ThetaProbe ML2x

Principles of operation and applications

MLURI Technical Note (2nd ed)

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MACAULAY LAND USE RESEARCH INSTITUTE

CONTENTS *Page*

1. INTRODUCTION

The ThetaProbe is designed to measure volumetric soil water content (θ_v) using a novel technique that matches other methods, such as time-domain reflectometry (TDR) or capacitance measurement, for accuracy and ease-of-use, whilst reducing the complexity and expense.

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

ThetaProbes have been developed jointly by the Macaulay Land Use Research Institute (MLURI), Aberdeen and Delta-T Devices, Cambridge and are subject to the following patents:

UK – 2300485
Europe – 96303190.1
USA – 08/706,675.

2. VOLUMETRIC SOIL WATER

Volumetric soil water content (θ_v) is the ratio between the volume of water present in the soil and the total volume of the sample and is therefore expressed as:

$$\theta_v = (\text{volume of water}/\text{total volume})$$

This is a dimensionless parameter, expressed either as a percentage (% volume) or as a ratio (m^3m^{-3}). Thus a completely dry soil corresponds to 0 m^3m^{-3} whereas pure water gives a reading of 1.0 m^3m^{-3}. The volumetric water content of a wet mineral soil and a wet very organic soil could approach 0.5 m^3m^{-3} and 0.8 m^3m^{-3} respectively.

Historically gravimetric soil water content (θ_g) was determined using:

$$\theta_g = (M_w/M_s)$$

where M_w is the mass of water in the soil sample and M_s is the total mass of the dry sample.

Gravimetric soil water contents can be converted to volumetric soil water contents using the expression:

$$\theta_g = \theta_v.(\rho_w/\rho_s)$$

where ρ_w is the density of water (1.0) and ρ_s is the bulk density of the soil sample.

Therefore:

$$\begin{aligned}\theta_v &= \theta_g.\rho_s \\ &= (M_w/M_s).(M_s/V_s) \\ &= (V_w/V_s)\end{aligned}$$

ThetaProbes measure volumetric soil water content by determination of the apparent dielectric constant using the following equation:

$$\theta_v = (\sqrt{\varepsilon} - a_0)/a_1$$

where ε is the apparent dielectric constant and a_0 and a_1 are constants dependent on soil type.

3. PRINCIPLES OF OPERATION

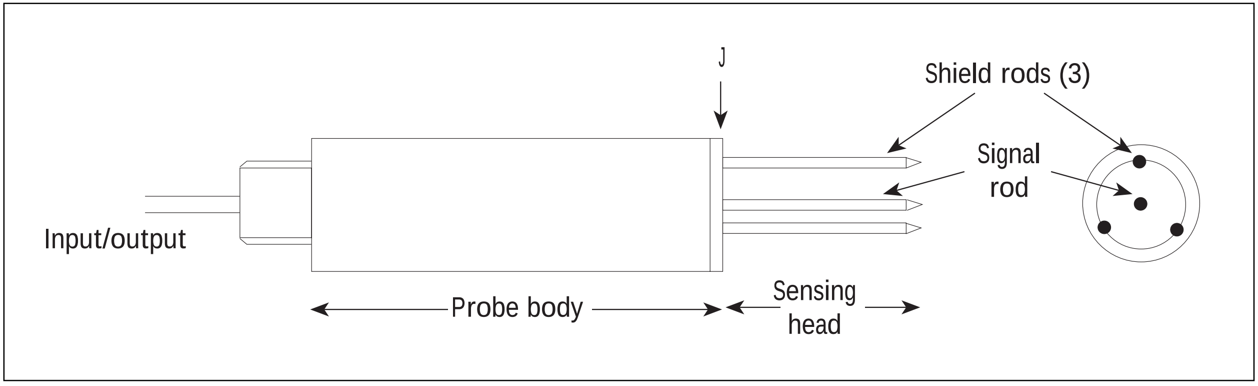
3.1 Theory

The impedance (Z) of a coaxial transmission line is dependent on its physical dimensions and on the dielectric constant of the insulating material:

$$Z = (60/\sqrt{\varepsilon}).\ln(r_2/r_1)$$

where r_1 and r_2 are the radii of the signal and shield conductors respectively.

The ThetaProbe consists of an input/output cable, probe body and a sensing head. The cable provides connection for a suitable power supply and for an analogue signal output. The probe body contains an oscillator, a specially designed internal transmission line and measuring circuitry within a waterproof housing. 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 that depends on the dielectric constant of the matrix into which it is inserted. If this impedance differs from that of the internal transmission line, then a proportion of the signal is reflected back from the junction (J) between the probe array and the transmission line.



This 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 the impedance of the transmission line and Z_M is the impedance of the probe inserted into a matrix, then ρ, the reflection coefficient, is:

$$\rho = (Z_M - Z_L) \,/\, (Z_M + Z_L)$$

The transmission line is designed so that the peak voltage at its start (V_O) is:

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

where a is the voltage amplitude of the oscillator output. The peak voltage at the junction (V_J) is:

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

Therefore the difference in amplitude is:

$$V_J - V_O = 2a\rho$$

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

The linear relationship between the square root of the dielectric constant $\sqrt{\varepsilon}$ and volumetric water content has been established by many authors, including Whalley (1993), White *et al* (1994) and Topp *et al* (1980).

Full background to the technique can be found in Gaskin and Miller (1996).

3.2 Development

ThetaProbes apply a 100MHz sinusoidal signal via a specially designed transmission line to a sensing array whose impedance depends on the dielectric constant of the soil matrix. Because the dielectric constant of water (80) is significantly greater than that of the other soil matrix materials (3-4) and of air (1), the dielectric constant of the soil depends primarily on soil water content. The signal frequency has been chosen to minimise the effect of ionic conductivity.

The internal transmission line is designed to give a delay of $\frac{1}{4f}$ where f is the frequency of the oscillator to maximise the output signal when the probe rods are immersed in water. Additionally, the rod lengths are chosen to be 60mm so as to maximise the standing wave pattern on the transmission line.

Each ThetaProbe is adjusted during manufacture to provide a consistent output when measuring media of known dielectric constants.

The output signal is 0 – 1 V DC for a range of soil dielectric constants from 1 to 32, that is for a range of 0 to approximately 0.5 m^3m^{-3} volumetric soil water content for a generalised mineral soil.

Improvements in the performance of the ML2 compared to the original ML1 are listed in Table 1.

Property	ML1	ML2x
Power supply	7-15v 33mA	5-15v 20mA
Response time	1-10 sec	1-5 sec
Reading stability	Changes due to higher harmonics (200,300MHz) can cause small changes in reading (~ 10mV)	Completely stable
Salinity	Reading affected by soil salinity	Very slight improvement over ML1 - now fully documented in ML2 manual
Sealing	Sealed for continuous burial	ML2 similar but case can be dismantled to allow recalibration or repair

Table 1. Improvements of ML2 over ML1 ThetaProbe.

4. MODELLING THE THETAPROBE PERFORMANCE

4.1 Theory

A theoretical approach has been used to predict the ThetaProbe behaviour given the electrical characteristics of the material surrounding the probe rods. Equations were derived which describe mathematically the amplitude difference produced on the probe's transmission line assuming that a) the transmission line was lossless, b) the oscillator generated a pure sinusoidal signal voltage and c) the output impedance of the oscillator matched exactly the impedance of the transmission line.

The equations were incorporated into a computer programme permitting the effects of altering constructional parameters to be studied.

These included:

- probe constant (geometric factor derived from the sensing rod array).
- amplitude of applied signal.
- frequency of applied signal.
- transmission line impedance
- transmission line delay time
- rod length.

4.2 Results

The predicted response curve for a ThetaProbe is shown in Figure 1.

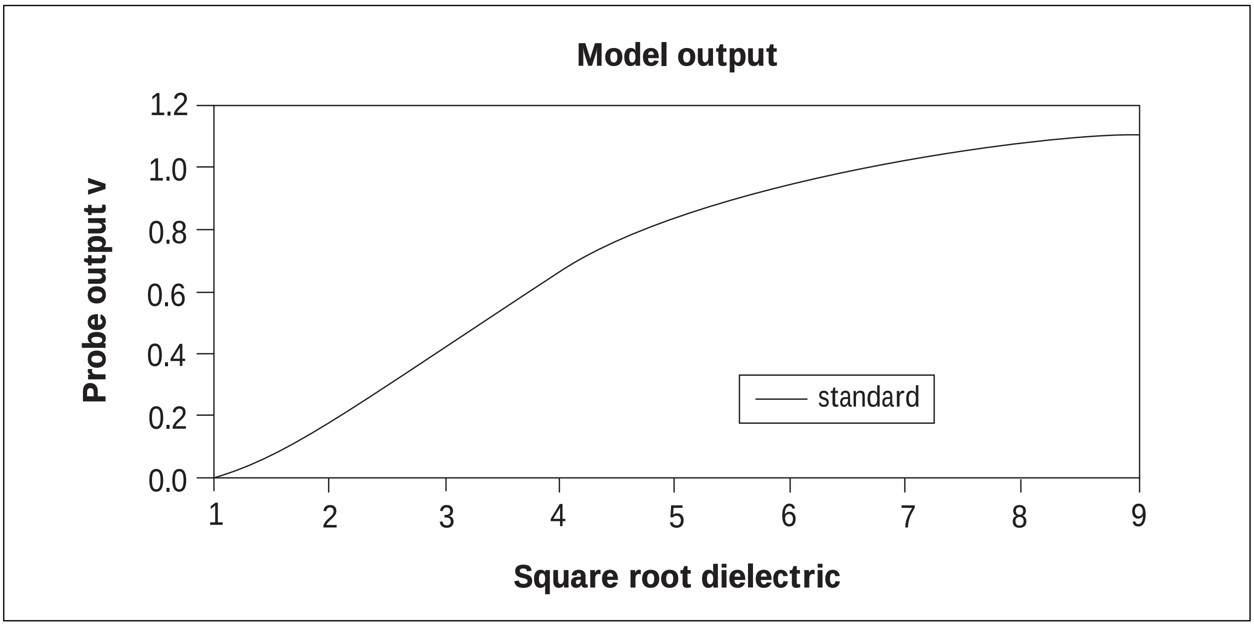


Figure 1. Modelled probe output (V) against refractive index using standard parameters.

