NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE of HYDROLOGY

REPORT No 22 February 1974

THE APPLICATION OF NEUTRON PROBE TECHNIQUES TO IRRIGATION RESEARCH AND MANAGEMENT IN JAMAICA

by

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P M Holdsworth

ABSTRACT

This project was carried out by the Institute of Hydrology, Wallingford, under a Technical Assistance scheme to the Jamaican Water Resources Division. It was funded by the UK Overseas Development Administration, during a five month period starting in February 1973.

Its main object was to demonstrate the application of neutron probe techniques to the improvement of the efficiency of irrigation of bananas and sugar cane at two experimental sites.

Although the project was of very short duration the information gained made it possible to estimate the consumptive requirements of both crops. In conjunction with measurements of soil reservoir storage characteristics this information enabled us to suggest improvements in the existing irrigation regimes and to recommend lines of future research to extend and refine these provisional findings.

MAP SHOWING TOPOGRAPHICAL CONTOURS OF JAMAICA

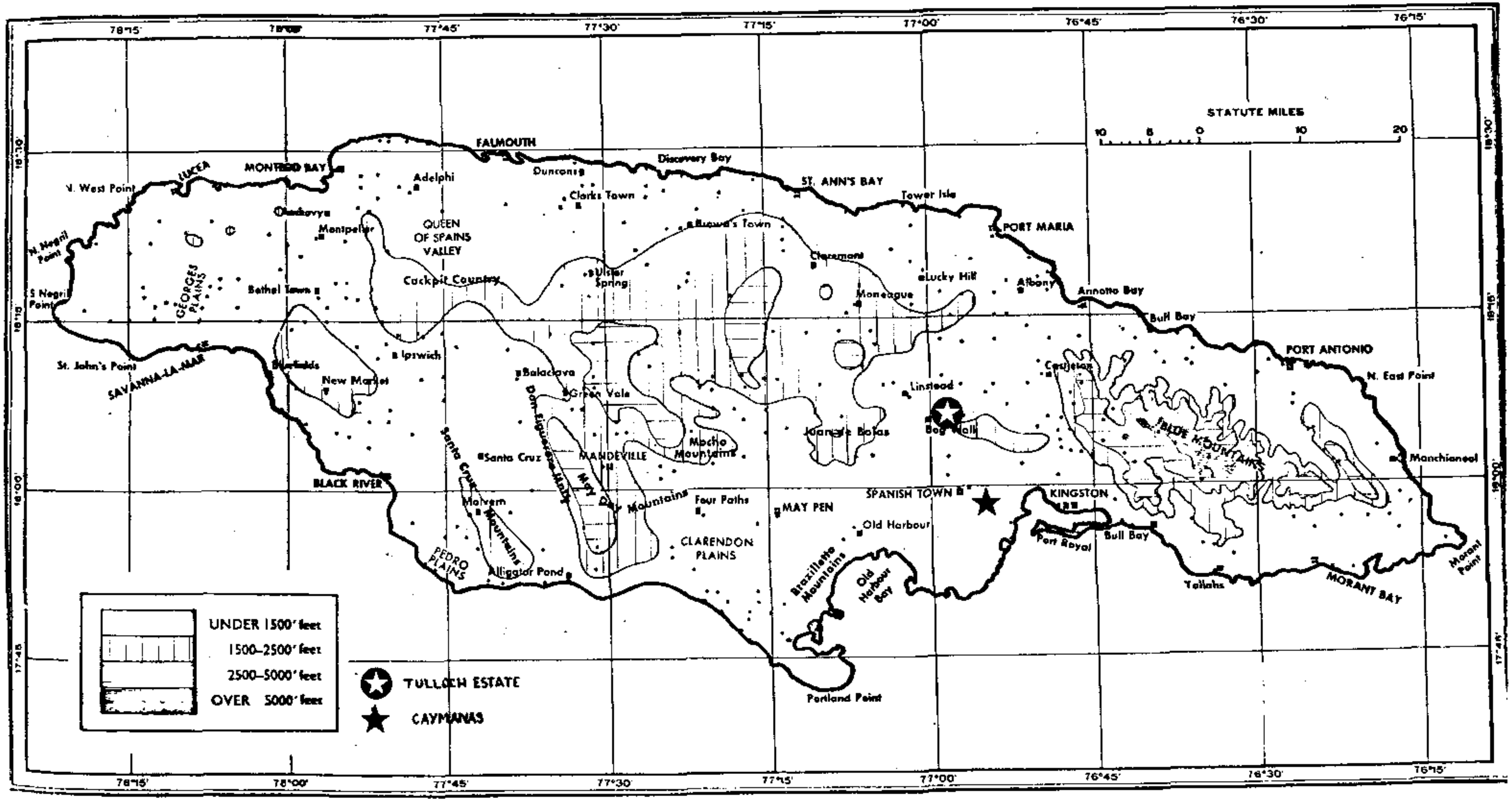


Figure 1

INTRODUCTION

Farmers all over the world tend to use as much water as they can get for irrigation because they believe that the more water they can deliver to their fields, the better the crop will be. In practice, over-irrigation can cause water-logging of the irrigated land thereby reducing its productivity and even the maintenance of potential transpiration rate may be neither necessary nor desirable for maximum yield of some crops. As water resources become increasingly scarce and more expensive to develop, wastage must be reduced and more precise guidance should be given to farmers as to optimum crop requirements.

