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Comparison of soil water measurement using the neutron scattering, time domain reflectometry and capacitance methods

Results of a consultants meeting
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COMPARISON OF SOIL WATER MEASUREMENT USING THE NEUTRON SCATTERING, TIME DOMAIN REFLECTOMETRY AND CAPACITANCE METHODS

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FOREWORD

Soil water is one of the most important requirements in agricultural production. Crop yields are generally more closely related to soil water availability than to any other soil and meteorological variable. The effective use of soil water requires frequent and accurate measurements; the technique should be rapid, reliable, simple, cost effective and non-destructive.

Soil water measurement based on neutron scattering has been a valuable tool for the past 40 years because it possesses many of the above mentioned qualities. However, licensing, training of users and safety regulations pertaining to the radioactive source in these devices make their use preventive and expensive in some situations such as unattended monitoring. Disposal of gauges is also increasingly expensive.

In past years, the high dielectric constant property of water at high frequencies has been used as the basis to estimate the soil water content. The two major techniques that make use of this property are the capacitance sensors and time domain reflectometry (TDR).

— The capacitance approach makes use of radio frequencies for determining soil dielectric constant and thus its water content. Significant progress has been made in this approach, with the ability to carry out profile measurement in recent improvement. However, poor precision, dependant on soil types, salinity and temperature are some of the concern relating to the method, making its use difficult for routine soil water measurements.
— The TDR measures the propagation of an electromagnetic pulse along the transmission lines (wave guides). By measuring the travel time, the velocity and hence the apparent dielectric constant of the soil can be estimated. This then allows the water content of the soil to be determined. Major advances in TDR equipment, probe configurations, data logging and multiplexing, make this a promising technique for point specific monitoring of soil water.

In view of the restrictive use of neutron probes, the rapid advancement and the decreasing cost of the non-nuclear methods in recent years, there is a need to compare these methodologies in order to formulate recommendations and establish guidelines for future uses. The objectives of the consultants meeting, as defined by the IAEA in agreement with its mandate, were:

— To compare the advantages and disadvantages in the various soil water measuring techniques.
— To consult on the procedures for adopting alternative techniques for soil water measurement in the IAEA's future research and training programmes.

This technical document is intended as a guide to those choosing a water measurement technology, however, a point by point comparison between the technologies is not presented here. The individual reports presented at that meeting are contained in this publication which, as a comprehensive treatment of the subject, is expected to serve as an invaluable source of information for future agricultural research involving soil water balance evaluation and soil water content monitoring. The IAEA officers responsible for this publication were P. Moutonnet and L.K. Heng of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. The assistance of A.R.J. Eaglesham in the preparation of this publication is gratefully acknowledged.

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SUMMARY

Soil water is essential for plant growth and is the vehicle for solute transport, including nutrients and soil contaminants. Accurate measurement of soil water is crucial for the better management of irrigation water and rainfall capture. The soil moisture neutron probe (SMNP), based on neutron scattering by the hydrogen atoms of water, was developed about 40 years ago, and has progressively become the most popular device for surface and sub-surface soil water content measurement. However, due to the mounting pressure against the utilization of any radioactive source, it is becoming increasingly difficult and expensive to use the SMNP. More recently, non-radioactive devices have been developed, including time domain reflectometry (TDR) and capacitance probes (CP). Both devices measure the dielectric capacity of moist soil in situ. Nevertheless, the efficacy of these new technologies is the subject of debate.

Therefore, as part of its normative function, the Soil and Water Management & Crop Nutrition Section of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture organized a consultants meeting of internationally recognized experts to compare the advantages and disadvantages inherent in the various soil water measuring techniques, and to advise the IAEA on the appropriate use of such techniques in its future research and training programmes. This technical document contains the experts' state-of-the-art reviews and their synthesis and analysis of available scientific information, including a comprehensive bibliography, of the performance and safety aspects of the three soil moisture measurement technologies.

The experts considered the following aspects:

— *Precision of soil water content needed.* If an indication as to whether the soil is wet or dry is all that is needed, then most technologies will work satisfactorily if installed intelligently in the root zone, taking care to avoid changing the soil water conditions adjacent to the measurement point. If greater precision is required then the following criteria need to be addressed.

— *Soil texture.* Most technologies respond differently in soils of different clay content. One then needs to know if a technology is: (a) insensitive and does not require calibration, (b) sensitive but gives good accuracy and sensitivity to water content change if calibrated, or (c) will not give good sensitivity to water content in certain soil textures or certain water content ranges.

— *Variation of clay content across the field and/or down the soil profile.* This variation is the primary source of experimental error when measuring water content. Some knowledge of the range and scale of this source of error is essential for experimental design. The range of clay content will determine the highest and lowest values of water content at a given level of field dryness. This variability may be at a centimetre or metre scale (as in cracking clay effects) or on a scale of hundreds of metres (as in variation of soil types across a field). The critical question then is: How many soil water content measurements will be required to get an acceptable measure of soil water content in this field? This decision cannot be made without a minimal survey to measure variability.

— *Precise measurement of a small volume of soil compared with the average over a large volume.* This refers mainly to the SMNP which cannot give precise values for thin layers in texture-variable soils.

— *One-dimensional (e.g. in water balance of a cereal crop) versus a 3D problem (e.g. vines with a cover crop between rows).* Is lateral variation in soil water a significant factor in the experiment? This substantially affects the number of measurement points required per treatment.

— *Salinity of the soil water.* Many sensor technologies fail to work or require special sensors or special techniques to obtain useful results in saline conditions.

— *Gravel soils or existence of gravel layers.* Few sensors work well in gravely soils.

— *Presence of iron or other substances.* This may affect the technology chosen or the need for in situ calibration.

— *Necessity to automate field water content measurement.* Applications where dynamic changes are important require automatic logging techniques, particularly when the event to be studied is unpredictable. However, in most field crop water balance studies, automatic logging of water content is usually unnecessary.

— *Cost.* This needs to be considered at different levels:
  - initial setup cost — purchase of minimal equipment, training/licensing of supervisors/operators, review of literature to reliably use the device;
  - incremental cost of additional measurement points — purchase of additional sensors. installation of access tubes, labour costs to measure additional points;
  - cost of automation of data collection;
  - cost of equivalent installations in different technologies sufficient to provide a measure of field water content at the required level of precision;
  - cost of converting raw data to final measurement (labour or suitable software).

The level of sophistication of technologies alternative to the SMNP has grown considerably in the past few years. These technologies can produce good measures of soil water content when used with skill and in situations appropriate to the technology. Most of these technologies also have the substantial advantage of being able to take automatic readings over time (loggability), and do not have the difficulties of usage and transport imposed by the radiation safety requirements controlling the use of the SMNP. Both TDR and capacitance methods, originally developed as 'single point' sensors, have now been produced in forms which allow easy installation to measure a soil water content profile in the same manner as the SMNP (however the accuracy and reproducibility of these profiling devices has still to be proven). Each of these technologies will certainly play an increasingly important role in soil water estimation in the future. However, there is concern that most manufacturers (and some researchers) are presenting their preferred technology as appropriate for all conditions, which is unlikely to be true, at least in the immediate future. All of these technologies have soil, plant and functional environments where they will work well, but equally, there are environments where particular devices will perform badly. Indeed there are circumstances for all the devices, including the SMNP, where they will give measures of soil water content and soil water usage, which are inaccurate.

At present there is ongoing research into increasing the volume of measurement of capacitance technologies, devising ways to improve TDR response in saline situations and efforts with both technologies to improve measurements from moisture profiling systems. Before these technologies can mature, there needs to be more reporting of research on their performance against the chosen reference method, the SMNP. This information is being accumulated slowly. Unfortunately, as with the SMNP in the past, it will be much more difficult for the novice user to find out the difficulties and problems in using these technologies as users seldom publish their mistakes. For information like this, we are dependent upon the responsibility of suppliers and word of mouth from colleagues. A good test of the maturity of each of these technologies would be to give sets of instruments (with manufacturers instructions only) to a group of inexperienced graduates in soil science or agriculture and have them measure soil water in a field, and then compare the results with volumetric water content from soil samples taken by a competent, experienced technician. Ideally, of course, this experiment should be repeated in different soil environments.

The consultants did not recommend replacement of the SMNP as the preferred soil water measurement technology at this stage. The decision was based on three factors:

The ability of the SMNP to average soil water content over a large volume of soil. The primary difficulty for field measurement of soil water is its variability across the field and down the soil profile. The second most significant problem is that of modification of the soil properties in the measurement zone during the installation process, such that it is no longer representative of the surrounding soil. For most applications, the large sampling volume of the SMNP presented substantial advantages over alternative technologies in dealing with these two problems.

The stability, reliability and ease of effective use of the technology. It was felt that the SMNP was the technology most likely to provide the best measure of soil water content under 'average' field conditions in the hands of a novice user. While the alternative technologies could produce equivalent results without the problems presented by radiation safety laws it was felt that reliable results could not be obtained without knowledge and experience beyond that likely in the average user.

The maturity of the technology. The SMNP, like all other methods, is affected by a number of soil properties and installation problems. Unlike other technologies, these problems are well understood and documented widely enough to enable the conscientious user, even a novice, to read about them with little difficulty.

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SOME ASPECTS OF TIME DOMAIN REFLECTOMETRY, NEUTRON SCATTERING, AND CAPACITANCE METHODS FOR SOIL WATER CONTENT MEASUREMENT*

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Abstract

Soil-water measurements encounter particular problems related to the physics of the method used. For time domain reflectometry (TDR), these relate to wave form shape changes caused by soil, soil water, and TDR probe properties. Methods of wave form interpretation that overcome these problems are discussed and specific computer algorithms are presented. Neutron scattering is well understood, but calibration methods remain critical to accuracy and precision, and are discussed with recommendations for field calibration and use. Capacitance probes tend to exhibit very small radii of influence, thus are sensitive to small-scale changes in soil properties, and are difficult or impossible to field calibrate. Field comparisons of neutron and capacitance probes are presented.

1. AUTOMATIC TDR WAVE FORM INTERPRETATION

Time domain reflectometry became known as a useful method for measurement of soil water content and bulk electrical conductivity in the 1980s through the publication of a series of papers by Topp, Dalton, Dasberg and others [1–5]. Automated TDR systems for water-content measurement were described in the late 1980s and early 1990s by Baker and Allmaras [6], Heimovaara and Bouten [7], Herkelrath et al. [8], Evett et al. [9], and Evett [10]. Commercial systems became available in the late 1980s and continue to evolve with TDR probes, multiplexers, and instruments available from a few companies, usually with proprietary and fairly rudimentary software interfaces embedded in proprietary data-acquisition units. A few papers have been published describing some aspects of wave form interpretation, notably Topp et al. [11], Baker and Allmaras [6], and Heimovaara [12]. Evett [13] described the TACQ computer program for controlling an automatic TDR system and interpreting wave forms. Wave form interpretation is a particular difficulty of the TDR method, and robust computer algorithms for interpretation are critical for unattended, automatic data acquisition. Several soil, soil water, and TDR probe properties influence wave form shape and the robustness of interpretation methods, and are discussed here. Discussion continues on graphical algorithms for automated wave form interpretation, used in the TACQ program, that respond to these influences.

1.1. The TDR wave form and relationship to the probe

In the TDR method, a very fast rise time (approximately 200 ps) step voltage increase is injected into a wave guide (usually coaxial cable) that carries this pulse to a probe placed in the soil or other porous medium. In a typical field installation, the probe is connected to the instrument through a network of coaxial cables and multiplexers. Part of the TDR instrument (e.g., Tektronix TDR cable tester) provides the voltage step and another part, essentially a fast oscilloscope, captures the reflected wave form. The oscilloscope can capture wave forms that represent all, or any part of, the wave guide (this includes cables, multiplexers and probes), beginning from a location that is actually inside the instrument and ending at the instrument's range (e.g., 500 m or about 5.5 μs for a Tektronix cable tester).

For example, Fig. 1 shows a wave form that represents the wave guide from a point inside the cable tester, before the step pulse is injected, and extending beyond the pulse injection point to a point

along the cable that is 4.5 m from the cable tester. The step nature of the pulse is clear. The relative height of the wave form represents a voltage, which is proportional to the impedance of the wave guide. Although most TDR instruments display the horizontal axis in units of length (a holdover from the primary use of these instruments in detecting the location of cable faults), the horizontal axis is actually measured in units of time. The TDR instrument converts the time measurement to length units by using the relative propagation velocity factor, Vp, which is a fraction of the speed of light in a vacuum. For a given cable, the correct value of Vp is inversely proportional to the permittivity, ε (dimensionless), of the dielectric (insulating plastic) between the inner and outer conductors of the cable:

$$Vp = v/c_o = (\varepsilon\mu)^{-0.5} \quad (1)$$

where

v is the propagation velocity (m s^{-1})of the pulse along the cable,
c_o is the speed of light in a vacuum (m s^{-1}),
and μ is the magnetic permeability (usually very close to unity) of the dielectric material.

The amount of the wave form visible on the screen is determined by both the Vp and the distance per division setting, the latter of which determines the width of the instrument display in length units.

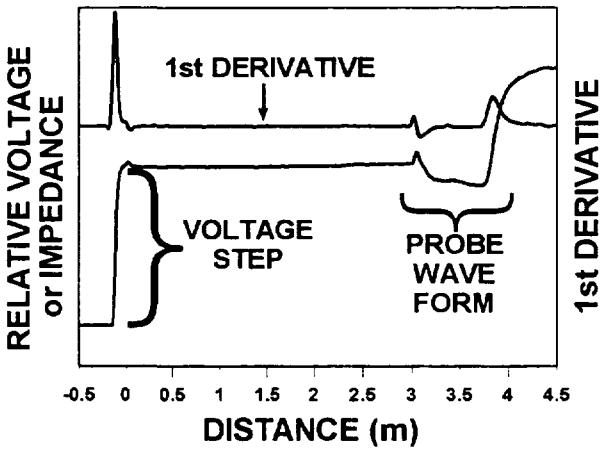

FIG. 1. Plot of wave form and its first derivative from a Tektronix 1502C TDR cable tester set to begin at -0.5 m (inside the cable tester). The voltage step is shown to be injected just before the zero point (BNC connector on instrument front panel). The propogation velocity factor, Vp, was set to 0.67. The Vp value multiplied by the speed of light in a vacuum gives the speed of the signal in the coaxial cable connected to the instrument. At 3 m from the instrument a TDR probe is connected to the cable.

The TDR method relies on graphical interpretation of the wave form reflected from just that part of the wave guide that is the probe (Fig. 2). Baker and Allmaras [6] described how the first derivative of the wave form could be used to find some of the important features related to travel time of the step pulse. These and other features are illustrated in Fig. 3. An example of graphical interpretation of the wave form, for a 20-cm TDR probe in wet sand, shows how tangent lines may be fitted to several wave form features (Fig. 4). Intersections of the tangent lines define times related to i) the separation of the outer braid from the coaxial cable so that it can be connected to one of the probe rods, t1.bis; ii) the time when the pulse exits the handle and enters the soil, t1; and iii) the time when the pulse reaches the ends of the probe rods, t2. The time taken for the step voltage pulse to travel along the probe rods, t_t = t2 - t1, is related to the propagation velocity as:

$$t_t = 2L/v \quad (2)$$

where

L is the length (m) of the rods (Fig. 2),
and the factor 2 is due to the time being for two-way travel.

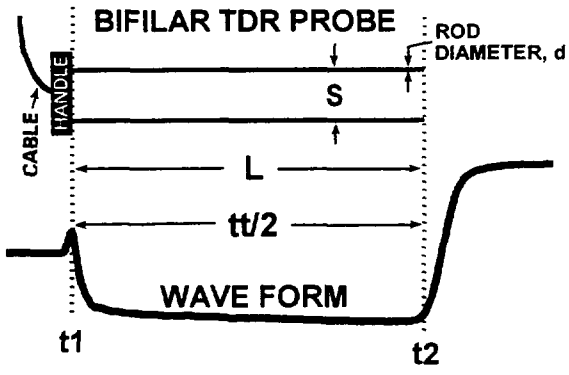

FIG. 2. Schematic of a typical bifilar TDR probe and the corresponding wave form, illustrating probe rod length, L; one way travel time, tt/2; rod spacing, S; and rod diameter, d.

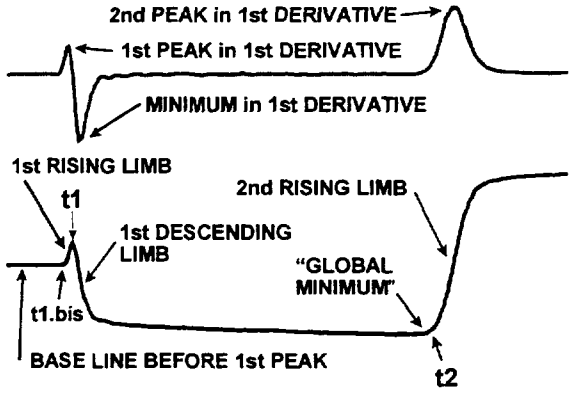

FIG. 3. TDR wave form for a wet sand (bottom) and its first derivative (top) showing features useful for graphical interpretation.

For a TDR probe in a soil, the dielectric is a complex mixture of air, water and soil particles that exhibits an apparent permittivity, ε_a. Substituting ε_a and Eq. 2 into Eq. 1, and assuming $\mu = 1$, we see that ε_a may be determined for a probe of known length, L, by measuring t_t:

$$\varepsilon_a = [c_o t_t/(2L)]^2 \quad (3)$$

Topp et al. [1] found that a single polynomial function described the relationship between volumetric water content, θ_v (m^3 m^{-3}), of four mineral soils and values of ε_a determined in this fashion. Since 1980, other researchers have shown that the relationship between t_t and θ_v is linear for many practical purposes (e.g. [14]).

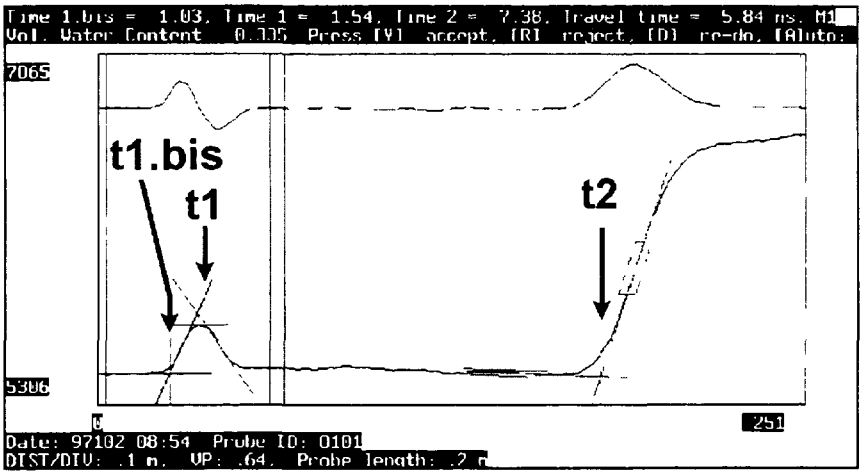

FIG. 4. Example from the TACQ program of graphical interpretation of a wave form from a probe in wet sand. Times t1.bis, t1, and t2 have been labeled. The water content was calculated from Eq. 7 of Topp et al. [1].

Graphical interpretation depends on the fact that the probe design itself introduces impedance changes in the wave guide. The impedance, Z (Ω), of a transmission line (i.e., wave guide) is:

$$Z = Z_0(\varepsilon)^{-0.5} \tag{4}$$

where

Z_0 is the characteristic impedance (Ω) of the line, when air fills the space between conductors,
and ε is the permittivity of the homogeneous medium filling the space between conductors.

For our parallel transmission line (the two rods in the soil) the characteristic impedance is a function of the wire diameter and spacing [15]:

$$Z_0 = 120 \ln\{2s/d + [(s/d)^2 - 1]^{0.5}\} \tag{5}$$

where

s is the spacing (m), and
d is the wire diameter (m).

Or, if d<<s:

$$Z_0 = 120 \ln(2s/d) \tag{6}$$

For a coaxial transmission line, the characteristic impedance is:

$$Z_0 = 60 \ln(D/d) \tag{7}$$

where

D is the diameter (m) of the outer conductor.

From Eqs. 4–7 it is apparent that impedance, Z, increases as wire spacing increases, and decreases as ε (or water content) increases for any probe type (Fig. 5). In the probe handle, the wire spacing increases from that of the coaxial cable to that of the probe rods. The resulting impedance increase causes the wave form level to rise (first rising limb in Fig. 3). If the porous medium in which the probe rods are embedded is wet, then the permittivity of that medium will be higher than that of the epoxy probe handle. This causes a decrease in impedance, which results in the descent of the reflected wave form level as the step voltage leaves the handle and enters the rods in the soil (first descending limb, Fig. 3). The combination of impedance increase at the handle and impedance decrease after the handle gives the peak in the wave form. The rod ends are another impedance change in the wave guide, in this case an open circuit. The remaining energy in the voltage step is reflected back at the rod ends, which represent an impedance increase (second rising limb, Fig. 3). As will be discussed later, wave form shapes different from that shown in Figs. 2–4 result from different soil types and conditions (e.g., dry soil or wet clays). A computer program for automatic TDR data acquisition must be able to acquire the wave form from the probe and correctly interpret it graphically. It should be able to accomplish this despite different cable lengths to the probes, different probe lengths and rod spacings, and different soil conditions.

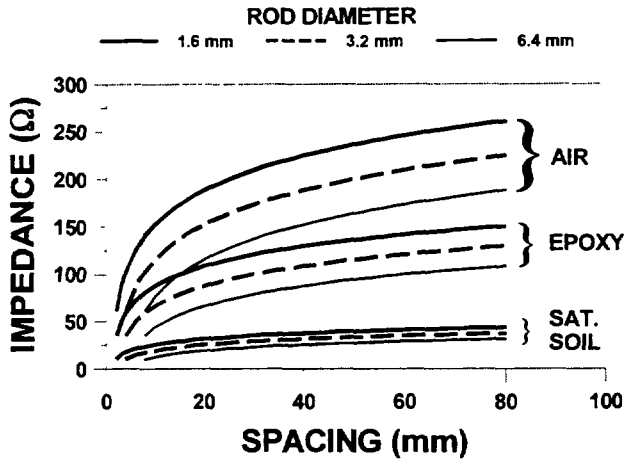

FIG. 5. Influence of rod spacing, rod diameter, and permittivity of the medium on impedance of the waveguide according to Eqs. 4-5. Permittivities are: AIR, unity; EPOXY, close to 3; and SATurated SOIL, approx. 35.

1.2. Wave form interpretation

Topp et al. [11] described a method of interpreting wave forms captured on paper using a chart recorder, or by photographing an oscilloscope screen. This analysis involved two graphical algorithms. Algorithm 1 consisted of drawing a horizontal line across the top of the first peak, and drawing a line tangent to the descending limb of the first peak (Fig. 3). The intersection of these lines defined t1, as illustrated in Fig. 4. Algorithm 2 consisted of drawing a horizontal line tangent to the base line between the first peak and second inflection, and drawing a line tangent to the second inflection, the intersection of which defined t2. The pulse travel time, in the part of the wave guide that was buried in the soil, was t_t = t2-t1. Peaks and inflections were identified by eye and no computer code or algorithms were presented.

Later, Baker and Allmaras [6] discussed a computer program for interpretation of wave forms, which followed the ideas of Topp et al. [11], and added the concept of using the first derivative of the wave form to identify important wave form features. The program included the following steps applied to a wave form consisting of 200 data points (Fig. 6):

- Smooth and differentiate the data [16].
- Use a loop to search the wave form data for the global minimum, VMIN, and associated time, t2.1.

- Find the local maximum, V1MAX, and associated time, t1p, in the data between the first point and t2.1. This is the time, t1p, of the first peak.
- Find the most negative derivative, DMIN, the corresponding time, tDMIN and wave form value, VtDMIN, in a region of 25 points following t1p. The slope of the first descending limb is DMIN.
- Define a line, with intercept V1MAX and slope of zero, that is horizontal and tangent to the first peak. Define a second line, with slope DMIN and intercept such that it passes through VtDMIN at tDMIN. Solve for the intersection point of the two lines, and the associated time, t1, that corresponds to the point where the rods exit the handle.
- Find the maximum derivative, D2MAX, in a region of 25 points following VMIN, and associated time t2.2 and wave form value Vt2.2.
- Define a line tangent to the second inflection with slope D2MAX and passing through Vt2.2 at t2.2. Define a horizontal line tangent to VMIN. Solve for the intersection of these lines to find t2, the time corresponding to the ends of the rods.

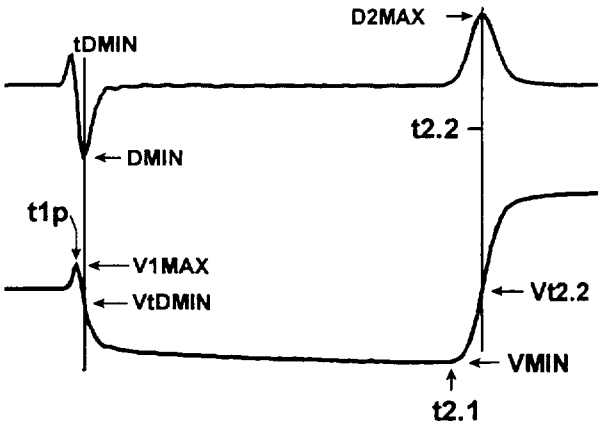

FIG. 6. The TDR wave form (bottom) and its first derivative (top) with features identified by Baker and Allmaras [6] (my nomenclature).

The travel time of the pulse through the exposed length of the rods was t_t = t2-t1. While these algorithms worked well for relatively moist soils, there were problems with the absence of DMIN and absence or movement of VMIN and associated times in wave forms for dry, low bulk density soils (see Section *1.3.2.* on wave forms from dry soils).

Heimovaara and Bouten [7] described a computer program that involved fitting lines to the second inflection and to the base line between t1 and t2. The regions of data points, to which these lines were fit, were determined empirically for a given probe. Also, they recognized that the wave form might not always descend at t1. So, they introduced the concept of fitting lines to the rising limb of the first inflection and to the base line before the first inflection, and using the intersection of these lines to define a time corresponding to the point of separation of the cable conductors. This time is termed t1.bis in this paper, and is illustrated in Figs. 3 and 4. A correction time was added to t1.bis to get t1. This correction time was determined by performing a single measurement in air before probe installation.

1.3. Factors influencing wave form shape

Many conditions may alter the wave from the classical forms displayed in Figs. 2–4. Early computer algorithms emphasized finding the minimum, VMIN, and its time, t2.1; the second maximum in the first derivative, D2MAX, and its time, t2.2; and the minimum of the first derivative, DMIN, and its time, tDMIN (see Fig. 6). In humid environments, where soils are seldom dry and are well leached so that bulk electrical conductivity is low, these features are found in almost all wave forms and can be reliably used as keys for computer analysis. Today, most commonly available TDR probes are connected

directly to 50-Ω coaxial cables. For these probes in dry soils, DMIN and the descending limb of the first peak may disappear, making t1 difficult to find. Also, in dry soils, the position of VMIN may change dramatically, moving from the right side to the left side of the wave form between t1 and t2, and causing interpretation problems. Some of the first field probes consisted of two stainless steel rods connected to 200-Ω twin-lead antenna cables. Because impedance in the soil is almost always less than 200 Ω (Fig. 5), there was always a drop in the wave form at the transition from cable to probe rods. This fact tended to favor the use of the earlier algorithms. However, even for these probes, the position of VMIN may be closer to t1 than to t2 in dry soils. In soils with high bulk electrical conductivity, the wave form may rise only slowly at the point corresponding to the ends of the rods, making the value of D2MAX so low as to be lost in the noise level of the first derivative. These and other factors influencing wave form shape are discussed below. A suite of algorithms will be presented that allow interpretation of wave forms despite these changes in shape.

1.3.1. Probe design

The height of the first peak increases with the separation distance of the rods because the impedance at this point in the wave guide increases with the separation distance (Eq. 5; Fig. 5). The impedance and peak height are inversely proportional to the diameter of the rods. The height is also influenced by the permittivity of the material separating the proximal ends of the probes (in the handle) (Eq. 4). For a handle made of epoxy (ε_a approximately 3), rod diameter of 3.2 mm and spacing of 30 mm, the characteristic impedance increases from 50 Ω in the cable to 152 Ω in the part of the stainless steel wave guide embedded in the handle (Fig. 5). The pulse travel time between t1.bis and t1 increases with the permittivity of the material between the point of splitting the antenna cable and the connections to the rods. It also increases with the separation distance of the rods. Finally, this travel time increases with the distance between the split in the cable and the point of connection to the rods.

Let us consider an early type of TDR probe that consisted of two stainless steel rods buried parallel to one another in the soil, with the proximal ends connected to the split ends of a bifilar (two-wire) antenna cable. Connections were sometimes made using alligator clips, sometimes soldered, and sometimes by clamping the wire to the rod with a screw. The perpendicular span between the rods was the separation distance. Typically, the antenna cable would have a characteristic impedance of 200 Ω. An impedance matching transformer (balun) was generally used to connect the antenna cable to the cable tester, in order to lower signal loss and distortion between the antenna cable and the 50-Ω wave guide of the cable tester. For this probe, the connections, and some of the split wire, are separated by the soil between the proximal ends of the rods. There is no first peak for this probe, because the wave form always drops from a level corresponding to the 200-Ω cable to a level corresponding to the impedance at the proximal ends of the rods. But, the point at which the wave form drops is influenced by the water content of the intervening soil, assuming the probe is buried. For dry soil, the impedance may be nearly the same as for epoxy, but, for wet soil, the value of ε_a may approach 35 and the impedance may be 30 Ω or lower (Fig. 5).

Using our probe made with antenna cable and two rods, we can see several reasons why the position of the drop in the wave form and the time of t1 might not be reproducible between probes in the field. The length of cable split may vary, the separation distance at the proximal rod ends may vary (over time even if controlled at installation), and the permittivity of the porous medium separating the two wires of the cable may vary in time and space between the cable split and the point of connection to the rods. If the rods are installed vertically, and the point of connection is at the soil surface, the split cable may be separated by air; whereas if the probe is installed more deeply in the soil, the split cable will be separated (along at least some of its length) by soil that varies in permittivity as it wets and dries.

For these reasons, the TDR probes commercially available today are invariably made with the split in the cable (usually coaxial cable) and the connections to the rods, fixed in some sort of rigid configuration, usually called the handle, which is encased in a material of consistent and constant permittivity. The handle may be made of epoxy resin, delrin, polymethyl methacrylate (acrylic), room temperature vulcanizing (RTV) silicone or some other plastic, and may contain metal for shielding or connection of rods. These handles share the properties of a fixed separation distance, fixed permittivity

of the material separating the conductors of the wave guide in the handle (with some minor temperature variations), fixed distance between the cable split and the point of connection to the rods, and fixed distance between the point of connection at the proximal ends of the rods and the point at which the rods exit the handle and enter the soil. Such handles provide optimal conditions for reliable algorithms determining t1.bis and t1, and the rest of this discussion assumes such a handle.

It has been argued (e.g., [17]) that, in order to match impedances (thus lowering signal loss and distortion) between the coaxial cable and the two rods in a bifilar probe, a balun should be used at the point of connection. Also, the balun should serve to convert the unbalanced signal in the coaxial cable (where the inner conductor carries the wave form and the outer conductor remains at virtual ground) to a balanced signal in the two rods (where both conductors carry the wave form). The argument states that, absent a balun, the unbalanced signal will tend to balance as it travels down the rods, eventually becoming closely balanced at some point along the rods. But, between the handle and that point, the signal reflections will be distorted due to the partial imbalance. If the rods are very short, the distorted part of the wave form may interfere with the second inflection. The trifilar (three-wire) probe responds to this concern by providing a wave guide that is geometrically more similar to a coaxial wave guide [18]. Measurements by Zegelin et al. [18] show only minor differences in wave form shape between trifilar and coaxial wave guides.

1.3.2. Dry soil

As the soil dries, the first descending limb (Fig. 3) becomes less steep. Because dry soil has approximately the permittivity of plastic materials used in most probe handles, there may be little or no impedance change between the wave guide in the handle and in the soil. Indeed, if the soil is dry and of low bulk density, the impedance of the wave guide may actually increase in the soil compared with the handle. Both conditions cause the first descending limb to be almost absent, and may cause the wave form level to rise between t1 and t2 (between vertical lines in Fig. 7), so that VMIN is located close to t1. This renders ineffective both algorithm 1 of Topp et al. [11] and the corresponding methods of Baker and Allmaras [6]. Dry soils of low bulk density are usually close to the surface, where the TDR method enjoys its greatest advantage compared with neutron scattering. Thus, it is imperative that the method be usable in such soils. For dry soil, the second inflection, caused by the distal ends of the rods, is invariably steep and high, making it easy to find by searching for D2MAX. However, at the same time, the global minimum may not occur after t1, or the position of the local minimum may shift from just before the second inflection to a point just after the first peak, or to any intermediate position. This causes variations in the intersection of the two lines (horizontal tangent to global minimum and tangent to second inflection) that have no relation to the travel time, t_t.

Another phenomenon sometimes found in low bulk density soils is the double peak. This may be due to compression of a thin layer of soil next to the handle during probe insertion into the soil at installation. This higher bulk density soil will exhibit a lower impedance due both to lower porosity (air has a permittivity of 1, soil minerals have permittivities of 3 to 5, so denser soils have higher apparent permittivities) and to correspondingly higher water content (at equilibrium with surrounding soil), and will cause the dip in the wave form after the handle. As the pulse enters less compressed soil, it encounters a higher impedance and the reflected wave form rises, only to lower again as the pulse travels further down the rods (if the soil is at all moist). It is important to have an algorithm to discriminate between these peaks.

1.3.3. Bulk electrical conductivity

As the bulk electrical conductivity (BEC) of the soil increases, the impedance of the wave guide in the soil decreases due to the lowering of the resistance component of impedance. Also, there is a lowering of signal voltage along the length of the rods due to conduction through the soil. This causes the wave form level after the first peak to decline relative to that for a soil of lower BEC. It also lowers the slope, D2MAX, of the second rising limb [19] and the final height to which the wave form rises after the second inflection. The latter fact has been used successfully to find the BEC of soils (e.g., [2, 5, 20]).

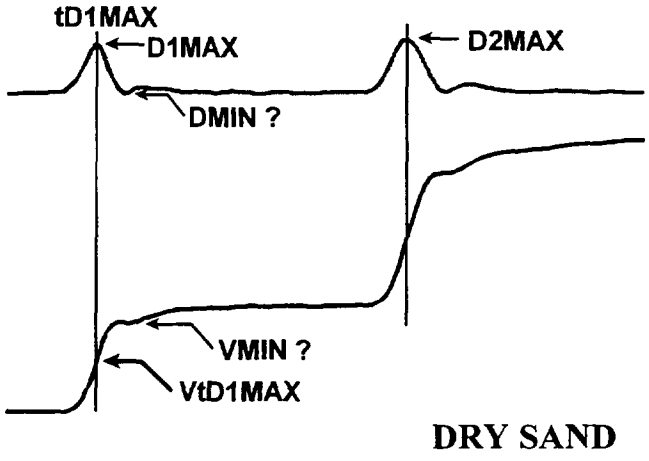

FIG. 7. Influence of dry soil on wave form shape, illustrating difficulty of finding DMIN and VMIN.

However, these effects can make it difficult to reliably find the second rising limb by searching for D2MAX. Smoothing of the wave form and its first derivative can make the determination of D2MAX more reliable by reducing the relative height of peaks in the first derivative that are caused by random noise in the wave form. However, in the case of a very weak second rising limb, the peak in the first derivative can be so spread out that the apparent position of the second rising limb, deduced from the position of D2MAX, is not consistent (Fig. 8). Fortunately, in these cases the high BEC guarantees that the wave form will slope downward between t1 and t2, in turn guaranteeing that the position of VMIN is always just before the second rising limb. In this situation, VMIN can be used reliably as the key to an algorithm used to find t2.

Unfortunately, increased soil salinity is only one source of increase in BEC. Another source of BEC is the conductivity arising from certain clays, especially those with high cation exchange capacity (CEC). These are often expanding lattice clays containing cations entrapped between clay layers. When such soils are dry they exhibit low BEC, probably due to the contracted nature of the clay micelles, discontinuous water film on soil particles, and resulting low mobility of cations. As these soils wet, their BEC increases, as shown in Fig. 9 for an expansive Pullman clay loam with mixed mineralogy, at Bushland, TX; the effects are apparent as a lowering of the second inflection and final wave form height. Although the problems posed by this phenomenon, vis-à-vis the finding of t2, can usually be solved, the implications for relating TDR wave forms to soil salinity cannot be ignored.

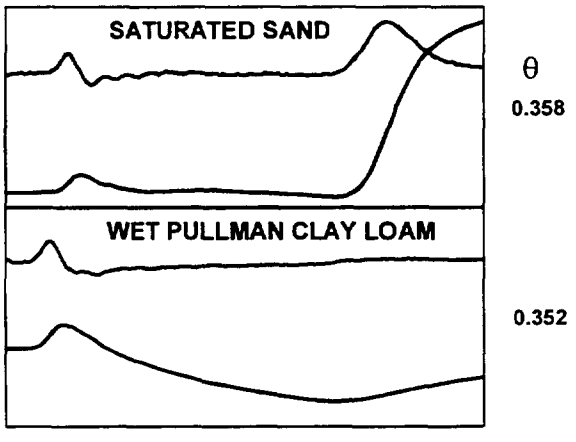

FIG. 8. Wave forms and their first derivatives (top lines in each plot) for two soils showing the lack of a distinct peak in the first derivative corresponding to the second rising limb of the wave form for the wet clay loam. Although the sand is slightly wetter, there is a distinct peak in the derivative useful for finding t2.

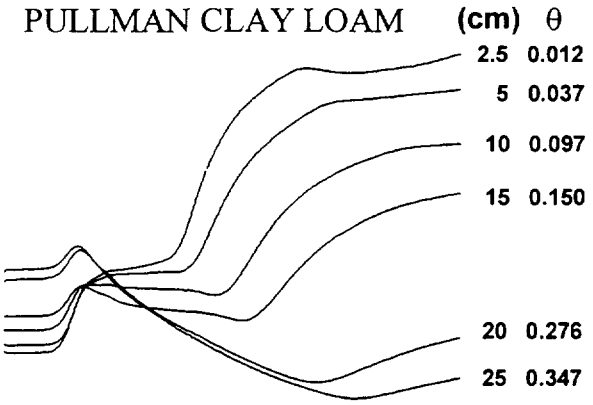

FIG. 9. Effect of soil water content (θ, m^3 m^{-3}) on the bulk electrical conductivity of a non-saline soil at several depths (cm) in the silty clay loam A horizon (2.5 to 15 cm) and the clay B horizon (20 and 25 cm).

Furthermore, this phenomenon has implications for the application of frequency domain (FD) probes to water content determination in these soils, similar to the implications and reported problems related to salinity effects on water content determination by FD probes. Such probes rely upon the change in frequency of an oscillator circuit caused by the change in permittivity of the soil around the probe. For the oscillator to change states, the reflected voltage must reach the set point voltage of the oscillator at which time the oscillator changes state and drives the wave guide to the opposite polarity. The time it takes for the reflected voltage to reach the set point is determined not only by the travel time to t2, but by the additional time between t2 and the time at which the second rising limb rises to the set point. Thus, the frequency of oscillation is dependent not only on t2 or t2-t1, but on the BEC of the medium. Because the BEC may be altered by changes in salinity, clay content, and/or water content in a clayey or saline soil, it is obvious that calibration of an FD probe for routine field use, where these factors may change in time and space, is problematic.

Figure 9 illustrates that the width of the wave form increases as the soil becomes wetter. This has implications for correct positioning of the wave form in the window and choice of window width settings Vp and Dist/Div, as will be discussed later. Not all clay soils show increases in BEC with water content, as shown in Fig. 10 for a Cecil clay of kaolinitic mineralogy from Watkinsville, GA. Figures 9 and 10 illustrate the loss of the first descending limb and VMIN as the soil dries.

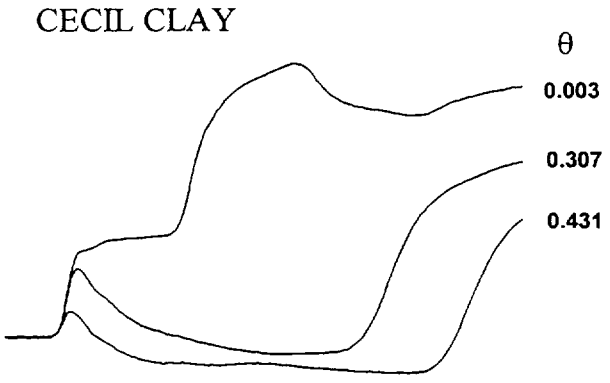

FIG. 10. Effect of soil water content (θ, m^3 m^{-3}) on the bulk electrical conductivity of a non-saline Cecil clay (kaolinitic).

1.3.4. Cable length

As the pulse moves down the cable to the probe, its higher frequency components are selectively attenuated because the cable acts as a low pass filter. This means that the longer the cable, the slower is the rise time of the pulse at the probe, and the less steep are the rising and descending limbs of the inflections caused by probe handle and end of rods [19, 21]. If the wave form is correctly interpreted, then the travel time, t_t, should be constant despite cable length. However, if the probe is short enough, the descending limb of the first peak will intersect the rising limb of the second inflection causing the travel time to be incorrect. The longer the cable, the lower the slope of the descending limb and the longer the probe must be to avoid this problem. Since the slope of the descending limb also decreases with increasing BEC of the soil, a probe length adequate for a given cable length is difficult to predict. Another problem associated with long cable length is the loss of the first peak altogether.

1.4. Setting window width

To date, there have been no reports describing a method for setting the TDR window width that allows for reproducible and consistent computerized finding of t_t. Yet, positioning has a direct effect on whether there are enough data to reliably fit lines to various portions of the wave form. Consider wave forms similar to those in Figs. 2–4. Because the data are digital representations of an analog phenomenon, there are only a fixed number of data pairs of voltage and time representing a screen of data. For instance, for the Tektronix model 1502B/C cable testers, there are 251 data pairs. For Fig. 2 there were only four data pairs in the first rising limb, twelve in the first descending limb, and about 25 data pairs in the second rising limb. If similar wave forms were compressed horizontally, even by 50%, it would be difficult to find enough data points to reliably fit tangent lines to key parts of the wave forms. Thus, it is best to have the wave form occupy as much of the screen as possible. This is easily accomplished using the distance per division, Dist/Div, and propagation velocity factor, Vp, settings of the cable tester. However, the width of the wave form increases with soil water content, and unless the cable tester is set when the water content is at saturation the wave form may widen enough, with increasing water content, that the second rising limb can no longer be seen on the screen. Figures 9 and 10 illustrate this. If the wave form width had been set to occupy the full screen for dry soil, the wave form for wet soil would be too wide for the second rising limb to appear on the screen.

Fortunately, if the approximate saturated water content for a given soil is known, the desired screen width may be calculated as follows. First, compute the apparent permittivity from Eq. 8 [1] and the saturated water content θ_s ($m^3\ m^{-3}$):

$$\varepsilon_a = 3.03 + 9.3\theta_s + 1462\theta_s^2 - 76.7\theta_s^3 \qquad (8)$$

The saturated water content can be estimated from the soil dry bulk density, ρ_b (Mg m^{-3}). The total soil porosity ($m^3\ m^{-3}$) is calculated from $f = 1 - \rho_b/\rho_p$, where ρ_p is the particle density (assumed equal to 2.65 Mg m^{-3}). If all air is displaced when the soil is saturated then $\theta_s = f$.

Second, re-arrange Eq. 1 to calculate the velocity, v, of the signal in the wave guide:

$$v = c_o(\varepsilon_a\mu)^{-0.5} \qquad (9)$$

Then calculate the travel time over the length of the probe from:

$$t = L/v \qquad (10)$$

where

L is the probe length (m).

Adding additional time for the base line before the first peak and for the second rising limb after t2, we have the time that we wish to have represented by the full-screen width. Then we have only to

find a combination of Dist/Div and Vp settings that results in a full-scale horizontal axis at least equal to this time. Experience shows that it is best to have at least one tenth of the screen width (one division) between the left side of the screen and the first peak, in order to reliably fit the base line. Also, it is best to have at least 20% of the screen width between t2 and the right side to reliably fit the tangent to the second rising limb. A computer algorithm for finding appropriate combinations of Dist/Div and Vp, given the soil's saturated water content and the probe length, is given in Section 5. Example results for several probe lengths and saturated water contents are in Table I. These are for the Tektronix 1502B or 1502C cable testers, which allow variation of Vp settings in hundredths.

TABLE I. OPTIMUM PROPAGATION VELOCITY FACTOR (V_P), DISTANCE PER DIVISION SETTING AND RESULTING SCREEN WIDTHS FOR SEVERAL COMBINATIONS OF PROBE LENGTH AND SATURATED WATER CONTENT (θ_s, m^3 m^{-3}). SETTINGS GIVE SCREEN WIDTHS WITHIN 2% OF THOSE CALCULATED USING THE ASSUMPTIONS IN THE TEXT

	$\theta_s = 0.5$			$\theta_s = 0.4$			$\theta_s = 0.3$		
Probe length (m)	Vp	Dist/Div (m)	Screen width (ns)	Vp	Dist/Div (m)	Screen width (ns)	Vp	Dist/Div (m)	Screen width (ns)
0.05	0.59	0.025	1.40	0.69	0.025	1.20	0.85	0.025	0.98
0.10	0.59	0.05	2.80	0.69	0.05	2.39	0.42	0.025	1.96
0.15	0.39	0.05	4.20	0.46	0.05	3.59	0.56	0.05	2.94
0.20	0.59	0.10	5.61	0.69	0.10	4.78	0.42	0.05	3.92
0.30	0.39	0.10	8.41	0.46	0.10	7.18	0.56	0.10	5.87

For the older Tektronix model 1502 cable tester, the Vp setting has much less flexibility. There are three buttons for Vp. Pressing Solid PTFE gives a Vp of 0.70; pressing Solid POLY gives a Vp of 0.66; and pressing OTHER allows the Vp to be adjusted from 0.55 to 0.99 by turning the VAR screw. When all three buttons are out, the Vp is 0.99; or, when the OTHER button is pressed in and the VAR screw is turned all the way clockwise, the Vp is 0.99. Unfortunately, there is no simple way to know the exact Vp value that is set with the VAR screw, so the user is left with just three usable Vp settings, 0.66, 0.70, and 0.99. If the Tektronix 1502 is selected in Software Setup in TACQ, then pressing D for defaults will, in addition to allowing the user to set the Vp and Dist/Div settings, give two recommendations for Dist/Div (using the Vp value chosen by the user). The first recommendation will show a negative percent error, and the second will show a positive percent error. These are the percentage differences from the optimum screen width in ns. If the negative percent error is small, then the user may be able to use the corresponding Dist/Div recommendation. Otherwise, the user should use the Dist/Div recommendation that gives a positive percent error. This will result in a screen width in ns that is wider than absolutely necessary, but that will ensure that the second rising limb of the wave form is not lost off the right side of the screen when the soil becomes saturated. The user should employ Vp values of 0.66, 0.70, and 0.99, and determine which gives the smallest percent error. Tables II and III give some possible combinations of probe length and Dist/Div, and associated errors as a percentage of the optimum screen width in ns for Vp values of 0.99 and 0.70, respectively. These Tables are given in units of feet because most of the model 1502 cable testers were built at the factory to use British units.

TABLE II. DISTANCE PER DIVISION SETTING, AND ASSOCIATED ERRORS COMPARED WITH OPTIMUM SCREEN WIDTH, FOR Vp OF 0.99 AND FOR A RANGE OF SATURATED WATER CONTENTS (θ_s, $m^3\ m^{-3}$) AND PROBE LENGTHS

	$\theta_s = 0.5$		$\theta_s = 0.4$		$\theta_s = 0.3$	
Probe length (m)	Dist/Div (ft)	Percent error	Dist/Div (ft)	Percent error	Dist/Div (ft)	Percent error
0.05	0.1	-27	0.1	-14	–[a]	–
0.05	0.2	47	0.2	72	0.1	5
0.10	0.2	-27	0.2	-14	0.1	-48
0.10	0.5	83	0.5	115	0.2	5
0.15	0.2	-51	0.2	-43	0.2	-30
0.15	0.5	22	0.5	43	0.5	75
0.20	0.5	-8	0.2	-57	0.2	-48
0.20	1.0	83	0.5	7	0.5	31
0.30	0.5	-39	0.5	-28	0.5	-13
0.30	1.0	22	1.0	43	1.0	75

[a]No data.

It is obvious that, for some combinations of probe length and saturated water content, there is no combination of Dist/Div and Vp settings possible with the push buttons on the Tektronix 1502 cable tester, that comes close to providing an optimum screen width. This does not necessarily mean that good data cannot be obtained, but it does mean that the user may want to choose probe lengths that lend themselves more easily to optimization of this sort.