The programme was used to predict the changes in the response curve if any of the design parameters were changed. Figures 2a and 2b are the modelled outputs if a) the rod length was allowed to vary between 50 and 70 mm and b) the frequency was allowed to vary from 90 to 110 MHz.

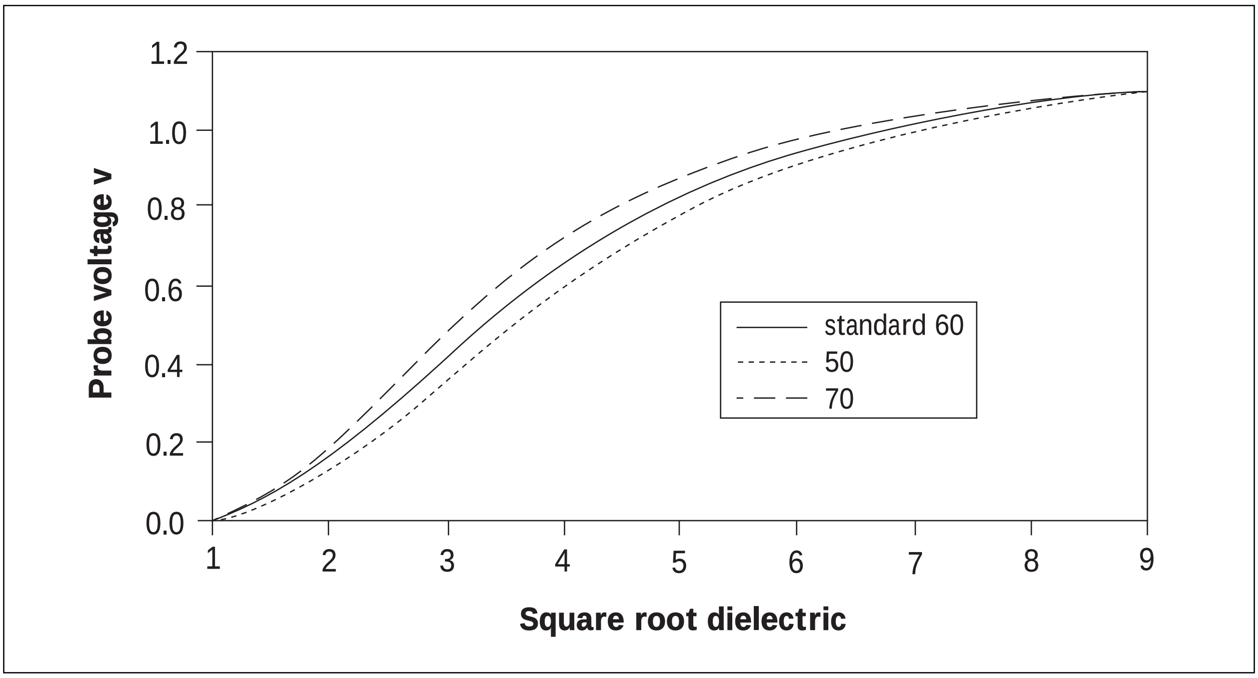


Figure 2a. Modelled output for rod lengths between 50 and 70 mm.

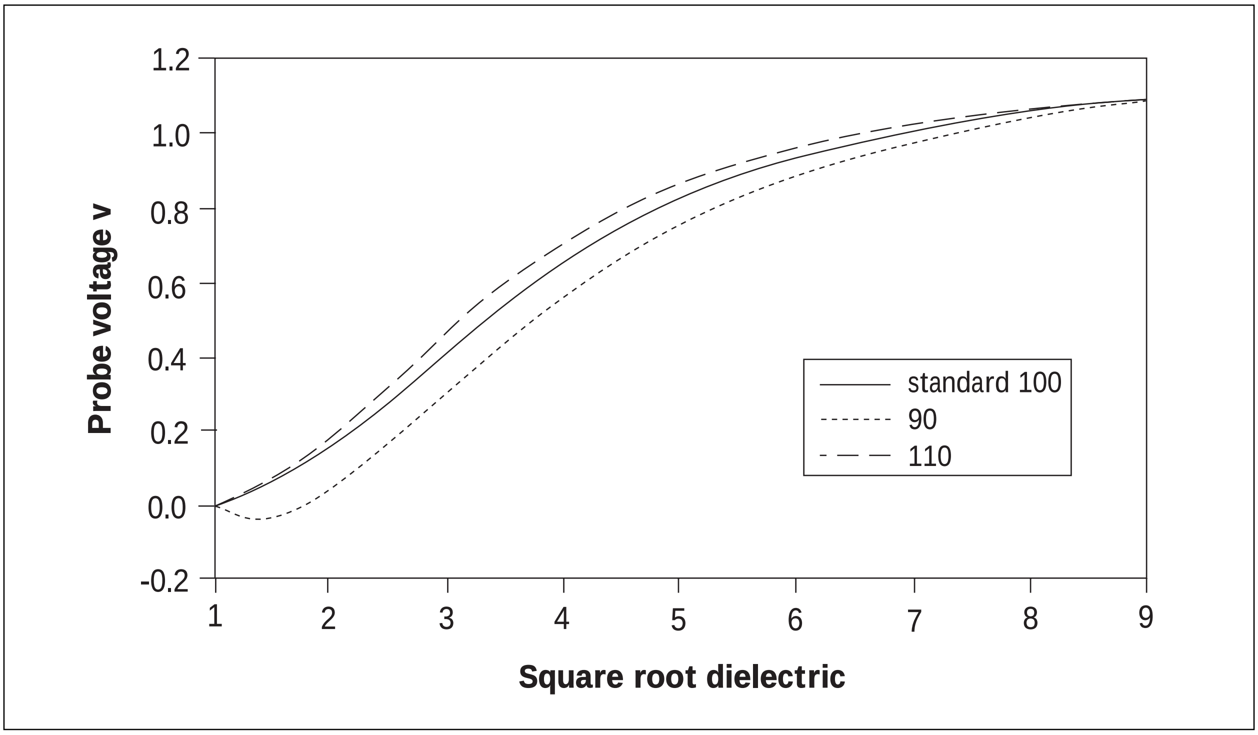


Figure 2b. Modelled output for a range of frequencies between 90 and 100 MHz.

Complete details of the model are given in Gaskin, Miller and Meeusen.

5. THETAPROBE TESTS

5.1 Performance

The original tests on the ThetaProbe ML2 were carried out to assess its performance in pure solvents of known dielectric constants. Results in Figure 3 for triplicate probes show very similar responses to the behaviour predicted by the model.

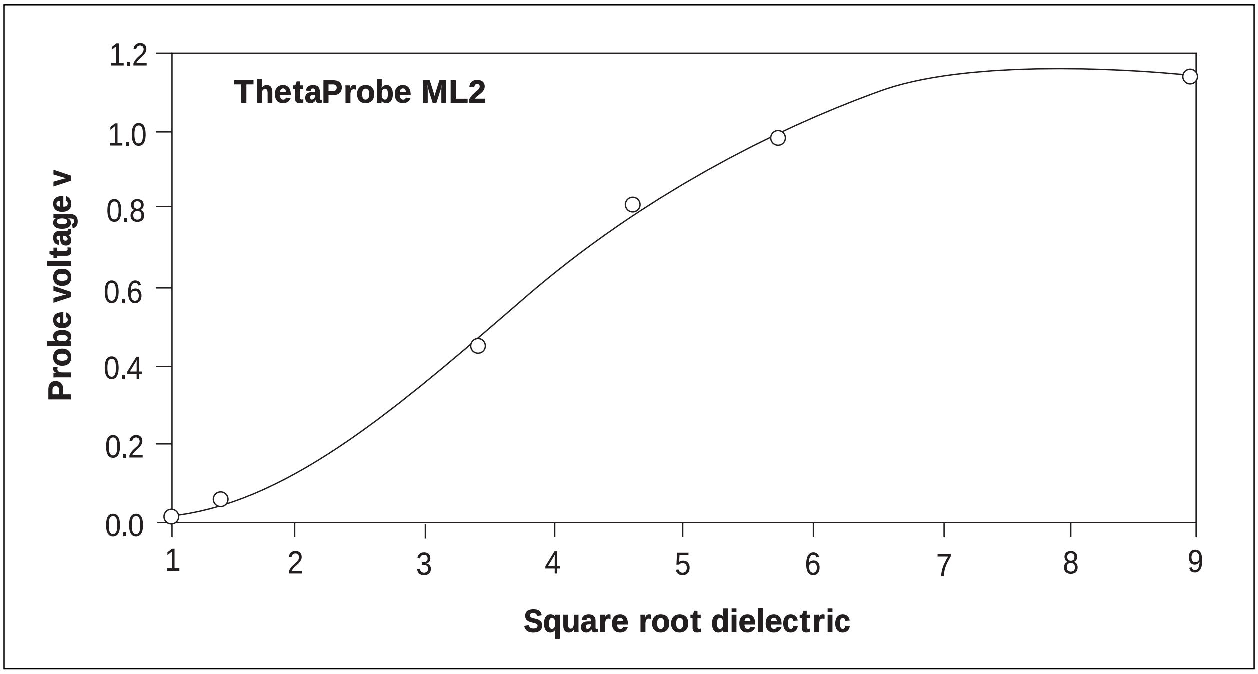


Figure 3. ThetaProbe ML2 output volts for a range of pure solvents of known dielectric constants.

The reproducibility between ML2 ThetaProbes is generally extremely good, normally ±2mV across the voltage range as demonstrated in Table 2.

