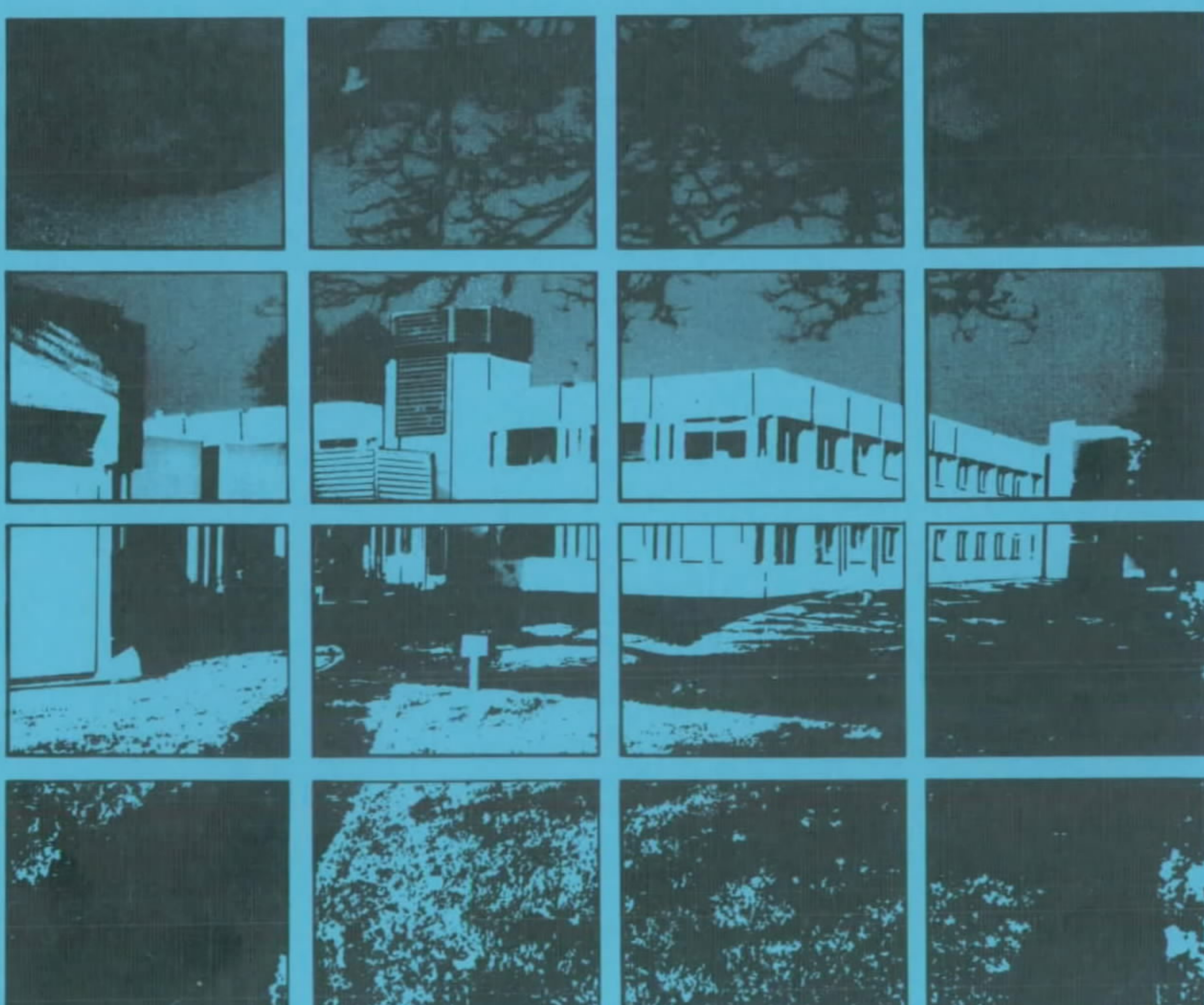
INSTITUTE of HYDROLOGY

Neutron probe practice



Report 19

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(Third edition)

Neutron probe practice

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Preface

This report is intended as a basic guide to the practical use of the neutron probe, its working principles and some of its applications. It is hoped that it will help the user or intending user to avoid the mistakes and frustrations commonly encountered by those new to the field. Properly used and understood the neutron probe can provide *in situ* measurements of soil moisture change to a precision obtainable in no other way. However, bad practice too often leads to the production of poor data containing large and often unrecognised errors.

The principle of measuring soil moisture by the moderating effect of water on fast neutrons was first proposed in the late 1940s and field instruments were soon developed once the principle was shown to be practicable. The great advances in electronics since then have led to the development of highly reliable and stable systems and the dubious reputation earned for the technique by some of the early instruments is now entirely unjustified.

The original use of neutron probes was mainly for the measurement of soil water storage changes for water balance purposes, but in the last few years the improvements in performance have opened up new research applications in agronomy and hydrology which are now overtaking the original uses.

During recent years the principal advance has been the introduction of microprocessor controlled systems, which offer the advantage that data can be recorded in a built-in memory and either processed directly into readouts of soil water content or, perhaps more usefully, the memory can be quickly and easily unloaded into a microcomputer for providing immediate listings of processed data.

Although it is the "Wallingford Probe" and its successor, the "IH Neutron Probe System" which is often exemplified in this report, most of the information is applicable to any type of neutron probe.

1. Basic Principles

The Neutron Soil Moisture Gauge, usually referred to more simply as the 'Neutron Probe', consists of a probe containing essentially a fast neutron source and a slow neutron detector, a pulse counter ("ratescaler"), a cable connecting the two, and a transport shield.

Most systems are designed broadly to the same mechanical principles, although in detail they differ considerably. There is perhaps more variation in electronic design philosophy, although even here the most fundamental principles of pulse counting are common to all probes.

For most systems, to use the probe the transport shield is fitted to the protruding upper end of an aluminium access tube which is positioned vertically in the soil. The probe is lowered directly into the access tube to successive measurement depths by means of the cable; a depth indicator and clamp mechanism operating on the cable are mounted within the transport shield. The transport shield usually incorporates a plastic moderator which provides some shielding for the source and also acts as a field standard. The counter unit remains at the surface; this incorporates the electronic controls, the readout display, the battery which powers the system and the circuits which count the pulses from the probe.

The probe contains a radioactive source which emits fast neutrons into the surrounding soil. Collisions with the nuclei of the soil atoms, predominantly those of hydrogen in the soil water, cause the neutrons to scatter, to slow and to lose energy. When they have slowed to the so-called 'thermal' energy level they are absorbed by other nuclear reactions. Thus a 'cloud' of slow neutrons is generated within the soil around the source. The density of this cloud, which is largely a function of the soil water content, is sampled by a slow neutron detector in the probe. The electrical pulses from the detector are amplified and shaped before passing up the cable to the counter unit where their mean count rate is displayed. The count rate is translated into soil moisture content (by volume) using an appropriate calibration curve.

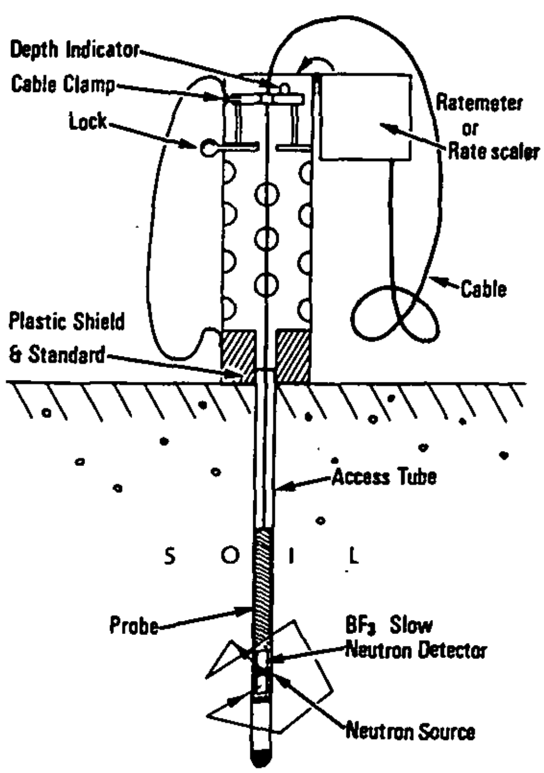
Although it is the hydrogen in the soil, including that of bound water and organic material, which exerts the principal effect on the count rate, the nuclei of most other soil elements have some additional effects. Every element has some ability to scatter fast neutrons, which as a result lose energy progressively with each collison, and to capture or absorb the resulting slow 'thermal' neutrons. Although in practice most soil elements have a relatively low ability to act in either of these ways, all contribute to some extent to the count rate measured by the probe, in addition to the principal effect derived from the hydrogen of the soil water.

The scattering ability of an element is expressed as its 'scattering cross section' and its capturing ability as its 'capture cross section'. The sum of the products of the concentration of each element per unit volume of soil space and its cross section gives the macro-scattering and -capture cross sections of that soil which determine its calibration characteristic. These numbers are constants for a given soil and proportional to its dry bulk density.

FIGURE 1 The Wallingford Soil Moisture Probe (*ca.* 1972).

Hydrogen is the only element with a significant scattering cross section found in soil and which also causes a large energy loss when a collision occurs. Several elements such as cadmium, boron and chlorine (and to a lesser extent iron) have large capture cross sections, and these absorb slow neutrons and reduce the number of them which return to the detector. The dry soil matrix thus producees its own background contribution to the count rate which then increases from that value with increasing water content at a rate also dependent upon the macro cross sections. Every soil therefore has a unique calibration relationship between count rate and water content. For most systems this curve can be considered to be linear, and be defined simply by its gradient and intercept. Fortunately, for most soils the difference in gradient of the calibration lines is small, and if it is moisture *changes* that are being measured rather than absolute values, calibration is fairly simple. For most commercial equipment the general form of the calibration curve is given and in order to define the slope and intercept of the line for each soil, it is necessary only to establish a few very accurate calibration points.

The neutron probe is best used in situations where non destructive measurements of moisture change are required in the same profiles on many occasions. It is a research tool which may be used for routine work providing that the field procedures are carefully supervised and the data scrutinised as soon as possible after the readings are taken. The method can produce very good or very bad results, depending on the skill and interest of the field staff.



2a

FIGURE 2 Diagram and photograph of neutron probe in use.

2. Design Features and Working Principles of Neutron Probes

2.1 Source detector and geometry

The use of Americium - Berylium neutron sources in probes is now general, partly on grounds of safety, because the attendent gamma radiation level is relatively innocuous compared with sources used in earlier probes, and partly because this material has a very long half-life (450 years) and hence there is little problem of drift due to loss of activity. Sources employed usually have an activity of between 30 and 100 millicuries (mCi)* and although generally in capsular form, some probes employ annular sources.

The boron trifluoride (BF_3) proportional counter is the most commonly used detector, being cheap, reliable, robust and stable. Helium 3 (^3He) detectors are now available as standard items and although more expensive than BF_3 tubes. have the advantage of being more sensitive. However, their use is more difficult electronically and it seems that BF_3 tubes will continue to be used until something better is discovered. Lithium glass and other scintillation detectors have been used in some designs because they also have a higher sensitivity than the BF_3 tubes, but the electronics are again more complex. For probes designed to measure wet bulk density as well as moisture by the additional measurement of back-scattered gamma radiation (usually generated by a 137 caesium source) a scintillation detector is used because its output energy spectrum can be analysed independently for both measurements.

There is an optimum geometry for each source/detector system to obtain the maximum sensitivity and a linear calibration. Ideally perhaps the source and the detector should lie at the same point, but in practice the linearity is acceptable providing no part of the detector is more than about 6 cm away from the source. BF_3 and ^3He detectors are metal tubes, usually 25 mm in diameter; their sensitive length, gas pressure, etc vary with design. The source is usually placed in contact with and half-way along the side of the sensitive length of the tube, although annular sources are sometimes used. In the case of scintillation detector systems the source is usually located 2 or 3 cm below the scintillation disc, the upper surface of which contacts the photomultiplier window. A geometry which should be avoided is a 10 cm or longer BF_3 or ^3He tube with a bottom-placed source; this can lead to loss of sensitivity in the lower part of the moisture range and to errors in measurements near soil layer interfaces.

Stable voltage supplies varying between 1000 and 2600 volts are necessary to feed the various types of detector, and this voltage may be generated from the 12V supply either in the probe or in the counter unit. In the latter case a thicker cable with more complex terminations is required and this has been found to produce a high proportion of field failures due either to internal fracturing or to

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* Conversion from these old SI units to current SI units is as follows:

1 mCi = 3.7×10^7 Bq = 0.037 GBq

where mCi = millicuries

GBq = Gigabecquerels.

the entry of damp or dirt into the connections. Probes are therefore more reliable if the high voltage is generated inside the probe, the probe being fed with a non-stabilised 12V supply via a simple cable. In the case of the Wallingford probe a coaxial cable is used, not because screening is necessary but because the round cross section makes it easier to feed the cable through the clamping mechanism.

2.2 Power supply

All field instruments are battery powered, usually by means of Ni-Cd rechargeable cells in a 12V pack housed in the counter unit. Some counters have provision for operating from mains supply and contain built-in chargers, but usually are the older designs based on scalers which were originally intended for laboratory use and are thus not only heavy but vulnerable to dirt, damp and shock. The battery of this type of counter is also usually built-in and this can be a disadvantage when the battery runs out as there is no alternative but to abandon the work until the battery has been recharged for 12-14 hours, thus putting the entire system out of use until the next day. Designs in which battery units can be exchanged in the field are therefore generally favoured. Recent advances in lower power circuitry have made it possible to use smaller batteries which have sufficient capacity for several days work and there is now a tendency to return to the built-in battery.

Modern electronic circuits need very little power if they are designed efficiently. Low power consumption is important for field instruments which have either to be carried or left unattended because more readings can be taken per unit battery weight. Systems designed in the late 60s should not consume more than about 100 mA at 12 volts, except perhaps during the brief period while the display is operative. More recent designs can consume as little as 40 mA in total, or less.

The display from the scaler unit is digital. In early models this was frequently an electro-mechanical register or some form of neon tube display. Both tended to add to the weight of the scaler; the former was unreliable and the latter difficult to read. These have been replaced in turn by LED, tungsten filament and liquid crystal displays. Liquid crystal displays have now superseded all other displays due to the rapid advances in this field, becoming usable over a wide temperature range and consuming a negligible amount of power.

2.3 Electronic Stability

One of the main problems associated with the use of neutron probes has been their electronic instability and poor reliability. Both factors can prove expensive and frustrating and while a complete breakdown causes loss of data, it is perhaps less serious than the existence of electronic instability which, if undetected, can give rise to faulty measurements. The three principal types of instability are:

Warm-up drift. This is a drift in the indicated count rate which occurs after initial switch-on, in bad cases for up to several hours. This type of drift should be considered unacceptable if during 8 hours of continuous operation it exceeds 0.25% of the count rate in the water standard.

Thermal drift. In this case the indicated count rate is influenced by the temperature of the probe. This can give rise to serious seasonal and diurnal biases, reflecting fluctuations in ambient temperature.

Age drift. This is the least serious of the drifts and may be expected to some extent with every design. The standard count procedure outlined below overcomes any errors caused by this (see "The use of laboratory standards").

2.4 Depth indicator and cable clamp

The depth indicator should be a digital device and usually operates mechanically by means of a wheel held against the cable by friction. This should have an accuracy of not less than ± 5 mm. Depth location is one of the main sources of error and attempts should be made to achieve ± 1 mm as soon as possible.

The cable clamp should be positive in action and non-slip even in wet, muddy and cold conditions. It should be in a convenient position and easy to use with cold, wet hands.

The marked cable system employed on most early designs has in recent years tended to re-appear. The only advantage of this system is cheapness. Being at fixed positions the operator has no facility to set the probe at other depths, and a standard tube height (the length of the access tube protruding above the ground) is required, something that is not always easy to achieve. Marks or stops fitted to the cable provide a locus for fracture of the cable on the insulation.