TABLE III. DISTANCE PER DIVISION SETTINGS, AND ASSOCIATED ERRORS COMPARED WITH OPTIMUM SCREEN WIDTH, FOR Vp OF 0.70 AND FOR A RANGE OF SATURATED WATER CONTENTS (θ_s) AND PROBE LENGTHS

	$\theta_s = 0.5$		$\theta_s = 0.4$		$\theta_s = 0.3$	
Probe length (m)	Dist/Div (ft)	Percent error	Dist/Div (ft)	Percent error	Dist/Div (ft)	Percent error
0.05	–[a]	–	–	–	–	–
0.05	0.1	4	0.1	21	0.1	48
0.10	0.1	-48	0.1	-39	0.1	-26
0.10	0.2	4	0.2	21	0.2	48
0.15	0.2	-31	0.2	-19	0.2	-1
0.15	0.5	73	0.5	102	0.5	147
0.20	0.2	-48	0.2	-39	0.2	-26
0.20	0.5	30	0.5	52	0.5	85
0.30	0.5	-14	0.2	-60	0.2	-51
0.30	1.0	73	0.5	1	0.5	24

[a]No data.

1.5. Algorithms for wave form interpretation

This section briefly describes algorithms used by TACQ for automatic graphical interpretation of a wide variety of wave forms The user may choose from several methods described in the literature, or apply methods available only in TACQ These methods assume wave forms correctly positioned in the instrument window as described in the preceding section Features of the wave form and its first derivative, discussed below, are defined in Figs 3, 10, and 11 Pre-defined, recommended values of all user choices are stored in TACQ The TACQ program and documentation, in Adobe PDF format, are available free at http //www cprl ars usda gov/programs/

1 5 1 Wave form smoothing

Following the method of Baker and Allmaras [6], wave forms are smoothed using the Savitsky-Golay procedure [22] The user may choose any degree of smoothing from none to a twenty-one-point smooth To provide a symmetrical smooth, only odd numbers of points are allowed Derivative smoothing may vary from none to a nineteen-point smooth Derivative smoothing must be over a number of points at least two lower than the number chosen for wave form smoothing The user should specify only enough smoothing to reduce extraneous peaks in the first derivative Excessive smoothing can cause errors, most particularly loss of sharp wave form features such as the first peak The default setting for smoothing is nine points on the wave form and three points on the first derivative

1 5 2 Circumscribing wave form interpretation

In order to avoid dealing with sudden drops or rises in level that may occur at the beginning or end of the wave form (seen with the older analog model 1502 cable tester), the user may set any number of points not to be used in wave form interpretation at either end of the wave form Vertical lines on the screen show the parts of the wave form thus excluded The number of excluded points for either end may be set by entering a number or by moving the lines interactively using the cursor keys

Also, the user may exclude data in the right-hand side of the wave form from being used to find the first peaks in the wave form and first derivative This excludes the second peak in the first derivative from consideration for finding time 1 and eliminates confusion between the first and second rising limbs Correspondingly, the user may exclude a portion of the left side of the wave form from consideration when determining the location of the second rising limb Again, these limits may be set by entering a number or by using the cursor keys to move the vertical lines that represent the limits on the computer screen Table IV summarizes the user-set limits

TABLE IV USER SET LIMITS ON DATA SEARCHED FOR WAVE FORM FEATURES

Limit name	Description
StartPt	Time before which to exclude data from examination
EndPt	Time after which to exclude data from examination
D2Lim	Time at which to begin search for second maximum in the first derivative Search ends at EndPt
D1Lim	The data between StartPt and D1Lim are searched for the first peak in the first derivative, D1MAX
SafetyLim	If t1 is less than this time then zeros are written to the output
t1Swath	Number of data points after tD1MAX to use when searching for V1MAX

1.5.3. Choosing wave form interpretation methods

1.5.3.1. Time 2.2 and tangent to rising limb

For finding the center of the second rising limb (t2.2), the user may choose to use: i) only a global minimum method (i.e. find VMIN and t2.1, and set t2.2 as t2.1 plus a user-set number of points), ii) only a method that finds D2MAX and associated time t2.2, or iii) an automatic method that uses the global minimum method if the value of D2MAX is below a user-set threshold, D2Thresh, and that uses the time of D2MAX otherwise. The third method is recommended. The global minimum method for t2 is similar to that of Baker and Allmaras [6], except that the search for VMIN is conducted in the data between t1p and EndPt rather than over all the data. Regardless of the method for finding t2.2, the line tangent to the second rising limb is found by linear regression on a swath of points around t2.2 (user chosen swath width).

1.5.3.2. Time 2.1 and tangent to VMIN or fit to base line

The user may choose how to fit the "horizontal" intersecting line that partially defines t2. The line is either: i) a horizontal line passing through the wave form at t2.1, or ii) a line fit by regression to a swath of points just prior to t2.1 (user chosen swath width). The second method is recommended. Travel times found with it are less susceptible to temperature induced errors [23]. If the horizontal tangent method is chosen, the program will examine the slope of a line fitted to the swath of points; and, if the slope is positive, the program will use the fitted line rather than the horizontal tangent. This avoids improper interpretation of wave forms from dry soils for which VMIN may be located closer to t1 than t2 and the wave form slope may be upward between t1 and t2.

1.5.3.3. Time 1

For finding t1, the user may choose between methods M1 and M2. Method M1 is similar to that of Baker and Allmaras [6], and finds t1p by searching for V1MAX and DMIN. But, it starts the search from the time of D1MAX. If it fails to find V1MAX and D1MAX, it assigns values as explained in Section 6. Method M2 finds D1MAX and fits a line tangent to the first rising limb. It also fits a horizontal line tangent to the baseline before the first rising limb and solves the intersection for t1.bis. Method M2 then adds a user set time, t_C, to t1.bis to get t1. The time t_C = t1 - t1.bis is found by measurements on probes installed in wet soil using method M1. This is different from the method proposed by Heimovaara and Bouten [7] involving a single measurement in air. Method M2 is recommended.

In Section 6 are described the steps the program takes to find times t1.bis, t1, and t2.

1.6. Measuring bulk electrical conductivity

Several papers discuss how to calculate the BEC of a porous medium from the relative wave form heights measured at several points along the TDR wave guide (e.g., [2, 3–5, 17, 18, 20, 24–26]). The measurement of BEC is discussed here in order to lend insight into its effect on the TDR wave form and its interpretation. There are six points along the wave guide where these heights are measured in the various studies cited. No single method of calculating BEC uses all six, but they are discussed here for completeness. The wave form heights at these points may be designated V_{01}, V_{min}, V_{02}, V_F, V_I, and V_R, which are defined for a Tektronix model 1502B/C cable tester as follows (Fig. 11):

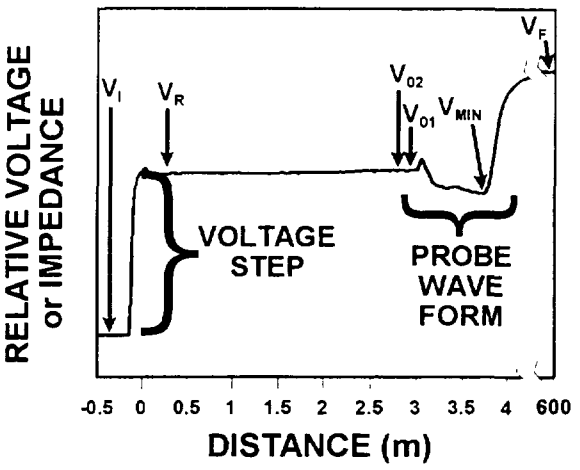

FIG. 11. Wave form showing the relative voltages or impedances measured for determination of BEC.

V_{O1} This is the voltage of the wave form before the first peak, i.e., the pre-incident pulse height. This is taken from the regular wave form that the user sets up for determination of water content. If the first peak is set to occur just at or after the first vertical division on the screen, then this value of V_O will be the average of about 15 to 25 points. The actual number of points depends on what the program determines to be the flat part of the wave form before the first peak. This value is determined by the program for the use of those who might want to apply a particular method cited in a paper. This value is somewhat noisier than the second value of V_O (see below). The second value of V_O is preferred for BEC calculations.

V_{MIN} Again, this value is taken from the regular wave form that the user sets up for determination of water content. It is the voltage of the minimum of the wave form between the first peak caused by the probe handle and the final reflection caused by the ends of the rods. This value has been used for BEC calculations, but better methods are now available. It is output by TACQ for compatibility with older techniques. The value of V_{MIN} is more noisy than the others because it is a single point value, not an average. Applying more wave form smoothing will reduce the noise somewhat; but the extra smoothing may cause problems with wave form interpretation for water content. This is the only value that is taken from the smoothed wave form.

V_{O2} The second value of V_O is acquired by first moving the "regular" wave form view one tenth of its length to the left (one Dist/Div to the left), and then taking the average of the first 25 data points. These are the first 25 data to the left of the beginning of the regular wave form that the user set up for determination of water content. Normally the two values of V_O should be the same, but the first value is slightly more noisy because of the possibility that some data from the initial part of the rise of the first peak may inadvertently be included in the averaging.

V_F This is the voltage of the wave form at great distance (final voltage). To find it, the program sets Dist/Div to 1 m or 2 feet, sets the wave form to start at 599 m or 1,980 feet (maximum distance setting on the cable tester), and then takes the mean of the last 50 data points.

V_I The initial voltage of the wave form, before the voltage pulse is injected, is virtual zero for the TDR system, and all other voltages may be normalized by subtracting V_I from them. The program sets Dist/Div to 0.1 m or 0.5 foot, sets the start of the wave form to -0.51 m or -2 feet, and takes the mean of the first 25 data points. The negative distance setting means that the wave form that we are looking at here is inside the cable tester, before the BNC connector on the front panel and before the pulse is injected (see Fig. 1).

V_R This is called the relative voltage and is used in the paper by Baker et al. [27]. It is determined from the same wave form as for V_I, but is the mean of the last 25 data points of the wave form. This is in the cable outside the cable tester and after the pulse is injected. Note that the values of V_R, V_{O1}, and V_{O2} are all approximately the same, differing only due to changes in impedance due to cable resistance, cable type before and after the multiplexer (if there is one), noise, etc. In general, V_R tends to be slightly smaller than either V_O value.

The measured load impedance, Z_L, (Ω) is used in most methods of calculating bulk electrical conductivity:

$$Z_L = Z_{REF}(1 + \rho)/(1 - \rho) \quad (11)$$

where

Z_{REF} is the output impedance of the cable tester (50 Ω),
and ρ is the dimensionless ratio:

$$\rho = E-/E+ \quad (12)$$

and the dimensionless potential difference E- is:

$$E- = V_F - V_{O2} \quad (13)$$

and the dimensionless potential difference E+ is:

$$E+ = V_{O2} - V_1 \quad (14)$$

For most methods, only V_{O2}, V_1, and V_F are needed. Because BEC calculation from TDR data is still a subject of active research, the other values are included for backward compatibility with methods of calculating BEC reported in the literature.

1.7. General remarks

The TDR method for soil water content measurement is widely applicable and may be used for unattended, automated data collection. But, obtaining precision and accuracy in automated measurement is very much dependent on the robustness of wave form interpretation methods used in the software or firmware of the data logging equipment. Interpretation methods presented here allow TDR to be used for a wide variety of agricultural soils that are primarily mineral in nature. For these soils, TDR is the only method for which a nearly-universal calibration exists [1]. Soils high in swelling clays may exhibit a bulk electrical conductivity that is not related to soil solution salinity, but which conducts and weakens the TDR signal and limits both the usefulness of the method and the length of probes. But, TDR may be used easily in other clay soils such as those high in kaolinite, which affects the signal no more than does sand. Commonly used probes are bifilar or trifilar configurations that must be inserted into the soil or buried, limiting their use to near the surface in soils whose structure is disturbed by digging of pits. Probe length is limited both by conduction losses and by the difficulty of insertion into soil. Thus, they are commonly in the range of 10 to 50 cm. In deep sands, probes may be installed more deeply, up to 3 m in at least one case; and length may be 1.5 m or more in sand if the soil water is not saline. Probes with shorting diodes exist in versions up to 1.5 m or more for use in most soils. Shorting the diodes and measuring signal differences enhances the signal-to-noise ratio and thus the length possible. But, there is no soil between the two sides of the wave guide in these probes and they are sensitive to only a small volume of soil outside the probe. Small measurement volume is both a weakness and strength of TDR. For bifilar and trifilar probes, most of the TDR signal is concentrated in a volume that extends about 2 cm above and below the plane of the rods, and about 2 cm outside the rods. However, the capacity to custom-tailor measurement volume by changing rod length and spacing is a major advantage of TDR.

2. NEUTRON SCATTERING

Neutron scattering (NS) was first successfully used for measuring soil water content in the 1950s [28]. Since then, NS gauges have improved in portability, programmability, weight and size. The advent of more efficient detectors resulted in the use of smaller and thus safer radioactive sources. The precision of measurements possible with NS has always been high and satisfactory for many soil water investigations (standard error <0.01 m^3 m^{-3}, [29, 30]). However, safety regulations requiring costly licensing and training of users, and considerable (and apparently growing) paperwork cause the NS

method to remain expensive and difficult or impossible to use in some situations, particularly unattended monitoring Storage and disposal of the radioactive sources in these gauges is also increasingly expensive The theory of operation of NS gauges and field calibration methods are described in several publications including [30] and [31] Careful calibration and use remain essential to accurate soil water measurement with NS gauges The following discussion will concentrate on some calibration methods explored in the 1990s, and recommendations for calibration and use

2.1. Calibration

Stone et al [32] conducted the American Society of Civil Engineers (ASCE) Neutron Probe Calibration Study on three agricultural soils, Millville silt loam, Nibley silty clay loam, and Kidman sandy loam Sub-studies were done on methods of bulk density measurement, effects of the geometry of source and detector tube (source at bottom of detector, or source centered around detector), and effects of access tube material [aluminium, steel or polyvinyl chloride (PVC) plastic] No attempt was made to produce calibrations for different soil horizons, probably because sample numbers were inadequate (from six to eighteen for the entire profile) Three access tubes were installed in a wet site and three in a dry site for each soil, with 10 cm of the tube protruding above ground level Sampling depths were at 15 cm below ground surface and in 15-cm increments to a depth of 150 cm Shield counts used to calculate count ratios, were taken with the gauges resting on the top of an access tube at 1 5 m above the soil surface Calibration equations were calculated by linear regression analysis of measured volumetric water content vs count ratios

A probe with the source centered around the detector tube (model 3223, Troxler Electronic Laboratories, Inc , Research Triangle Park, NC) showed greater sensitivity to water content than the probe with the source at the bottom of the detector [model 503DR, Campbell Pacific Nuclear (CPN) International, Martinez, CA] [33] The two probes were equally sensitive to proximity to the surface The centered detector-source probe showed slightly better resolution of vertical changes in moisture content and of a cavity placed in the soil adjacent to the access tube Both probes were sensitive to placement above the bottom of the augered access hole Changes were 1 64 standard deviation (SD) for the Troxler and 1 19 SD for the CPN, from readings with the probes about 10 mm above the bottom of the hole, when the hole was augered another 15 cm more deeply and readings were taken at the same depth This suggests that calibration efforts should ensure that the augered hole extends well beyond the lowest depth of reading Despite the greater sensitivity of the Troxler probe, there was no significant difference in the precision of calibration curves developed for the two brands of gauges [34] Standard errors of estimate ranged from 0 0068 to 0 0193 m^3 m^{-3} for CPN gauges and from 0 0056 to 0 0197 m^3 m^{-3} for Troxler gauges [35]

Access tube materials strongly affected the calibration, but changed the intercept only slightly Both brands of gauge were more sensitive to water content when used with aluminum tubing and least sensitive with PVC, sensitivity with steel tubing was intermediate [34] Calibration equation standard errors of estimate ranged from 0 0056 to 0 0147 m^3 m^{-3} for Al access tubes and from 0 0111 to 0 0193 m^3 m^{-3} for PVC, indicating a slight reduction in precision of calibration with the latter

For neutron probe calibration, three soil sampling methods that do not destroy the site were compared by Allen et al [35] and Dickey et al [36] Two were in-situ methods for which samplers were pushed into the soil at the bottom of an augered hole to take fixed volumetric samples Of these, the SCS Madera sampler, with a 60 cm^3 sample volume, resulted in better calibrations (lower standard error of estimate) than the Utah State University sampler that had a volume of 15 cm^3 The third method, involving a Giddings coring tube, produced the smallest calibration error estimates, the coring tube was inserted by a hydraulic coring machine (Giddings Machine Co , Fort Collins, CO) and the soil core was pushed out onto a tray where it was cut into sections of known length, which were placed in soil cans Volume of each sample was calculated from the inside diameter of the coring tube cutting edge and the sample length Use of the Giddings coring tube compacted the soil around the hole in which the access tube was subsequently installed, which caused the calibration slope to change Thus, although the calibration error estimate was smaller, the calibration probably did not provide an accurate representation of the field soil water content An added disadvantage of the Giddings coring method is that it requires

an expensive tractor- or trailer-mounted hydraulic coring machine, which may be difficult to operate in the field. Two types of driven, ring samplers were also tested [36]. These required destruction of the site because holes had to be dug to take samples at every depth. These samplers were closed at the ends causing some samples to be compacted. Calibration equation error estimates were higher with data from the ring samplers.

Evett and Steiner [37] calibrated three Troxler and three CPN gauges in an Amarillo fine sandy loam with a sandy clay loam B horizon between 30 and 110 cm depth and a calcic horizon (Btk) below 110 cm. We used schedule 10, galvanized steel electromechanical tubing for access tubes, which were installed by pushing them into hand-augered holes of the same diameter as the outside of the tube. A dry soil site was found in a fallow field and an adjacent wet area was created within a berm by applying water until the soil was wet to a depth of 2 m. Three access tubes were installed in each site. The wet soil was allowed to drain to field capacity (43 h), then samples were taken within an 11-h period to minimize changes in moisture content due to drainage.

Shield counts were taken before and after counts in the access tubes, and each standard count used for calculating count ratios was the average of at least six shield counts. The CPN gauges reported a χ ratio for each standard count. This statistic, valuable for screening shield counts, is the ratio of the standard deviation of counts to the square root of the mean count. Because the count of thermalized neutrons behaves as a Poisson distribution, the χ ratio should equal unity. Shield counts for which the χ ratio was <0.9 or >1.1 were eliminated from consideration. In order to avoid any influence of soil moisture on the count, shield counts were taken with the gauge resting on a stand 82 cm above the soil surface. Counts in the access tubes were also made with the gauge resting on the stand. The stand was designed to fit over the access tube and rest on the soil surface around the tube. This procedure provided two benefits. First, the cable stops, used to position the probe at each sampling depth in the tube, were fixed on the cable such that the first reading was at 10 cm below the bottom of the stand, and thus 10 cm below the soil surface. With the stand resting on the soil surface, readings were always at the correct depth regardless of the height of an individual access tube above the soil surface. Second, because the probe and shield were separated by at least 90 cm, for the shallow 10-cm reading there was no question of the count being influenced by the gauge shield, as has been suggested by Stone et al. [33]. Neutron probe readings (1-min counts) were made at 10-cm depth and in 20-cm increments to 190 cm.

Four soil samples were taken at each depth with a Madera sampler. For the 10-cm depth, the sampler was pushed vertically into the soil until the sampling volume was centered at 10 cm, the sampler was twisted to shear the soil at the bottom and then pulled out. For depths below 10 cm, the soil was excavated on one side of the access tube and samples were taken by pushing or driving the sampler horizontally into the soil on either side of the access tube. Two samples were taken on opposite sides of the access tube just above and just below each reading depth in order to integrate the soil volume measured by the neutron probes. The Madera probe was chosen for soil sampling because its cutting edge is sharp and has a low cross-sectional area that reduces soil compaction, and because it is an open-ended sampler, which allows the operator to observe any soil compression or shattering that would compromise the sample. If a sample was obviously compressed or shattered, it was discarded and another taken adjacent. During data reduction, the four samples were commonly averaged to give one water content per sampling depth for each access tube. However, the existence of four samples per depth for each access tube allowed samples identified as outliers during regression analysis to be discarded, particulary if values of water content and bulk density for those samples were widely divergent from the mean of the other samples. Another advantage of the Madera probe is that it disturbs the soil outside the probe very little, thus allowing adjacent samples to be obtained within 1 or 2 cm. Other volumetric samplers, such as ring samplers, tend to compress and greatly disturb the soil outside, and even in front of, the sampler as it is pushed into the soil.

A wide range of water contents was achieved between the wet and dry sites (Fig. 12). Results of these techniques were very good (Table V). Root mean squared errors were less than 0.012 $m^3\ m^{-3}$ for all calibration equations, and often were approximately 0.005 $m^3\ m^{-3}$. There was no difference in the precision of calibration equations obtained for the two brands of moisture gauge. Enough samples were obtained to allow individual calibration equations to be calculated for the 10-cm depth, and the 30- to 90-

cm and 110- to 190-cm depth ranges There were important differences in the slopes and intercepts of these equations

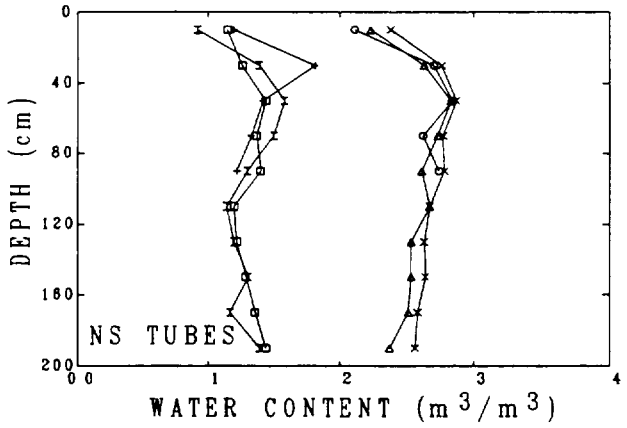

FIG 12 Water content profiles at neutron scattering (NS) access tubes dry site tubes (□) (I), *and (+) and wet site tubes (X) (Δ) and (O) From Evett and Steiner (1995)*

Earlier, similar results were obtained using these calibration techniques on a Pullman clay loam (Table VI) and a Ulysses silt loam (Table VII) (Evett, 1991, unpublished data) with only two access tubes installed in each site The Pullman soil is a Paleustoll in the US taxonomy and has a strong Bt clay horizon (illuvial clay), and a calcic horizon with up to 45% by mass of $CaCO_3$ Distinctly different calibration equations were found for these two horizons, as well as for the 10-cm depth In 1993, field calibrations using these methods were done on the Ulysses silt loam and the Amarillo fine sandy loam (Table VII) Standard errors of estimate were less than 0 01 m^3 m^{-3} for all horizons, and there were important differences between calibration slopes for different horizons of the Amarillo soil For the Ulysses soil, which lacks strong illuvial clay and calcic horizons, there was no important difference between calibration equations for any depth range below 10 cm It is noteworthy that the calibration equations for probes with serial numbers 5447 and 6190 on the Amarillo soil changed between 1993 and 1995 Both gauges underwent repairs in the interim, altering the calibrations Although the locations of these calibrations were different, they were in the same field and it is assumed that the differences in the equations between the two dates did not result from soil differences between the two locations

TABLE V. REGRESSION EQUATIONS FOR NEUTRON SCATTERING WATER CONTENT GAUGES IN AMARILLO FINE SANDY LOAM, BIG SPRINGS, TEXAS, USA [37]

Serial no.[a]	Model	Regression equation	r^2	RMSE[b] (m^3 m^{-3})	N[c]
		A horizon (10-cm depth)			
5447	503DR	θ_v[d] = 0.014 + 0.2172(CR)[e]	0.997	0.004	6
6190	503DR	θ_v = 0.001 + 0.2196(CR)	0.999	0.002	6
0698	503DR	θ_v = 0.021 + 0.2105(CR)	0.996	0.005	6
386	3331	θ_v = 0.054 + 0.5270(CR)	0.992	0.006	6
385	3331	θ_v = 0.028 + 0.5388(CR)	0.997	0.004	6
326	4301	θ_v = 0.001 + 0.4943(CR)	0.999	0.002	6
		B horizon above calcic B (30 to 90 cm)			
5447	503DR	θ_v = -0.066 + 0.2421(CR)	0.988	0.008	24
6190	503DR	θ_v = -0.070 + 0.2464(CR)	0.982	0.009	24
0698	503DR	θ_v = -0.070 + 0.2273(CR)	0.989	0.007	24
386	3331	θ_v = -0.003 + 0.5206(CR)	0.985	0.009	24
385	3331	θ_v = -0.016 + 0.5406(CR)	0.985	0.009	24
326	4301	θ_v = -0.010 + 0.4646(CR)	0.970	0.012	24
		Calcic B horizon (110 to 190 cm)			
5447	503DR	θ_v = -0.057 + 0.2299(CR)	0.992	0.006	20
6190	503DR	θ_v = -0.062 + 0.2352(CR)	0.992	0.006	20
0698	503DR	θ_v = -0.053 + 0.2086(CR)	0.992	0.006	20
386	3331	θ_v = 0.001 + 0.5049(CR)	0.993	0.006	20
385	3331	θ_v = -0.014 + 0.5276(CR)	0.993	0.006	20
326	4301	θ_v = -0.017 + 0.4741(CR)	0.992	0.006	20
		Complete B horizon (30 to 190 cm)			
5447	503DR	θ_v = -0.063 + 0.2371(CR)	0.988	0.007	44
6190	503DR	θ_v = -0.067 + 0.2419(CR)	0.984	0.008	44
0698	503DR	θ_v = -0.062 + 0.2189(CR)	0.987	0.008	44
386	3331	θ_v = -0.001 + 0.5142(CR)	0.988	0.007	44
385	3331	θ_v = -0.016 + 0.5360(CR)	0.988	0.008	44
326	4301	θ_v = -0.013 + 0.4696(CR)	0.979	0.010	44

[a]Four-digits, Campbell Pacific Nuclear gauges; three-digits, Troxler Electronic Laboratories gauges.
[b]Root mean squared error.
[c]Number of samples in the regression analysis.
[d]Water content (m^3 m^{-3}).
[e]Count ratio; the neutron count in the access tube divided by the standard count.

TABLE VI. CALIBRATION EQUATIONS FOR FOUR CPN NEUTRON MOISTURE GAUGES IN THE PULLMAN CLAY LOAM, BUSHLAND, TEXAS, USA, ILLUSTRATING EQUATIONS ESTABLISHED FOR DIFFERENT SOIL LAYERS (EVETT, 5-12 JUNE 1991, UNPUBLISHED DATA)

Depth (cm)	Equation	N	r^2
	Ser. No. H35066190		
10	$\theta_v = 0.0271 + 0.2442(CR^a)$	7[b]	0.91
30–210	$\theta_v = -0.0665 + 0.2641(CR)$	39	0.96
30–110	$\theta_v = -0.1062 + 0.2908(CR)$	19	0.96
130–210	$\theta_v = -0.0580 + 0.2599(CR)$	20	0.97
30–130	$\theta_v = -0.0895 + 0.2798(CR)$	23	0.95
150–210	$\theta_v = -0.0578 + 0.2593(CR)$	16	0.97
	Ser. No. H34055446		
10	$\theta_v = -0.0036 + 0.2547(CR)$	4	0.92
30–210	$\theta_v = -0.0618 + 0.2414(CR)$	39	0.96
30–110	$\theta_v = -0.1009 + 0.2658(CR)$	19	0.96
130–210	$\theta_v = -0.0532 + 0.2375(CR)$	20	0.97
30–130	$\theta_v = -0.0862 + 0.2569(CR)$	23	0.96
150–210	$\theta_v = -0.0528 + 0.2370(CR)$	16	0.97
	Ser. No. H34055447		
10	$\theta_v = 0.0037 + 0.2583(CR)$	4	0.90
30–210	$\theta_v = -0.0599 + 0.2484(CR)$	39	0.96
30–110	$\theta_v = -0.0973 + 0.2724(CR)$	19	0.96
130–210	$\theta_v = -0.0521 + 0.2450(CR)$	20	0.97
30–130	$\theta_v = -0.0830 + 0.2633(CR)$	23	0.96
150–210	$\theta_v = -0.0522 + 0.2451(CR)$	16	0.97
	Ser. No. H36046503		
10	$\theta_v = 0.0013 + 0.2582(CR)$	4	0.87
30–210	$\theta_v = -0.0624 + 0.2526(CR)$	39	0.96
30–110	$\theta_v = -0.1025 + 0.2787(CR)$	19	0.96
130–210	$\theta_v = -0.0534 + 0.2480(CR)$	20	0.97
30–130	$\theta_v = -0.0861 + 0.2684(CR)$	23	0.95
150–210	$\theta_v = -0.0528 + 0.2470(CR)$	16	0.96

[a]Count ratio: the neutron count in the access tube divided by the standard count.
[b]Number of samples in the regression analysis.

TABLE VII. CALIBRATION EQUATIONS FOR AMARILLO AND ULYSSES SOILS FOR TWO CPN NEUTRON MOISTURE GAUGES [Evett 1993, unpublished data]

Depth (cm)	Equation	N[a]	SEE[b]	r^2
	AMARILLO fine sandy loam			
	Ser. no. 5447			
10	θ_v[c] = -0.0214 + 0.2505(CR)[d]	6	0.0047	0.94
30–190	θ_v = -0.1048 + 0.2546(CR)	53	0.0063	0.95
30–90	θ_v = -0.0878 + 0.2435(CR)	24	0.0061	0.96
110–190	θ_v = -0.1328 + 0.2739(CR)	29	0.0055	0.96
30–110	θ_v = -0.0945 + 0.2482(CR)	30	0.0063	0.96
130–190	θ_v = -0.1291 + 0.2708(CR)	23	0.0054	0.96
	Ser. no. 6190			
10	θ_v = -0.0666 + 0.2984(CR)	6	0.0036	0.97
30–190	θ_v = -0.1139 + 0.2732(CR)	53	0.0066	0.95
30–90	θ_v = -0.0988 + 0.2636(CR)	24	0.0067	0.96
110–190	θ_v = -0.1415 + 0.2926(CR)	29	0.0052	0.97
30–110	θ_v = -0.1046 + 0.2676(CR)	30	0.0067	0.95
130–190	θ_v = -0.1391 + 0.2904(CR)	23	0.0052	0.97
	ULYSSES silt loam			
	Ser. no. 5447			
30–190	θ_v = -0.0321 + 0.2444(CR)	54	0.0076	0.98
30–90	θ_v = -0.0363 + 0.2469(CR)	24	0.0060	0.94
110–190	θ_v = -0.0331 + 0.2457(CR)	30	0.0088	0.98
30–110	θ_v = -0.0310 + 0.2424(CR)	30	0.0074	0.92
130–190	θ_v = -0.0368 + 0.2502(CR)	24	0.0073	0.99
	Ser. no. 6190			
30–190	θ_v = -0.0352 + 0.2579(CR)	54	0.0089	0.98
30–90	θ_v = -0.0436 + 0.2633(CR)	24	0.0077	0.90
110–190	θ_v = -0.0366 + 0.2598(CR)	30	0.0099	0.98
30–110	θ_v = -0.0383 + 0.2587(CR)	30	0.0085	0.90
130–190	θ_v = -0.0405 + 0.2648(CR)	24	0.0088	0.99

[a]Number of samples in the regression analysis.
[b]Standard error of estimate.
[c]Water content ($m^3\ m^{-3}$).
[d]Count ratio.

2.2. Temperature effect on standard counts

Figure 13 shows data collected in 1985 using a Campbell Pacific Nuclear 503DR gauge during a field calibration exercise at Marana, Arizona. The calibration required the manual installation of access tubes and extraction of soil samples at several depths as the hole was augered. This was time consuming, and installation of a particular access tube could finish at any time of the day. Just before taking count readings at the various depths in the access tube, a standard count in the shield was taken and the mean count, χ ratio and time were recorded. The gauge was in the field during the entire period and was equilibrated to air temperature as much as possible. A weather station in the field recorded air temperature every 15 min. The nearest 15-min average air temperature and standard counts for which χ ratios were above 0.9 and below 1.1 were used to build the data set that is shown in the graph.

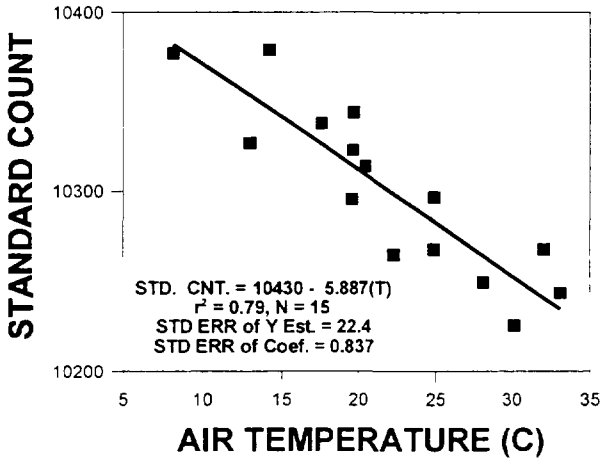

FIG. 13. Standard counts from a neutron moisture gauge (model 503DR, Campbell Pacific Nuclear International, Martinez, CA) and corresponding ambient air temperatures at Marana, Arizona, USA, 1985.

Linear regression (Fig. 13) showed that the ambient temperature explained 79% of the variation in standard count. The correlation was negative, with lower standard counts for higher temperatures. For a temperature change of 30°C, one could expect a change in standard count of 177. The calibration equation for this probe had a slope of 3.59×10^{-5}. Multiplying the slope by the change in standard count gives a change in measured water content of 0.006 m^3 m^{-3}. This is close enough to a 1% change in water content to cause some concern.

There are reasons to expect that the primary source of temperature dependency is the detector tube, which contains boron trifluoride gas. Gas pressure is responsive to temperature changes and the detection process may be influenced by gas pressure. The counting circuitry may also be involved, particularly the high voltage and detector circuits, which are somewhat analog in nature. The rest of the circuitry in the probe would be insensitive to temperature because it is basically digital. Certainly the electronics in the gauge readout assembly, where the microcontroller is housed, are entirely digital, so the problem almost certainly resides in the probe.

In the semiarid environment at Bushland, Texas, we may see a 17°C air temperature swing during the working day. There is potential for the probe to be subjected to even wider temperature changes because it is used in the access tube, as well as in the shield for standard counts. The temperature of the probe changes while in the access tube. During passage from one access tube to another, the probe is locked in the shield and may equilibrate with ambient. At the bottom of the access tube it may be much cooler or warmer depending on air temperature. The probe temperature changes each time it is moved to a new depth stop for a reading. Without a measure of probe or detector tube temperature, correction for such change is impossible. We can measure the effect from standard counts

in the field or by using an environmental housing set to different temperatures for each standard count. But, that information is meaningless unless probe temperature can be determined during each reading in the access tube and during routine standard counts in the field.

2.3. Suggestions for neutron probe calibration and use in a scientific setting

(1) Ensure a wide range in the water content data by finding or creating a dry site (e.g., by growing a crop of sunflowers), and then flood an adjacent bermed area until the soil profile is wet to the depth desired. Allow drainage to "field capacity" before sampling, to avoid changes in water content due to drainage during sampling. The degree of spread in water content has a direct effect on the calibration equation r^2 value and thus the proportion of the variability in water content that is explained, through the calibration equation, by variations in count ratio. In Fig. 14a the original data for a calibration at wet and dry sites are shown along with the

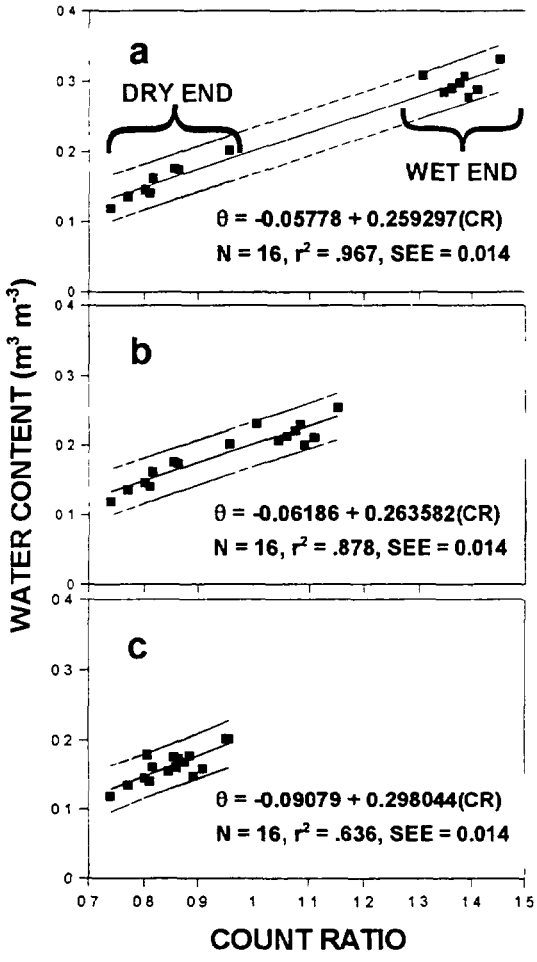

FIG. 14. An unaltered set of data from a wet site-dry site neutron probe calibration (a), and calibrations for the same data but with the wet end points moved closer (b) and still closer (c) to the dry end by sliding them along the regression slope. In each plot, the middle line is the regression line and the upper and lower lines are the 95% confidence intervals.

calibration equation, which had r^2 of 0.967 and SSE of 0.014 m^3 m^{-3}. In Figs. 14b and 14c the wet end data points have been moved closer to the dry end points. The relative positions of the points have not been changed and they have all been moved an equal distance along a line whose slope is equal to the regression slope for the unaltered data. Thus, the degree of noise in the data due to noise in counts or in volumetric water contents has not been altered. This fact is reflected in the standard error of estimate, which remained the same at 0.014 m^3 m^{-3} for regressions on the altered data sets. But, the intercept became increasingly negative and the slope more positive as

the range of water contents decreased. For Fig. 14b, the differences in slope and intercept were not large, but for Fig. 14c the slope increased by 0.039. This represents an error of about 0.04 m^3 m^{-3} over a range of 1 in count ratio, which is equivalent to a water content range of about 0.26 m^3 m^{-3} for the original data, or about a 16% error rate. The apparent invariant width of the 95% confidence intervals is misleading. Although the confidence intervals around the data points do not change, the confidence intervals outside the range of the data points (not plotted) increase dramatically, illustrating that another advantage of a wide range of water contents is greater confidence in accounting for extremes in soil moisture likely to be encountered in the field.

(2) Ensure adequate numbers of samples by installing at least three access tubes in both the wet and the dry areas, and by taking four samples around each tube at each depth that is read with the neutron probe. This typically gives enough samples that calibration equations can be broken out by soil layers or horizons (see Tables V–VII), and the slopes can be shown with some confidence to be equivalent, or not, between layers. The 10-cm depth always requires a separate calibration equation due to loss of neutrons to the atmosphere; and enough samples should be taken around the access tubes to ensure a good calibration for this depth. With the Madera probe, six vertical samples can usually be obtained around each access tube for the 10-cm depth.

(3) Ensure that samples are good, by trenching alongside the access tubes and sampling horizontally around the tube with a Madera[1] probe. This probe has a small cross sectional cutting area and is machined inside to a larger diameter past the cutting edge (Fig. 15) Thus, it compresses samples very little. Also, after driving in the probe, one can see easily if the sample is compressed, by comparing the soil surface inside and outside the probe body. Likewise, one can see if the sample is shattered, which would result in bulk density being too low. Bad samples can be discarded on the spot and replacements taken. Because this probe gives a 60-cm^3 sample volume, the volumetric water content can be determined directly and the heterogeneity of bulk density and water content assessed at each depth. With four samples per depth per tube, outliers can be discarded later if prudent, and there will still be enough samples to give a good mean water content at each depth and tube. Our experience with ring samplers is that the extra width of the cutting edge, required to accommodate the ring inside the sampler, increases the cross-sectional area of the cutting edge and thus increases compression of soil ahead of the sampler as it is driven into the soil. Trench walls are stair-stepped or shored up to prevent collapse and injury to workers.

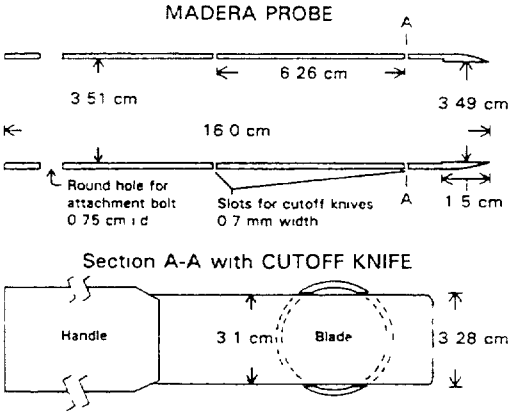

FIG 15 Madera probe schematic

It is noteworthy that the Madera probe was developed for sampling down the auger hole as access tubes are installed. Having used the probe extensively in this way, I have concluded that the down-hole method is less desirable for two reasons. First, only one sample per depth is obtained. Second, despite the utmost care, samples may be compressed, which is impossible to directly assess.

[1]Madera probes and accessories may be purchased from Precision Machine Company, Inc., 2933 North 36th Street, Lincoln, NE 68504-2498, USA. Tel 402 467.5528, FAX 402.467.5530.

Madera probes are available for different soil types, the wall thickness depending on soil resistance. At Bushland, we use the "clay" probes. We have not used the driver from PMCI. Instead, a 2-kg hammer is driven against a block of wood on top of the probe. This probe works well because of the small cross sectional area normal to the axis of insertion, and the reamed body behind the cutting bit (Fig. 15), which relieves the core from frictional forces as it moves through the body of the probe. The bayonet-mount ears on the top of the probe provide an ideal place to insert a rod to use to twist the probe before pulling it out of the soil.

The twisting action shears the soil at the front end of the probe. We have found that lubricating the probe with silicone spray reduces compaction in some soils. Most of the lubricant is pushed off the probe by the soil that first passes through, so that a negligible amount finds its way into the sample.

These probes have two slots for cutting to produce the 60-cm^3 volumetric sample Spatulas, as sold by VWR, Cole-Parmer, PGC Scientifics, etc., insert easily into these slots. The same is possible with spatulas sold in hardware stores, though most are too wide and must be tailored to the right width on a bench grinder.

(4) Ensure that the probe is at the correct depth for each reading. We take readings at 10-cm depth and in 20-cm increments below that. We have built stands (Fig. 16) that slide over the access tubes and keep the gauges at a constant height above the soil surface (in our case, 82 cm from gauge base to soil surface). We then set cable stops to give the desired depths of measurement With this system we always get reading depths referenced to the soil surface, not to the top of the access tube. For normal field use, the gauge can be carried in one hand and the stand in the other. Other advantages of the stand are that the user can operate the gauge while standing, avoiding the back strain incurred when the gauge is set directly on top of the access tube, and that any interference of the gauge shield with the 10-cm depth reading is eliminated. Because cable stops may slide on the cable or the insulation may move up or down the cable, it is advisable to check the positions of cable stops periodically during the measurement season.

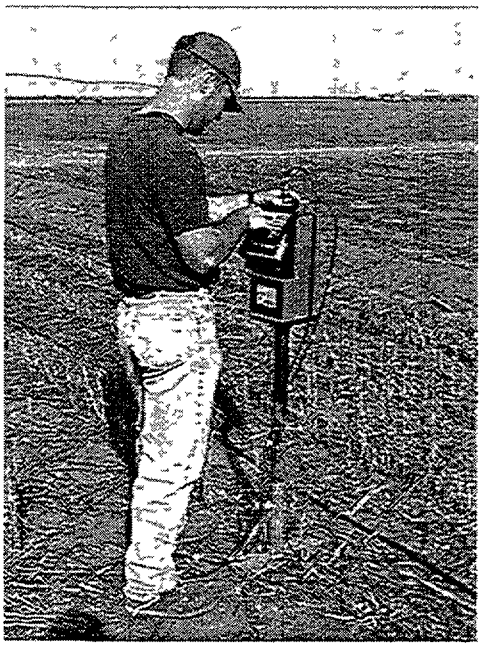

FIG. 16 A CPN model 503DR neutron probe mounted on a stand, which has been placed over an access tube. The feet of the stand are designed to fit between plants in a row, yet provide enough surface area to not sink into the soil The protrusion of the access tube above the soil surface prevents the stand from falling over.

(5) Ensure that standard counts are not influenced by soil water content. This is another advantage of the stand, which is set up on a base plate to take standard counts in the field away from vegetation (Fig. 17) Previous to this, we saw that standard counts varied depending on whether

the soil was very wet after a heavy rain or dry (this with the gauge case set on the soil surface and the gauge set on the case for the standard count).

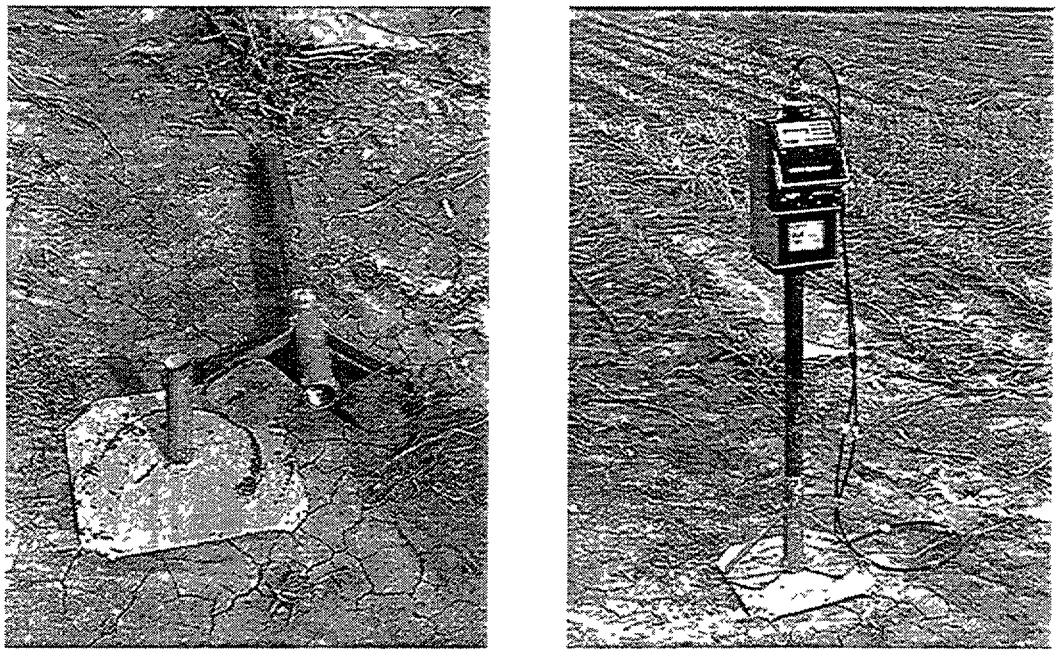

FIG 17 On the left are the stand and base plate to support a neutron moisture gauge 82 cm above the soil for standard counts On the right the stand is placed on the base plate and the neutron moisture gauge is in position for a shield count

3. USE OF TDR AND NEUTRON SCATTERING FOR SOIL WATER BALANCE STUDIES

Weighing lysimeters have been used for many years for precise (e.g., 0.05 mm) measurement of evaporation (E) and evapotranspiration (ET) from bare and cropped soils [38]. However, lysimeter installations suffer from some serious drawbacks including disturbance of the soil profile, interruption of deep percolation and horizontal flow components, and uneven management of lysimeter compared to field soil [39]. Other drawbacks include heat flux distortions caused by highly conductive steel walls [40, 41] and high cost, e.g., US$65,000 [42] and US$80,000 [43].

Alternatives to lysimetry for the measurement of E and ET include mass balance techniques that involve measuring the components of the water balance equation for a soil profile of given depth:

$$\Delta S = P - (E \text{ or } ET) - D - R \quad (15)$$

where

ΔS is the change in soil profile water storage (mm),
P is precipitation, including irrigation (mm),
R is runoff (mm),
and D is deep percolation, i.e., water moving across the bottom boundary of the soil profile (mm).

Solving for E or ET gives:

$$E \text{ or } ET = -\Delta S + P - D - R \quad (16)$$

Measurement intervals commonly range between hours and weeks, and are usually no smaller than the required period of ET measurement. Measurement of each variable in the right side of Eq. 16 presents its own unique problems, and it should be stated that lysimetry has three sources of measurement error as

well [lysimeter mass (ΔS), precipitation (P), and runoff (R)]. However, the water balance technique is applicable in many situations for which lysimetry is inappropriate or impossible, and is, in addition, much less expensive. The focus of this section will be the measurement of changes in water storage, ΔS, using combined TDR and NS, compared with lysimeter measurements.

