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UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE PESQUISAS HIDRÁULICAS
PROGRAMA DAS NAÇÕES UNIDAS PARA O DESENVOLVIMENTO
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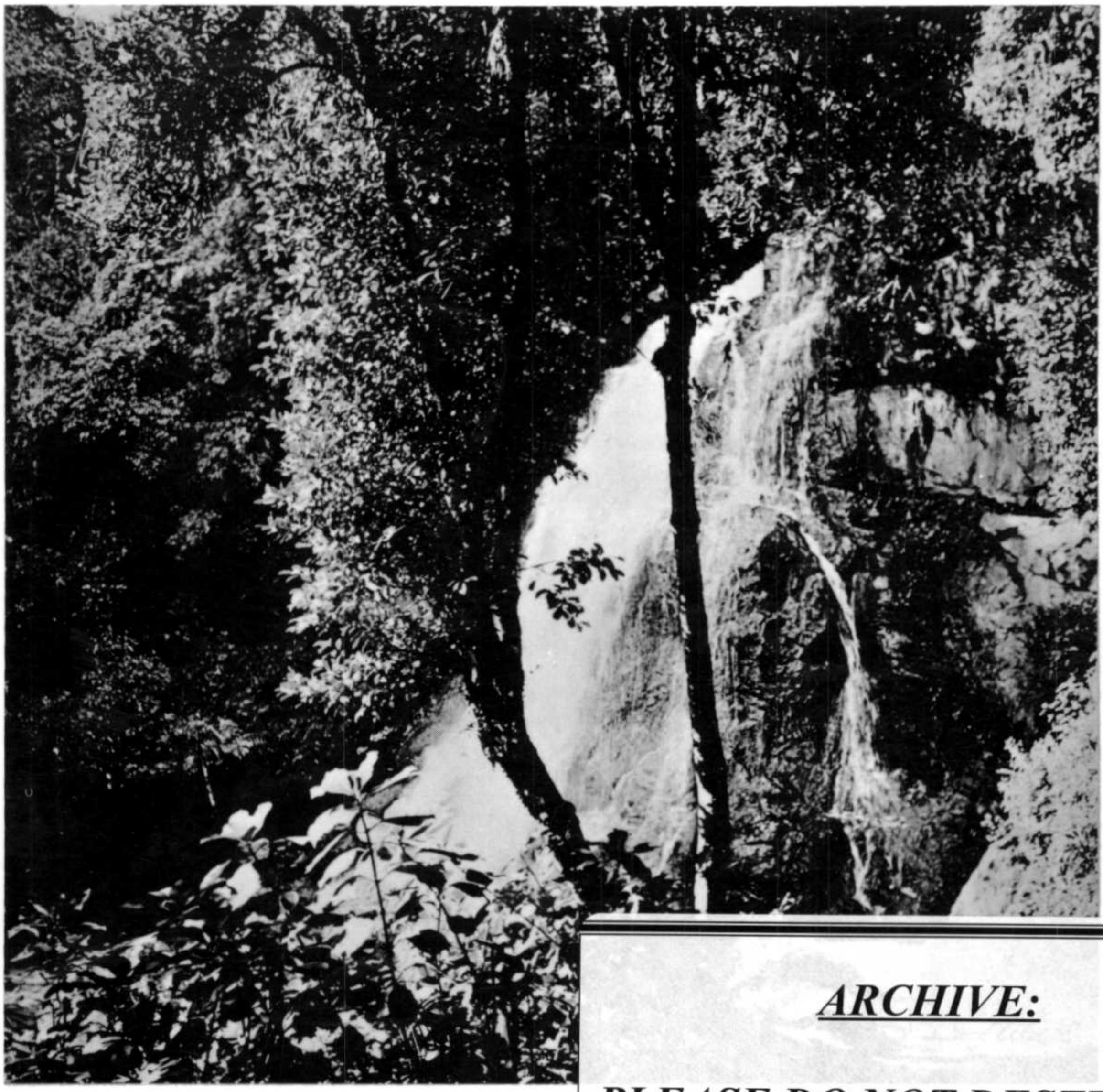
PROJETO PNUD/UNESCO/BRA/75/007

"ASSISTÊNCIA AO INSTITUTO DE PESQUISAS HIDRÁULICAS DA UFRGS"



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UTILIZAÇÃO DA SONDA DE NEUTRON

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A presente publicação constitui um documento interno do Projeto PNUD/UNESCO/BRA/75/007. Tem como objetivo a divulgação das atividades desenvolvidas no âmbito do IPH.

ÍNDICE

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INTRODUÇÃO

O presente documento está dividido em duas partes. A primeira refere-se à teoria do Método da Sonda de Neutrons. A segunda contem a descrição da sonda de neutrons do Instituto de Hidrologia de Wallingford,assim como as indicações oportunas para seu uso.

