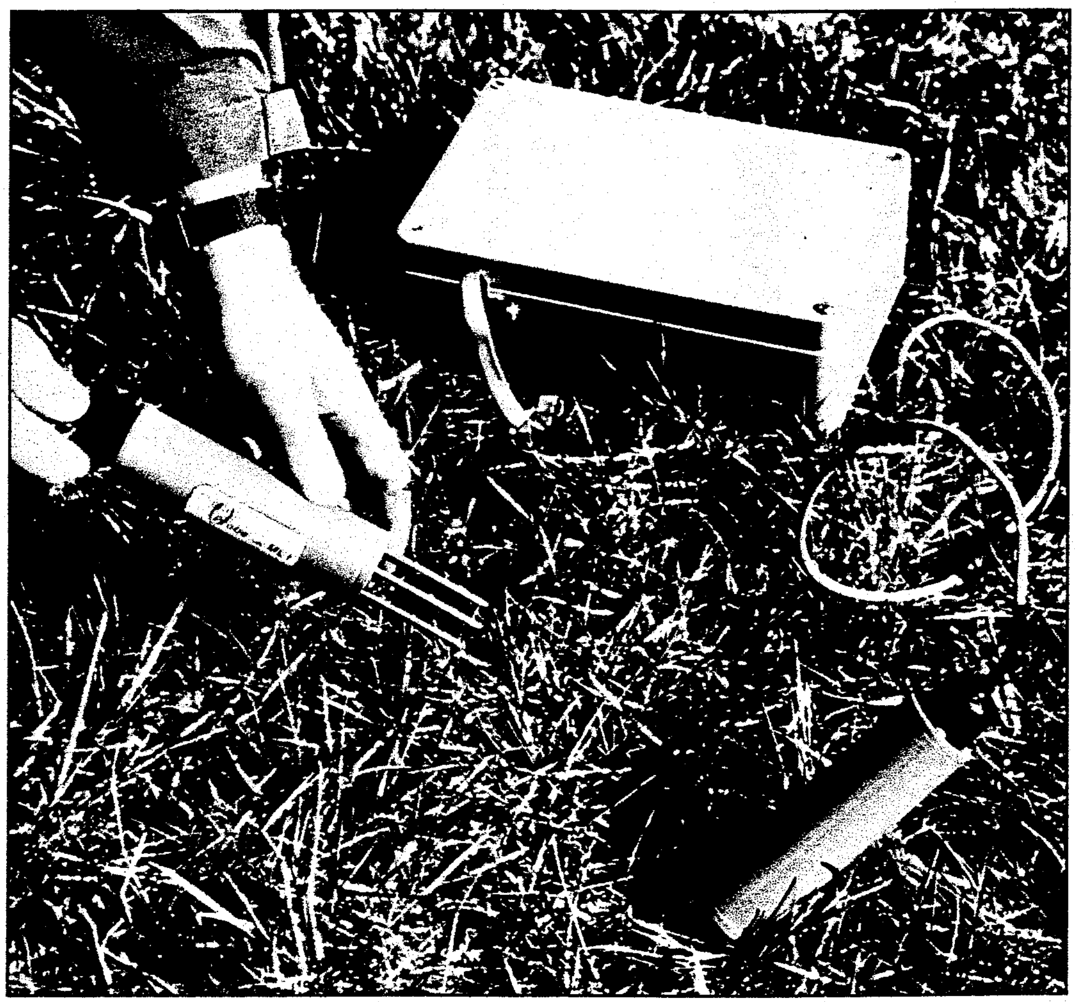
The development and application of the ThetaProbe soil water sensor

Reference # 76



J.D. Miller and G.J. Gaskin

MLURI Technical Note

Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH

Introduction

The ThetaProbe is designed to measure soil water content using a new technique that matches time-domain reflectometry (TDR) for accuracy, but without the complexity and expense.

A simplified voltage standing wave method is used to determine the impedance of a sensing rod array and hence the water content of the soil matrix.

Full details are given in Gaskin and Miller (1996).

Principles of operation

1. *Volumetric water content,* θ_v

$$\theta_v = \frac{\text{Volume of water}}{\text{Total volume}}$$

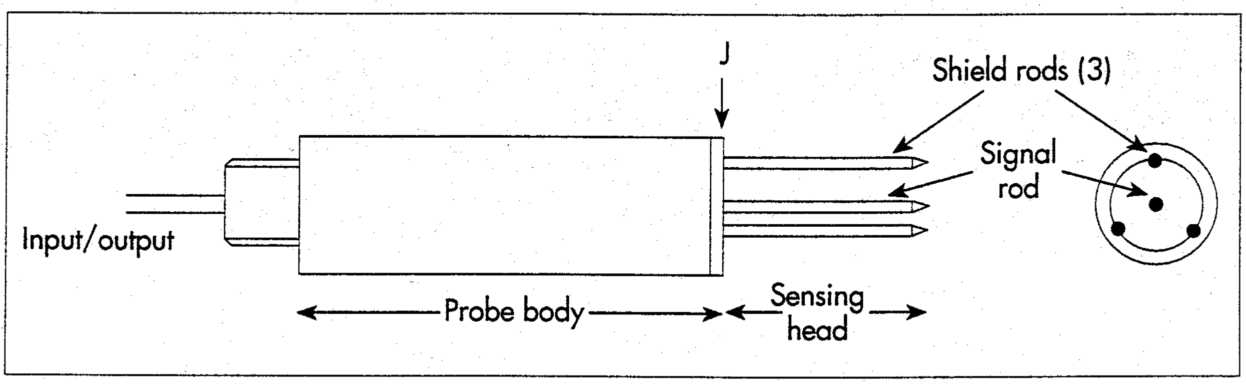
2. For soils $\theta_v = \left(\frac{\sqrt{K} - q}{p}\right)$

   where K is *dielectric constant* and p and q are constants contingent on soil type.

3. The *impedance* (Z) of a coaxial transmission line is dependant on its physical dimensions and the dielectric constant of the insulating material

$$Z = \frac{60}{\sqrt{K}}\left(F \cdot \frac{r_2}{r_1}\right)$$

   where r_1 and r_2 are radii of the signal and shield conductors and F is a geometric factor



4. The body of the probe contains a 100 MHz sinusoidal oscillator, a section of coaxial transmission line and measuring circuitry. The sensing head has an array of four rods, the outer three of which, connected to instrument ground, form an electrical shield around the central, signal rod. This behaves as an additional section of transmission line, having an impedance which depends on the dielectric constant of the matrix into which it is inserted. If this impedance differs from that of the fixed internal transmission line, then a proportion of the signal is reflected back from the junction (J) at the signal wire and the transmission line (ρ = reflection coefficient).

   The reflected component interferes with the incident signal causing a voltage standing wave to be set up on the transmission line, i.e. a variation of voltage amplitude along the length of the line.

If Z_L is impedance of transmission line and Z_M is impedance of probe in matrix then

$$\rho = \left(\frac{Z_M - Z_L}{Z_M + Z_L}\right)$$

The transmission line is designed so that the peak voltage at start (V_o) is

$$V_o = a(1 - \rho)$$

and peak voltage at the junction (J) is

$$V_J = a(1 + \rho)$$

Therefore the difference in *amplitude* is

$$2a \left(\frac{Z_M - Z_L}{Z_M + Z_L}\right)$$

where a is voltage amplitude of oscillator output.