2.5 Counting the pulses from the probe

2.5.1 Analogue ratemeters

A ratemeter is the simplest device for counting pulses and produces a voltage analogue of the count rate which is displayed on a dial. Because radioactive decay is a random process, the count rate fluctuates about a mean, and although this fluctuation is damped according to the time constant selected, it causes a fluctuation of the needle and this easily leads to subjective reading errors; furthermore the reading accuracy of a dial (even with a steady needle) is only about 1%. Another disadvantage of a ratemeter is the comparatively large 'dead time' which causes the loss of a proportion of pulses which increases steeply with count rate. One minor advantage which the ratemeter offers is that it provides a simple voltage analogue output which can be recorded easily with a chart recorder or logger. Ratemeters provide a very inferior method of measuring count rate and digital systems have made them obsolete for most purposes. Although the ratemeter is a much simpler instrument than the ratescaler (see below), the interpretation of the data obtained with it is much more complex.

2.5.2 The digital ratemeter

This is generally referred to as the 'scaler' or 'ratescaler'. Incoming pulses from the probe are counted for a preset period of time, at the conclusion of which the mean count rate for that period is displayed digitally in the form of counts per second or per minute (eg. Figure 2a).

The standard deviation of the count rate due to random neutron emission, σ_r, is used to define the scatter of a population of replicate readings about the true mean count rate. 68% of the readings lie within σ_r of the true mean, or looking at it another way, there is a 68% probability that any individual reading is within σ_r of the true mean count rate. $2\sigma_r$ gives 95% probability level and $3\sigma_r$ for 99% probability. The value of σ_r is calculated from the expression:-

$$\sigma_r = (R/t)^{1/2} \qquad \text{.... (1)}$$

where R is the count rate and t is the counting time.

The ratescaler is normally readable to one count per second, although some systems are readable to 0.1 cps.

Ratescaler electronics have no thermal dependence and the circuit is normally designed so that with a failing battery a count rate display is not possible below the critical voltage level. There is no way therefore that a correctly functioning ratescaler can adversely influence the count rate derived from the probe so as to produce any additional errors.

2.5.3 Microprocessor ratescalers

The most recent advance in the development of the neutron probe has been the incorporation of microprocessor technology, and ratescalers which incorporate microprocessors are now available from several manufacturers. These tend to offer an excessively wide range of complex choices and facilities. An intending purchaser, particularly one with little or no previous experience of neutron probe use, can easily be persuaded to acquire a system which is over-sophisticated, with the result that data is produced with more difficulty and less reliability than with a simple manual system.

Three broad categories of probe user can be identified:

The first is one who requires precise data and wishes to apply his own calibration curves, but who is dealing with a relatively small number of access tubes and/or relatively infrequent observations. In this case there is little advantage in becoming involved in the complications inherent in the microprocessor ratescaler and a simple, proven ratescaler (or equivalent) is probably the best choice. Count rate, depth and other data are written on field sheets and subsequently processed manually or keyed-in to a suitable computer for processing. However, the possibility of a future growth in use of the probe should be borne in mind, and the system purchased should have the facility for upgrading later with a microprocessor ratescaler, while still retaining the existing probe and ancillaries.

The second category of user is one who wants to obtain in the field a direct readout of soil water content which still has to be recorded manually; such a user will be content with results of only moderate accuracy. A system which has a choice of three or four permananent built-in calibrations for (eg) sandy soils, loamy soils and clays would suffice, giving a direct digital readout in terms of soil water content rather than count rate, and offering no option for storing the data electronically. It should be noted here that scope for errors is introduced by giving the field operator the responsibility of selecting the appropriate calibration for each access tube, soil layers, or reading depth, with little chance of detecting any errors subsequently.

The full potential of a microprocessor based system is exploited only by the third category of user, who has to deal with large quantities of data, probably from a number of different sites, read possibly at different time intervals and depth increments, such that there would be great difficulty in processing and presenting the data without using a computer. The primary requirement here is that data can be recorded automatically in the field and transferred quickly and easily in the office to a computer via a suitable interface, there to be stored on disc and processed as required to produce data listings, summaries, profile and time series graphs, etc. Thus, the scientist can have rapid access to the results in a form amenable to examination, if necessary on the same day that the observations were made.

The microprocessor system with a data 'memory' enables data to be manipulated and stored in a wide variety of ways within the ratescaler, in accordance with a program stored permanently in its memory. Great flexibility is possible, limited only by the program which controls the system. The main advantages of a microprocessor ratescaler are

(1) data can be stored in memory and subsequently read out into a computer for permanent storage and full processing;

(2) the program can be interactive with the field operator, presenting him with a variety of options and prompts, which if well conceived, will guide him through the sequence with little if any opportunity to make mistakes.

However, unless the built in software field operating system is well designed, there is the danger than numerous choices presented to the operator coupled with the need to enter numerous commands, will make the system tedious and confusing, and the potential for errors will be greatly increased.

The memory system of the ratescaler should store the following basic data:

(1) Access tube identification number (to be keyed in by the operator).

(2) Date and time each time a sequence of readings is commenced - ideally recorded automatically from a built in clock, but otherwise keyed in by the operator.

(3) Counting period - keyed in by operator.

(4) Count rate at each depth (recorded automatically at the end of each count, together with the depth).

(5) Reading depths: three alternatives may arise here, the depth may have to be entered each time by the operator, the depths may be a standardised sequence and therefore implicit and not entered, or depth can be entered automatically from an electronic up-down counter incorporated in the cable lowering device.

In general. the fewest possible operations should need to be performed by the field operator, giving the least opportunity for error. The data should be displayed for examination by the operator before being entered into the memory by means of an "enter" button. Some method of avoiding errors due to low battery voltage should be incorporated. Where the operator has any choice (eg. count time), this should be recorded automatically once selected to preclude errors or confusion arising at a later stage.

A useful facility is the incorporation in the ratescaler of a site directory EPROM. The site directory at its simplest would contain the reading depths for each access tube. Once the access tube number, counting time etc had been entered the first reading depth would be displayed as a prompt to the operator. After entering the first observation, the next reading depth would be displayed, and so on until the sequence was completed. If the system had an automatic depth recorder, the indicated depth could be matched with the required depth before a count rate could be initiated, thus precluding errors due to incorrect depth placement. However, such a system would need to have an override facility to permit the operator to observe at non-standard depths if he wished.

The facility to step backwards and forwards through the memory in the field might be seen as an advantage to some users.

A further extension of this would be a system which incorporates in the site directory the calibration gradient and constant for each depth in each access tube, thus being able to convert count rates directly into water contents which are stored and displayed. Some might regard this as an advantage but others might wish to make decisions about calibration factors and standard count at a later stage and thus prefer to store count rates rather than water contents. There would of course still be the option to do the latter with this system merely by entering a calibration gradient of unity an intercept of zero, and a standard count rate of unity.
A further consideration is how to deal with the tube height - the length of access tube projecting above ground level. It is not always convenient (or even possible) to arrange for all access tubes to project by a standard amount, and the software therefore needs to be able to cope with different tube heights. Tube heights often vary seasonally as the soil swells and shrinks and it is a moot point as to whether it is more valid to assume a constant tube height (which can be entered into the directory) or to have the operator measure it each time and enter it by the keyboard. The ability of a system to deal with this problem should be considered.

Last, but not least, the ratescaler should be hermetically sealed; the effect of damp air being drawn into the housing as, for example, when it rains onto a sun-warmed instrument, can be disastrous to the electronics.

One of the potential advantages of the microprocessor ratescaler is simplicity of use and virtual elimination of operator errors, achieved through good programming and user interaction. Some systems now available are so complex and offer so many options that a skilled operator becomes essential, and this negates the potential advantages.

Perhaps the best advice that can be offered to anyone intending to purchase a microprocessor based system is to obtain one or two systems on loan for full evaluation before purchasing.

3. Measuring precision and random counting error

Soil water content θ is defined on a volumetric basis, as "volumetric water content" (VWC) i.e. :

$$\theta = \frac{\text{Volume of water}}{\text{Volume of wet soil}}$$

Expression of water content in relation to weight of soil is inappropriate not only to the method but to most of the used for which soil moisture data is required.

There is one source of error inherent in the design of the neutron probe which cannot be avoided and with which the user is therefore obliged to come to terms. This is the so-called "random counting error" which arises from the randomness of the radioactive decay process in the source which generates the neutrons. Because this process is truly random, the more counts that are integrated for the purpose of deriving each mean count rate measurement, the smaller the random error attached to it. Put simply, this means that if a series of counts are taken with the probe in a 'standard' environment (i.e. unchanging), each will give a somewhat different count rate, because in each identical counting period a different number of returning neutrons will have been detected. The longer the counting period the nearer to the true mean will the count rate be and the less will be the difference between the replicated counts. Clearly it is impracticable to count for the very long time necessary to obtain an answer which differs from the true count rate by an amount which is insignificant. A compromise therefore has to be made, counting for the minimum time required to achieve the minimum required precision. This can be calculated from one of the equations given below.

The random error is given by an expression which defines it in the form of standard deviation for a normal distribution (σ); i.e.

$$\sigma = N^{\frac{1}{2}} \quad .... \quad (1)$$

where N is the number of counts.

This may be re-expressed as the equivalent error in terms of count rate, σ_r, or in terms of moisture, σ_θ, thus:

$$\sigma_r = N^{\frac{1}{2}} \cdot t^{-1} = (R/t)^{\frac{1}{2}} \quad .... \quad (2)$$

where R = count rate (counts per second)
and t = counting time (sec)

$$\sigma_\theta = m \cdot \sigma_r \quad .... \quad (3)$$

where m is the gradient of the line relating θ to R. (m is the inverse of the sensitivity, ie. the change in count rate per unit change in moisture volume fraction.) This line is the calibration line in its simplest form, plotting volumetric water content (y axis) against count rate.

Thus, the random counting error in terms of soil moisture for any measurement can be calculated combining expressions 2 and 3:

$$\sigma_\theta = m \,.\, (R/t)^{\frac{1}{2}} \qquad \ldots \qquad (4)$$

In practice it is better to calibrate not in terms of count rate, R, but count rate ratio, R/R_s, where R_s is the count rate in a standard moderator (Figure 3). This procedure has many advantages (discussed below) and one disadvantage. This is that there is a small increase in overall error caused by the additional random counting error inherent in the term R_s. This must be minimised by taking a very long standard count (or by taking the mean of many short standard counts). It is

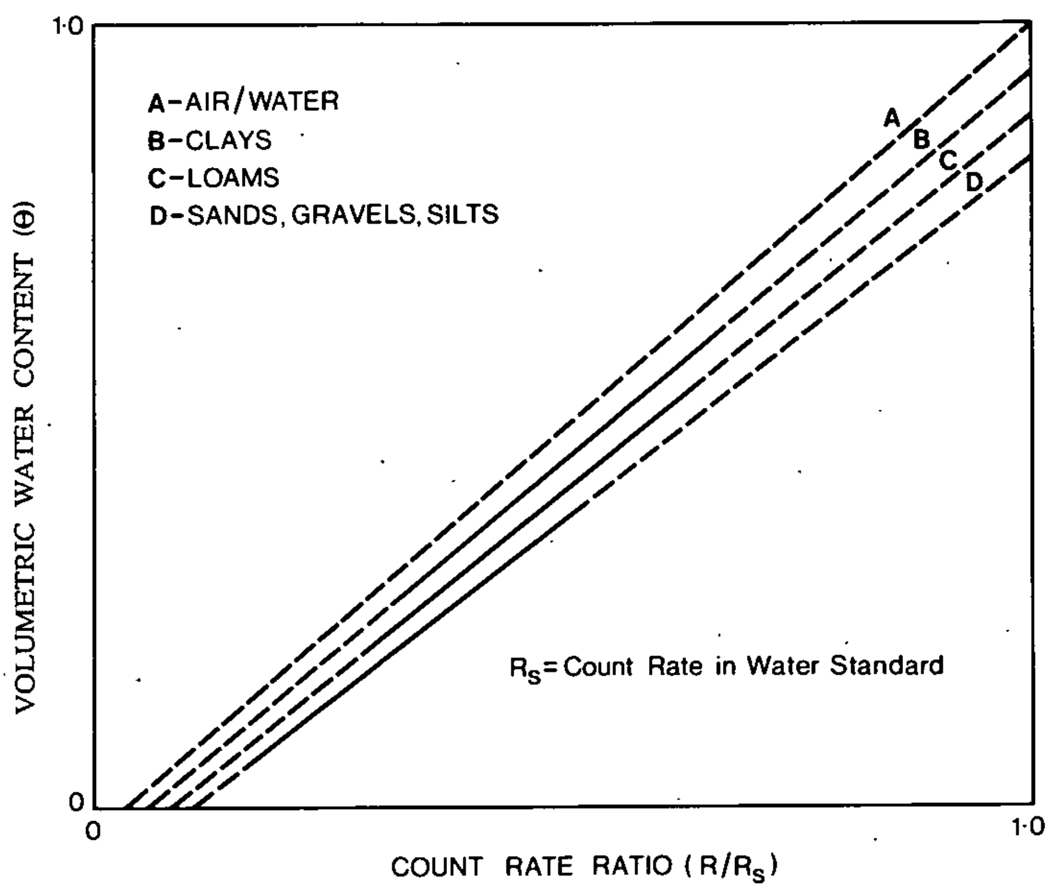

FIGURE 3 Typical calibration lines for the Wallingford probe, illustrating the differences between the basic soil types; individual soils will vary according to their bulk chemistry and density.

important that the measurement of R_S should be as precise as possible because one value for this term is usually applied to a whole day's readings. Equation 5 may be used to calculate the total random error, E_θ:

$$E_\theta = m' . \left[\frac{1}{Rt} + \frac{1}{R_S.t_S} \right]^{1/2} . \frac{R}{R_S} \quad .... \quad (5)$$

where m' is the gradient of the calibration line, $d\theta/d(R/R_S)$.

From this it is evident that the random counting error is minimised by increasing the counting times. Incidentally, it should be noted from the above that the random error increases with increase in soil moisture. A longer counting time may be appropriate in very wet soils to compensate for this factor (Fig. 4).

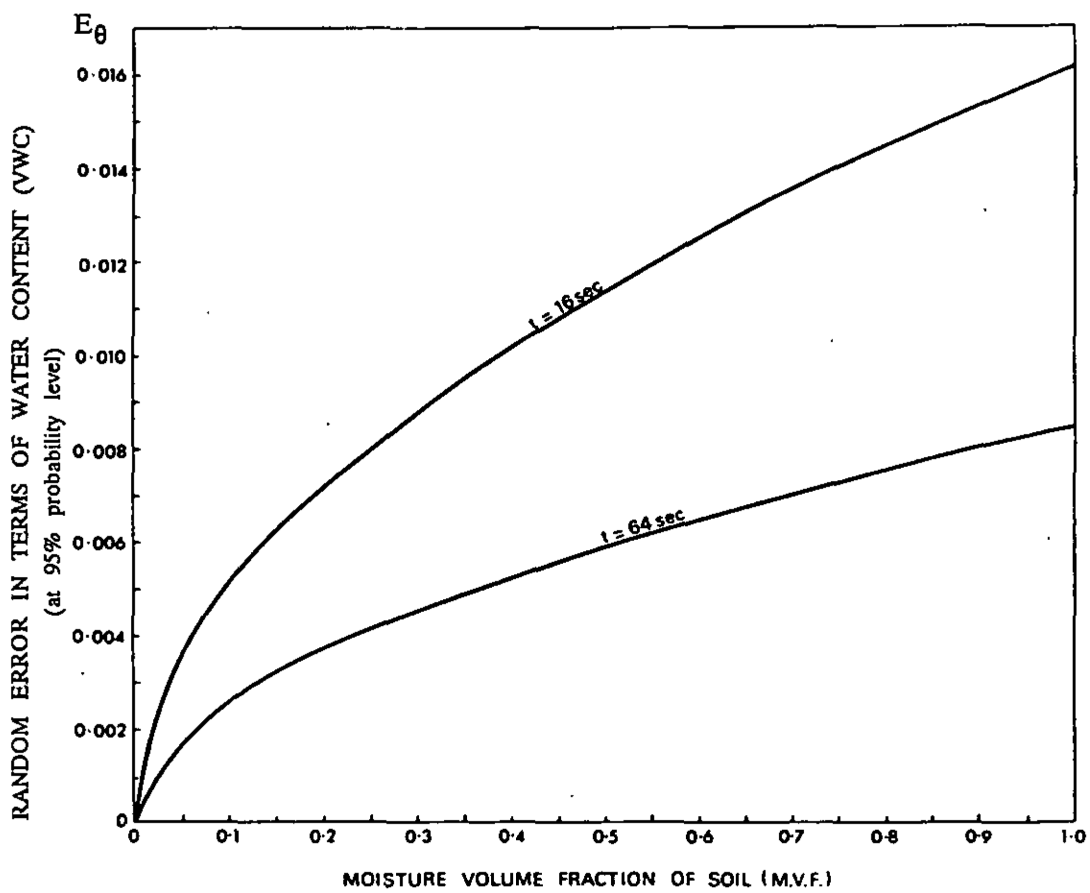

FIGURE 4 The variation of random error in relation to soil water content and counting time.