THE THEORY OF THE NEUTRON PROBE METHOD

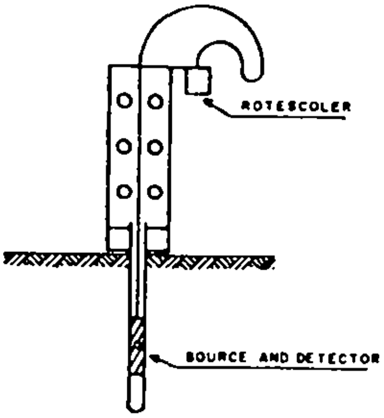
Preface

This report is based on a seminar given at the Instituto de Pesquisas Hidráulicas in December 1978. The objectives are to outline the physical basis of the neutron probe method, to describe the source of measurement errors and suggest ways in which they may be minimized and also to indicate design strategies for neutron probe access tube networks. The report is intended to act as a supplement to, and not as a replacement of, the more comprehensive account given in the Institute of Hydrology report nº 19 "Neutron Probe Practice" by J.P. Bell.

NEUTRON PROBE PRINCIPLES

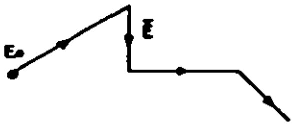
A neutron probe consists of (Fig. 1):

1. a radio-active source of fast neutrons of energy ~ 1 MeV
2. a detector of slow neutrons of energy $\lesssim \frac{1}{40}$ eV
3. a rate-scaler



Collision Theory

Fast neutrons emitted from the radioactive source collide with the surrounding nuclei and energy is lost on each collision (Fig. 2)



If neutron absorbers are not present in the surrounding material it is reasonable to assume that an "elastic" collision takes place (eg a billiard ball collision) which can be described by the equation:

$$\frac{\bar{E}}{E_o} = \left(1 - \frac{2A}{(A+1)^2}\right)$$

where E_o is energy before collision

$\bar{E}$ is mean energy after collision

A is the atomic number of the surrounding nuclei (the number of protons and neutrons in the nucleus)

Differentation of this equation with respect to A shows that the mean energy loss is maximal when:

$$\boxed{A = 1}$$

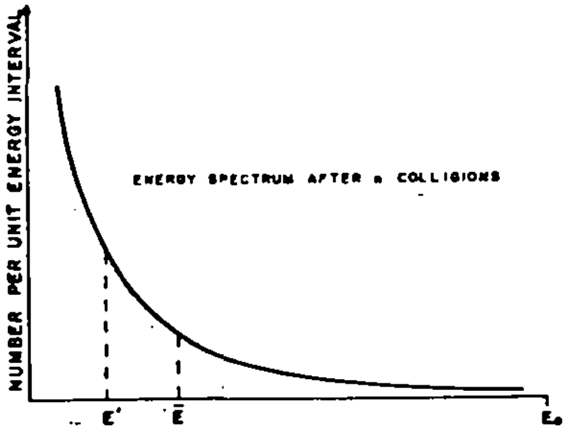
and neutrons collide with <u>hydrogen</u> nuclei in which case:

$$\frac{\bar{E}}{E_o} = (1 \quad \frac{2A}{(A+1)^2}) = \frac{1}{2}$$

After n collisions the average energy is

$$\bar{E}_n = (1 \quad \frac{2A}{(A+1)^2})^n \; E_o$$

but the <u>median</u> energy after n collisions is much less (Fig.3) and is given by (see e.g. Fermi, Nuclear Physics, University of Chicago Press)



$$E_n{}' \quad e^{-n(1 \quad \frac{(A-1)^2}{2A} \quad \ln \frac{(A+1)}{A-1})} \; E_o$$

Fig. 3

It is instructive to calculate for different materials the number of collisions, n, required to reduce most of the fast neutrons (of energy E_o= 1 Mev) to thermal energies ($E_n{}' = \frac{1}{40}$ ev) which are detectable by the probe. Rearranging the above equation gives:

$$n = \frac{-\ln(\frac{E_n}{E_o})}{(1-\frac{(A-1)^2}{2A} \; \ln\frac{(A+1)}{A-1}}$$

Thus for H, A =

$$\frac{\ln\ (1/40,000,000)}{1} \qquad 17.5 \quad \text{collisions}$$

For C, A = 12

$$\frac{\ln\ (1/40,000,000)}{.158} \qquad 110 \quad \text{collisions}$$

For O, A = 16

$$- \frac{\ln\ (1/40,000,000)}{.120} \qquad 146 \quad \text{collisions}$$

On average a neutron after reaching thermal energy in carbon and making ∿ 110 collisions will be much further away from the radio-active source and detector than one that has thermalised in hydrogen and has made only ∿ 18 collisions. In fact it can be shown that the number of neutrons per unit-volume in a given energy range (n(r,E)) at a distance r from a radioactive source in an infinite medium follows a Gaussian distribution ie.

$$n\ (r,E)\ \alpha\ e^{\frac{-r^2}{4\tau}}$$

where the parameter τ determines the spread of the distribution and is proportional to the square of the mean free path (λ) of the neutrons in the medium and inversely proportional to the mean energy loss per collision ($\overline{E}/E_0$). In general changes in the energy loss term ($\overline{E}/E_0$) with respect to changes in the atomic number of the surrounding medium dominate the changes in the λ^2 term. The slow neutron 'cloud' is therefore <u>smaller</u> and <u>denser</u> in hydrogen than in any other material.

Basis of Neutron Probe Method

The neutron probe method is based on the approximate relationships between the count rate at the detector, the slow neutron 'cloud' density, the hydrogen density of the soil and hence the volumetric water content (moisture Volume Fraction, MVF) of the soil.

