USE OF THE NEUTRON PROBE IN THE LOWVELD OF ZIMBABWE

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Abstract

As part of a water management project initiated by the Zimbabwe Sugar Association Experiment Station (ZSAES), three large sugar estates and the ZSAES have imported a commercially available irrigation scheduling package which is based on neutron probe measurements of soil water. Analysis of selected data collected using the package highlighted inefficiencies in irrigation, *viz.* inflated drained upper limits (DUL) or 'full' points, irrigation water applications that were too large and too frequent when determined using a water budget and inflated to cater for assumed low efficiencies, and too short a 'drying-off' period. At the sites discussed in the paper, potential savings in water of approximately 200 mm/ha are evident and the inefficiency in irrigation water applications is the likely cause of yield reductions in the order of 15 t/ha. The amounts of water that a soil could 'store' just prior to an irrigation, and the magnitude of the irrigation, were the major determinants of application efficiencies, even with furrow irrigation which is often assumed to be self-compensating through a wetter soil having a more rapid advance front. Procedures which accommodate typical estate land husbandry are described to perform a practical check on the neutron probe's calibration, and to determine an *in situ* drainage curve and obtain an objective 'full' point which is representative of in-field conditions.

Introduction

As part of an effort to improve water management, three large sugar estates in the Lowveld of Zimbabwe and the Zimbabwe Sugar Association Experiment Station (ZSAES) have imported a commercially available irrigation scheduling package which is based on neutron probe measurements of soil water. The package encompasses all aspects of neutron probe use for irrigation scheduling, including hardware, software, calibration relationships, and guidelines for operating the neutron probe and for the interpretation of data. The neutron probe was selected from a range of soil water measurement devices because its usefulness has been proven (Cull, 1992) and, when compared with instruments that are left in the field, potential problems of theft are reduced.

The suppliers of the neutron probe package commissioned the system in the Lowveld and trained the operators. They also made a subsequent visit to assess the situation and presented their findings at a Zimbabwe Sugar Seminar (Lanser, 1998). In this paper, a further, independent assessment of neutron probe use in the Lowveld is reported. This assessment is set in context by providing a broad perspective of issues and tools for the management of irrigation water, especially with regard to the potential role of neutron probes. Data from two furrow irrigation sites have been selected to focus discussion on various key topics, *viz:*

- drained upper limits (DUL) or 'full' points
- 'refill' points, estimated daily crop water use
- neutron probe calibration,
- irrigation application efficiencies
- irrigation system performance evaluation.

Irrigation water management

The context of neutron probe use in irrigation water management is illustrated and discussed with reference to Figure 1, with the focus on the 'Information' aspects of irrigation scheduling. When scheduling irrigation water applications, the status of soil water is most often used as the irrigation decision variable, *viz.* to determine when and how much water to apply. The soil water status can be measured directly, for example, using a neutron probe or some other instrument, or it can be estimated using indirect means, which usually involves a water budget. In most water budgets, an estimate of atmospheric evaporative demand (AED) is used together with information on the crop's development/canopy status to determine potential water withdrawals. These estimates can be relatively simple:

- the crop status represented by a time dependent crop coefficient and AED represented by evaporation from an A-pan

or relatively complex:

- the crop's status being determined by more physically or conceptually explicit relationships, for example, by relating canopy development to thermal time in a crop model
- AED represented by more physically explicit combinations of weather measurements, for example, the Penman-Monteith evaporation equation
- the interaction between AED and the crop represented by soil dependent patterns of potential and actual root water uptake, as, for example, are used at different levels of complexity in the *ACRU* (Lecler and Schulze, 1995) or CANEGRO/DSSAT ([1]personal communication) models.

Arguments for measuring the soil water status directly are:

- whether a simple or a complex water budget is used, there are many unknowns in estimating evaporation from a cropped surface and these can lead to significant errors in