A simple worked example of the calculation of the random counting error is as follows:

Assume:
1. The standard is a water drum with a count rate, R_S, of 1000 c.p.s.
2. The gradient of the calibration curve, m' is 1.2
3. R, the count rate in the soil, is 500 c.p.s.
4. The counting time in the soil is 16 sec
5. The counting time in the water standard is 640 sec (the mean of ten 64 sec counts).

Then:

$$E_\theta = 1.2 \times \left[\frac{1}{500 \times 16} + \frac{1}{1000 \times 640} \right]^{1/2} \times \frac{500}{1000} = 0.0067 \quad \ldots \quad (6)$$

i.e. there is 68% probability that the error does not exceed 0.0067 VWC
there is 95% probability that the error does not exceed 0.0134 VWC
there is 99% probability that the error does not exceed 0.0201 VWC

4. Procedures for using the Neutron Probe

This section outlines basic procedures for measuring soil moisture storage changes in experimental catchments and plots by the neutron method.

4.1. Access tubes

The advantages gained by the use of this method are wasted if the access tubes are incorrectly installed, giving rise to unknown biases. Different problems of installation arise at every site and thus the following comments should be taken as a guide only on which to base improvisations where necessary.

4.1.1 Construction

Aluminium, aluminium alloy, brass, stainless steel and plastic tube have all been used. The factors affecting choice of material are susceptibility to corrosion, the need for mechanical strength, the cost, the intended depth of installation and the need to obtain the maximum count rate. Aluminium is the most 'transparent' material to thermal neutrons; brass reduces the count rate slightly but might corrode less in an alkaline soil. Stainless steel is the most durable material but due to the large neutron absorption cross-section of iron this gives a considerably reduced count rate: it has the advantage however that it is strong enough to be flush-coupled, making it possible to reach greater depths.

The access tubes normally used are constructed from drawn aluminium alloy tubing, 44.5 mm (1.75 inches) outside diameter, 41.25 mm inside diameter and 16 s.w.g. (0.054 inches or 1.6 mm) wall thickness, closed at the bottom by a tapered plug of the same material which may be either turned or cast. Some neutron probes require 2 inch OD (50 mm) access tubes. The end plug has a tapered shank which is forced into the open bottom of the access tube and its external shape is conical. The conical nose of the plug assists the location of the tube as it is forced down the hole and presses back into the side any projecting stones. A Bostik sealant is applied to the inner taper to act as a second seal. The tube is closed by a rubber bung at the top, and provision may have to be made to protect the bung against the curiosity of animals and the public.

4.1.2. Installation

While it is possible to prepare the hole for the access tube by means of a suitably sized soil auger, this method is unsatisfactory. The presence of stones can easily deflect the auger bit and where a stone is forced aside a cavity may be made in the side of the hole. The repeated movement of the auger up and down the hole when removing soil tends to enlarge the top of the hole, leaving room for water to run down the outside of the access tube. This can be overcome to some extent by backfilling from the surface, but this is not only difficult to do properly but leaves a zone of different density and structure around the access tube. Mechanical augers share the disadvantages of hand augers and cause much more disturbance.

The equipment used by the Institute of Hydrology for installing access tubes is listed in detail in Appendix 1 and shown in Figures 5, 6 and 7. Essentially, it consists of a guide tube, auger, rammer and base plate. For ease of handling guide tubes are made up as a set, with lengths of 1, 2 and 3 m; the auger can be extended to corresponding lengths of 1.15, 2.15 and 3.15 m. The guide tube has the same external diameter as the access tube and the auger head fits loosely inside it. The top end is strengthened with a collar to receive the blows from the rammer; it also has holes for a tommy bar, used for turning and withdrawing the guide tube. The lower end of the guide tube has a 45° internally bevelled cutting edge.

Disturbance to the ground surface is minimised if all the following operations are performed through a strong metal plate, about 50 cm x 50 cm x 0.5 cm with a 4.5 cm hole in the middle. This can be seen in Figure 5 with a guide tube inserted through it. All operations should be conducted from wooden duckboards to prevent damage to the surrounding area (Fig 5). If the installation is being made in a tall crop, a temporary overhead platform must be constructed so that the crop is not disturbed in any way.

The 1 m guide tube is used first, and is pushed gently into a 30 cm pre-augered hole. The auger is then used inside the guide tube to remove the soil to its full length, i.e. 15 cm beyond the bottom of the guide tube. The guide tube is rammed to this new depth (no more!) and the auger again used to clear the cuttings and to extend the hole a further 15 cm. This procedure is repeated until the hole is nearly 1 m deep, when the guide tube is replaced by the 2 m guide tube and the auger extended to 2.15 m; the same procedure is then continued changing to the 3 m guide tube if required. The technique has been used successfully in soil to 4 m and works quite well in soft rock such as chalk. Stones larger than the guide tube usually fracture without much trouble but small stones can be a nuisance as they block the guide tube and cannot be removed with the auger. Each situation can have its own problems and the basic technique may be adapted as required.

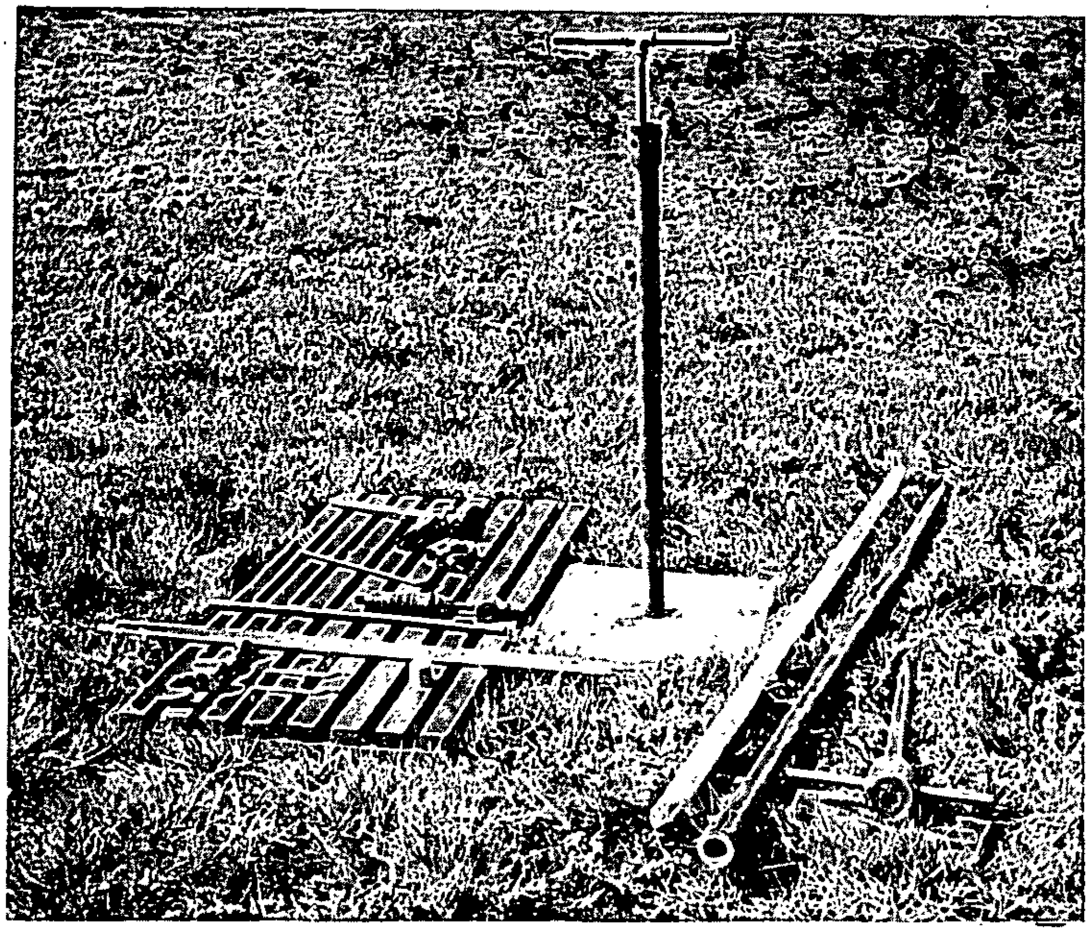

FIGURE 5. Access tube installation equipment, showing the 1 m guide tube inserted into the ground through the base plate with the 1.15 m auger inside.

The hole should be driven to about 5 cm longer than the total length of access tube to be below the ground, allowing in most cases a standard length of, say, 10 cm to protrude above the ground after installation. The access tube should be a tight fit and require gentle use of the rammer to push it in. It is important to make sure that the tube is fully "home" as otherwise it subsequently may sink further and confuse the position of the reading depths. If mowing or other operations with machinery are likely to occur, access tubes may be terminated at ground level, but this increases the possibility of water and dirt entering the tube, and a better type of bung may be called for. If the soil is freely draining at depth an open bottom tube can be used, allowing any surface water that gets in to drain out.

The access tube is closed at the top with a 50 mm rubber bung and if farm animals or squirrels are about, a short length of 5 cm tubing can be dropped over the protruding part of the access tube to prevent removal of the bung.

A wooden duckboard or similar device should be kept near to each site and always used to stand on when reading the tube. This prevents the surface soil and vegetation immediately around the access tube from being progressively damaged, thus affecting the soil water regime which is being measured.

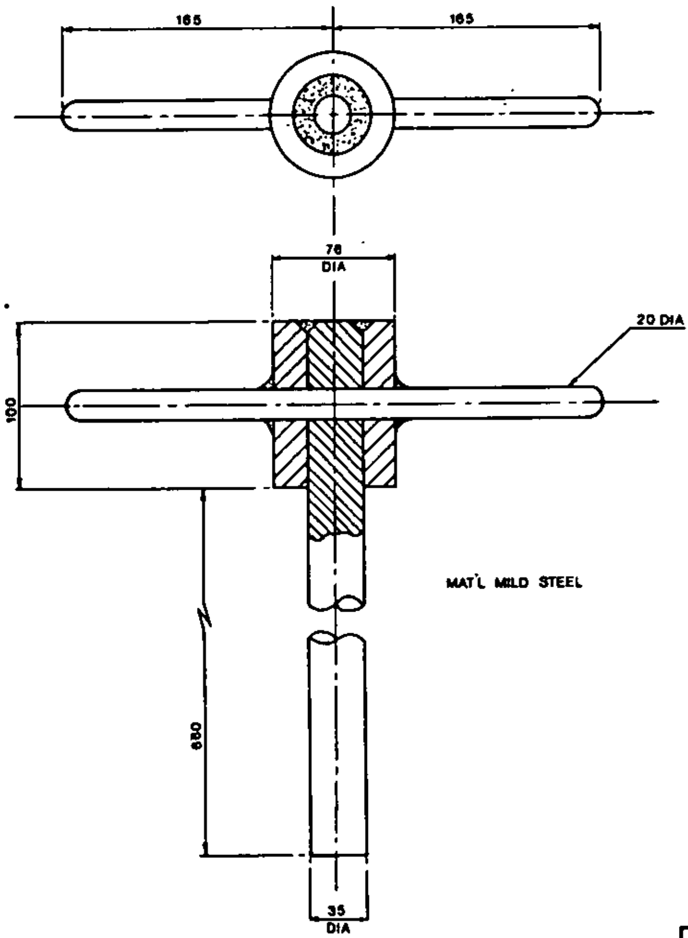

FIGURE 6.

Rammer for guide tubes

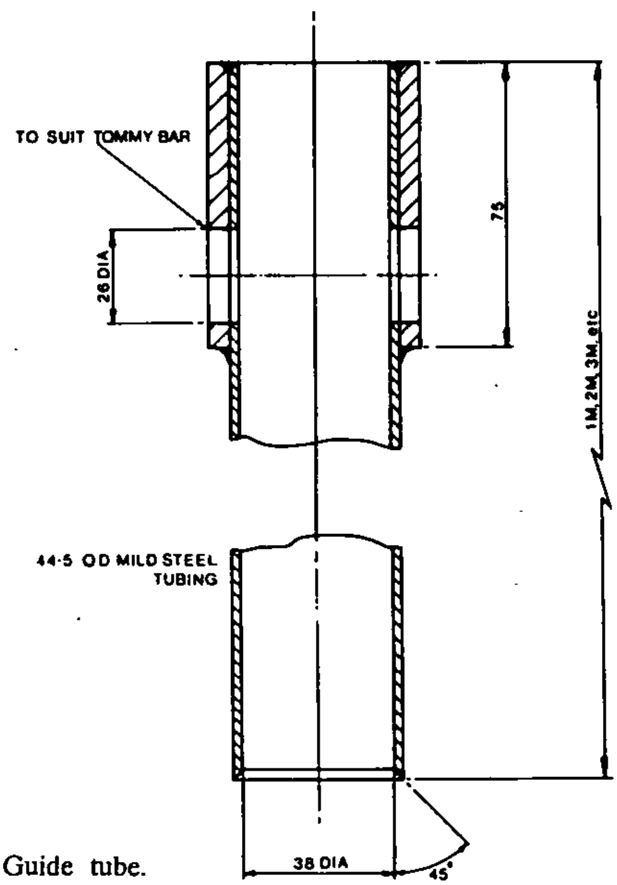

FIGURE 7. Guide tube.

It is essential both when driving in the guide tubes and when removing them to avoid lateral movements; there is always a tendency for the upper part of the hole to be enlarged due to this.

Guide tubes can be removed in light soils by lifting the tommy bar at both ends and at the same time rotating the tube. If this fails a jack can be used. A standard Volkswagen jack is ideal (Fig. 8), the foot engaging a stud in the base plate and the arm fitting into a socket clamped to the guide tube. A standard scaffolding clamp with a welded-on box section is easily made for this purpose.

A better but more expensive means of removing guide tubes (and access tubes) is to use a commercially available jack made by Messrs Flygt Pumps Ltd, Colwich, Nottingham and referred to as a "two-handled rod puller and ball clamp".

Under favourable conditions a two man team can be expected to install properly only 3 or 4 two-metre access tubes per day. If the tubes are longer or the soil conditions are difficult, one access tube per day may be the most that should be attempted.

When planning a research programme the time allocated for installing the access tubes properly should always be generous - poorly installed tubes give suspect data!

If large numbers of access tubes are to be installed in hard ground, a portable petrol driven jackhammer is useful, fitted with a rammer stem and adaptor to fit into the top of the guide tube. An Atlas Copco "Cobra" is shown in use in Figure 10.

4.2 Soil calibration

Soil water content (Soil moisture) is conventionally defined for the purposes of neutron probe calibration as the water that is, or would be, expelled from the soil by drying it at 105 °C. This is expressed as volumetric water content (VWC), the volume of water per unit volume of soil, or volume percentage, the former figure multiplied by 100.

Not all water is expelled at 105 °C, some remaining as water of crystallisation or hydration of various minerals, nor is all the hydrogen present as water. Hydrogen in organic compounds is not expelled at 105 °C but affects the count rate exactly as if it were the equivalent amount of water. However, these fixed forms of hydrogen are relatively constant for a given soil so that changes of count rate may be attributed entirely to changes in water content, assuming a constant bulk density.

Accurate measurement of the absolute soil water content is very difficult to achieve because it demands calibration for every site and, in some soils, for every depth. Both the slope and the intercept of the line must be established. Accuracy of moisture change measurements is much easier to achieve as it depends only on establishing the slope of the calibration line, and most soils differ very little in this respect within their own group, ie. clays, sand and loams. Precision of measurement depends upon the random counting error involved in each determination, and this can be predetermined by the use of equations 1 to 6.