The count rate/MVF relationship, although approximately linear varies with:

(a) different neutron probes because of different source strengths and different detector geometries etc.

(b) different soils because of different elements in composition and hence different proportions of neutron moderators and absorbers

and thus to determine the count rate/MVF relationship both the neutron probe and the soil must be calibrated.

CALIBRATION

Neutron Probe Calibration

The neutron probe is normally calibrated by determining the count rate in a laboratory standard of known MVF.

Water is perhaps the best standard: it is cheap, readily available it has a high hydrogen density and an exactly known MVF which by definition is equal to unity.

Plastic transport shields are not good standards: they are usually too small for the neutron cloud to be wholly contained within the shield and the count rate is influenced by material outside the shield. The coefficient of expansion of plastic is also relatively high and count rates are likely to be temperature dependent.

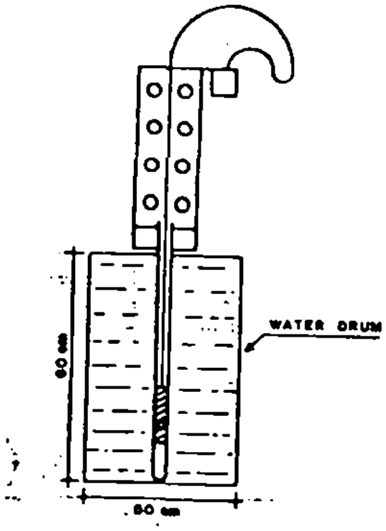


Fig. 4

It is recommended that the calibration be performed in a water drum of minimum diameter 50 cm. (Fig.4) A precision of 0.1% in the count rate in water, R_w, is perfectly feasible. This requires a total of ~1.000.000 counts to be obtained and for the Wallingford probe with a 50 mCi source - R_w ~1000 cps and the counting time should be ~16 min.

Soil Calibration

This can be obtained from:

1. A knowledge of the elemental composition of soil and the elemental neutron capture and absorption cross sections. The analysis is however difficult and expensive to perform although a new technique which involves obtaining macro-cross sections by bombarding soil samples with neutrons in an atomic pile holds promise (see eg Comparison of methods of calibration of a neutron probe by gravimetry or neutron capture model, G Vachaud, J M Royer and J D Cooper, 1977. Journal of Hydrology 34,343-356).

2. Drum calibrations performed in the Laboratory. This method is very time consuming and laborious as large volumes of soil have to be dried and repacked to obtain each calibration point.

3. Field calibrations. This method involves:

   (i) Determining the count rate, R, in the soil

   (ii) Obtaining soil cores at each measurement depth

   (iii) Determining the moisture volume fraction (MVF) of the soil cores by dividing the change in weight (gm) of the soil core following drying at 105°C by the volume of the core (cc)

   (iv) Plotting the MVF of the soil core against the ratio of the count rate R to the count-rate in water R_w.

Typical Results

Bell (Institute of Hydrology, Report nº 19) gives the following calibration curves M.V.F. for different soil types (Fig. 5)

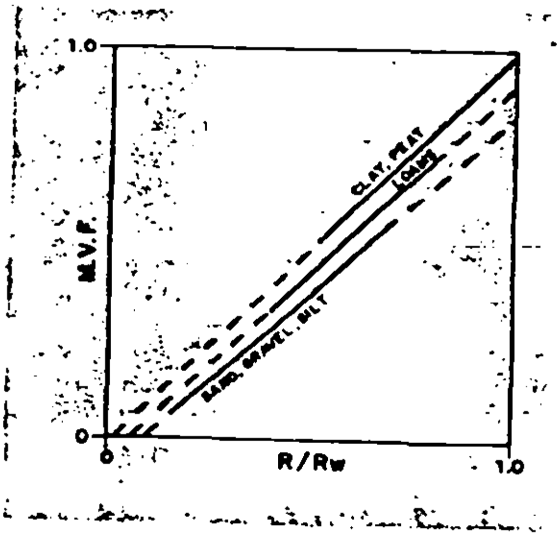


Fig. 5

Sand, gravel, silt $\mathrm{MVF} = 0.790 \times \frac{R}{Rw} - 0.024$

Loams $\mathrm{MVF} = 0.867 \times \frac{R}{Rw} \cdot 0.016$

Clay, peat $\mathrm{MVF} = 0.985 \times \frac{R}{Rw} - 0.012$

Measurement Errors

The neutron probe is normally used to measure changes in moisture content with time (ΔS) rather than the absolute moisture content of the soil (S). In most cases it is the spatial mean change in moisture content ($\overline{\Delta S}$) of the soil that is required and hence the error that should be minimized is the:

ERROR IN THE SPATIAL MEAN MOISTURE CONTENT CHANGE WITH TIME.

i.e. ERROR in $\overline{\Delta S}$

This error will have both random and systematic components which arise from both errors inherent in the neutron probe method and those due to the real spatial variability of changes in soil moisture (see Table 1).