Measuring this *amplitude* difference will give us the relative *impedance* of the probe, hence the *dielectric constant* and therefore a measure of *volumetric water content.*

Calibration and performance

The field performance of the ThetaProbe is dependent on:

A
- ❑ The accuracy of calibration during manufacture against materials of known dielectric constants.
- ❑ The relationship between dielectric constant and volumetric water content.
- ❑ The conversion method used within the datalogger or other acquisition instrumentation.

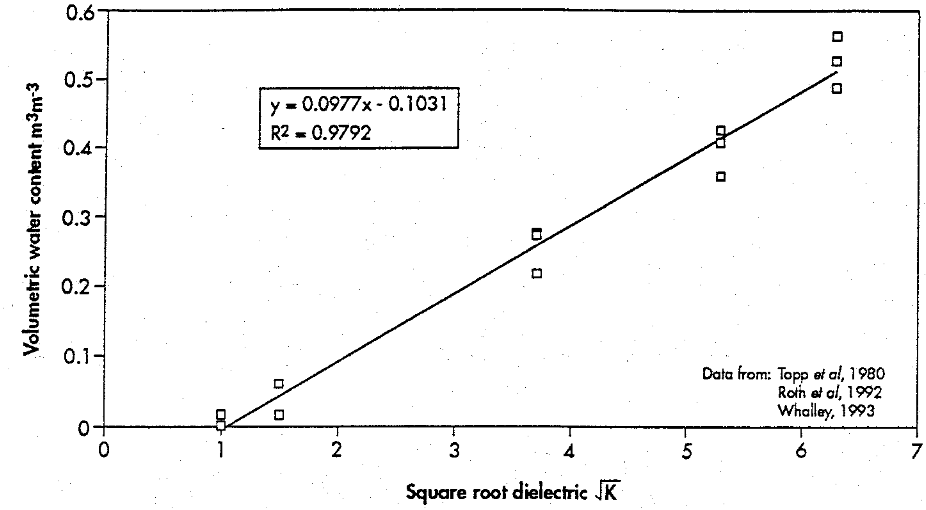
B
- ❑ Calibration sensitivity due to ambient temperature variation.

C
- ❑ Calibration sensitivity due to ionic conductivity (salinity).

Test results follow showing typical variations experienced, together with data obtained from a constructed theoretical model (D).

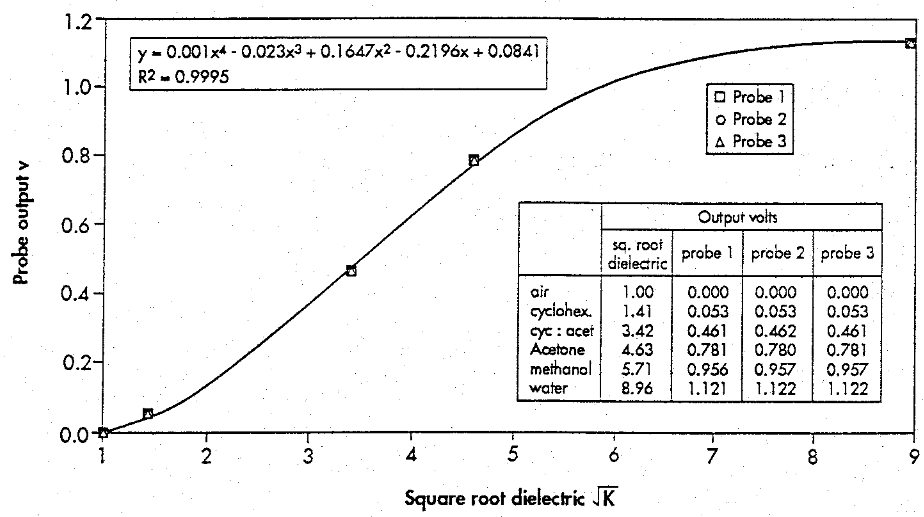
A. CALIBRATION

Initial calibration of ThetaProbe using pure solvents of known dielectric constants and in a range of soils.



(i)

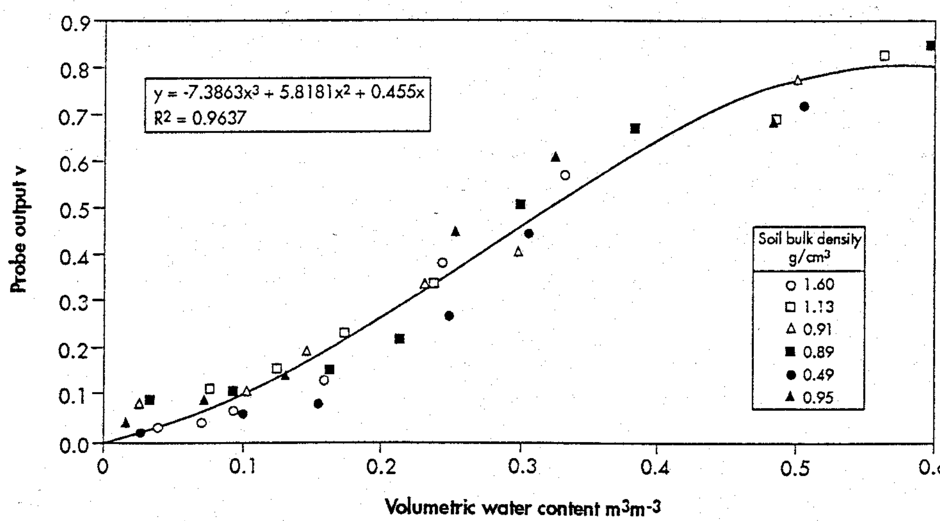
The relationship between dielectric constant (K) and volumetric water content (θ_v) has been derived by many researchers.



	Output volts			
	sq. root dielectric	probe 1	probe 2	probe 3
air	1.00	0.000	0.000	0.000
cyclohex.	1.41	0.053	0.053	0.053
cyc : acet	3.42	0.461	0.462	0.461
Acetone	4.63	0.781	0.780	0.781
methanol	5.71	0.956	0.957	0.957
water	8.96	1.121	1.122	1.122

(ii)

Theta probe calibration against pure solvents of known dielectric constants. Results from three probes.



(iii)

Theta probe calibration using a range of soils – water content determined by drying at 105°C.

From (ii) $\sqrt{K} = 1 + 4.52V$ $\quad R^2 = 0.9993$

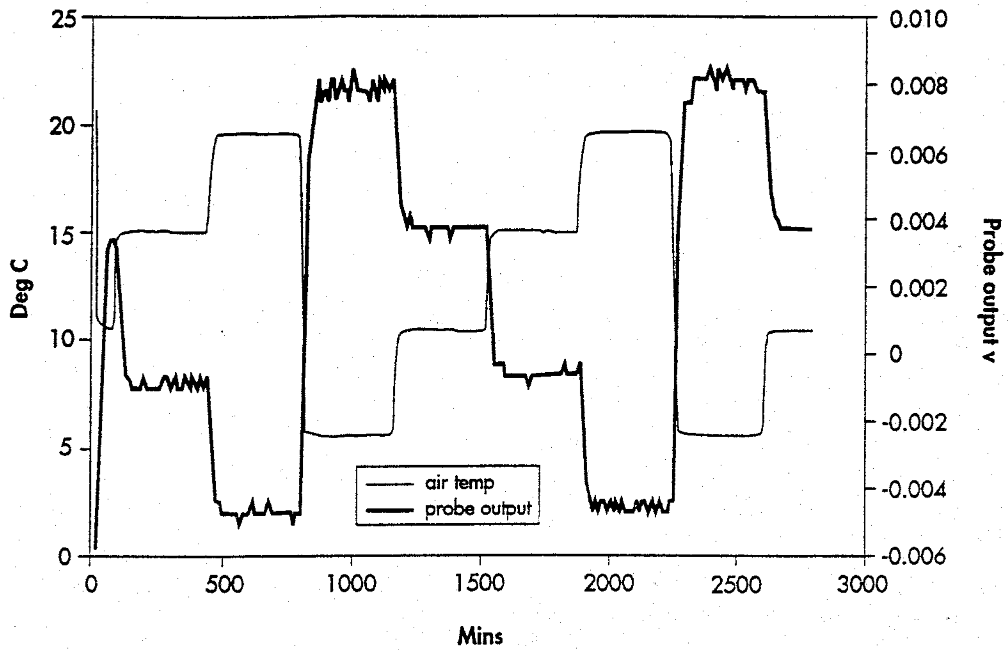
or $\sqrt{K} = 1 + 6.25V - 5.96V^2 + 4.39V^3 - 300.84V^4$ $\quad R^2 = 0.994$