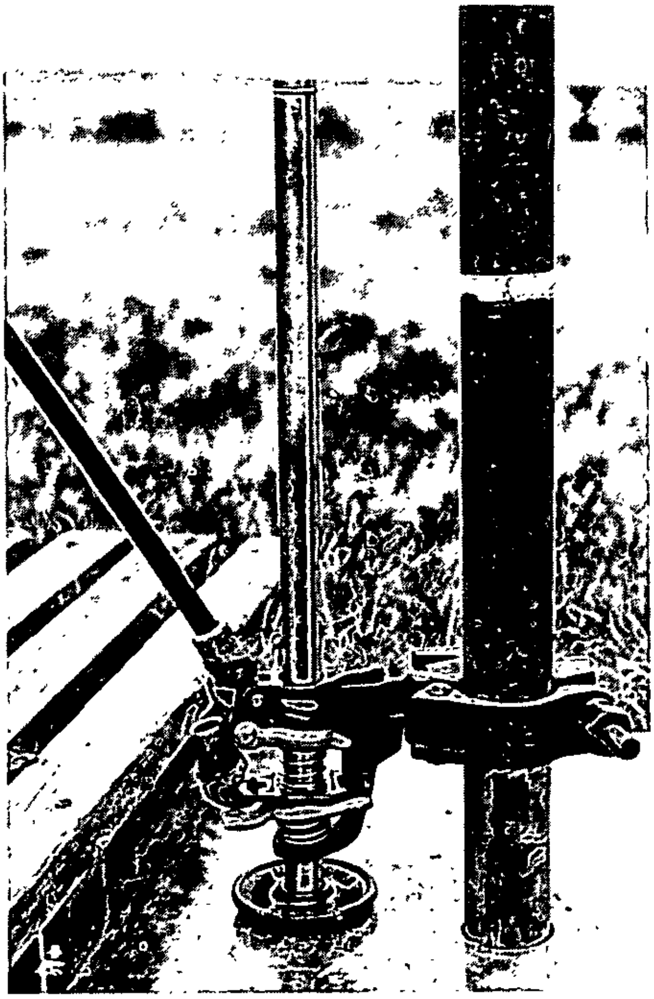

FIGURE 8

Volkswagen jack engaged in clamp fitted to guide tube.

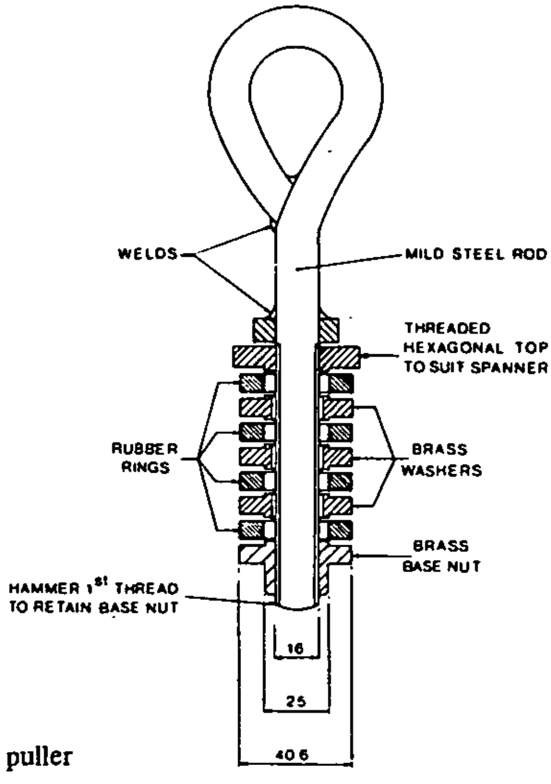

FIGURE 9

Access tube puller

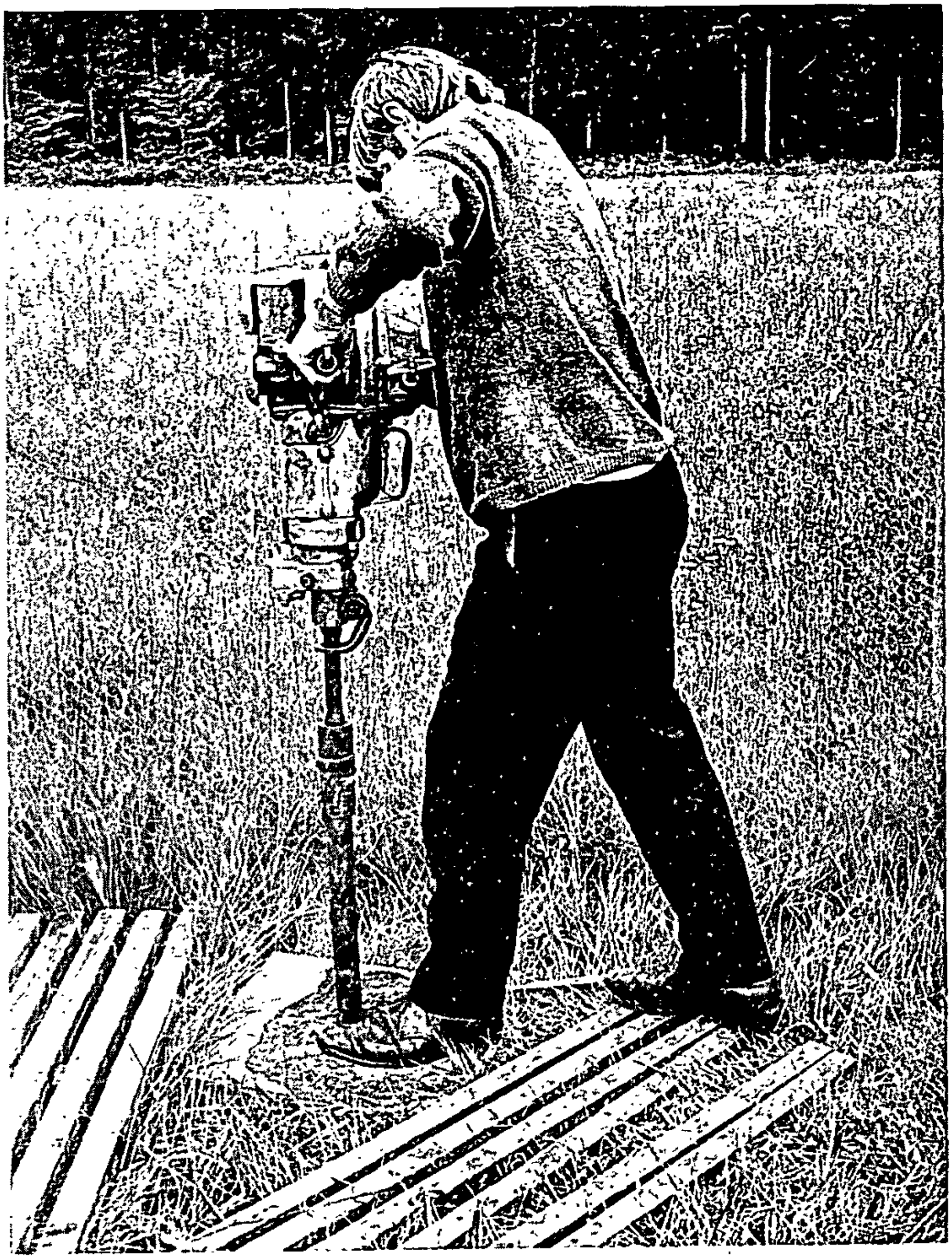

FIGURE 10. Petrol driven Atlas Copco mechanical hammer being used to drive in a guide tube.

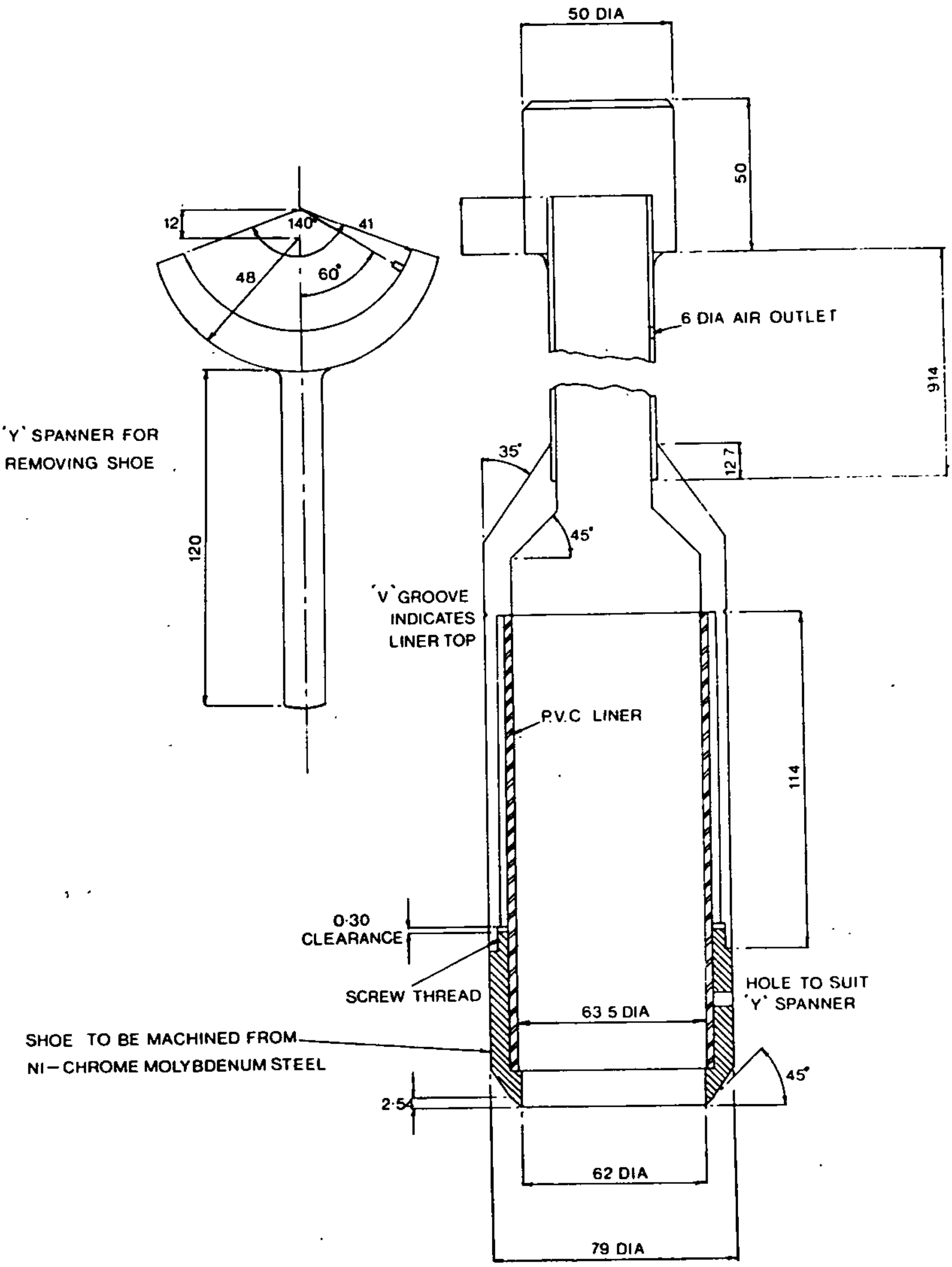

FIGURE 11. Design for corer with removable plastic liner.

Typical calibration curves for the Wallingford Probe are:

Silts, sand and gravels	$\theta = 0.790\ R/Rw - 0.024$
Loams	$\theta = 0.867\ R/Rw - 0.016$
Clay (and also Peat)	$\theta = 0.958\ R/Rw - 0.012$

There are three basic techniques for calibrating soil moisture against count rate or count rate ratio:

*theroretical calibrations based on soil chemistry or measured macro-cross sections;

*drum calibrations in the laboratory;

*field calibrations.

The count rate in a given soil is dependent upon the soil chemistry, which is constant, and upon the soil bulk density and water content, which are variable.

Theoretical calibrations are based on the very complete and accurate chemical analysis of about 25 soil elements. For certain elements like boron, chlorine and cadmium the accuracy required is of the order of a few parts per million.

The scattering and capture cross sections of these elements are known and hence the macro-scattering and capture cross sections of soil can be derived. From this information it is possible to predict the calibration curve for any bulk density value. This prediction is not perfect as mathematical approximations of the true physical situation are involved; for some soils results are poor. The method therefore is for most purposes of theoretical interest only, particularly as a single full chemical analysis may be very expensive and many might be required. A method developed in France by the Commissariate a l'Energie Atomique utilises direct measurement of the macro-cross sections of field samples in an atomic pile.*

Laboratory calibrations are performed in large drums in the laboratory and can be very accurate. However, only soils which are homogeneous in chemistry and texture, which can be repacked uniformly in the laboratory to something like their field conditions, and which do not change their dry bulk density with water content are suitable. According to these criteria only gravel, sand or silt soils are suitable for drum calibrations. The drum must be of accurately known volume, water-tight and at least 1.5 m in diameter and 1.2 m deep; a smaller drum is often used but the results can only be regarded with suspicion due to the escape of neutrons, particularly at the dry end of the moisture range. The four or five tonnes of soil required to fill the drum is taken from an accurately dug pit, mixed, air-dried and weighed in portions into the drum where it is packed as uniformly as possible to the original field bulk density. An access tube is

installed in the centre of the drum and a count rate profile plotted to confirm that the packing is uniform; this should be demonstrated by a uniform plateau in the count rate profile through the central part of the drum. The probe is set in

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the centre of this plateau and a large number of counts are taken and averaged. The mean count rate is plotted against the calculated moisture content of the drum through a pre-placed point. Water is then measured into the drum through a pre-placed plastic tube reaching to the bottom, so that air is displaced upwards as the water rises. When the profile is saturated the counting operation is repeated and the mean count rate plotted against the calculated moisture content to give the second calibration point. Some workers repeat this operation for a different packing density but this is difficult because unless the soil is packed to a high density it tends to contract in volume when the soil is added. The success of the method is heavily dependent upon the work at all stages being performed with great experimental rigour; if there is any doubt about either of the two points the entire operation is invalidated. It also depends upon the validity of the assumption that the calibration curve is effectively linear over the entire range.

Field calibration is the simplest and easiest method of calibration, but due to soil heterogeneity and various sampling errors there is often a fairly wide scatter in the calibration points. Many points are required from each site, therefore, to perform a linear regression; since these must span the moisture range of the soil, it usually takes a year to finalise the calibration. The main possibility of error lies in the introduction of a common bias in the measured moisture content which is obtained thermogravimetrically from soil cores. All soil corers tend to compress the soil to some extent unless great care is taken and this results in error in the volume water content.

To obtain each point a temporary access tube is installed at the chosen site fairly near to a permanent tube. Precise count rates are obtained from the appropriate depth or depths and six known-value soil cores are then taken from close around the tube at each depth. The soil corer used in this relatively undisturbed sampling technique is shown in Figure 11. Figure 12 shows the corer and a 10 cm 'Jarrett' auger which is marked by tape at the depths at which samples are to

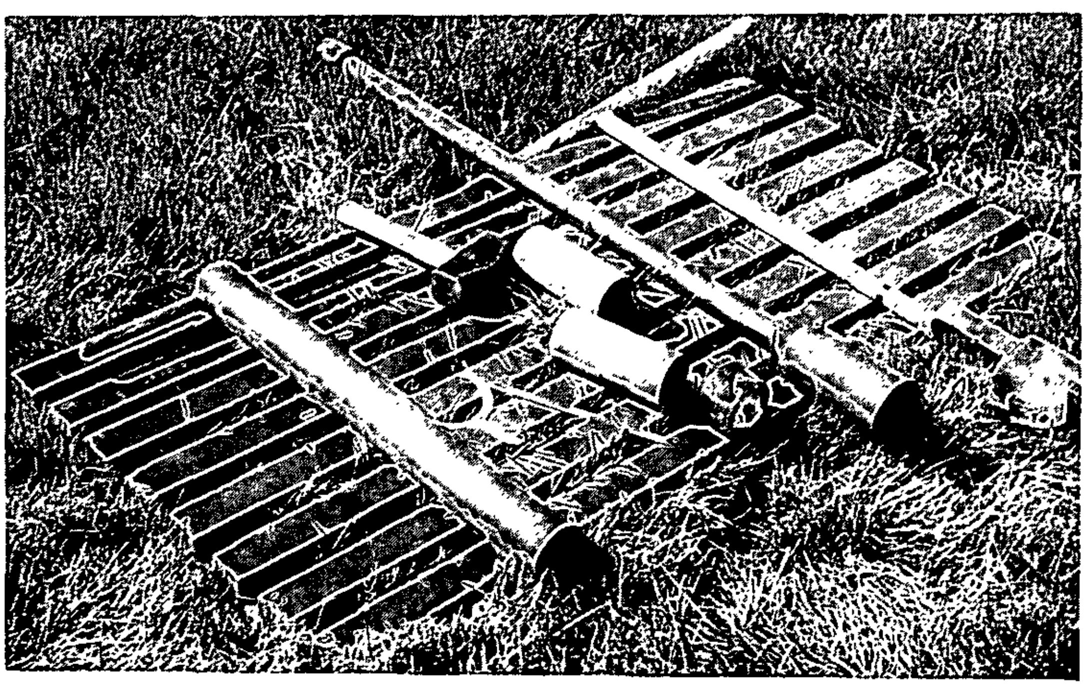


FIGURE 12 Corer with accessories and Jarret auger

be taken.; it is used to open a hole to these depths. The corer is then used to take the soil sample. The corer is shown with the PVC liner exposed between it and the cutting shoe. Any tendency for the core to be compressed, is reduced if the plastic liner is clean, smooth and lightly greased. An actual sample is shown next to this with one end trimmed and the other end with the surface grass still attached to the soil core. The PVC liner retains the sample but care must be taken to drive the corer to exactly the correct distance so as not to compress the sample. A groove on the outside of the corer barrel shows where the top of the PVC liner is in relation to the soil surface, and the corer should not be driven beyond this mark. The volume of the cores is known and hence their loss in weight after drying at 105 °C (for about 2 days) gives the moisture volume content and the dry bulk density. The moisture content is plotted against the count rate to give one calibration point. It is difficult to apply this method to depth exceeding 1 m without digging a pit. An example of a form used to record the data needed for one calibration point is shown in Fig. 13.