Random errors are manifest as an increased variability in the change in soil moisture recorded at different access tubes. This results in an increase in the standard deviation of the change in soil moisture ($\sigma_{\Delta S}$) recorded at different access tubes and hence results in an increase in the

STANDARD ERROR IN THE SPATIAL MEAN MOISTURE CONTENT CHANGE WITH TIME.

i.e. $\sigma_{\Delta S}/\sqrt{n}$ (where n is the number of access tubes)

Ideally then we should minimize the systematic errors as far as is practicable and then reduce the random component ($\sigma_{\Delta S}/\sqrt{n}$) until this is at least of the same order of magnitude. To do this it is worthwhile considering in more detail how these component errors arise. The following treatment considers only those which are normally significant.

TABLE 1

Source of error in $\overline{\Delta S}$

RANDOM	SYSTEMATIC
Errors inherent in the neutron probe method:	
Random counting error	
Soil calibration error	Soil calibration error
Interface error	Interface error
Errors which should be insignificant if modern equipment and the correct measurement techniques are used;	
Depth location errors	Depth location errors
Thermal drift of the neutron probe count-rate	Thermal drift of the neutron probe count-rate probe calibration error

Errors due to the real spatial variability of ΔS arise from:

Spatially-variable precipitation

Spatially-variable root abstraction

Spatially variable drainage

Random Counting Error

This arises from the random nature of the radio-active decay process. The number of neutrons counted per fixed time interval is likewise random and has a distribution in which negative values are not possible, a Poisson distribution (Fig. 6)

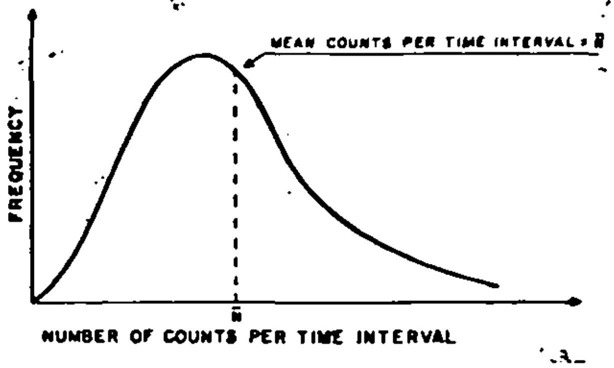


Fig. 6

For a Poisson distribution the standard deviation is equal to the square root of the mean.

$$\text{i.e. } \sigma = \sqrt{N}$$

Hence the standard error of the mean number of counts per time interval

$$= \frac{\text{standard deviation}}{\sqrt{\text{n° of observation periods}}}$$

$$= \frac{\sigma}{\sqrt{n}}$$

(where n is number of observation periods)

i.e.

standard error of mean counts per time interval	$\frac{\sqrt{N}}{\sqrt{n}}$

and the coefficient of variation = $\frac{\text{standard error}}{\text{mean}}$

ie, $\boxed{\text{coefficient of variation} = \frac{1}{\sqrt{\bar{N}\,n}}}$

Example:

Calculate the random counting error in the neutron probe observation of 625 cps determined over a 64 second period.

The mean counts $\bar{N}$ in a 1 second period = 625

The number of observation periods n = 64

$$\boxed{\text{standard error} = \frac{\sqrt{\bar{N}}}{\sqrt{n}}}$$

$$= \frac{\sqrt{625}}{\sqrt{64}}$$

$$\frac{25}{8}$$

$$= \underline{3.125 \text{ cps}}$$

$$\boxed{\text{coeff. of variation} = \frac{1}{\sqrt{\bar{N}\,n}}}$$

$$= \frac{1}{\sqrt{625 \times 64}}$$

$$= \frac{1}{200}$$

$$= 0.5\%$$

Soil Calibration Errors

These are manifest as both random and systematic errors.

They can be random in the sense that if the same soil calibration is used for all the tubes in a network and genuine variations in soil properties (and hence calibrations) do occur within the network then $\sigma_{\Delta S}$ will be increased as will the standard error of the mean change in soil moisture, $\sigma_{\Delta S}/\sqrt{n}$.

They will be systematic if the soil calibration that is used differs from the areal mean calibration of the network.

In practice it is unrealistic to hope to reduce the systematic error to below ~5% and this sets an effective limit on the accuracy of the neutron probe method.

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n.b.

As the range of slopes of calibration lines from all soils is only 19% (provided no neutron absorbers are present) it may be valid to use a previously determined soil calibration which is selected according to the soil type (Fig. 7)

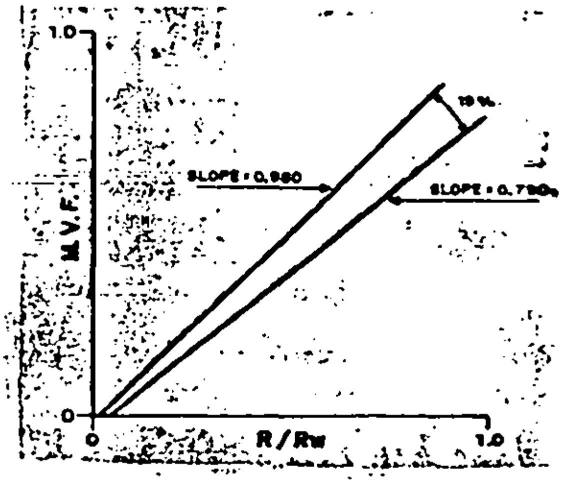

Fig. 7

For highest accuracy a field calibration should always be performed.