Soil profile water content measurement techniques range from destructive sampling, using augers or coring tubes, to non-destructive techniques such as γ-ray attenuation, neutron scattering and capacitance measurements in access tubes, and various sensors including resistance blocks, heat flux based sensors, and TDR probes buried at specific depths. Destructive techniques are commonly avoided due to the need to repeatedly measure the same locations and the time involved in handling the samples. Of the non-destructive techniques, NS, proposed by Van Bavel and Stirk in 1967 [44] for ET studies, has been used often [45, 46]. Due to the small changes in water content associated with single-day ET and the limited precision of NS, especially near the surface, the water balance method is usually restricted to measurement of ET over several-day periods [47]. Wright [46] compared ET measured by a weighing lysimeter to that measured by soil water balance using NS, and concluded that large errors in the water balance method occurred if the depth of the profile measured by NS did not exceed the depth of wetting due to irrigation. The errors were then due to excessive water flux through the bottom of the profile.

Time domain reflectometry has more recently become available and lends itself to automated monitoring of soil water content [6–10]. One disadvantage of TDR is the difficulty of installing probes at depth. However, since the short-term rapid changes in soil water content due to infiltration events and evaporation may be confined to the near-surface layers, TDR may be used for these measurements while NS is used at greater depths. The spatial sensitivity of TDR may be confined to a region as small as 2 cm above and below the plane of horizontally installed probes [48, 49] so a great deal of information about the vertical variability of soil water content may be gathered relatively easily in the near-surface soil, where such variation is most likely to occur and where the NS technique is most difficult to calibrate and properly apply. Evett et al. [9] investigated the joint use of TDR and NS for estimating ET and compared it to weighing lysimeter measurements as follows.

3.1. Methods

The experimental site was at Bushland, Texas, during 1992 from day of year (DOY) 80 to 108 in the northeast lysimeter field on a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll). The 3-m square $\times$ 2.3-m deep weighing lysimeter was in the center of a square 4.7-ha field. Lysimeter measurements of ET were precise to 0.05 mm [50]. Winter wheat was planted the previous fall and leaf area index changed from 4.2 to 6.7 over the experimental period, while crop height increased from 20 to 60 cm.

Prior to planting wheat, TDR probes were installed in two vertical TDR/Temperature arrays in the lysimeter for measurement of soil water content. For each array, probes were installed horizontally at depths of 2, 4, 6, 10, 15, 20 and 30 cm, with Cu-Co thermocouples at the same depths. Probe traces were automatically measured and recorded at 30-min intervals using an IBM PC/XT compatible computer equipped with an analog to digital conversion card, and running a precursor to the TACQ program. A Tektronix model 1502 cable tester provided the TDR trace output. These older, analog cable testers are available for less than half the cost of the digital models, and were modified for electronic control of trace output. A 16-channel multiplexer with 50-Ω characteristic impedance was designed to switch the TDR signals among probes while introducing minimal signal distortion (model TR-200, Dynamax, Inc., Houston, TX) [51]. Signals were provided through the PC's parallel port for both switching and toggling the cable tester for trace output.

Trifilar TDR probes were used (model TR-100, Dynamax, Inc., Houston, TX). Each consisted of an epoxy resin and polymethylmethacrylate handle from which extended three parallel, type 316 stainless steel rods. The rods were spaced in a single plane at 3 cm center to center and were 3.18 mm (nominally 1/8 inch) in diameter and 20 cm long from the tip to the point of emergence from the handle. The probes were inserted into the soil from the side of a pit so that the rods were parallel to the soil surface and the three rods for each probe were at the same distance from the soil surface. The outer two

rods were soldered to the outer conductor of a type RG/58U coaxial cable and the inner rod was soldered to the inner conductor The solder joints, proximal ends of the rods and distal end of the cable were encapsulated together in the handle The three-wire configuration is semi-coaxial in nature and eliminates the need for a balun used with a two-rod design [18] In addition, the range of sensitivity above and below the plane of the rods is narrower for the three-wire configuration than for the two-wire configuration most commonly used in the past [49], allowing for better discrimination of soil water content with depth

The TDR method depends on the change in apparent permittivity of the soil that occurs when water content changes The permittivity of the mineral matter in soil varies between 3 and 5 Although air may make up a large part of the soil volume, its permittivity is unity By contrast, the permittivity of water is about 80, depending on temperature As soil wets and dries, its apparent permittivity ε_a changes accordingly, though not linearly We computed ε_a as

$$\varepsilon_a = \mu^{1}[c_o t_T/(2L)]^2 \qquad (17)$$

where

t_T is the two-way travel time (s) for the cable tester voltage pulse to travel from one impedance change to the other and back again (i e , round trip from probe handle to end of rods) as measured with TACQ,
L is the distance (m) between the impedance changes.
c_o is the speed of light, (m s^{1}),
and μ is the magnetic permeability, assumed to be unity

For four fine-textured mineral soils, Topp et al [1] experimentally determined a polynomial function describing the relationship between ε_a and volumetric water content, θ

$$\theta = (-530 + 292\varepsilon_a - 5\ 5\varepsilon_a^2 + 0\ 043\varepsilon_a^3)/10^4 \qquad (18)$$

The Pullman clay loam is a similar soil and Topp's equation was used

The TDR water contents and first derivatives with respect to time were smoothed and calculated using center weighted quadratic polynomial least squares estimation with weights computed using an algorithm that allows calculation of off-center weights for smoothing end points [22] A nine-point data smooth followed by a five-point derivative smooth was used for water content data from the 2- to 20-cm depths And, a twenty-five-point data smooth followed by a fifteen-point derivative smooth was used for data from the 30-cm depth which, although noisier than that for shallower depths, did not change rapidly Change in storage in mm per unit time was calculated by multiplying the layer thickness (mm) by the first derivative

Water content measurements by NS were taken at two sites on each lysimeter at depths from 10 to 190 cm in 20-cm increments using a Campbell Pacific Nuclear model 503DR neutron moisture gauge Access tubes were 4 1-cm (1 62 inch) ID, 4 4-cm (1 75 inch) O D steel electromechanical tubing, 2 3 m long Counts were taken for 32 s Prior to and after measurements, standard counts were taken until at least three were obtained with χ ratios in the range $0\ 9 \leq \chi$ ratio $\leq 1\ 1$ Standard counts taken after the measurements in the tubes showed that no appreciable drift occurred over the measurement time All standard counts were taken with the neutron probe sitting on top of its case, which rested on bare, dry soil The Pullman soil has three horizons that differ in ways that are important for neutron probe calibration Calibration equations for these are given in Table V

3.2. Results

Although separated by only 40 cm horizontal distance, the two TDR arrays showed markedly different soil wetness (Fig 18) This was due to array 1 being in the inter-row where soil surface wetness tended to be lower and wetness at depth higher than for array 2 which was in the wheat row

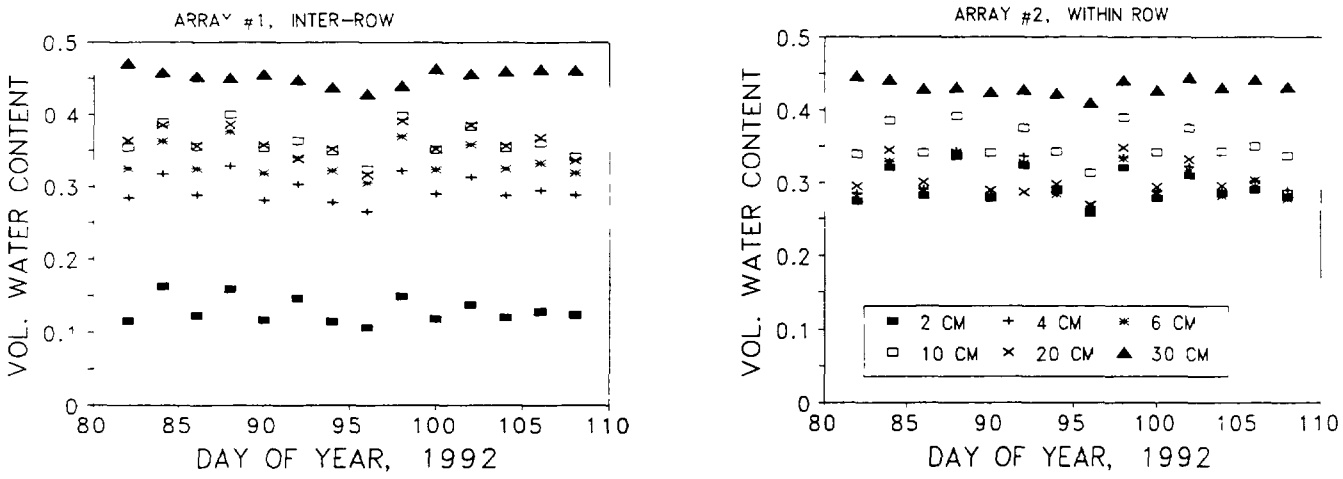

FIG. 18. Smoothed TDR water contents for two TDR arrays.

Despite this difference, data from the two arrays reflected very well the dynamics of multiple infiltration and drying sequences. Mean water storage changes in the top 40 cm of the soil profile followed closely the whole profile storage as measured by the lysimeter, including response to infiltration, daily drying and night-time plateaux (Fig. 19).

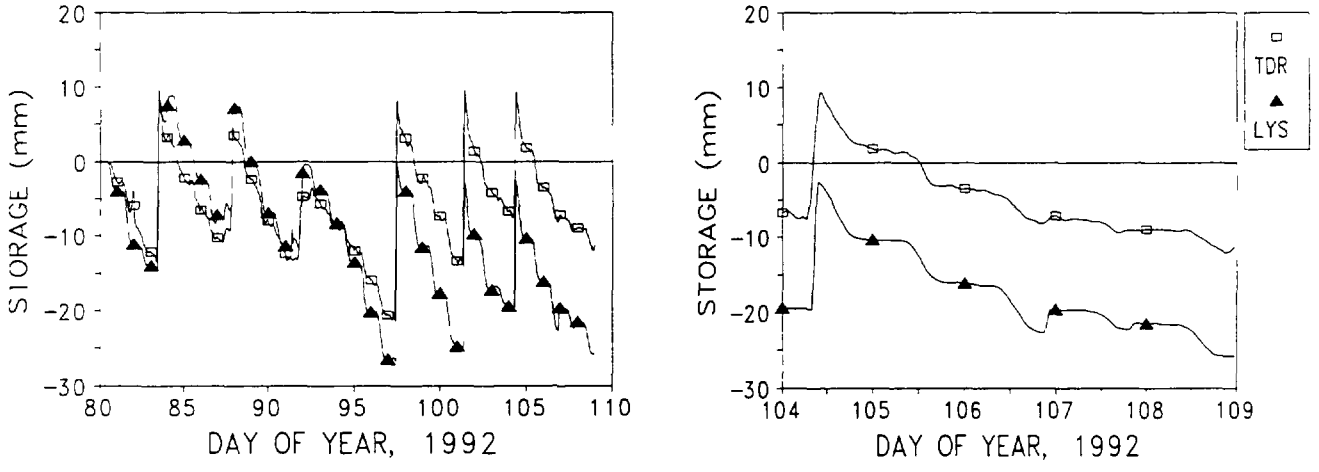

FIG. 19. Lysimeter (LYS) storage compared with mean storage from TDR for the entire period (left) and final five days (right).

The daily storage change measured by TDR averaged 88% of that measured by lysimeter, confirming that by far the largest part of daily change in storage was in the top 40 cm of soil (Fig. 20). Implications of this are threefold. First, TDR arrays may be used to measure precisely the largest part of daily storage change. Second, the NS method, no matter how well calibrated, is unlikely to ever give good daily storage change measurements because it is most imprecise near the surface where most storage change occurs. Third, combining TDR with daily NS measurements holds great potential for precisely defining the daily change in soil profile water storage.

Deep percolation and runoff were zero for the lysimeter. Therefore, daily ET could be calculated from Eq. 16 by adding precipitation amount to storage change. There were large discrepancies between lysimeter-measured ET and that calculated from change in storage based on TDR data alone (Fig. 21). The TDR method overestimated ET on precipitation days (including irrigation) in the first part of the period shown, due to drainage flux out of the bottom of the 0- to 40-cm layer. These precipitation events were followed by dry periods during which the TDR method underestimated ET due to upward soil water flux into the 0- to 40-cm layer.

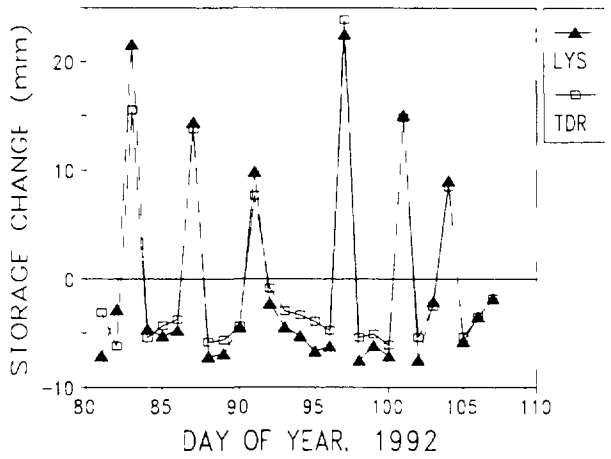

FIG 20. Daily change in storage from lysimeter (LYS) and TDR arrays.

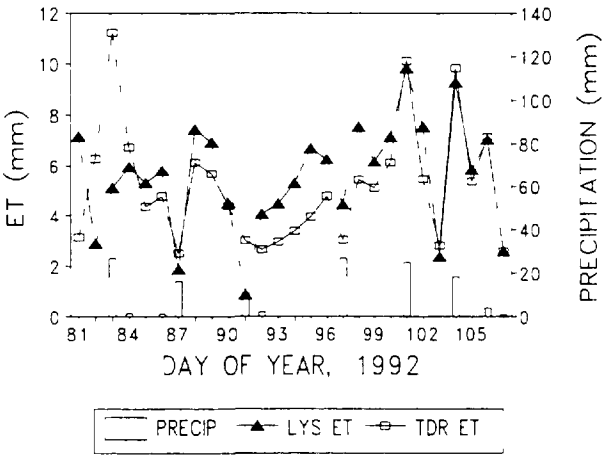

FIG 21. Evapotranspiration calculated from lysimeter and TDR change in storage

Despite the underestimation, the TDR method closely followed the changes in daily ET during the drying periods. Also, during the last 8 days of the period, the TDR method matched closely the lysimeter-measured ET even on days 101 (24 mm) and 104 (18 mm) when irrigation occurred. The good match for days 100 through 107 may be due to swelling of the B horizon after repeated precipitation and irrigation events. In this soil, once the cracks close the hydraulic conductivity decreases markedly, effectively sealing the bottom of the 0- to 30-cm soil layer. There is also some evidence that soil swelling may increase root axial resistance to water flow. This, combined with the tendency for the root system to remove water from the top soil layers first, may have caused most root water uptake to occur in the top 30 cm of soil. These results agree with those of Zegelin et al. [52], who found that TDR-measured changes in soil water storage agreed with lysimeter-measured values to better than 10% for a soil with a heavy clay subsoil.

Lack of NS measurements precluded completion of the soil water balance on a daily basis. However, NS measurements on days 90 and 106 allowed the change in storage to be calculated for the intervening period. Lysimeter storage decreased by 9.31 mm over the 16-day period, but NS measurements showed a 12.9-mm decrease or a 3.55-mm error. Combining the change in storage calculated for the 40- to 200-cm profile by NS with the TDR-based change in storage for the surface to 40-cm profile, gave an 8.65-mm change in storage, for a smaller error of 0.67 mm.

Some insight into the problems involved in measuring near-surface soil water content with NS is given by Fig. 22, which shows NS measurements at 0.1 m and deeper, and TDR measurements at several depths in the top 0.2 m of soil. The vertical structure of water content near the surface is complex, with a layer at 0.1-m depth that is at 0.31 m^3 m^{-3} and represents a wetting front from a recent rain. Just 5 cm below that layer the water content is only 0.22 m^3 m^{-3}. At 0.2-m depth, the water content increases again due to the presence of an illuvial clay horizon. The NS measurement at 0.1-m depth appears to respond mostly to the water at 0.06 and 0.1-m depths, and not to the drier soil nearer the surface.

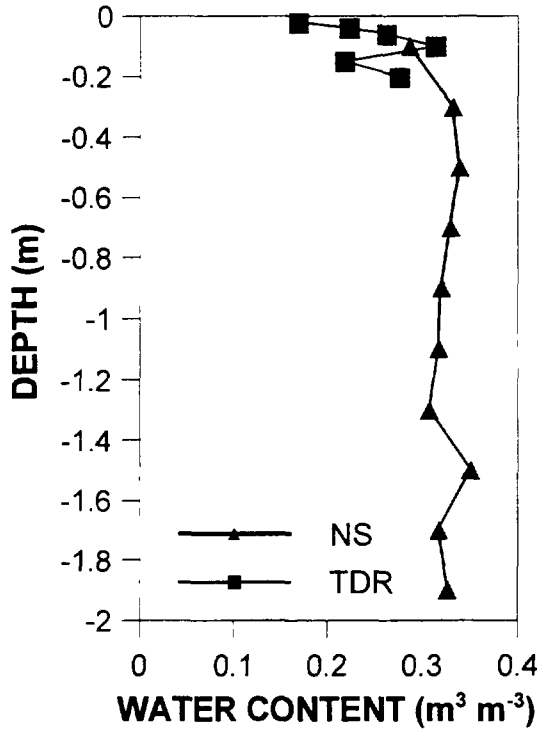

FIG. 22. TDR and neutron scattering (NS) measurements taken in a Pullman clay loam soil profile at Bushland, Texas, USA.

3.3. Conclusions

Vertical arrays of horizontally installed TDR probes showed good potential for accurately measuring change in water storage in the top 40 cm of soil over periods of a day or less. Our TDR technology allowed us to show that, for our wheat crop, an average of 88% of the daily total soil profile change in storage occurred in the top 40 cm. Since neutron scattering is most imprecise near the soil surface it thus becomes doubtful that neutron moisture gauges alone could be used for daily ET estimates, no matter how well calibrated. However, the combination of neutron scattering measurements at depths below 40 cm with TDR measurements above 40 cm allowed the change in storage over a 16-day period to be calculated to within 0.7 mm of that measured by the weighing lysimeter. This error was one fifth of that realized with neutron scattering. Future research will combine daily neutron scattering measurements at depth with TDR measurements in the near-surface soil of a lysimeter to find if accurate daily ET measurements can be made.

4. COMPARISON OF NEUTRON AND CAPACITANCE PROBES

A capacitance probe (CP) soil moisture gauge, as described by Dean et al. [53], consists of an electrode pair separated by a plastic dielectric. The upper and lower electrodes and the plastic separator are in the shape of a cylinder that fits closely inside a plastic access tube. A resonant LC (L = inductance, C = capacitance) circuit in the probe includes the ensemble of the soil outside the access tube, the access tube itself, plus the air space between the probe and access tube, as one of the capacitive elements. Changes in the resonant frequency of the circuit depend on changes in the capacitance of the soil-access tube system. The difference between the resonant frequency of the probe in the access tube and a baseline resonant frequency (often measured with the probe in air) is the D value and is that reported by the gauges studied here.

Care is taken to center the capacitance probe in the access tube with minimal space between probe and tube. Access tube installation is also done so as to eliminate air gaps between the tube and soil and minimize soil disturbance. When these conditions are met, changes in the capacitance of the soil-access tube system are those induced by changes in soil water content, temperature, bulk density and macroporosity. The capacitance change caused by water content change is due to the high permittivity, ε_w (dimensionless), of water that is about 80 and is much higher than that of soil minerals (3 to 5) or air (1).

The capacitance of the soil-access tube system, C (F), is [53]:

$$C = g\varepsilon_a \tag{19}$$

where

ε_a is the system apparent permittivity,
and g has a value (F) dependent on the geometry of the system.

The resonant frequency, F (Hz), is [53]:

$$F = [2\pi(L)^{0.5}]^{-1} (C^{-1} + C_b^{-1} + C_c^{-1})^{0.5} \tag{20}$$

where s

C_b, C_c are the electrode capacitances (F) including the capacitances of internal circuit elements to which the electrodes are connected,
C is the capacitance of the soil-access tube system defined in Eq. 17,
and L is the inductance (H) of the coil in the LC circuit.

As soil water content increases so also does C, and F decreases. The temperature dependency is induced by the temperature dependence of water's permittivity (assuming that the probe electronics are practically temperature insensitive).

An idea of what the geometry parameter, g, refers to can be obtained from the classical equation for capacitance of a simple two electrode plate capacitor:

$$C = \varepsilon_o K_a a/d \tag{21}$$

where

ε_o is the permittivity of free space (8.9×10^{-12} F m^{-1}),
a is the overlapping area (m^2) of the plates,
and d is the thickness (m) of the dielectric separating the plates [54, Eq. 2-29].

This equation is valid only if the plates are parallel and the dielectric separating them is uniform For this simple capacitor the value of g in Eq 19 is $\varepsilon_o a/d$.

For the capacitance probe, the soil-access tube system that forms the dielectric between the two probe electrodes is complex, and no relationship has been established for computing g and thus C for this geometry The plates take the form of two surfaces on a cylinder separated by an insulator, and the access tube and soil are outside of, not between, the plates Thus, the electric field permeating the soil forms a more or less elliptical torus around the probe with lines of force originating in one plate and ending in the other This was called a *fringing field* by Thomas [55]. Although Eq 21 does not apply to this configuration, any equation that does apply has to include terms that describe the plate (electrode) surface area and the interaction of the electric field and the soil volume that it permeates The latter is described by d in Eq 21 since the simple geometry of a plate capacitor confines almost all the electromagnetic flux to the volume of dielectric between the plates For the CP probe electrodes, the surface area of the electrodes is well known, but the degree to which the torus of electric force lines permeates the soil is not Thus, it seems that any term equivalent to d is particularly ill-defined in this soil-access tube system since the soil, with all its variability in bulk density and water content, becomes the dielectric in the capacitive system and the shape of the field may be influenced by soil heterogeneity including any gaps between the soil and tube wall induced by tube installation

Bell et al [56] described methods for access tube installation and calibration for this type of capacitance probe Plastic tubes were installed, with a steel liner and cutting head operating through a guide plate to prevent lateral movement and the creation of air gaps between soil and tube. Installation proceeded in 4-cm increments using a screw auger placed inside the tube and augering no more than 4 cm ahead of the cutting head. All soil was placed in plastic bags and the procedure was assumed to provide a volumetric sample over a 4-cm depth. Calibration of the probe in four soils resulted in coefficients of determination (r^2) ranging from 0 55 to 0.74 for regressions of frequency vs. volumetric water content for three soils, and r^2 values of 0.86 and 0.92 for two horizons of the fourth soil The latter calibration was based on four measurements Comparison of predicted and measured soil water profiles indicated good correspondence, but the r^2 values of some calibrations suggested that standard errors of estimate might be high

A soil water content CP gauge (Troxler Electronic Laboratories, Inc., model SENTRY 200AP) was patterned after that of Dean et al. [53] and included improvements while retaining desired characteristics Heathman [57] reported an r^2 of 0.62 for a field calibration of this gauge. Evett and Steiner [37] conducted a rigorous field calibration of four of the Troxler gauges in comparison with six NS gauges, using wet and dry sites as described above. Calibrations for the CP gauges exhibited low r^2 values, ranging from 0 04 to 0 71, and root mean squared error values of 0.036 to 0.058 $m^3\ m^{-3}$ (Table VIII) Example plots illustrate the much greater scatter of CP gauge data as compared with NS gauge data (Figs 23 and 24)

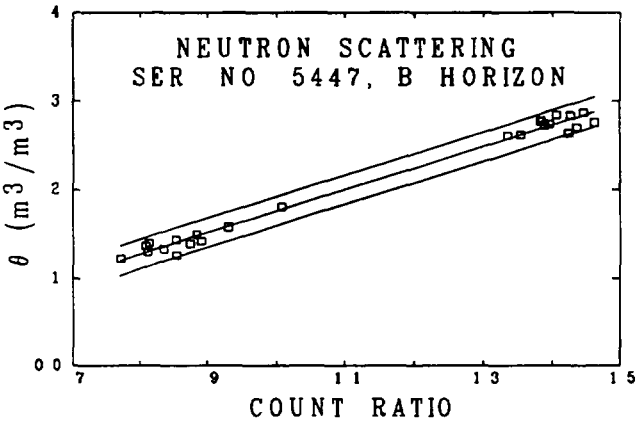

FIG 23 Typical volumetric water content (θ) vs count ratio relationship in the B horizon (tubes 1-6) Middle line is the regression line, upper and lower lines are 95% confidence limits on the predictions

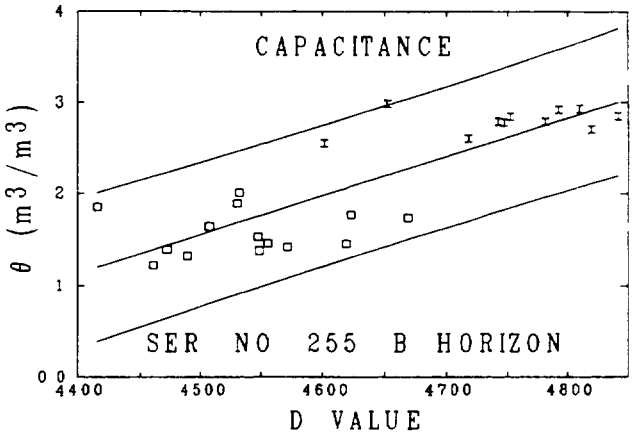

FIG 24 Typical relationship between volumetric water content (θ) and the absolute value of the measured frequency shift (D) from capacitance gauges (tubes 7-13) showing dry site data (□) and wet site data (I) Middle line is the regression line upper and lower lines are 95% confidence limits on predictions

In preliminary data analysis, Evett and Steiner [37] used stepwise linear regression of θ against frequency shift D, D^2, soil bulk density ρ (Mg m^{-3}), ρ^2, and $\rho^{0.5}$ to find the independent variable(s) that were a significant source of variability in the dependent variable Other than the intercept, only the coefficient for D^2 was significant at the 0 50 level of probability For the model, $\theta_v = B_0 + B_1D^2$, the coefficient for D^2 was so low ($B_1 = 4\ 6 \times 10^{-8}$) that the plot of θ_v vs D was nearly linear and differed only slightly from a plot of the linear model Because of this and the low significance of the $\theta = B_0 + B_1D^2$ relationship, this model was omitted from further consideration

Some possible sources of variability in the CP gauge readings can be discounted For instance Dean et al [53] showed that, for their design, total thermal (0–30°C) and temporal (over 3 h) stability errors in water content amounted to <0 005 $m^3\ m^{-3}$ They also showed that air gaps between the tube and soil would introduce large errors, thus the exacting tube installation procedure They did not measure the probe's sensitivity to ρ variations But, in a companion paper, Bell et al [56] noted that ρ appeared to affect the slope of calibration equations and concluded that more work was required in this area

The CP gauge is responsive mostly to a soil layer as thin as 8 cm [56] or 12 cm [58] vertically, and within 11 cm of the probe centerline [58] Thus, small-scale variations in soil properties are more likely to influence the probe's readings than would be the case for the NS gauge Our soil samples were generally taken within the 11-cm radius and 12-cm vertical range, but there was considerable variation in individual water contents for a given depth and access tube The electric field induced in the soil by the CP is influenced by boundaries between soil volumes having different permittivities [53] Thus, ρ or θ_v variations on a small scale could set up boundaries that would influence the size and shape of the sampled volume Boot and Watson [59] noted that sample heterogeneity can cause anomalous readings from capacitance probes applied to building materials, especially when the wavelength approaches the scale of heterogeneity Wobschall [60] pointed out that heterogeneous soils can also cause poor results

TABLE VIII. REGRESSION EQUATIONS FOR THE CAPACITANCE TYPE WATER CONTENT GAUGES; WATER CONTENT (θ)VS. D VALUE, AND D VS. MEAN D VALUE

Serial no.	Regression equation	r^2	RMSE[a] ($m^3\ m^{-3}$)	N
	A horizon (10-cm depth)			
255	$\theta_v = -0.140 + 0.000073(D)$	0.041	0.058	7
256	$\theta_v = -0.700 + 0.000215(D)$	0.211	0.052	7
257	$\theta_v = -0.273 + 0.000115(D)$	0.019	0.058	7
294	$\theta_v = -0.110 + 0.000067(D)$	0.010	0.058	7
	B horizon (41- to 102-cm depth)			
255	$\theta_v = -1.750 + 0.000423(D)$	0.698	0.036	25
256	$\theta_v = -1.460 + 0.000365(D)$	0.712	0.036	25
257	$\theta_v = -1.404 + 0.000380(D)$	0.681	0.037	25
294	$\theta_v = -1.583 + 0.000410(D)$	0.704	0.036	25
	D value vs. Mean D value (41- to 102-cm depth)			
255	D = 500 + 0.93(Mean D)	0.970	23	25
256	D = -271 + 1.09(Mean D)	0.974	25	25
257	D = -339 + 1.03(Mean D)	0.989	16	25
294	D = 110 + 0.96(Mean D)	0.960	27	25

[a]Root mean squared error.

Another possible explanation for the poor results with the CP gauges is that the measurement volume is considerably smaller than reported by Bell et al. [56] and Troxler Electronic Laboratories [58]. If this were so, then the soil sampling method that we used would be inappropriate. However, the 15.24-cm measurement interval provided by the stops on the CP gauge probe handle would be too large if the sampling volume were smaller than that stated by Troxler Electronic Laboratories [58]. If the sampling volume is indeed much smaller than reported, then the use of the CP gauge must be re-evaluated because many more samples at much smaller vertical sampling intervals must be taken to provide accurate integration of the soil water content profile. In fact, if this hypothesis is true, it may be difficult to accurately portray the soil water content profile in many soils because the representative elemental volume may be larger than the gauge's sampling volume. Field calibration of this gauge would also be problematic in this case, because an exacting relationship between probe position in the tube and position of soil sampling is implied.

Tomer and Anderson [61] obtained better results with the Troxler CP gauge in a comparison with an NS gauge in a deep aeolian sand (Zimmerman fine sand). Samples for calibration were obtained by taking 5-cm diameter vertical cores. Access tubes were then installed in the coring holes. Because the sand was not cohesive, bulk density values were not used from these samples, but bulk densities from a previous study were used to calculate volumetric water contents. The NS gauges calibration resulted in an r^2 value of 0.966 (N = 31). The CP gauge calibration gave an r^2 value of 0.888 (N = 73), and was similar to the manufacturer's calibration equation, a fact that is not surprising given that the

manufacturer calibrates in sand. Soil water lost in a 1.5-m profile over 2 weeks averaged 1.2 cm less as measured by the CP gauge compared with the NS gauge, and the CP gauge routinely gave higher water content measurements. The CP gauge had much higher spatial resolution, a fact that rendered it susceptible to problems with access tube installation.

Mohamed et al. [62] compared the Humicap (Nardeux, Loches, France) capacitance probe to a neutron probe (Solo 25, Nardeux). The capacitance probes were buried in augered holes with direct contact between the electrodes and the soil. The capacitance probes were highly sensitive to change in soil structure and texture, but provided better accuracy than the neutron probe, which was calibrated by a theoretical method. It is likely that the better results obtained for capacitance probes in this study were due to the lack of an air gap between the electrodes and the soil.

Paltineanu and Starr [63] calibrated a capacitance probe (EnvironSCAN, Sentek Pty Ltd., South Australia) in the laboratory using a silt loam soil with good results ($r^2 = 0.992$, N = 15, θ_v range = 0.07–0.37 $m^3\ m^{-3}$, RMSE = 0.009 $m^3\ m^{-3}$). Their calibration equation was:

$$\theta_v = 0.490\ SF^{2.1674} \tag{22}$$

where

SF is the scaled frequency (dimensionless),

$$SF = (F_a - F_s)(F_a - F_w)^{-1} \tag{23}$$

where

F_a, F_w are readings (Hz) in air and water, respectively,
and F_s is the reading (Hz) in the access tube.

Boxes were packed very uniformly (CV for ρ_b = 0.5 to 2.9%, CV for θ_v = 0.0054 to 0.065%) with soil at four different water contents for the calibration. The extreme uniformity of packing brings into question how appropriate the calibration would be for a field soil, which is likely to be much less uniform in bulk density and water content on a small scale. Tests of radial sensitivity showed that 99% of the sensitivity was within a 10-cm radius outside of the access tube, and 92% of the sensitivity was within a 3-cm radius of soil outside the access tube (Fig. 25). This reveals that the probe will be quite sensitive to small-scale variations of soil properties close to the access tube. Later, the same authors [64] installed these probes in the field for long-term measurements of profile water content. Though they reported success, they did not determine if the laboratory calibration proved accurate in the field. The tests they did conduct were comparisons with crop water use estimated using an atmometer, and cannot be considered rigorous. Oddly, they did not report any water contents, only soil water storage and change in storage data. Paltineanu and Starr [63] considered it inappropriate to compare the capacitance method with NS due to differences in measurement method and sphere of influence. However, such differences might well be the point of a comparison, as was shown by Evett and Steiner [37].

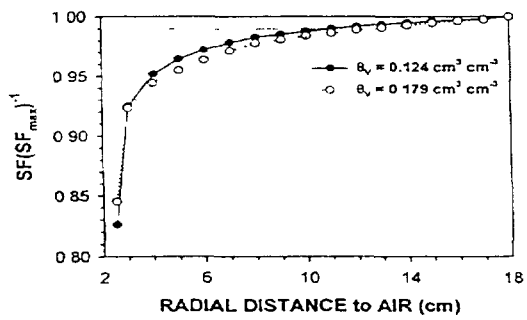

FIG. 25. Relative radial sensitivity of EnviroScan sensors as a function of radial thickness of soil around the access tube. From [63]

At this writing (1998), many capacitance-type soil moisture probes or gauges are being introduced in the marketplace. Some of these respond quite well to the dynamics of soil water content, including that due to plant water uptake. Demonstrations have shown that the dynamic behaviour of plant water uptake can provide important information needed for irrigation scheduling. But, there is a lack of scientific literature supporting claims of accuracy of soil water content measurement with these devices, demonstrating that laboratory calibrations may be used successfully in the field, or demonstrating successful field calibrations. Capacitance probes that employ sensors in a plastic access tube are the closest analogue of the neutron probe deployed in an access tube. However, studies to date show that capacitance probes have a very narrow radial range of sensitivity outside of the access tube and thus suffer from disadvantages that include 1) sensitivity to soil disturbance during tube installation, and 2) sensitivity to small scale variations in soil bulk density (including macroporosity), water content, and texture, which are common to many soils. Other studies have shown that capacitance probes are still sensitive to soil salinity, temperature, and texture, but perhaps less so than in the past. Though it may be useful for some irrigation scheduling needs, the capacitance probe still cannot be considered a replacement for the neutron probe for soil water content measurements for which accuracy is important.

5. BASIC CODE FOR SETTING TDR WINDOW WIDTH

```
SUB BestDistDv.Vp (ProbeLen, FtMtrs, Theta)
'Routine for choosing the best combination of Dist/Div and Vp for a
given
'probe length based on inversion of Topp's equation for permittivity,
Ka,
'as a function of water content. Written in Microsoft BASIC 7.1 by
S.R. Evett
'ProbeLen is probe length in meters.
'FtMtrs 'If 1 then units are feet else units are m.
'Theta is volumetric water content (m^3/m^3).

SHARED Vp
SHARED Dist
SHARED DistDv
SHARED CardType%
i% = 10
DIM TimeErr(i%)
DIM DistVal(i%)

'Limit values of water content:
IF Theta < 0 THEN Theta = 0
IF Theta > .6 THEN Theta = .6
'Calculate the apparent permittivity (Ka) (Topp et al., 1980 [1]):
Ka = 3.03 + 9.3 * Theta + 146! * Theta * Theta - 76.7 * Theta *Theta
*Theta
'The velocity of propagation is a function of Ka:
v = .299792 * 1E+09 / SQR(Ka)
'The travel time is a function of v and probe length:
tt = ProbeLen / v

'Assume that the travel time should occupy 70% of the screen max.
NewTtFull = (tt / .7) * 1E+09  'in ns

row% = CSRLIN
col% = POS(0)

TryAgain% = 0
SELECT CASE CardType%
```

```
CASE 5
Start.Search:
  'Try smallest Dist first, then next biggest, etc.
  'Get Dist for i=1 to 10:
  FOR i% = 0 TO 10
    DistDv = i%
    ReturnDistDv 'This returns one of the 11 possible Dist/Div
settings.
    'Make sure DistM is in meters: DistM is the distance per
division.
    IF FtMtrs = 1 THEN
      'was in feet, convert to meters
      DistM = Dist * .3048
    ELSE
      'was in meters
      DistM = Dist
    END IF
    'Try biggest Vp first, then go to smallest
    FOR Vp = .99 TO .39 STEP -.01
      TtFull = DistM * 10 / (Vp * .2997925)
      IF TtFull >= NewTtFull THEN EXIT FOR
    NEXT Vp
    IF TtFull >= NewTtFull THEN EXIT FOR
  NEXT i%
  TimeError = (TtFull - NewTtFull) / NewTtFull
  BestDist = Dist
  IF ABS(TimeError) > .02 THEN
    PRINT "Best Dist/Div and Vp not found."
    PRINT "Error was"; TimeError * 100; "%"
    PressAKey (5) 'Wait for a key press before continuing.
  END IF
  'One combination of Vp and Dist/Div is known.
  'The Dist/Div value is in BestDist. Print both Vp and Dist/Div:
  PRINT "    For VWC ="; Theta;
  LOCATE row% + 1, col%
  PRINT USING "recommend Vp: .## "; Vp;
  PRINT "and Dist/Div:"; BestDist;
  IF FtMtrs = 1 THEN
    PRINT "ft";
  ELSE
    PRINT "m";
  END IF

CASE ELSE
'For Tektronix 1502 cable tester, not 1502B/C.
'Provide two closest Dist/Div values for given Vp.
Start.Search2:
  'Get Dist for i=1 to 10:
  FOR i% = 0 TO 10
    DistDv = i%
    ReturnDistDv
    'Make sure DistM is in meters:
    IF FtMtrs = 1 THEN
      'feet
      DistM = Dist * .3048
    ELSE
      'meters
```

```
      DistM = Dist
    END IF
    'Use actual Vp first, and return error if TimeErr is too great
    TtFull = DistM * 10 / (Vp * .2997925)
    TimeErr(i% + 1) = (TtFull - NewTtFull) / NewTtFull
    DistVal(i% + 1) = Dist
    IF TimeErr(i% + 1) > 0 THEN EXIT FOR
  NEXT i%

  LOCATE 22, col%
  PRINT "For VWC ="; Theta;
  PRINT USING " and for Vp: .## "; Vp;
  FOR j% = i% TO i% + 1
    LOCATE 22 + 1 + j% - i%, col%
    PRINT "could use Dist/Div:"; DistVal(j%);
    IF FtMtrs = 1 THEN

      PRINT "ft";
    ELSE
      PRINT "m";
    END IF
    PRINT USING ". Error: ###"; TimeErr(j%) * 100;
    PRINT "%";
  NEXT j%
END SELECT
REDIM TimeErr(0)
REDIM DistVal(0)
END SUB
```

6. FINDING TRAVEL TIMES

Times t1.bis, t1, and t2 are reliably found by a combination of searches and decisions based on the results of those searches. In this discussion the wave form is assumed to consist of NP digitized data pairs of voltage and time with equal increments of time between consecutive data pairs.

(1) Smooth data and first derivative using the Savitsky-Golay method and user set number of points, and find the maximum and minimum first derivative, maxDeriv and minDeriv.

(2) Scan the wave form data from D2Lim to EndPt to find the lowest value, VMIN, and corresponding time, t2.1.

(3) Scan the first derivative in a loop from StartPt to D1Lim to find the first maximum value, D1MAX, and associated time tD1MAX. If tD1MAX is greater than t2.1 then reduce D1Lim by NP/40 and try again. If D1Lim reaches 0 then write zeros to output.

(4) Scan wave form data from tD1MAX+30 to EndPt for the lowest value, VMIN, and associated time, t2.1.

(5) Scan wave form data from tD1MAX to tD1MAX + NP/8 to find the highest value, V1MAX, and associated time, t1p. Update V1MAX whenever the wave form value is higher than V1MAX and accumulate a count whenever the wave form value is lower. If count is greater than t1Swath then stop the search. This avoids finding the second peak if double peaks exist. If the wave form is continuously rising then t1p may be greater than tD1MAX + NP/20. If so then set t1p equal to tD1MAX + NP/20 and set V1MAX to the wave form value at that time.

(6) Unless the global minimum method for finding t2 is forced, scan the derivative data from D2Lim to EndPt for the maximum derivative, D2MAX, and corresponding time, t2.2.

(7) If the t2 derivative peak method is forced or if the t2 method is automatic and D2MAX is larger than D2Thresh then scan the data from t2.2 to t2.1 to find the zero derivative nearest to t2.2. Redefine t2.1 at this point and take the value of the wave form at this point as VMIN. If no zero derivative is found in this range of data then set t2.1 equal to t1p plus tatVMINFrac times the quantity (t2.2 - t1p) and set VMIN equal to the corresponding value of the wave form.

(8) If the method for t2 is automatic and D2MAX is less than D2Thresh then set t2.2 equal to t2.1 plus the offset (RiseLimbOffset) specified by the user and set D2MAX equal to the corresponding value of the first derivative. Then set t2.1 equal to t1p plus tatVMINFrac times the quantity (t2.2 - t1p) and set VMIN equal to the corresponding value of the wave form.

(9) If the local minimum method for t2 is forced then set t2.2 to t2.1 plus RiseLimbOffset (limited to less than or equal to NP) and set D2MAX to the corresponding value of the first derivative.

(10) Regardless of how t2.2 is determined set Vt2.2 equal to the wave form value at t2.2.

(11) Fit by linear regression a line to the base line between t2.1 and t2.1-BaseSwathWidth where BaseSwathWidth is a user chosen number of data points. If the slope of this line is positive then force a regression fit to the base line rather than a horizontal line tangent to VMIN.

(12) Scan the derivative data from t1p to t1p plus t1Swath to find the lowest derivative value, DMIN, and corresponding time, tDMIN, which are associated with the descending limb of the first peak.

(13) If DMIN is greater than -0.01 then set DMIN=(yll-yuu)/(xuu-xll), and set tDMIN equal to t1p + 1. The values of yll and yuu are the minimum and maximum of the wave form, respectively, and the values of xll and xuu are the minimum and maximum of the x-axis. Thus, the slope is scaled to the wave form amplitude.

(14) Set VtDMIN equal to the wave form value at tDMIN, and if this value is greater than V1MAX then set VtDMIN to V1MAX.

(15) Calculate the time of the intersection of tangent lines for t1 and if this time is less than t1p then increase the value of tDMIN and the magnitude of the slope, DMIN, until the intersection is at t1p or greater.

(16) If t1 is less than the safety limit, SafetyLim, then write zeros to the file.

(17) Set up limits on data used to fit tangent line to second rising limb as t2.2-Xinc and t2.2+Xinc where Xinc is user chosen. If these limits are out of range then write zeros to file.

(19) If actual point to point slope near tD1MAX is greater than smoothed slope, D1MAX, then set D1MAX to actual maximum slope.

(20) Examine derivative before first rising limb for slope close to zero (slope lesser in magnitude than [maxDeriv-minDeriv]/100). If such points are found then use the average wave form value for those points as the intercept for a line tangent to the baseline with slope of zero. If such points are not found then set the intercept of the horizontal line to the minimum wave form value to the left of tD1MAX.

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FACTORS AFFECTING THE SELECTION OF A SOIL WATER SENSING TECHNOLOGY

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Abstract

Reviews of soil moisture measurement technologies are counterproductive in attempting to identify the single approach that has the best overall performance for a range of soil, crop and landscape conditions. Not only does such an approach preclude the addition of new technologies, but it also obscures the fact that we have available today sensors and technologies that cover most field conditions, are well understood in terms of technical capability and are mechanically and electronically reliable. This review defines decision-making processes for assessing the characteristics, good and bad, of technology in relation to project objectives. Two processes are needed. The first links soil texture and scale of variability with the nature of the project, single-plant to catchment scale, to the needs for soil water measurement. The second lists the capabilities of some devices and shows how they can be selected to accommodate necessary criteria. It is concluded that the "best technology" is a function of the project and soil conditions.

1. INTRODUCTION

Fifty years ago, the first proposal was made to use fast neutron thermalisation as a means of measurement of soil water. The neutron moisture meter (NMM) that developed from that proposal is now used throughout the world, but the dominance it enjoyed in the 1980s is being challenged by ever-cheaper electronic sensors and logging systems. However, the initial fanfare associated with the development of a new soil moisture sensing technology invariably is muted as problems with the technology are found or unskilled operators apply it in circumstances that were not envisioned, or tested, by the developers. Reviews of single technologies prove quite useful as they bring up to date and summarize new technical understanding [1]. Comparative reviews of competing technologies [2, 3] often attempt the nearly impossible task of identifying "the best technology." Assumptions as to the nature of the soils, climate and application for which the conclusion is valid are often not enunciated and are left to the reader to infer [4]. Inexperienced readers frequently assume that each conclusion applies in all circumstances, including the application they are planning. The result is either endorsement of the product, "This sensor is perfect – it works here too!" or otherwise, "This sensor is rubbish – I tried it and it didn't work." Both conclusions are usually wrong.

In the past 20 years, competing technologies have been hailed as "the answer" for measuring soil water, and each has been found to have hidden difficulties. It is the aim of this paper to set out, not a comparative review, but a simple means by which a (relatively unskilled) user of soil water measurement technology can match the design aims of the project, the properties of the soil(s) of interest, and the capabilities of available technologies. The instruments used as examples are well understood and available from a number of commercial sources.

2. PROJECT REQUIREMENTS

Initial classification of projects is by scale of operation and vegetation geometry.