Vachaud et al (1977) performed calibrations using disturbed soil samples, such as can easily be obtained with a screw auger, to derived θ_w values (defined below). They used a gamma density probe to determine wet bulk density (ρ_w) values at the same depths. Volumetric water content can be determined from these data using the expression:

$$\theta = \rho_w \times \theta_w$$

where ρ_w = weight of soil in field condition/volume of soil and

$$\theta_w = \frac{\text{weight (volume) of water lost in oven drying}}{\text{weight of soil in field condition}}$$

A technique developed by IH for capacitance probe access tube installation and calibration offers a promising alternative to the above methods. Disturbed samples of known *in situ* volume are taken continuously from within the access tube as it is installed; this method gives great detail to the profile, the samples each representing a 4 cm layer (Bell, Dean and Hodnett, 1987).

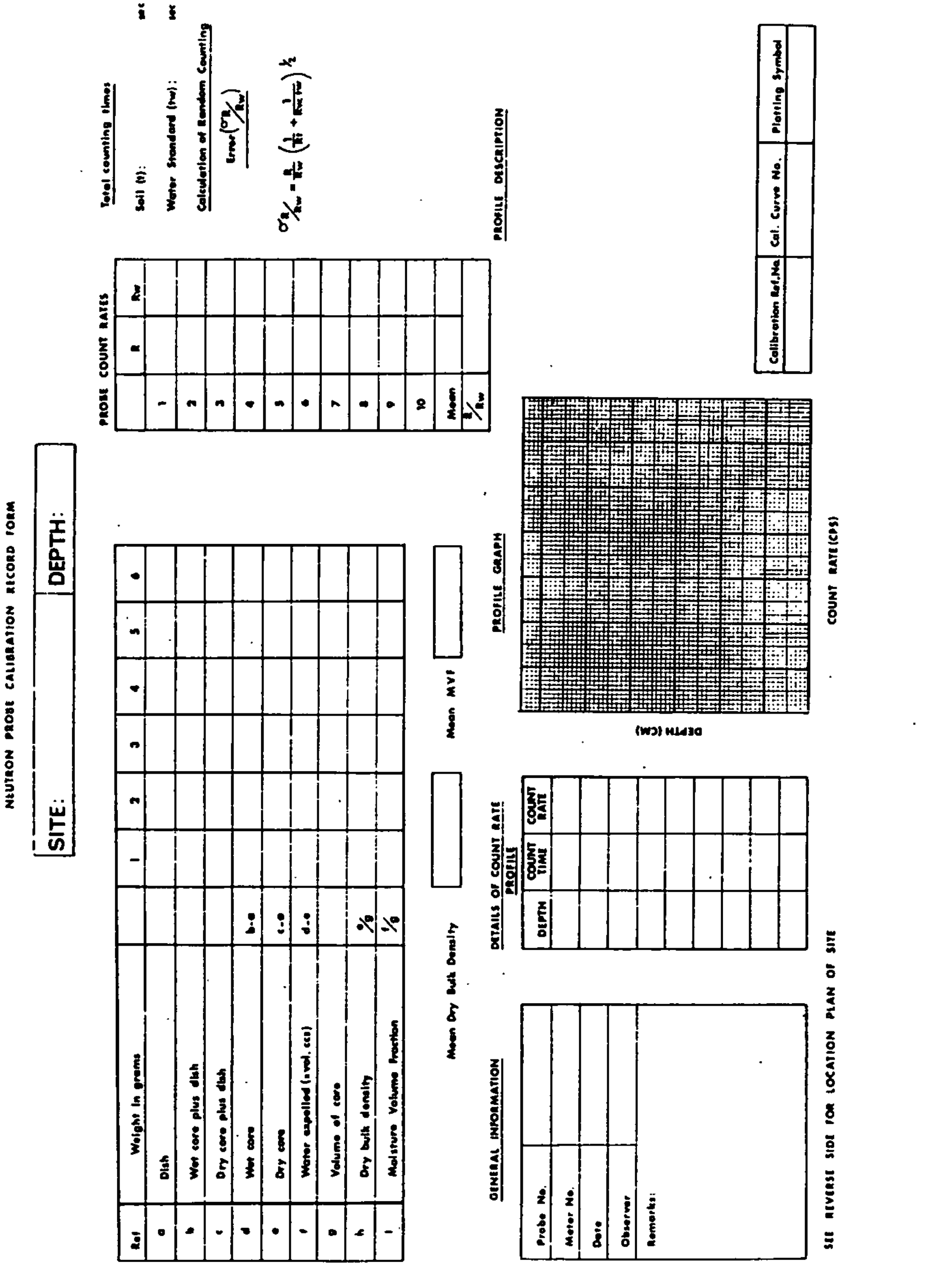
4.3 The use of laboratory and field standards

It has become general practice to calibrate in term of R/R_s against moisture content, where R is the count rate in the soil and R_s is the count rate in a laboratory standard. This procedure ensures continuity of records and removes any bias due to the following causes:

- if the probe should fail and, after repair, have a different sensitivity

- if slow ageing of components occurs

- if more than one probe is in use, because no two probes have exactly the same count rate.



NEUTRON PROBE CALIBRATION RECORD FORM

SITE:	DEPTH:

Ref	Weight in grams		1	2	3	4	5	6
a	Dish							
b	Wet core plus dish							
c	Dry core plus dish							
d	Wet core	b-a						
e	Dry core	c-a						
f	Water expelled (=vol. ccs)	d-e						
g	Volume of core							
h	Dry bulk density	e/g						
i	Moisture Volume Fraction	f/g						

Mean Dry Bulk Density

Mean MVF

PROBE COUNT RATES

	R	Rw
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
Mean		
R/R_w		

Total counting times

Soil (t): sec

Water Standard (tw): sec

Calculation of Random Counting

Error $\left(\sigma_R/R_w\right)$

$$\sigma_R/R_w = \frac{R}{R_w}\left(\frac{1}{Rt} + \frac{1}{R_w t_w}\right)^{\frac{1}{2}}$$

GENERAL INFORMATION

Probe No.	
Meter No.	
Date	
Observer	
Remarks:	

DETAILS OF COUNT RATE PROFILE

DEPTH	COUNT TIME	COUNT RATE

PROFILE GRAPH

DEPTH (CM)

COUNT RATE (CPS)

PROFILE DESCRIPTION

Calibration Ref. No.	Cal. Curve No.	Plotting Symbol

SEE REVERSE SIDE FOR LOCATION PLAN OF SITE

FIGURE 13 Example of form used to record all the data required for one field calibration point.

Laboratory standards may be made of any moderating material (ie. one containing a high hydrogen density) which is also chemically and physically stable. Among solid materials probably the best choice is a non-chlorinated plastic such as polythene, while water is the ideal liquid moderator. The use of small moderators as standards is not desirable, partly because they are difficult to reproduce accurately, partly because they do not contain the sphere of influence and this allows external influences to affect the concentrate, but mainly because the count rate produced in them is dependent upon their own temperature. This is why transport shields are not good standards. The advantage of water above anything else is that it is cheap, available anywhere, has no unpleasant characteristics and contains as much hydrogen per unit volume as virtually any possible alternative. A drum full of water is reproducible anywhere and gives a count rate which effectively is that obtained in an infinite volume of water providing that it is not less than 60 cm deep and 50 cm in diameter; this count rate seems to be substantially independent of the temperature of the water. The access tube is fixed vertically in the axis of the drum and counts are taken at a standard point in the centre of the water profile.

Before use each day the probe should be put in the laboratory standard and a long count taken, based preferably on at least 5×10^5 counts (about 8 min at 1000 c.p.s.). This figure should be recorded as a routine procedure in a special book kept for that purpose, detailing the date, operators name, probe number, scaler number, and any other relevant remarks. It is helpful also to plot these figures at the same time on a wall chart so that any drift or abnormality is immediately noticed. This figure is adopted for R_S.

In the field it is best to do a short count (eg. 16 sec) at each site before and after the readings, with the probe locked in its shield, standing on the access tube.. This 'shield count' is entered on the field card (Figure 14) as a rough confirmation that the probe was functioning at that time. This information may prove useful during analysis many months later if a query is raised about the validity of a certain measurement; this figure is not used for calculation purposes. The shield is too small to be used as a standard because the count rate is influenced by its temperature and the presence of the soil and surrounding matter.

4.4 The sphere of influence concept and measurement in the surface layer

The count rate of slow neutrons depends upon the probability of any fast neutron emitted eventually being scattered back to the detector. It is easy in a homogeneous material to plot surfaces of equal slow neutron density around the source and to show that the maximum flux is at the source. However, the

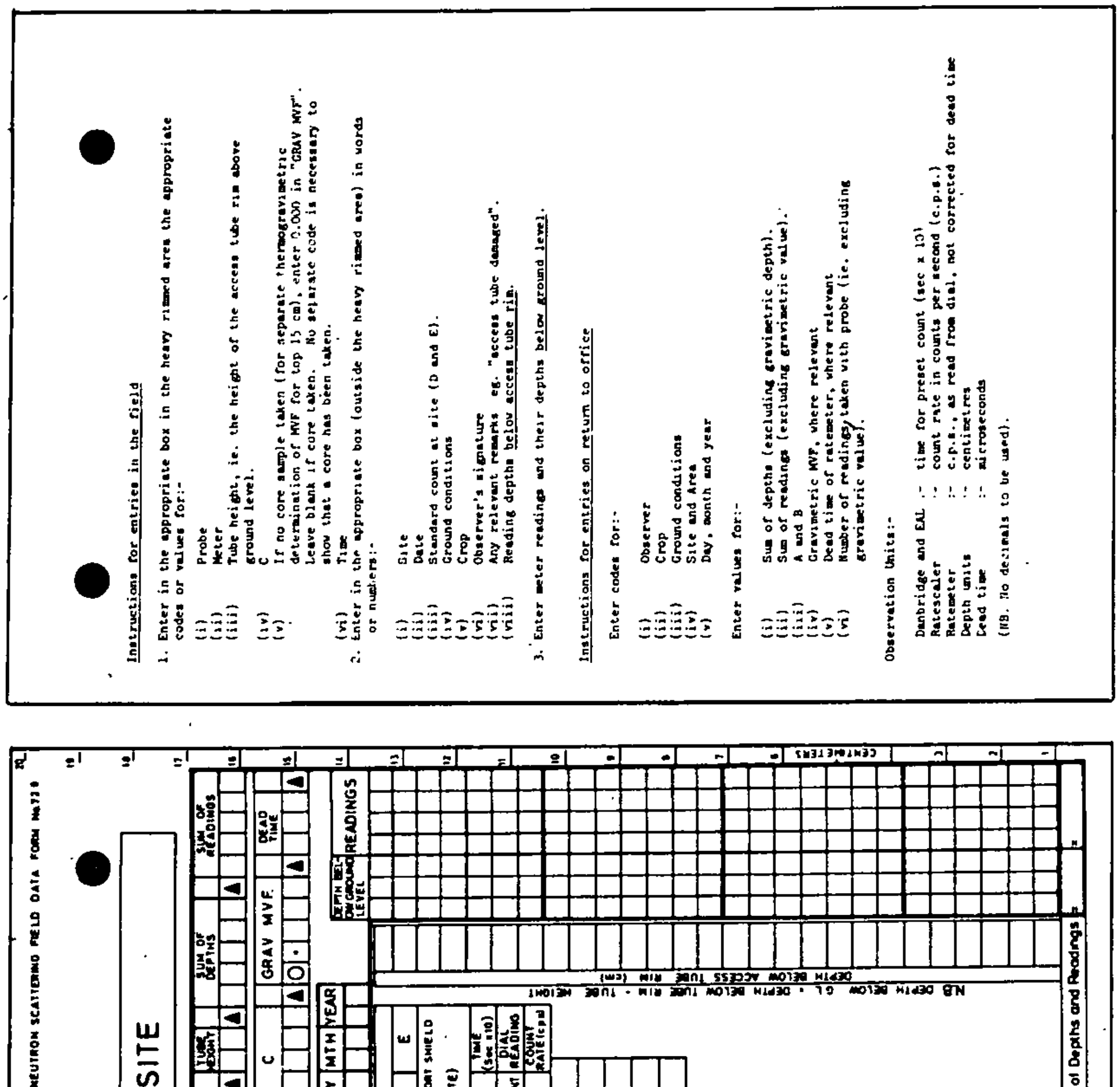


FIGURE 14. An example of a field data card; figures are entered in the field and punched directly from the card.

The reverse side of card gives the instructions for filling it in correctly.

neutrons which become thermalised farthest away from the detector have very little chance of getting back to it, partly due to inverse square law and partly because thermal neutrons are easily absorbed. It is thus very difficult to define a distance at which a certain change in moisture will affect the count rate significantly. In non-homogeneous, natural soil the situation is very complex and perhaps the nearest one can get to defining the radius of influence is in the laboratory using two homogeneous soils of differing count rate separated by a sharp, horizontal interface. In this simple situation the radius can be defined as the distance from the interface at which the count rate is changed by a certain value, equivalent to, (eg.), 1% by volume of water. However, this is dependent not only on the water content of each of the two materials but also on the difference between these water contents. In practice, for soil in the field it is reasonable to assume that unless there is a marked interface involved, the effective radius is about 15 cm in wet soil and up to perhaps 30 cm in very dry soil. Expressed in another way this may be taken to mean that the indicated moisture value is the mean for a sphere of that radius, centred at the measuring point. The optimum spacing of readings is therefore 10-15 cm and no greater resolution can be gained by decreasing this figure. It is inherent in the method that the resulting moisture profile is smoothed, although the integrated profile total water content is not affected by this to any significant extent unless there are very steep moisture gradients in the profile.

It should be noted that the size of the sphere of influence depends not upon the source strength but on its energy. All probes employing the same source material will have the same sphere of influence, irrespective of the strength of the source, assuming the access tubes are of the same diameter and material and that the source/detector geometries are effectively the same.

A disadvantage of the neutron method is the difficulty of obtaining reliable readings in the top 20 cm of soil. The density of the 'cloud' of thermal neutrons which is in dynamic equilibrium with the surrounding soil is affected by the probe approaching the surface where there is a loss of fast and thermal neutrons from the soil system. The extreme difference in count rate between these two media means that as a probe is brought near to the surface a negative error is introduced which rises to a significant level (1%) about 20 cm below the surface in wet soil and at 30 cm in dry soil. Some workers attempt to overcome this by the use of so-called 'neutron reflectors' which increase the density of the thermal neutron 'cloud' in the soil. However, the apparent improvement in count rate so gained is not a true measure of the moisture present but largely represents only the back-scattering property of the reflector. Even if the reflector is made from material of high atomic mass which can return fast neutrons to the soil the geometry is no longer spherically symmetrical about the source. The difficulty of carrying and fitting a heavy reflector in the field is also a disadvantage.