$$\theta_v = \left(\frac{\sqrt{K} - q}{p}\right)$$ p and q can be determined from water content of moist soil (p) and dry soil (q).

or use 7.8 and 1.3 for organic soils   8.4 and 1.6 for mineral soils

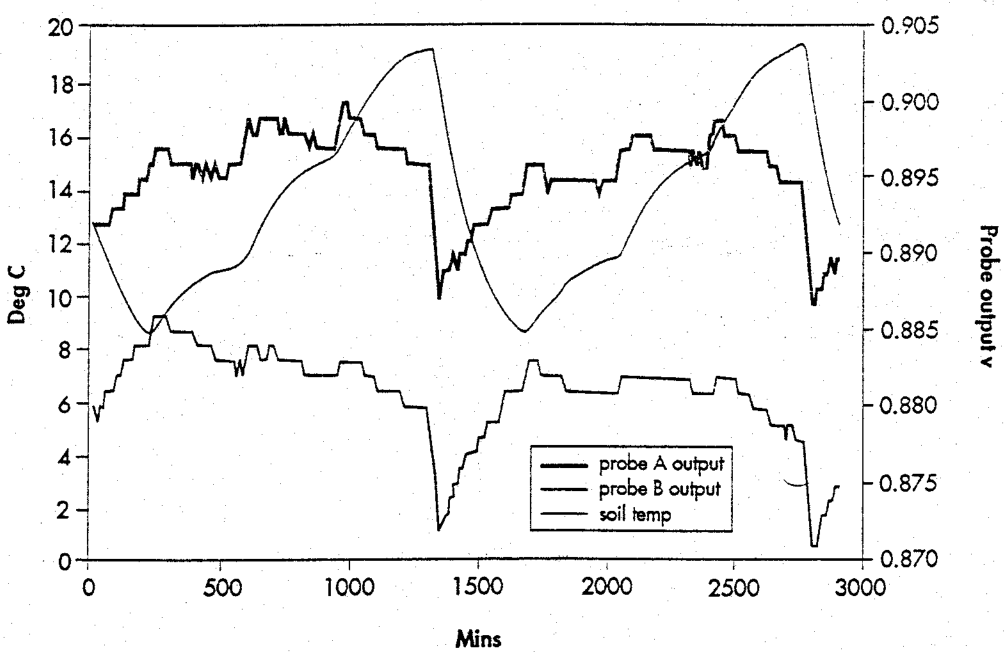
B. TEMPERATURE EFFECTS

Temperature effects on probe output were studied using controlled environment chambers.



(i)

Probe response to temperature shifts (5°C) in air.



(ii)

Probe responses to temperature shifts in damp soil.

Two adjacent probes.

The effects of temperature on the dielectric constant of water are known and can be calculated from

$$\sqrt{K} = -0.0208x + 9.3808$$

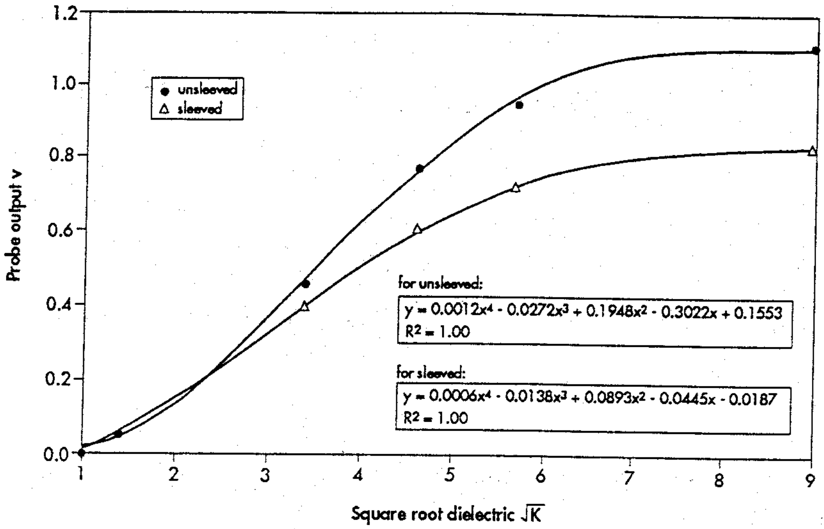
$$x = \text{temp}°C$$

For probes in air (i) the shifts of about 0.012v are due to the temperature dependence of the oscillator circuitry.

For probes in soil (ii) a shift in temperature of 15° results in only a 0.010v change in voltage output.

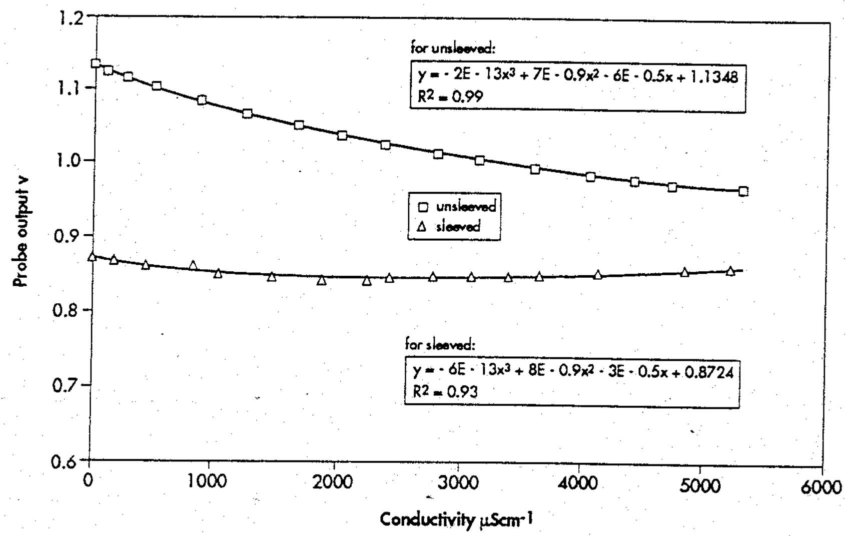
C. SALINITY

Probe output can be affected in soils of high salinity due to the attenuation of signals on probe rods. This can be reduced when making measurements in soils of high bulk conductivity either by sleeving the signal rod to reduce attenuation effects or by calibration in these specific soils.