Interface Errors

The neutron probe method does not provide a "point" measurement of moisture content. In fact the probe has a "sphere of influence" which decreases with distance from the source/detector. The size of this "sphere of influence" varies with the moisture content of the soil, it being larger in dry soils than wet soils.

Variation in the size of the sphere of influence with moisture content can therefore lead to significant errors in the measurement of S and ΔS particularly when non-linear gradients of moisture content occur with depth. This effect is normally most pronounced for surface measurements where large moisture gradients occur at the soil/air interface. Thus as the surface soil dries the sphere of influence increases and a higher proportion of neutrons are "lost" (Fig.8). Hence the R/R_w ratio is reduced and the slope of calibration curve is changed.

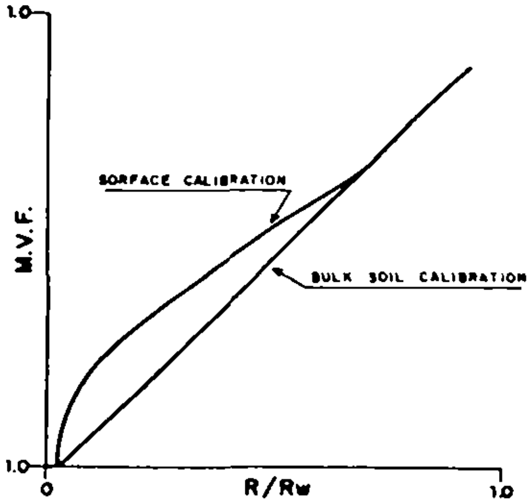

Fig. 8

Avoidance of interface errors

A number of methods exist and the choice is determined to some extent by the individual circumstances:

1. Perform a separate soil calibration for the surface layer. (This is probably the most accurate method).
2. Use a numerical correction based on an empirical relationship derived for idealised soils (see eg ARC Great Britain, Letcombe Laboratory Annual Report 1973, A method for improving the accuracy of measuring soil moisture near the soil surface with a neutron meter, W Harris).

3. Use a surface extension tray. This involves filling a fibreglass tray with a sample of the surface layer of the soil and then placing the tray around the access tube (Fig. 9). The "loss" of neutrons is reduced but the method does have disadvantages; if measurements are made regularly the crop may become trampled. Furthermore the moisture content of the soil may not be representative of that in the top layer of the soil unless the tray is filled each day with a new sample of soil. This method is however simple to use and can give good results in certain circumstances.

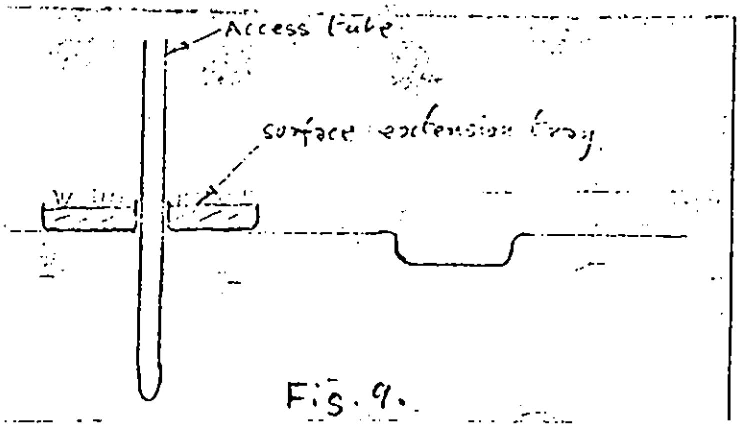

Fig. 9.

4. On wet soils (>0.7 MVF) interface errors arising from measurements taken at 10 cm or more below the soil surface can probably be ignored.

Spatial variability of ΔS

The spatial variability of the change in soil moisture is determined mainly by:

1) Spatially variable precipitation
2) Spatially variable root water abstraction
3) Spatially variable soil water drainage

These effects are perhaps best illustrated by example. Observations of the change in soil moisture made with a forest access tube network of 20 Tubes with approximately 2 m spacing (Calder 1976 The Measurement of water losses from a forested area using a "natural" lysimeter, J. Hydrol., 30: 311-325.) indicated a standard deviation ($\partial\Delta S$) of approximately 5 mm during dry periods.

However, following rain especially rain which did not return the soil to "field capacity" a very high variability was found ($\sigma_{\Delta S} \doteq 15$ mm).*