The application of special calibration curves for exact specific depths in the surface zone can give reasonable results, but it is often difficult to define accurately the exact surface of the soil, and an error in depth relocation of as little as 1 cm can cause a significant error in indicated moisture where there are steep moisture gradients (Figure 15). Furthermore, if the probe is placed at 10 cm depth, the same quantity of water within the top 20 cm can give a different count rate, depending on its distribution within that zone, eg. following heavy rainfall.

Another solution to this problem, for flat surfaces at least, is the use of 'surface extension trays' (Figure 16). These are circular, perforated fibreglass trays, 15 cm deep with a central tube which can be fitted over the normal access tube protruding

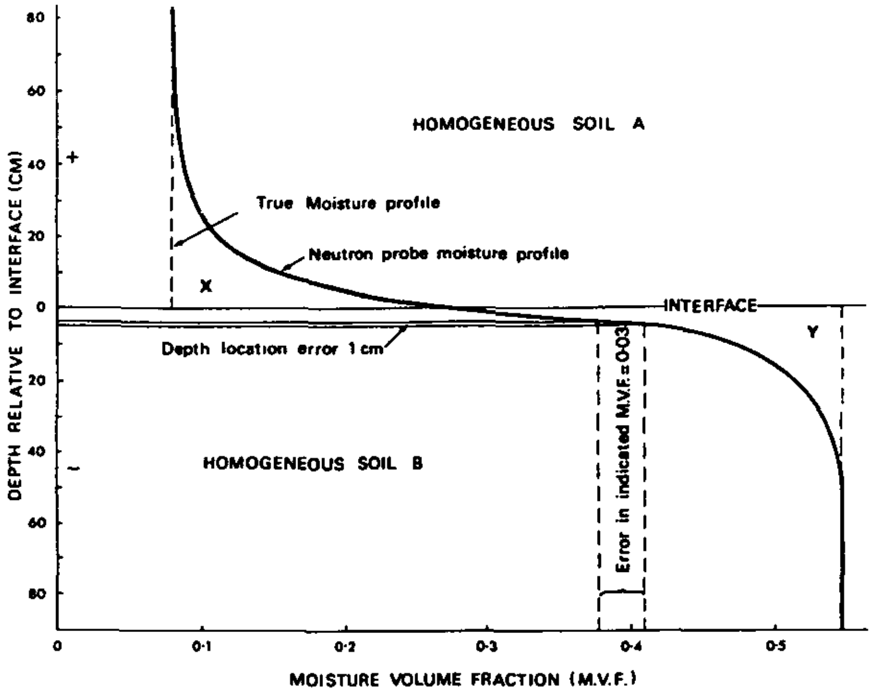


FIGURE 15 An illistration of the importance of accurate depth location of the probe in the vicinity of steep moisture gradients. Another error illustrated here which is unavoidable from the inequality of areas X and Y; this is usually neglected.

from the ground. The tray is filled with the local topsoil in which the appropriate crop is grown. When not in use the tray is kept nearby in a lined, open-bottomed recess in the ground with its top surface at ground level. When readings are to be taken the tray is lifted out of its recess and placed over the access tube, where it acts as an extra layer of topsoil with approximately the same chemistry, density and moisture content. This effectively raises the soil-air interface by 15 cm and so allows reasonably valid readings to be taken only 10 cm below the real ground surface, utilising the normal calibration curve. One such unit should be kept at each site. The method cannot be applied where a growing crop would be damaged by the tray, nor where the tube is installed in sloping ground.

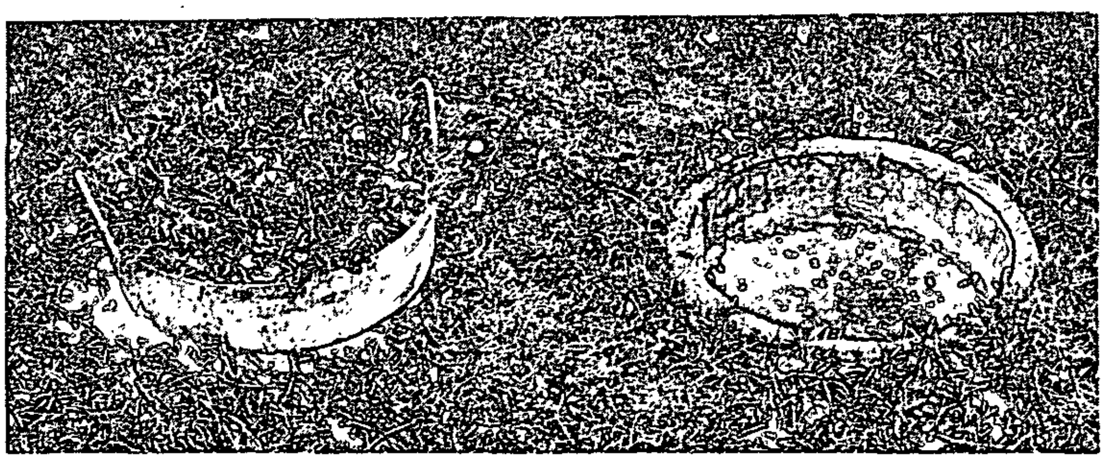


FIGURE 16 The surface extension tray fitted over an access tube.

4.5 The design of access tube networks

Neutron probe design has improved steadily during the last thirty years. The instruments now available are generally smaller, lighter and reliable and their principles of operation are better understood and applied. Emphasis must now be placed on improving the design of access tube networks.

As with the installation of access tubes and calibrations, network design should not be treated lightly nor left to uninterested staff. At least one person who also has an interest in the analysis of the results should closely supervise all stages of the work. If this is not done, undetectable biases can be built into the data.

4.5.1 Absolute measurements or moisture changes?

Most research interest is in soil moisture *changes* rather than *absolute* measurements. The neutron method is ideally suited to this purpose because it can measure changes very precisely. The worst problems of calibration are thus avoided because the absolute moisture values need never be known accurately; only the slope of the calibration curve of count rate against moisture is therefore important and this greatly reduces the need for numerous calibrations. The differences between the slope of the calibration lines for most soils is small and unless there are large densities or chemical variations in the soils within an experimental area, the use of a single representative calibration curve is probably justified. Inevitably, each depth at each site may be expected to deviate to some extent from the calibration applied, but provided that the curve used is carefully established and tested by field calibrations, the unknown but small calibration biases at each depth will tend to cancel out in the calculation of profile and areal moisture totals.

4.5.2 Measuring precision and number of sites

One of the most important factors to consider is the balance between the number of measurements which it is practicable to make in one working day, the acceptable random counting precision required for each measurement and the number of sites necessary for the network to be representative of the catchment or plot. The precision of any measurement for a given source-detector system depends on the number of pulses counted (equation 1); the longer the time spent on each determination, the greater will be its precision. However, there is usually only a limited time available to take readings in the field and a compromise between two extremes therefore has to be made. These are:

(a) measuring the maximum number of sites, devoting the least possible time to each and thus accepting a relatively high random error (i.e. a low individual precision), or

(b) long, high precision determinations at only a few sites.

As a general principle (because of the arealy variable nature of soil textures) for areal estimates of soil moisture storage changes it is better to set up an experimental project with the maximum possible network of access tubes that can be read in the time available. After careful analysis of the first year's work it is generally possible to reduce and refine the network. This emphasis on sampling the largest possible number of sites is particularly important when dealing with short-term water balances as the change in stored soil moisture may be very large. Because the number of sites sampled in a given time period is maximised, an attendent loss of precision of individual measurements is experienced. This is acceptable becase the random errors will tend to cancel out due to the large number of determinations involved in the areal estimate and the biggest possible sample of soil water variability within the catchment will have been achieved. After several years' records have become available it should be possible to define 'index' sites which correlate closely with the network (catchment) mean, and it may then be feasible to abandon the main part of the network. Ideally, the few index sites remaining can then be read more frequently and more precisely. This conclusion also applies to plot experiments.

4.6 Factors affecting network design

The setting up of an access tube network so as to sample a catchment area in a fully representative way demands much care. Inevitably there has to be a compromise between the availability of funds, time and manpower on the one hand and the ideal network on the other. The design of a sampling network for a catchment depends on so many variables that each case is unique.

Various factors liable to affect soil moisture storage are soil permeability, texture, layering, depth, geology, water table conditions, slope angle, position on slope, altitude, aspect and vegetation. The relative importance of these differs with locality, but the dominant factors must be identified and taken into account in the network design so that each situation is sampled adequately.

Consideration must be given to the problem of how best to distribute the sites within an experimental area, having first decided what the maximum practicable number of tubes is likely to be. There are two basic approaches which may be summarised as follows:

Stratified random sampling. Individual sites or groups of sites are assumed to represent defined 'strata' of the catchment, the areas of which are used as weighting factors in the computation, so that weighted mean catchment soil moisture storage changes are calculated. In this (statistical) context a 'stratum' is an area of land, continuous or otherwise, the soil moisture characteristics of which are presumed to behave in a reasonably consistent way, distinguishing it from the adjacent strata. This area would be defined provisionally according to a classification based on one or more of the relevant criteria suggested above (e.g. slope angle and aspect), but the results would have to be tested as soon as sufficient data had accumulated. Alternatively a number of sites is allocated to each stratum in proportion to its area so that a simple average will give directly the catchment mean soil moisture storage change.

Random sampling . The siting of the access tubes is randomized completely for this approach which demands much less prior knowledge of the factors controlling the distribution of soil moisture in the catchment. It may be the easiest way of deriving enough knowledge to apply a stratified random sampling technique at a later stage. The main objection to a completely randomised network is that many more sites are necessary to obtain an overall estimate of the mean to a given degree of precision, and this requirement may conflict with practical aspects such as the difficulty of reaching and reading large numbers of sites in the time available.

4.6.1 Small-scale siting considerations

Having defined on a map the proposed sites for the access tubes, there remains the problem of actually selecting the position in the field of each tube. Unless the map is of extremely large scale, the exact site position will be imprecisely defined on the ground and this will allow an undesirable degree of subjectivity to be introduced by the person who sites the tube: a metre one way or the other can sometimes make a big difference. In this way a significant and network bias can arise at this stage. For example, if there are trees in the vicinity of the site, the tubes might unintentionally be sites equidistantly between the trees, a situation which might not represent the mean behaviour of the soil of the area as a whole. If the crop is planted in rows or has any form of systematic periodicity, this must be known so that the access tube distribution is not accidently matched to it.

4.6.2 Network design for plot experiments

Much of the preceding discussion has been more relevant to catchment hydrology than to plot experiments for the study of water use by crops. Factors such as lateral variation of soil type, slope, altitude and aspect tend to be constant over small areas and thus are less important when designing a network for a plot. The most important factors controlling soil moisture variability within plots are usually the planting pattern and small-scale heterogeneity (which may be very large!).

In general it is probably better to install a regular grid network rather than a random one, extending at least over the smallest areas which may be considered to be representative of the area or crop being studied. To start with as many access tubes should be installed as can possibly be read in the allocated time, allowing a reading rate of about 8 to 10 tubes per hour (assuming about ten 16-sec readings per tube).

The alignment of the grid, spacing of the rows and choice of origin might be based on either of two alternative philosophies, depending upon circumstances.

(a) with the tube spacing and alignment of rows in no way matching the intervals between the rows of plants, or

(b) with the layout chosen deliberately to match the alignment and spacing of the planting rows, perhaps (for example) with the tube lines alternately running along and between the rows.

The choice will depend upon the questions which the study is designed to answer.

When crops are densely planted, repeated access over an extended period of time by observers may cause disturbance to the crops and the soil and some sort of overhead bridge must be constructed for access. Even in the case of short grass, precautions must be taken against the effects of trampling by the observer. If the readings are taken weekly or more frequently the soil surface rapidly becomes depressed in a ring around the access tube, the soil surface sometimes actually rising 2 or 3 cm adjacent to the access tube within a radius of 15 cm. This is accompanied by changes in water inputs, balance of species and their degree of growth in the area around the tube, which thus soon becomes non-representative. To prevent this from happening duck-boards should be used while readings are being taken and care taken to reduce human activity in the area generally.

4.7 Data processing

4.7.1 Data errors

Measurements taken in the field with a neutron probe can contain many errors, most of which can be categorised as follows:

human error	-	misreading the display or entering the data incorrectly on the field card; applying the wrong calibration curve.
		setting the probe at the wrong depth, or wrong setting of scaler controls;
instrument error	-	intermittent spurious readings which are not bad enough to be obvious, or various types of drift.

Computer processing of soil moisture data with built-in quality control facilitates the detection and removal of most of these errors, although data can be processed manually if no computer is available or if the project is short and the amount of data small. The computation procedure briefly described below (see also Figure 18) is that which has been developed at the Institute of Hydrology over a number of years; this is offered merely as a general example and different users would almost certainly re-organise the details to suit their particular circumstances.

The depths, count rate readings and other data are entered in the field on to field cards (Figure 14) which are based on sections of normal computer coding sheet. The cards are later inspected in the office, after which the information is entered on to punched cards directly from the field cards, thus avoiding the need for manual transcription and the possibility of more errors being introduced.

4.7.2 Quality control of data

The punched-up data is run with a quality control program which checks for a number of possible errors. Two examples of such checks are:

(i) The field operator on return to base totalises the depth and the count rate columns on each card and enters these figures in special boxes on the card. The computer adds up the same two columns of figures and checks that the answers agree. If a "keying-in" error has been made they will not agree and the data is rejected for manual re-checking.

(ii) Reasonable upper and lower limits for the moisture value are pre-allocated for each depth at each site, and these figures are stored in the computer. Calculated moisture values are checked by the computer to confirm that they are within these limits and this reveals any gross errors. Care must be taken to make sure that the limits selected are not too strict as there is a possibility of rejecting a few genuine readings which reflect extreme but transient conditions.

4.7.3 Processing data to produce line printouts and graphs

When the data are 'clean' they are run with a test processing program in monthly batches; this produces a line-printer output detailing the readings and results for each depth for each site and gives the water content of each soil layer and the total profile water content (Figure 17). The line printer also produces a simple profile graph for each day. Visual inspection of this constitutes the final stage of the quality control. In order to deal with different soil calibrations for various depths and sites, each site/depth has a soil code allocated to it; this is stored in the computer and tells the computer which calibration equation to apply.

At the end of a longer period, usually a year, the data are re-run to produce site summary sheets and catchment summary sheets from the line-printer and also various graphical outputs, as required. The raw data and the processed data are stored on separate magnetic tapes for future use.

The foregoing procedure maximises the chance of detecting errors and each type of data is presented in a standard way which aids retrospective analysis and understanding.

DATE 060578 TIME 0945 GMT CATCHMENT RFTJA(92) TUBE 34

PROBE 151 METER 319 OBSERVER M HODNETT(49) CROP BARE SOIL(03) GROUND CONDITION DRY/CRACKS(01)

METER TYPE - RATESCALER

COUNT TIME FOR STANDARD 6400 SECS. COUNT RATE IN WATER STANDARD 977. COUNT TIME FOR SOIL 16 SECS.

DEPTH (CM)	READING	MVF+/-ERROR	DOWN ACC. WATER TO RDG DEPTH(MM)	QUALITY CONTROL PROFILES	LAYER (CM)	WATER IN LAYER +/-ERROR (MM)	DOWN ACC. WATER IN (MM)
20	150.	.1146+/- .0025	22.9		0- 30	34.4+/- .8	34.4
40	297.	.2377+/- .0036	58.1		30- 50	47.5+/- .7	81.9
60	339.	.2720+/- .0038	109.1		50- 70	54.4+/- .8	136.3
80	351.	.2829+/- .0039	164.6		70- 90	56.6+/- .8	192.9
100	377.	.3045+/- .0041	223.3		90-110	60.9+/- .8	253.8
120	411.	.3331+/- .0042	287.1		110-130	66.6+/- .8	320.4
140	443.	.3599+/- .0044	356.4		130-150	72.0+/- .9	392.4
160	466.	.3792+/- .0045	430.3		150-170	75.8+/- .9	468.2
180	488.	.3975+/- .0045	508.0		170-190	79.5+/- .9	547.8
200	495.	.3951+/- .0046	587.3		190-210	79.0+/- .9	626.8
220	479.	.3929+/- .0046	665.8		210-230	78.0+/- .9	704.8
240	495.	.3959+/- .0046	744.8		230-250	79.2+/- .9	784.0
260	474.	.3892+/- .0046	822.9		250-270	77.8+/- .9	861.8
280	477.	.3960+/- .0046	900.6		270-290	78.0+/- .9	939.8
300	471.	.3833+/- .0045	978.9		290-310	76.7+/- .9	1016.5
320	491.	.3917+/- .0046	1055.7		310-330	78.3+/- .9	1094.8

WATER CONTENT OF UPPER 320 CM. = 1055.7+/-3.4 MM.