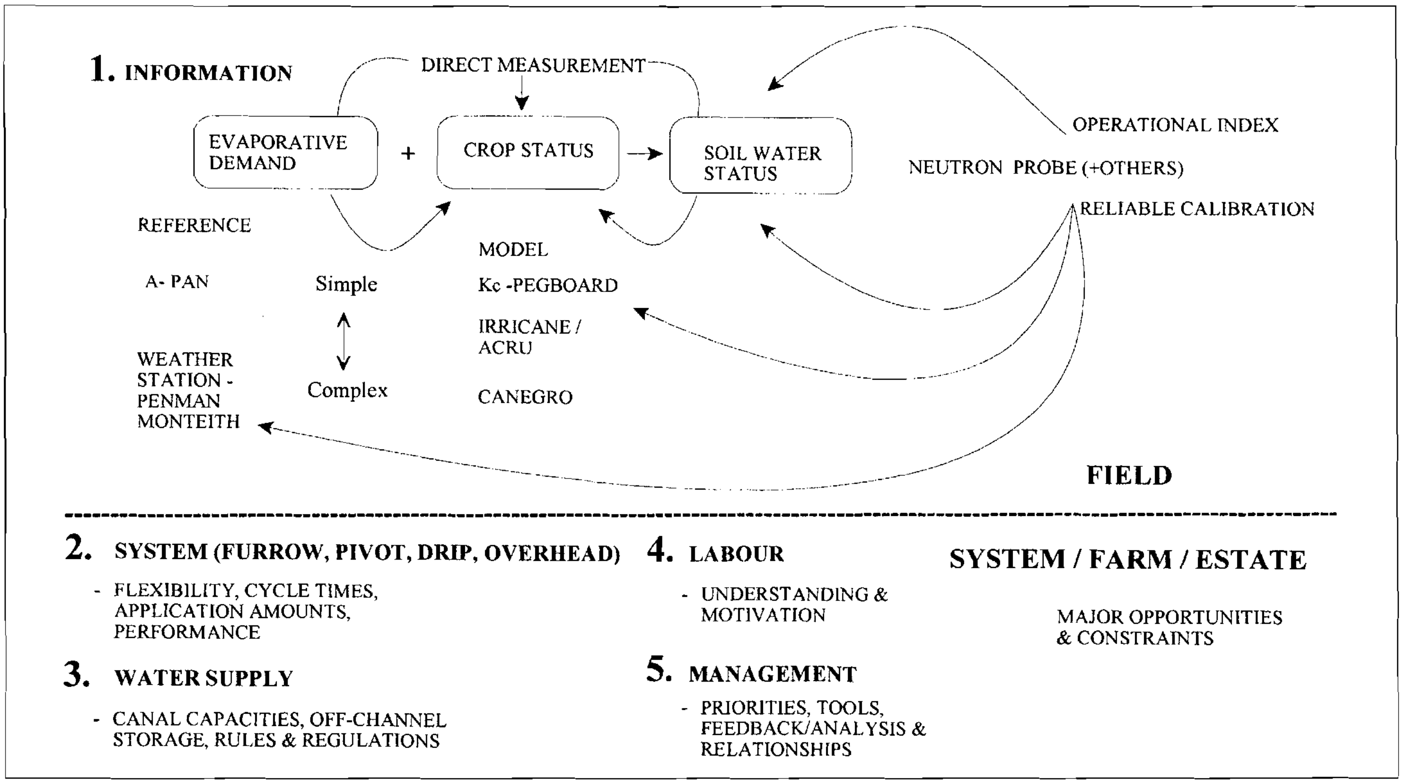

Figure 1. Aspects of Irrigation Water Management

day-to-day estimates of soil water status
- even if a perfect model of crop water use was available, the computed water status is still dependent on the initial estimate (measurement) of soil water status
- due to variations in the performance of irrigation systems, especially with regard to furrow irrigation, it is often the additions (irrigation applications) to the water budget that are estimated with the least accuracy.

Therefore, if a water budget is to be used to estimate soil water status, some direct measurements of soil water are advised in order to ensure that the water budget is tracking the 'ground truth', otherwise consistent under or over-irrigation can result.

A water budgeting approach is nevertheless favoured by many irrigation practitioners because the costs are normally lower and it is often easier and more practical to estimate water contents over large areas with a water budget than it is to take many 'point' measurements of soil water and analyse the associated data. In addition, because direct measurements of soil water normally represent only very small portions of a given field area, these could give rise to substantial sampling errors.

Given the above perspective (Figure 1), there is great potential for the neutron probe to be used as an irrigation water management tool. Within practical limitations it can be used on its own to schedule irrigation water applications, or it can be used to periodically check on the accuracy of a modelled water budget, and also to refine or tailor a water budgeting model (whether simple or complex) to specific field circumstances. In addition neutron probe measurements can be used to investigate the performance of irrigation systems, for example, the uniformity of furrow irrigation applications.

Materials and Method

The total neutron probe irrigation scheduling package that was purchased for use in the Lowveld, including hardware, software and operating guidelines, is referred to in this paper as the 'Probe'. Use of the neutron probe to measure soil water is well reported in the literature (Hauser, 1984; Gear *et al.*, 1977). Measurements of soil water are made *in situ*, in thin walled aluminium access tubes which are installed vertically in the soil to the maximum depth at which the measurements are required. The probe contains a small sealed radioactive source which continuously emits high energy 'fast' neutrons into the soil surrounding the access tube. These are scattered and 'slowed' through collisions with elements in the soil of similar mass, primarily hydrogen. The slow neutrons are counted by a detector in the probe and displayed and stored in an electronic data acquisition system. Most hydrogen present in the soil is from water, therefore the count rate is related to the water content of the soil (Hodnett *et al.*, 1991).

The objective of the 'Probe' package is to facilitate rapid and effective analysis of neutron probe counts. The software has a data structure to manage different access tube sites on different fields and farms, and includes facilities to:
- input neutron probe counts and other pertinent data, for example, rainfall, irrigation or A-pan measurements for

the various sites, and to sort and order these data
- convert counts through a given calibration relationship to estimates of soil water
- display through numerous graphing options the variations in soil water content with respect to time and with respect to depth and time.

Results and Discussion

Variations of neutron probe estimated soil water content over time are shown in Figures 2a-c, and 3a-c, for two furrow irrigated sites. An outline of the trials pertaining to the graphs is given in Table 1. The data shown on the graphs are for the period from when the probe readings were started, *viz.* mid February 1998, to harvest, i.e. for approximately half the season. All the sugarcane was at full canopy when probe readings were initiated. The graphs were produced using the software that is part of the 'Probe' package and which has been used to plot:
- estimated volumetric soil water in the 0 to 1,1 m zone
- the so-called 'full' point, *viz.* soil water at maximum desired 'wetness', which approximates 'field capacity' or the drained upper limit (DUL)
- the so-called 'refill point', *viz.* the point at which an irrigation should be applied
- estimated daily water use determined from differences in neutron probe readings. These have been normalised by dividing them by measured A-pan data, i.e. equivalent to a crop coefficient
- the delivered and effective rainfalls and irrigations - effective as estimated using the 'Probe' software and operator judgement, *viz.* estimated daily water use rates have been extrapolated back to the date of irrigation in order to predict what the soil water content after an irrigation was likely to have been.