Square root dielectric	ML2 probe a	ML2 probe b	ML2 probe c
0.00	0.001	0.002	0.001
1.41	0.055	0.058	0.056
3.42	0.448	0.451	0.448
4.63	0.802	0.802	0.803
5.71	0.985	0.985	0.987
8.96	1.138	1.142	1.141

Table 2. Comparative results for three ML2 ThetaProbes output voltages in solutions of known dielectric constants.

The responses vary slightly between ML2 and the original ML1 ThetaProbes probably due to the differences between their respective oscillators. The ML2 produces a purer oscillator voltage waveform with reduced second and fourth harmonics

Their comparative responses in pure solvents are shown in Figure 4. Generally ML1 Thetaprobes give slightly greater voltage outputs than ML2 for the same dielectric solutions, especially around mid range.

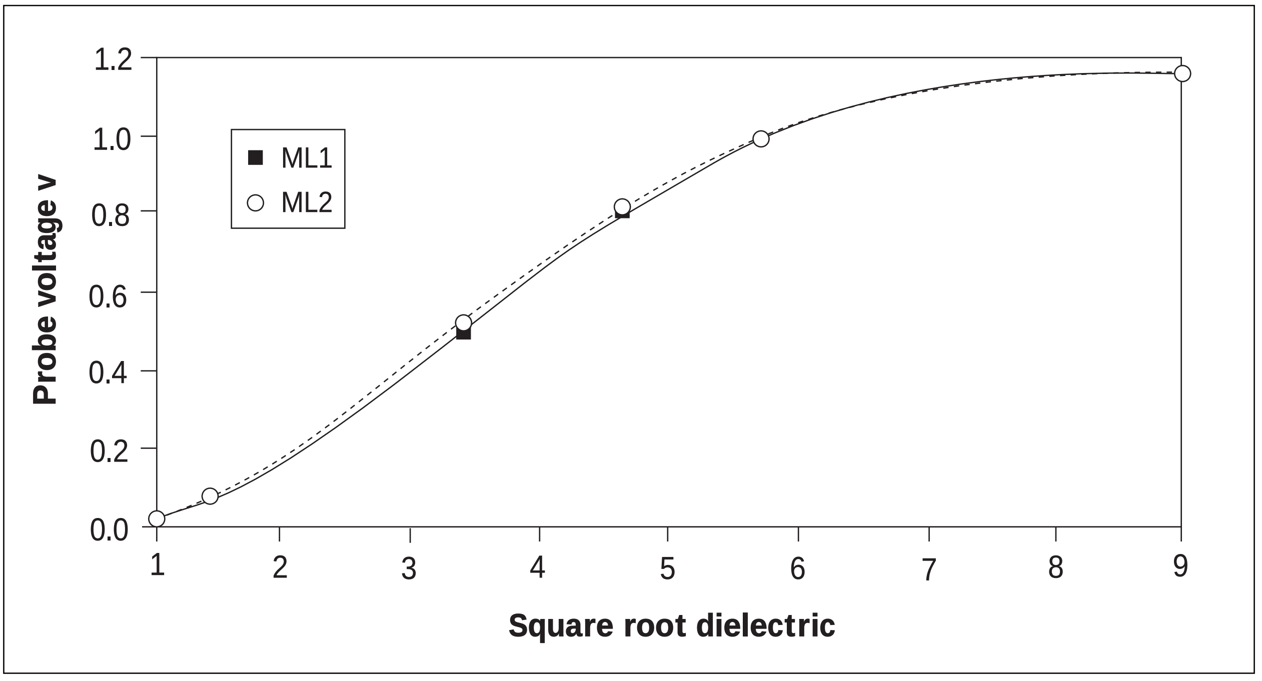


Figure 4. Responses of ML2 and ML1 in solvents of known dielectric constants (ML1 dotted line gives slightly higher outputs especially around mid range).

5.2 Probe Calibration

The relationship between probe output and the square root of the dielectric constant $\sqrt{\varepsilon}$ is exactly the same for all ML2 ThetaProbes and can be calculated from Figure 5. This abbreviated scale covers the most frequently occurring range of probe outputs

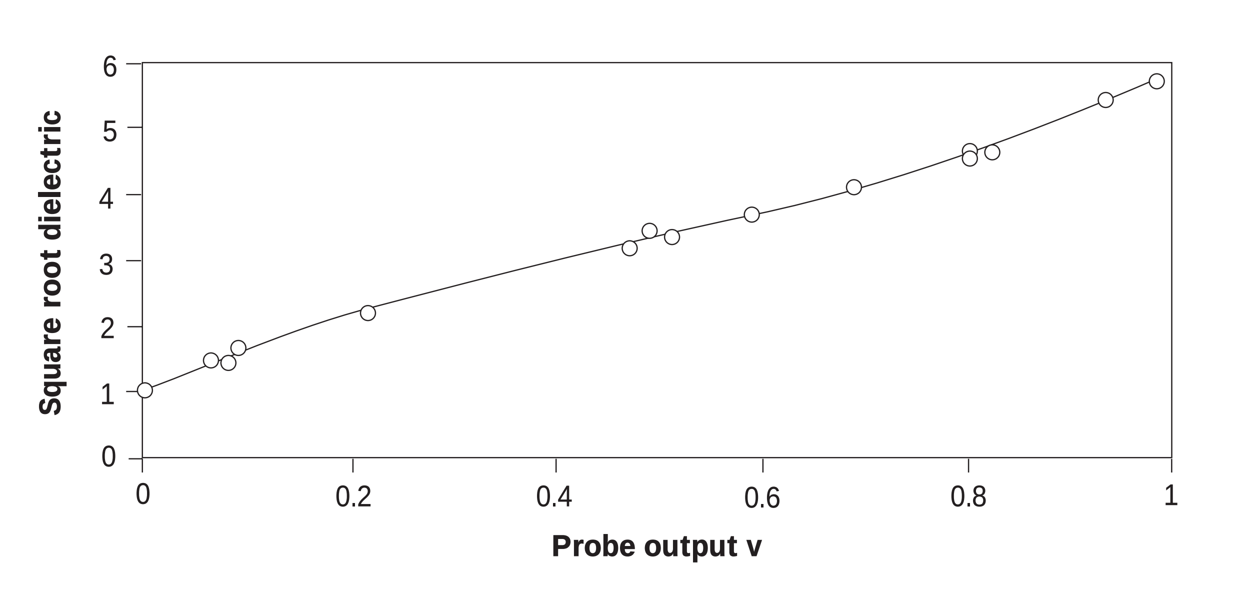


Figure 5. ThetaProbe output for a realistic range of solvents of known dielectric constants.

In the range of 0 to 1 volt, which corresponds to an approximate soil water content of 0 to 0.6 m^3m^{-3}, this relationship can be described either by the linear relationship:

$$\sqrt{\varepsilon} = 4.44V + 1.10$$

or more precisely by the third order polynomial:

$$\sqrt{\varepsilon} = 4.70V^3 - 6.40V^2 + 6.40V + 1.07$$

5.3 Calibration in soils

The relationship between the complex refractive index (equivalent to $\sqrt{\varepsilon}$) and the volumetric water content has been established by many researchers including Whalley, White and Topp. This is shown in Figure 6 for some summary data from those authors.

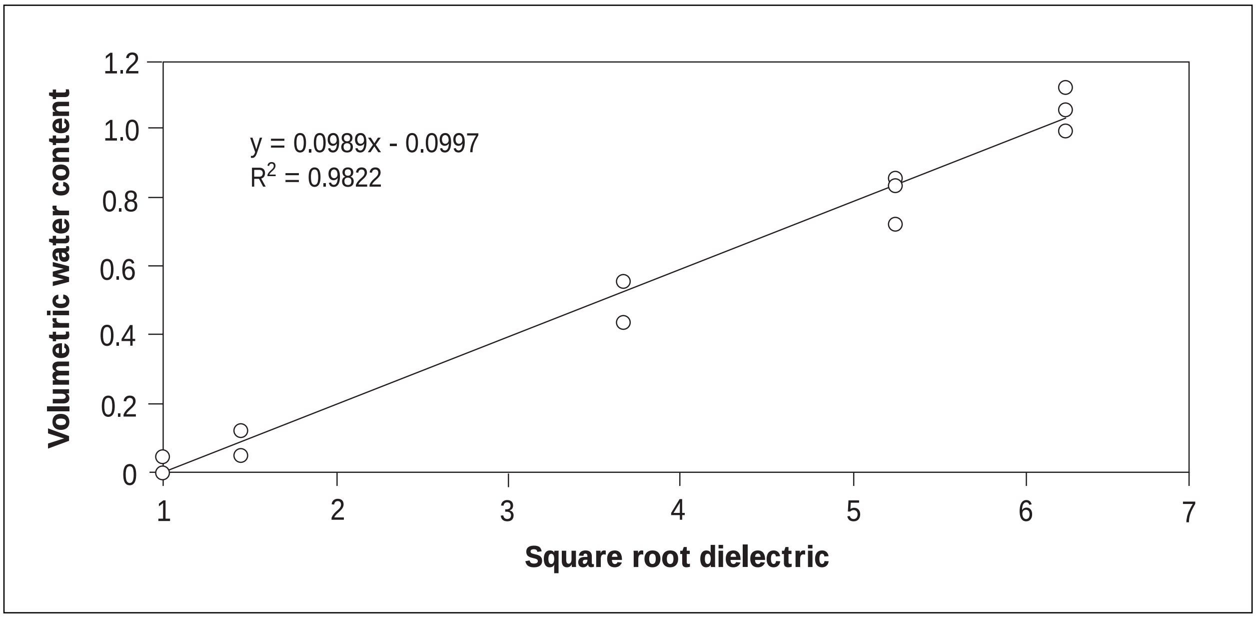


Figure 6. Relationship between refractive index and volumetric water content (m^3m^{-3}).