2.1. Single-plant scale

At one end of the range are studies in which the objective is to measure water uptake by a single plant, or plant root, from a soil layer or layers. The project may take place in a volume of, say, 100 mm in height and 20 mm in radius and would rarely occupy an area of more than a few m^2. For a valid determinations of water uptake rates in these situations, measures of soil water at the scale of 1 mm are

useful and a scale of less than 10 mm is highly desirable Clearly the NMM or time domain reflectometry (TDR) are inappropriate because of their larger volume of measurement More appropriate are heat dissipation sensors or single unit capacitive sensors that can be scaled to mm sizes

2.2. Catchment scale

At the other end of the spectrum are catchment-scale studies in which soil water is measured as part of a general balance that includes stream flow or runoff to calculate the evapotranspiration of vegetation Such may involve several scales of measurement e g the water-extraction patterns across tree/grassland boundaries and the water contents of soil profiles in grassland and forested areas at different positions in the landscape The scale of measurement is such that TDR or capacitive technologies would, if used in adequate quantity provide too much detail, the first task would be to compute averages In general, these projects must answer such questions as, 'What is the profile water content of north-facing slopes with vegetation x ?" Estimates of population variation of interest are typically in term of "What is the standard error (SE) of profile water content of north-facing slopes?" rather than "What is the SE of soil water measurements in the 0–100 mm depth of a particular slope within 1 m of a tree?" This a clear case for use of the NMM because its very large sampling volume measures soil water content and its level of variation, at a scale relevant to the aims of the project [5] Problems with the NMM of near- surface measurements and poor vertical definition are not relevant Changes in soil type are usually part of the error measurement

2.3. One-dimensional projects

One-dimensional water balance studies are common such as determination of water use of a cereal crop under uniform irrigation or natural rainfall In such projects the crop can be considered to cover the soil surface uniformly and its roots to uniformly explore each layer of the soil profile Measures of soil water need to be taken in the vertical direction only, and differences in lateral directions can be considered as error These projects are usually plot-size in scale – of the order of 1 ha or less therefore variation in soil type is usually not a consideration

2.4. Three-dimensional projects

Where irrigation is not uniform or the vegetation either does not uniformly cover the surface or explore the soil volume, the design must include lateral variation as part of the soil water system under study, and instrumentation must be set out to measure that lateral variation Here, lateral variation in soil water is not ' error," but is a critical part of the project

2 4 1 Medium scale

Measures of soil water are needed on a scale of 1–2 m An example would be drip irrigation on grape vines and interaction between dripper wetted soil and root zone These projects would be plot-size in scale or of the order of 1 ha, and change in soil type is not usually a consideration

2 4 2 Large scale

Studies involving trees require a scale of measurement of the order of 10–20 m These include native vegetation systems and agroforestry applications with which two or more forms of vegetation compete for the same soil water They may be relatively simple studies of the water use patterns of a tree or at a forest/crop boundary, or considerably more complex investigations of multiple vegetation layers in native vegetation systems [6–8]

2.5. Projects involving shallow-rooted crops

Projects involving crops of this type (<300 mm depth e g potato) commonly exhibit rapid changes in soil moisture that imply the use of loggable sensors Generally they do not suit the NMM because of its large measurement volume [9–11] Where the surface is to be tilled or otherwise changed

considerations of disturbance and damage to sensors must be considered, in some respects, the NMM has advantages in this regard [12, 13]

3 THE SOIL ENVIRONMENT

Although soil properties play a major role [14], many scientists tend to limit themselves to describing soil characteristics and otherwise ignore the potential effects of those characteristics, leaving it to the reader to infer what results would be obtained on a different soil The interaction between soil properties and the measurement of soil water is too frequently the cause of poor decision making on measurement techniques, and is often the cause of failed projects or equivocal results [15, 16] I have identified five classes of soils that may affect decisions on selecting technology for water measurement

3.1. Sandy soils

Sandy soils rarely have volumetric water contents greater than 0 3 mL/mL, therefore they are uniquely suited to heat-dissipation technology, which is unaffected by salt and can be scaled anywhere from 1 to 100 mm sensor measurement range The rapid reduction of hydraulic conductivity with water content in sands means that, once partially drained, sands can exhibit extraordinarily high variability in soil water as the zones around plant roots dry, leaving inter-root spaces relatively wet, and unlikely to equilibrate [17] This is particularly noticeable in the lower sections of plant root zones where the distance between roots may be metres [7] The large sampling volume of the NMM and capacitive sensor types with a large measurement volume would have an inherent advantage

3.2. Deep uniform loams or silts

Most measurement technologies work well in these soils – the measurement technology decision can be made on other grounds

3.3. Soils of variable texture

3 3 1 Texture gradient soils

Soils that change in texture down the profile present some difficulties for the NMM [18–21], particularly if the gradients are sharp and detail is required in the estimation of soil water If detail is required, then capacitive or TDR technology would be the better choice However, if detail of the exact water content at each depth is not required, then the NMM can be used, and the advantages of its large sampling volume can be utilised if special precautions are taken during calibration [22, 23]

3 3 2 Soils that vary in texture across the field

If variation is on a large scale (i e greater than plot size) then the normal techniques of replicated plot design will usually deal with the problem Whatever the scale, any measure of water content in this environment will have high error [24, 25] For maximum precision, any soil water data in this situation are best analysed as differences with time (i e water use)

In homogenised soil in a calibration vessel, water content and water-content change are indeed, the same In the field, water content and water-content change are often quite different because all soils are variable The effect is particularly pronounced in soils with a varying amount of clay at a particular depth Measurements near the A/B horizon in duplex soils with varying depth to the B horizon is an extreme case For example, assume the soil in such a field is all at the same (relatively low) matric suction, a determination of water content at a fixed depth near the A/B interface will show a large error because the near saturated water content of a clay and sand are quite different A similar sample taken at a time of high matric potential will also show a large error – at high matric potential, clays and sand also have quite different water contents (Fig 1)

In the vast majority of soil water studies the interest is in calculating the change in water content or the water "use" of vegetation Normally this is done by estimating the water content at the beginning of a period and subtracting the final water content However, if the change over the period is calculated at each measurement point, and these results are then averaged across the field, the result usually has a much smaller error term than is implied by the change in the water content at each time (Fig 2) The reason is that the range of moisture contents in a clay is much the same as the range in a sand Thus, the error associated with water use (and the number of sensors to "sample" that error adequately) may be much less than if the water content is needed to a particular precision

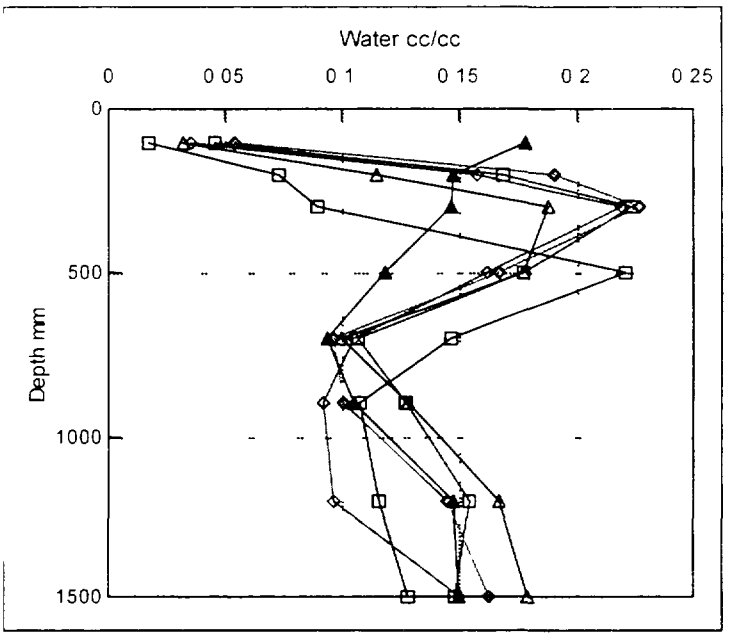

FIG 1 Typical water contents recorded by NMM in a field with variable soil The range of variation is of the order of 0 1 cc cc at depth 400 mm

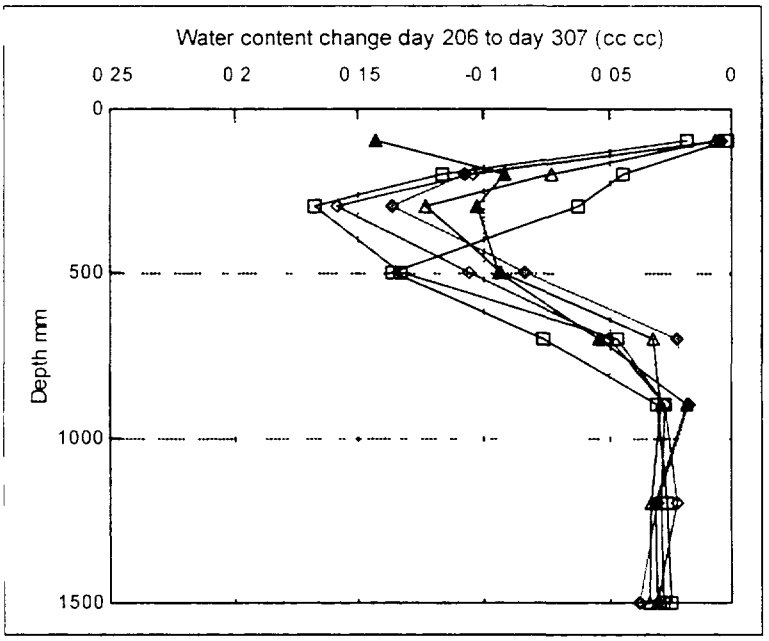

FIG 2 In the same NMM tubes as Fig 1 showing the change in water content over a 100-day period has a range of 0 05 at depth 400 mm

This has particular connotations for the field calibration of water sensing instruments in such an environment. In particular, it affects the NMM, which is especially sensitive to clay content and requires special care if the calibration is not to be biased.

3.4. Soils with gravel or texture variability at <100 mm scale

Small-scale texture variability precludes the use of TDR sensors. TDR does not measure water that is in "packets" once the soil dries sufficiently to make the water film between packets and matrix discontinuous. Capacitive sensors do not have this problem, but the effect of soil water variability and the short measurement range of the sensor would mean that a large number of sensors may be required to get a good measure of the population mean unless sensors with a large measurement volume are used.

The presence of gravel, particularly if it is in layers, presents physical difficulties for the installation of instruments, particularly of access tubes that are tightly fitting. The presence of quantities of ironstone gravel will affect the calibration of all technologies [26–28].

3.5. Clay soils

3.5.1. Clay soils that do not crack or crack on a small (<100 mm) scale

Provided clay soils do not crack, or crack on a scale so that the measurement volume of the sensor includes several peds, most sensor technologies can be used. However, these soils are often particularly sensitive to compaction and special care should be taken with the installation of access tubes. The high hydraulic conductivity of these materials – even when relatively dry, will help to average out water contents across the medium scale, but the short-sensing range of capacitive sensors and the probability of some compaction during installation of a column capacitive system would seem to preclude their use in such substrates.

Clay materials have a wilting point of 0.3 mL/mL and the range of field water contents of interest is likely to be beyond the range of sensitivity of heat-dissipation technology – therefore these sensors should not be used in clays.

3.5.2. Clay soils that crack on a large (>100 mm) scale

This environment is the most hostile of all for soil water sensing technologies. Drying of the soil is not only vertical but horizontal [29] – so even 1-D projects must be treated as 3-D problems. Sensors with wires (TDR and single-sensor capacitance type) are often pulled out of position by soil movement. Measurement volumes of all sensor types are often inadequate to average the variability across, say, a 1-m diameter ped. Access tubes (NMM and column capacitive) often form nuclei for cracking, and the soil may dry with the tube at the join of several wide cracks. The massive variability on the scale of cracking, up to 1 m, precludes the use of most small sample volume sensors in these soils.

Techniques have been developed, however, for the successful measurement of water content in these soils. The most successful rely on the combined use of the NMM, simultaneous estimation of density by γ-ray absorption and knowledge of the density vs. water-content relationship for the soil to detect and correct for the massive density variability in the readings caused by cracking and uneven drying patterns [30–37].

However, even when a measure of "soil water content" is obtained, it must be interpreted with great care to obtain a meaningful measure of the water content of the field for crop water use assessment. The volumetric water content in a "ped" needs to be "averaged" across, not only the volume of the cracks, but also in relation to a depth datum sufficiently deep in the soil that it is fixed as the soil swells. (The soil surface is no longer constant, the relationship between the top of the access tube and the surface is not constant, therefore the summation from the surface to, say, a 2-m depth, is a nontrivial calculation).

From the discussion above, it should be clear that experiment design must include consideration of the scale of the project, the scale of the error required, and the scale accuracy and precision with which various instruments measure soil water Sensor characteristics are the starting point, but behind them must be the characteristics of the technology itself – if we are using heat dissipation or dielectric constant as a measure of the soil water, how does that surrogate correspond with soil water? Does it measure soil water on a gravimetric basis, a volumetric basis or does it respond to soil suction? Is it sensitive over the full range or only part of the expected range? Next is the consideration of the device as manufactured in its ability to sense this chosen surrogate for soil water How is the technology and the device affected by factors not related to soil water, e g temperature or pore connectivity or air-filled pores? How is it affected by soil water related variables such as salinity and pH? If the device is repeatedly placed in the same environment, will it give the same response every time or is it subject to a random error? What volume of soil does it measure? How difficult is it to install without disturbing the zone of measurement? Finally, how is the device, technology and calibration affected by soil type and variations in soil parameters?

Ideally, studies of instrument precision and accuracy should be separated from considerations of soil or plant variability, but rarely are The literature has many examples of attempts to address this question, but they must be read in relation to the author's project-design aims and the soil types on which the project was carried out Many authors have reported on studies relating soil variability and estimating sensor numbers for a certain precision of measurement [2, 5, 7 8 20, 25.]

4.1. Field checks

Any substantial project that uses a sensor for soil water should include a check that the manufacturer's calibration is reasonable in the soil type of interest Many authors report discrepancies such as negative water use [38] that result from using untested calibrations Checking can be relatively simple – such as putting a known depth of water onto the soil and making sure that the sensor reads the same amount [39–41]

Differences between sensors of a similar type from different manufacturers is always a possible cause of unforeseen problems especially with newer devices Generally, a mature technology will have different problems, because assumptions that are valid for newer machines may be non-valid for older machines Obtaining a firm understanding of the history and technology behind each sensor is a good investment

4.2. Installation of access tubes for TDR (columns) and NMM

Installation of access tubes should be in a manner that minimises soil disturbance and, in compressible soils, should preferably be done when the soil is dry Specifically, soil core sampling or tube "ramming" techniques in moist soil [42, 43] will cause compaction some distance from the tube A more time consuming but reliable method is the centre withdrawal method [44] The discrepancy caused by compaction is serious, but ephemeral and difficult to detect The effect prevents root accession and water extraction from the zone being measured during the early soil drying period, but reaches the correct end point as water is removed from close to the affected tubes by capillary forces rather than by plants

The unstructured and incompressible nature of most sands means that access tubes can be installed with a minimum of cost and almost zero local disturbance of the soil

4.3. TDR

Time domain reflectometry measures a basic physical property of the material, i e the time to reflect a high frequency electromagnetic pulse, and should give the same reading in the same material to a precision better than 1% from any instrument with the same type of antenna (sensor) The literature

implies that the surrogate for the soil water that it measures is 95% dependent on volumetric soil water content, implying that it can be used with modest precision without calibration But, in some materials with discontinuous water films (clay peds in a sand matrix) and in highly saline conditions, it does not work at all Most problematical are borderline cases with which the instrument works, but is unreliable

TDR comes in three forms

- Surface probes, twin steel rods that must be inserted vertically and in parallel, for near-surface measurement,
- Buriable probes for deeper measurements, which require a reflectometer for measurement,
- Stand-alone loggable sensor

Problems reported with surface probes are that they do not work if not perfectly parallel – which is hard to achieve if the probes are longer than 200 mm Repeated readings are possible, but not advisable, on the same rods as they give false readings if loose in the soil This is mainly a problem with tilled or lightly textured soils The buriable probes must, of course, be inserted with minimal profile disturbance

The volume of measurement is claimed to be the area of soil between the rods, with a thickness of around 10 to approximately 200 mm

4.4. Capacitive sensors

Capacitive sensors also measure a surrogate for volumetric soil water content – the dielectric constant, which depends to a large degree (95%) on soil water only, and is largely unaffected by soil composition or density It is affected by salinity, however

Capacitive sensors should be calibrated because manufacturers do not do so for dielectric constant Output is a voltage or frequency, and the factory calibration is usually in conditions of unknown salinity Highly conductive soil solutions, e g acid, and quantities of ironstone in the soil will affect the calibration, which is not always linear and depends on the design of the electronics Quite frequently the electronics are sensitive to temperature

The volume of measurement of capacitive sensors depends on the configuration The soil within 10 mm of the sensor is responsible for most of the reading Thus, the type that comes installed in a 50-mm diameter tube and are installed as a column will measure a ring of soil 10-mm thick around the sensor Installation of this type of sensor array must be done with particular care or only the disturbed soil next to the tube will be measured [44] A linear capacitive sensor with an element 0 5-m long will sense a volume of 10 mm radius and 0 5m long, i e about 150 mL Also popular are point sensors that measure volumes as small as 5mL

For successful use of capacitive sensors, it is vital that, with such a small sensing distance, the device is installed with almost no disturbance of the soil in the measured zone

4.5. Heat dissipation sensors

These sensors use either the thermal conductivity of soil or its heat capacity as a surrogate for soil water content Both depend substantially on water content up to 0 3 mL/mL The technology works well in light texture soils giving an effectively large measurement volume (which is variable – depending on amount of heat used) Over 0 3 mL/mL soil water content, the method has little sensitivity, therefore does not work well for clay soil projects Heat dissipation sensors usually require calibration

4.6. The NMM

4 6 1 Precision

The neutron moisture meter measures the slow neutron flux produced by a source with fixed emission characteristics The slow neutron flux in a given environment depends solely on the rate at which fast neutrons are released which is a Poisson process with variation (SE) equal to the square root of the number of counts measured Thus, the precision of the instrument itself is controlled by the length of count taken Any other error in a survey is either field error or calibration error A study over 10 years with thirteen different NMMs [45] revealed that they were extremely stable and reproduced the same result unless major changes were made to the machines, e g replacement of the counter tube Modern instruments collect many more counts per second than do older ones due to more-efficient counter tubes, therefore they appear to achieve greater precision for a given counting period [46]

4 6 2 Zone of measurement

Extensive studies of the radius of measurement of the NMM have been done with a range of results [47–50] The reason for variation is that the radius of measurement of the NMM differs with composition of access tube, soil density, hydrogen composition of soil and soil water content There seems to be general agreement that minima of 0 2 m laterally and 0 25m vertically are reasonable average values for a "typical" soil However, it is worth noting that these are for a moist soil (0 3 mL/mL) and probably of substantial (30%) clay content An important feature of the NMM is that in soils with low-clay or low-water content (hence low hydraulic conductivity and potentially high variability) the NMM will increase its volume of measurement to, for example, 0 8-m radius in a sand with a water content of 0 15 mL/mL This variable radius of measurement makes the NMM so valuable in large-scale studies, and so difficult to use when small-scale measurements are needed, such as the exact water content of a soil layer in a texture-differentiated soil [51]

The large sampling volume of the NMM makes it unsuited to projects for which near-surface measurements are needed Special surface calibrations have been derived [52] and various other methods seem to have been used successfully for correcting the readings near clay interfaces [53–56] Near-surface measurements also present an increased safety hazard for operators [57]

4 6 3 Calibration

The calibration of the NMM is more complicated than of other sensors as it is sensitive to soil factors other than water I am not aware of any accurate "universal" calibration, even if correction is made for density and the hydrogen content of soil materials [58–61] Quite rapid calibration techniques have been developed and can give reliable results for little more work than the installation of the access tubes [62]

4 6 3 1 The access tube

The NMM calibration is affected by the composition, thickness and diameter of the access tube Aluminium is usually recommended as it has minimal neutron absorption However, steel is only slightly different, is much cheaper and more long lasting, especially in alkaline soils PVC and other plastics containing hydrogen have the effect of confining the measurement volume and increasing the sensitivity of the instrument [63] Plastics also have an advantage in stony soils as they can allow small degrees of curvature needed to avoid small stones without leaving a cavity next to the tube

Analyses of various types of error with the NMM are available [18, 64, 65] As a matter of routine, the NMM should be used to measure a standard material [1], ideally an unchanging container of plastic [26, 66], to detect electronic faults – especially those causing slow changes If this standard is further related to the count in a container of water with an access tube the same as that used in the field and counts expressed as a fraction of this figure, then many of the differences between meters can be ignored [67]

4.6.3.2. Effect of non-water hydrogen

The NMM measures hydrogen content, and the single largest (non water) effect on the calibration is caused by the hydrogen content of the (dry) soil. This hydrogen is present in most clays and in organic matter, and can be measured by heating the (oven dry) soil in an oxygen atmosphere to 700°C and measuring the water that is given off [68]. An approximate relationship for the water equivalent of this hydrogen may be calculated from clay content in low organic matter soils [1]:

$$We = 0.124\ (\pm 0.012)C + 0.015$$

where

C is clay content (g/g),
and We is equivalent water (g/g) measured relative to 105°C soil weight.

A similar estimate is available for hydrogen in organic matter [69, 70].

4.6.3.3. Effects of density, stones, iron and trace amounts of neutron absorbers

The NMM calibration is also affected by soil density [71, 72], mainly as a result of the soil hydrogen. The remaining effects are the scattering of fast neutrons and neutron absorption by small quantities of chloride, oil, boron [73] and gadolinium [74]. The latter are relatively rare as soil constituents, but occur in some localities in sufficient quantity to be significant. Stones [75, 76] and ferruginous gravel [77] are more common problems.

4.6.3.4. Calibration of the NMM in a field with variable clay content horizons

The NMM is especially sensitive to errors caused by lateral variation in clay content, which is particularly important during calibration where the number of samples is usually kept to a minimum and is often "insufficient" for a proper sampling of the field. The effect of this problem on the NMM is more than just an inaccurate calibration. Frequently the resulting calibration gives the correct answer for water content, the aim of the calibration, but gives the wrong answer when one water content is subtracted from the other to calculate water use. The different sample variance in wet and dry conditions can bias the slope of the calibration.

The following calibration procedure is recommended for the NMM in clay-variable soil horizons. i) Make the decision as to the number sacrificial calibration access tubes, based on the project design aims and the estimated soil variability. ii) Group those tubes into pairs – and situate each pair as closely as possible, one to be sacrificed in the dry condition and one in the wet. The assumption will be made that the field soil texture is the same for the two tubes in the pair, and field error will be manifested between pairs. In my experience, this assumption is reasonable if the tubes are positioned within 2 m, which may not always be the case [24]. iii) Treat each soil horizon in each pair as a separate calibration. A series of parallel lines should result, each defined by two points (mini-calibrations).

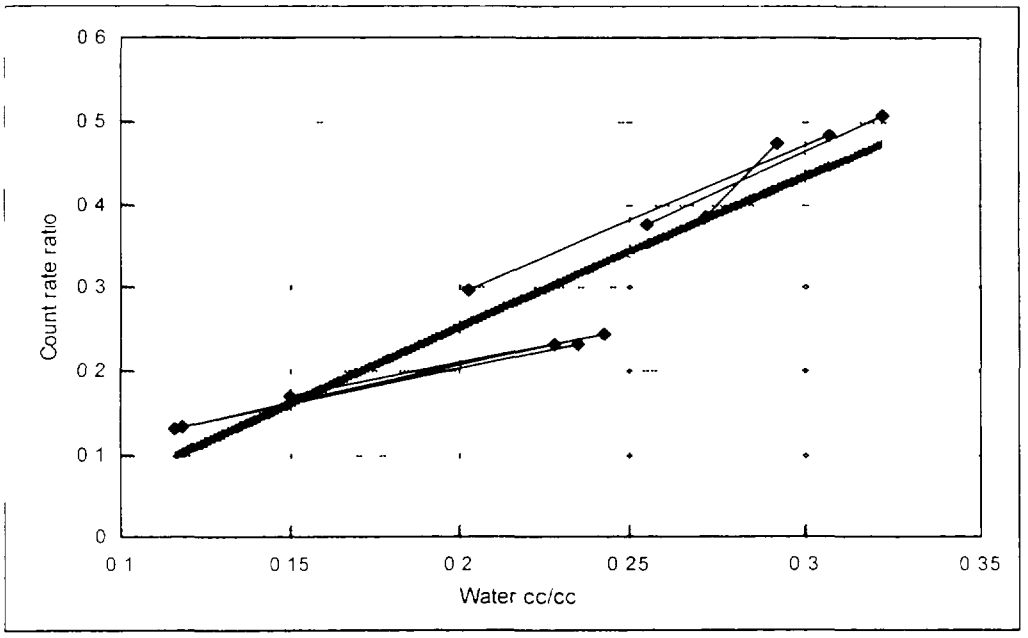

FIG 3 NMM calibration in a clay-variable horizon Symbols and fine lines are mini-calibrations Heavy line is overall (conventional) calibration Although conventional calibration is a good estimator for water use in one soil type, it will underestimate water use by 50% in the other type but is an adequate estimator for water content in both

Ideally, within each horizon mini-calibrations will be identical, and the data can be combined in the normal way to produce a calibration for water content that can safely be used to calculate water use also In clay-variable horizons (Fig 3), mini-calibrations are often displaced relative to one another When this happens, the slope of the combined calibration may be quite different to that of the average of the mini-calibration slopes If this is so, then it is necessary to produce two calibrations The first combines all data to produce a calibration for estimation of field water content that must not be used to calculate water use [51] The second is a slope calibration only, produced by averaging the slopes of all the mini-calibrations, which must be used to estimate water use from the field by calculating NMM count rate change by the slope

5 CONCLUSION

Each soil water sensing method has strengths and weaknesses A strength in one application may be a weakness in another Reliable sensing of soil water in the field requires that the user has an understanding of the qualities and problems associated with the sensors that are available To select the right sensor, the user must have a good understanding of how its qualities fit the requirements of the project

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CALIBRATING THE NEUTRON MOISTURE METER: PRECISION AND ECONOMY

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Abstract

Established laboratory and field calibration procedures for the neutron moisture meter are demonstrated on a uniform soil and alternative, low cost procedures on a duplex, less uniform soil. The effect of field variability on the calibration methodology is discussed with the aim of optimising calibration reliability at minimal cost. The difference between calibration for a soil material, or for a field (a range of soil materials) is considered. In particular, calibration for the estimation of water content change is shown to be a different problem from calibration for the estimation of water content in a variable field. Techniques aimed at detecting field variability problems during calibration are suggested, and methods for optimising the results for the intended use of the instrument are outlined. Pairing of calibration tubes, alternative methods of analysis of calibration data, and use of other information from the field to measure its variability, can improve the precision of calibration procedures to the point where minimal calibration effort, with careful analysis, can provide reliable results.

1. INTRODUCTION

The neutron method provides a rapid, non-destructive means of measuring water content and water-content change in soils. Current models have proven popular with commercial water monitoring consultants for estimating soil water content on farms and for irrigation scheduling. But, the cost of the calibration of the neutron moisture meter (NMM) has induced many users to avoid site specific calibration and place reliance on either the factory calibration supplied with the instrument or a general calibration derived for a soil type or an area. Factory calibrations are usually carried out with water/sand mixes that bear little resemblance to most soils. The calibration slope is dependent on soil composition and density and its intercept is dependent on clay content [1–3].

General calibrations for a particular region or soil type can provide acceptable results, but can be seriously in error if used indiscriminately. For example, published calibration data [4], while purporting to be valid for a region, fail to provide the most vital information, that of the profile of clay content of the soils calibrated. This is particularly important in the duplex soil type in which the soil content varies with depth at a location, and can occur at variable depth in the profile from site to site. Both factors can substantially affect the calibration.

Calibration for a specific site or soil will increase both the accuracy and precision of the NMM method, but field calibration traditionally requires that a sufficiently large number of access tubes be randomly installed for destructive sampling of volumetric water content. Unless the field variability is known, the term "sufficiently large" is an unknown quantity and a large number of destructively sampled sites are often undesirable for economic, logistic, or aesthetic reasons.

† Deceased March 1996.

This paper provides a guide to answer the questions most frequently asked by users

- What is the best calibration method for the NMM where time and money are limited?
- Given that, in most cases, little will be known about site variability how many calibration tubes should be used and how should they be laid out?

If variability exists in a field, then the calibration must either exclude it (have a separate calibration for each soil variant) or include it within the uncertainty associated with a calibration for the field as a whole The difference between these cases might be described as calibration for each soil or "calibration for the field" Which is more desirable depends entirely on the purpose for which the instrument is to be used, and the precision required

For example, for the NMM, the laboratory drum calibration is a common procedure Field material is brought into the laboratory, homogenised, and a calibration obtained between the instrument and the soil at a range of water contents This calibration has an associated experimental error that is usually very small and unrelated to field variability When this calibration is used in a perfectly uniform field with soil identical to that in the drum, all the variability seen in the field measures of water content will be due to variation in field soil water content However, if the field varies in density or composition, then it is impossible to separate real variation in soil water content from apparent variation in water content due to these other factors Unless the field is known to be the same in both composition and density as the laboratory material, this procedure cannot be used to give information about field water content because the relevance of the calibration is not established

This lack of relevance can be assumed for a factory calibration based on sand/water mixtures

The alternative calibration procedure involves installing a number of randomly placed access tubes in the field and, when the soil is wet, NMM readings are made at a range of depths and half the tubes are destructively sampled to measure volumetric water at each reading depth This process is repeated after the field has dried with the remainder of the tubes, thus producing a calibration In a carefully executed calibration, using a sample volume for the soil water measure approaching the volume of influence of the NMM (about 150 mm radius), the experimental error associated with each single point on this curve is quite small (usually <1%), as both NMM count and water content at a point can be established with high precision A field perfectly uniform in composition and density will produce points along a common calibration line Scatter of points off the line is caused by the effects on the NMM due to variability in composition and density

If an adequate number of calibration tubes has been used, then adding more may increase confidence in the mean of field water content, but should not reduce the scatter of points around this mean because the field "population" has been adequately sampled The scatter is caused by field variability

Further improvement in precision becomes a matter of identifying and accounting for as much of the variation as possible If necessary, by having variants of the calibration for different horizons or different parts of the field This may be a simple process if the variability is associated with another easily measured factor – such as soil texture Many soils vary in composition with depth (e g texture contrast soils) in a reasonably uniform manner and a measure of the depth at which these changes occur can be obtained cheaply and quickly So, a separate calibration for each depth with considerably reduced error can be obtained just by associating each calibration point with a simple measure of its soil texture The textural measure may be as simple as a visual estimate or as elaborate as a particle-size analysis

A simple variation to the usual field calibration procedure, as described above, is to distribute the calibration tubes in pairs making use of the assumption which is usually valid, that variation in a field will be less between two points that are in close juxtaposition than two points that are much further apart Here one tube of each pair is sampled in the wet condition and the other, placed about 2 m from it in the dry The resulting calibration then comprises, not a scatter of unrelated points but a series of pairs of points each defining a calibration line for a depth in a part of the field These lines might be termed "mini calibrations" specific to a particular location and depth in the field

If the field is uniform, then these mini-calibrations will form a readily identified common line the same line that would be obtained by the unpaired method In a non-uniform field, however, a common calibration line is not likely But, additional information is now available that may be used to map the mini-calibrations to the field and improve the precision of the NMM method as applied to that field This requires little additional calibration effort, just a different experiment design and different analysis of calibration information

An extension of this approach is described below By matching the calibration method to the desired application, the maximum information and calibration precision may be obtained from a reduced number of calibration tubes or simpler lower-cost sampling methods Depending on the ultimate application of the instrument, savings in time and effort can be made in the calibration process without much loss of precision

2 MATERIALS AND METHODS

Four calibration techniques are provided as examples of procedures The first two represent cases where time, site damage, and expense are not limiting The other two are modified techniques that while less rigorous, are less expensive and more appropriate to commercial applications such as irrigation scheduling, or for monitoring water in research cropping trials

- Method 1, laboratory drum calibration is used primarily for research, and is intended to provide maximum information regarding the relation between an homogenised soil sample its water content, and the NMM count rate [6],
- Method 2, this "ideal" field calibration is where a large number of calibration sites are selected at random across a field and NMM access tubes installed at each site are destructively sampled by taking large volumetric samples as closely to the tubes as possible [6],
- Method 3, this is a limited field calibration like Method 2, but involves fewer access tubes where random location is not always possible, because of cost or site considerations, soil water sampling may be by the less onerous gravimetric method, supplemented by a few measurements to establish the profile of bulk density in the field, soil sampling is done as close to the access tube as possible, but with smaller samples than for Method 2, a variation of this method allows soil sampling from inside the access tube during installation,
- Method 4, this follows a procedure that may be used to calibrate an existing installation where the access tubes are used for long term monitoring and may not be destructively sampled Soil sampling in wet and dry conditions must take place at random across the field (at a distance from the access tubes) to be compared with NMM counts also obtained from across the field Soil sampling may again be by the gravimetric method supplemented by a bulk density profile

Calibrations by Methods 1 and 2 were carried out in Pakistan and 3 and 4 in Australia The Pakistan instrument was a Campbell Pacific Hydroprobe model 502[1] and the Australian work was done with a locally manufactured instrument based on an annular americium source and a BF_3 counter tube In both cases, an attempt has been made to minimise differences between source, counter tube and electronics by expressing NMM counts in the field as a fraction of the count in a standard medium And in both cases the medium was a 200-L container of water fitted with an access tube of the type used in the field This "count ratio" will be referred to as NMM "count "

Because the NMM reading is based on a Poisson-distributed radioactive decay process, the standard error of the NMM is equal to the square root of the total count taken Thus, to reduce error in the NMM reading to 0 3% requires 100,000 counts at each point This precision was obtained by summing counts from three 16-second periods

A large, uniform area of saline sodic soil at the field station of the Biosaline Research Station (Pakistan) has been, and will continue to be, used for agronomic experiments for a number of years Thus, considerable effort can profitably be invested in precisely calibrating of the NMM for this

[1]Use of a brand name does not imply recommendation

environment Methods 1 and 2 were used on this soil which was uniform in composition and density to a depth of 1 m but with high salt content (EC 16 dS/m) The experiment was however carried out as for a texture-differentiated profile to verify its uniformity Methods 3 and 4 were used on a duplex red-brown earth at the Waite Agricultural Research Institute South Australia

A brief description of the conventional calibration methods (1 and 2 below) is given for comparison Details of and references to these methods are published elsewhere [5]

2.1. Laboratory drum calibration (Method 1)

Approximately 2 m of soil were excavated from three locations in the field to a depth of 1 m and transported to the laboratory where it was dried and ground to pass a 5-mm sieve After thorough mixing the soil was packed into a steel drum (0 8 m diameter × 1 0 m) which was open at both ends and divided so that it could be split into two halves to simplify removal of the soil after each packing During packing the two halves were bolted together

The soil was added to the drum in quantities of 40 kg spread evenly, and lightly packed in layers to a measured depth Samples were taken for gravimetric water content throughout the packing and mean density and volumetric water content for the whole drum were calculated An aluminium access tube was installed in the centre of the drum by augering ahead of, and down through it to produce a tightly fitting access tube without compacting the surrounding soil For the first few drum packs a range of depths was measured with the NMM because the packing is unlikely to be perfect and the air and floor material will influence counts near the surface and the base of the drum respectively Three depths, the centre point and at 0 1 m above and below it were chosen for NMM measurements and the average count rate for each packing calculated

The drum was then split into its halves the soil removed any cohering lumps crushed, and repacked using a greater packing pressure (a smaller rammer) to achieve a higher density Count rates were again taken and the soil removed and crushed as before A calculated amount of distilled water was added from a fine watering can, the soil was thoroughly mixed and left to stand overnight under a cover After mixing again, the drum was repacked at the low and then the high density This process was repeated until the soil became too wet to work The average density and the gravimetric water content of the drum was established and the count rate of the NMM recorded for each pack

2.2. Randomised paired-tube field calibration (Method 2)

Six plots (2 × 3 m) were selected randomly on an experimental field that had been under Kallar grass (Leptochloa fusca) for five years The soil, a sandy loam (clay 22%, silt 23%, sand 55%) was uniform chemically and texturally to 1 5 m Two aluminium access tubes were installed on each plot 1 m apart using the slurry method [4], the ground and sieved field soil was used as the solid component of the slurry Irrigation water was ponded on the plots until saturated at depth Standing water was then removed, and the profile allowed to drain to near field capacity NMM count rates were measured at depths of 0 1 0 25 0 5, 0 75 and 1 00 m

Volumetric water content and bulk density samples were then taken from the soil volume adjacent to one of the tubes in each pair This involved excavating a trench near the tube so that three thin-walled sampling tubes (72 mm diameter × 75 mm long × 1 5 mm wall thickness) could be inserted vertically next to the access tube at each depth (i e within the volume sampled by the NMM)

The soil had extremely low permeability, and drying the plots required 1 5 years even though they were covered with polythene sheets during periods of rain NMM monitoring continued at one sampling per month during the drying period, and when there was no further change in count rate the second tube in each plot was sampled as above

2.3. Limited field calibration with "near" sampling (Method 3)

This work was carried out on a duplex red-brown earth, with properties previously described [7] Because of the different texture of the sub-soil, two horizons were calibrated separately

The soil comprised a surface loam (not included in the calibration) grading to a light clay at 0 45 m (28% sand 23% silt 48% clay) over a heavy clay to 0 8 m (19% sand 19% silt 60% clay) Calibrations were centred on 0 3 m and 0 6 m depths A plot, 20 × 30 m, was selected within a larger area and three pairs of aluminium access tubes were installed, 2 m apart, to a depth of 1 m

The soil was dry at the end of the dry season and NMM count rate was measured at depths of 0 3 and 0 6 m One tube of each pair of access tubes was sampled destructively by taking three gravimetric samples (56 mm diameter × 0 2 m long) as close as possible to each of the three tubes centred on depths of 0 3 and 0 6m In the discussion following, these samples will be described as the "near" samples In-situ bulk densities of the 0 3- and 0 6-m soil layers were established by the sand replacement method at one site adjacent to an access tube

NMM count rate and soil water sampling were repeated after wet-season rains had wetted the profile to the full depth The bulk density of the soil layers of interest was again established to detect if serious swelling had occurred

2.4. Limited field calibration with "far" sampling (Method 4)

At the time of taking the "near" samples for Method 3, the same number and size of gravimetric samples were taken from points randomly distributed across the field These samples are referred to as the "far" samples and a calibration was obtained from the mean of these samples and the mean of the NMM readings taken in Method 3.

3 RESULTS

All regressions have been calculated using θ (volumetric water content) as the independent variable for reasons, which are discussed below

3.1. Drum calibration

Figure 1 shows the calibration obtained in the laboratory drum calibration Exclusion of the lowest water content points was considered in case they showed reduced count rate below the expected linear relation that might indicate that the drum was too small to confine all the neutrons at low water contents Omitting these points made no significant difference to the calibration, therefore, they have been retained in the analysis Three points at the highest water content and highest density were omitted because compaction caused free water to pond on the soil surface There was almost no effect of packing density, possibly because of the high salt content of this soil, which would counter the neutron scattering effect of higher density Data from all drum packs are treated together

A linear regression fitted to the data points produced the following equation

$$n = 0\ 033 + 1\ 285(\pm 0\ 051)\theta \qquad r^2 = 0\ 98 \qquad (1)$$

where

n is the count rate ratio (relative to water)
and θ is volumetric water content (cc/cc)

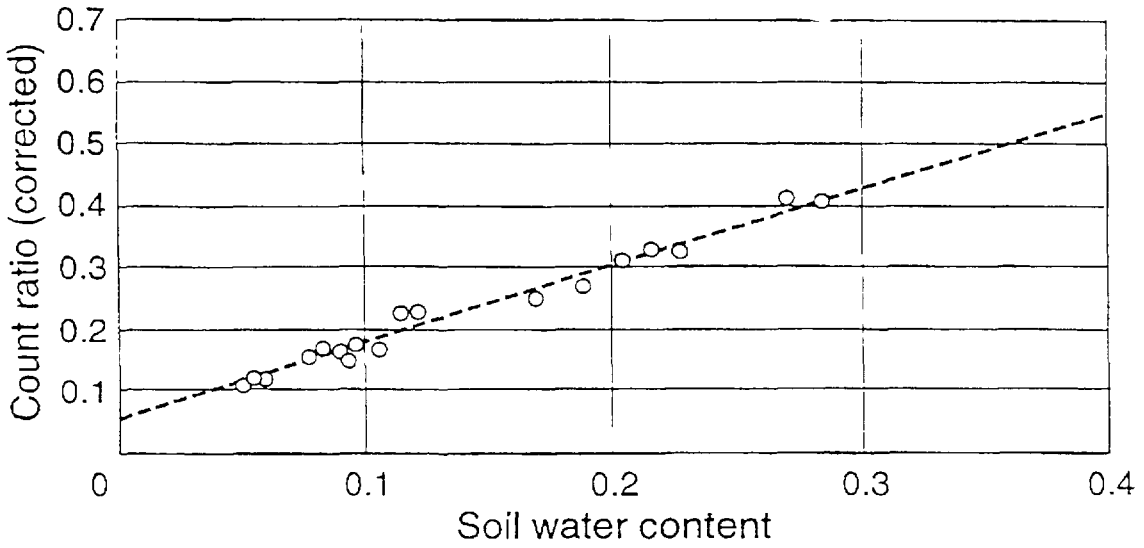

FIG. 1 Relationship between NMM count rate ratio and volume water content of Biosaline station soil using a drum calibration (Method 1)

Applying a "density correction" to each point to adjust it to the mean packing density of all points was found to reduce the relative error in the calibration slope [3]. This implies that a further correction is necessary to the curve slope before it may be used in the field if the field density is different to the mean drum density. The average density of drum packs was 1.42 t/m^3. It was not possible to pack the drum to field density except under near-saturated conditions. Since the field averaged 1.6 t/m^3 we chose to correct the calibration points directly to this value. Choosing the field density also facilitates comparison with Method 2 below. Applying this correction gives.

$$n' = 0.053 + 1.246\ (\pm 0.047)\theta \qquad (2)$$

where

n' is $n \times (Ds/Di)^{0.5}$,
D_S is the mean density for the field soil,
and Di is the density of the packed soil in the drum for each measurement point

Inverting this equation to predict water content from measured count rate ratio gives the drum calibration for this soil as:

$$\theta = 0.802n' - 0.042 \qquad (3)$$

3.2. Random paired-tube field calibration

All layers were analysed separately to detect any differences that might exist. Results from the 0.25, 0.5 and 0.75 m layers were not significantly different, therefore, they have been treated here as a single group. Accurate volume sampling was difficult at 1.0 m and while the calibration was similar, poor sampling resulted in an error in the slope of the calibration for that depth of 25%, almost twice that for other layers. On this account, the data for this layer have been omitted from the analysis.

The calibration for the 0.1-m layer was quite different probably due to neutron loss from the soil surface. The regression equation is:

$$n = 0\ 028 + 0.98(\pm 0\ 10)\theta \qquad r^2 = 0.90 \qquad (4)$$

Below the surface horizon, the soil density was quite uniform, averaging 1.63 t/m^3. While, in this case, it resulted in negligible change, counts were corrected from the density of the sampling point to a density of 1.6 t/m^3 by the method described above (Eq. 2) because this procedure often reduces scatter in the calibration and error in the regression coefficient by accounting for some field variation.

The combined data from the 0.25, 0.5 and 0.75m layers are shown in Fig. 2 with the regression:

$$n' = 1.42(\pm 0.057)\theta - 0.009 \qquad r^2 = 0.95 \qquad (5)$$

Inverting gives the calibration:

$$\theta = 0.704n' + 0.006$$

Since all soil layers average the same density, n = n', and this curve can be used with no further correction in any soil layer.

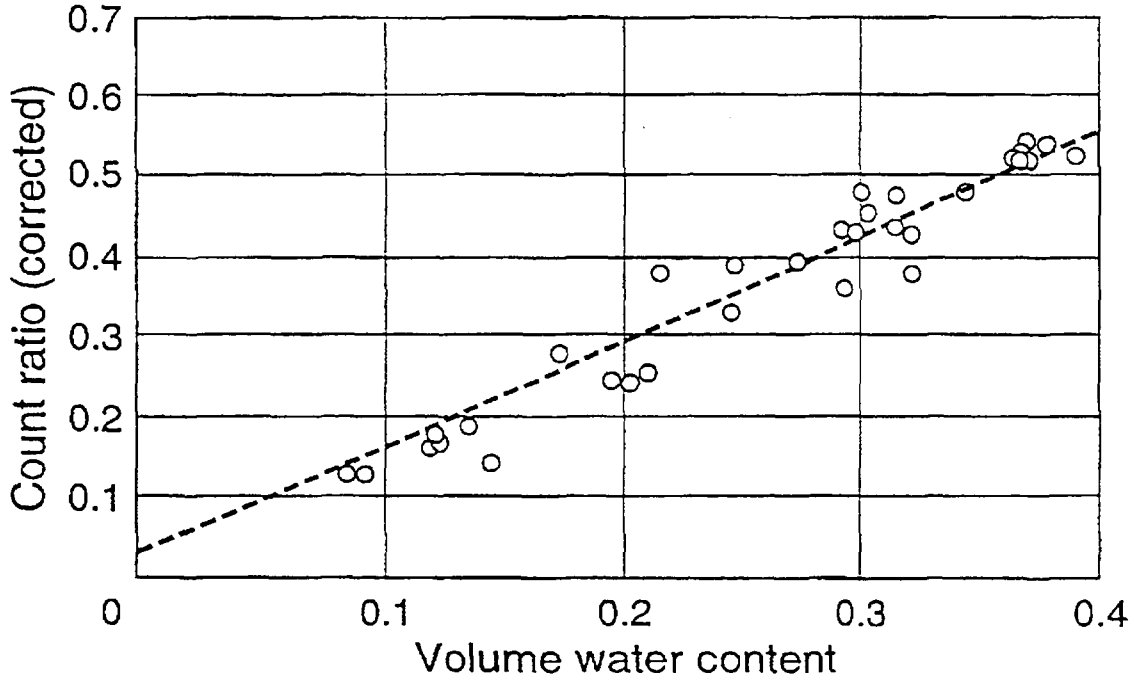

FIG. 2. Field calibration of Biosaline station soil using volumetric sampling and 6 pairs of volumetrically sampled access tubes (Method 2). (---) Combined calibration for 0.25m, 0.5m and 0.75m horizons.

3.3. Limited field calibration with "near" sampling

The data obtained for the calibration using the "near" sampling method at the Waite Institute site are listed in Table I. The volumetric water content was calculated using the mean soil density of 1.5 and 1.22 t/m^3 for the 0.3- and 0.6-m layers, respectively, and the calibration is plotted in Fig. 3.

The regression equation for the data from the 0.3m layer is:

$$n = 0.86(\pm 0.03)\theta + 0.033 \qquad r^2 = 0.99 \qquad (6)$$

and for the 0.6-m layer:

$$n = 1.85\ (\pm 0.19)\theta - 0.089 \qquad r^2 = 0.96 \qquad (7)$$

Regression slopes for the two layers are quite different and should not be combined into a single equation, even though the r^2 for the combined data is 0.85 (see Discussion below).

TABLE I. DETAILED RESULTS OF "NEAR" SAMPLING OF WAITE INSTITUTE SOIL. THE TEXT DESCRIBES SEVERAL METHODS OF ANALYSING THESE DATA

	Gravimetric water content (g/g)				Volumetric water content (cc/cc)		Count ratio	
Site	Dry	Wet	Mean dry	Mean wet	Dry	Wet	Dry	Wet
				Depth 0.3 m				
Tube 1	0.08	0.151						
	0.076	0.151						
	0.077	0.155	0.077	0.152	0.116	0.228	0.131	0.232
Tube 2	0.1	0.163						
	0.104	0.162						
	0.096	0.162	0.1	0.162	0 15	0.243	0.169	0.243
Tube 3	0.078	0 157						
	0.081	0.155						
	0.076	0.159	0.078	0.157	0.118	0.235	0.132	0.232
	Mean all tubes		0.085	0.157	0.128	0.235	0.144	0.235
	SD all tubes		0.01	0.004	0.057	0.006	0.018	0.005
				Depth 0.6 m				
Tube 1	0.206	0.265						
	0.211	0.26						
	0.209	0.266	0.209	0.264	0.255	0 322	0.376	0.507
Tube 2	0.222	0.242						
	0.228	0.239						
	0.22	0.238	0.223	0.24	0.272	0 292	0.386	0.473
Tube 3	0.17	0.252						
	0.159	0.262						
	0.17	0.242	0.166	0 252	0.203	0.307	0.295	0.484
	Mean all tubes		0.199	0.252	0.243	0.307	0.352	0.488
	SD all tubes		0.024	0.01	0.029	0.012	0.041	0.014

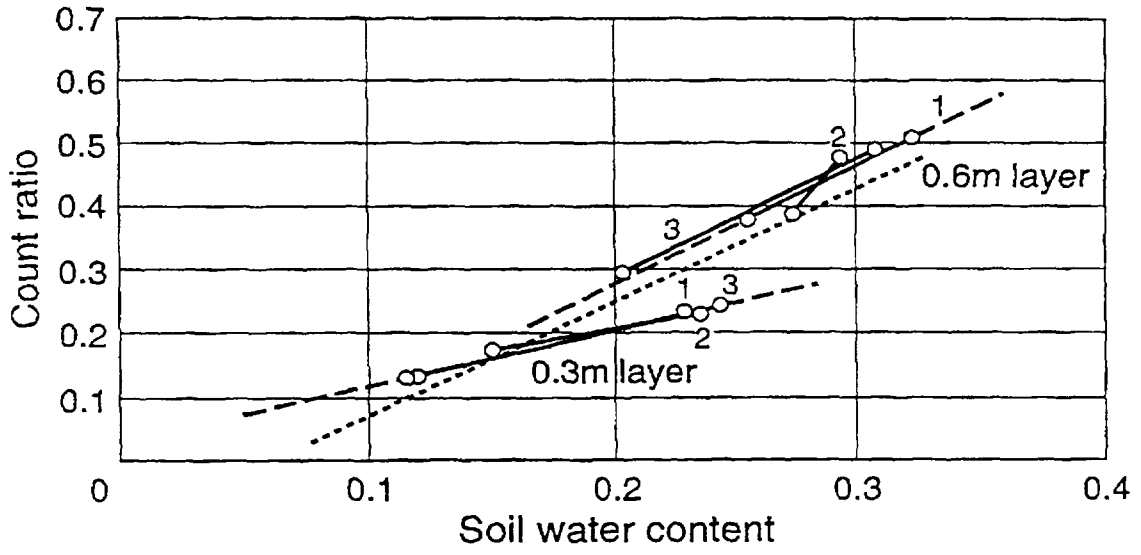

FIG 3 Field calibration of Waite Institute soil using three pairs of access tubes and gravimetric sampling adjacent to the tube (Near sampling method) This duplex soil shows clear differences in slope for each layer Calibration lines are (____) individual tube pairs, (---) combined data for each horizon ( ) all data combined Note the substantial slope difference between loam (0 3m horizon) and combined, regression line.

3.4 Limited field calibration with "far" sampling

Table II gives the gravimetric water content from samples collected at the same depths as above, but at nine randomly selected sites within the field. The mean of these data was converted to volume water content by multiplying the gravimetric water content by the appropriate horizon soil density Figure 4 shows the resulting calibration and, as before, the two layers have different calibrations. The line through the mean values of water content and count ratio for the 0.3-m layer is:

$$n = 0.978\theta - 0.005 \quad (8)$$

and for the 0 6-m layer:

$$n = 3\ 49\theta - 0.632 \quad (9)$$

The calibration in Fig. 4 is based on only two points, the mean of the field NMM value and mean water content in the wet and the dry states. The calibration is the line through these points Figure 4 also shows the individual soil water content values plotted against the mean NMM value and individual NMM counts against the mean soil water value. The scatter of these individual points becomes critical to the analysis below.

