which was not related to the soil layer or to the probe used. We believe that this was the result of the small volume of measurement and the large variability of the actual soil water content.

REFERENCES

Alksnis, H., Daniel, P. and Kalma, J.D. (1990). The regional evaporation project: soil moisture and rainfall data. CSIRO Div. of Water Resources, Tech. Memo. 90/12.

Birchak, J.R., Gardner, C.G., Hipp, J.E. and Victor, J.M. (1979). High dielectric constant microwave probes for sensing soil moisture. Proc. IEEE. 62: 93-98.

Dalton, F.N. and Th. van Genuchten, M. (1986). The time domain reflectrometry method for measuring soil water content and salinity. Geoderma 38: 237-250.

Dasberg, S. and Hopmans, J.W. (1992). Time domain reflectometry calibration for uniformly and nonuniformly wetted sandy and clayey loam soil. Soil Sci. Soc. Amer. J. 56: 1341-1343.

Dirksen, C. and Dasberg, S. (1993). Improved calibration of time domain reflectometry soil water content measurements. Soil Sci. Soc. Amer. J. 57: 660-667.

Dobson, M.C., Ulaby, F.T., Hallikainen, M.T. and El-Rayes, M.A. (1985). Microwave dielectric behaviour of wet soils. Part II: Dielectric mixing models. IEEE Trans. Geosci. Remote Sensing GE 23: 35-46.

Heimovaara, T.J. (1993). Time domain reflectometry in soil science: theoretical backgrounds, measurements and models. Ph.D. Thesis, University of Amsterdam, Netherlands.

Heimovaara, T.J. and Bouten, W. (1990). A computer controlled 36 channel TDR system for monitoring soil water contents. Water Resour. Res. 26: 2311-2316.

Herkelrath, W.N., Hamberg, S.P. and Murphy, F. (1991). Automatic, real time monitoring of soil moisture in a remote field area with TDR. Water Resour Res. 27: 857-864.

Hook, W.R., Livingston, N.J., Sun, Z.J. and Hook, P.B. (1992) Remote diode shorting improves measurement of soil water by time domain reflectometry. Soil Sci. Soc. Am. J. 56:1384-1391.

Knight, J.H. (1992). The sensitivity of time domain reflectometry measurements to lateral variations in soil moisture content. Water Resour. Res. 28: 2345-2352.

Patterson, D.E. and Smith, M.W. (1981). The measurement of unfrozen water content by TDR. Can. Geotech. J. 18: 131-143.

Roth, K., Schulin, R., Fluehler, H. and Attinger, W. (1990). Calibration of TDR for water content measurement using a composite dielectric approach. Water Resour. Res. 26: 2267-2273.

Topp, G.C., Davis, J.L. and Annan, A.P. (1980). Electromagnetic determination of soil water content: measurement in co-axial transmission lines. Water Resour. Res. 16: 574-582.

White, I., Zegelin, S.J., Topp, G.C. and Fish, A. (1994) Effect of bulk soil electrical conductivity on TDR measurement of water content in porous media. In: Time Domain Reflectometry, in environment, infrastructure and mining applications. USDI, Bureau of Mines, Special Publication SP19-94.

Whalley, W.R. (1993). Considerations in the use of TDR for measuring soil water content. J.Soil Sci. 44:1-9.

Zegelin, S.J., White, I., and Russell, G.F. (1992) A critique of the time domain reflectometry technique for determining field soil-water content. In: Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice, 187-208. Soil Sci. Soc. Am.: Madison, Wisconsin.

The Cooperative Research Centre for Catchment Hydrology is a cooperative venture formed under the Commonwealth CRC Program between:

Bureau of Meteorology

CSIRO Division of Water Resources

Department of Conservation and Natural Resources

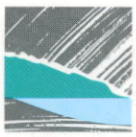
Melbourne Water

Monash University

Murray-Darling Basin Commission

Rural Water Corporation

The University of Melbourne



COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Centre Office
Department of Civil Engineering, Monash University, Clayton, Victoria, 3168 Australia
Telephone: (03) 905 2704 Facsimile: (03) 905 5033 International: +61 3 905 2704