From previous page $\sqrt{\varepsilon} = a_0 + a_1 . \theta_v$

and therefore $\theta_v = (\sqrt{\varepsilon} - a_0) / a_1$

Since the relationship between the ThetaProbe output (V) and the refractive index has already been established from Figure 5, it is only necessary to determine the two coefficients a_0 and a_1. These can either be calculated from a two-point calibration in dry and wet soils or a generalised calibration can be used as follows:

	a0	a1
Mineral soils	1.6	8.4
Organic soils	1.3	7.7

Soil specific calibration should achieve a typical accuracy of at least ± 0.02 m^3m^{-3}, whereas use of the generalised calibration parameters may lead to errors of the order of ± 0.05 m^3m^{-3}.

Full calibration instructions are included in the Delta-T Devices user manual supplied with each ThetaProbe.

5.4 Soil results

ThetaProbe ML2 responses have been assessed using a range of soils of varying volumetric water content, ranging from highly organic peat soils through to mineral soils. Typical results are presented in Figure 7 comparing values calculated from soil specific calibrations with volumetric soil water content from gravimetric and bulk density calculations. Although these comparisons have practical difficulties in maintaining a constant volume (for bulk density calculation) across a wide range of soil water content, there is general agreement of around ± 0.02 m^3m^{-3}.

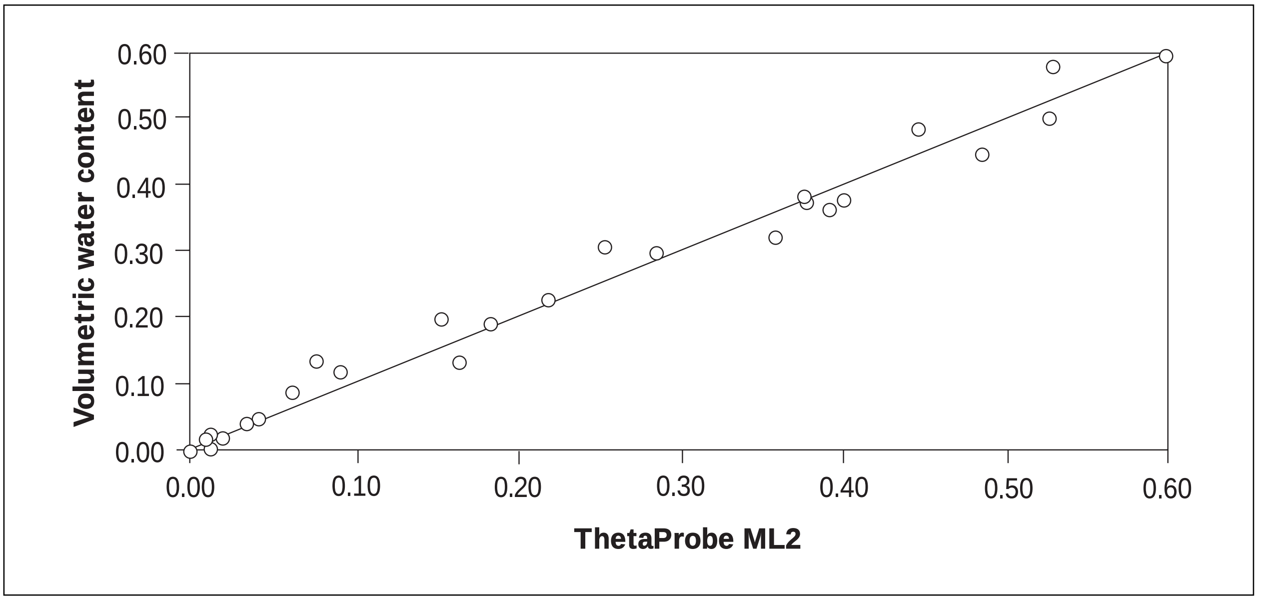


Figure 7. Comparison of volumetric soil water content (m^3m^{-3}) as determined by ThetaProbes and from gravimetric/bulk density measurements.

There are small differences when comparing data derived from ML2 probes with that from the original ML1 probes, probably primarily due to the difference in their oscillator output waveforms (see Figure 4). An example of the respective responses is shown in Figure 8.

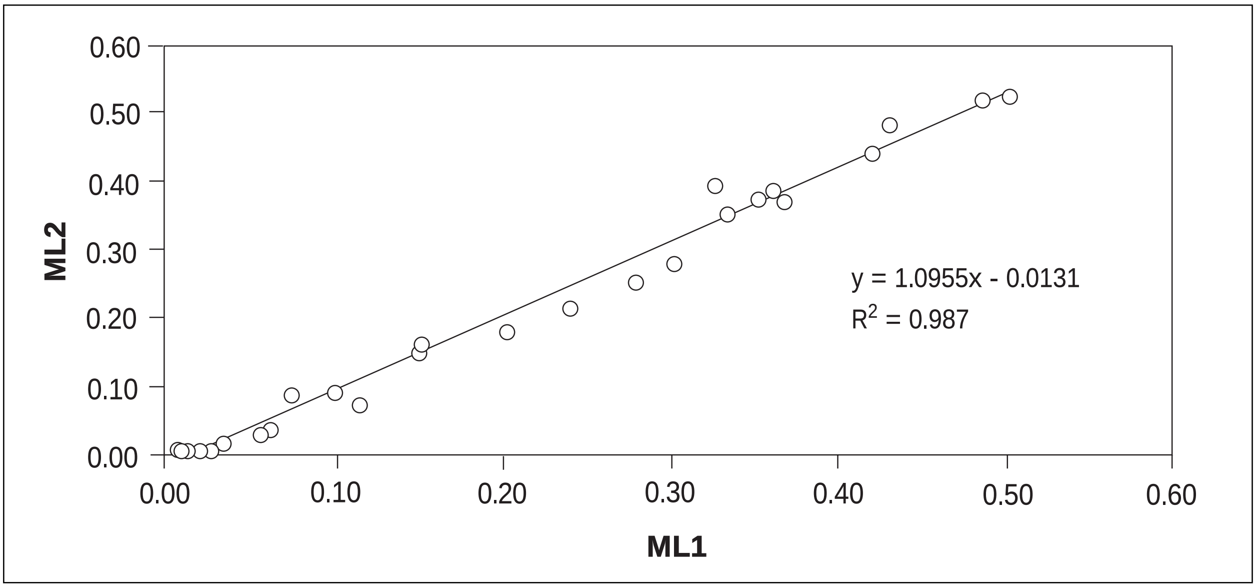


Figure 8. ML2 and ML1 comparisons for a range of volumetric soil water content.

5.5 Sensing volume

The sensing volume of ML1 ThetaProbes was established as being a cylinder of about 60mm long (rod length) by about 60 mm diameter, but this is difficult to determine in practise as it is a function of soil density and particularly of soil water content. However independent tests by Wright confirmed these dimensions, which are also likely to apply to ML2 probes.

Wright also confirmed the stability of the probe output, the fast stabilisation time and the minimal responses to changes in temperature for a range of soils under laboratory conditions for ML1 ThetaProbes.

5.6 Comparison with other techniques

Data comparing ThetaProbes ML1, TDR and neutron probes are shown in Figure 9.

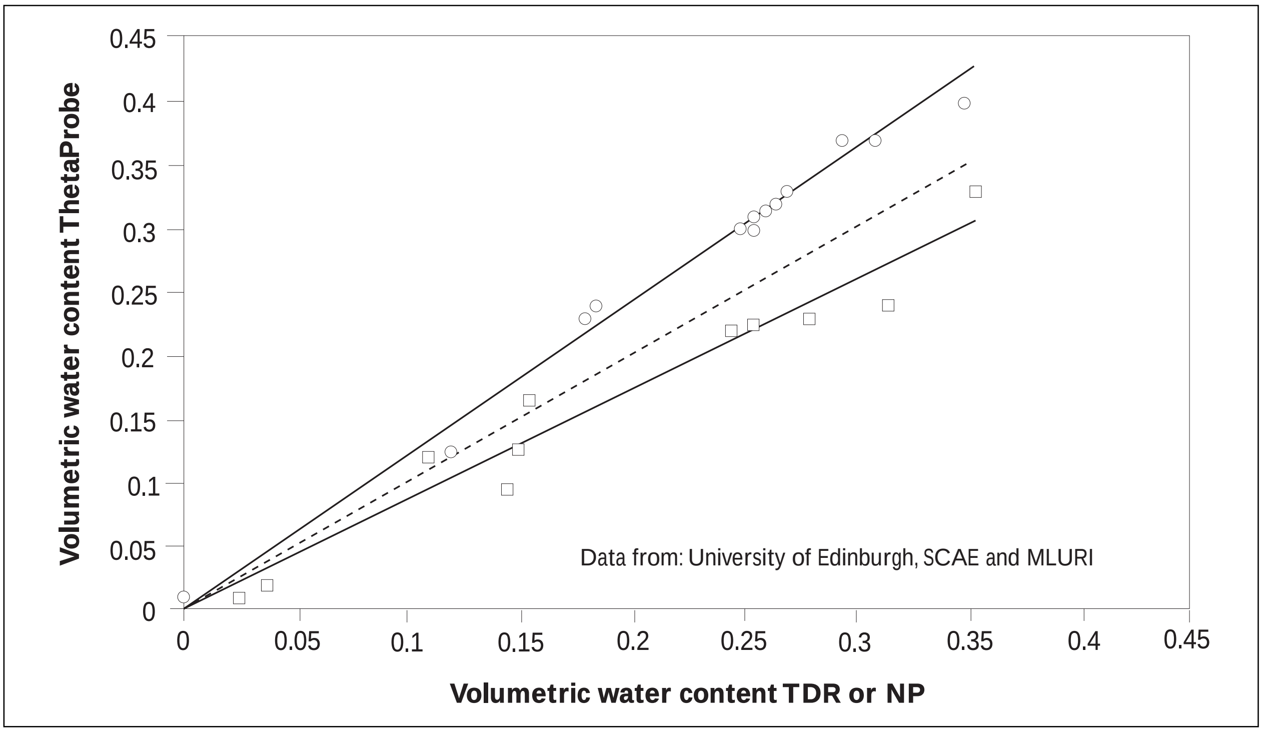


Figure 9. Comparisons between Thetaprobe and time-domain reflectometry (TDR) and neutron probe (NP).