TABLE II. RESULTS OF "FAR" SAMPLING IN WAITE INSTITUTE SOIL

Gravimetric water content (g/g)			
0.3 m depth		0.6 m depth	
Dry	Wet	Dry	Wet
0.081	0.154	0.206	0.253
0.086	0.149	0.213	0.284
0.084	0.152	0.221	0.268
0.102	0.155	0.231	0.280
0.075	0.160	0.226	0.258
0.099	0.161	0.264	0.259
0.120	0.152	0.256	0.259
0.098	0.158	0.222	0.269
0.112	0.150	0.241	0.238
Mean gravimetric water content			
0.095	0.155	0.231	0.263
Volumetric water content (cc/cc)			
0.143	0.232	0.282	0.321
Mean count ratio (from Table I)			
0.144	0.235	0.352	0.488

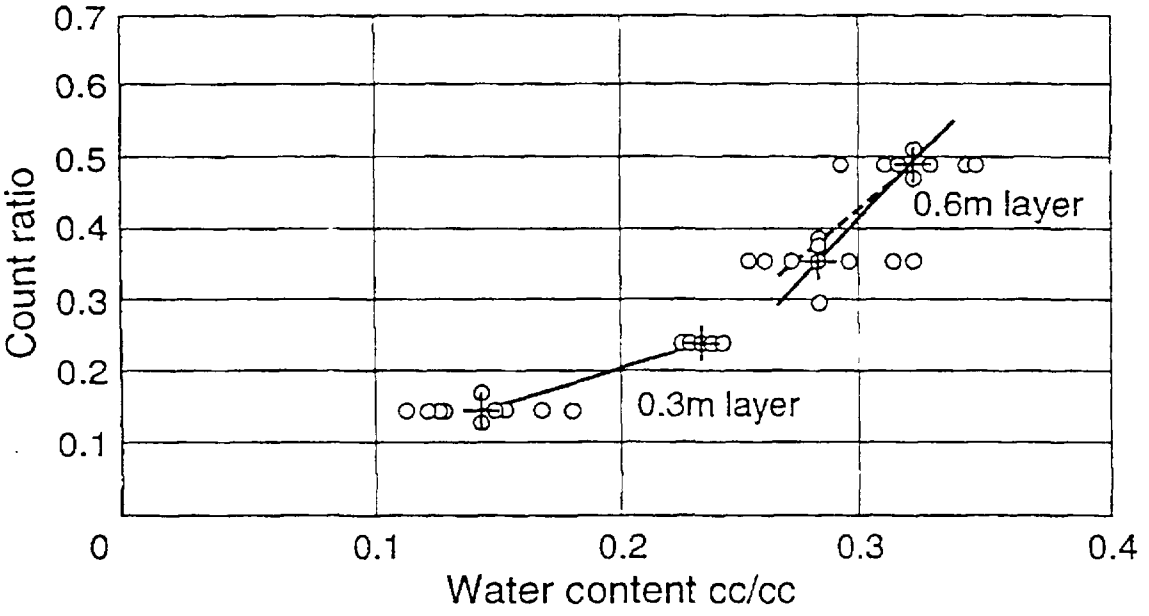

FIG. 4. Field calibration of Waite Institute soil using the mean [–] of three access tubes and nine gravimetric samples samples taken randomly about the field (Far sampling method) Individual soil water sample values are plotted against the mean NMM count and vice versa [ ]. The ringed point is the outlier count ratio discussed in the text. Calibration lines are (___) soil horizons, (---)0.6m horizon omitting the outlier.

4. DISCUSSION

4.1. The regression θ vs. n or n vs. θ

Calibration of the NMM is aimed at establishing an equation for predicting volume water content, θ, at a point in the soil from the count rate ratio, n, measured at the same point. The relationship is linear and regression analysis is normally used to fit the calibration line to paired observations of θ and n. The usual regression analysis assumes that the independent variable is known precisely and usually both θ and n have some error.

Morris et al. [8] provided a general discussion of this important problem; calculating the regression with the wrong independent variable can lead to serious error in the calibration slope. Drum and detailed field calibrations have been discussed by Greacen et al. [6], with the conclusion that for both methods, the regression should be n on θ because θ is known (with very small error), but it is very difficult to estimate the sampling variance of n because it includes not only the usually negligible counting error, but also variance due to field heterogeneity in density and composition.

In the case of Method 3, the situation is less clear as not all the soil sampled by the NMM is used for water content estimation, therefore, the estimation of water content at a point will have greater error. But, we have used the same analysis for uniformity. In Method 4, only two points defined the calibration and a regression was irrelevant.

In both cases, the regression equation is inverted to give the calibration equation, i.e. the volumetric water content in terms of measured count rate ratio.

4.2. Calibration for near-surface soil layers

Calibration for soil layers closer to the surface than 0.25 m is affected by both the depth and the near surface water content profile. Techniques for surface layer calibration have been described by Grant [9] and Harris [10]. Nevertheless, Method 2 provided a useful calibration of the 0.1-m layer in this work.

4.3. Better precision from calibration data

The objective of this paper is to gain maximum precision from the minimum of expense and effort in calibrating the NMM. The first step in the process is to define the purpose of the meter. In particular, the NMM is most frequently used to estimate, not water content, but difference in water content between one reading and the next or between the current water content and some base value such as the minimum water storage of the field. If the field is uniform, the analysis used is the same in all cases, but if the field is non-uniform, we will demonstrate that these are quite different problems.

Much of the error in the calibration for water content does not affect a calibration for water-content change, because soil composition at a point in the field, does not change. Thus a calibration compiled from data expressed as change in water content vs. change in NMM count at that point will have less error than the equivalent calibration for water content. Such a calibration cannot be used to estimate water content; however, the actual water content is often not a requirement. Using a calibration designed to estimate water content to calculate water-content changes (over time) by calculating the difference in water content at two times, doubles the already high error associated with this type of calibration. It can also lead to serious bias, i.e. the wrong value, in estimates of water-content change due to certain common types of field variability.

The NMM responds not to water, but to the presence of the hydrogen atoms. While it also responds to a range of neutron-absorbing atoms, the dominant effect is caused by hydrogen within the structure of clay lattices, which has the same order of effect as water. Variation in volumetric clay hydrogen across the field is, therefore, usually the major source of error in a calibration that is not accounted for in the measurement of soil water content during the calibration process. There are two ways to use this information, depending on the intended use of the instrument.

Firstly, if the NMM is to be used for the estimation of water content, then it may be possible to map field characteristics and produce a special calibration for each soil variant This may be a simple matter of correlating mini-calibration slope with position on a map or with texture, and noting which calibration variant applies to each tube In many cases, it might be expected that clay hydrogen will correlate highly with soil density, density correction [3] is one way in which such a method may be implemented The effect is one of creating a three-dimensional calibration relating water content, NMM count, and density Greacen and Schrale [3] showed that much of the error in a simple calibration was accounted for by this density correction

A second simpler, and more accurate, solution may be used if the NMM is aimed at measuring change in water content Because soil composition at any point in the field does not change with time the calibration error associated with field composition has a much reduced effect when the calibration is expressed as change in water content vs change in count This type of calibration relies on the pairing of access tubes in the calibration process so that the assumption can be made that the composition is the same for the wet and dry readings Such a calibration cannot, of course be used to estimate water content

If water-content change and water content at a point in time are both required, then the two functions of the NMM must be separated and different calibration curves should be used for each function Since the same data are being used in both cases, the separate calibrations can be found with no additional field work In some cases they will have the same slope, but in soils with clay content variation this is unusual

The worst case of field variability occurs when duplex soil clay horizons vary in depth such as to dramatically change the soil texture and NMM count across the field at a depth This appears in the calibration as substantial variability and can cause serious bias if an ordinary calibration procedure is used Such a calibration may have a good r^2 value and may estimate water content well, but will give seriously biased estimates of change in water content To illustrate these problems and the benefits of paired-tube calibration designs, consider the data for the two soil layers in Table I as coming from the same depth but different parts of a field with different clay content at the calibration depth

Without tube pairing, all the data must be considered as a single undifferentiated set, the correlation is

$$n = 1\ 81\ (\pm\ 0\ 23)\theta - 0\ 11 \qquad r^2 = 0\ 86 \qquad (10)$$

That is, a calibration of

$$\theta = 0\ 55n + 0\ 06$$

This indicates 0 55 change in θ for unit change in count Yet the calibration slopes derived from the separated soil textures (Eqs 6 and 7), indicate the water-content change for this count change in the loam was 0 11, i e a 500% error In Fig 3, the combined regression is superimposed on the calibration lines for each tube pair Although the regression is a reasonable fit to the data points, the regression slope is quite wrong for some tube pairs

This error does not affect the estimation of water content to the same degree At the worst point, for a count ratio of 0 2, Eqs 6 and 7 indicate a water content of 0 19 and 0 15 m/m respectively, compared to Eq 10 at 0 17 m/m

In some cases, using the soil bulk density correction technique described above to change all count ratios to a common density can have some reduction of the error However, to use this calibration, an estimator of the density at each reading point would be required to calculate n' before using the corrected curve The texture range is too wide for this technique to work here, but has been used successfully on other soils For demonstration purposes, the combined regression on n' at 1 4 t/m^3 is

$$n' = 2\ 017(\pm\ 28)\theta - 0\ 144 \qquad r^2 = 0\ 82 \qquad (11)$$

This technique makes use of a probable correlation between density and soil texture. Higher count rates probably correspond with high clay content and low bulk density – this approximates the "universal" calibration discussed below.

4.4. Calibration specifically to estimate water-content change

In the above example, the mini-calibration lines from the two textures of soil form clearly defined classes, each of which can be used for a section of the field provided some mapping to other tubes can be devised, e.g. by noting texture during tube installation. In some situations, such clearly defined classes do not eventuate. In these cases, a calibration for change in water content will provide the best available solution. While not accounting for all changes in calibration due to composition, this method avoids the worst effect, that of clay hydrogen variation.

A calibration for change in water content is a correlation between count change and water-content change at points in the field. For example, again using the data in Table I as from a single layer, the average change in water content ($d\theta$) for the field between wet and dry condition is 0.085 m/m for an average count ratio change (dn) of 0.113. Hence a difference calibration would be:

$$d\theta = 0.75dn \qquad (12)$$

For an horizon with areas of 50% clay soils and 50% loam soils, this gives a better estimate of field water-content change than does Eq. 10 because, while the error is still high, now it is distributed about the mean. If Eq. 10 is used to calculate the field water-content change between the wet and the dry states, it gives a result that is so badly biased in the loam areas that the overall mean is compromised.

4.5. Towards a "universal" calibration

If clay hydrogen is measured then much of the variation between soils can be accounted for. An empirical approximation for clay hydrogen from a range of Australian soils may be expressed as the equivalent amount of water (We kg/kg) [6], as:

$$We = 0.124\ (\pm 0.012)C + 0.015$$

where

C is clay content of the soil (kg/kg).

If clay is measured, or estimated, for the calibration data and expressed in terms of "total" water, i.e. normal water plus equivalent water, then quite large differences in soils may be resolved into a single calibration. However, for this calibration to be used, the clay content must also be available for each access tube and depth in the field.

Using the data in Table I again: the clay content of the 0.3-m layer is approximately 18% and in the 0.6-m layer, 60%. The water equivalent of this clay hydrogen, using the equation above, is 0.057 and 0.108 m/m, respectively. Figure 5 shows the calibration in relation to total water content. For a wide variation in texture, this is usually a curved calibration, best fitted by quadratic expression – in this case:

$$\theta = 0.011 - \theta_e + 1.42n - 1.22n^2 \qquad (13)$$

where

θ_e is the "equivalent" water on a volumetric basis.

This is similar in effect to the "density correction" method, but more rigorous.

This calibration can be used to estimate water content at any point in the field given the count ratio and clay content In this case the difference between two count ratios should also give a good estimate of water-content change, but this is not always so and should be confirmed for each case

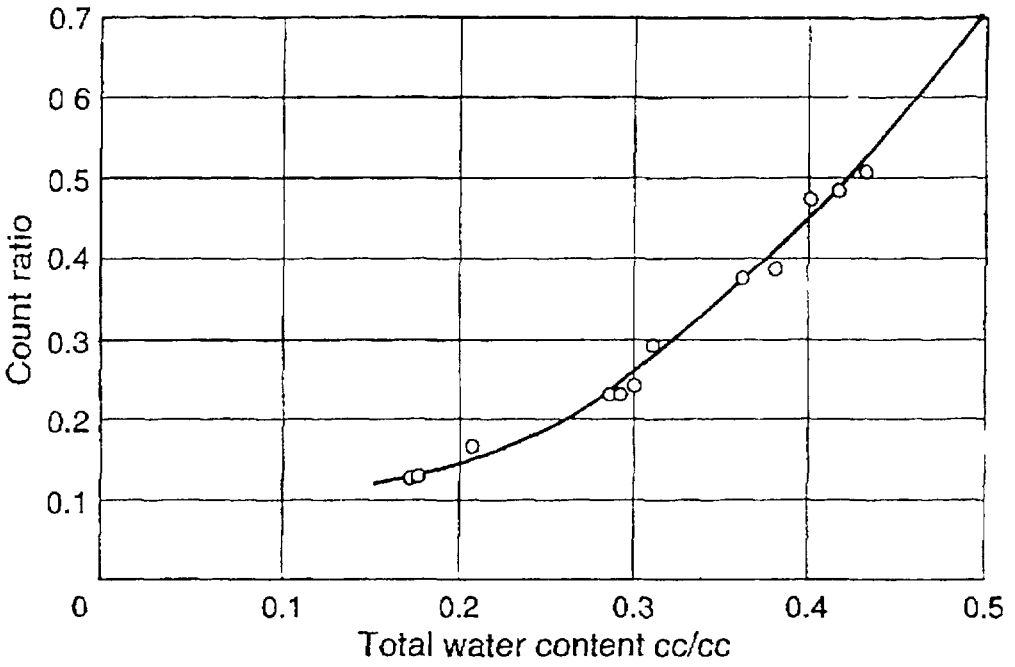

FIG 5 Combined loam clay data from Near sample method expressed in terms of total water equivalent A single expression (usually quadratic) can be used to predict water content from both loam and clay areas (or horizons) provided that the equivalent water in the clay can be estimated for each reading point

4.6. Use of "far" samples to increase confidence in the calibration

In deriving an economical calibration method the statistical ideal of a large number of field samples must usually be compromised In a uniform field the problem will be minor, but in many fields there may be error or bias introduced because one or more of the calibration access tubes does not behave like the field mean It is important to be able to detect this condition if it occurs A frequent problem is that the soil at one site does not wet up or dry out in the same way as the major part of the field during the calibration Localised heterogeneity in field texture can cause this, as can poor root development in the vicinity of a calibration site if a crop is drying the soil

Irrespective of the cause of variability, it is useful to know how different from the mean for the field is a particular calibration point This is particularly important when Method 3 is used with a small number of access tube pairs Generally, gravimetric sampling for water content is rapid, inexpensive and not destructive of the site, and well distributed sampling may be used to provide information at low cost about water content distribution in the field This information may then be used to weight data from the more intensive "near" sampling sites If the water content data from a NMM access tube fall a long way from the mean for the field then it can be given a lower weight or ignored, when calculating the calibration

For example, it is useful to compare the calibration slopes obtained for the Waite Institute soil in the 0 6-m horizon by Methods 3 and 4 The mean slope for Method 3 was 0 54 (with 10% error), quite different from 0 29 as obtained by the "far" sample method Analysis of the data shows that the difference was largely due to the third access tube pair located in a section of the field that dried out atypically Since the "near" samples taken for this tube also sampled the dry region the Method 3 calibration was unaffected because both NMM and water content values are low However, in using these same count data for the "far" sampling method, the outlier datum point biased the mean NMM

count ratio and hence the calibration slope. The "far" samplings detected only one such dry site, out of nine samples, and the mean water content for Method 4 was almost unaffected.

If pairs 1 and 2 only of the NMM sampling, which are close to the field mean water content, are used to estimate the field average dry NMM count rate at 0.6 m, the slope (0.36) for the 0.6-m calibration was closer to that obtained by Method 3. Such an approach can be justified because a) the "near" sampling results indicate that the NMM values obtained for the tube pair on pair 3 were not anomalous, i.e. they fit the same calibration obtained from the other two access tube pairs, and b) because the "far" samples established that this water content was an outlier representing only a small fraction of the field.

A similar approach can be taken with a Method 4 calibration to remove the effects of abnormal samples from the calculation of the mean of both NMM and gravimetric water content data. In the data presented here, there were insufficient samples of NMM count ratio to establish a distribution for the field, but where there was a large number of NMM tubes, such as where they were installed for irrigation scheduling (i.e. Method 4 is being used to avoid destructive sampling of access tubes), a better calibration could well be established by using the distribution of NMM and sampling values to ensure that abnormal sites are not included in the calibration.

5. CONCLUSIONS

We have investigated various calibration methods, with the aim of defining the best and most accurate for application at minimal cost. Where detail of the interaction of the NMM and a soil is required, e.g. in studies of the physics of the NMM, a drum calibration that removes the effect of field variability, is essential. It is useable in some circumstances where a field calibration is not possible. This may be because the time required to dry, or wet, the field is too long. The drum calibration may also have an advantage if the field is extremely variable on a small scale.

For most field uses of the NMM, we recommend the field calibration technique set out in Method 2, with volumetric and density sampling next to the access tubes with at least three, and preferably six, pairs of access tubes randomly distributed on the field and the location of each pair mapped. It is also recommended that each soil horizon be treated as a separate calibration until it can be established that one calibration curve will suffice for all.

Pairing of access tubes is strongly recommended as results will be little different to the same number of randomly distributed single tubes in a uniform field, but will provide much more information in non-uniform fields by alternative analysis methods.

If Method 2 cannot be used for economic or other reasons, the less precise procedures set out in Methods 3 and 4 can produce reliable calibrations. Again, pairing of access tubes is of more value than the same number of randomly placed single tubes. If field variability is substantial, the calibration may be imprecise, but it must be emphasised that an imprecise calibration is a considerable improvement over a calibration that may result in wrong estimates of water-content change.

With Methods 3 or 4, it is useful to establish the relationship between the limited number of (expensive) NMM sample sites and the rest of the field. A combination of both "near" and "far" sampling techniques is recommended, especially if these data are available from other aspects of the work on site.

If the NMM is to be used to measure water-content changes, and if the slope on individual tube pairs is significantly different to the combined calibration slope, then a difference calibration should be calculated and used for estimation of water-content changes with the conventional calibration curve used only for estimation of water content.

Method 4 can be recommended only where the numbers of access tubes and sampling sites are quite large and well enough distributed, to establish the distribution of count rate ratio and water content across the field. If field heterogeneity is small, then such a calibration can be quite precise. However, knowledge of field heterogeneity is usually not available until after the calibration is complete, and precision cannot be assured with this method. Addition of even two pairs of (Method 3) tubes on the periphery of the field will increase confidence considerably.

Calibrations of a precision, adequate for most uses of the NMM can be obtained by inexpensive methods. Such calibrations, if analysed with care, are much more reliable than the factory provided, or general, soil-type-based calibration.

ACKNOWLEDGEMENTS

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PROFILING WATER CONTENT IN SOILS WITH TDR: COMPARISON WITH THE NEUTRON PROBE TECHNIQUE

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Abstract

In November 1996, at a site on the Grenoble campus a 1 2-m-long neutron access tube, a 0 8-m fibreglass Trime access tube and three sets of 1-m twin-rod TDR probes were installed Weekly measurements were made over a 9-month period In addition, soil samples were taken from time to time with an auger, to determine gravimetric water-contents The soil bulk density profile was initially characterised by gammametry using a Campbell™ probe A Troxler™ 4300 was used for the neutron-probe measurements The TDR signals, for further processing by TDR-SSI, were logged using a Trase 2000 from Soil Moisture Equipment Corporation™ TDR methods were employed without any special calibration of the permittivity/water-content relationship standard internal calibrations of the devices or Topp polynomial relation were always applied The results of all these water-content profiling methods were compared in three ways (i) the water-content profiles were plotted directly on the same graph for different dates, (ii) all the water contents measured at all dates and all depths were plotted against a corresponding "reference," namely neutron probe or gravimetry, (iii) water balances were calculated for each method and their respective time-profiles analysed There was fairly good agreement among the three profiling methods, indicating that TDR is now a viable alternative to nuclear techniques for soil water-content profiling

1 INTRODUCTION

Great effort has been devoted in the last decade to the development of new soil water-content sensors based on the capacitance technique (FD: frequency devices) or working in the time domain (TDR. time domain reflectometry). Only a few papers have described comparisons of these dielectric methods with the neutron-probe technique [1–6]. The aim of this experimental work – undertaken with the financial support of the IAEA – was to contribute to this area of applied research by comparing the neutron probe technique with two recent TDR methods for soil water-content profiling [7] the Trime-Tube method from Imko™, already commercially available, and TDR-SSI (TDR Signal Spatial Inversion), a new TDR signal processing technique proposed by scientists at the Laboratoire d'Étude des Transferts en Hydrologie et Environnement (LTHE).

2. TIME DOMAIN REFLECTOMETRY

2.1. Principle

Time Domain Reflectometry measures the velocity of a wave in a transmission line. With a reflectometer, this wave originates from the fast switching of a voltage step applied at the input of the line or wave-guide. The TDR signal that is recorded at the output of the step generator is the sum of the incident and reflected tensions. The amplitude of this signal is time-dependent because when the wave encounters an impedance discontinuity in the propagating medium, a fraction of its energy is reflected back to the generator

TDR was developed for detecting and localising faults in electrical cables, for which the rising-time of the step has to be much less than the propagation times into the line itself to reach sufficient spatial resolution. Typically, most TDR generators have rising-times less than 200 ps (2×10^{-10} second) which corresponds to frequencies up to 10 GHz, i.e. in the micro-wave range. If a discontinuity is located at a distance L from the wave-guide origin, an echo will be observed after a time-delay Δt given by

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$$\Delta t = \frac{L}{V} \tag{1}$$

where

V is the velocity of the wave in the considered wave-guide

With some assumptions (no dispersion, losses by conduction or relaxation negligible) V is simply related to the speed of light, c, in a vacuum (3×10^8 m s^{-1}) and to the *relative electrical permittivity* K of the dielectric material filling the wave-guide by

$$V = \frac{c}{\sqrt{K}} \tag{2}$$

Although K is usually called "dielectric constant," this term is, strictly speaking, incorrect because it depends on physical components frequency, temperature, and humidity Combining Eqs (1) and (2), produces the "basic equation" for TDR

$$\Delta t = \frac{L}{c}\sqrt{K} \Rightarrow K = \left(\frac{c\Delta t}{L}\right)^2 \tag{3}$$

Equation (3) allows the evaluation of K from the analysis of a TDR signal From a "materials" point of view, TDR can be considered as a *method for measuring electrical permittivities of dielectric materials*

2.2. Soil application

Since the early work of G C Topp in the late 1970s [8], TDR has been used for assessing water content of soil This is possible as a result of the contrast between the permittivity of water ($K_e \approx 80$) and those of most minerals that constitute the solid matrices of soils $4 \leq K \leq 10$ [e g 9–12] Therefore, the bulk permittivity of a wet soil is affected by its water content On the basis of a set of measurements taken on different soils at various water contents, Topp proposed an empirical relationship to calculate the volume fraction of water θ of a soil from a measurement of its permittivity K by TDR

$$\theta = -5.3\ 10^{-2} + 2.92\ 10^{-2} K - 5.5\ 10^{-4} K^2 + 4.3\ 10^{-6} K^3 \tag{4}$$

Theoretically, this polynomial should be used only in soils of the same type and with bulk densities similar to those considered by Topp However, in most cases, it gives fairly good first estimates of water content For that reason and for simplicity, it is in common use When more accuracy is required, a particular *calibration* relationship $\theta(K)$ has to be determined for a particular soil Many papers have been published on this problem [13–23] A synthesis and a unified presentation of the models was recently developed by Zakri [24]

2.3. Soil probes

To run TDR in soils, a wave-guide with the soil as dielectric material has first to be established For that purpose, *probes* are introduced into the soil generally from its surface There are three main types (Photo 1)

- "Twin-rod" probes are the most commonly used on the field because they are easy to install, a particular type of twin-rod probe that can be placed at different depths in an access tube was recently developed by Imko Gmbh [25],
- "Three-rod" probes provide better definition of the investigated soil volume (Fig 1), they can be bu at different depths to get water-content profiles,

– "Coaxial" probes are preferred for experiments in the laboratory for calibration, for instance, the measured volume is defined, i e the whole inner space of the wave-guide

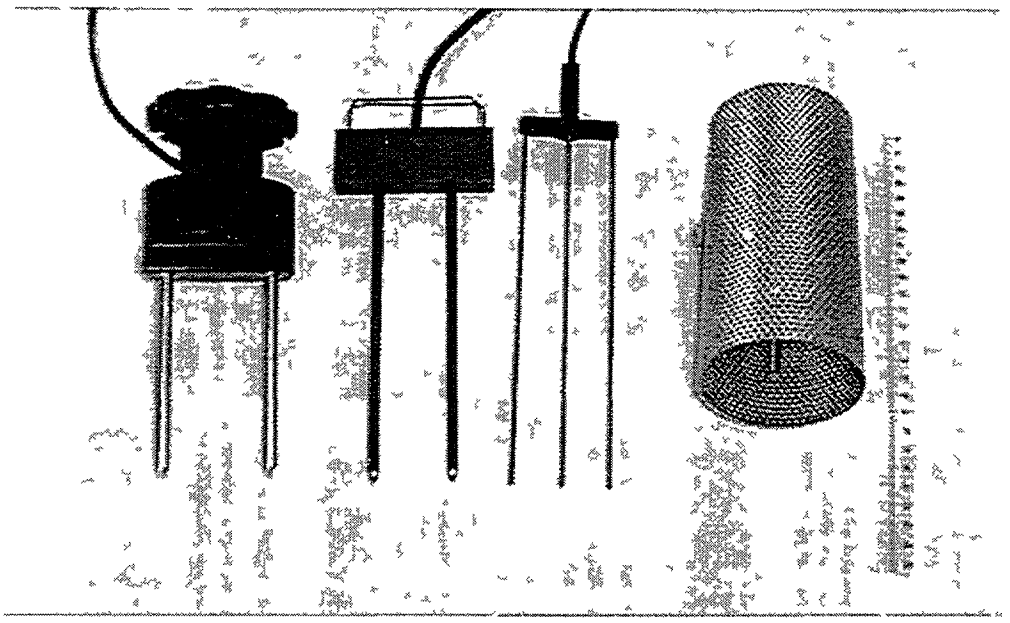

PHOTO 1 Several types of TDR probes From left to right twin-rod probes "Connector" from Soil Moisture Eqt Corp and from the TRIME of Imko, three-rod "Buriable" probe of Soil Moisture, coaxial probe (LTHE)

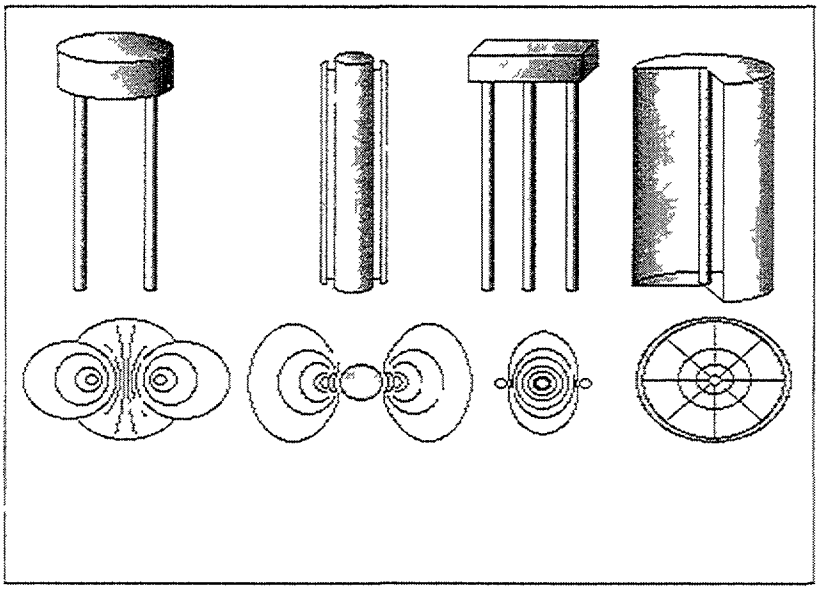

FIG 1 Shape of the investigated volume of some TDR probes From left to right twin-rod, Imko "Tube", three-rod, coaxial, probes Adapted from [Zegelin & White, 89] , [Whalley, 93]

With a given geometry, a TDR probe has a characteristic impedance (Ω) Z_{sa} in air For a twin-rod probe

$$Z_{sa} = \frac{1}{\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\cosh^{-1}\left(\frac{D}{d}\right) \approx 120\cosh^{-1}\left(\frac{D}{d}\right) \qquad (5)$$

where

D is the distance between rods,

d is the rod diameter,
m_0 is vacuum permeability (4p 10^{-7} H m^{-1}),
e_0 is vacuum permittivity ($1/36\pi$ 10^{-9} F m^{-1}) .

For the "connector" probe of the Trase device for instance, D = 50.8 mm, d = 6.35 mm $\Rightarrow Z_{sa} \approx$ 330 Ω. For a coaxial probe of outer radius R_e with an inner conductor of radius R_i:

$$Z_{sa} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\left(\frac{R_e}{R_i}\right) \approx 60\ln\left(\frac{R_e}{R_i}\right) \tag{6}$$

For such a probe, with R_e = 100 mm and R_i = 5 mm, $Z_{sa} \approx$ 180 Ω. Placed into a medium of permittivity K, the impedance of a TDR probe becomes:

$$Z = \frac{Z_{sa}}{\sqrt{K}} \tag{7}$$

The characteristic impedance of a TDR probe influences the shape of the recorded signal. The measured voltage is the sum of those applied and reflected, V^+ and V^-, respectively. Therefore, the TDR signal is directly related to the *reflection coefficient* ρ defined as:

$$\rho = \frac{|V^-|}{|V^+|} \tag{8}$$

Besides that, ρ is determined by the discontinuities that exist along the line. If the wave goes out a portion of line of impedance Z_1 to enter a new zone of impedance Z_2, a corresponding reflection coefficient r_{12} will be recorded with an amplitude given by:

$$\rho_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{9}$$

In practice, discontinuities are always between two extreme cases:

- Short-circuit ($Z_2 = 0$): $\rho = -1$,
- Open circuit ($Z_2 \rightarrow \infty$): $\rho = 1$.

In a medium of permittivity K in which a twin-rod probe has been placed and connected to the reflectometer through a cable impedance Z_1, the TDR signal will show a variation of amplitude given by (9) with Z_2 calculated by (7). Manufacturers of TDR devices often include in the probe heads a transformer, commonly called "balun," which has the effect of increasing the apparent impedance of the medium seen from the generator. Thus, the reflection coefficients are amplified (Fig. 2), and it is easier to detect particular points like the beginning, or the end, of the probe.

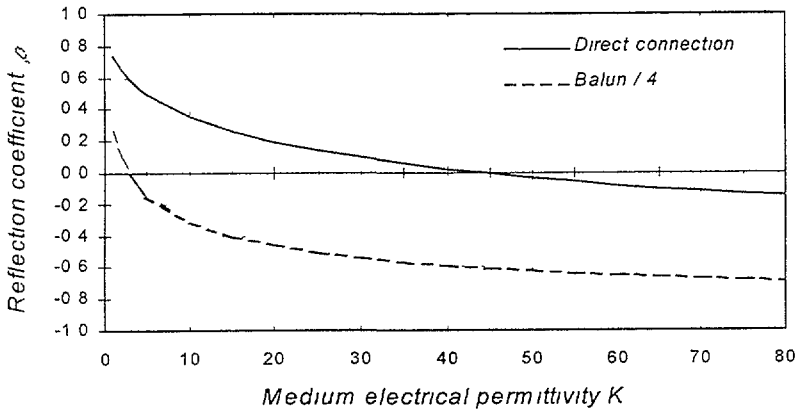

FIG 2 Influence of the permittivity K of the medium on the reflection coefficient measured by TDR with a twin-rod probe of characteristic impedance $Z_{ca} \approx 330\ \Omega$ in air. Top . direct connection to a 50 Ω cable Bottom same but with a X4 "balun" inserted into the circuit

2.4. Soil physics applications

Early use of TDR in soil physics necessitated the employment of devices designed for other purposes, e.g the cable-tester Tektronix 1502B/C (Photo 2).

Nowadays, several devices are available, especially designed for in-situ water-content measurement in soils (see Section 7. MANUFACTURERS LIST) The LTHE has at its disposal a Tektronix 1502C, two Trase devices (Photo 3) and one TRIME-FM. with its "tube" probe (Photo 4)

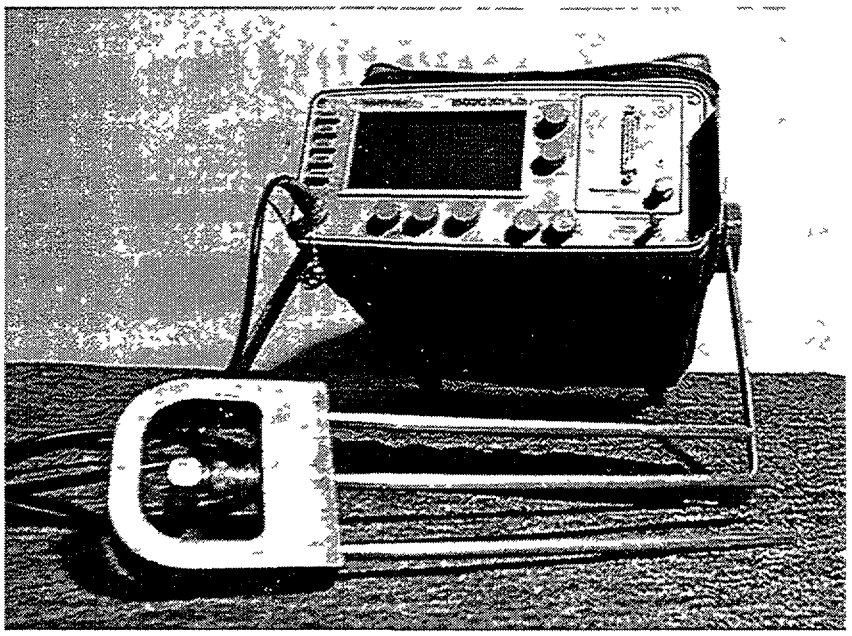

Photo 2. Tektronix cable-tester 1502C with a 30 cm long three-rod probe developed by B Clothier, Hort Res Lab , Palmerston North (N Z.)

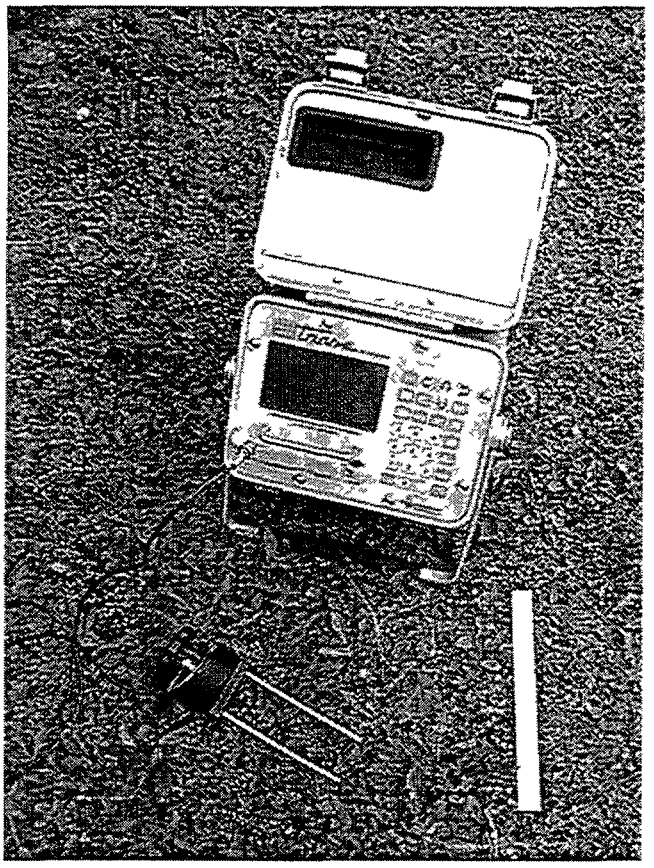

Photo 3 Soil Moisture Equipment Corp "Trase" system ref 6050X1 with the "Connector" surface probe

Photo 4 TRIME device from Imko Gmbh. with a "Tube" probe and its fibreglass access tube

2.5. Signal processing

Most currently available devices have systems that automatically process the TDR signals: their internal electronic circuitry, or software, measures the times t_1 and t_2 of the two main reflections at the

beginning of the probe and at its end (e.g. Fig. 3), to calculate the propagation time $\Delta t = t_2 - t_1$ and, finally, the permittivity K by (3).

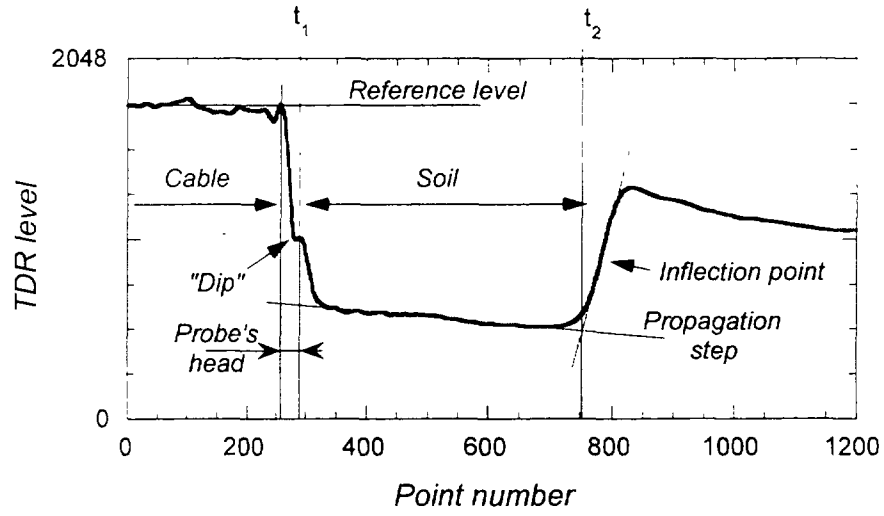

FIG. 3. Principle of classical TDR signal processing, wet river sand, Trase system, Connector probe 30 cm, 12 ns timebase.

In a Trase system, the signal is first acquired on an adjustable time base of 12, 24, 48, etc. ns, and stored in an internal memory as 1,200 points digitized on 12 bits (4,095 levels). The first reflection is detected via a marker on the signal itself (electronic "dip") created by a small inductance inserted in the "connector" probe's head. The position of the second reflection is calculated using the tangents method: t_2 is identified as the intersection of the propagation step with the tangent to the inflection point. These calculations can be done directly by the system processor, or on a computer after downloading the TDR traces through the serial interface.

In contrast, the whole TDR signal is not acquired in the Trime system. A counter is turned on when the signal enters the probe and switched off when the terminal reflection is electronically detected. For the electronic detection to work properly in every case, the level of the reflection has to be higher than the reference level of the initial step. This is obtained by coating the rods of the Trime probes with a dielectric polymer. Propagation times are directly converted into water contents using an internal calibration curve [25]. This simple electronic design allows miniaturisation of the device and reduces its cost (< \$5,000) in comparison to other more classical systems like the Trase (about \$13,000). Furthermore, the data generated by the Trime are stored in a memory placed directly in the probe's connector, such that it acts as a "push-button" system.

Initially, the Tektronix 1502B cable tester was purely an analog system. However, an optional serial, or parallel, interface can be installed by which the TDR signals are acquired and transferred to a computer as files of 250 points digitized on 128 levels (7 bits). Afterwards, they can be treated in the way described above. It is possible to use the Tektronix as a stand-alone system by using its front-panel. With an on-screen index where the signal is displayed, like on an oscilloscope, manual propagation-time measurements are possible.

2.6. Profiling water content

The TDR procedure described above is a method for accessing *mean* water content in a volume whose length is equal to that of the probe, but with a lateral dimension not so clearly defined (*cf.* Fig. 1). If a water-content *profile* has to be determined by TDR, it is possible to:

- Install probes horizontally at different depths; this necessitates digging a trench, which is not always possible and can be tedious,
- Install vertical probes of increasing lengths directly from the surface, which leads to a more complex calculation: the water-content estimates for the above layers have to be used for

evaluating the fraction of the propagation time in the considered layer and thus calculating the mean permittivity and water-content, moreover, this procedure can be affected by spatial variability in the soil between the different probes

Neither of the above solutions is very satisfactory mainly because of their poor spatial resolution Two other TDR systems are now presented as alternatives to the neutron probe technique

- The "moisture point" system from E S I (see Section 7) uses a single TDR probe, the apparent length of which can be electronically adjusted through diodes in the probe [18] by tuning the voltages applied to these diodes (diode "blocked" open circuit, or "conducting" short-circuit) it is possible to isolate alternately each section of the probe and, thus to obtain a propagation time measurement in the corresponding zone however, the spatial resolution is relatively weak – typically, the 1 2-m "moisture point" probe is segmented by six diodes in two zones of 15 cm near the surface, followed by three zones of 30 cm.
- The Imko "tube" system uses an access tube in the soil like the neutron probe method, and dielectric materials, PVC, polymethylmethacrylate (e g plexiglas altuglass) fibreglass, etc have to be used to allow wave propagation, their relative fragility necessitates caution while inserting the tubes, to measure the water-content profile in the soil around the tube the 17-cm probe is positioned successively at different depths (Photo 4), here again, the analogy with the neutron probe is obvious

3 TDR-SSI

To correct some of the disadvantages of the techniques described above, the LTHE developed the TDR-SSI method [28–30] It is based on a simple idea a TDR signal is not only useable for determining overall propagation time and the corresponding mean water-content, as is done classically, it can also be considered as a set of elementary signals reflected, not only at the beginning and at the end of the probe, but, also, every time an impedance discontinuity is encountered in the propagating medium If there are any variations of water content in the soil, this will lead to fluctuations of the electrical permittivity and, thus, of the impedance, creating reflections contributing to the recorded TDR signal $\rho(t)$ Finally, a TDR signal can be regarded as an "image" of the impedance along the probe The main problem is to find the correct method to reconstruct the impedance profile from the measured time-evolution of the reflection coefficient This kind of problem is classical in the fields of Geophysics and Remote Sensing, for instance Generally speaking, it is called an "inverse problem "

To solve it, we learned from studies in hydrology [31, 32] and electronics [33] Rather than adopting a classical discrete approach leading necessarily to a numerical resolution we chose an analytical method based on the formulation developed by Collin [34] to solve the problem of impedance adaptation on a continuously heterogeneous line In the frame of "small reflections" (Rayleigh's assumption), we first established an expression of the reflection coefficient $\rho(t)$ as a function of the impedance profile $Z(z)$ Then, with some simplifying assumptions on the shape of the input signal and on the boundary conditions at the probe's ends, we solved the inverse problem determination of the impedance profile from the measured reflection coefficient

Section 6 provides details of our analytical approach Figure 4 presents the general scheme of TDR-SSI

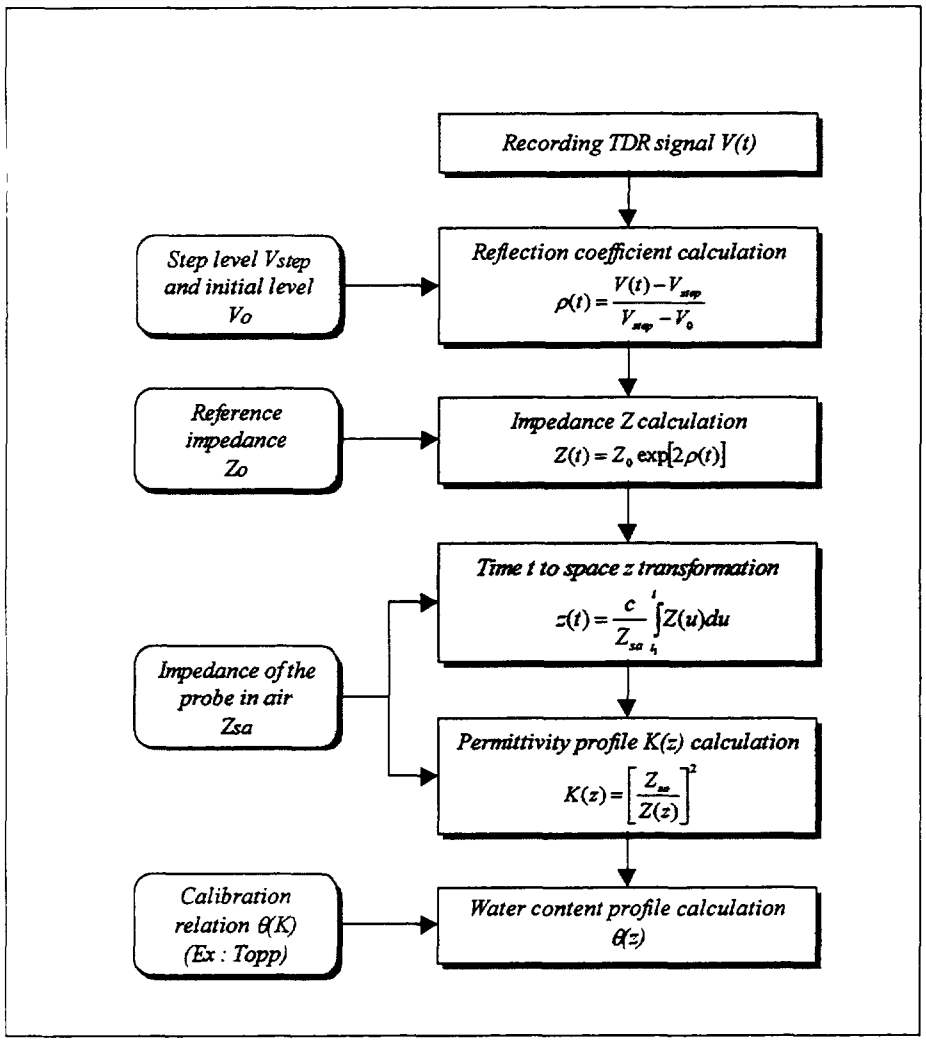

FIG. 4. TDR_SSI Algorithm

4. THE CAMPUS 97 EXPERIMENT

4.1. Site description, probe arrangement

In November 1996, we started to install probes at a site on our campus in Saint Martin d'Hères where the LTHE is located. It is an urban site (Photo 5) where the soil was disturbed during building, to a depth of approximately 50 cm [35]. First, a 1.2-m-long aluminium neutron tube T0, an 80-cm Trime tube T1 and a set of two 1-m-long 8-mm diameter stainless steel rods T2, were installed (Fig. 5). At that time, the set-up device in Photo 6 was unavailable and it became apparent that the signals recorded on the T2 rods were unusable, probably because of poor contact with the surrounding soil. For that reason, at the beginning of 1997, two other sets, T3 and T4 twin-rod probes, were installed, this time using our set-up device, which gives good results both in terms of contact and parallel rods.

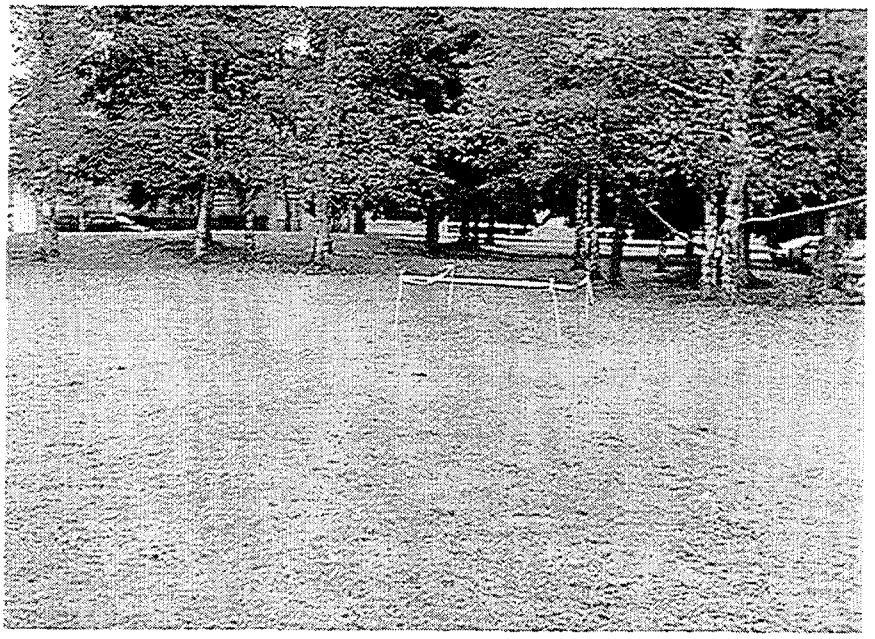

PHOTO 5. General view of the experimental site on the campus.