Daily water use, irrigation and rain have been scaled to plot on the same axes as the soil water measurements and the original 'full' and 'refill' points shown are as determined by the suppliers and operators during the initial training and commissioning of the system. The legend on the graphs is not ideal, but illustrates what is available in the 'Probe' package.

'Full' points

Although the concept of a static 'field capacity'/'full' point or DUL can be criticised from a soil physics perspective, it has immense practical value (Hillel, 1980). Irrigation applications in excess of the 'full' point result in periods of poor root aeration and much of the excess water is not used by the crop but percolates below the root zone, taking with it many nutrients and other soluble chemicals. The procedure advocated for the determination of the 'full' point (Anon, 1990), was to take probe readings after a big irrigation event or rainfall 'after excess water has drained'. This is open to much interpretation and not as easy as it sounds. Alternatively, a best-fit straight line through two or more adjacent probe readings subsequent to an irrigation can be extrapolated back to the date of the previous irrigation in order to determine a 'full' point (Gear *et al.*, 1979). Care must be exercised when extrapolating as the adjacent probe readings may reflect some deep percolation.

Examination of soil water content measurements, displayed with reference to time and also with reference to depth and time, as advocated by the suppliers of the 'Probe' package, is essential when trying to determine the 'full' point. The data shown on the depth graphs are especially useful for indicating water extraction patterns and deep percolation. For example, in Figures 2a-c, the original 'full' point appears to have been set at too high a level. The data in Figure 2a show that, between the 'Probe' reading taken on 11/2/98, which was just after an irrigation, and the subsequent 'Probe' reading taken on 16/2/98, there was a rapid change in soil water. In Figure 2b it can be seen that much of this change was at depths below 60 cm, the depth to which a subsequent probe reading taken on 18/2/98, indicated root water uptake occurred. If a line is projected from the two probe readings taken on 16/2/98 and 18/2/98, back to the date of the irrigation on 11/2/98 a 'full' point approximating the probe reading taken just after the irrigation on 26/2/98, and similar also to the reading on 26/3/98, is indicated. This 'full' point is also substantiated by the data shown on the depth graph in Figure 2c (cf. readings taken on 26/3/98, 30/3/98 and 2/4/98).

Establishing a 'full' point using the data shown in Figures 3a-c is even more difficult. In Figure 3b, early probe readings show relatively wet conditions at depth (30/3/98), relatively large changes in water content at depth (2/4/98) and relatively dry conditions near the surface. The likely explanation is as follows: in the early part of the season with a young crop, water was extracted mainly from the upper layers. It is likely that the large irrigation applications (averaging approximately 60 mm) percolated to below this root water uptake zone and, since there was little abstraction from the deeper soil, the water content there built up relative to the surface layers.

Establishing a new 'full' point by projecting straight lines from paired probe readings later in the season (in June, late August and mid-September) back to the date of a previous irrigation a 'full' point close to the probe reading taken on

Table 1. Information for selected furrow irrigated sites monitored with the neutron probe.

Block name	Crop	Planted/ harvested	Harvest date	Crop age (months)	Irrigation (mm)	Soil texture			Cane yield (t/ha)	ERC % cane	ERC (t/ha)
						Cl %	Si %	Sa %			
Sable-N2B	Plant	15.04.97	17.06.98	14,06	1 239	23	7	70	134,53	14,95	20,04
Sable-K4	3rd ratoon	23.10.97	05.10.98	11,40	1 670	28	4	68	106,96	16,22	17,35

the 15/6/98 is indicated and substantiated by the depth graphs in Figure 3c. While the magnitude in terms of soil water content of this reading is similar to that taken on the 30/3/98, the distribution with depth is markedly different. The 15/6/98 'full' point is also substantially lower than the original 'full' point, which helps explain the relatively low irrigation efficiencies.

The procedures recommended by the 'Probe' suppliers for the establishment of 'full' points is difficult and a little subjective. This can result in irrigating for long periods without being sure about a 'full' point, which is not an ideal situation. A far better approach to establishing a 'full' point which circumvents many of these problems, is to establish a drainage curve, as described, for example, by Vanassche and Laker (1989). A small area of the field is well watered, covered with a plastic sheet to prevent evaporation and neutron probe measurements are taken daily in the centre of the covered area in order to monitor the drainage rates. The DUL ('full' point) is indicated when drainage is negligible relative to other aspects of the water budget.

For sugarcane, the ideal time to establish the drainage curve is after planting or harvesting when a large irrigation is normally applied. Covering a small area, say 2 m x 2 m, of a recently harvested/planted crop with plastic for a few days is unlikely to have any major implications and the 'full' points (DUL) are determined at the probe sites which are used and therefore representative for the subsequent season.

'Refill' points

The 'refill' point can be established using three criteria:

- at what depletion should irrigation result in optimum (not necessarily maximum!) yields?
- at what depletion should the crop show water stress?
- at what depletion would the farmer irrigate (Gear *et al.*, 1977)?

The 'Probe' suppliers recommend using the soil water content at which the crop shows signs of water stress. This point is said to be indicated by a reduction in the relative rate of daily water use and a change in the pattern of water extraction, with relatively more water being extracted from the deeper depths. For the data shown in Figures 2a and 2c, the 'refill' point as defined above is close to the probe readings taken on 2/4/98 or 21/4/98 and a level close to the original 'refill' level is indicated. For the data shown in Figures 3a-c, because the 'Probe' has been used purely for monitoring, the timing of irrigations (having been according to the traditional A-pan approach) was such that no obvious 'refill' point was indicated. This suggests that:

- irrigation water had been applied too frequently (if viewed in conjunction with estimates of irrigation efficiency)
- too short a 'drying-off' period was allowed to enhance sugarcane ripening and save water.