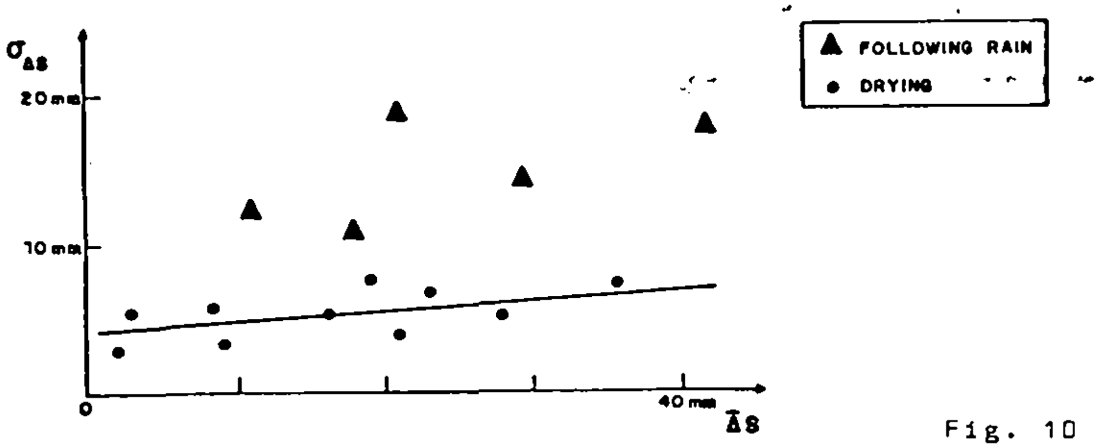

Fig. 10

This high variability is a reflection of the "spotty" nature of throughfall and stemflow beneath a forest canopy. Such high variabilities in ΔS are not normally found on grassland sites following rain.

Thus during dry conditions the standard error of the mean change in soil moisture content determined with a 20 access tube grid is

$$= \frac{\text{standard deviation of change}}{\sqrt{\text{number of observations}}}$$

$$= \frac{\sigma_{\Delta S}}{\sqrt{20}} = \frac{5}{\sqrt{20}} \quad \underline{1.1 \text{ mm}}$$

During wet conditions the standard error is:

$$\frac{15}{\sqrt{20}} = \underline{3.4 \text{ mm}}$$

---

*n.b.

The standard deviation $\sigma_{\Delta S}$ is determined both by the real spatial variability and by the random errors inherent in the neutron probe method

i.e., $\sigma_{\Delta S} = \sigma_{RSV}^2 + \sigma_{rc}^2 + \sigma_x^2$

where σ_{RSC} = standard deviation of real spatial variability

σ_{rc} = standard deviation of random counting

σ_x = standard deviation of all other random errors of neutron probe method

NETWORK DESIGN

Two questions which always arise in the design of access tube network are:

1. How long to count (for the Wallingford neutron probe the choice is normally between 16 and 64 sec).

2. How many tubes.

The following treatment is concerned only with providing answers to those questions in situations where the time spent travelling between access tubes is small compared with the time taken to read the access tubes; the experimental plot rather than the large catchment situation. (It is intended to describe a solution to the more general catchment situation problem in a separate publication).

Remember that we wish to minimize the error in the spatial mean change in soil moisture, the random component of which is given by:

$$\frac{\sigma_{\Delta S}}{\sqrt{n}}$$

which can be expressed as:

$$\frac{\sigma_{\Delta S}}{\sqrt{n}} \qquad \frac{\sqrt{\sigma_{rc}^2 + \sigma_{sv}^2}}{\sqrt{n}}$$

where σ_{rc} = standard deviation of random counting

σ_{sv} = standard deviation of real spatial variability and other neutron probe random errors

= number of tubes

Optimum counting time/number of tubes

The optimum counting time (optimum in the sense that $\sigma_{\Delta S}/\sqrt{n}$ is minimized for a given amount of operator effort) can be determined from a knowledge of spatial variability (σ_{sv}) and the fact that an operator takes approximately twice as long to read a tube on 64 sec counts as he does to read a tube on 16 sec counts.

Thus for the same effort an operator can read either:

(a) n tubes on 64 sec counts in which case the standard error =

$$\sqrt{\frac{\left(\frac{\sigma_{16}}{2}\right)^2 + \sigma_{sv}^2}{\sqrt{n}}}$$

or

(b) 2 n tubes on 16 sec counts in which case the standard error =

$$\frac{\sqrt{\sigma_{16}^2 + \sigma_{sv}^2}}{\sqrt{2n}}$$

(where σ_{16} is the random counting error on 16 sec counts)

Hence if error (b) < error (a) the operator should read 2 n tubes on 16 sec count rather than n tubes on 64 sec count.

ie, if $\dfrac{\sqrt{\sigma_{16}^2 + \sigma_{sv}^2}}{\sqrt{2\ n}}$ $\sqrt{\dfrac{\left(\frac{\sigma_{16}}{2}\right)^2 + \sigma_{sv}^2}{\sqrt{n}}}$

ie, if $\boxed{\sigma_{16} < \sqrt{2}\ \sigma_{sv}}$ read more tubes else increase counting time

Example

if $\sigma_{rc} < \sqrt{2}\ \sigma_{sv}$ read more tubes

For the forest access tube grid in dry conditions the standard deviation of ΔS was found to be $\sim$ 5 mm.

ie. $\sigma_{\Delta S} = 5$ mm

From theory the standard deviation of random counting for a typical tube read on 16 sec counts is

$$\sigma_{rc} = 1.8 \text{ mm}$$

hence

$$\sigma_{sv} = \sqrt{\sigma^2_{\Delta S} - \sigma^2_{rc}}$$

$$4.6 \text{ mm}$$

thus

$$\sigma_{rc} = \frac{1.8}{4.6}\,\sigma_{sv}$$

$$= 0.39\ \sigma_{sv}$$

thus $\sigma_{rc} < \sqrt{2}\ \sigma_{sv}$ and it is better to read <u>more</u> tubes.