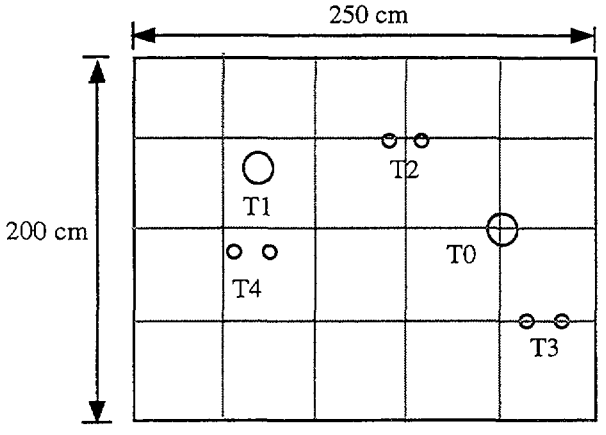

FIG. 5. Probe arrangement on site "Campus". T0 : neutron probe; T1 : Trime tube ; T2, T3, T4 : twin rod probes to be monitored with the Trase for running TDR_SSI.

Photo 6. Set up device developed at the LTHE by J.L. Thony to make use of the TDR_SSI method on TDR signals acquired by the Trase on up to 1.2 m long twin-rod probes.

4.2. Measurements

Measurements were made weekly from the beginning of spring 1997. We first used an old Solo neutron probe, then a new Troxler model 4300. The measurements in the Trime tube T1 were taken every 10 cm. TDR signals on probes T3 and T4 were acquired using a Trase model 2000 in its measure-screen fully automatic mode. Moreover, on dates 4/6, 7/7, 31/7, 14/8 and 21/8 1997, samples every 15 cm were drilled out with an auger. The gravimetric water-contents so determined were used to construct the calibration curve presented in Fig. 6. To convert gravimetric water contents to volumetric, we used bulk density measurements obtained with a Campbell gamma probe (Table I) [36].

The Trime has been used with its standard internal conversion table. The TDR traces $N(t)$ acquired with the Trase were stored on a PC diskette and transformed into reflection coefficients $\rho(t)$ assuming that the TDR generator always delivered a step with an amplitude ΔN = 1500. This corresponds to the following conversion formula:

$$\rho(t) = \frac{N(t) - N_1}{\Delta N} \approx \frac{N(t) - N_1}{1500} \tag{10}$$

where

N_1 is the reference TDR level into the cable (Fig. 3).

TABLE I. DENSITY PROFILE MEASURED BY GAMMAMETRY

z (cm)	d (g/cm^3)
10	1.27 ± 0.02
20	1 35 ± 0 03
30	1 43 ± 0.02
40	1.57 ± 0.05
50	1 57 ± 0.05
60	1 56 ± 0.03
70	1 51 ± 0.02
80	1.48 ± 0.02
90	1.43 ± 0.02
100	1 39 ± 0 02

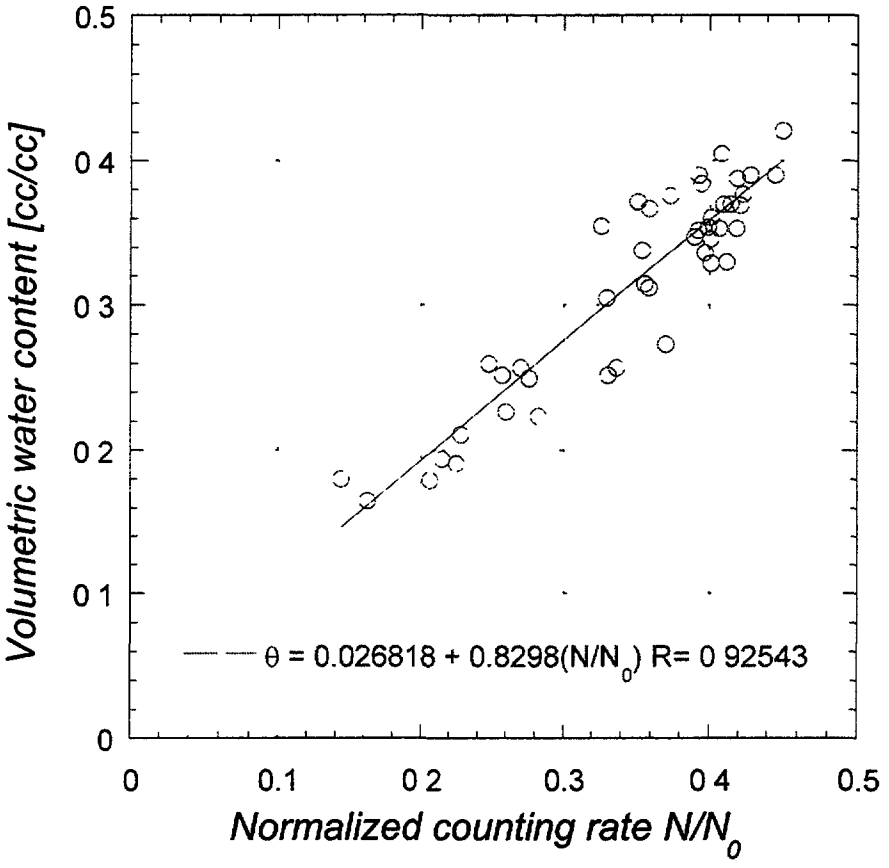

FIG. 6 Calibration curve determined for neutron probe tube T0.

The TDR-SSI method was implemented as a Visual Basic application initially written by Peirera dos Santos [28]. We have run it on all our data with the following parameters: Z_c = 50 Ω, reference impedance, and Z_{sa} = 72.5 Ω, probe's impedance in air. In TDR-SSI, we always used the Topp's polynomial (4) to convert the measured permittivities into volumetric water contents.

4.3. Results and discussion

To analyse the results of our tests during summer 1997, we first compared directly the profiles obtained by the different methods: see examples in Figs. 7 and 8.

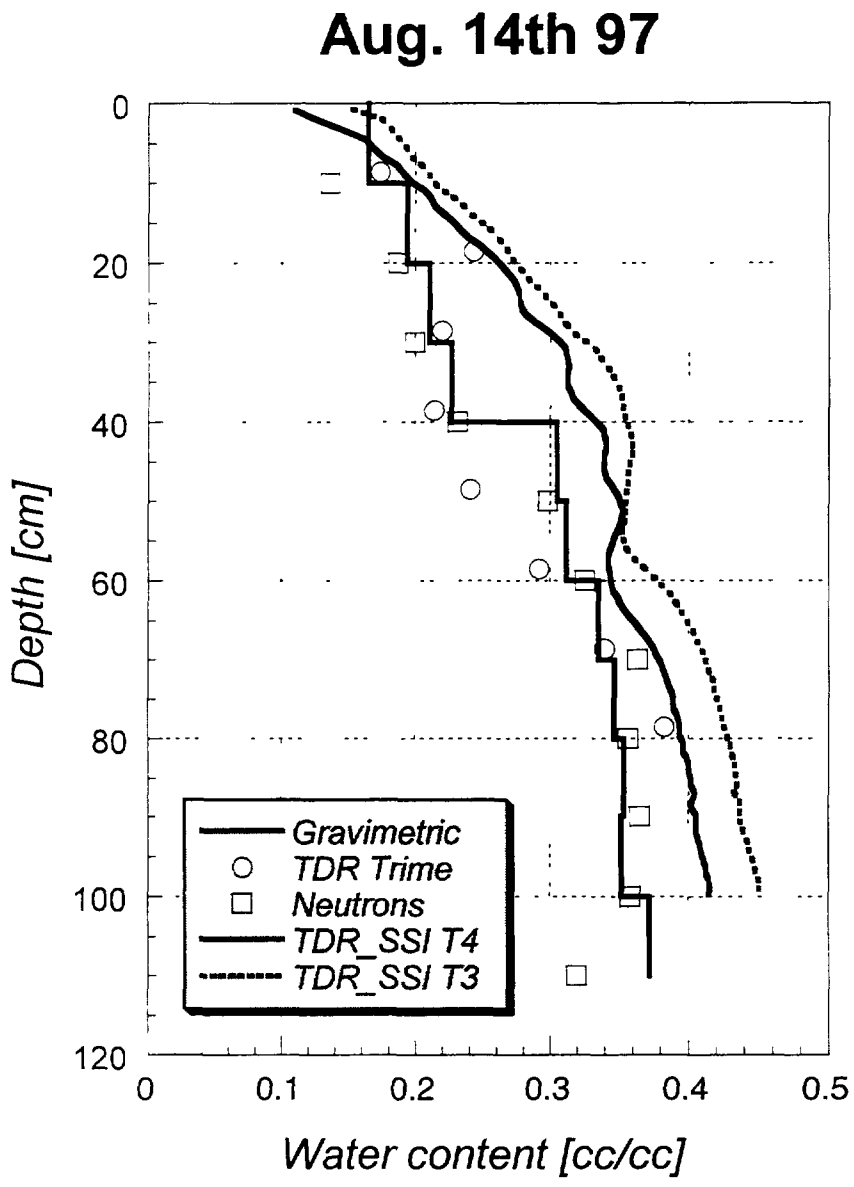

FIG 7 Profiles comparison on August 14th 1997. The step curve is constructed from the gravimetric water-contents

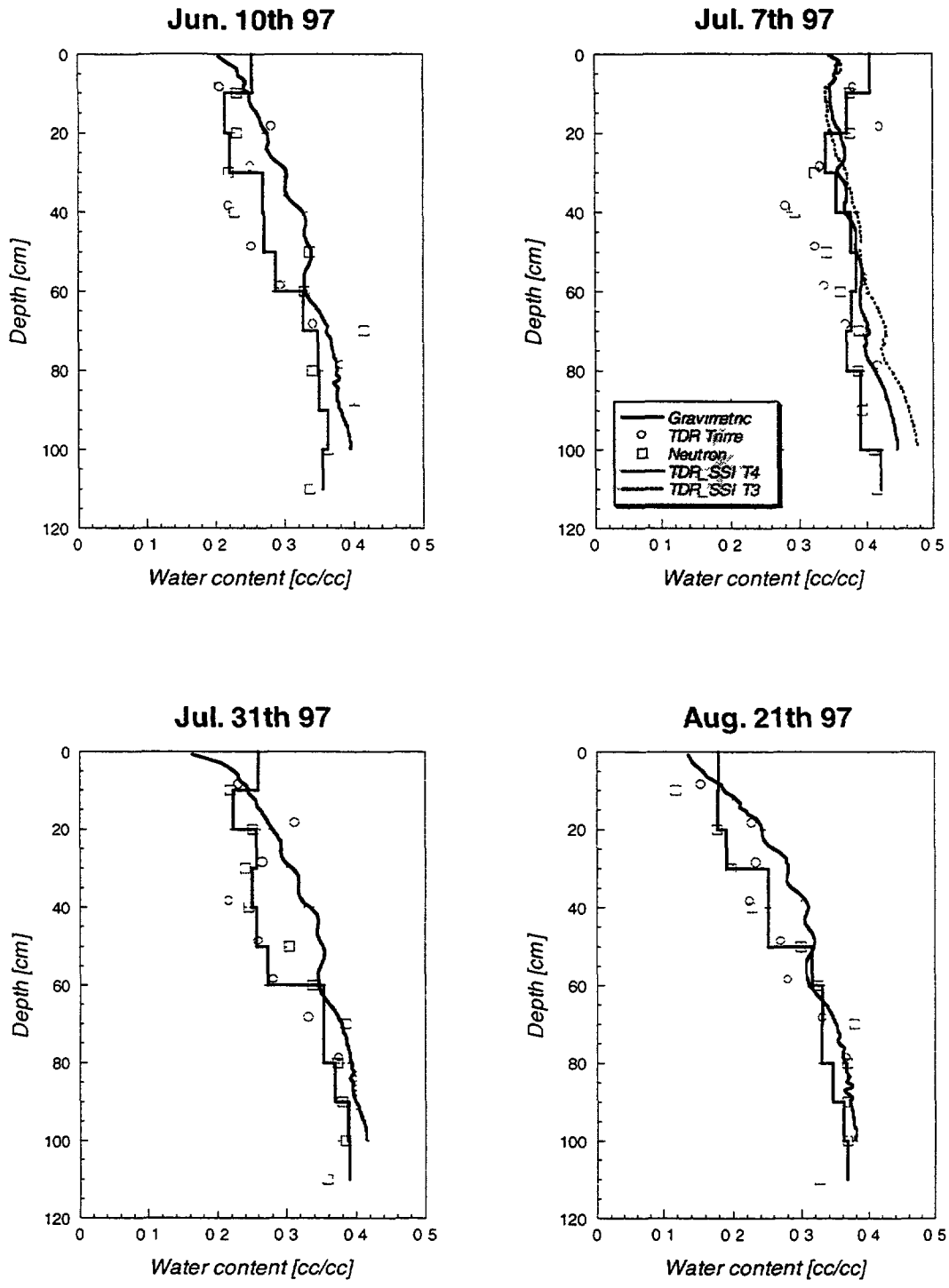

FIG 8 Examples of water-contents profiles obtained by different methods : gravimetry (step curves), neutron probe (□), TDR Trime tube probe (o) and TDR_SSI (solid line : T4, dashed line · T3)

Generally there was good agreement, both at a given date and as a function of time; the profiles were similar. Nevertheless, it appears that there was a zone, roughly from 20- to 60-cm depth, where the TDR-SSI profiles were significantly shifted; also, near the surface, fast-changing water-content gradients were detected by TDR-SSI.

To explain the observations in the 20–60 cm layer, contact problems may again be evoked. But, more likely, the correct interpretation is related to the physical properties of the soil disturbed in that zone, as was mentioned before. It is clear that the TDR-SSI profiles had much better spatial resolution near the surface than did the other more integrative methods. For estimating the resolution of TDR-SSI, let us consider that the rising-time of the TDR generator (200 ps) defines approximately

sampling rate: for a time-base of 24 ns, for instance, this corresponds to 120 points. At best, if this time window can be adjusted on the length of the probe (1 m), this yields a spatial resolution of about 1 cm.

When one wants to go deeper into the comparative analysis, the following problems are to be faced:

- Each method has its own measured volume, which change with water content and density, and, thus, with depth; the neutron probe integrates an approximately 20-cm diameter sphere [37]; the auger has a 45-mm diameter and the samples are taken every 10 cm; the TDR probe measured volume lateral extension is not precisely defined (Fig. 5); the Trime's probe integrates on its 17-cm length,
- Each method has its own calibration problems: strictly speaking, the neutron probe should have be calibrated for each soil horizon; for the auger samples, we always consider the density profile of Table I, neglecting any spatial variability; no specific calibrations were used for TDR.

The different methods were close to each other (Fig. 5) but not installed exactly at the same spot. Again, there can be spatial variability effects.

With all these biases, it was difficult to construct a completely rigorous statistical treatment like in previous works on the neutron probe [38, 39]. We then preferred to perform direct correlations between all the measurements taken at various dates between 0- and 80-cm depths considering either gravimetry or neutron probe as a reference (Table II, Fig. 9).

TABLE. II. LINEAR CORRELATION $\theta = M_0+M_1\theta_{REF}$ WITH: (a) θ_{REF} = GRAVIMETRIC WATER-CONTENTS.(b) θ_{REF} = NEUTRON PROBE WATER-CONTENTS ; R : CORRELATION COEFFICIENT.

(a)			
	Trime	**Neutron**	**TDR_SSI**
M_0	0.046	-0.009	0.129
M_1	0.843	1.047	0.695
R	0.839	0.898	0.854

(b)			
	Trime	**Gravi.**	**TDR_SSI**
M_0	0.070	0.062	0.149
M_1	0.749	0.770	0.615
R	0.869	0.898	0.880

Results in Table II show that the highest correlation was obtained for gravimetry vs. neutron probe. This is perfectly logical since the neutron-probe calibration curve of Fig. 6 was constructed precisely on these data. TDR-SSI measurements were more closely correlated to the references than were those with the Trime. However, the latter had "M_1" coefficients closer to 1. It is likely that a calibration of the TDR measurements, i.e. determination of the water content/permittivity relationship $\theta(K)$ of this particular soil, would have improved the results. On the other hand, it is noteworthy that the data were acceptable even without calibration.

Alternatively, *water storage S* may be evaluated as a function of the water-content profile $\theta(z)$:

$$S(z) = \int_0^z \theta(u)du \qquad (11)$$

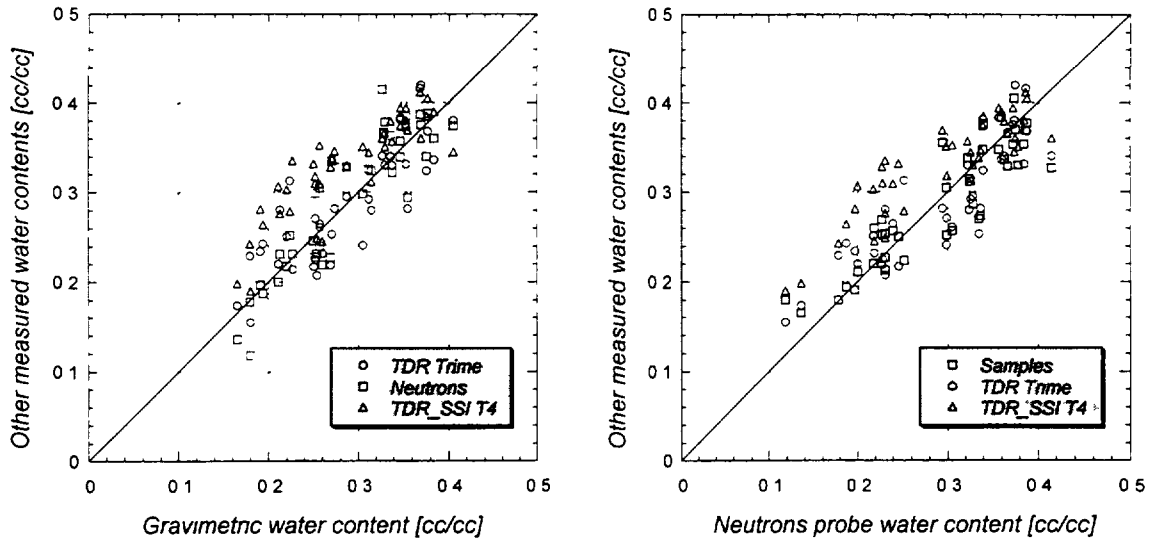

FIG. 9. Comparison of all water-content measurements : all dates, all depths between 0 and 80cm. Left . as a function of gravimetric water-contents , Right · as a function of neutron probe water contents

Usually, to permit a direct comparison with the rainfall input, S is expressed in mm of water. We kept this convention while doing two set of calculations:

- Between 0 and 80 cm (maximum depth of the Trime tube), we integrated all our profiles from April 21st to September 1st 1997 (Fig. 10),
- Between 0 and 100 cm, we compared the storage calculated from: i) neutron probe profiles, ii) TDR-SSI T4 probe profiles, and iii) same as the latter, but considering the mean water content on the probe length as in classical TDR (Fig. 11).

These evaluations appeared to be similar (Fig. 12), considering either the 0–80 cm or 0–100 cm layer. Furthermore, the profiles over time were similar and consistent with moisture uptake during the period. Examining more closely the respective profiles, there was a phase-shift between TDR-SSI and the other methods, possibly the effect of better measurements near the surface, or due to the above-mentioned different behaviour in the 20–60 cm layer.

The storage calculation from the mean TDR permittivity value (classical analysis) seemed closer to that calculated from the neutron-probe water contents. This may indicate again that the shapes of the TDR-SSI profiles were not totally realistic.

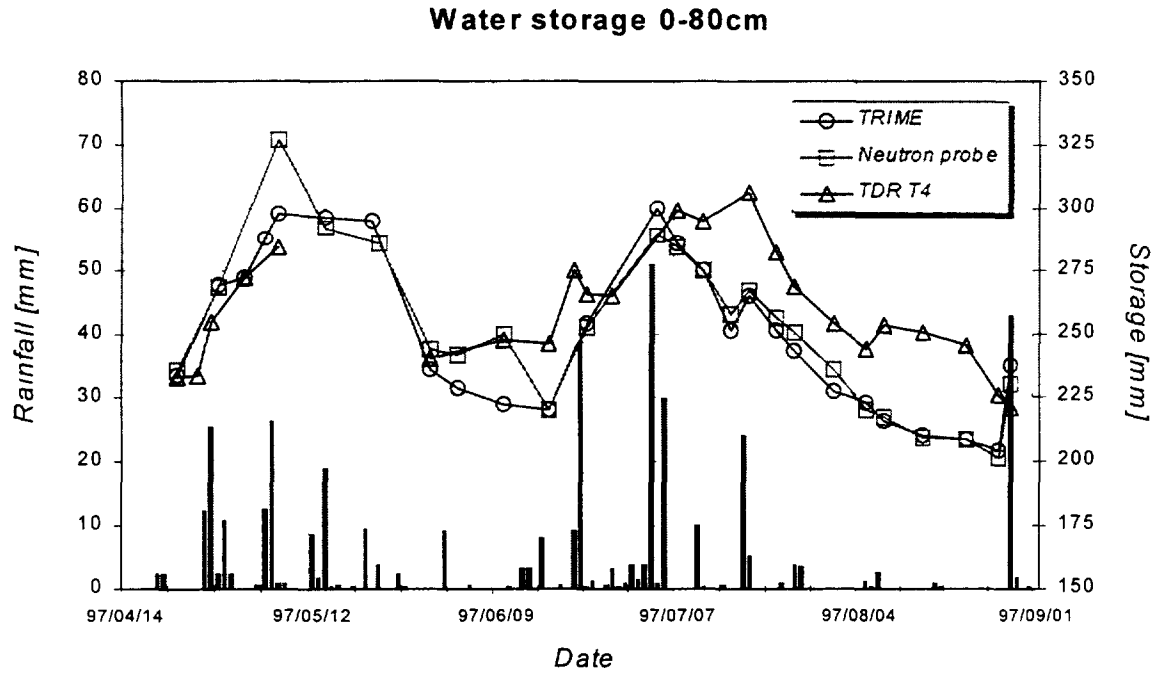

FIG 10 Water storage on the Campus site between 0 and 80 cm for the 21/4 to 1/9/97 period calculated from the water-contents profiles measured by i) the Trime , ii) the neutron probe , iii) TDR_SSI Daily rainfall in the same period

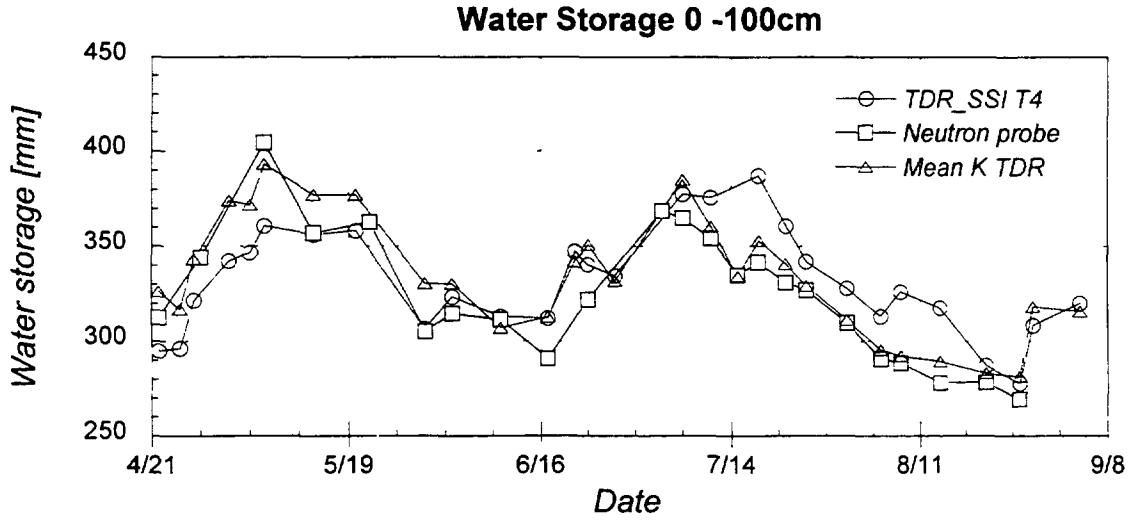

FIG 11 Water storage on the Campus site between 0 and 100 cm for the 21/4 to 1/9/97 period calculated by integration of the water-contents profiles measured by TDR_SSI on tube T4 or by neutron probe Comparison with the storage estimated from the mean water-content calculated by a classical TDR analysis

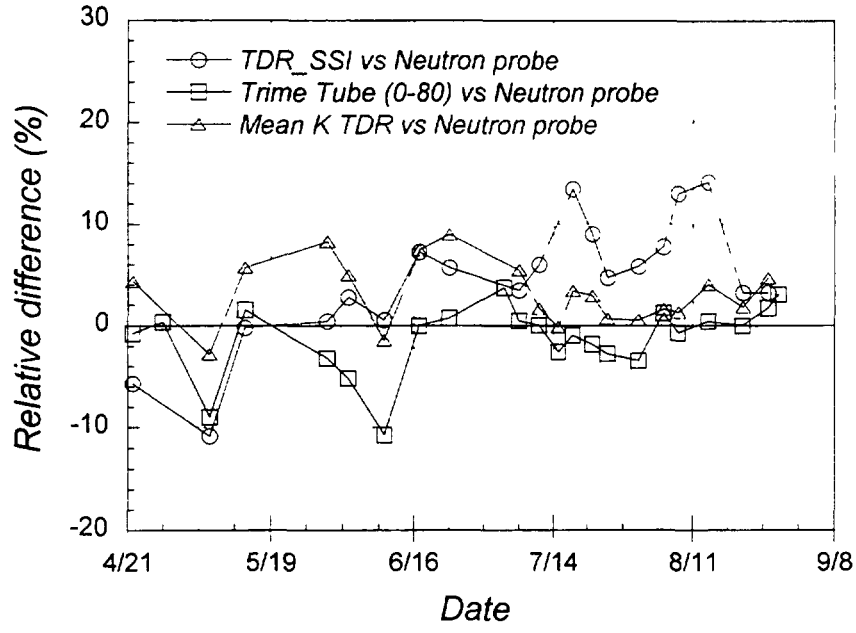

FIG. 12. Relative differences between evaluations of FIGS. 10 & 11.

5. CONCLUSION

Our results demonstrate that the Trime device can be effectively utilised to profile water content in soil, and the data can be used to calculate water balance with sufficient accuracy. In the same way, TDR-SSI appears to be an attractive method because of its simplicity and good resolution.

Nevertheless, severe limitations of these two methods have to be kept in mind.

5.1. Practical considerations

Introducing long plastic tubes or long parallel rods into soil is not always feasible, because of heterogeneity of the substrate. Moreover, to run TDR-SSI on twin-rod probes, the corresponding TDR signals should remain "useable," meaning that their amplitude must be related to soil impedance only, with no significant attenuation. This excludes situations where conduction into the soil is high because of solutes and/or high water saturation, for instance. We have addressed such cases [29, 40].

5.2. Theoretical considerations

To apply TDR-SSI, its main assumptions must be verified (Section 6). There are the already mentioned problems associated with attenuation, but, also, the scattering effect (i.e. variation of K with the frequency due to distribution or relaxation times in the medium). Furthermore, imperfect electronics (bad TDR generators, particularly) can be a source of error. Last but not least, calibration of the measured permittivity/water-content relationship is a general problem to be faced when running dielectric methods. This is particularly true for composite systems [probe + polymer + soil] like those created when using the Trime-tube technique [41, 42].

Despite the above points that will have to be addressed, we think that TDR can be regarded now as an operational method in soil physics for water-content profiling purposes. It has become a viable alternative to the neutron probe technique.

Expressing the contribution $d\Gamma$ of an impedance discontinuity dZ located at a distance z to the reflection coefficient Γ measured at the beginning of a line, Collin obtains:

$$\frac{d\Gamma}{dz} = 2j\beta\Gamma - \frac{1}{2}\left(1-\Gamma^2\right)\frac{d(\ln Z)}{dz} \qquad \text{(T, 1)}$$

where

j is $\sqrt{-1}$,
and β is the propagation constant, a function of z given by:

$$\beta(z) = \frac{\omega}{v(z)} = \frac{\omega}{c}\sqrt{K(z)} \qquad \text{(T, 2)}$$

where

ω is the pulsation (s^{-1}),
v is the propagation velocity (m s^{-1}),
c is the speed of light ($\approx 3.10^8$ m s^{-1}),
and $K(z)$ is the permittivity profile.

Equation (T2, 1) is a particular non-linear differential "Riccati equation." It has no analytical solution in the general case. To solve it, Collin, first, neglects the Γ^2 term ("small reflections" or "Rayleigh" assumption) and then introduces the following variable change:

$$\phi(z) = \int_0^z 2\beta(u)du \Rightarrow \frac{d\phi}{dz} = 2\beta(z) \qquad \text{(T, 3)}$$

which permits eliminating b and reducing (T, 1) to:

$$\frac{d\Gamma}{d\phi} = j\Gamma - \frac{1}{2}\frac{d(\ln Z)}{d\phi} \qquad \text{(T, 4)}$$

Integration of (T,4) yields:

$$\Gamma = -\frac{1}{2}\int_0^{\phi_L} e^{-j\phi}\frac{d(\ln Z)}{d\phi}d\phi \qquad \text{(T, 5)}$$

with :

$$\phi_L = \int_0^L 2\beta(u)du \qquad \text{(T, 6)}$$

where

L is the probe's length.

With a supplementary assumption of impedance adaptation at the probe ends, the above integration interval can be extended to [-∞, +∞] (T2, 5) becomes formally the Fourier's transformation of the function $\frac{d(\ln Z)}{d\phi}$. Consequently, its inverse can be written as follows:

$$2TF^{-1}[\Gamma] = \frac{d(\ln Z)}{d\phi} \qquad \text{(T, 7)}$$

where

TF^{-1} is the inverse Fourier's transformation.

Integrating this expression:

$$Z(\phi) = \exp\left[2\int^{\phi} TF^{-1}[\Gamma]du\right] \qquad \text{(T, 8)}$$

which can be used as the inverse of the measured reflection coefficient Γ (T, 8) giving the impedance profile in the space of the variable *f*. Hence, a supplementary operation has to be applied to come back to the space of the variable *z*. To do that (T, 2) is first combined with the expression of the wave-guide impedance when placed in a medium of permittivity *K*:

$$Z = \frac{Z_a}{\sqrt{K}} \qquad \text{(T, 9)}$$

where

Z_a is the characteristic impedance (Ω) of the probe that depends only on its geometry.

In this way, we get: $\frac{dz}{d\phi} = \frac{1}{2\beta} = \frac{c}{2\omega Z_a} Z$ that can be integrated over *L* and normalised to yield finally:

$$z(\phi) = \frac{\int^{\phi} Z du}{\int^{\phi_L} Z du} \qquad \text{(T,10)}$$

that associates a *z* to any *f*. The definition of the reflection coefficient Γ in (T, 8) is:

$$\Gamma = \frac{S(f)}{E(f)} = \frac{\mathrm{TF}[\rho(t)]}{\mathrm{TF}[e(t)]} \qquad \text{(T, 11)}$$

where

f is frequency (s^{-1}),
ρ is the output TDR signal in the time domain,
e is the input TDR signal in the time domain,
S is the equivalent of ρ in the frequency domain, using Fourier's transformation, denoted TF,
E is the equivalent of *e* in the frequency domain, using Fourier's transformation, denoted TF,
e(t) is the step delivered by the TDR generator,
and $\rho(t)$ is the measured TDR signal.

Using the property TF(g') = jwTF(g), ρ and e can be replaced in (T, 11) by their derivatives. Moreover, since $e(t)$ is normally close to a perfect step (fast rise time), $e'(t)$ is close to a Dirac pulse $d(t)$ in which TF is unity. Then (T, 11) becomes:

$$\Gamma = \frac{\mathrm{TF}[\rho'(t)]}{\mathrm{TF}[e'(t)]} \approx \frac{\mathrm{TF}[\rho'(t)]}{\mathrm{TF}[\delta(t)]} = \mathrm{TF}[\rho'(t)] \qquad \text{(T, 12)}$$

which, put into (T, 8), finally gives the simple expression used in TDR-SSI:

$$Z(t) = Z_c \exp[2\rho(t)] \qquad \text{(T, 13)}$$

where

Z_c is a reference impedance (Ω) for the circuit.

7. TDR-DEVICE MANUFACTURERS

List: http://iti.acns.nwu.edu/clear/tdr/tdr_eq_db.html

Campbell Scientific Ltd. *(sonde CS615)*
http://www.campbellsci.com/
80 Hathern Road, Shepshed, Leicestershire LE12 9RP, UK
Contact:
Andrew Sandford
(44) 0 1509 601141
(44) 0 1509 601091 FAX
E-mail: andrew@campbellsci.co.uk

E.S.I. Environmental Sensors Inc. *("Moisture point" system)*
http://www.esica.com/products/index.html
100 - 4243 Glanford Avenue, Victoria, B.C., Canada V8Z 4B9
Contact:
Michael Marek (North American inquiries)
Pierre Ballester (International inquiries)
(800) 799-6324 (US and Canada)
(250) 479-6588
(250) 479-1412 FAX
E-mail: mmarek@esica.com
and pballester@esica.com

IMKO GmBH *(TRIME)*
http://www.imko.de
http://www.alive.de/imko/trime-tube-com.htm
Im Stoeck 2D-76275, Ettlingen, Germany
Contact:
Robin Fundinger
(49) 7243-592110
(49) 7243-90856 FAX
E-mail: IMKO-GmbH@t-online.de

Soilmoisture Equipment Corp. *(Trase system)*
http://www.soilmoisture.com/
P.O. Box 30025, Santa Barbara, CA 93105
Contact:
Herb Fancher, Sales Manager
(805) 964-3525
(805) 683-2189 FAX
E-mail: sales@soilmoisture.com

Tektronix, Inc. *(1502B/C cable tester)*
http://www.tek.com/Measurement/Products/catalog/1503c/
625 SE Salmon Ave., P.O. Box 1197, Redmond, OR 97756-0227
Contact:
Rick Puckett
(503) 923-4446
(503) 627-8010 FAX
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MEASUREMENT OF SOIL WATER CONTENT USING TDR AND THE NEUTRON PROBE IN TILLAGE EXPERIMENTS IN SEMI-ARID SW SPAIN

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Abstract

Some examples of soil water content measurements using Time Domain Reflectrometry (TDR) and the neutron probe are presented in this paper. The data are from experiments on water recharge and water conservation in the soil profile under different tillage methods. TDR is a useful technique with which to follow changes of soil water content in the top soil layers. Under sunflower, measurements showed differences in soil water content within and between the plant rows. Measurements with the neutron probe showed changes of soil water content profile down to a depth of 2 m. Soil water profile recharge and water depletion by the sunflower crop were established from measurements with both techniques. The combined use of TDR and neutron probe is very appropriate to establish the soil water balance in such experiments.

1. INTRODUCTION

Increasing interest in the conservation of soil and water resources under rainfed conditions over the last two or three decades has prompted increased research on effects of different tillage systems on soil properties and crop development and yield. This interest in the conservation of soil and water has favoured the development of conservation tillage practices. Conservation tillage is a term covering a range of approaches that have, as a common characteristic, the potential to reduce soil and water loss compared with conventional tillage [1].

Effects of conservation tillage on crop yields have been extensively studied under various conditions of soil and climate. In contrast, there is limited information about its effects on soil physical properties [2] and water storage in the soil. This, together with the increase of process modelling of water balance in tillage experiments, has imposed a demand of accurate measurements of soil physical properties, particularly soil water content. The dependence of conservation tillage on the soil and climatic conditions [3] makes necessary the study of its effects on soil physical properties, water storage and depletion, and crops, for different areas of the world.

In semi-arid conditions, such as southern Spain, water availability is the most important limiting factor in rainfed agriculture. In soils of the Andalusian Plain, climatological conditions, characterized by the concentration of rainfall in the autumn-winter period, lead to replenishment of water storage capacity at the end of the winter. Subsequent shortage of precipitation and very high temperatures are responsible for the water depletion observed at the end of summer. Recently, Moreno et al. [4] showed in detail the effects of tillage methods on storage and conservation of water in the soil in southern Spain.

The objective of this paper is to present some examples of the change of soil water content under traditional and conservation-tillage management, determined using TDR and neutron probe.

2. MATERIAL AND METHODS

Field experiments were carried out on a sandy clay loam soil (Xerofluvent) at the experimental farm of the Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC) located 13 km southwest of the city of Seville. An area of about 2,500 m^2 was selected to establish the experimental plots. The area was divided into six plots each of approximately 300 m^2 (22 × 14 m). Two treatments were applied: traditional tillage (TT) used in the area for rainfed agriculture and conservation tillage (CT). Traditional tillage consisted mainly of mouldboard ploughing after burning the straw of the previous crop, and several passes with a cultivator and disc harrow. The conservation tillage was

characterized by not using mouldboard ploughing, chiseling once per year, by reduction of the number of tillage operations and leaving the crop residues on the surface as mulch. In both tillage treatments a wheat/sunflower (*Triticum aestivum*, L. / *Helianthus annuus*, L) rotation was established. More details can be found in a previous paper [4]. Three replications per treatment were used, distributed in random blocks.

Changes in soil moisture content due to water infiltration during the rainy period, and water depletion by crops, were monitored using a neutron probe and TDR. The neutron probe was a Troxler 3333. Two access tubes for the probe were installed in each individual plot of each treatment, to a depth of 2.3 m. Measurements were carried out at 0.1-m intervals, every 6–10 days during the crop seasons, and at variable intervals during the period when the soil was bare. Changes of water content in the surface layer (0–15 cm) were monitored by TDR with a Tektronix Model 1502C. The TDR waveguides comprised three parallel stainless rods, 2 mm in diameter and 0.15 m long. A portable computer was used to record and analyse the TDR wave-forms using an analysis similar to that of Baker and Allmaras [5]. The results shown in this paper correspond to the experimental period between 1995 and 1997.

3. RESULTS AND DISCUSSION

3.1. Soil water content and its depletion

Soil water content in the top soil layer (0–15 cm) was monitored with TDR in both tillage treatments (TT and CT) during the sunflower seasons of 1995 and 1997. The results for 1995 [4] are shown in Fig. 1. In that year, rainfall was much lower (245 mm) than the average (500 mm). From the beginning of the cropping season, the soil water content was significantly higher with CT than with TT. For the TT treatment, no differences in the soil water content were observed between the plant row and the central positions between rows. In contrast, for the CT treatment a different soil water content was observed between the two positions of measurement. This difference was maintained throughout the season, being maximum at 50 days after sowing. This can be due to both higher evaporation from the soil surface due to alteration during sowing, and higher water uptake by roots in the plant row position than in the centre between rows. During the sunflower season in 1997 the changes of soil water content (plant row position) in the top layer (0–15 cm) showed a similar pattern to that of 1995 (Fig. 2). These results clearly show that the CT treatment improved the storage and conservation of water in the surface layer of soil.

Figure 3 shows the changes of soil water content in the surface layer (0–15 cm) of the two tillage treatments during the wheat crop (1995–96). Due to the heavy rainfall from the beginning of November 1995 to the end of January 1996 (over 500 mm), the soil water content was not significantly different between treatments from the sowing date (27-11-95) to the end of March 1996 (123 days). From this date to harvesting, the soil water content was significantly higher in the CT than in the TT treatment.

The changes of water profile down to 2.3 m depth during the sunflower season in 1995 reported by Moreno et al. [4] are compared with the results obtained in 1997 (Fig. 4). In 1995 the water storage replenishment of the soil in the TT treatment took place down to 1 m depth only (Fig. 4a). In contrast, replenishment of the soil water profile in the CT treatment was observed down to 1.4 m (Fig. 4b). A few days before sowing (16-2-95), the water content of the soil layer 0–1.4 m was higher in the CT than in the TT treatment. It seems that the water recharge of the profile during the autumn and early in the winter (bare soil period) was more effective in the CT than in the TT treatment. These results showed that, under a situation with much lower rainfall than the average during autumn and winter, the CT treatment was able to recharge the profile much better than TT. The presence of residues of the preceding crop in the soil surface in the CT treatment seems to have been highly effective in enhancing water infiltration and water conservation under dry weather conditions, as has been reported by Unger et al. [6] among others.

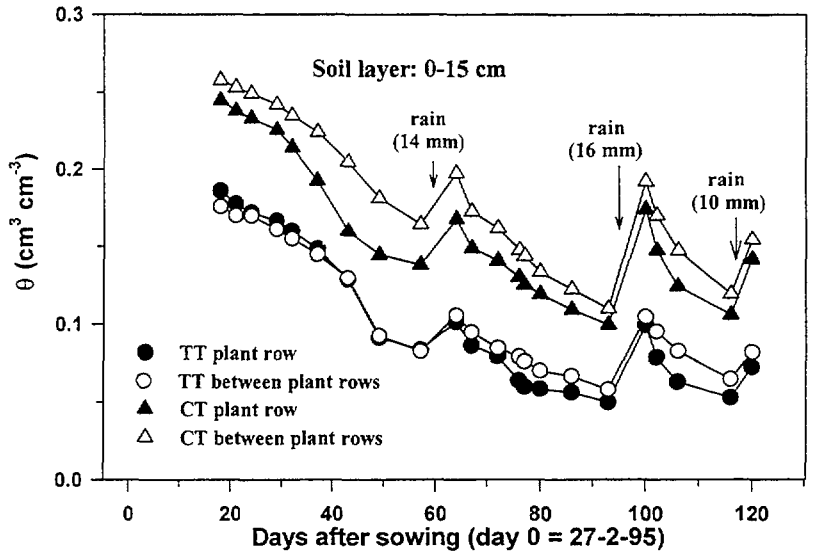

FIG. 1. Change of the soil water content in the soil layer 0–15 cm depth in traditional tillage (TT) and conservation tillage (CT) treatments during the sunflower crop season in 1995 (from Moreno et al. [4]).

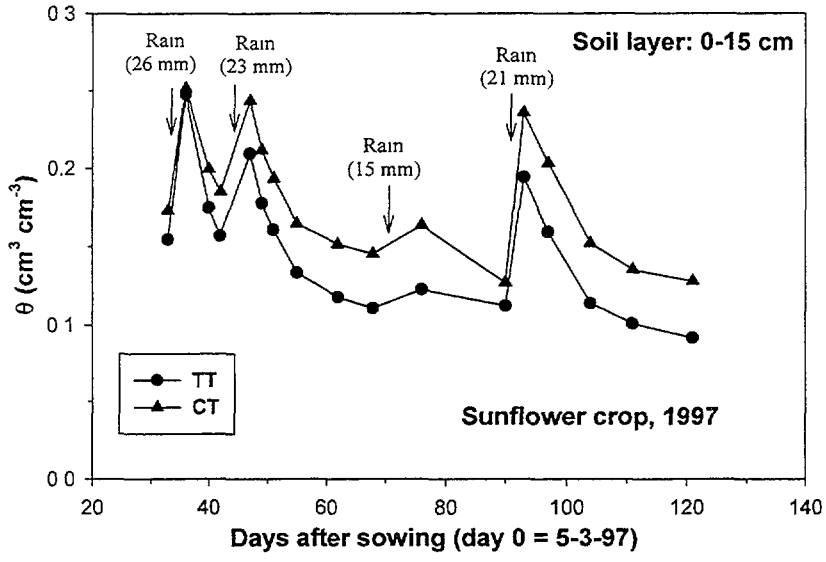

FIG. 2. Change of the soil water content in the soil layer 0–15 cm depth in traditional (TT) and conservation tillage (CT) treatments during the sunflower crop season in 1997.

During 1995, the sunflower depleted water down to 1 m and 1.6 m in the TT and CT treatments, respectively. In contrast, during 1997, a year with much higher rainfall than the average (the total amount of rainfall in the hydrological year September 1996–August 1997 was 718 mm), the water storage replenishment of the soil, some days before sowing the sunflower, was practically the same in the two tillage treatments (Fig. 4c, d). The water uptake by the crop during the growing period was also similar in the traditional tillage and the conservation tillage.

3.2. Crop yield

The yields of sunflower and wheat crops in the two tillage treatments are shown in Table I. The seed yield of sunflower in 1995 was significantly, and much, higher in the CT than in the TT treatment. This was due to the higher water storage in the former in a year with much lower than average precipitation. In contrast, the seed yield of sunflower in 1997, a year with much higher than average precipitation, was practically the same in the two tillage treatments.

The wheat crop grown in 1995–96 showed higher grain yield in the TT than in the CT treatment, but the difference was not significant.

4. CONCLUSIONS

From the results of our experiments we conclude that TDR is a practical tool to monitor changes of soil water content in the top soil layers. At the same time, is a method that allows a high number of replications in space and time.

In our experiments, the use of the neutron probe to follow the changes of soil water profile was successful.

The conservation tillage applied was highly effective in enhancing soil water recharge and water conservation, particularly in years with much lower than average precipitation.

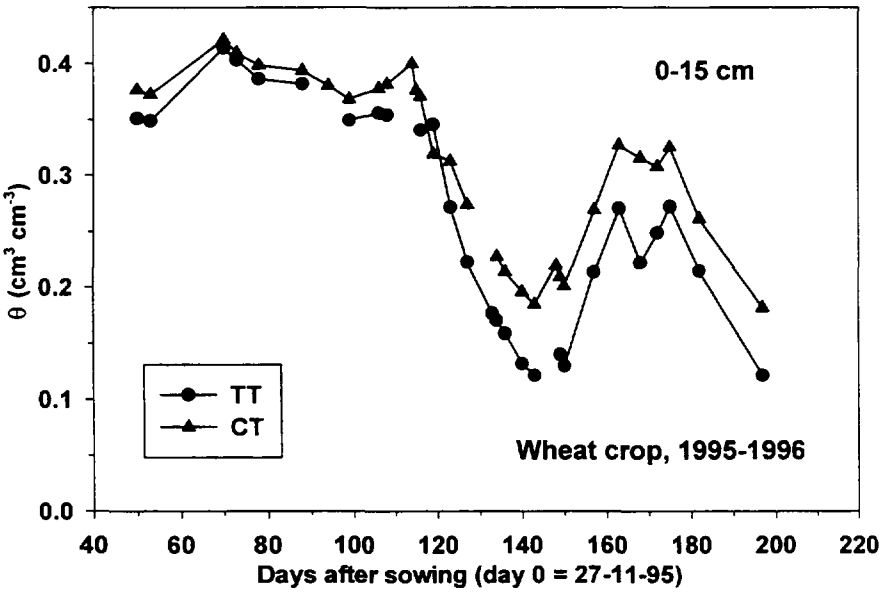

FIG. 3. Change of the soil water content in the soil layer 0–15 cm depth in traditional tillage (TT) and conservation tillage (CT) treatments during the wheat crop season in 1995–96.

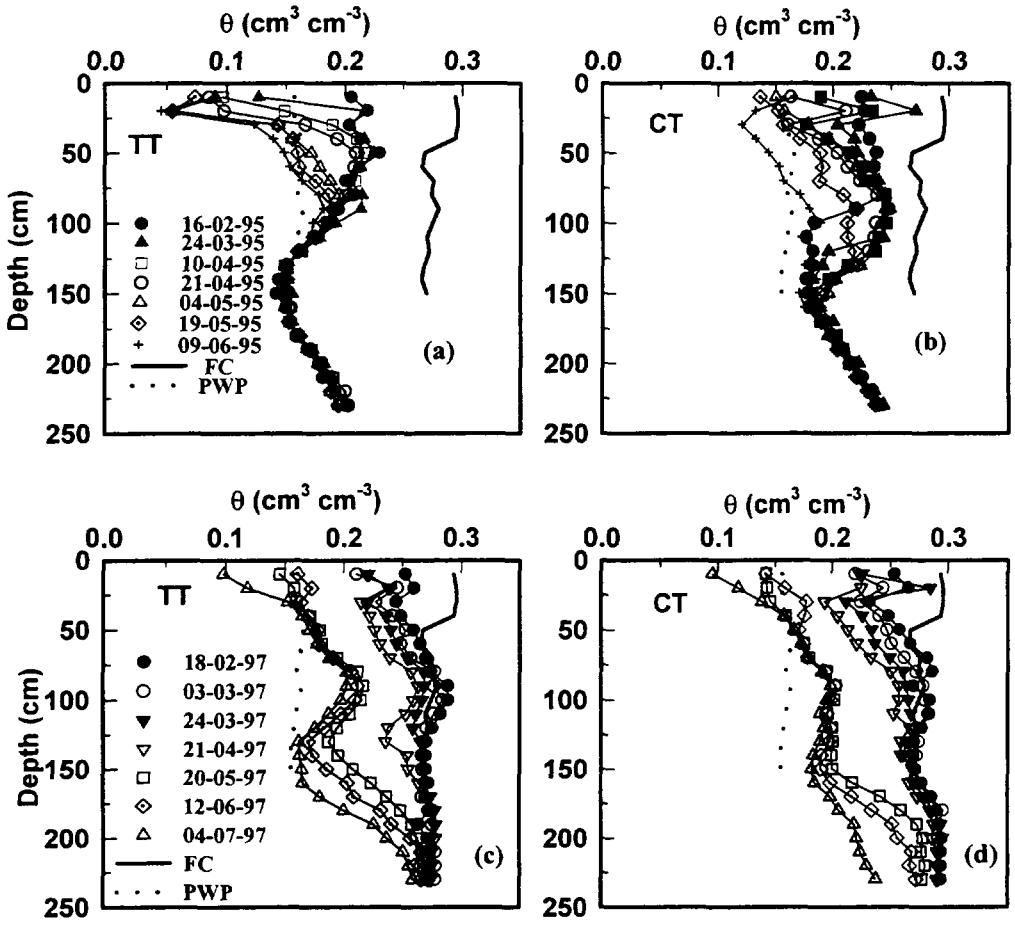

FIG. 4. Change of the water profile in traditional tillage (TT) and conservation tillage (CT) treatments: (a) and (b) during the sunflower crop season in 1995 (from Moreno et al. [4]); (c) and (d) during the sunflower crop season in 1997.