'Probe' estimated daily water use

The estimated daily water use determined from differences in neutron probe readings, when compared with A-pan data, can be used:

- in a relative sense, for example, to compare between treatments as an index of crop vigour
- in an absolute sense as a check on crop coefficients and to verify water budgeting models (cf Figure 1).

Readings that do not reflect drainage should be selected and in order to reduce errors, such readings should be spaced at least three days apart. Careful cross-checking between the time and depth graphs is required to avoid assigning deep percolation to crop water use. A careful analysis of the data shown in Figures 2a-c and 3a-c, revealed that the ratio of 'Probe' estimated daily water use to A-pan peaked at approximately 0,65 when readings reflecting drainage were excluded. The ratio is generally lower for the data shown in Figure 3a than it was for the data shown in Figure 2a. The value of 0,65 for the ratio of crop water use to A-pan was lower than expected. Values of this ratio reported in the literature, including those from lysimeter studies range between 0,85 and 1,0 (Cackett, 1982; Thompson, 1986; Nyati, 1996). The low values reflected in the data could possibly be attributed to the method of calibrating the neutron probe.

'Probe' calibration

The suppliers advocate a generalised calibration relationship for all soils and all 'Probe' users have their neutron probes 'calibrated' using this general relationship. The rationale is practical and based on the reasoning that the only changes to conditions affecting paired probe readings are due to changes in water content. Different neutron probes are normalised by dividing counts measured in the soil by counts measured in a water drum, so that all the user needs to do is take water drum counts, send these to the suppliers who then adjust the slope of the generalised calibration relationship by the water counts of a specific probe, as explained in Equations 1 and 2 (users can also back-calculate to obtain the original coefficients, if required).

$$VSW = (S_{count}/W_{count}).\ X + C \qquad \text{..Equation 1}$$

$$VSW = S_{count}.(X/W_{count}) + C \qquad \text{..Equation 2}$$

where VSW = volumetric soil water (%)

S_{count} = neutron probe counts measured in the soil

W_{count} = neutron probe counts measured in a water drum

X = slope of the generalised calibration relation

C = constant of the generalised calibration relation

(X/W_{count}) = slope of the calibration relationship sent by the suppliers to the users.

In order to check for faulty electronics, including instrument drift, it is therefore important for a user of the 'Probe' to take regular water drum counts and check for any changes. A water drum is a far better standard than the shield of the probe apparatus. Counts taken in the shield of the probe apparatus can vary due to surrounding conditions, slight differences in the position of the 'fast' neutron source relative to the shield and variation of wax content in the shield.

The supplier's approach to calibrating the neutron probes is largely sound and very practical. However, estimated daily water use is highly dependent on the slope of the calibration relationship, which is soil dependent and can range from 0,65 to 1,1 (Hodnett *et al.*, 1991). Errors in the assumed calibration relationship can also lead to erroneous 'Probe'-based estimates of irrigation efficiencies. If the slope of the assumed calibration relationship is too low, probe readings before and after an irrigation will reflect that water added is lower than the true value. Therefore, if the calibration relationship provided by the suppliers of the 'Probe' package is not verified for specific soil conditions, drawing conclusions about the absolute values of crop daily water use, irrigation efficiencies, or estimates of readily available water is of dubious value, and users should rather concentrate on relative differences. Problems can also arise as a result of fast neutrons escaping when probe readings are taken near the soil surface, say the top 20 to 30 cm (depending on soil wetness), which then gives rise to counts and estimated water contents that are biased on the low side (Hauser, 1984).

Although site-specific neutron probe calibrations would be ideal, undertaking such detailed in-field calibrations for all sites is impractical. An alternative and more practical approach is to take probe readings before and after a known depth of water is added to the profile. A good time to do this is just after harvest before the first general irrigation application. After application of a carefully measured depth/volume of water, the area surrounding the access tube is covered with plastic and further probe readings are taken daily for two to three days afterwards. If no deep percolation is indicated, the irrigation application measured under very controlled conditions can be compared with the change in soil water estimated by the 'Probe'. This is also a good reference for the analysis of irrigation application efficiencies during the subsequent season.

Efficiency of irrigation applications

Efficiency of irrigation applications is defined here as the ratio of water applied through the irrigation system to the amount of water retained in the root zone of the crop. Bearing in mind the above discussion on calibration, the data shown in Figure 3a indicate low irrigation efficiencies relative to the efficiency of irrigations shown in Figure 2a. The ratio between the magnitude of irrigation water applications and A-pan summed for the period between irrigations, *viz.* a calculated crop coefficient, is:

- 1,1 for the data shown in Figure 3a
- 0,76 for the data in Figure 2a.

The average magnitude of the irrigation applications is very similar:

- 57 mm for data shown in Figure 3a
- 53 mm for the data in Figure 2a.

The data shown in Figure 3a illustrate the problems of irrigating using a water budgeting approach without regular checks on soil water content, which in this case has led to over-wet conditions and large inefficiencies. This has probably been caused by assuming low irrigation efficiencies and trying to compensate by applying larger irrigation water applications. This is bad practice because when a low irrigation efficiency is assumed, the actual efficiency is also likely to be low and *vice versa*.

It is apparent by comparing the data in Figures 2a and 3a, that the amount of water that a soil can 'store' just prior to an irrigation, and the magnitude of the irrigation, are major determinants of the application's efficiency, and knowing this figure is essential for efficient irrigation, even with furrow irrigation, which is often assumed to be self-compensating through a wetter soil having a more rapid advance front.