(STANDARD ERRORS QUOTED IN ALL CASES)

FIGURE 17. Example of line printer output of a single set of observations from one access tube.

4.8 Integrated profile water contents

The individual measurements of moisture content down the soil profile are each multiplied by a layer factor, F, to give the water content of that layer, normally expressed as depth of water in centimetres, W. The layer factor is usually taken as the distance between the half intervals on either side of the appropriate measuring depth. The random counting error, E_m, is multiplied by the same factor to give the equivalent error in water depth, E_w. The total water content of the profile to any given depth is the sum of the individual water contents, while the error attached to the total is the square root of the sum of the squares of the individual errors. This may be tabulated as follows:

Depth (cm)	Moisture Content M (MVF)	Random Error E_m (MVF)	Layer Factor F (cm)	Water in Layer W (cm. water)	Random Error E_w (cm. Water)
1	M_1	$E_{m\,1}$	F_1	$M_1 \quad F_1$	$E_{m\,1} \quad F_1$
2	M_2	E_{m_2}	F_2	$M_2 \quad F_2$	$E_{m_2} \quad F_2$
3	M_3	E_{m_3}	F_3	$M_3 \quad F_3$	$E_{m_3} \quad F_3$
n	M_n	E_{m_n}	F_n	$M_n \quad F_n$	$E_{m_n} \quad F_n$
Total Profile Water Content				ΣMF	$\pm (\Sigma E_W{}^2)^{½}$

5. Some Applications for the Neutron Probe

The labour involved in setting up an access tube network and performing the necessary calibrations restricts the use of the neutron probe to medium or long term experiments requiring repeated determinations from the same sites and depths. While the main applications of the neutron probe tend at present to be hydrological and agricultural research, the possibilities of extending its use into routine management in the context of irrigation and water resource studies should be considered seriously. The main application of the neutron probe may be summarised as follows:

	Application	Context
1.	Measurement of soil water storage for water balances	*catchment and plot studies for various hydrological purposes
2.	Determination of soil water reservoir characteristics	*process studies *land use capability studies *agricultural research *planning irrigation regimes
3.	Measurement of crop water use and drainage	*feasibility studies for irrigation schemes *optimisation of irrigation water use *soil salinity control *evaporation measurement *groundwater recharge measurements *infiltration and drainage studies *studies of chemical pollution of the unsaturated zone.

5.1 Measurement of soil water storage for water balances

The water balance equation at its simplest may be written:

$$Q = P - E - \Delta S$$

where Q = runoff (output)
P = precipitation

E = evaporation
ΔS = increase in soil water storage

This version of the equation (which excludes groundwater inputs and outputs) is applicable both to the one-dimensional, single profile situation, and to the catchment (or plot) situation, In the latter case, areal mean values are used for P, E and ΔS, and the accuracy of these terms is dependent upon the representivity of the sampling network.

The most indirect of the measurements of these components is evaporation. Even when meteorological data are available to permit reasonable Penman or Monteith-Penman calculations, there is still considerable uncertainty attached to this term, particularly in hilly and/or forested catchments. The provision of reliable measurements of ΔS removes an area of uncertainty from the water balance and makes it much easier to test the other terms. The simplest use of soil moisture determinations is as an indicator of 'null-point' conditions when the soil moisture storage is at a standard state, so that ΔS can be put to zero.

5.2. Determination of soil water reservoir characteristics

The neutron probe can be used to measure *in situ* soil characteristics such as:

*the field capacity profile (in situations where this is a valid concept)
*the available water capacity
*the abstraction limit profile
*the saturation profile
*the drainage capacity
*the drainage time constant

With the addition of soil water potential measurements taken with tensiometers other characteristics can be determined, such as:

*the moisture characteristic (the curve relating soil water potential to water content)
*the unsaturated conductivity characteristic (relating soil water potential to conductivity)

This type of information is needed for many purposes - agricultural research, catchment modelling, agricultural soil surveys and physical studies of soil and water interaction.

The advantages of determining these qualities *in situ* are that unacceptable disturbances are avoided, no artificial conditions are imposed and the values obtained are almost certainly much closer to the natural 'macro' values than values derived from laboratory measurements conducted on comparatively tiny samples. For example, the biggest component of conductivity in some soils might be due to fissures, root channels, worm holes or shrinkage cracks, none of which can be adequately reproduced in laboratory determinations conducted on small samples.

These parameters are best obtained by means of specially designed short term experiments, but retrospective analysis of long term routine records will also yield some useful information. The former approach is more suitable for intensive plot scale studies and depends on very frequent measurements. The latter is perhaps more useful with long sequences of readings taken regularly on a routine basis, weekly or monthly, as is usually the case in catchment studies. Examples of each category are given below:

5.2.1 Example 1 - Artificial saturation of a soil profile and plotting the soil water storage decay curve

An access tube is installed in the centre of a reasonably uniform area having a diameter at least as extensive as the access tube depth. This is saturated by surface irrigation or ponding and the neutron probe is used to monitor the profile to determine when this stage is reached. Irrigation is then stopped, the site covered by a plastic sheet to stop additional input from rain or loss by evaporation. Frequent soil moisture measurements are then taken until the profile has drained to an equilibrium. The data from this can be presented in the form of graphs as in Figures 18 and 19, from which it is possible to define constants such as the drainage capacity, saturation limit, field capacity and some sort of drainage time constant. Where artificial wetting of the profile is not possible a suitable period of wet weather can be used, probably in the winter, and the same procedure is followed. In this case it may be possible only to determine field capacity if there is any doubt that maximum wetting was reached.

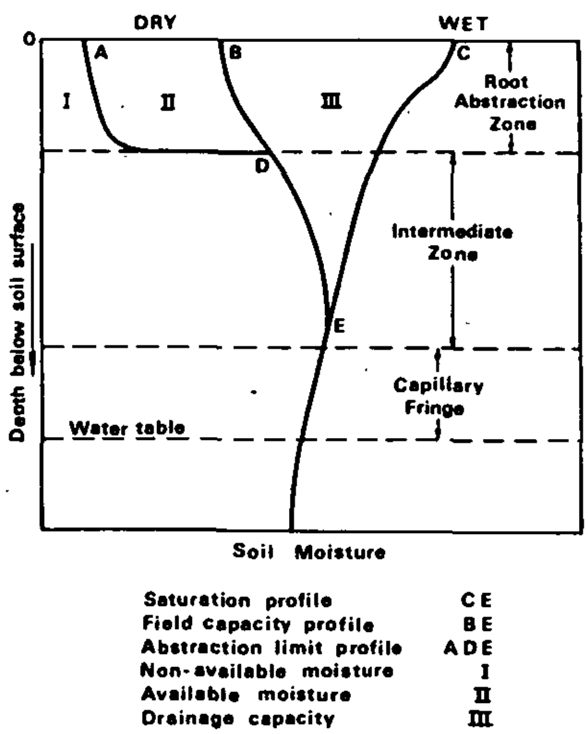


FIGURE 18

An idealised representation of the definable soil water storage profiles - 'saturation', field capacity and abstraction limit

5.2.2. Example 2 - Determination of soil parameters from long term soil moisture records

The results of this type of analysis may be less accurate than in the case of a specially designed experiment, but useful results of some kind can nearly always be obtained, depending on the quality of the data, the frequency of the readings and the length of records. In climatic and soil situations where there is a meaningful field capacity value, records can be analysed to extract data for all profiles during the winter months of (eg.) December, January and February, excluding those taken where there was rain within (eg.) the preceding three days. Examination of these

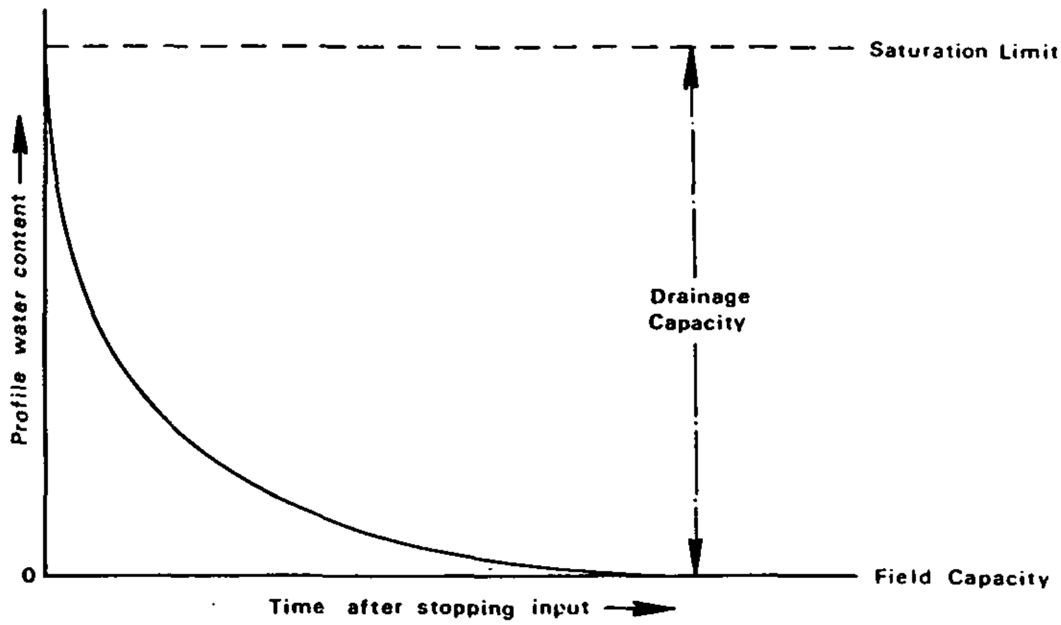


FIGURE 19 An idealised curve of drainage of total water stored in a soil profile, decaying from a state of nominal 'saturation' down to field capacity.

profiles should show very little variation and the mean of these profiles may therefore be adopted as the field capacity profile. The abstraction limit profile can be derived in a similar way during the growth season, providing that this is sufficiently dry - in other conditions knowledge of the abstraction limit and available moisture capacity would in any case be of less practical interest. A soil moisture deficit plateau is eventually reached at each depth, after which little further abstraction can take place from that depth; the water to satisfy transpiration requirements is then taken from deeper in the profile where water is still available (Figure 20). If rain has recently fallen some recharge of the surface layers may have occurred and abstraction will be resumed until this is removed again. The mean value of the basal plateau for each depth may be adopted as the 'abstraction limit' for that crop at that depth, and thus the 'abstraction limit profile' may be built up by using data from different depths at different dates and stages of crop growth. This may not necessarily agree with the 15-bar definition of wilting point as the latter does not take account of soil conductivity or crop characteristics. However, the difference between the abstraction limit profile (so defined) and the field capacity profile is probably the best measure of 'available moisture'.

Time series graphs of water content changes at each depth (eg. Figure 20) also show at what stage during the growing season the roots start to abstract water from each depth, the root abstraction zone (total effective rooting zone) and the date when each depth returns to field capacity at the end of the growing season. The abstraction zone may extend considerably below the depths where roots occur due to the establishment of upward potential gradients.

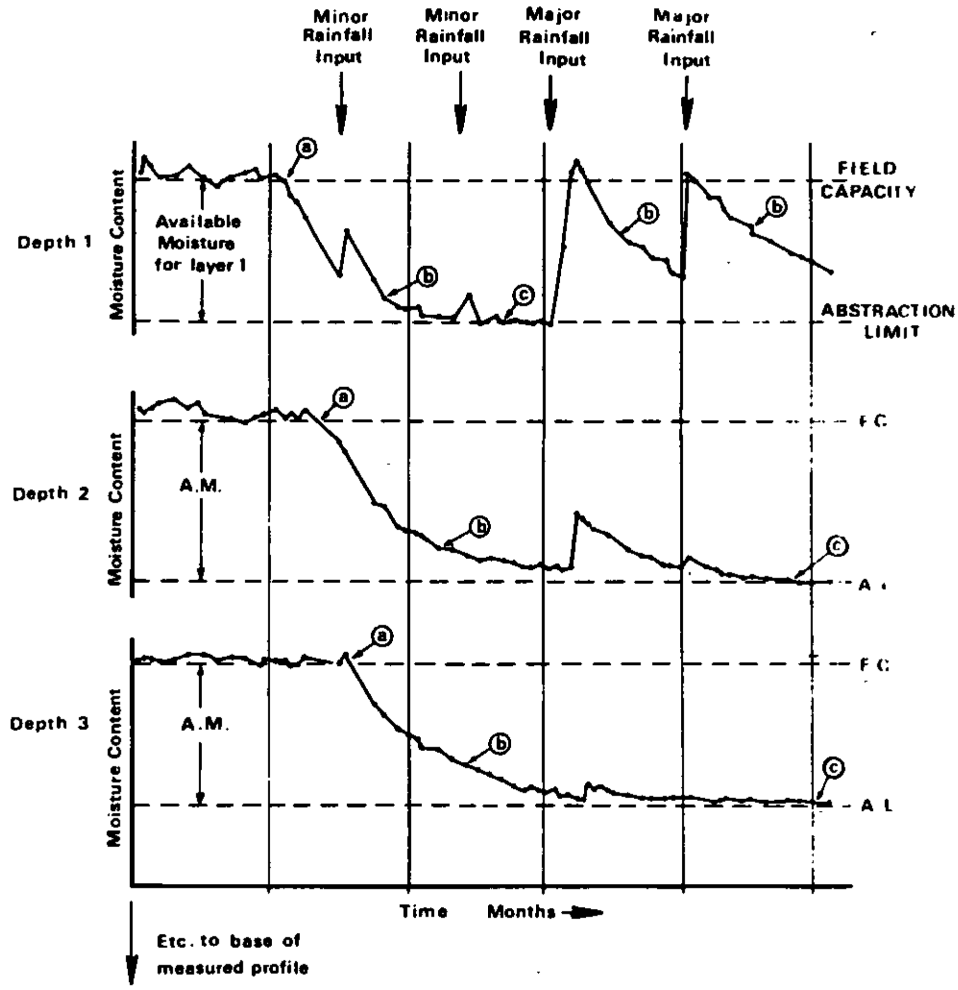


FIGURE 20 Changes in soil moisture at different depths as the root system of an annual crop develops in a freely drained profile; from this kind of record field capacity and abstraction limit profiles may be derived and the available moisture determined. If the data is sufficiently precise and frequent, transpiration estimates may be made, which can be very accurate if inputs or losses at the base of the measured profile are known.

5.2.3 The use of field-measured soil characteristics in mathematical models of catchment response

With the advent of the neutron probe, soil moisture deficit (SMD) has become one of the easiest variables to measure and this is therefore used increasingly, for example, for testing the validity of predicted soil moisture deficits and for short period models when changes in the soil moisture storage become important. It seems likely that in addition to providing these measurements of the soil water storage variable, the neutron probe could be valuable for obtaining numerical values for soil constants for use in mathematical models.

The reason for developing more physically based models is that although models of the optimised parameter type can be used to predict the ouput hydrograph of a catchment very accurately from a given rainfall input, their use is limited. Because of the absence of 'real' identifiable physical components these models cannot be used with any confidence to predict the response of nearby catchments or even of their own internal sub-catchments. Neither can the results of land use changes such as afforestation be predicted. Lastly, the success of the model depends upon the availability and reliability of long-term rainfall and runoff records.

Eventually, therefore, the use of field-measured soil parameters for use in mathematical models in place of optimised parameters may increase. The problem is that soil is such a variable material that to sample any one quality to produce a realistic representation of its areal mean value is very difficult. At present perhaps the best that can be done to help the modeller is to give him some idea of the magnitude and variability of various soil factors such as, for example, available water capacity, field capacity, drainage rates and deficit probabilities, the unsaturated conductivity characteristic and the moisture characteristic.