(i)

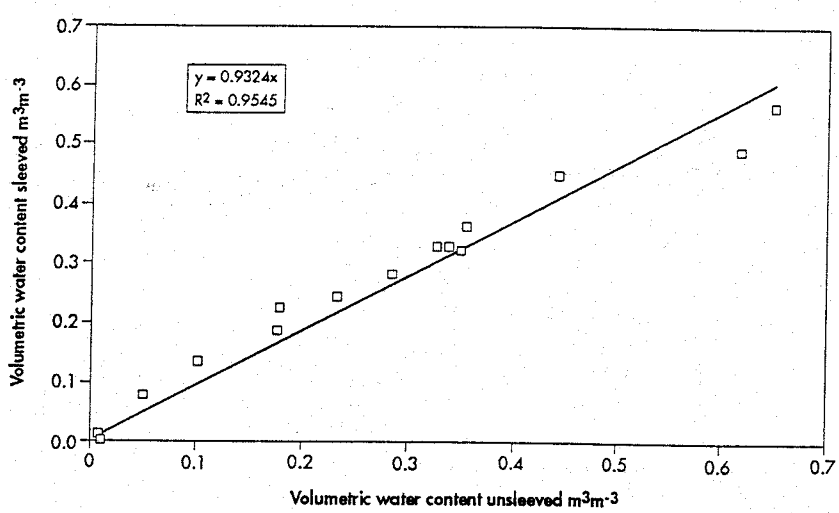
Effects of sleeving on calibration of probes in pure solvents of known dielectric constants.



(ii)

Reduced effects of salinity on probe using sleeved rods. Conductivity adjusted by solutions of potassium chloride.

Note change of y-axis scale.



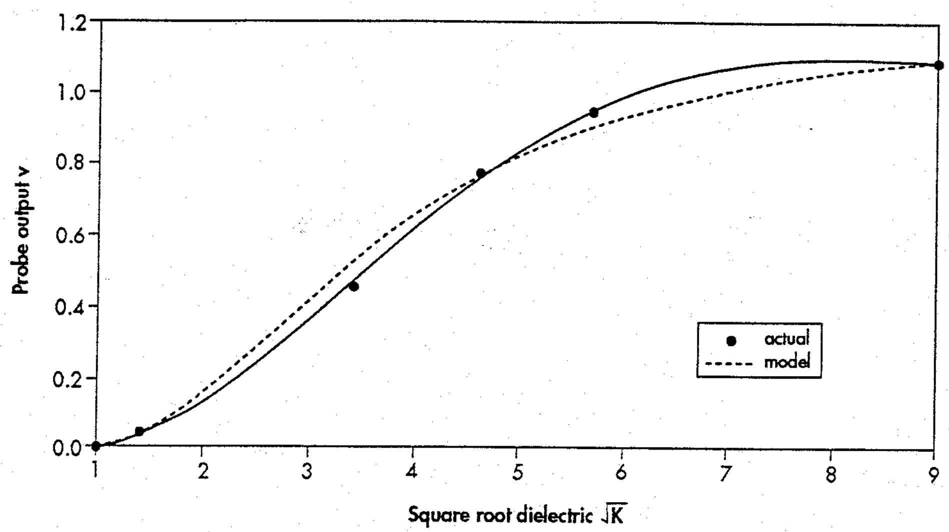
(iii)

Comparison of soil water contents of a range of soils determined by both original and sleeved probes.

Soils are classified as slightly (2000-4000µScm^{-1}), moderately (4000-8000µScm^{-1}) and strongly (8000-14000µScm^{-1}) saline. Measurements of soil water content in these soils can be made using modified ThetaProbes with sleeved signal rods.

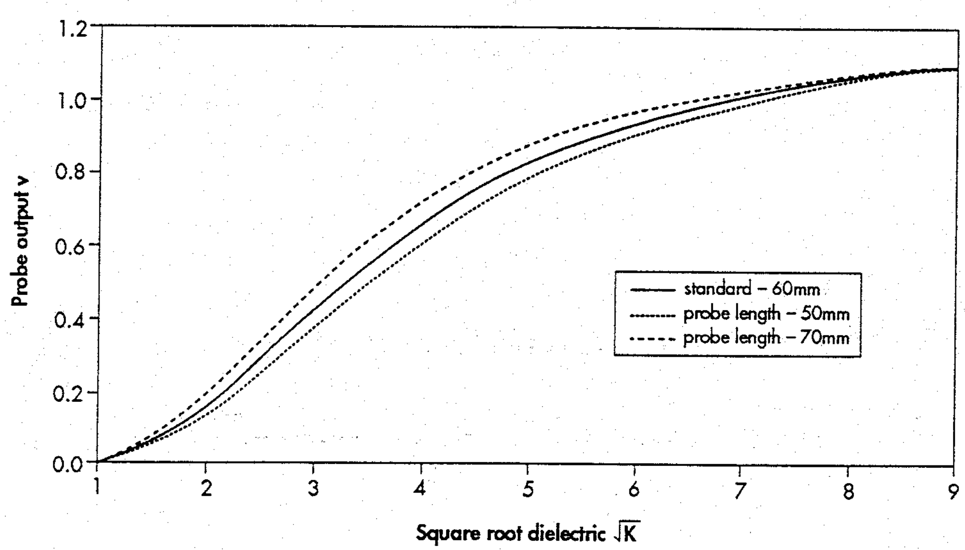
D. THEORETICAL MODEL

A model was constructed to allow the prediction of the consequences of changing sensing probe dimensions, transmission line characteristics and oscillator amplitude, and of the influence of the bulk conductivity of the soil.



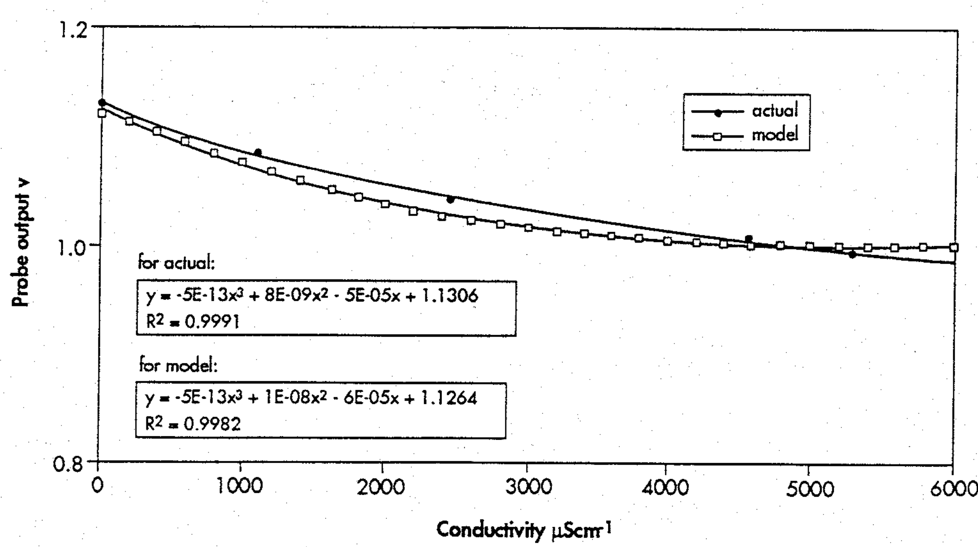
(i)

Probe output volts compared with modelled output using standard parameters.



(ii)

Effects of changing one physical parameter on model output.