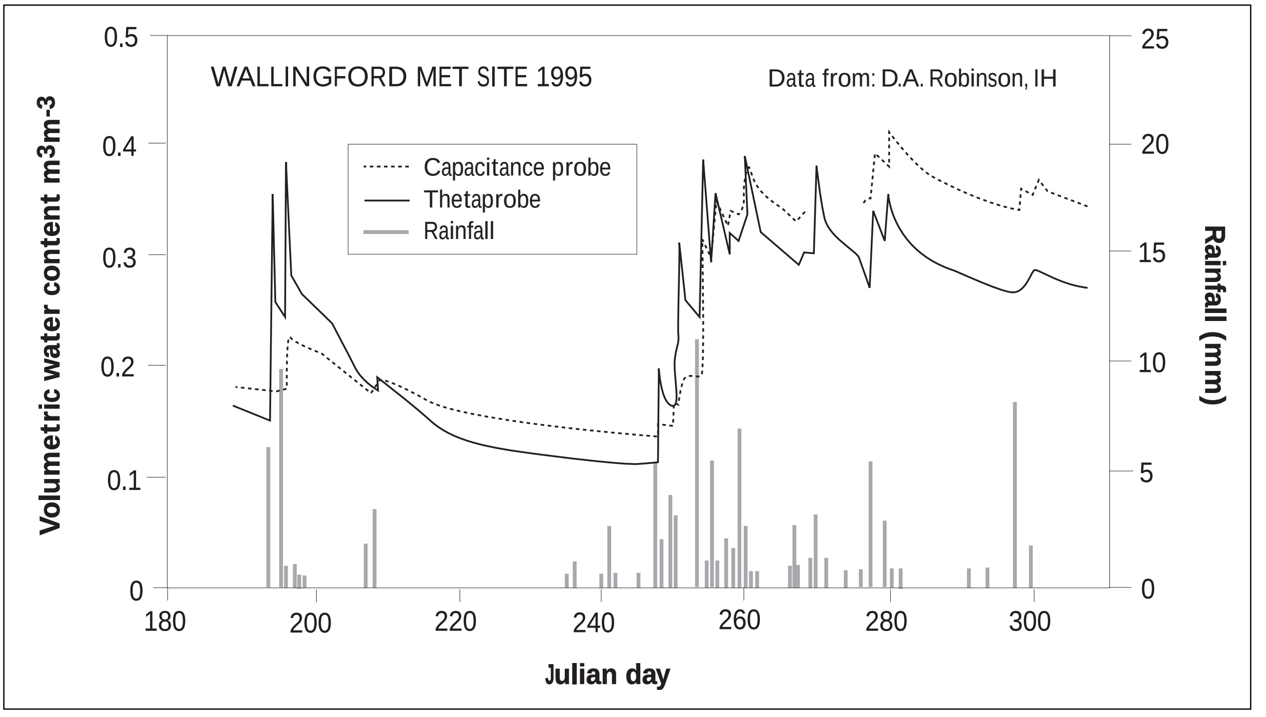


Figure 10. Comparisons of continuous measurement of soil water determined by ThetaProbe and capacitance probe.

6. IONIC CONDUCTIVITY

The output from ThetaProbes, as for all dielectric measuements, is affected by soil salinity. When the material surrounding the probe is conductive, the signals travelling along the probe will be attenuated. Although work has been published on bulk conductivity, it is difficult to predict the bulk conductivity resulting from mixing solutions of known ionic conductivity into simple, inert matrices. This effect is more complex in soils where additional processes, such as ion exchange, will take place.

However, an attempt has been made to use the model (detailed in section 4) to assess conductivity effects. Data in Figure 11 show the theoretical responses in probe output when immersed in solutions of increasing conductivity. The effect is limited and occurs primarily for salinity levels between 0 and 5000 $\mu S\ cm^{-1}$.

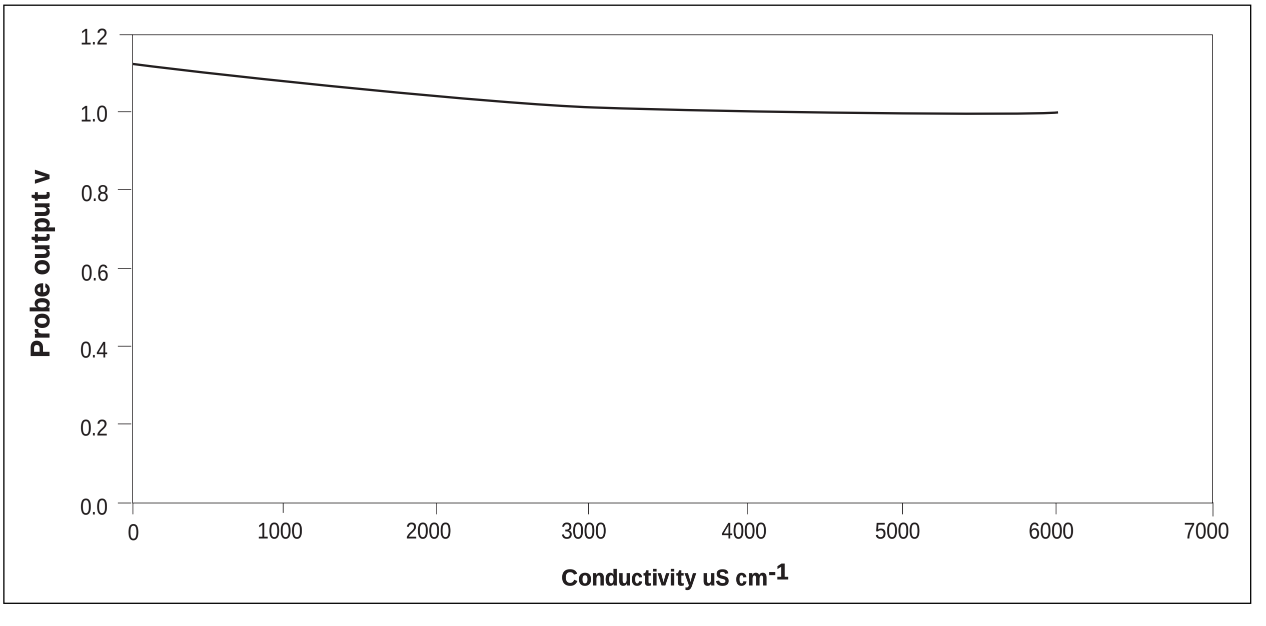


Figure 11. Modelled output for salinity responses.

$10\ \mu S\ cm^{-1} = 1\ mS\ m^{-1}$.

ThetaProbe responses were measured using pure solutions of potassium chloride up to around 20000 µS cm^{-1} in Figure 12.

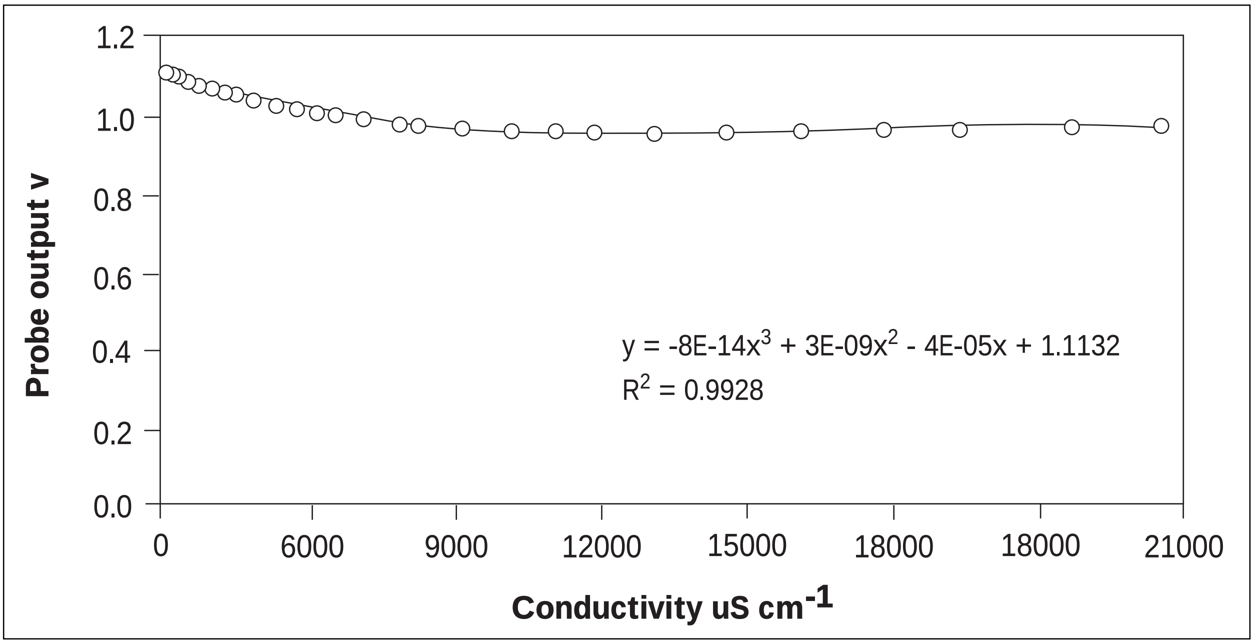


Figure 12. ThetaProbe responses to aqueous solutions of potassium chloride.

These responses are similar to the predicted outputs shown in Figure 13.