The general philosophy is therefore to determine the counting time from a knowledge of the spatial variability of the change in soil moisture content ($\sigma_{\Delta S}$) (which will in most cases be 16 sec) and then to insert as many tubes as is practical bearing in mind that when $\frac{\sigma_{\Delta S}}{\sqrt{n}}$ is of the same order as the systematic error in the soil calibration, the law of diminishing returns sets in.

B - OPERATIONAL PROCEDURE FOR THE INSTITUTE OF HYDROLOGY SOIL MOISTURE NEUTRON METER

Introduction and design philosophy

The IH Soil Moisture Neutron Meter manufactured by the Didcot Instrument Co., Abingdon, comprises a neutron probe, 38 mm diameter and 735 mm long, a connecting cable (customarily 5 m long, but it can be of any practicable length) and a rate-scaler powered by rechargeable batteries. All these components are assembled into a single integrated instrument which also includes a heavy polythene safety shield to absorb the fast neutrons from the probe when it is not being used in the soil.

The design philosophy of the system has been to improve portability, to simplify field operation and to minimize operational failure by careful attention to the most frequent causes of such failure. The use of complex multicore cables for transmission of a variety of voltages and signals to and from the probe resulted in frequent malfunctioning of previous designs of neutron probe: the Institute of Hydrology probe, like the Wallingford probe which preceded it, has all the probe electronics housed within the probe itself. Thus the EHT voltages of the order of 2000V are generated in situ from the 12 V input provided via the coaxial cable; the pulses from the BF^3 thermal neutron counter are amplified and shaped before being passed up the cable to the rate-scaler which totals the number of pulses received in a preset time of 16 sec. or 64 sec.

Measurements of the moisture content of soils are made by lowering the probe down a previously-installed access tube (an aluminium tube of 1 3/4 "O.D" sealed at the bottom end with a die-cast aluminium plug and at the top with a rubber bung). The count rate is then determined at a series of measurement depths and this can be related to the MVF of the soil via soil and probe calibration equations.

Operation of Probe

The controls are revealed by opening the clip at the top of the carrying housing and hinging back the ratescaler. The rate-scaler has three switch controls: on the right is the on/off switch , on the left is the counting switch with two time options of 16 or 64 sec. which allows a choice of counting precision, and in the centre is a test switch. A count is initiated by pressing the switch in either direction as appropriate to the chosen count time; a flashing display and an audible bleep at one second intervals will then indicate that a count is in progress. The volume of the bleep can be adjusted by turning the knob mounted to the right of the display. After the chosen counting time has elapsed the count rate will be indicated on the digital display. To check that all the filaments of the display are operational the central test switch should then be pressed and if satisfactory a reading of 888 will be displayed.

The probe can be connected to the rate scaler by means of the cable wound between the lugs on the housing. Should the cable be removed altogether from probe and rate scaler, note that the end marked red is to be connected to the probe. With the equipment mounted on the access tube but the probe locked in the housing, take a trial reading of the count in the shield. If the probe has not been switched on leave it "on" for 30 seconds before beginning the trial count. Note that the depth counter at the top of the housing shows 9994 i.e. - 6 cm with the probe locked securely away. If this has been altered, it can be reset by manipulation of the knurled screws which control the friction wheels between which the cable is released.

Now the probe can be unlocked by turning the key to the horizontal. If it is difficult to turn, gentle pulling of the cable may secure the release of the key. The cable and the probe may now be lowered through the depth counter by the operator pulling the T grip towards himself to release the cable. When the depth counter is reading 0000 the centre of sensitivity of the probe (i.e. the central point of the annular ring source) is at the top of the acces tube. Because the equipment may not be centred exactly on the access tube it may be difficult to drop the probe down the tube. This may be resolved by moving the housing until it is obvious that the probe can be lowered smoothly down the access tube.

Normally the access tube is left some 10 cm proud of the soil to ensure that water and soil do not fall down the tube. All measurements using the counter are made from the top of the tube so it is essential to check and note the precise distance of this from the soil surface. Thereafter all measurements of soil moisture are made in 10 cm increments down the access tube. Thus if the access tube was intended to be 10 cm above the surface but in fact is only 9 cm, readings should then be taken at 19 cm, 29 cm, 39 cm, etc.

Probe Calibration

Each day, prior to the taking of soil moisture readings, it is recommended that the neutron probe calibration be checked by taking 10 readings of 64 sec. duration in a water drum using an access tube of the same material as that used in the field. The mean of these readings (R_w) should then be plotted graphically to provide a record and check on the stability of the probe(Fig. 11). As the standard error of R_w obtained with 10 readings of 64 sec. is not entirely insignificant (~1.3 c.p.s) it is preferable to use the mean of a series of R_w values in water content calculation and to continue to use this mean value until such time as the graph of R_w values indicates that a significant systematic change in R_w has occurred (perhaps after 1 year of operation of the probe).