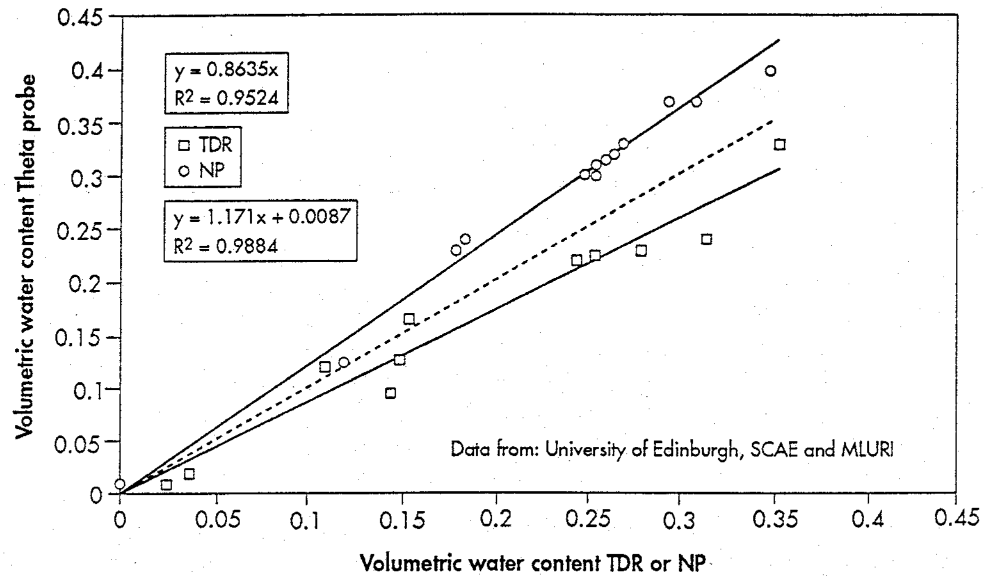
(iii)

Effects of increasing bulk conductivity on model output.

Note change of y-axis scale.

COMPARISONS WITH OTHER TECHNIQUES AND THETAPROBE APPLICATIONS IN A RANGE OF SOIL TYPES

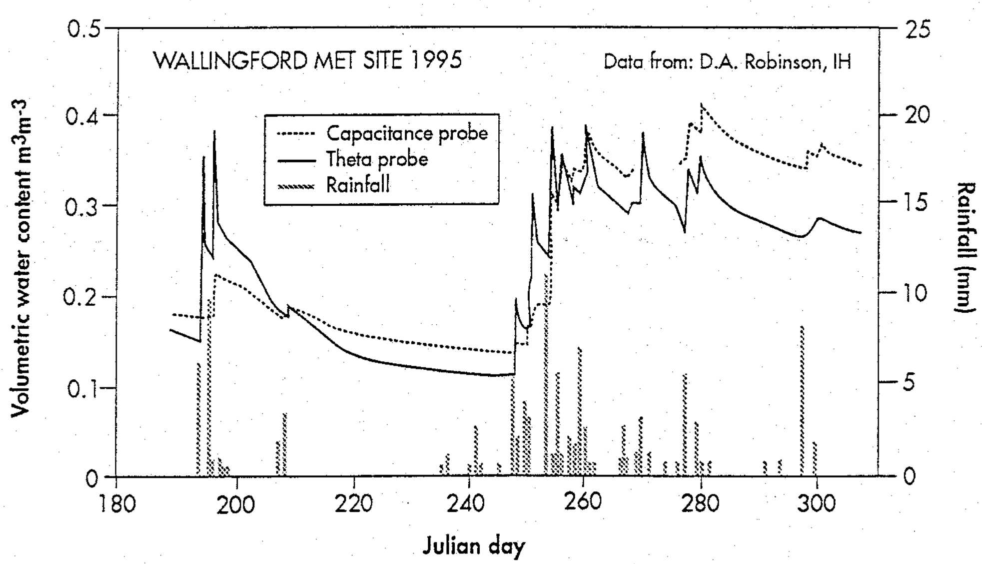
Tests have been carried out within MLURI and by independent researchers comparing ThetaProbe responses with other techniques.



(i)

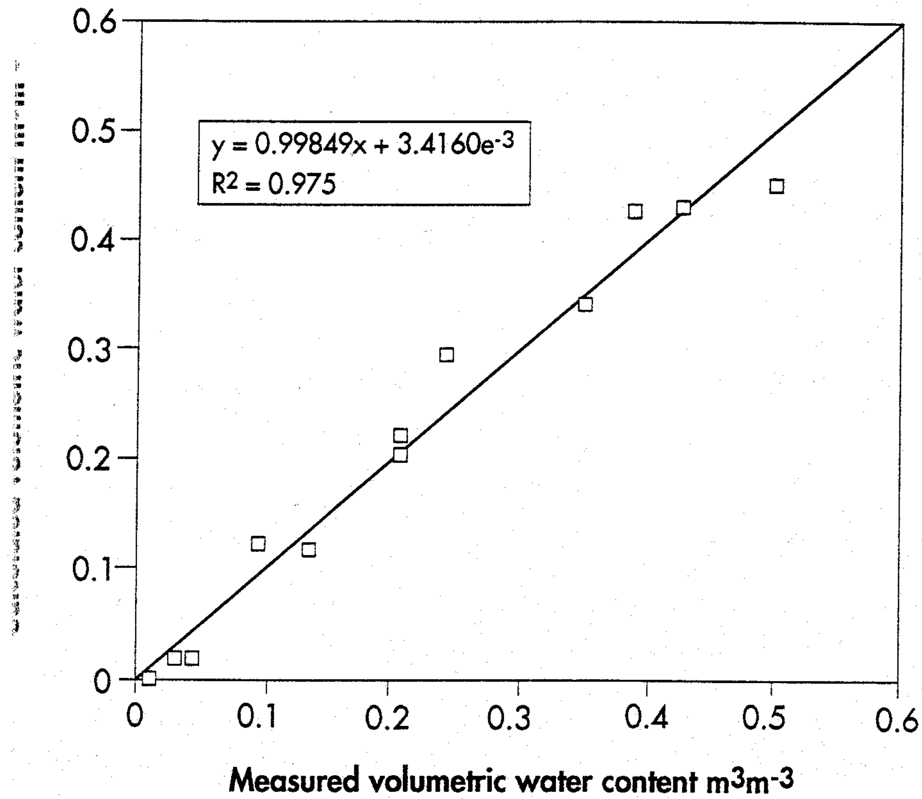
Comparisons between ThetaProbe, TDR and neutron probe. Regressions depend on choice of neutron probe equations.

NP – neutron probe
TDR – time domain reflectometry



(ii)