Assuming slight under-estimation of the magnitude of water additions (cf 'Probe' estimated daily water use) no more than 45 mm of water should be applied during a furrow irrigation. The figure of 45 mm is corroborated by laboratory determined estimates of 'field capacity' (water content at –10 kPa) and wilting point (water content at –1 500 kPa) which, together with an estimate of rooting depth, indicate total available moisture (TAM) of 76 mm for site Sable-K4 and 80 mm for site Sable-N2B. Readily available water (RAW) (at 60% depletion of TAM) is then 45 and 48 mm respectively.

Using the 'Probe' to estimate RAW for site Sable-N2B indicates readily available water to be approximately 34 mm, which is 14 mm lower than the laboratory based estimate. However, this lower estimate of RAW obtained using the 'Probe' is consistent with the low estimates of crop daily water use and could also be attributed to an erroneous calibration relationship (cf 'Probe' estimated daily water use). This provides even further motivation to check whether the generalised calibration relationship given by the suppliers of the 'Probe' is representative of the soils in question.

In practice, especially when sugarcane is planted in the furrow, it is often difficult to apply irrigation amounts of less than 60 mm and get adequate coverage due to the length of the furrows and the slow advance times, especially mid to late season when sugarcane tends to clog the furrows. It is apparent from data shown in this paper that serious attention should be given to researching a switch to interrow furrow irrigation. Interrow irrigation should provide for reduced advance-front times, and therefore be more flexible and allow for smaller irrigation application depths. From a technical perspective, interrow irrigation should also result in improved irrigation uniformities and efficiencies, as shown in Swaziland (Dlamini, 1998).

Irrigation system performance evaluation

A major potential use of the probe, especially with regard to furrow irrigation is to check on irrigation system performance, especially the uniformity of irrigation water applications. Assuming a furrow length of 'L' m, sets of access tubes (say three) are placed at distances of 1/4, 1/2 and 3/4 L down a set of furrows, with probe readings being taken immediately prior to an irrigation and daily for two to three days after an irrigation. Differences between the probe estimated soil water contents and patterns before and after the irrigation application are then a relatively efficient and direct measurement of irrigation performance and, in particular, irrigation uniformity. Such 'Probe' readings can then be used in an iterative procedure to adjust, say, furrow flow rates and cut-off times, and so optimise irrigation guidelines for given field and soil conditions, something which is nearly impossible to do on a purely theoretical basis. At a monitoring site on an estate, initial assessments show relatively large amounts of water infiltrated at the top and lower end of a furrow, with relatively small amounts of water infiltrating in the middle of the furrow.

Conclusions

By facilitating the measurement and subsequent analysis of soil water variations with respect to time and depth, the 'Probe' package can be a useful water management tool. However, the time and judgement required to record and analyse data using the 'Probe' should not be under-estimated. Communication with agronomists and irrigation engineers on the estates revealed that frequently other responsibilities precluded such detailed analysis of the 'Probe' data. In addition, problems with the equipment are exacerbated in Zimbabwe because communication with the suppliers is difficult and costly as they are stationed in another country.

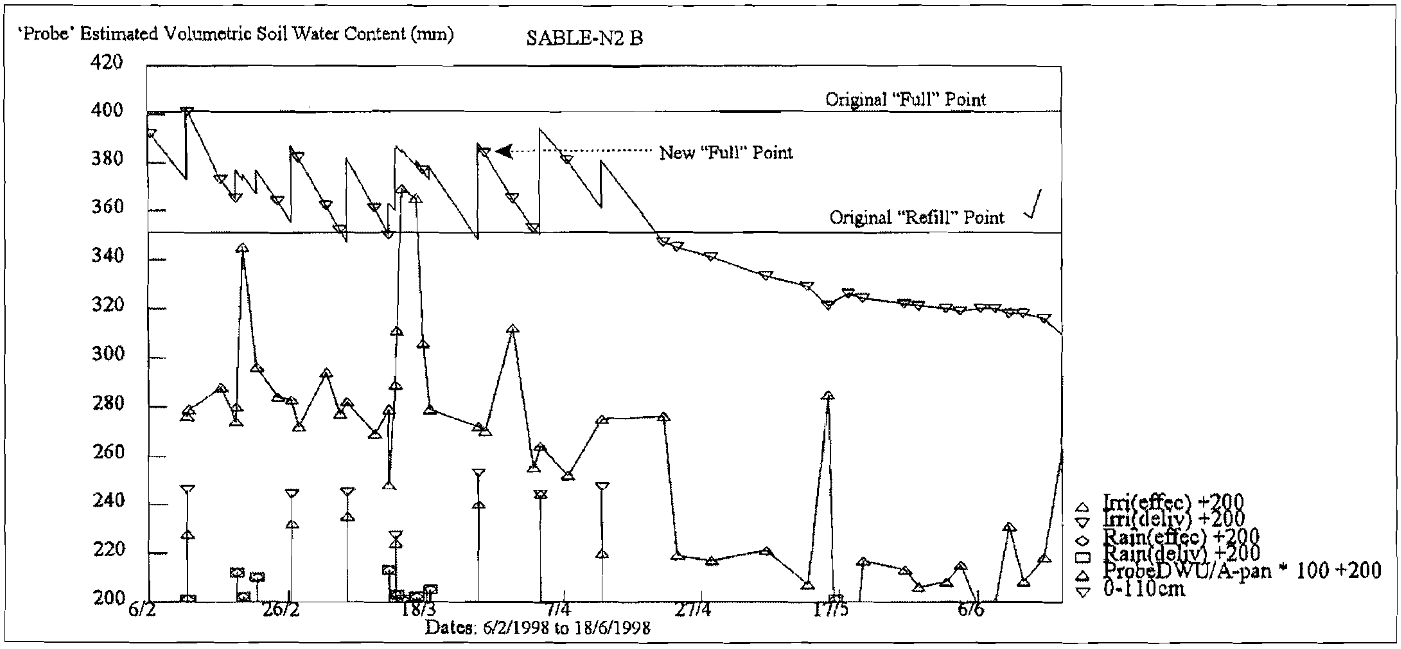

Figure 2a. Variations of 'Probe' estimated daily water use (DWU) /A-pan, and effective delivered irrigations and rain.