TABLE I. YIELD OF SUNFLOWER AND WHEAT CROPS UNDER TWO TILLAGE TREATMENTS

Tillage treatment	Sunflower		Wheat
	1995	1997	1995–96
		(kg ha^{-1})	
Traditional (TT)	473a[a]	3,467a	6,265a
Conservation (CT)	1,521b	3,447a	5,602a

[a]Values per columns followed by the same letter are not significantly different (P<0.05).

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MEASURING WATER CONTENT IN SOIL USING TDR: A STATE-OF-THE-ART IN 1998

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Abstract

Over the past decade or so, the development and continuing refinement of the time-domain reflectometry (TDR) technique for in-situ, nondestructive measurement of water content has revolutionized the study and management of the transfer and storage of water within the soil profile. The principles for the application of TDR to water content are now well accepted and straight forward. For many mineral soils, the calibration for water content has a linear relationship with the square root of the relative permittivity measured by TDR. This allows a two-point calibration. TDR-measured water content has been applied successfully to water balance studies ranging from the km scale of small watersheds to the mm scale of the root-soil interface. Soil probes can be designed to meet many and varied requirements. The performance of a number of probe geometries is presented, including some of their strengths and weaknesses. Although coated soil probes allow measurement in more conductive soils, the probe coatings alter the water-content calibration both in sensitivity and linearity. Three general options are available for determining profiles of soil water content from the soil surface to a depth of 1 m. Soil probes of differing total depths extending to the surface are the most accessible. Soil probes buried at selected depths provide easily repeatable values. The vertically installed single probe, with depth segments separated by diodes, allows repeated measurement in a single vertical slice. The portability of TDR instrumentation coupled with the simplicity and flexibility of probes has allowed the mapping of spatial patterns of water content and field-based spatial and temporal soil water content distributions. The usefulness and power of the TDR technique for characterizing soil water content is increasing rapidly through continuing improvements in instrument operating range, probe design, multiplexing and automated data collection.

1. INTRODUCTION

The use of dielectric techniques to determine water content of soil has increased greatly since the early application of high frequency methods to soil materials over thirty years ago [1]. The time domain reflectometry (TDR) technique was applied successfully to soil in the mid-seventies [2, 3]. Over the intervening twenty-five years, TDR has become widely accepted for the measurement of water content of soil, and more than ten companies are marketing instruments or components to measure soil water content based on the application of TDR. All of these make use of the unique electrical properties of water in a soil matrix. The TDR technique is electromagnetic and, as such, makes use of measurement techniques from the communications sector of society for which instrumentation has been developed with very good temporal and temperature stability. This provides for TDR a significant advantage over many other approaches.

Water, ionic solutes and air are vital inputs to the soil – as the basis of agricultural production of food, in the form of anthropologic contamination of the soil and near surface water, or as major factors in the mass and energy balances of the soil profile. In spite of their significance, only in the last 15 years has rapid, in-situ, nondestructive measurement of soil water content, ionic solute concentration and soil air content (indirectly) become possible in the form of TDR [4–6]. This radar-based technology has revolutionized our ability to characterize the storage and movement of water, solute and air in the soil profile [7]. With TDR, it is now practical to monitor simultaneously the soil water, ionic solutes and air (indirectly) in both space and time with high accuracy and relatively low equipment and labour costs. This capability, in turn, provides better evaluations of the impacts of agricultural practices on the soil-plant-atmosphere continuum.

This paper gives a brief overview of the operating principles of TDR, as well as a review of how it is used to measure water content in the soil profile. As the effective use and development of TDR depends critically on probe performance, we give a summary of probe-design developments and some of the important considerations that must be made when using TDR.

2. MEASUREMENTS

The high dielectric constant or relative permittivity of water (about 80) compared to those of the other soil components (1 for air, 2–5 for soil solids) makes determination of the relative permittivity an attractive way to measure water content. The TDR approach, which is a radar technique applied within the soil, is used to determine the soil's bulk relative permittivity. A fast rise step voltage pulse is propagated along a transmission line in the soil. The voltage pulse propagates as an electromagnetic (EM) wave, traveling in the soil and guided by the conductors of a probe, which may have a variety of configurations. The properties of the soil that govern the propagation of EM waves are expressed in terms of velocity, v (m s^{-1}), and attenuation, α (m^{-1}), which can be written as [8, 9]:

$$v = \frac{c}{\sqrt{\varepsilon_{ra}}} = \frac{2L}{t} \qquad \text{from which } \sqrt{\varepsilon_{ra}} = \frac{ct}{2L} \tag{1}$$

$$\alpha = \frac{60\pi(\omega\varepsilon_0\varepsilon_r'' + \sigma_0)}{\sqrt{\varepsilon_{ra}}} \tag{2}$$

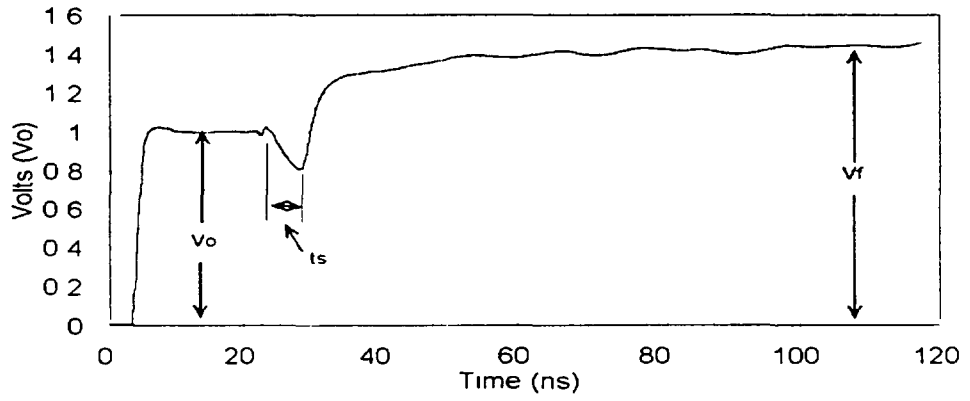
where

c is the velocity (m s^{-1}) of an EM wave in free space (vacuum),
ε_{ra} is the apparent relative permittivity (dimension-less) measured by TDR,
L is the length (m) of the transmission line (probe) in the soil,
t is travel time (s) of the EM wave along the probe,
ω is the frequency (rad s^{-1}) of the propagating wave,
ε''_r is the imaginary component of the relative permittivity,
σ_0 is the zero frequency (dc, S m^{-1}) electrical conductivity of the bulk soil,
and ε_0 is the permittivity of free space.

By applying Equations (1) and (2) sequentially, both water content and bulk electrical conductivity are determined by analyses of TDR traces (Fig. 1) [8, 9]. For TDR measurements in soil, ε''_r can be usually neglected without incurring large error [4, 9].

An empirical relationship between relative permittivity, ε_{ra}, and volumetric water content, θ was initially used for conversion of TDR data to θ [8]. A variety of researchers have confirmed that the "Topp equation" is quite broadly applicable to inorganic soils [6, 10]. Later improvements and refinements have made use of dielectric mixing formulae that require more prior knowledge of the soil properties, such as density, texture and/or organic matter content [11, 12]. From these analyses and related experimental work [10–13], it has been shown that $\sqrt{\varepsilon_{ra}}$ is essentially a linear function of the water content over the usual water-content range. From the assumption that the dielectric properties of the soil phases (solids, water and air) are additive, a further simplification of the calibration approach has been achieved where θ is related linearly to the travel time of the TDR signal [14–16]. The ratio of the TDR travel time in soil to that measured in air, t/t_{air}, is equivalent to $\sqrt{\varepsilon_{ra}}$,which means that calibrations for water-content measurements in mineral soil can be developed from as few as two measurements. For organic soil, there is some nonlinearity at high water contents.

The use of TDR for electrical conductivity measurements developed rapidly after its introduction [4, 8, 17]. The approaches now in use to convert TDR data to electrical conductivity, σ_0, are equivalent to that of Giese and Tiemann [9, 18–21]. This approach depends on a knowledge of the characteristic impedance of the TDR probe, Z_0, output impedance of the TDR instrument, Z_t and impedance or voltage measurements from the TDR waveform (Fig. 1). This analysis is often applied for rapid electrical conductivity measurement during solute transport experiments, and for the determination of mass flux of solute.



For 0 2 m length probe. t_{air} = 1 33 ns, Z_0 = 228 ohms

$$\theta = 0.115\frac{t_s}{t_{air}} - 0.176 = 0.34 \qquad \sigma_0 = \frac{\epsilon_0 c}{L}\frac{Z_0}{Z_t}\left(\frac{2V_0}{V_f} - 1\right) = 0.0234\ S\ m^{-1}$$

FIG. 1. A representative TDR trace showing how the travel time, t_s, is determined for water content, θ calculations. Also V_0 and V_f are given for the calculation of bulk conductivity, σ_0. The other symbols are defined in the text (after [7])

3. MASS BALANCE AND MONITORING WATER CONTENT USING TDR

TDR serves effectively for monitoring hydrological water balance, measuring agricultural or forest water use efficiency, and monitoring changes in water content for irrigation scheduling. This type of monitoring requires rapid, reproducible recovery of data from a number of representative locations, requirements that led to the development of automated analyses of the TDR trace for water content [6, 15, 19, 22–24]. Associated with this automation was the development of multiplexing, or switching capabilities that allow periodic monitoring of water content at multiple locations by a single TDR instrument. A number of custom systems have been developed and used in recent years [15, 19, 22, 23, 25]. Most commercial TDR-based instruments now offer automated water content analysis as a part of the basic instrument with the multiplexing capability as an option.

TDR for monitoring water content must be approached in relation to three different scales of measurement:

- Point or near point (i.e. regions within 1 m and/or within a soil profile) with replication and real-time continuous data recovery,
- Spatial replication at tens of metres (up to 100 m) with real-time continuous data recovery,
- Spatial replication >100 m.

The first two are currently available using an appropriate TDR instrument, multiplexers and probes. Instruments measuring over separations greater than 25 m between instrument and probe require better-quality cables and give rise to associated cost increases. At the present time, the third option would require separate instruments for widely spaced locations or the loss of real-time possibilities for data retrieval. Intermittent sampling would be dependent on operator availability [26].

Field water balance studies using TDR have been carried out at differing scales, referenced to rain gauges, weighing lysimeters and Bowen ratio mass balances [6, 15, 27]. Over a one-year period, in a forested plot, Herkelrath et al. [15] measured the water budget using vertically installed 50-cm-long TDR probes. They found excellent concurrence for the timing of rainfall events with only a 13% discrepancy between TDR and precipitation gauge. Using TDR (0- to 0.8-m deep probes) and weighing lysimeter (0- to 2.0-m deep) in a wheat field, Zegelin et al. [6] compared the changes in stored water for two periods, one of 6 days involving wetting and drying cycles and the other of 16 days involving depletion by evapotranspiration. The amounts of wetting and drying were similar for both techniques with an average deviation of less than 10% in both periods. Changes in TDR-measured soil water storage below a turfgrass cover showed excellent temporal coincidence and response times with those measured by weighing lysimeter [28]. During daily irrigation of the turfgrass, the TDR probes underestimated the amount of water added and lost, but this was probably due to the daily storage and loss of water from within the surface thatch of the turfgrass for which the TDR could not account. By contrast, during an unirrigated 6-day interval, the TDR probes were able to measure the water loss, with the longest probes recording 96% of the lysimeter-measured loss. Water exchange between soil and atmosphere was measured by TDR and verified intermittently by weighing microlysimeters, and by Bowen ratio and rain gauges [29]. For bare soil, the 21-day water balance for these systems was in agreement to within 10% when drainage beyond the TDR probe depth was taken into account.

In addition to total mass transfers, TDR has been used to indicate the distribution of water extraction with depth. Using vertical probes of differing length, Young et al. [28] characterized the increasing amounts of water being taken up from deeper layers as the soil dried during the 6-d drying interval. Zegelin et al. [6] compared hourly water content changes measured using TDR, lysimeter, and Bowen ratio techniques over a 12-h period. The TDR-measured soil-water losses agreed very well with those of the other two techniques until 11:00 h, after which the results diverged. A plausible interpretation is that the wheat extracted water from depths below 0.8 m while the evaporative demand was low, i.e. before 11:00 h, and used deeper roots to extract water after this time, which was not detected by the 0.8-m length TDR probes.

Although plant roots have been recently identified as responsible for over half of the water transfer and much of the chemical relocation within the soil profile, their effects are often neglected in water and solute transport studies [30]. Clothier and Green [30] have shown examples of how TDR is one of several emerging technologies being used to overcome the neglect of roots as agents of mass and energy transfer in soil [26, 31, 32].

Lateral spatial variability of water content is a common occurrence that may arise from soil factors such as topography, texture, and structure, as well as from crop factors. Attempts to characterize such variability are relatively recent. For example, Van Wesenbeeck and Kachanoski [27] installed a hundred TDR probes to a depth of 20 cm in an equally spaced linear array across twenty-five maize rows and over a depth of 0 to 20 cm. In addition to showing the distributing effects of leaf and stem flow on rainfall infiltration (Table I) and subsequent water uptake by roots, they further calculated an average TDR-measured soil water recharge of 7.9 mm, which differed by only 5% from the 8.2 mm recharge measured by rain gauge.

TABLE I. MEAN SOIL WATER RECHARGE FROM 8.2 mm RAINFALL ON DAY 220 (FROM [27])

Sampling location	Soil water storage		
	1h before rainfall, S_i	0.5h after rainfall, S_f	Recharge, $S_f - S_i$
	(mm)		
Row	54.2	64.4	10.2a[a]
Quarter row	52.4	60.3	7.9b
Inter-row	55.8	61.4	5.6c

[a]Values in the same column with the same letters are not significantly different ($P<0.05$).

After cutting grass hay in late summer, we made TDR measurements with repeated insertions to a depth of 0.15 m using a portable probe similar to that described by Topp et al. [33]. From 750 locations on a 10 × 10 m grid, a mean water content of 0.236 ± 0.024 m^3 m^{-3} and ranging from 0.16 to 0.32 was recorded [34]. In spite of apparently uniform cropping practices and nearly level topography (<0.5 m elevation difference over 7.44 ha), a distinct spatial pattern emerged (Fig. 2). As we have found less variability during wetter spring conditions, this spatial variation at the end of a growing season includes effects of spatially variable losses (e.g water use and drainage).

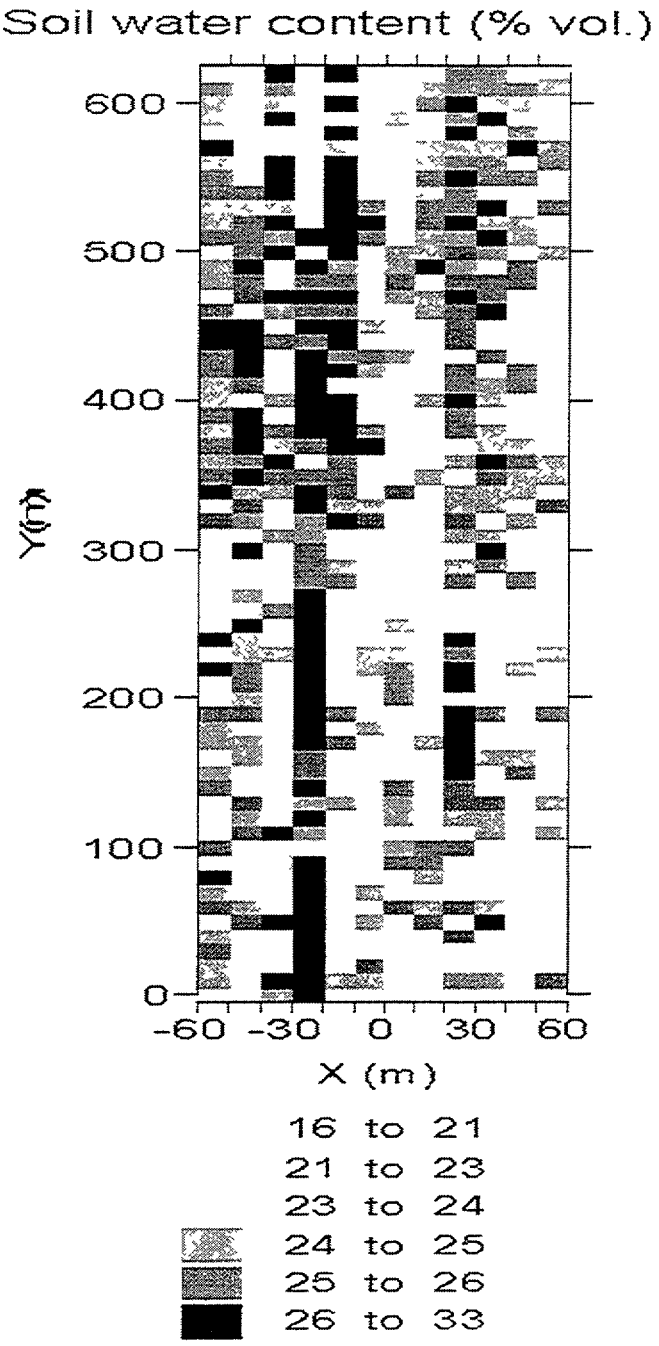


FIG 2 The spatial pattern of soil water content in the 0-15 cm depth range of a 7 44 ha level, clay loam field after cutting hay

With TDR, it is now possible to determine hydrological balances more effectively and efficiently, and obtain spatial and temporal details of water content that were not feasible a decade ago.

4. DEVELOPMENTS IN PROBE DESIGN

The initial laboratory research made use of coaxial transmission lines varying in length from 0.1 to 1 m, with diameters in the range of 0.03 to 0.08 m [8]. Although the coaxial configuration was electrically well defined, it was unsatisfactory for field use. The TDR measurement process interfered with the natural exchange of water between the measured soil and its surroundings. The balanced pair transmission line, consisting of two parallel rods, soon became the probe of choice for use in field measurements. These probes were shown to measure the correct, length-weighted average water content along their length, even in the presence of sharp wetting fronts [35]. Dalton [4], Patterson and Smith [36] and Zegelin et al. [19] have discussed various criteria and related probe configurations for their application. The most critical design component for accurate water-content determination is probe length. Excessive conductive loss, extinguishing the reflection from the rod ends [36, 37], and the increased potential for relaxation losses with increased length [38, 39] limit the maximum useable length. The minimum length is determined by the precision of the measurement system. Very short (2.5 to 7.5 cm), gold-plated probes were used successfully with a specially designed, wide-band instrument [40]. However, there is no convincing published evidence that probes shorter than 10 cm in length measured using standard cable testers can produce consistent, reliable waveforms [41–43]. In general, the measurement error is inversely related to the rod length [44]. A further concern for short rods involves the effects of fringing fields beyond the ends of the rods. "Zero mechanical length" probes, terminated at the ground surface, have been shown to measure the physical properties in the underlying soil [45]. These probes have an effective length greater than their physical length. It is reasonable to expect that parallel-rod TDR probes have some sensitivity beyond the probe ends as well, and that this additional length becomes more significant for shorter probes.

It has been customary to use impedance matching transformers between the balanced line in the soil and the unbalanced line from the TDR instrument. These were given the name balun, implying the matching role between balanced and unbalanced signals. Early results showed that the balun improved the signal transmission to and from the soil, giving better measures of the water content. Initial measurements of the electrical conductivity of soils failed to include the influence of the balun in the calculation. More recently, Spaans and Baker [46] developed baluns to overcome the problem of signal attenuation by the balun. Ledieu et al. [14] cite DeClerk [47] as showing that a balun was not necessary to connect a coaxial transmission line to a twin-rod probe. However, baluns continued to be used for most twin-rod applications until recently [41, 48–50]. Dasberg and Hopmans [51] compared the water-content response of two- and three-rod probes. Hook and Livingston [49] did not find any clear difference in the frequency content of two- and three-rod probes connected to a 75-Ω coaxial transmission line without a balun.

Zegelin et al. [19] introduced the multi-wire probe that emulates a coaxial transmission line. In its simplest form, three parallel conductors form a plane. The centre wire acts as the "centre" conductor and the outer two as the "shield" of the simulated coaxial line. These probes offer the advantage of improved impedance matching between the usual coaxial output of TDR instruments and the line in the soil being measured. Except that one additional rod or wire has to be inserted in the soil for measurement, these three-pronged probes have proven quite successful for measurement of both water content and electrical conductivity.

As with any measurement technique, it is important to ensure that the installation of TDR probes cause as little disturbance to the medium as possible. Topp et al. [52] examined the effects of inserting the rods directly into the ground or into predrilled pilot holes, finding no difference in the measured water contents. An x-ray computed tomography investigation [53] clearly showed compression due to rod installation; this disturbance was minimized by predrilling pilot holes. Balancing this concern with

the errors introduced by air gaps around the rods [54–56], it appears that pilot holes may be justified in highly compressible soils or for large-diameter rods. For routine application, especially for measurements of the spatial distribution of water content on the field scale, the added effort of drilling pilot holes is not justified. In addition to the need to ensure intimate contact of the sides of the rods with the soil, gaps beyond the end of the rods have been shown to affect the measured relative dielectric permittivity [57]. Therefore, if pilot holes are used, they should not extend as far as the ends of the rods.

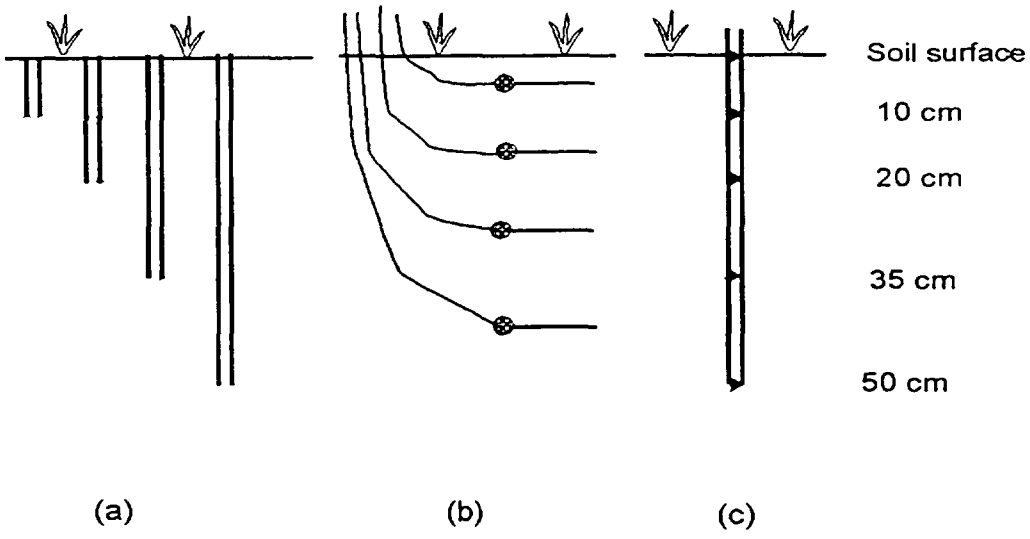


FIG. 3. Three options for measuring water content profiles, using different probe designs and configurations.

Oftentimes, the soil properties causing signal attenuation limit the maximum probe length. Applying resistive coatings to the rods can minimize these losses. The first published example of measuring the water content with coated rods was presented by Topp et al. [52]. However, this use was not directed at minimizing conductive losses. Coatings had come into general use when Kelly et al. [40], in an examination of the use of a wide-band instrument, found better results using Teflon coatings than epoxy or PVC heat-shrink coatings. Ferré et al. [55] presented an analytical description of the behavior of coated rods. Their analysis extended the work of Annan [54] to show that coated rods do not measure the arithmetic average of the dielectric permittivities of the coatings and the surrounding medium. Because common coating materials have low dielectric permittivities, coated rods are more sensitive to low water contents than to higher water contents. One result of this variable sensitivity is that, unlike uncoated rods, coated rods do not measure the correct length-weighted average water content along their length if the water content varies along their length. Therefore, probes that measure water content through coatings should be installed in a manner that minimizes water content throughout their sample volume.

One of the great advantages of uncoated TDR rods is their ability to measure the correct average water content over their length. This is especially useful for measurements of the total water depth of soil, such as for hydrologic balances. However, this limits the ability of TDR to measure the water-content profile. If vertical water-content gradients are desired, a series of probes can be buried at different depths (Fig 3b), or probes extending to differing depths (Fig. 3a) can be used and differencing the water contents of two adjacent depths gives the water content of the nonoverlapping depth interval [58]. Topp [58] described the error considerations applicable to these approaches. Similarly, Lundberg [59] designed a ladder-type horizontal rod probe that was left on the ground surface, snowed-in over the winter, and used to measure the unfrozen water-content profile of the snow pack. Davis and Chudobiak

[3] presented the first probe designed to be installed without excavation to measure the water-content profile. This probe included changes in the diameter of the rods along their length to produce a series of reflections; the travel times to any pair of discontinuities can be used to calculate the water content of the intervening soil interval. To alleviate the problem of air gaps forming around the smaller diameter intervals, a dielectric coating was placed around these sections to produce rods of uniform outer diameter along their length [52]. This probe was later shown to produce water-content profiles that compare well with horizontally installed parallel rods [60]. Multiple reflections and attenuation due to the discontinuities limited the number of depth intervals that could be measured accurately with this probe. A further advance alleviated the problem of multiple reflections with the use of electrically shorted diodes [61]. These probes include diodes embedded in a plastic probe body placed between two or three metal rods (Fig. 3c). Each of a sequence of diodes can be shorted individually. The points of divergence of the superposed unshorted and shorted waveforms define the travel times between the diodes at either end of a probe segment. This allows for the determination of the average water contents along each segment by systematically shorting the diodes in pair sequences from the ground surface, from which a profile can be developed to each diode depth. These probes allow for very accurate determination of the water-content profile [62] and are the only probes that can make automated water-content profile measurements, but the number of depth intervals is practically limited by the cost of probe production. Finally, Ferré et al. [50] designed a profiling probe that measures the water content through two parallel access tubes. Large diameter target rods, connected to the transmission line by smaller diameter wires, are lowered to the measurement depth. These probes allow for water-content measurement over any depth interval within the tubes. However, they require manual placement of the probes and face the same limitations as other coated-rod probes.

Given the restrictions on the minimum lengths of TDR probes, vertically installed rods cannot measure the water content very near the ground surface. Horizontally installed rods can be used to measure the water content near the ground surface. Petersen et al. [63] showed how close to the surface these rods, placed in either the horizontal or the vertical plane, can be located before they are adversely affected by the air/ground interface. Schneebeli et al. [64] used horizontal rods glued to the surface of a rock core to measure the water content. Using analytical descriptions, Maheshwarla and Venkatasubramanian [65] estimated the response of parallel rods placed on the surface of cores and bore holes. Selker et al. [66] designed a probe including parallel rods embedded in a plastic probe body. The probe was placed on the ground surface, measuring some average of the relative dielectric permittivity of the probe body and the near-surface soil. To increase the effective length of the probe, they laid the rods on the block in a serpentine pattern. Previously, Kachanoski et al. [67] showed that the travel time along smoothly curved rods corresponded to the physical rod length. However, it is not clear whether the same is true for sharply bent rods of the surface probe presented by Selker et al. [66].

The simplicity of the parallel-rod TDR probe makes it attractive for combination with other sensors. Early attempts recognized the advantages of combining TDR with a thermal conductivity probe embedded in one of two rods [68]. A recent modification of this probe used a heating coil in a three-rod design [69]; the measured water content was not affected by the application of the heat pulse. Furthermore, given that the heat probe instrumentation is embedded within the rods, there is no reason to expect that this addition will change the response of the probes. Two designs aimed at combining TDR with tensiometers: one attaching a porous stainless steel tip to the end of one of two rods [70], the other attaching a porous section to, or within, one of three rods [71, 72]. There were no effects of the porous segment on the TDR waveforms. Two concerns with these probes must be addressed. Firstly, is the water in the porous segment being measured as part of the soil water, and secondly, is the water in the porous segment affecting the water in the soil. The design of Topp et al. [71] minimizes the possibility of these complications. The future promises many exciting developments from experience with TDR. For example, we are coupling TDR measurements of water content with cone penetrometery for measurement of soil strength. Figure 4 shows the probe configuration on the left and on the right, an example of profiles of cone resistance and water content.

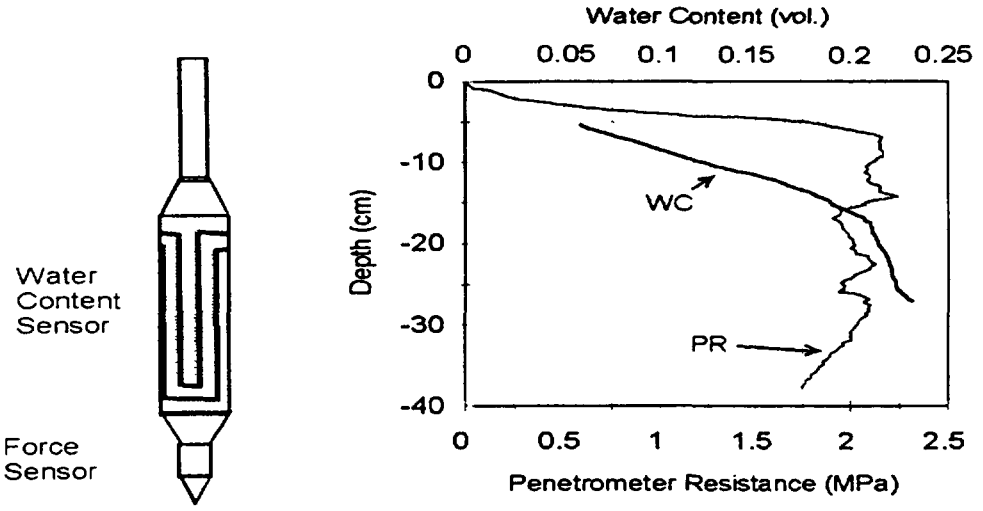


FIG. 4. A soil probe which combines the TDR for water content with a cone penetrometer to measure cone resistance (strength). An example of field-measured profiles is displayed.

5. SPATIAL SENSITIVITY OF TDR PROBES

The volume of soil measured by a TDR probe and the sensitivity of the measurement to the spatial distribution of the soil's dielectric permittivity has been recognized as key to adequate interpretation of TDR measurements. Experimental and theoretical analyses have demonstrated that the distribution along the length of a probe has an effect that is represented by a linear-weighted average [14–16, 35, 73]. For the lateral distribution, the situation is more complex. Zegelin et al. [19] used an approximate calculation of the electric field around transmission-line probes to illustrate the sensitivity of embedded transmission lines to the dielectric surrounding the probe wires. They recognized that contours of electric potential do not tell how a TDR measurement averages the spatial distribution of apparent permittivity of a material in which the probe is immersed. Baker and Lascano [74] used known placements of water-filled tubes to map the spatial sensitivity and weighting in the plane perpendicular to parallel pair transmission line probes. Knight [75] and Knight et al. [76] examined theoretically the spatial weighting function for parallel pair and multi-wire "coaxial" probes inserted in a medium of nearly uniform permittivity. Using small variations in water content, they were able to show that the weighting function is proportional to the distribution of electric energy, that is, to the square of the gradient of the electric potential around the probes. Analytic expressions for the two-dimensional weighting functions were derived for these probes and other similar geometries.

From these analytical expressions Knight [75] showed that the ratio of the wire spacing to the wire diameter in a transmission line is an important geometric descriptor of all TDR probes, and should be considered for design and installation purposes. The scaled spatial sensitivity of thin, closely spaced wires may be identical to that of thick wires spaced further apart, but additional factors need to be considered. Ease of insertion and minimizing soil disturbance suggest that probe wires should have as small a diameter as possible. In contrast, the effects of air gaps, measurement volume and the mechanical strength of soil require probe wires of larger diameters. Knight [75] proposed that the ratio of wire spacing to wire diameter should not exceed 10 and White et al. [13] reasoned that the wire diameter should be at least ten times the representative pore size or particle diameter to provide sensible averages.

One important finding of this analytical investigation is that the sample volume of TDR is independent of the water content of the medium. In contrast, the sample volume of a neutron probe decreases with increasing water content [77]. Petersen et al.[63] provide experimental evidence confirming the applicability of these results.

Dowding et al. [78] applied finite element numerical modeling to define the capacitance that would be measured by coaxial probes following deformations of the outer shield. Knight et al. [56] and Ferré et al. [79] applied a numerical analysis to the response of parallel-rod probes embedded in a porous medium. This numerical approach allowed for the investigation of heterogeneous distributions of dielectric permittivities in the transverse plane. One aspect of this work was the definition of sample areas in the transverse plane that are not limited to predefined shapes, allowing for a more realistic description of the lateral sensitivity of different probe configurations. Another result is the discovery that the sample area of coated-rod probes varies with the water content of the medium, decreasing sharply with increasing moisture. Finally, the results show that partial air gaps, surrounding only a fraction of the probe perimeter, do not adversely affect the measured relative dielectric permittivity. Given the simplicity of application, the analytical treatment of Knight [75] is most appropriate when designing uncoated probes for use in columns or near the ground surface to ensure that the sample area of the probe is confined to the medium of interest. The numerical analyses of Knight et al. [56] and Ferré et al. [79] are more appropriate in the design of alternative probes when attempting to maximize their sample areas and to minimize the dependence of the sample area on the water content of the medium.

6. SUMMARY AND CONCLUSIONS

The development of TDR has greatly enhanced our ability to measure and monitor the storage and movement of water in the crop-root zone and beyond. Hydrological mass balance estimates have shown TDR comparable to weighing lysimeters, Bowen ratio and rain gauges, but with an improved response time and greater operational flexibility, especially improved spatial sampling options. The choice of probe type and distribution of measurement location allows mapping both lateral and vertical distribution patterns of water content with TDR. As TDR is an electromagnetic technique there is available a body of knowledge that describes well the response characteristics of an assortment of probes. The flexibility in probe design possibilities allows one to develop a TDR measurement system that meets the requirements of a wide variety of field applications.

The importance of TDR alone or in combination with other techniques has only begun to be realized. The use of TDR should increase significantly as continuing developments in instrumentation both reduce the instrument costs and increase the flexibility and applicability of the technique. In addition, high frequency electromagnetic instruments, based on principles learned from TDR applications, are appearing on the market. Such approaches offer less flexibility, but have the advantage of lower cost. Their validity is not yet clearly established, however. Continued development of TDR and related "spin off" techniques such as high frequency methods will undoubtedly contribute substantially to our understanding and exploitation of water content and its transfer in soil.

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SOIL WATER STATUS UNDER PERENNIAL AND ANNUAL PASTURES ON AN ACID DUPLEX SOIL

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Abstract

A comprehensive field study of soil water balance, nitrogen (N) cycling, pasture management and animal production was carried out on an acid duplex soil at Book Book near Wagga Wagga in southern New South Wales. The experiment, carried out over a 3-year period, tested the hypothesis that sown perennial grass pastures improve the sustainability of a grazing system through better use of water and N. The treatments were: annual pastures without lime (AP-), annual pastures with lime (AP+), perennial pastures without lime (PP-) and perennial pastures with lime (PP+). Soil water measurement was made using a neutron probe on one set of the treatments comprising four adjacent paddocks. Over three winter and spring periods, the results showed that perennial grass pastures, especially PP+, consistently extracted about 40 mm more soil water each year than did the annual grass pastures. As a result, surface runoff, sub-surface flow and deep drainage (percolation below 180 cm depth) were about 40 mm less from the perennial pastures. The soil water status of the four pasture treatments was simulated reasonably well using a simple soil water model. Together with the long-term simulation of deep drainage, using past meteorological records, it is shown that proper management of perennial pastures can reduce recharge to groundwater and make pastoral systems more sustainable in the high rainfall zone. However, to completely reduce recharge, more-deeply rooted plants or trees are needed.

1. INTRODUCTION

The southeastern part of Australia is important for meat production, accounting for nearly 50% of the nation's cattle and sheep output. However, surveys show that much of the pasture base in the high rainfall zone (HRZ) (>600 mm per annum) is in a degraded condition. This is due to the replacement of native perennial summer-active species by exotic annuals that are generally winter-active and shallow-rooted. The change in land use and shift in physiological function have contributed to the degradation, notably by accelerating soil acidification and dry-land salinization, which not only reduce productivity but also threaten sustainability of agriculture in the region.

Greater storage of sub-soil moisture, as a result of incomplete use of seasonal rainfall by annual pastures under rain-fed agriculture, has augmented deep drainage and consequent recharge to groundwater. Rising water tables have been widely reported on the western and northern slopes of the Great Dividing Range (GDR) in New South Wales (NSW) and Victoria in the HRZ and drier areas. Further, with the increased N inputs and N cycling in grazed subterranean clover-based pastures, more mineral N accumulates in the soil profiles at the end of the usually dry summers. The combination of enhanced nitrification and leaching of NO_3^- ions (accompanied by cations) in the wet autumns and winters has led to an increase in soil acidity, especially in the surface layers (A horizon) of the duplex soils that predominate in the region. Thus, increased nitrate leaching has added to the acid inputs associated with an increase in soil organic matter under "improved" pastures and the removal of C and N in animal and plant products.

In Australia, the total area of acid soils (defined as having a pH in 0.01 *M* $CaCl_2$ <4.8) is approximately 24 Mha, with some 14 Mha in NSW and Victoria, much of which is on the western and northern slopes of the GDR in the Murray-Darling Basin. Production losses exceed $134 million per annum, with estimates for NSW at approximately $100 million (see [1]). These figures do not include costs of amelioration through the application of lime, which, at an average rate of 2.5 t ha^{-1}, can amount to as much as $40 ha^{-1} $year^{-1}$ when amortised over 5 years. Accelerated soil acidification is,

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therefore, a widespread problem in the HRZ, but is not of great concern to landholders partly because it has no strikingly visible effects and partly because one of the main strategies to combat it has been to select increasingly tolerant species. However, the use of acid-tolerant species is not a long-term solution to the problem, which is expressed through decreased productivity and reduced versatility in land use.

The overall hypothesis of the Temperate Pastures Sustainability Key Program (TPSKP) was that it is practical to use grazing management and other low-cost inputs to achieve and maintain a pasture that is both more productive and more sustainable than current, degraded pastures. Sustainability studies of TPSKP were based on the premise that sown perennial grass pastures, with a longer growing season and deeper root system than common annual pastures, can improve the sustainability of the grazing system through better utilization of soil water and N, and can reduce recharge to groundwater and minimize nitrate losses from the soil. To test the "sustainability" hypotheses, a comprehensive field study on soil water, N cycling and pasture management was carried out at Book Book, near Wagga Wagga in NSW.

2. OBJECTIVES

The objectives of the project were to quantify:

- The components of the water balance,
- The major nutrient (N) pool sizes,
- Turnover rates and pathways by which nutrients (N) leak from the system,
- Soil and pasture properties that have potential as indicators of sustainability.

A summary of this work will be published elsewhere [2], only the soil water component is given here.

The experimental site is situated in the upper Kyeamba Valley, near Book Book in southeast NSW. The topography is undulating, and the soil is a red podzolic duplex, with the depth to the B horizon varying between 20 and 60 cm. The profile description of the soils is also given elsewhere [2]. The average annual rainfall of the region is approximately 650 mm.

2.1. Experimental design

Figure 1 shows the plan of the experiment site. Sixteen 0.135-ha (30×45 m) permanent pasture paddocks were chosen within the eighty paddocks of the MASTER experiment (Managing Acid Soils Through Efficient Rotations), set up by Dr K. Helyar in 1992. They represent the following four treatments: annual pastures without lime (AP-), annual pastures with lime (AP+), perennial pastures without lime (PP-) and perennial pastures with lime (PP+). Each treatment was replicated four times.

The perennial pasture contained sown species phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*), subterranean clover (*Trifolium subterraneum*) and volunteer species such as annual ryegrass (*Lolium rigidum*) and broadleaf weeds. The annual pasture contained annual ryegrass, subterranean clover, *Vulpia* spp and broadleaf weeds. Lime was applied to maintain the pH of the top 10 cm of soil at 5.5 over 5 years. The lime was disced into the top 10 cm at sowing.

The treatments were chosen to represent the worst pasture condition (annuals with poor species composition on very acid soil) and best (phalaris-subterranean clover without constraints from soil acidity for the region. The pastures were rotationally grazed with weaner ewes or wethers. The stocking rate varied with seasons, but was kept 10 to 25% higher on the limed than the unlimed pastures.

2.2. Instrumentation and measurements

Water balance, plus soil chemical and biological properties, were measured on the sixteen paddocks from 1994 to 1997.

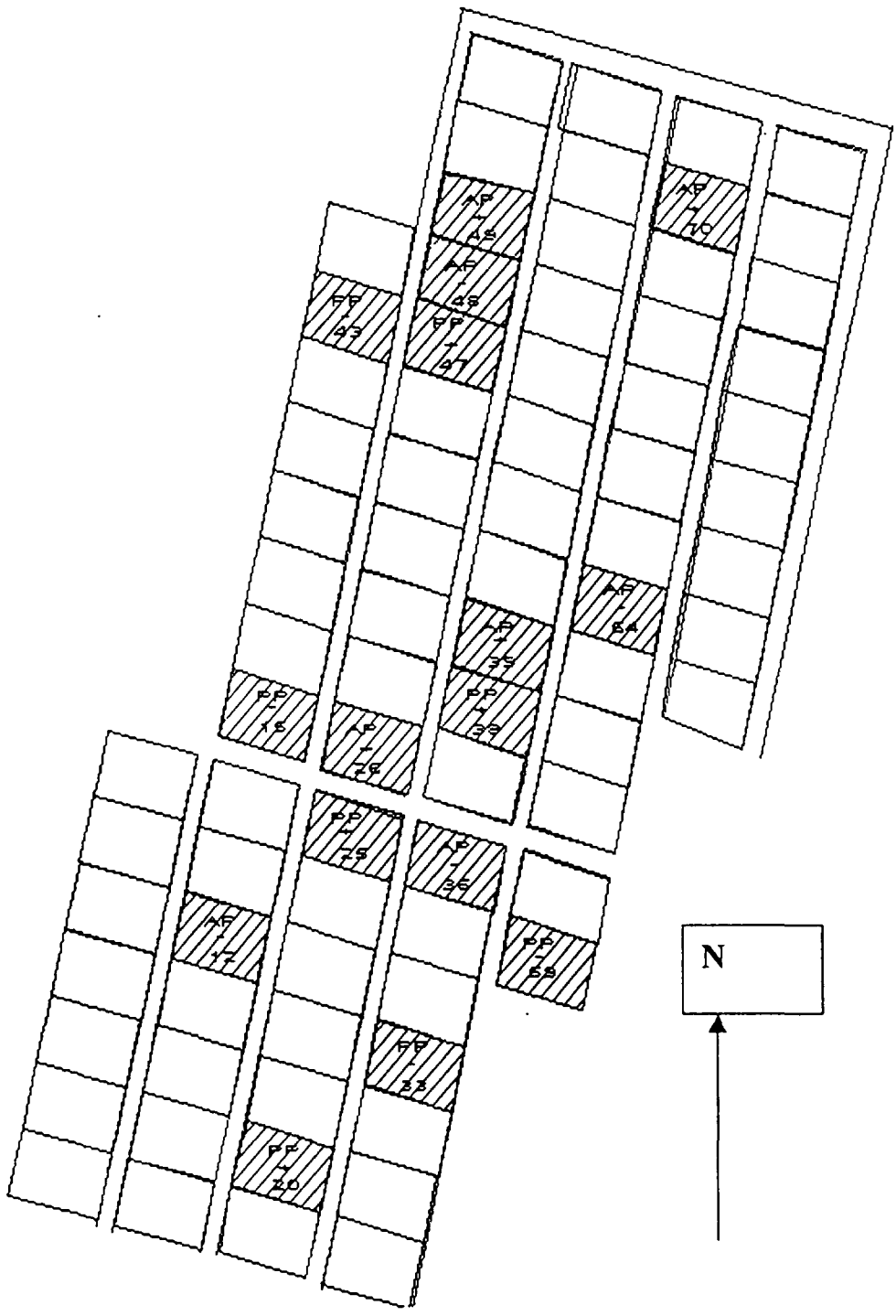

FIG. 1. Experiment layout.

Trenches (10 cm by 60 cm deep) were dug around each paddock and the wall lined with heavy-duty plastic sheets to isolate them hydrologically. A strip drain was placed at the bottom of the trench to collect sub-surface flow at the top of the clay B horizon from each plot and delivered it to

tipping-bucket flow meters. The drain was back-filled with sand and soil. The protruding plastic sheeting extended over the remainder of the excavated soil, forming into a surface barrier around each paddock. Surface runoff from each plot was also channeled to separate tipping-bucket flow meters. Four neutron access tubes were inserted to 180 cm depth in each of the four paddocks. Neutron probe readings were taken at several depths at intervals of 2 to 3 weeks. Neutron probe readings (two per paddock) were made at regular intervals also on the remaining twelve paddocks, in addition to the measurements made on the intensively monitored paddocks. However, only results from the four-instrumented paddocks are reported here.

Three sets of tensiometers were installed at three sites in each paddock, at depths of 30, 45, 60, 90 and 120 cm. Time Domain Reflectometer (TDR) probes were installed at one site in each paddock: horizontally at 20 and 40 cm in the A horizon, and vertically at 45–60 and 65–90 cm in the B horizon. Measurements of soil hydraulic properties were also made in the field and on samples in the laboratory.

An automatic weather station was installed on site, allowing meteorological data to be recorded. Rainfall was measured at hourly and 5-min intervals (using tipping-bucket rain-gauges). Global and net solar radiation, soil heat flux at 2 cm, air temperature, wet- and dry-bulb temperatures and soil temperatures at 2 and 10 cm depths, relative humidity and wind speed at 2 m height were recorded, either hourly or quarter-hourly at the site. Potential evapotranspiration (E_p) was calculated as described by Priestley and Taylor [3] and using Penman-Monteith equation [4], as given below.

$$E_{PT} = [\alpha\Delta(R_n - G)]/\lambda \quad (1)$$

and

$$E_{PM} = \frac{\Delta(R_n - G) + \rho c_p(e_a - e_d)/r_a}{\Delta + \gamma(1 + r_c/r_a)}/\lambda \quad (2)$$

where

$E_{p,PT}$ is Priestley-Taylor evaporation (mm),
$E_{p,PM}$ Penman-Monteith evapotranspiration (mm),
α is equal to 1.26 [3],
R_n is the net radiation (MJ m^{-2}),
G is soil heat flux (MJ m^{-2}),
λ is the latent heat of vaporisation (MJ kg^{-1}),
ρ is atmospheric density (kg m^3),
c_p is the heat capacity of air (MJ m^{-3} $°C^{-1}$),
(e_a-e_d) is the vapour pressure deficit (kPa),
r_c is crop canopy resistance (s m^{-1}),
r_a is aerodynamic resistance (s m^{-1}),
Δ is the slope of vapour pressure (kPa $°C^{-1}$),
and γ is the psychrometric constant (kPa $°C^{-1}$).

2.3. Calibration of neutron probe

The neutron probe was calibrated three times in both the wet- and dry-end ranges of soil moisture, from measurement of gravimetric water contents and bulk densities. Aluminium access tubes, 43 mm in internal diameter, 2 mm wall thickness, were installed to a depth of 2 m at various locations on the MASTER experimental site. Duplicate neutron count readings were taken over 15-s intervals at each depth (15, 30, 45, 60, 75, 90, 120, 150 and 180 cm) in each hole. Four soil cores to a depth of 1.8 m were then taken within 20 cm from the access tube hole, in opposite directions. The cores were cut into 15-cm lengths for gravimetric moisture-content determination. Data from the four replicate soil samples were averaged. Bulk density was measured on these samples and volumetric

water content (θ) calculated. Calibration equations for neutron probe were then established and used to determine the water content of the soil as a function of depth for all plots, including the four instrumented plots, at regular time intervals over the whole experimental period.

2.4. Bulk density

The bulk density and its associated standard deviation, measured during neutron probe calibrations, are given in Fig. 2. Considerable scatter, with a wide range of standard deviations, was observed throughout the whole profile, reflecting the heterogeneity of the soil. A bulk density value of around 1.3 Mg m^{-3} was observed in the top 10 cm, increasing to 1.6 Mg m^{-3} at 30 cm depth, at the top of the B horizon. It then decreased slightly before becoming relatively constant around 1.65 Mg m^{-3} from 80 to 180 cm depth.