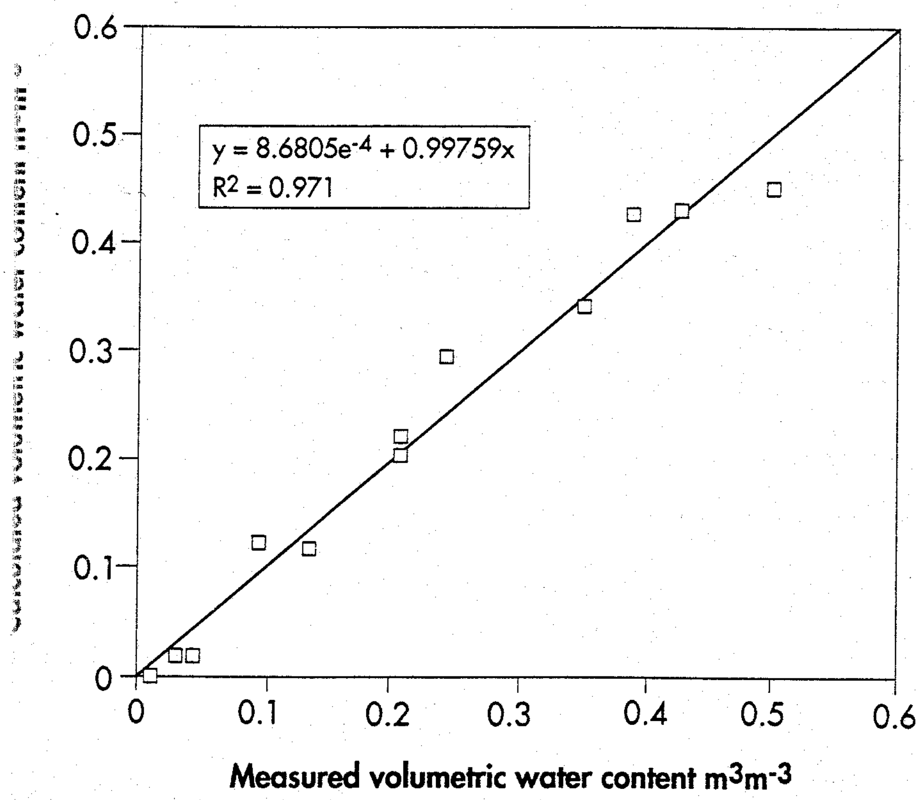
Comparison of continuous measurements of soil water determined by ThetaProbe and capacitance probe.



(i)

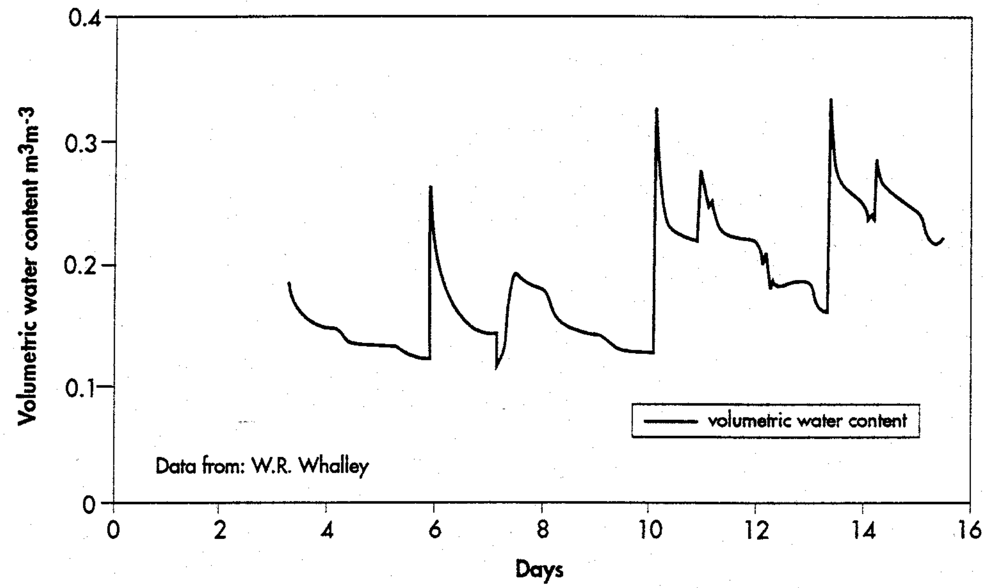
Volumetric water content of two soils, as measured gravimetrically and calculated from ThetaProbe output using the polynomial (i) and linear relationship (ii), p and q being determined for each soil.

Conclusion is that a two point calibration is adequate and the simplest method for using the ThetaProbe.



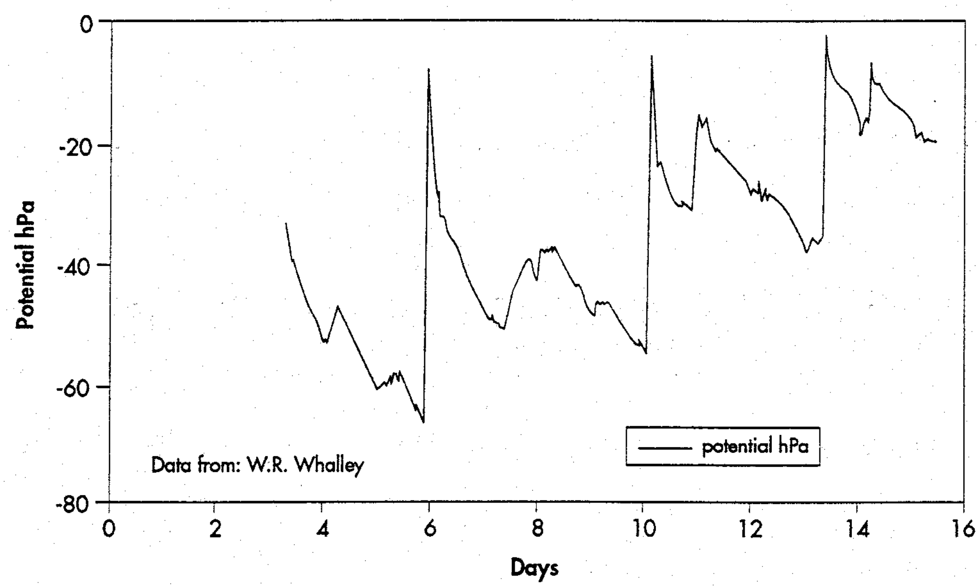
(ii)

Results on independant tests carried out by Lascano and Baumhardt.

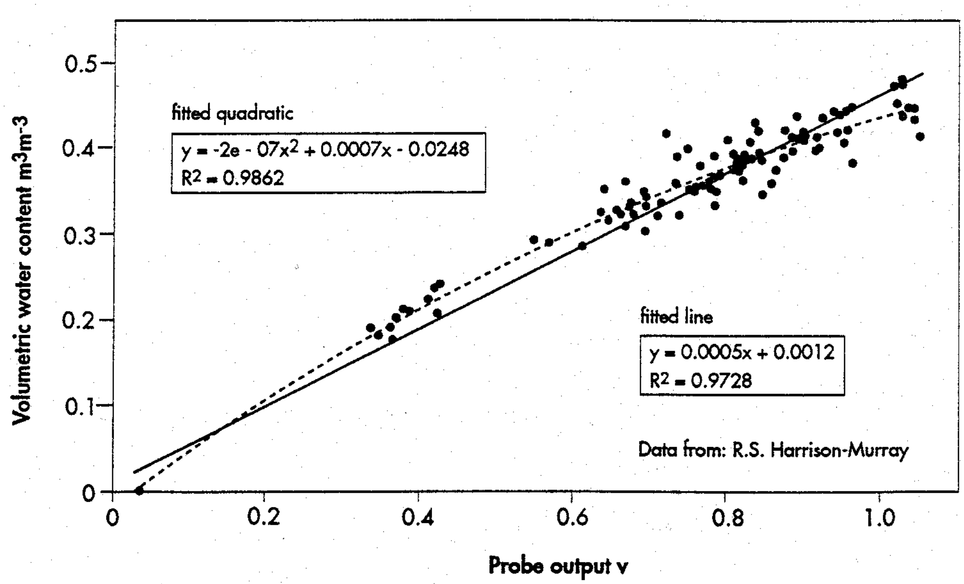


(i)

Water content measured by ThetaProbe (i) compared to tensiometer output (ii) from the same plot.