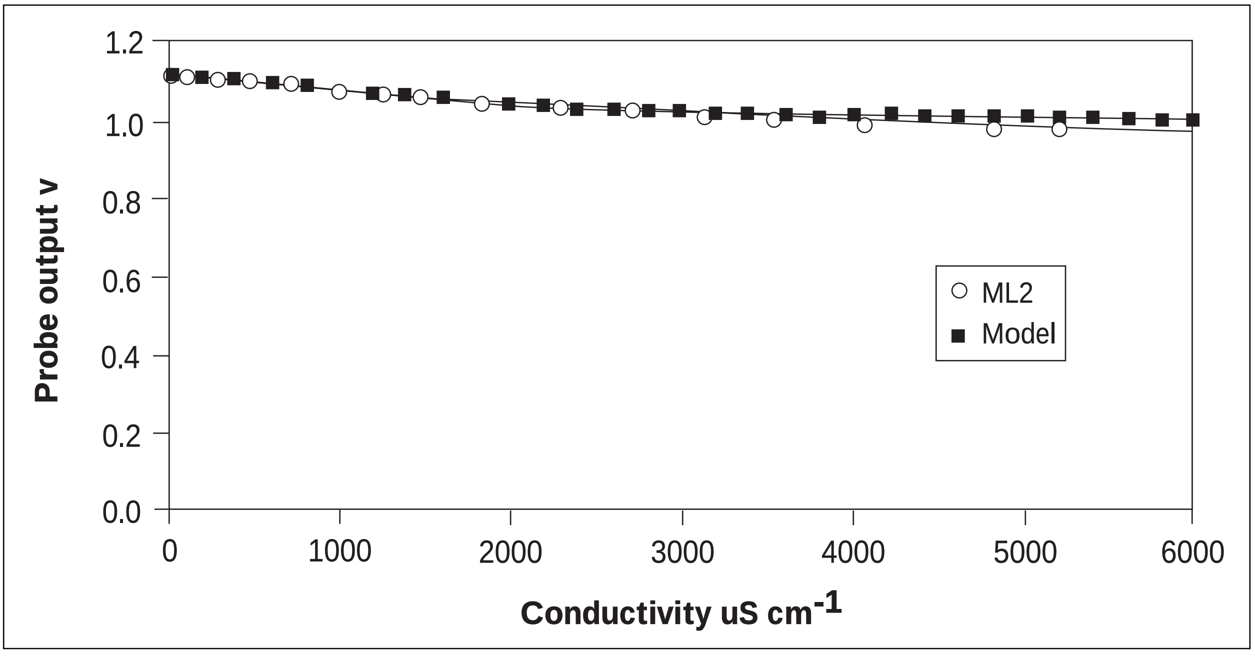


Figure 13. Modelled and actual probe responses to increases in salinity.

Generally, salinity effects will be minimised providing that soil specific calibration has taken place. Changes in salinity due to wetting/drying cycles do not significantly affect results. The only potential interference would be if a calibration were carried out on a soil of low salinity, which was subsequently irrigated with saline water, or vice versa.

Again a full discussion of salinity responses and potential calibration errors are given in the Delta-T users manual and full details of the modelling responses in Gaskin *et al.*

7. INSTALLATION AND DATA CAPTURE

Input requirements are 5-15V DC with a current consumption of 19 to 23 mA. The output signal is 0 to 1 V DC that approximates to 0 to 0.5 m^3m^{-3} volumetric water content.

ThetaProbes can be used to make point measurements by simply inserting into the soil so that all of the rods are fully covered and taking readings from the analogue output either using a meter or logger. The probes can be permanently installed into the soil profile either by using extension tubes or by excavation and back-filling, with periodic data being collected by data logger.

As for all soil water measuring devices, care should be taken to avoid air pockets, stones and channelling water directly onto the probe rods.

Full details of installation, calibration, achievable accuracy and technical specifications are listed in the user manuals supplied with ThetaProbes by Delta-T Devices.

8. FIELD APPLICATIONS

The Macaulay Land Use Research Institute (MLURI) is currently using ThetaProbes in a wide range of field installations. These include projects to investigate the impact of land use changes on catchment behaviour, specifically hydrology and hydrochemistry, the effect of afforestation on sensitive catchments in northern Scotland and as a contributor to the UK Environmental Change Network who have adopted ThetaProbes into their network.

8.1 Environmental Change Network

The UK ECN has currently 11 terrestrial and 42 freshwater sites within its network, including the MLURI Research Stations at Glensaugh and Sourhope. ThetaProbes have been installed at each of the terrestrial sites as part of the automatic weather stations to monitor changes in climate.

Typical temporal changes can be seen in Figure 14 for volumetric soil water content from the ECN ThetaProbe installed at 20cm compared to an alternative site at Glensaugh where probes have been installed in a range of soil horizons throughout the soil profile. Both probes show similar responses with gradual decreases in soil water content followed by wetting up in response to rainfall events in early October.

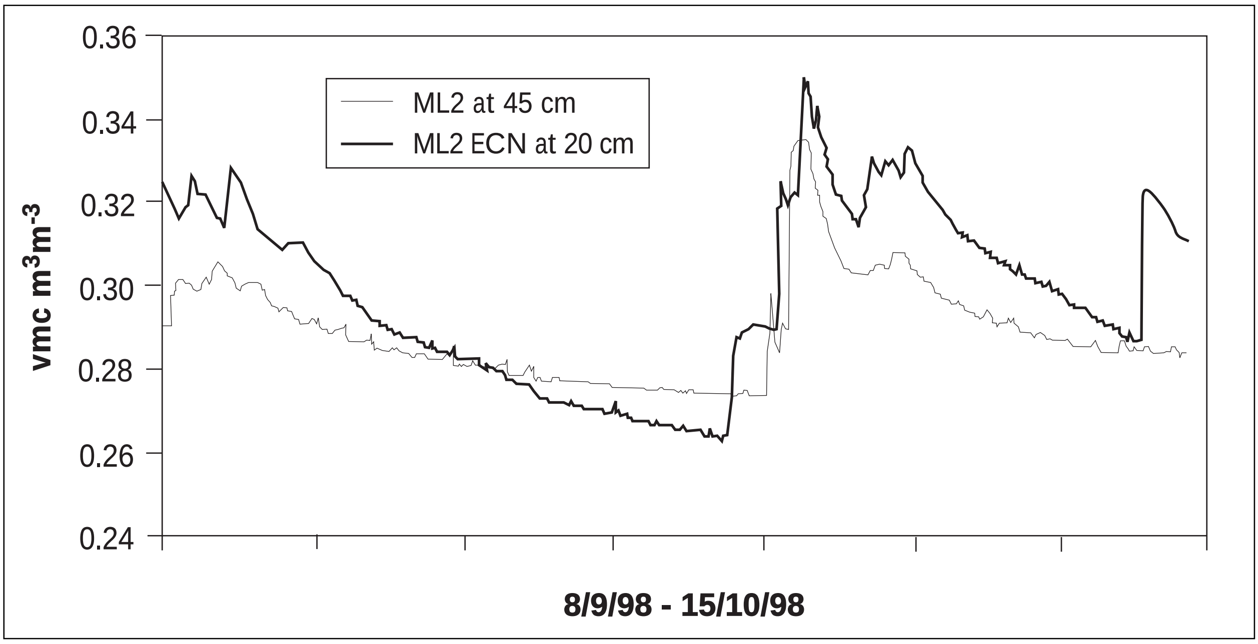


Figure 14. Comparative ThetaProbe responses in volumetric soil water content at two sites at Glensaugh in September - October 1998.

The response of ThetaProbes to rainfall events can be seen in ECN rainfall data and soil water content in Figure 15, where data has been logged at twenty-minute periods. There are extremely fast responses to rainfall inputs dependent on pre-conditions and soil horizon characteristics. For this site, and many upland freely drained soils, there are considerable changes in volumetric soil water content at major interfaces, such as organic to mineral, and at the base of the soil profile.

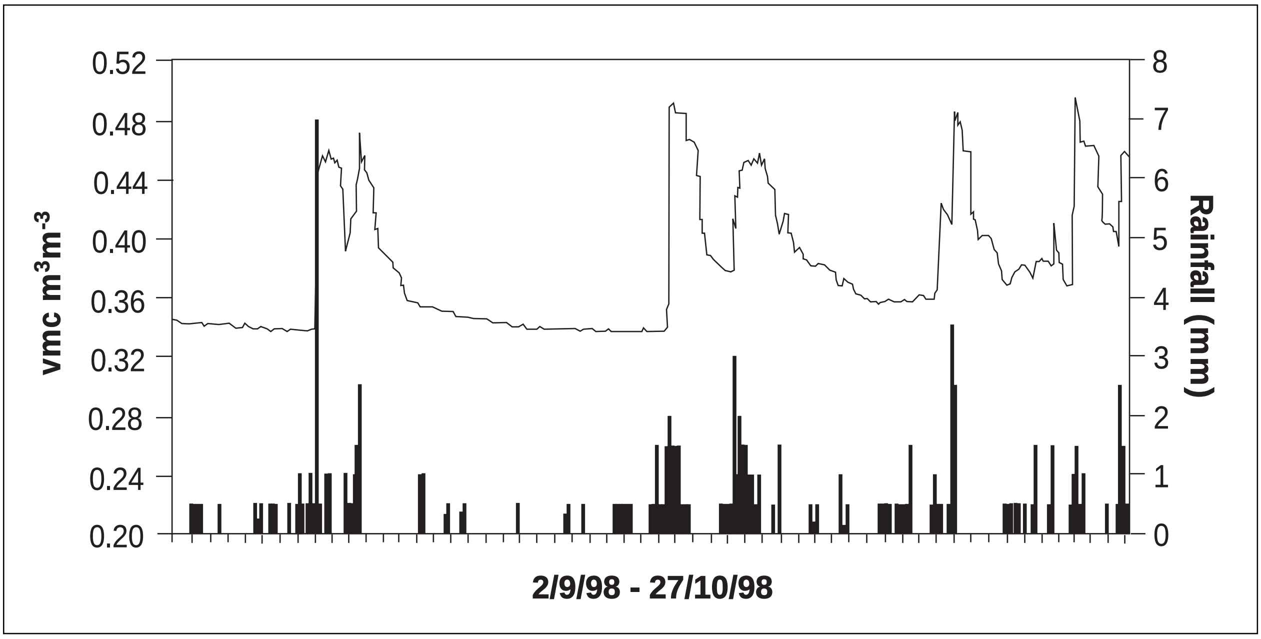


Figure 15. Responses of soil water content (solid line) to rainfall events (histogram) at Glensaugh.