Soil Calibration

While given careful calibration for each individual soil the neutron moisture gauge is capable of producing accurate absolute data, for most agricultural and hydrological purposes it is differences in soil moisture over a period that are required. Indeed no other soil moisture measuring technique is capable of repeated measurement without soil disturbance other than that necessary for installation of the access tubes. If differences only are required then the statistically most precise form of the equation for a given soil will give answers only marginally different from a generalised calibration curve

$$\text{Soil moisture} = 0.867 \frac{R}{Rw} \quad 0.016 \quad \text{loam}$$

Technically this curve is for loamy soils while for sands and clays respectively the equivalent relations would be

$$\text{Soil moisture} = 0.790 \frac{R}{Rw} \quad 0.024 \quad \text{sand}$$

$$\text{Soil moisture} = 0.958 \frac{R}{Rw} \quad 0.012 \quad \text{clay/peat}$$

Note that the use of the form of calibration $\frac{R}{Rw}$ ensures that results obtained by the probe do not depend in any way on the particular characteristics of a particular probe. Thus in catchment area research a number of probes may well be in use. Furthermore the characteristics of a individual probe may change with time due to the radiactive decay of the source (1/2 life 450 years) or perhaps because of some change in performance of the detector as when the BF^3 proportional counter is replaced. Whatever the reason for a difference in the count for a given time, "normalisation" by dividing the count by the count of the same probe in water will ensure lack of bias in the measurement of soil moisture.

For organisations such as the Institute of Hydrology which is responsible for soil moisture measurements in a wide variety of locations, computer processing of the results is practical and economic. Where only a single neutron moisture meter is in use computation by means of a simple electronic scientific calculator is quite adequate. Note that the neutron probe measurement is rather like a running average in that the measurements are not point measurements but average non-linearly the soil moisture (or rather hydrogen nuclei) in a layer of soil of thickness from 30 to 60 cm depending respectively on whether the soil is wet or dry. Thus in assigning "Layer Factors" of 10 cm each, it is assumed that each layer characteristics the soil moisture from the mid-point of a the measuring interval on either side of the appropriate measuring depth.

NEUTRON PROBRE: 156
RADIOACTIVE SOURCE No: AMN 70 6804
CALIBRATION IN WATER DRUM, Rw
INSTITUTO DE PESQUISAS HIDRÁULICAS
LABORATÓRIO DE HIDROLOGIA AGRÍCULA

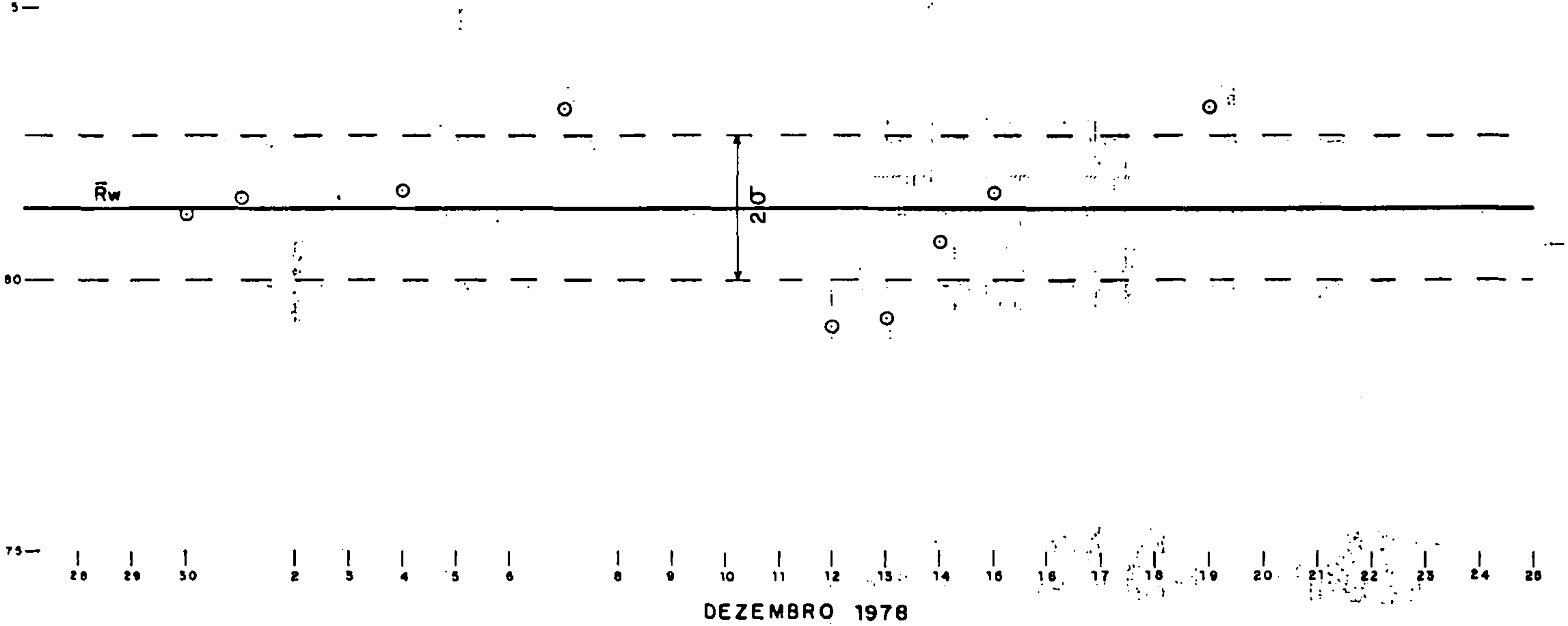

Fig. 11