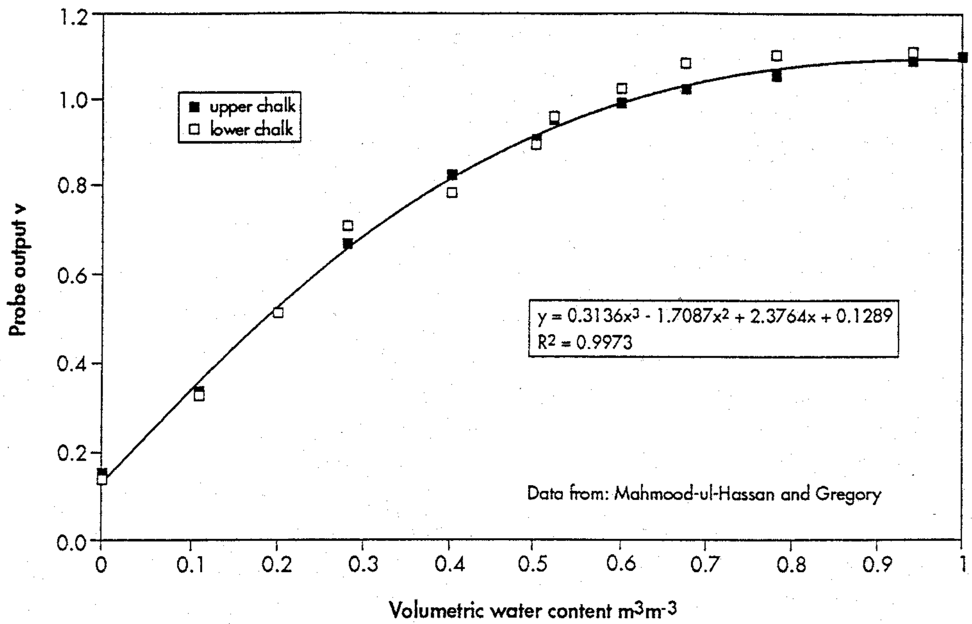


(ii)



(ii)

Calibration of ThetaProbe in organic media peat:bark (70:30)



(i)

ThetaProbe calibration and performance in chalk soils.

Acknowledgements are due to the following research scientists for permission to include their results using the ThetaProbe.

W.R. Whalley, Silsoe Research Institute, UK

J. Irvine, Edinburgh University, UK

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C. van Bavel, USA

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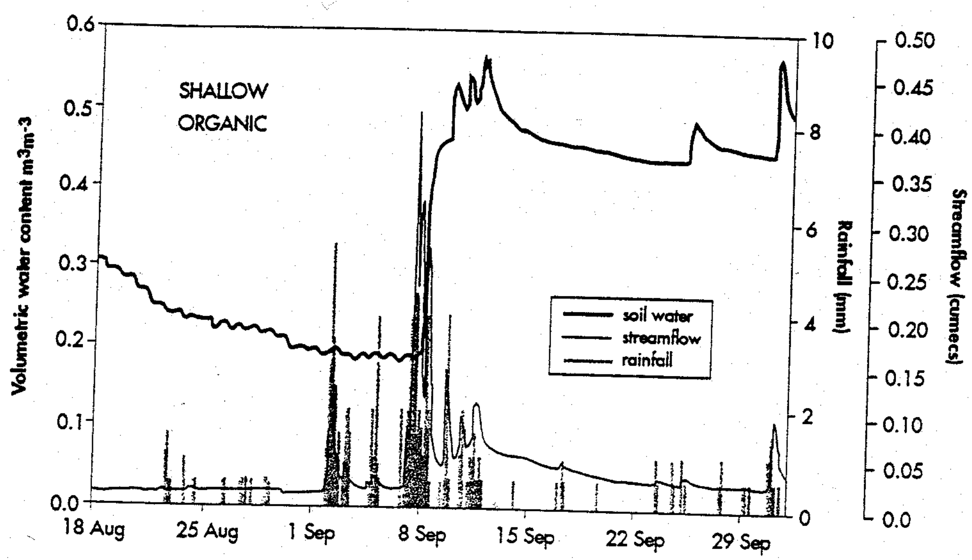
M. Mahmood-ul-Hassan, University of Reading, UK

E. Fisher, Macaulay Land Use Research Institute, UK

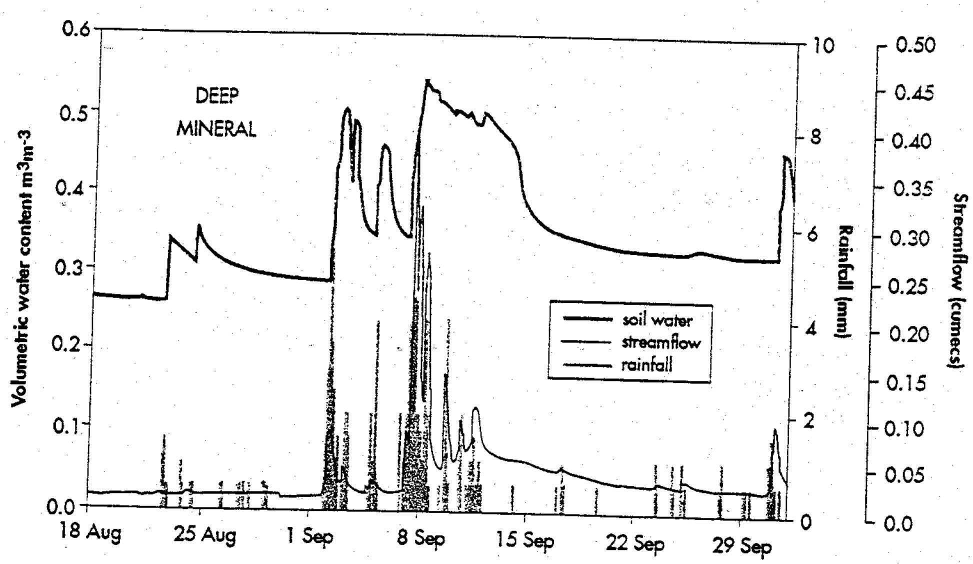
APPLICATION OF THETAPROBE TO CATCHMENT STUDIES

ThetaProbes have been successfully used in MLURI catchment studies in Scotland. Results below are from Glensaugh (MLURI research station) in 1995.

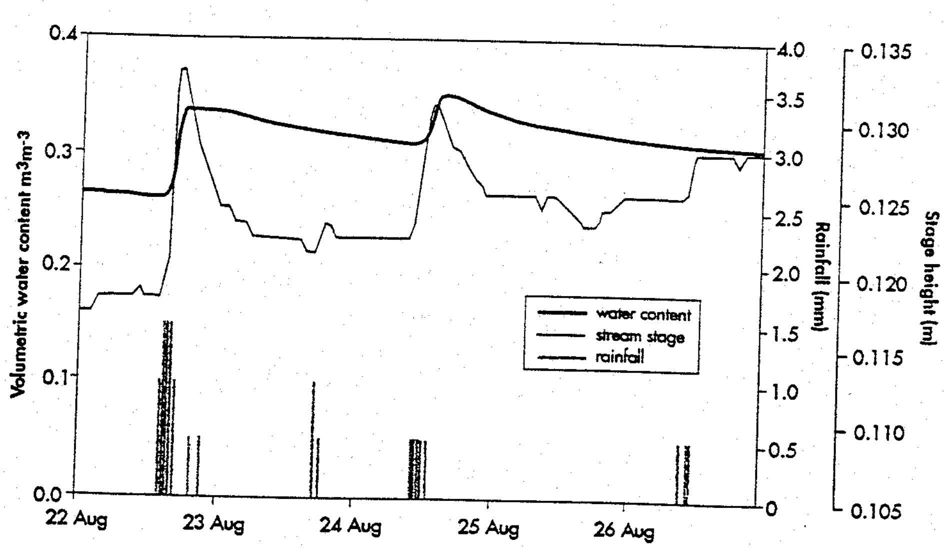


(i)

Soil water contents in two horizons in a podzolic soil during the transition from drought to flood.