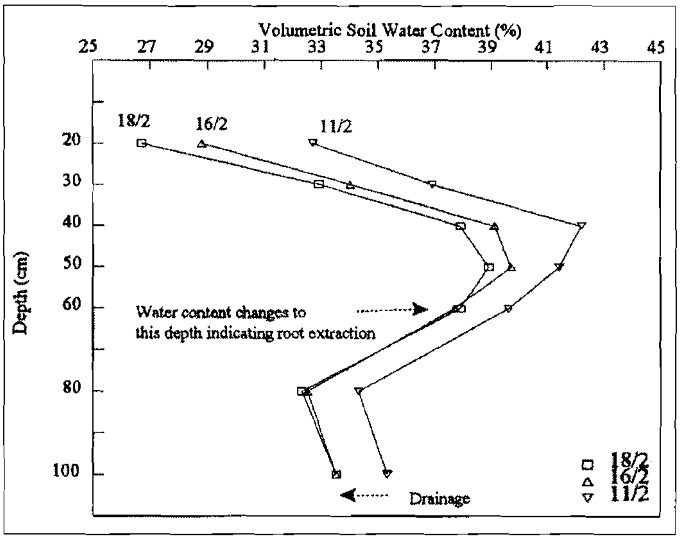

Figure 2b. Variations of 'Probe' estimated soil water, with respect to soil depth and time at Site Sable-N2B

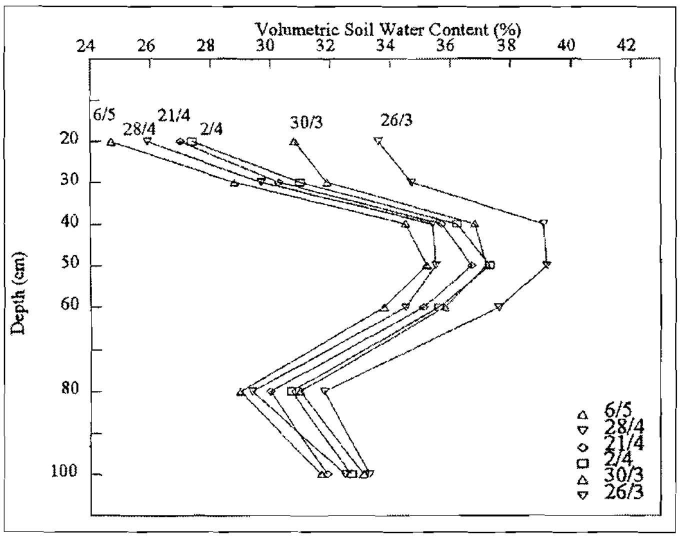

Figure 2c. Variations of 'Probe' estimated soil water, with respect to soil depth and time at Site Sable-N2B – shecking the 'refill' point.