8.2 MLURI Field sites

The relationship between soil water content and stream flow can be illustrated using data from a catchment experiment at Glensaugh in Figure 16. In this example ThetaProbes were installed at selected horizons in soil profiles some distance (200-400 metres) from the catchment outflow gauge. Although there are only relatively small changes in volumetric soil water content they correspond exactly to increases in stream flow.

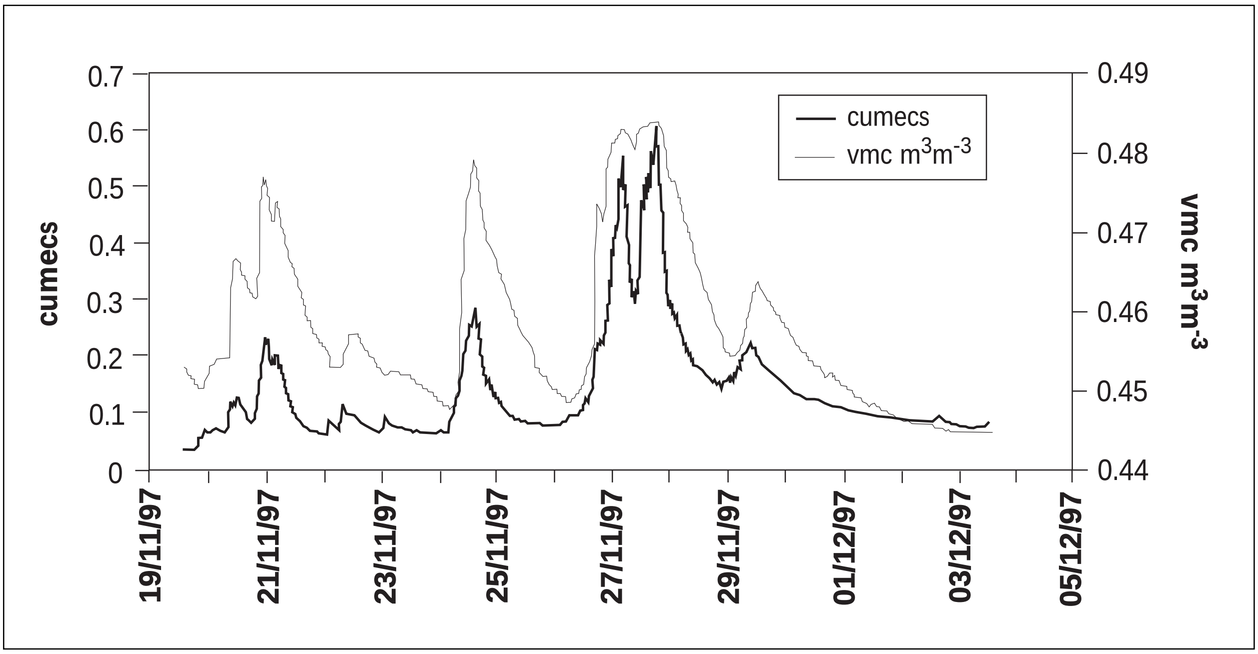


Figure 16. Changes in soil water content in a soil profile some distance from the flow (cumecs) measured at the catchment gauging station.

ThetaProbes are also providing detailed information on catchment soil responses for both organic and mineral soil profiles. For example, Figure 17a shows two ThetaProbe outputs from a) a mineral / organic interface (about 20 cm deep) in a podzolic soil in pit 1 compared to b) the base of an organic peaty soil (around 80 cm deep) in pit 2. Although the changes in volumetric soil water content differ by an order of magnitude, the respective responses are strikingly similar. If these are compared to the main catchment outflow in Figure 17b, their relative contributions to the stream flow can be seen. In this case the pits are separated by about 200m and both are at least 800m from the catchment gauge (catchment size is ~70 hectares).

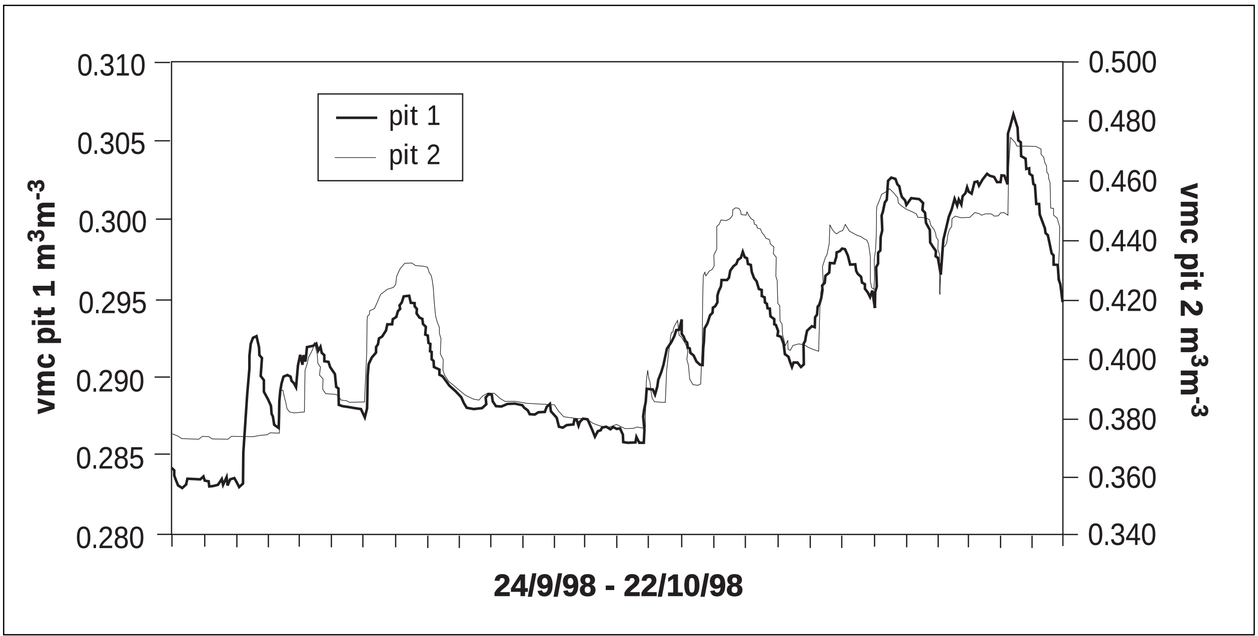


Figure 17a. Comparison of volumetric soil water content from two differing soil types. Pit 1 is a mineral soil whereas pit 2 is an organic peat soil.

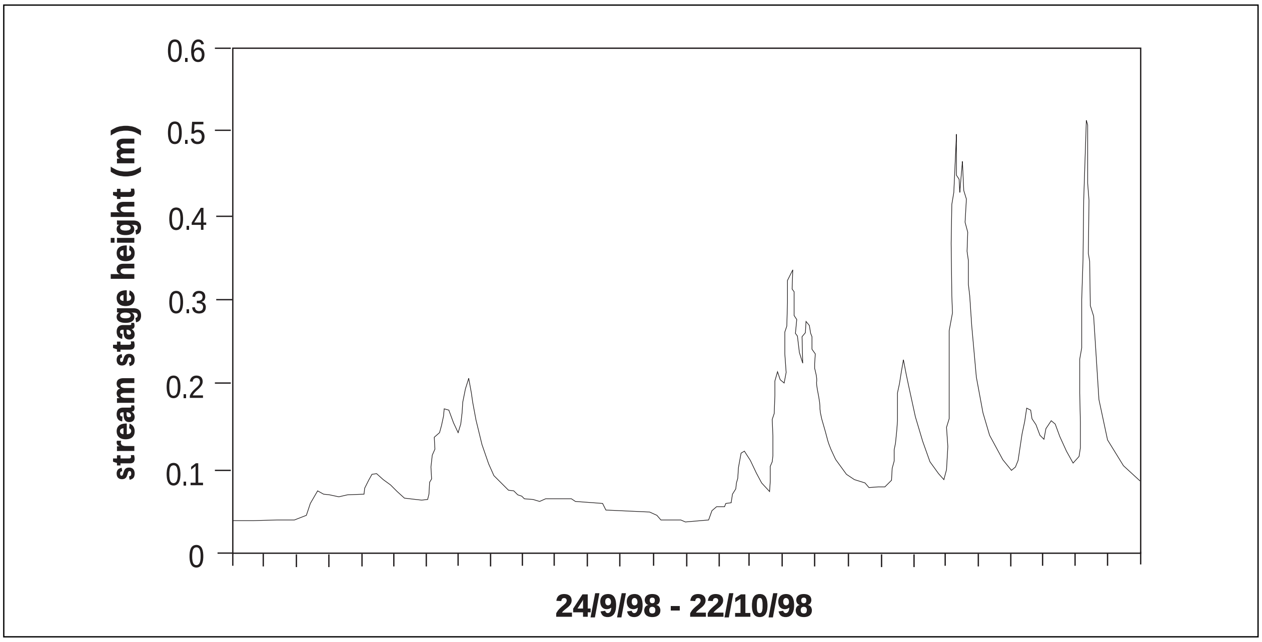


Figure 17b. Catchment stream outflow collecting from soils in Figure 17a.

These data are being used to assess the consequences of land use change, in this case afforestation, on catchment hydrology. Because we are able to continuously monitor these changes in volumetric soil water content both spatially and temporally within catchments even at these remote sites, the data will contribute to the parameterisation and validation of existing hydrological models.