5.3 Crop water use studies and recharge measurements

The neutron probe can be used in a number of ways at different levels of sophistication to estimate crop water use and drainage from the soil reservoir. During the active growth season the decay curve of the soil moisture reservoir can be used to estimate transpiration subject to certain reservations below. Periods with no rainfall can be used or rainfall can be added in to the calculation, providing that the input is less than the SMD (inputs exceeding the SMD would produce a drainage loss). The application of the neutron probe alone to estimate transpiration is limited because although the soil moisture changes can be measured very precisely, the direction of the movement remains unknown and can only be resolved properly by the additional use of tensiometers. For example, the total loss rate could include an unkown drainage component if the soil is a slow draining, relatively impermeable soil. Alternatively, a shallow water table may be supplying an additional transpiration component. The soil moisture depletion rate can be assumed to represent crop water use in the following situations, with shallow rooting vegetation:

(a) where the subsoil is a clay with very low hydraulic conductivity;

(b) where water inputs from rainfall and/or irrigation are insufficient to generate drainage losses through the base of the measured profile.

In some situations where the above criteria cannot be met, the soil moisture loss rate can be regarded as an upper limit of the transpiration rate. In the case of a poorly draining soil with a deep water table (greater than 3 m) the soil moisture loss rate can be regarded as the upper limit for the transpiration rate, because in the deeper part of the profile water may still be draining. Alternatively, where a short rooted crop is growing on a free draining soil with a shallow water table (say 1.5 m) the loss rate can be regarded as a lower limit for the transpiration rate because an additional upward component from the water table might be suspected.

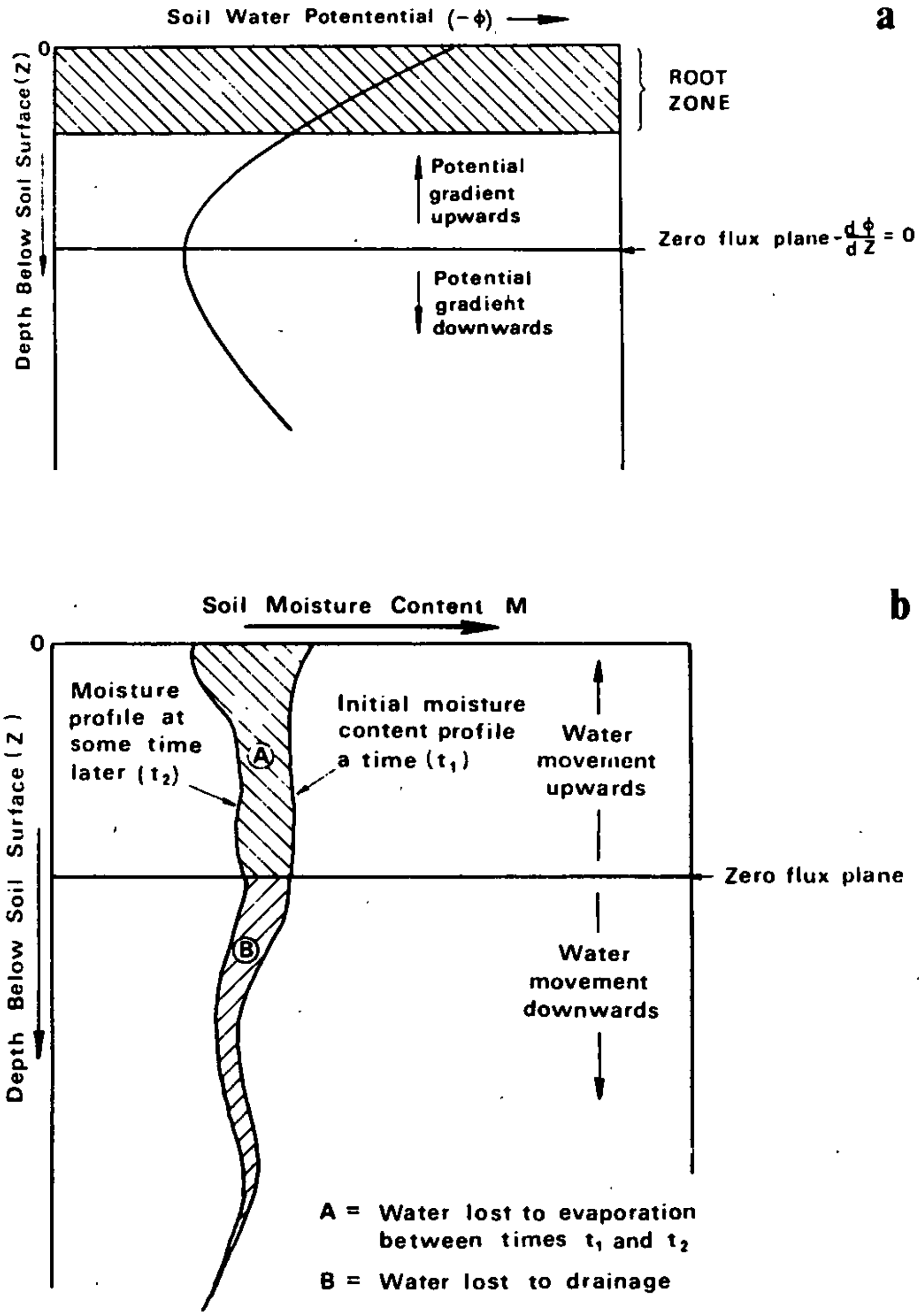


FIGURE 21

(a) Identification of zero flux plane from tensiometer measurements

(b) Calculation of moisture fluxes from moisture content measurements and depth of zero flux plane

A further problem associated with the use of the neutron probe for this purpose is that the biggest changes occur in the top layer, where the measurements are least valid due to the presence of the soil/air interface. The use of the surface extension tray or the application of a special calibration curve probably overcomes most of the difficulties, but if the sudden input of water to the surface occurs due to a storm or irrigation application, the temporary presence of a very non-uniform distribution of water in the top 20 cm will temporarily invalidate the readings for this zone.

The combined use of tensiometers and neutron probes provides a more sophisticated and powerful technique by which it is possible to measure unsaturated fluxes of soil water *in situ*. The methods described below are most easily applied in conditions where there is little lateral variability in soil properties or root distribution, ie. where vertical potential gradients can be assumed. Ideally this condition would occur in a short, uniform crop growing in deep soil. The methods can be applied in less ideal situations but the quality of the measurements may be less and more areal replication may be necessary to compensate for the lateral flux components resulting from various heterogeneities.

Applications include:

- *direct measurement of drainage to groundwater
- *direct measurement of crop water use
- *studies and control of irrigation efficiency
- *monitoring magnitude and direction of movement of chemical ions (pollutants) in the unsaturated zone; for this purpose chemical determinations of soil water samples are required.

Methods using meteorological data (eg. Penman) are widely used to estimate evaporation and drainage. While such methods may be quite successful in estimating potential evaporation, the derivation of actual evaporation from this is less reliable, particularly in non temperate climates. There is still little generally applicable data for the response of most tropical crops to soil water stress and atmospheric demand. Soil physical methods given below, referred to as the zero flux plane method and the hydraulic conductivity/potential gradient method respectively, offer a means of measuring evaporation and drainage directly although their applicability depends on the particular conditions in each case. They both require essentially the same measurements and instrumentation and are therefore complementary, being applicable in different seasonal conditions. Soil water potential is measured by means of tensiometers and the neutron probe is used to measure soil water content. The hydraulic conductivity/potential gradient method requires the additional knowledge of the hydraulic conductivity of the soil over a fairly wide moisture range. These methods are currently being developed and used by the Institute.

The zero flux plane method

Soil moisture content and soil water potential profiles are measured together, at daily or longer intervals, using the neutron probe for the first measurement and porous pot tensiometers for the second. From the tensiometer measurements the profile of total potential is derived, total potential being the sum of matric and gravity potential. Under growing conditions, inspection of this profile will normally reveal a position of maximum potential (see Figure 24) at which the potential gradient is zero. Because the potential gradient is zero the soil water flux at this point in the profile is also zero. This point defines the position of the 'zero flux plane' at that moment. Above the zero flux plane the potential gradient and hence the soil water flux is upwards, supplying the demands of evapotranspiration. Below the zero flux plane the gradient and flux are downwards, representing drainage to groundwater. Thus, the zones of upward and downward fluxes can be separated.

The second measurement, that of the water content profile, is used to quantify these fluxes. The change in water content of that part of the profile between the zero flux plane and an arbitrary second plane some distance below it represents the flux across the second plane during the time interval represented by the moisture change; this is the required measurement of water lost to drainage. Similarly, upward fluxes at the suface can be derived representing the losses to transpiration plus evaporation (with due allowance for rainfall inputs).

Limitations:

> A zero flux plane may not be present during and immediately after very long heavy rainfall in summer, and almost certainly will be absent during the winter, all movement being downwards.
>
> Porous pot tensiometers are only useable within the matric potential range 0 to -0.8 bars; however, in practice this may not be a serious limitation as the matric potential at the zero flux plane is unlikely to be outside this range under normal UK conditions.
>
> The presence of roots can create significant lateral potential gradients above the zero flux plane, particularly in the case of tree crops. This need not invalidate the method but more sites may be necessary in order that a mean value is obtained in which random lateral effects are cancelled out.
>
> If a significant number of roots cross the zero flux plane to the lower zone the method may be invalid.

The hydraulic conductivity/potential gradient method

This method relies on the application of Darcy's Law:

$$\nu = - K\frac{d\phi}{dz}$$

where ν is the unsaturated water flux
K is the unsaturated hydraulic conductivity of the soil at the relevant water content, θ, or matric potential, ψ.

and $\frac{d\phi}{dz}$ the gradient of total potential of the unsaturated soil water

This is used to calculate the water flux from a prior knowledge of hydraulic conductivity and measurements of soil water potential using tensiometers as in the case of the zero flux plane method.

Since the hydraulic conductivity is a stronger function of water content than of tension (typically it may vary over a factor of 10^6 within the range of water contents found in the field), the moisture content must be known also. The measurements needed are thus the same as for the zero flux plane method.

Measurement of the hydraulic conductivity can be made using Darcy's Law to relate an artificially imposed flux of water to the measured potential gradient. This is carried out for a number of different fluxes and hence water contents and conductivity. Ideally (but not necessarily) the hydraulic conductivity measurements should be made at the same point and using the same instrumentation as the subsequent flux measurements. Alternatively, the data obtained from the zero flux plane method can be reworked to produce that part of the conductivity characteristic relevant to the summer range of soil water potential or content.. Interpolation between this part of the curve and a laboratory determination of saturated conductivity can then provide the necessary range of K values for the wetter winter conditions when the conductivity/potential gradient method is applicable.

Limitations:

> The hydraulic conductivity measurements are difficult and expensive to perform in the field.
>
> The measurements are limited to the range of matric potential 0 to -0.8 bars, although only part of the profile need be within this range. This limits the method to use in winter conditions (conveniently, when the potential gradient is entirely downward and the zero flux plane method is inapplicable).
>
> The method cannot be used in the rooting zone if abstraction is taking place.

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Appendix I

Equipment for access tube installation and field calibration

Access tube installation equipment

1. Access tubes fitted with nose cones at one end, length as dictated by local soil conditions; usually 2 m to start with. The access tubes are made from aluminium alloy, 44.45 mm (1¾") o.d., 16 or 18 s.w.g. wall thickness, internal diameter not less than 42 mm.

2. Bungs for top closure of access tubes.

3. Tube cutter (hacksaw if not available).

4. File half-round, medium.

5. Guide tube, 44.45 mm o.d. x 1 m		Note: Ideally the guide tubes should be slightly smaller than the access tube: on no account should they exceed the diameter of the access tube.
6. Guide tube, 44.45 mm o.d. x 2 m	Fig 8	
7. Guide tube, 44.45 mm o.d. x 3 m		

8. Guide tube rammer (Figure 8)

9. Auger to fit through guide tube - 1.15 m

10. Auger to fit through guide tube - 2.15 m

11. Auger to fit through guide tube - 3.15 m

12. 45 cm tommy bar to fit holes at top end of guide tubes.

13. C spanners for augers (if augers are sectional).

14. Ground protection plate.

15. Duck boards

Note: Items 7 and 11 will only be require if 2 m or 3 m access tubes are used.

Calibration equipment

16. Items 5 to 13 inclusive, plus:-

17. Spare access tube.

18. Wallingford type core sampler (Figure 12) or equivalent for taking approximately 6 cm to 8 cm diameter undisturbed volume cores.

19. Liners for core sampler (at least 12).

20. Spare shoe for core sampler.

21. Shoe spanner.

22. Polythene bags for samples.

23. Jarret auger (Figure 13), posthole auger or posthole shovel (for making crude holes, at least 10 cm diameter).

24. 2 kg hammer or fence-post driver for driving core sampler.

25. Access tube and guide tube extractor (Figures 9 and 10).

Laboratory equipment

26. Ventilated drying oven (105° C).

27. Balance to weigh to 1 kg, readable to 1 g.

28. Dessicators to hold 6 cores.

29. Water standard or plastic standard for standard count rate determinations.

Appendix II

Terminology

Saturation

In the context of this report "saturation" is used to indicate the wettest condition a given profile ever reaches in the field under prolonged input of water at a supply rate that exceeds the infiltration rate; this term is not regarded as quantitatively precise used in this way.

Field capacity

The *in situ* measurement of field capacity has much more physical reality than laboratory determinations, being a true measurement of the moisture profile in the field when it has ceased draining for practical purposes (in zero transpiration conditions) after being well-wetted with excess water. This equilibrium may be controlled by the water table if it is shallow enough, by the conductivity characteristic of the soil, or both. Moisture contents less than the field capacity value are defined as "Soil Moisture Deficits" (SMD), and those in excess might be called "soil moisture excess". Field capacity has little physical validity in many soils, and should be used with caution.

Drainage capacity

The maximum water content that the profile can hold which will drain out under gravity, ie. the difference between "saturation" and the field capacity as defined above.

Transpiration limit

The soil water content beyond which further drying results in limitation of transpiration of a given plant species due to soil factors (moisture stress and reduced conductivity). Above this limit transpiration is limited only by available energy and plant resistances.

Abstraction limit

The soil water deficit set up at any point in that part of the profile affected by roots beyond which a given plant species is unable to extract water, due either to soil water stress, to reduced conductivity or to both. This is roughly equivalent to wilting point but may not result in wilting because water may be available to other roots lower in the profile. It probably has little relationship with the traditional 15 bar value.

Available water capacity

The water content between the abstraction limit and field capacity.

Appendix III

Safety regulations

The radiation dose rates from neutron probes are sufficient to attract the Ionising Radiations Regulations 1985[1] which make provision for the safety of those exposed to ionising radiation. Users must register their intention to use a probe with the Health and Safety Executive and implement a range of administrative and practical controls. Areas in which the dose rate exceeds 7.5 μSvH^{-1} must be designated as controlled and people who enter such areas must be classified and be provided with personal dosemeters, or must work under a written system of work which ensures that their doses do not exceed 3/10 of the annual limit which is 50 mSv. Other requirements of the Regulations include the appointment of a radiation protection adviser and the establishment of local rules governing the use, storage and movement of probes. Use of probes carries a commitment to regular measurement of dose rate and checks for leakage of activity to ensure that the source retains its integrity and the shielding remains effective. However, research workers using neutron probes may find that they are allowed to operate an "approved scheme of work" whereby the use of film badges and classified radiation worker status may be avoided. Users should refer to the Regulations for detailed requirements and the Approved Code of Practice[2] which provides guidance on the interpretation of the Regulations.

Users must also register their probes with the Department of the Environment who will issue a certificate authorising the keeping of radioactive materials. This certificate must be displayed. Transport of the probes on public roads is governed by the Radioactive Substances (Carriage by Road) Regulations[3] which contain detailed provision for the containment, labelling and conditions of carriage. Users should refer to the Regulations for the details of the requirements.

[1] The Ionising Radiations Regulations 1985. SI 1985 No.1333. HMSO

[2] Health and Safety Commission. The protection of persons against ionising radiation arising from work activity: approved code of practice. HMSO, 1985.

[3] Radioactive Substances (Carriage by Road) Regulations 1985. SI 1985 No.1729 HMSO