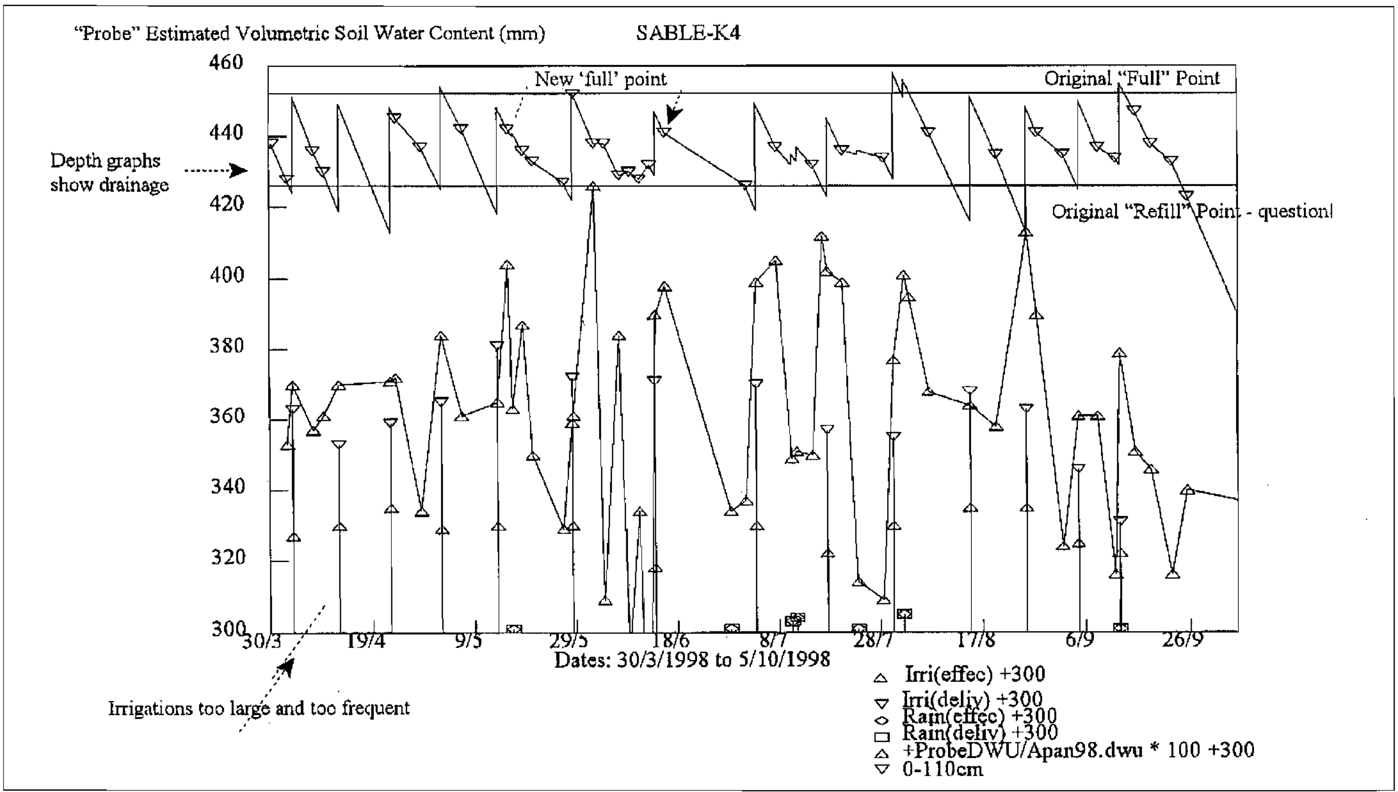

Figure 3a. Variations of 'Probe' estimated soil water, 'Probe' estimated daily water use (DWU) /A-pan, and effective delivered irrigations and rain.

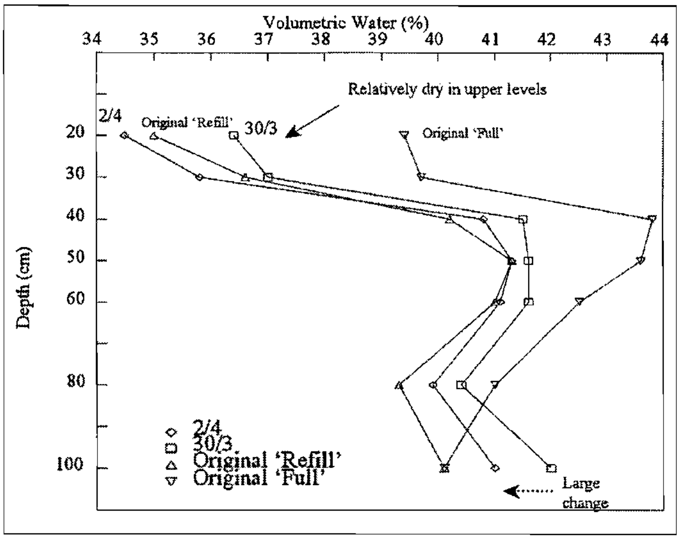

Figure 3b. Variations of 'Probe' estimated soil water, with respect to soil depth and time at Site Sable-K4.

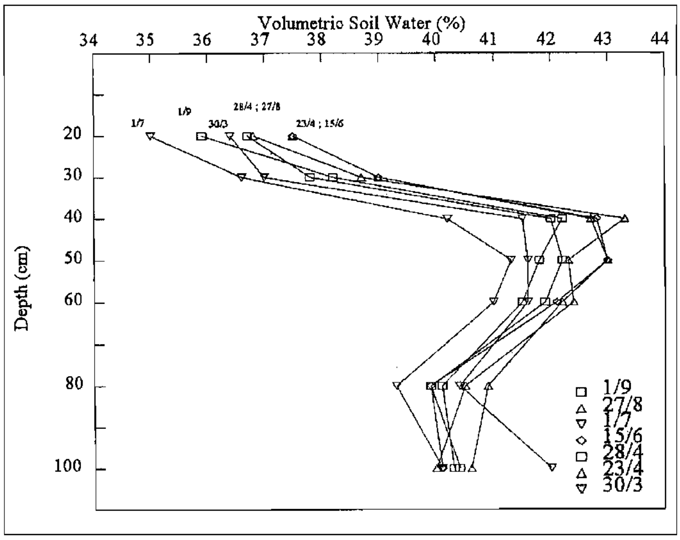

Figure 3c. Variations of 'Probe' estimated soil water, with respect to soil depth and time at Site Sable-K4.

Analysis of selected data collected using the 'Probe' highlighted the following inefficiencies in irrigation:

- an inflated 'full' point, leading to poor aeration in the root zone, and excessive deep percolation
- too large and too frequent irrigation water applications when these were determined using a water budget and inflated to cater for assumed low efficiencies, equivalent to using a crop coefficient (referenced to A-pan) of 1,1
- a 'drying-off' period that was too short.

At the sites discussed in the paper, potential savings in water of approximately 200 mm/ha are evident and the inefficiency in irrigation water applications is the likely cause of yield reductions in the order of 15 t/ha.

The amount of water that a soil could 'store' just prior to an irrigation, and the magnitude of the irrigation, were the major determinants of application efficiency. This shows that the widely expressed belief that furrow irrigation is self-compensating, through a wetter field having a more rapid advance front which leads to compensating smaller irrigation applications, is largely an erroneous oversimplification.