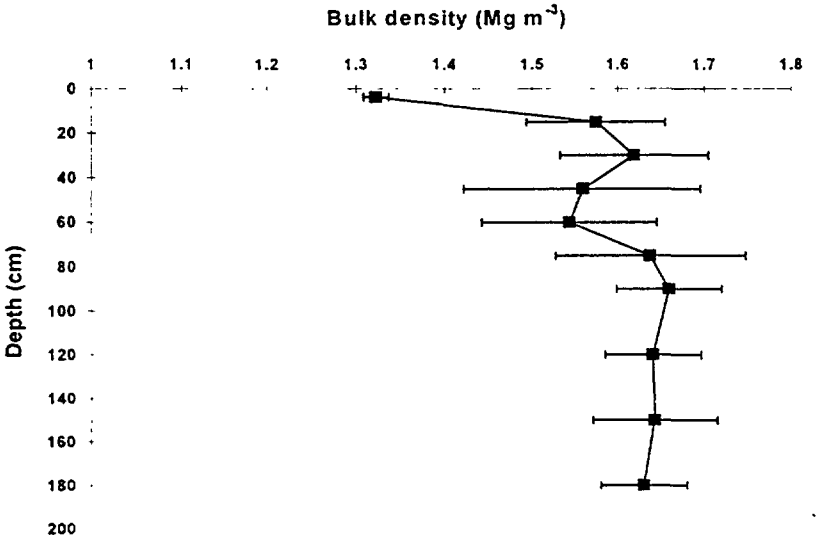

FIG. 2. Change in soil bulk density with depth.

2.5. Tipping bucket flow meters

The tipping bucket flow rates for surface runoff and sub-surface flow were individually calibrated during the course of the experiment. A range of flow rates similar to those observed in the field was generated during calibration. Table I gives the coefficients of the calibration equations for each individual tipping bucket.

TABLE I. CALIBRATION OF SURFACE AND SUB-SURFACE TIPPING BUCKET FLOW METERS

Treatment	Surface tipping bucket	Sub-surface tipping bucket
AP-	$Y^a = 5.997E\text{-}5X^2 - 7.922E\text{-}4X^b + 3.308$	$Y = 4.432E\text{-}3X + 1.365$
AP+	$Y = 3.925E\text{-}5X^2 + 1.167E\text{-}3X + 3.172$	$Y = 4.882E\text{-}3X + 1.258$
PP-	$Y = 5.989E\text{-}6X^2 + 7.611E\text{-}3X + 2.960$	$Y = 3.493E\text{-}3X + 0.992$
PP+	$Y = 2.604E\text{-}5X^2 + 3.245E\text{-}3X + 2.514$	$Y = 4.423E\text{-}3X + 1.325$

[a]Litres/tip.
[b]Tips/5 min.

3. METEOROLOGICAL DATA AND ET CALCULATION

Rainfall data from May 1994 to August 1997 are shown in Fig. 3. The winter, spring and summer periods of 1994–95 were unusually dry, as was the summer and most of the winter of 1996–97. The intervening period (autumn 1995 to spring 1996) was wetter than average. A comparison of the potential evaporation (E_p) calculated using the Priestley-Taylor [3] and Penman-Monteith [4] equations for 1994 to 1997 is shown in Fig. 4. High E_p estimates using the Penman-Monteith equation were obtained on some days in spring and summer. During winter, the estimates from the two methods agreed well. Because of its simplicity, the Priestley-Taylor equation was chosen for the soil water balance simulation described below.

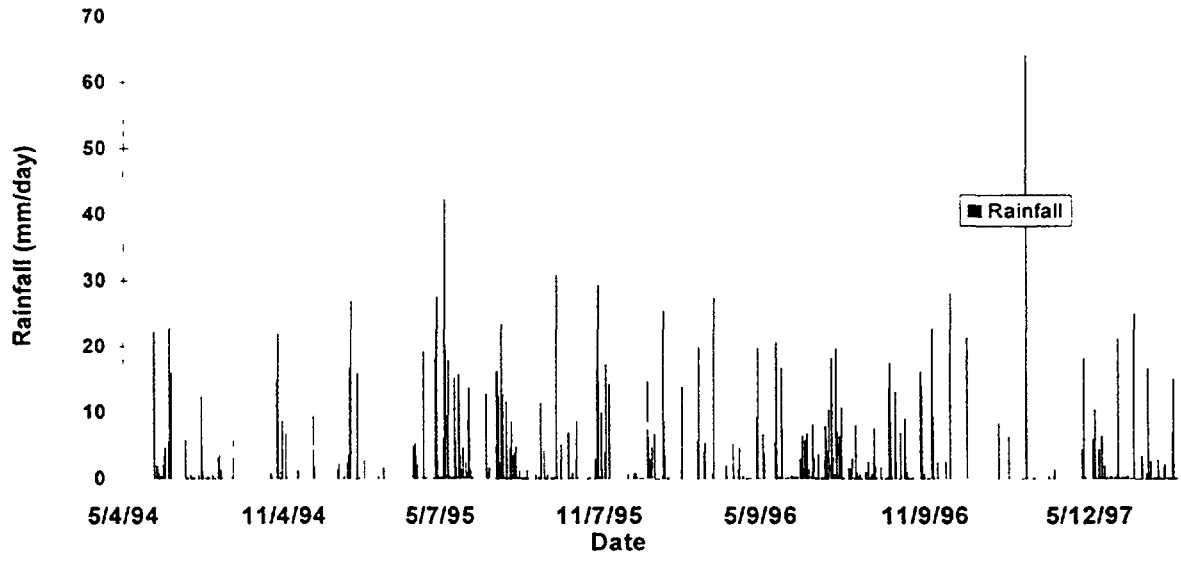

FIG. 3. Daily rainfall for 1994-1997.

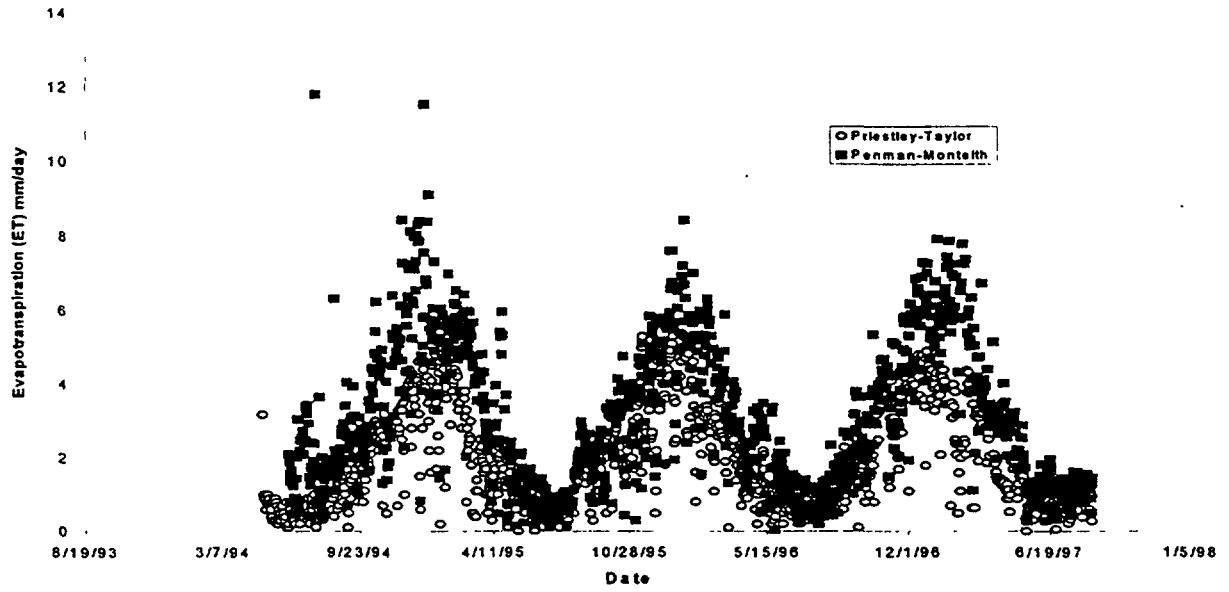

FIG. 4. Comparison between Penman-Monteith and Priestley-Taylor methods of calculating ET, using metdata from Book-Book, NSW.

The total amount of surface runoff and sub-surface flow over the impermeable B horizon for the four pasture treatments over the 3 years are given in Table II. No surface runoff was recorded in 1994, the pastures, particularly the annual pastures, were in poor condition after the drought in 1994–95. When the season broke in autumn 1995, surface runoff occurred from the two annual pasture treatments almost immediately, resulting in greater amounts for the whole year in 1995 and 1996.

TABLE II. SUMMARY OF RAINFALL, EVAPORATION AND SOIL WATER FLUXES MEASURED AND ESTIMATED FOR THE FOUR INTENSIVELY INSTRUMENTED PADDOCKS

Period Treatment	Rain	Actual evaporation E_a	Surface runoff	Sub-surface flow	Surface + sub-surface flow	Deep drainage (>180 cm)
	(mm)					
4/5–31/12 '94						
AP-	205	229	0	0	0	0
AP+	205	203	0	0	0	0
PP-	205	253	0	0	0	0
PP+	205	256	0	0	0	0
1/1–31/12 '95						
AP-	697	467	77	69	145	45
AP+	697	465	66	70	134	62
PP-	697	477	55	62	115	44
PP+	697	511	56	66	116	24
1/1–31/12 '96						
AP-	666	548	7	23	30	62
AP+	666	546	7	19	26	70
PP-	666	566	4	19	23	52
PP+	666	612	2	14	16	22
1/1–19/8 '97						
AP-	267	246	0	0	0	0
AP+	267	243	0	0	0	0
PP-	267	288	0	0	0	0
PP+	267	240	0	0	0	0

There was a significant difference in the absolute amounts of surface runoff for both years. Also, substantial sub-surface flow from all pastures occurred during the winters of 1995 and 1996. The amounts were greater in 1995 than 1996, mainly because of the very wet autumn and early winter of 1995. Sub-surface flow tended to be lower from the perennial than the annual pastures, and especially lower from PP+ plots. And, no surface or sub-surface flow was recorded towards the end of the monitoring period in 1997.

Overall, the amounts of surface runoff and subsurface flow were appreciable in both 1995 and 1996, and comprised a very significant component of the water balance in 1995. This means that

rainfall that is diverted to surface and shallow subsurface flow will contribute to stream flow, rather than to deep drainage and potential recharge to groundwater.

Soil profile volumetric water contents were calculated from neutron probe measurements down to 180 cm depth for all sixteen paddocks. Fig 5 (a-d) showed the profile water content at 90, 120, 150 and 180 mm depths for the four pasture treatments. In general, soil moisture variation became less with increasing depth and that the maximum depth of water extraction under the annual grass pastures was between 90 and 120 cm, whereas the perennials extracted water down to 150 cm.

The maximum depth of water extraction was, therefore, taken to be at 180 cm, and the changes in soil water content ($\pm \Delta S$) to 180 cm depth were expressed relative to "field capacity" of the soil, obtained from moisture values in the winter and spring of 1995 and 1996. The resulting trends in soil water deficit (SWD) or surplus, for the four pasture treatments from May 1994 to July 1997 are shown in Fig. 6. The soil did not regain "field capacity" in the winter of 1994, nor in 1997 (before measurements ceased). During the summer and autumn periods, the SWD increased to a maximum of between 142 and 182 mm under the perennial pastures, depending on the year. This maximum deficit was approximately 40 mm greater than the deficit under the annual pastures. There was little difference in the maximum SWD developed between pastures with and without lime.

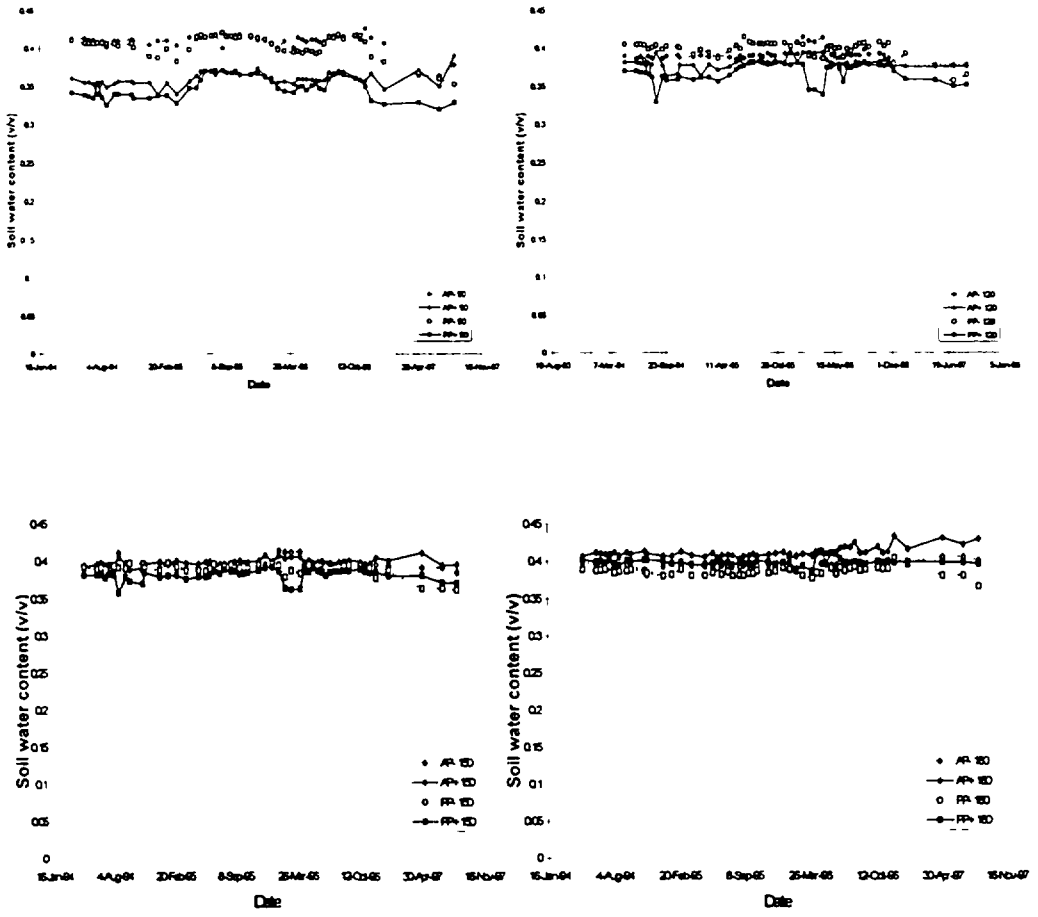

FIG 5 The profile water content at 90, 120, 150 and 180 mm depths for the four pasture treatments (AP-, AP+, PP- and PP+)

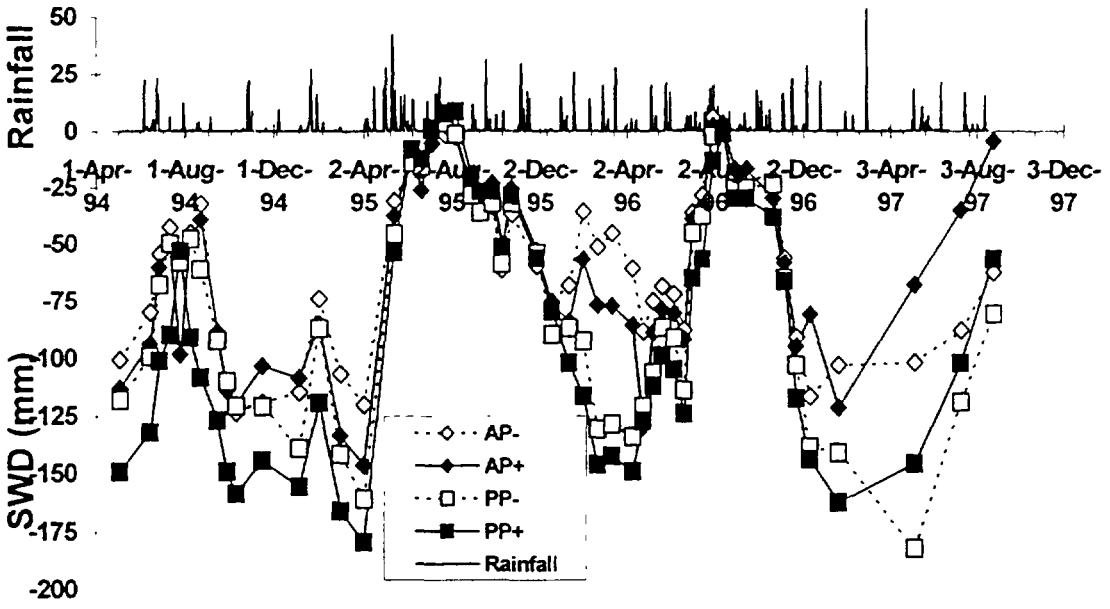

FIG. 6. Measured soil water deficit (0-180cm) for 4 instrumented paddocks of annual and perennial pasture, with and without lime.

3.1. Calculation of actual evaporation rate and simulated SWD

Based on the above information, the soil water balance was simulated for each of the four instrumented paddocks as follows.

$$\Delta S = I - R_s - R_{ss} - E - D \tag{3}$$

where

ΔS is the change in water storage in the soil profile (mm),
I is rainfall (mm),
R_s is surface runoff (mm),
R_{ss} is sub-surface runoff (mm),
E is evapotranspiration (mm),
and D is deep drainage (mm).

Over summer, when evapotranspiration is limited by soil water availability and actual evapotranspiration (E_a, mm) falls behind potential evapotranspiration (E_p), the following approach [5] was used:

$$E_a = a + bS \tag{4}$$

where

a, b are constants determined experimentally,
and S is soil water storage to the depth of interest (mm).

The value of E (mm) is then taken as the lesser of the two values (E_p and E_a). As in [5], the model also accounts for the effect of rainfall on a wet surface in an otherwise dry profile, when E is taken as E_p regardless of S. A total of 25 mm of soil water was allocated for evapotranspiration at E_p rates under this condition. Deep drainage D (mm) is then calculated as:

$$D = S_{n-1} + I - E - R_s - R_{ss} \quad (5)$$

Otherwise,

$$D = 0 \quad (6)$$

The soil water status expressed as the SWD was calculated between May 1994 and August 1997, and the daily amount of deep drainage calculated for the 4 years.

To calculate E_a, it was assumed that evaporation from the pasture continued at the potential rate until the SWD reached 25 mm, when the actual evaporation rate fell below the potential rate. Periods during the summers of 1994 and 1995 were identified when no rainfall or drainage occurred, and the changes in SWD were used to calculate E_a which were then plotted against the SWD value to obtain best-fit relationships for each pasture type. Using these relationships, and initializing the SWD on 4 May 1994, when measurements started, the values of E_a and ΔS were calculated on a daily time step and substituted into Eq. 5 to obtain D. A test of the model is how well the daily values of ΔS track the actual trends in SWD. The results of this comparison are shown in Figs. 7 and 8. The match was excellent for most of the period, particularly when the soil was near field capacity, when drainage is expected to occur.

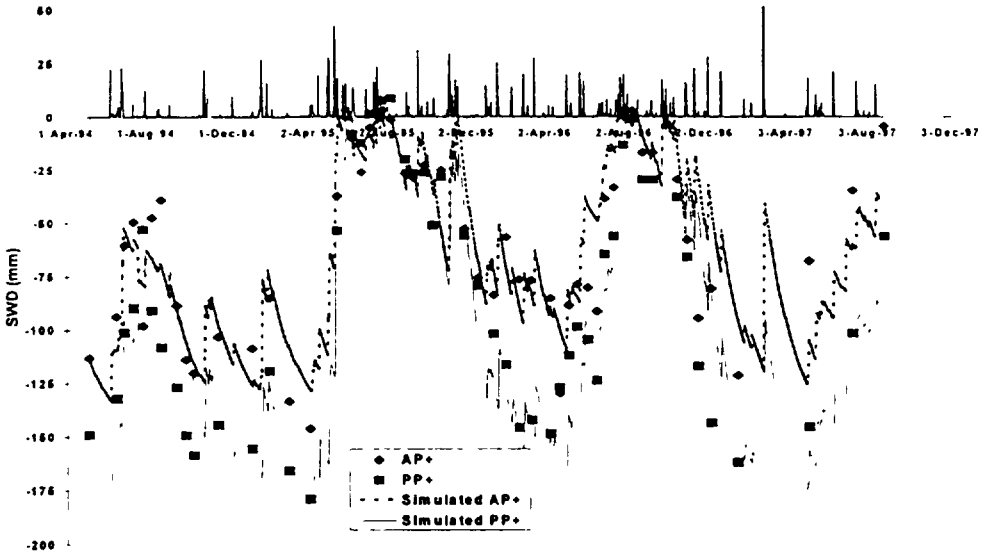

FIG. 7. Simulated soil water deficit (SWD) to 180 cm depth for AP+ and PP+ plots.

The D values were summed to obtain the cumulative drainage during each winter period. The results, given in Table II, show that the deep drainage ranged from 24 to 62 mm under PP+ and AP+, respectively, in 1995, and from 22 to 70 mm under these pastures in 1996. There was no drainage from any of the four pastures in 1994 or 1997 (up to mid-July). This indicates that well grown perennial pasture reduced deep drainage, and potential recharge to groundwater, in normal to wet years by approximately one half to two-thirds compared with annual pasture, with or without lime. It should also be noted that deep drainage was of a similar magnitude to sub-surface flow in 1995. Because sub-surface flow carries solutes from the soil's A horizon where the nitrate concentration is high, its contribution to soil acidification may be greater than that of deep drainage which carries solutes from the lower B horizon, where nitrate concentrations are usually low.

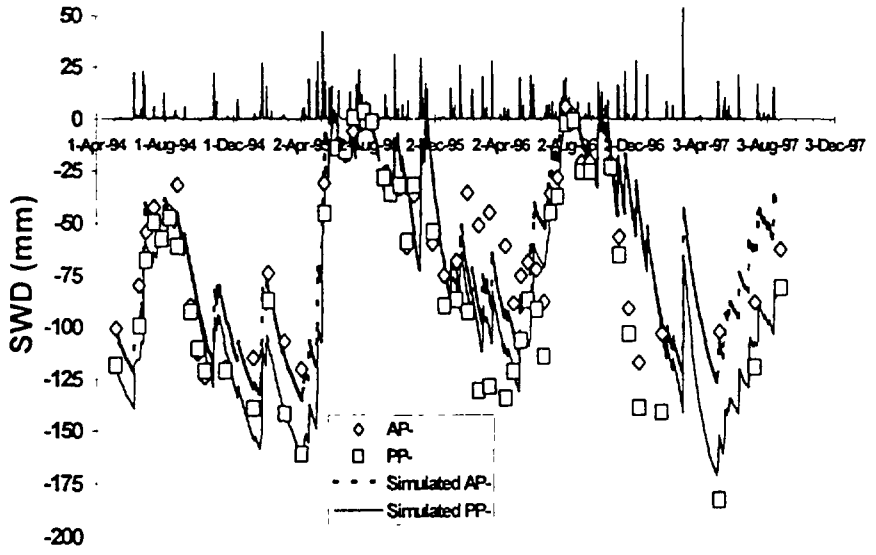

FIG. 8. Simulated soil water deficit (SWD) to 180 cm depth for AP- and PP- plots.

3.2. Long-term simulation of SWD

The results from this short period of measurement suggest deep drainage is likely to be variable between years. An attempt was made to simulate SWDs and deep drainage under annual and perennial pastures (AP- and PP+) over a 10-year period (1985–94), using meteorological data from Wagga Airport.

Sunshine hours were converted to solar radiation using the following equation:

$$R_s = (a + b\frac{n}{N})R_a \qquad (7)$$

where

R_s *is solar radiation (MJ m^{-2} d^{-1}),*
R_a *is extraterrestrial radiation (MJ m^{-2} d^{-1}),*
a, b *are empirical constants, for average climatic conditions, taken as 0.25 and 0.5, respectively,*
n/N *is relative sunshine fraction.*

In the long-term simulation, it was necessary to estimate the amount of surface runoff and sub-surface flow during each rainfall event. For surface runoff generation, the US Soil Conservation Service runoff curve numbers were used ([6] p.128). The approach takes into consideration the following factors: ground cover, soil type and drainage, and slope. As for sub-surface runoff prediction, a quadratic relationship was obtained from the measured sub-surface runoff and rainfall intensity during 1994–97. It was also assumed that sub-surface flow did not occur until the soil was relatively close to field capacity (SWD <30mm).

The SWD simulations, shown in Fig. 9, show consistently greater deficits (40–50 mm) under the perennial pasture by the end of summer each year. Deep drainage was estimated to average 55 ± 40 mm for a poor annual pasture compared with 39 ± 36 mm for a well grown perennial pasture. The estimated combined surface and sub-surface flow averaged 63 and 38 mm for the annual and perennial pastures, respectively. These points should be emphasized:

(1) The simulated drainage was highly variable, ranging from 0 to 129 mm for the annual pasture, and from 0 to 103 mm for the perennial. This was due to a combination of factors such as the variable annual rainfall (range 445 to 923 mm, mean 614 mm) and its distribution, and the variable incidence of surface and sub-surface runoff. Similar yearly variability in drainage was observed previously [7] on a duplex soil at Rutherglen for the period 1990–93, when the average annual rainfall was 693 mm. After allowing for sub-surface flow, the annual drainage was estimated to be 49–56 mm under a phalaris pasture and 80–87 mm under annual ryegrass. The overall reduction under the perennial pasture was about one-third.

(2) These deep drainage results for Wagga and Book Book (annual rainfall 614 and 650 mm, respectively) are much lower than the estimates of 228 and 314 mm for perennial and annual winter-active pastures at Bendigo, Australia (annual rainfall 605 mm) made by Clifton and Johnston [8] who predicted a reduction in deep drainage due to the perennial of approximately 25%. Their estimates were obtained from a one-dimensional simulation model (WAVES). Simulations were done for several sites of different annual rainfall and they concluded that lateral flow of water was very low at rainfalls up to 800–900 mm. These simulation results are inconsistent with our measurements and modelling of runoff (surface and sub-surface) and deep drainage at Book Book, where lateral flows (surface and sub-surface) can be comparable to, or exceed, the deep drainage flux.

(3) Estimates of deep drainage were made under perennial and annual pastures at Rutherglen in NE Victoria over 4 years (when the average annual rainfall was 693 mm) [7]. The drainage below 1.1 m depth was 49–56 mm per year under phalaris, compared to 80–87 mm per year under annual ryegrass. These estimates included any sub-surface flow component (not measured), but were still well below the simulation results reported by Clifton and Johnston [8]. In the wetter years of 1995 and 1996, the combined lateral flows and deep drainage were 43 and 38 mm more under the annual pastures than under the perennial pastures (see Table II). These numbers are very close to the difference in the maximum SWDs (approximately 40 mm) which developed under these pastures by the end of summer in those years.

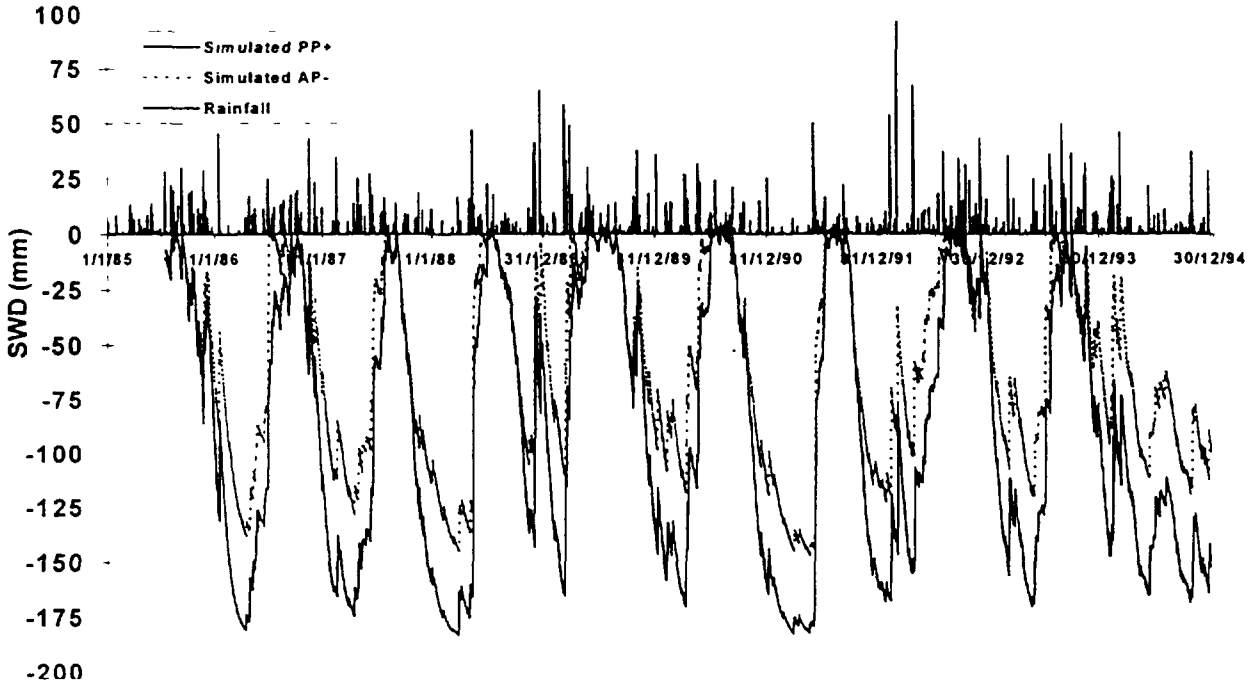

FIG. 9. Simulated SWD to 180 cm depth for AP- and PP+ pastures for years 1985-1994.

Similarly, the long-term simulation for Wagga shows that the combination of mean lateral flows and deep drainage was 118 and 77 mm for the annual and perennial pastures, respectively, again

consistent with a difference in SWD at the end of summer of about 40 mm. The data therefore show a remarkable consistency for the difference in SWD to 180 cm at the end of summer, translating into the difference in water shed from the annual and perennial pastures in winter. This water (with accompanying solutes) is shed either as lateral flows (which appear elsewhere in the landscape), or as deep drainage that can potentially be recharge to groundwater. The ratio of deep drainage to the total water flux ranged from 0.23 under the perennial pasture in 1995 to 0.70 under the annual pasture in 1996. The ratio for both pasture types over the period 1985–94 was close to 0.5, a figure that could be used to make long-term predictions. Thus, on duplex soils in the temperate HRZ, if the measured or predicted difference in SWD between annual and perennial pastures at the end of summer is 40 mm, the difference in deep drainage during the following winter on average is likely to be at least 20 mm.

4. CONCLUSIONS

The main conclusions from this study of productivity and sustainability of perennial and annual pastures are that perennial grass pastures, especially PP+, consistently extracted about 40 mm more soil water each year than did the annual grass pastures. As a result, surface runoff, sub-surface flow and deep drainage (percolation below 180 cm depth) were about 40 mm less from the perennial pastures. This means that well managed perennial pastures can significantly reduce recharge to groundwater and, hence, make pastoral systems more sustainable in the high rainfall zone. Phalaris is a more desirable perennial grass species than cocksfoot because of its higher palatability to stock. But for phalaris to grow successfully and persist, the soils must be limed to at least pH 4.8 (in $CaCl_2$); hence, the "sustainability package" for very acid soils (pH<4.8) must include lime together with the sowing of phalaris.

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RADIATION SAFETY OF SOIL MOISTURE NEUTRON PROBES

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Abstract

The neutron probe measures sub-surface moisture in soil and other materials by means of high energy neutrons and a slow (thermal) neutron detector. Exposure to radiation, including neutrons, especially at high doses, can cause detrimental health effects. In order to achieve operational radiation safety, there must be compliance with protection and safety standards. The design and manufacture of commercially available neutron moisture gauges are such that risks to the health of the user have been greatly reduced. The major concern is radiation escape from the soil during measurement, especially under dry conditions and when the radius of influence is large. With appropriate work practices as well as good design and manufacture of gauges, recorded occupational doses have been well below recommended annual limits. It can be concluded that the use of neutron gauges poses not only acceptable health and safety risks but, in fact, the risks are negligible. Neutron gauges should not be classified as posing high potential health hazards.

1. RADIATION PHYSICS

The neutron moisture probe measures sub-surface moisture in soil and other materials, by use of a probe containing a source of high energy neutrons and a slow (thermal) neutron detector. The neutrons are emitted from an encapsulated ^{241}Am - ^{9}Be source of 370–1850 MBq (10–50 mCi) activity:

$$^{241}Am \rightarrow {}^{237}N_p + {}^{4}\alpha + \gamma$$

$$^{9}Be + {}^{4}\alpha \rightarrow {}^{12}C + {}^{1}n + \gamma$$

The neutrons emitted have energies ranging from zero to 14 MeV the average energy being about 4.5 MeV.

Neutrons interact as follows, in the vicinity of atomic nuclei:

- Elastic collisions in which kinetic energy is conserved,
- Inelastic collisions in which part of the neutron's kinetic energy is absorbed by the nucleus,
- Absorption/capture by the nucleus.

The cross-section of these interactions depends on the:

- Energy of the neutron,
- Type of target.

Elastic scattering is the dominant mechanism by which the fast neutrons are slowed down or moderated to thermal velocities. Maximum energy transfer occurs when the nuclear mass is as close as possible to neutron mass, i.e. hydrogen nucleus. Hence, materials with high water content give higher readings. The thermalized neutrons are detected by Helium-3 filled proportional counters in a $^{3}He(n, p)^{3}H$ reaction.

2. RADIATION BIOLOGICAL EFFECTS

Exposure to radiation, including neutrons at high doses, can cause nausea, reddening of the skin or, in severe cases, more acute syndromes that are clinically expressed within a short period of time.

Such effects are termed "deterministic" because they are certain to occur if the dose exceeds a threshold level. Radiation exposure can also induce somatic effects such as malignancies that are expressed after a latency period, and may be epidemiologically detectable in a population; this induction is assumed to take place over the entire range of doses without a threshold level. Also, hereditary effects due to radiation exposure have been statistically detected in mammalian populations and are presumed to occur in human populations also. These epidemiologically detectable outcomes – malignancies and hereditary effects – are termed "stochastic" because of their random nature.

Deterministic effects are the result of various processes, mainly cell death and delayed cell division, caused by exposure to high levels of radiation. The severity of a particular deterministic effect in an exposed individual increases with the dose above a threshold.

Stochastic effects may ensue if an irradiated cell is modified rather than killed. Modified cells may, after a prolonged process, develop into a cancer. If the damage is to a germ cell, whose function is to transmit genetic information to progeny, hereditary effects of various types may develop in the descendants of the exposed individual. The likelihood of stochastic effects is presumed to be proportional to the dose received, without a threshold. The probability of occurrence of a stochastic effect is higher for higher doses, but the severity of the result is independent of the dose.

3. STANDARDS FOR PROTECTION AND SAFETY

Since a small likelihood of occurrence of stochastic effects at even the lowest doses is assumed, Basic Safety Standards (BSS) [1] cover the entire range of doses with the aim of constraining any possible radiation impairment. The BSSs are based on a concept of detriment as recommended by the International Commission on Radiological Protection, which, for stochastic effects, includes the following quantities: the probability of fatal cancer attributable to radiation exposure; the weighted probability of incurring a non-fatal cancer; the weighted probability of severe hereditary effects; and the length of lifetime lost if the harm occurs.

Human activities that add radiation exposure to that which people normally incur from background, or that increase the likelihood of their incurring exposure, are termed "practices" in the BSSs, e.g. use of neutron probes.

In order to keep doses from practices below regulatory limits, and as low as reasonably achievable (ALARA), there are safety restrictions are necessary [1].

3.1. Administrative requirements

3.1.1 Authorization

A system of registration or licensing must be in place. Any person applying for such authorization should:

- Make an assessment of the nature, magnitude and likelihood of the exposures attributed to the source, and take all necessary steps for the protection and safety of workers and the public,
- Have a safety assessment made and submitted to the Regulatory Authority as part of the application, if the potential for an exposure is greater than any level specified by the Regulatory Authority,
- Have the responsibility for setting up and implementing the technical and organizational measures necessary to ensure protection from, and safety of, the sources for which they are authorized.

Registrants and licensees have to notify the Regulatory Authority of any intention to modify any practice or source for which they are authorized, if there are significant implications for protection or safety, and must not carry out any such modification unless specifically authorized by the Regulatory Authority.

3.2. Radiation protection requirements

3.2.1. Justification of practices

No practice or source within a practice should be authorized unless the practice produces sufficient benefit to exposed individuals or to society to offset the radiation harm that it might cause, i.e. unless the practice is justified, taking into account social, economic and other relevant factors.

3.2.2. Dose limitation

The normal exposure of individuals must be restricted so that neither the total effective dose nor the total equivalent dose to relevant organs or tissues, caused by the possible combination of exposures from authorized practices, exceeds any relevant dose limit.

3.2.3. Optimization of protection and safety

In relation to exposures from any particular source within a practice, except for therapeutic medical exposures, protection and safety must be optimized in order that the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures, all be kept as low as reasonably achievable, economic and social factors being taken into account, within the restriction that the doses to individuals delivered by the source be subject to dose constraints.

3.2.4. Dose constraints

Except for medical exposure, the optimization of the protection and safety measures associated with any particular source within a practice must be subject to dose constraints that do not exceed either the appropriate values established or agreed to by the Regulatory Authority for such a source or values that can cause the dose limits to be exceeded.

3.3. Management requirements

3.3.1. Safety culture

A safety culture must be fostered and maintained to encourage a questioning and learning attitude to protection and safety, and to discourage complacency, in order to ensure that:

- Policies and procedures be established that identify the protection and safety of the public and workers as being of the highest priority,
- Problems affecting protection and safety be promptly identified and corrected in a manner commensurate with their importance,
- The responsibilities of each individual, including those at senior management levels, for protection and safety, be clearly identified and each individual be suitably trained and qualified,
- Clear lines of authority be defined for decisions on protection and safety,
- Organizational arrangements and lines of communication be effected that result in an appropriate flow of information on protection and safety at and between the various levels in the organization of the registrant or licensee.

3.3.2. Quality assurance

Quality assurance programmes must be established that provide, as appropriate:

- Adequate assurance that the specified requirements relating to protection and safety are satisfied,
- Quality control mechanisms and procedures for reviewing and assessing the overall effectiveness of protection and safety measures.

3.3.3. Human factors

Provision must be made for reducing, as far as practicable, the contribution of human error to accidents and other events that could give rise to exposures, by ensuring that:

(1) All personnel on whom protection and safety depend be appropriately trained and qualified so that they understand their responsibilities and perform their duties with appropriate judgement and according to defined procedures.

(2) Sound ergonomic principles be followed as appropriate in designing equipment and operating procedures, so as to facilitate the safe operation or use of equipment, to minimize the possibility that operating errors will lead to accidents, and to reduce the possibility of misinterpreting indications of normal and abnormal conditions.

(3) Appropriate equipment, safety systems, and procedural requirements be provided and other necessary provisions be made:
– To reduce, as far as practicable, the possibility that human error will lead to inadvertent or unintentional exposure of any person;
– To provide means for detecting human errors and for correcting or compensating for them;
– To facilitate intervention in the event of failure of safety systems or of other protective measures.

3.4. Technical requirements

3.4.1. Security of sources

Sources must be kept secure so as to prevent theft or damage, and to prevent any person from carrying out any unauthorized actions by ensuring that:

- Control of a source not be relinquished without compliance with all relevant requirements specified in the authorization and without immediate communication to the Regulatory Authority, and when applicable to the relevant Sponsoring Organization, of information regarding any decontrolled, lost, stolen or missing source,
- A source not be transferred unless the receiver possesses a valid authorization,
- A periodic inventory of movable sources be conducted at appropriate intervals to confirm that they are in their assigned locations and are secure.

3.4.2. Defence in depth

A multilayer defence-in-depth system of provisions for protection and safety commensurate with the magnitude and likelihood of the potential exposures involved must be applied to sources such that a failure at one layer is compensated for, or corrected by, subsequent layers, for the purposes of:

- Preventing accidents that may cause exposure,
- Mitigating the consequences of any such accident,
- Restoring sources to safe conditions after any such accident.

3.4.3. Good engineering practice

As applicable, the siting, location, design, construction, assembly, commissioning, operation, maintenance and decommissioning of sources within practices must be based on sound engineering that shall, as appropriate:

- Take account of approved codes and standards and other appropriately documented instruments,
- Be supported by reliable managerial and organizational features, with the aim of ensuring protection and safety throughout the life of the sources,

- Include sufficient safety margins for the design and construction of the sources, and for operations involving the sources, such as to ensure reliable performance during normal operation, taking into account quality, redundancy and inspectability, with emphasis on preventing accidents, mitigating their consequences and restricting any future exposures,
- Take account of relevant developments in technical criteria, as well as the results of any relevant research on protection or safety and lessons from experience.

3.5. Verification of safety

3.5.1. Safety assessments

Safety assessments related to protection and safety measures for sources within practices must be made at different stages, including siting, design, manufacture, construction, assembly, commissioning, operation, maintenance and decommissioning, as appropriate.

3.5.2. Monitoring and verification of compliance

Monitoring and measurements must be conducted of the parameters necessary for verification of compliance with the safety requirements.

For the purposes of monitoring and verification of compliance, suitable equipment must be provided and verification procedures introduced. The equipment shall be properly maintained and tested and must be calibrated at appropriate intervals with reference to national or international standards.

3.5.3. Records

Records must be maintained of the results of monitoring and verification of compliance, including tests and calibrations carried out in accordance with the Standards.

4. OPERATIONAL RADIATION SAFETY

In order to achieve operational radiation safety, there must be compliance with these safety requirements. In practical terms, these are translated to the following components.

4.1. Design and manufacture

With over 40 years experience in the industry, the design and manufacture of commercially available neutron moisture gauges are such that risks to health and safety of users have been greatly reduced. Sources and equipment should be manufactured to conform with applicable standards of the International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) or equivalent national standards. They also should comply with IAEA Safety Standards for transport safety (ST-1) [2].

The Am-Be sources used are in Special Form, i.e. doubly encased in stainless steel containers with welded seals. These are placed in radiation-shielding material made of high hydrogen content, e.g. paraffin or plastic. Emitted α-particles are stopped by the source capsule. Only neutrons and γ-radiation contribute to occupational exposure. The neutron shield is sufficient to contain the low energy γ-radiation from Am-Be. Therefore, Am-Be is essentially a neutron hazard. The shield also acts as the storage and transport containers.

4.2. Training

Users should be trained in the proper and safe use of the equipment. This training should include normal operations, and recognition of abnormal situations and necessary actions to be taken, i.e. emergency preparedness and response. This reduces the risk of potential exposures. Radiation protection

and safety training are essential for users as well as supporting staff. e.g. vehicle drivers. Periodic refresher courses are highly recommended for all certified users.

4.3. Operational instructions

Operational manuals on safe use, maintenance and emergency actions should be provided by the manufacturers. These may need to be translated to the local working language by the management of the operating organization.

4.4. Local rules

Local rules or codes specifying safe working practices must be in writing and posted in appropriate and designated places. All staff members are to be aware and trained in them to the extent that is relevant to their duties. The Local Rules should indicate clear lines of responsibilities for management, worker and radiation protection officer.

4.5. Designation of controlled areas

Controlled areas need to be physically delineated using a dose-rate meter and radiation warning signs posted at the boundaries. Controlled areas must be supervised to prevent access by unauthorized persons. Gauges should never be left unattended.

4.6. Transport safety

The gauge should be transported only in a container designed and tested to "Type A" standards, detailed in IAEA Safety Standards on Transport safety (ST-1). Two transport labels must be displayed conspicuously on the container: the radionuclide activity and Transport Index (TI), which is the dose rate at 1 m, in $\mu Sv\ h^{-1}$ divided by 10. During transport, the gauge should be blocked and braced to prevent movement. The driver must carry transport documents that give details of the sources. The vehicle must also display fire-resistant signs on the sides and rear of the vehicle, according to prevailing regulations, showing radiation warning and advice to call the police and the owner or operator of the vehicle, in the event of an accident. A vehicle for carrying the gauges should not be used for passengers. The driver needs to be trained and have certification in basic radiation protection, including emergency preparedness and response during transport.

4.7. Personnel monitoring and dosimetry

The gauge should be checked with a calibrated dose-rate monitor after use, to ensure that the source is in the shielded position in order to prevent accidental exposures. Personal dosimeters must be worn and evaluated, and doses recorded as required by regulation. A Radiation Protection Officer (RPO) must be appointed to be responsible for the implementation of radiation-safety requirements and conditions of the license.

4.8. Safe storage and disposal

Every gauge should be kept locked in its transport case in physically secure fire-resistant storage, separate from other materials, with two or three levels of locks.. The store should be designated as a controlled area, at least 5 m from normal working sectors. The door should be posted with radiation warning and a sign to show prohibition of access to unauthorized persons. The exterior dose rate should not exceed 7.5 $\mu Sv\ h^{-1}$ and, where practicable, should be less than 2.5 $\mu Sv\ h^{-1}$. This may be achieved by placing the source as far as possible from the door and walls, or by using additional shielding. Storage in a motor vehicle or residence is not recommended.

When a gauge is no longer in use, it should not be transferred to another user for service, disposal, sale or use without the authorization of the Regulatory Authority. It should be treated as

radiation waste and disposed of only as authorized by prevailing regulations. Return to the manufacturer for re-use, long-term storage or disposal, is recommended.

4.9. Maintenance

Maintenance should be with the procedures and equipment, and at the frequencies, recommended by manufacturers. These include leak tests twice per year to check that sources are intact, and cable maintenance to check for breaks or the separation of copper conductors.

The toxicity of americium is similar to that of other actinides like plutonium. When Am is deposited internally, the α-emission poses a serious hazard to bone, kidneys, etc.

4.10. Emergency preparedness

There must be radiation emergency plans for reasonably foreseeable accidents. Actions to be taken, persons to notify must be detailed in an emergency preparedness plan (EPP). Examples include a gauge being crushed by road roller or other site vehicle, road traffic accident during transport, a fault causing the sources to be incompletely retracted or shielded, probe lodged or lost in the bore-hole. The radiation protection officer and workers, including drivers, should be trained with practical exercises including dry runs of the EPP. The user should carry a copy of the EPP and some essential retrieval tools on field work.

Incidents and accidents must be investigated and appropriate remedial actions taken where necessary. The information gathered should be disseminated among the relevant parties as required by prevailing regulations.

4.11. Inventory and accountability

Removal of a gauge from, and return to, a store must be recorded in a "check-out-check-in" log . Details should include date, name and signature of worker, field site, model of gauge, type of source, transport vehicle, length of use, etc. Transfer to another registrant or return of gauges to the manufacturer must also be recorded.

4.12. Record keeping

The following records must be kept:

- Inventory of sources and accountability,
- Personnel monitoring doses,
- Training and re-training of workers,
- Maintenance and repair records of equipment,
- Results of leak tests,
- Log book of calibration and use of survey/dose-rate meters,
- Log book of off-site locations,
- Transportation documentation,
- Audits and review of radiation safety programme,
- Incidents and accidents investigation reports.

5. OCCUPATIONAL EXPOSURES

The major concern is radiation escape from the soil during measurement, especially under dry conditions and the radius of influence is large. With good practices outlined above as well as good design and manufacture of gauges, the occupational doses recorded in the industry have been well below annual dose limits. Applying ALARA principles, such as the use of Teflon plastics reflectors laid on the

surface, doses as low as 0.2 mSv yr^{-1} (1% of the annual dose limit) for both neutrons and γ-rays, have been reported [3].

5.1. Occupational dose limits

Effective dose	20 mSv yr^{-1} (averaged over 5 years) 50 mSv in any single year	
Equivalent dose	lens of the eye:	150 mSv in a year
	extremities and skin:	500 mSv in a year

Dose limits for 16–18 year olds:

Effective dose	6 mSv in a year
Equivalent dose	50 mSv in a year to the lens of the eye 150 mSv in a year to the extremities or skin.

6. IAEA ACTIVITIES IN RELATION TO NEUTRON GAUGES

In each country where gauges are used there must be in place an effective system of regulatory control, i.e. authorization, inspection and enforcement. This will ensure that appropriate equipment is used by well trained personnel in approved places.

The Agency has prepared a guidance document for Regulatory Authorities for safety assessment plans for authorization and inspections. Neutron-gauge use is one of the practices covered for which a "checklist" guide is provided.

In the future, Safety Reports on radiation safety of nuclear gauges will be published. This will cover both normal and potential exposures.

7. CONCLUSION

It can be concluded that, from the perspective of radiation safety on both normal and potential exposures, the use of neutron gauges poses not only acceptable health and safety risks but, in fact, the risks are negligible. The use of neutron gauges are not, and should not be, classified as a practice of high potential hazard to human health.

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