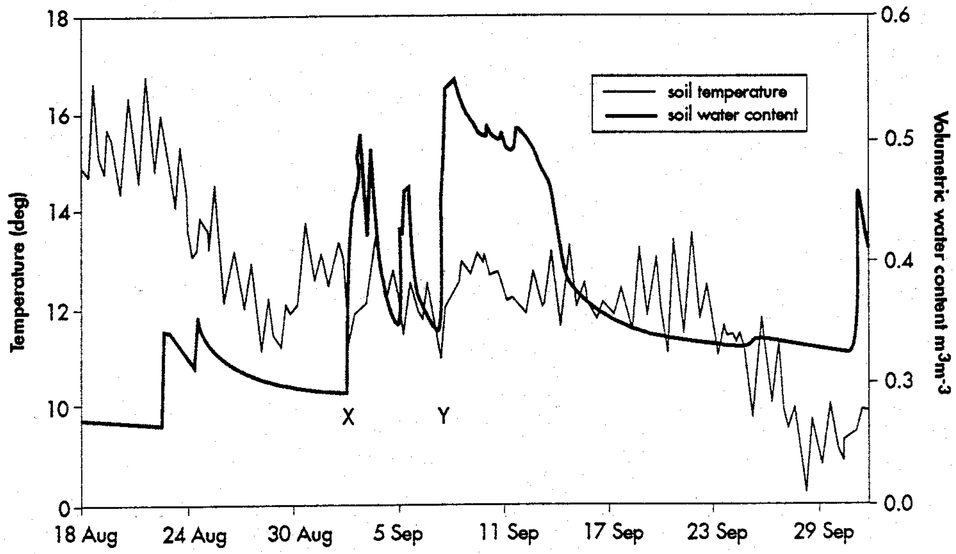
(ii)



(iii)

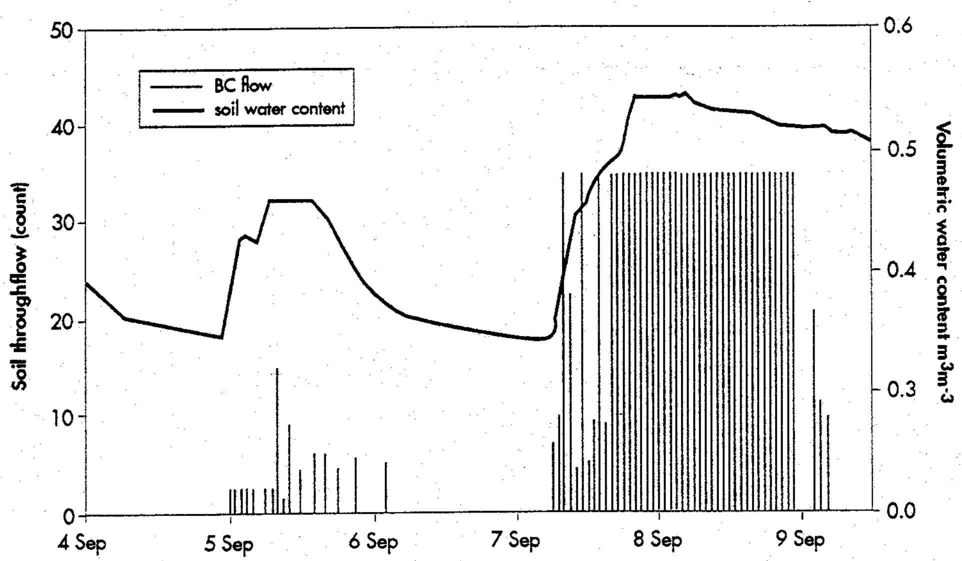
Example of increased hydrological understanding derived by continuously monitoring ThetaProbes. In this case the fast transfer of rainfall to depth in the soil profile and its movement downslope into streams.

Changes in soil water content can be related to other site parameters, both physical and chemical, to provide a more complete picture of catchment behaviour and responses.



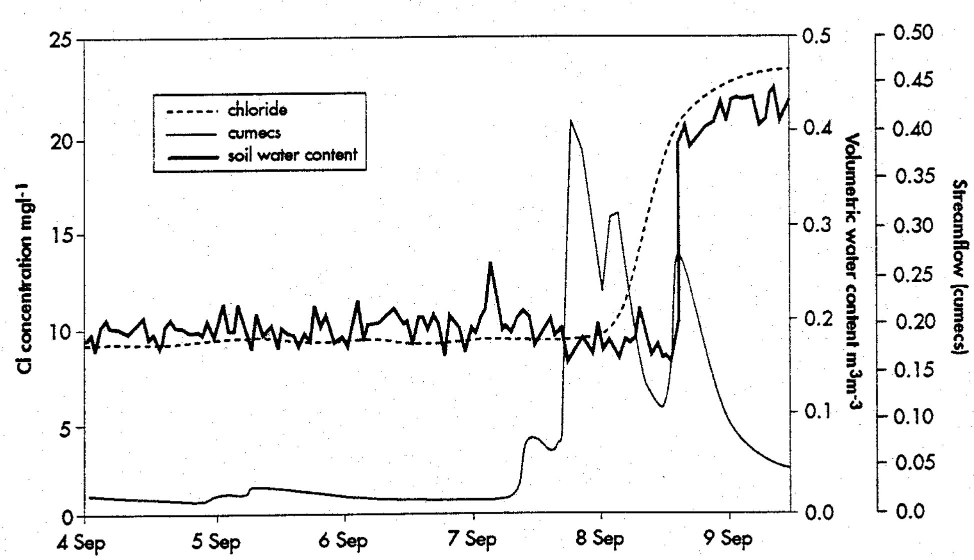
(i)

Disruption of the expected diurnal cycles of soil temperature by water movement through the soil profile at X and Y.



(ii)

Appearance of soil throughflow (tensionless) in soil pits compared to soil water content.



(iii)

Hydrochemical links with coincidental increase in Cl concentration in stream water derived
from wetting up of organic horizons.

Summary

- ❑ Simple to use – input 7 - 15vDC
  output 0 - 1vDC for 0 - 0.5m^3m^{-3}
  current ≈ 33mA
- ❑ Easily logged – no trace interpretation
- ❑ Bench calibrated or 2-point specific soil calibration
- ❑ Lower cost than alternative techniques
- ❑ Can be used in saline soils
- ❑ No complex cable requirements
- ❑ Wide range of applications
- ❑ Hand held read-out unit available

Acknowledgements

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The design is the subject of a patent application.

References

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7. Gaskin, G.J., Meeusen, J.C.L. and Miller, J.D. 1996. Modelling the behaviour of a new soil water probe (in prep)

A robust reliable version of the ThetaProbe is produced commercially by:

Delta-T Devices Ltd., Burwell, Cambridge
Telephone: 01638 742922
Fax: 01638 743155

Probe installation accessories, hand-held read-out unit and suitable dataloggers are also available from Delta-T Devices Ltd.

This Technical Note has been produced to share ThetaProbe applications with other users. To discuss any aspect of this information please contact the authors at MLURI or Delta-T Devices Ltd.

Macaulay Land Use Research Institute, Aberdeen
Telephone: 01224 318611
Fax: 01224 311556

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