As well as contributing to an improved understanding of catchment hydrology, ThetaProbes can also provide information on drying and wetting up cycles within catchments. For example, data in Figure 18 from a catchment in northern Scotland, demonstrates that the probe output is very stable during the relatively dry period in May 1998 with changes in this soil horizon of only ~0.02 m^3m^{-3}. This was followed by a wetting up period in early June with the soil horizon approaching saturation with subsequent more rapid responses to rainfall.

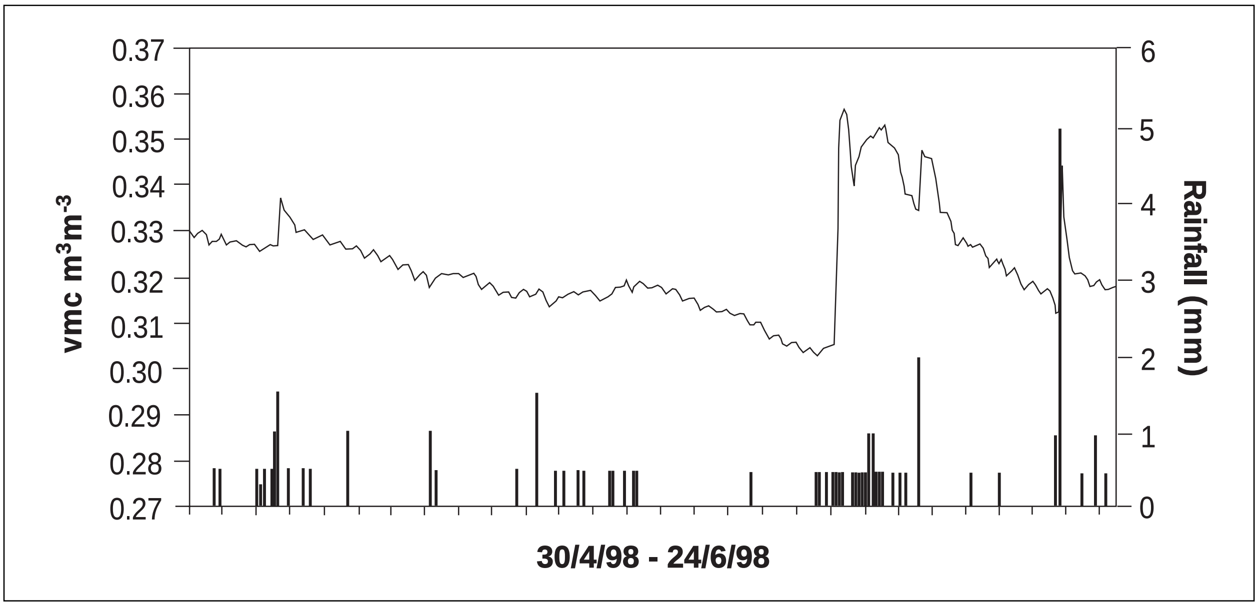


Figure 18. Long-term changes in volumetric soil water content (solid line) at a Highland catchment in relation to rainfall inputs (histogram).

These types of data can contribute to an improved understanding of the role of soil water in catchment responses to both dry periods, as a drought pressure on the water resource, and to flood, as an indicator of catchment water status and potential to respond to rainfall.

Volumetric soil water content can also contribute to the understanding of catchment hydrochemistries, especially when combined with other field measurements.

The installation of ThetaProbes and soil temperature probes at selected plots, along with stream flow gauging allowed the detection of those conditions leading to the loss of nutrients. In this case elevated phosphorus concentrations were determined in stream chemistries some time after P fertilizer had been applied during an afforestation project. Although there were large increases in stream flows during the period of losses, there were minimal changes in soil water content and little indication of major rainfall inputs. However, the inputs to the catchment were primarily due to snow melt and because the soils, especially near the surface were frozen, water was rapidly transported across or near the soil surface. This removed surface particles of fertilizer P into the streams effectively by-passing the soil profile. Data in Figure 19a shows the rapid catchment stream response on 19-20/2/97. The limited response in soil water content near the surface and the soil temperature responses at 20 cm are shown in Figure 19b.

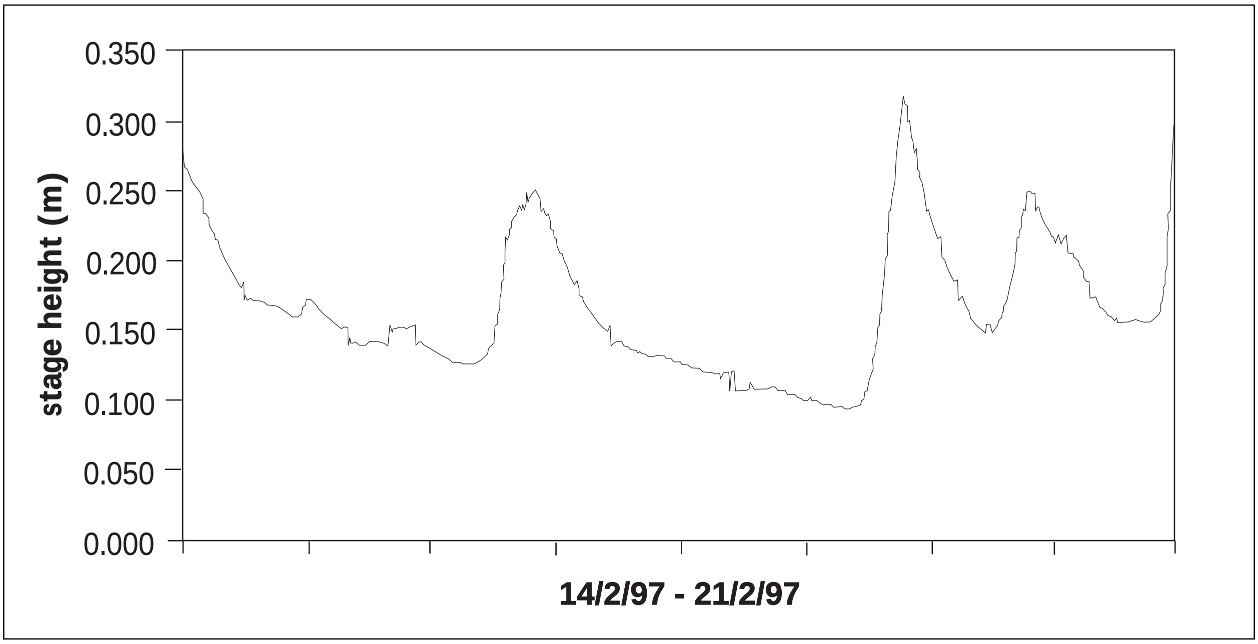


Figure 19a. Catchment stream outflows at Halladale in northern Scotland. The greatest observed losses of P were during the peak flows of 19/2/97.

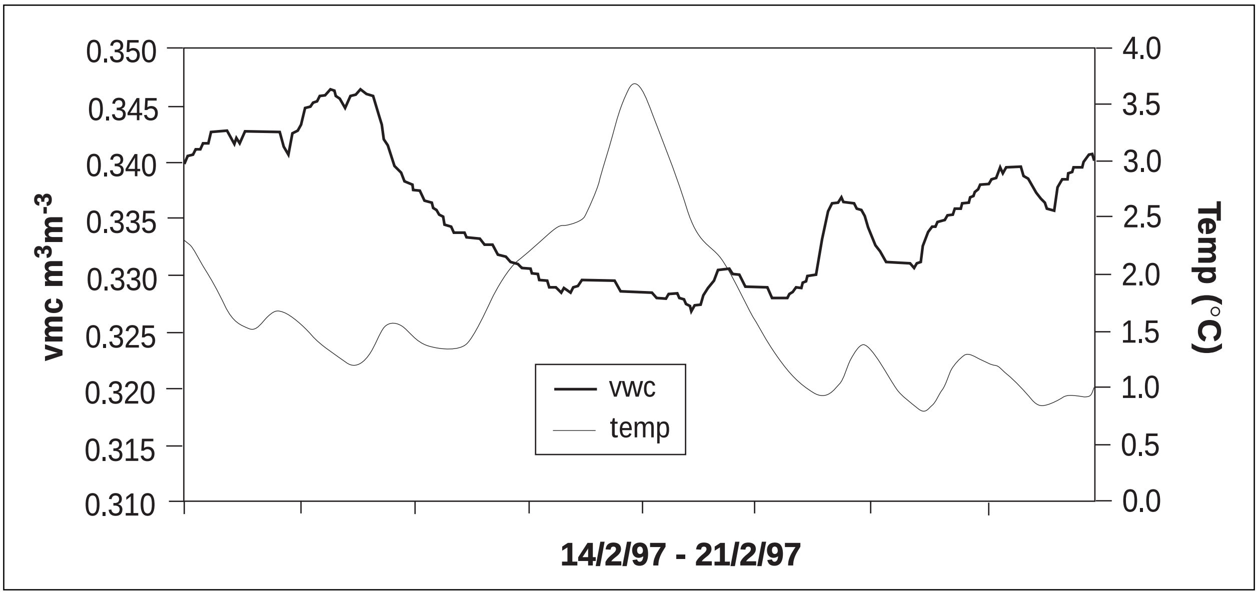


Figure 19b. Near surface changes in soil water content and soil temperatures. Note the low temperature in 19 to 20/2/97 with minimal changes in soil water content.

Stream P concentrations increased from around 0.005mg litre^{-1} to a maximum of nearly 0.080mg litre^{-1} during the peak flows of 19 – 20/2/97.

Further examples of ThetaProbe responses, including linkages to other hydrochemical responses, are illustrated in Miller *et al* and in the original ML1 MLURI Technical note.

9. AVAILABILITY AND CONTACT NAMES

The ThetaProbe ML2x is produced commercially by Delta-T Devices, Cambridge.

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

This Technical note has been produced to share information about the development of the ThetaProbe and its applications with other users. To discuss any aspects of this information please contact either MLURI or Delta-T Devices.

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