If sugarcane is planted in the furrow it is often difficult to apply irrigation in amounts that do not exceed the soil's storage capacity because of the slow advance front times, especially in mid to late season with ratoon crops which tend to clog the furrows. The data shown in this paper can be used to suggest that serious attention should be given to researching a switch to interrow furrow irrigation which allows for reduced advance-front times. This gives greater flexibility and allows for smaller and more uniform irrigation application depths, as proven at sites in Swaziland.

Weaknesses in the original 'Probe' operating guidelines that were suggested by the suppliers have been addressed, *viz.* practical methods have been proposed to:

- to check on the neutron probe's calibration
- determine an *in situ* drainage curve and objective 'full' point using procedures that fit in with typical estate land husbandry
- use the 'Probe' to assess furrow irrigation application uniformities.

A combination of an appropriate water budgeting procedure with less frequent 'Probe' measurements, taken largely to check on the 'ground-truth' of the water budgets, is likely to be the most practical method of utilising a neutron probe in general irrigation water management. Conflicting results regarding daily water use estimates for sugarcane in relation to A-pan data, indicate that the generalised calibration relationship provided by the suppliers of the 'Probe' needs to be checked for Lowveld soils. When confidence in a calibration relationship is established, 'Probe' based estimates of sugarcane water use can be compared to an A-pan and/or Penman-Monteith reference in order to provide a useful verification of water budgeting models used for various Lowveld conditions and sugarcane varieties.

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HERBICIDE DISSIPATION AND RUN-OFF FROM SOILS UNDER SUGARCANE IN MAURITIUS

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Abstract

Increasing concern about the potential pollution of surface and groundwaters by herbicides used in sugarcane cultivation in Mauritius is calling for a need to identify agricultural practices that would minimise the movement of herbicides to our water resources. In this context, the off-farm transport by surface run-off of atrazine, diuron, hexazinone and acetochlor were monitored on a plot scale (500 m^2) as well as on a 40 hectare catchment at a site (Valetta) receiving an annual rainfall of about 3500 mm. The results showed that rapid dissipation of herbicide occurred in the top 0-2,5 cm layer of the soil and little herbicide was transported down the soil profile to below 30 cm depth. There was no evidence of on-farm build-up of herbicide residues. Mean herbicide concentrations in run-off waters were low and did not exceed existing drinking water guidelines. The total mass of herbicide lost by run-off from the 40 hectare catchment over one growing season represented not more than 0,02% atrazine, 0,32% hexazinone, 0,07% diuron and 0,19% acetochlor with respect to the amount normally applied. Although at plot scale herbicide losses occurred mainly as sediment-bound residues, at the 40 hectare catchment, 70-95% of herbicide lost occurred as dissolved residues. Based on visual observation of crystal clear watercourses becoming loaded with mud during and after a heavy rainfall event, the perception of the general public is that quantities of herbicides representing a hazard to human health are being moved during soil erosion. The data obtained therefore showed that this perception is unfounded.

Introduction

Sugarcane cultivation in Mauritius relies heavily on the use of herbicides. Each year the 78 000 ha of land under cane receives approximately 460 tons active ingredient (a.i.) of herbicides. Although benefits from the use of herbicides are well recognised, the impact of these chemicals on the environment, particularly the contamination of surface and ground waters and the marine ecosystems, has become a major issue. The presence of low levels of herbicide residues in surface and ground waters of Mauritius has been demonstrated by Ng Kee Kwong *et al.* (1998) who also inferred that no freshwater source in Mauritius is completely exempt from possible contamination by herbicides used in sugarcane cultivation. Moreover, in view of the generally undulating topography of the island and with the fact that up to 70% of the yearly rainfall occurs as high intensity events between January and April, the potential for off-farm movement of herbicides by surface run-off and subsurface drainage is high.

While numerous studies on off-farm transport of pesticides have been done in the USA and Europe (Gaynor *et al.*, 1995; Lennartz *et al.*, 1997; Mathiessen *et al.*, 1972), there remains a general lack of information on this issue under tropical conditions. Yet this information is vital in the development of best management practices to minimise the environmental impact of herbicide usage. This study was therefore initiated with the objectives of (i) measuring the persistence of herbicide in soils and in surface run-off from a defined sugarcane catchment and (ii) to assess the impact of this movement on herbicide residue concentration in surface water.

Materials and methods

This study was initiated in 1997 as part of a large scale project aimed at measuring and predicting the movement of agrochemicals in tropical sugar production. The experiment site was located at Valetta in a superhumid zone of Mauritius receiving 3500 mm rain annually. The soil was a Humic Ferruginous Latosol (Humic Acrisol according to the FAO/UNESCO classification) with a silty clay loam texture and with an organic C content of 30 g/kg. The site was instrumented at four levels, namely 500 m^2 plot, 4, 10 and 40 ha catchments to measure surface run-off and soil loss.

Herbicide treatment and experimental set-up

At the plot scale of 500 m^2, with ratoon sugarcane and trash arranged in alternate interrows, atrazine, diuron, hexazinone and acetochlor were applied at 2,7, 2,7, 0,4 and 1,3 kg a.i./ha, respectively.

Sugarcane within the 40 ha catchment received the following herbicides: diuron (4 kg a.i./ha), hexazinone (0,8 kg a.i./ha), acetochlor (2 kg a.i./ha) and ioxynil+2,4-D (2,5 kg a.i./ha). All fields within the 40 ha catchment including the 500 m^2 plot also received 800 kg of the complex fertiliser 17:8:25 per hectare.

The 500 m^2 plot was equipped with a run-off collection system consisting of a metal trough laid downslope of the plot and tipping buckets (16 L) connected to dataloggers for measuring and recording run-off volumes and rainfall. Run-off samples were taken at each tip using a splitter (split ratio