At the design stage of an irrigation scheme there is a tendency to overestimate crop water requirements and this raises the capital costs of a project by oversizing canals and storages as well as increasing running costs when pumping is involved. The resulting increase in cost with consequent reduction in net benefits will make irrigation projects less attractive for investment than they might otherwise be. Engineers therefore also require more information on optimum crop requirements in different soil and climatic conditions.

Essentially there are two main problems in determining the optimum irrigation regime. Firstly, what are the water requirements of the crop for maximum yield given an adequate supply of water? Apart from the obvious seasonal factors, the effects of fertilizer and the quality of the water might be important. Secondly, what is the optimum way in terms of irrigation rate, frequency and method, by which water can be made available to the plant, utilising the natural storage of the soil? Here there are the practical considerations of cost and scale. Also leaching requirements, areal variability of the soil and the function of the water table need to be considered.

The first problem, that of determining the consumptive use of the crop, can be studied from a soil moisture approach provided certain boundary conditions are met. This can be a considerable advantage when we consider the drawbacks associated with the meteorological approach or the direct approach through a water balance study.

The second problem, that of making water available to the plant with maximum efficiency, can be studied effectively only through investigation of the soil-water regime. Continual, accurate measurements of soil moisture are essential. In addition, measurement of the soil moisture hydraulic potential profiles is necessary for a full understanding of the movement of water in the soil and the effect of the rooting system of the plant. Nevertheless, in some situations, crude but useful information can be obtained by soil moisture measurement alone.

It was in the context of these two problems that this project was designed. The principal objective was to demonstrate that soil moisture measurement by neutron probe could be applied to improve irrigation efficiency. To this end the programme of the study was:

1. To set up access tube networks and other instrumentation on representative sites, selected in conjunction with local research groups.

2. To obtain sufficient data from the networks for preliminary analysis while at the same time training local staff in the use of the neutron probe.

3. To analyse the data for making provisional estimates of the consumptive use of the crops in the study areas and if possible to make recommendations concerning the optimum frequency, application rate and amount of irrigation required.

4. To leave a viable experimental framework and recommendations for further work so that the project could be continued and, where necessary, expanded by Jamaican researchers.

One neutron probe was provided by the Water Resources Department and one, together with other equipment, was loaned by the Institute of Hydrology.

The project was divided into two parallel studies at separate locations as shown in Figure 1, one being a study of furrow-irrigated sugar cane at Caymanas Estate and the other of spray-irrigated bananas at Tulloch Estates. There were various on-going research programmes at both sites and the neutron probe work was carried out in close collaboration with these. Inevitably, only part of the climatic cycle and growth stages were sampled during the project. In this report, we first outline the commonly used methods of estimating consumptive use and also discuss briefly the disadvantages of the lysimeter and water balance methods of determining actual transpiration. Because neutron probe techniques are relatively new to practical investigations, we outline in some detail the principles of the technique and the practical problems of interpretation of the results. Finally, the two project studies are presented in detail.

The data available at the time of this report are limited to those collected during our field participation up to June 1973 and therefore the analysis we present here is of a preliminary nature. Although we can indicate the validity of the experimental design and discuss the processes observed during a wetting and depletion cycle, our estimates of transpiration and of irrigation efficiency, particularly in the case of Caymanas, must be considered in the light of the short period of data available to us.

TRADITIONAL METHODS

The equations of Blaney-Criddle, Thornthwaite and Penman are those most commonly used to estimate consumptive use of potential transpiration of crops. However, the actual rate of transpiration of a crop in particular circumstances will be less than the potential rate if the soil moisture supply is limiting. In arid countries where the potential transpiration is very high, the soil moisture supply under natural conditions is usually the controlling factor for transpiration.

The Blaney-Criddle and Thornthwaite methods use relationships between mean monthly temperature and mean monthly consumptive use and are based upon experience in the western and eastern United States respectively. The Blaney-Criddle method assumes a linear relationship between effective heat and potential transpiration and can include a humidity and crop factor; Thornthwaite assumes an exponential relationship of the same factors as Blaney-Criddle. The Penman method is based on the energy balance and can be applied over daily periods if the requisite climatic data is available. Unfortunately the amount of climatic data required and the extra effort in computation prevent the method being as widely used as the less satisfactory empirical methods.

The accurate measurement of actual transpiration, essential to any improvement in our knowledge of the soil-plant-water system, is not a simple problem on a field scale. The most commonly used method, the lysimeter, suffers from its small size and the atypical soil conditions within it. There are also difficulties in simulating hydraulic continuity across the base of the lysimeter. This can be a significant problem when the water table is near the surface as is often the case in an irrigated area. The larger scale, water balance approach suffers from the difficulty of measuring accurately the inflows and outflows to the study area. Also traditional methods of soil moisture measurement are clearly time-consuming, destructive and not repeatable at the same site.

THE NEUTRON PROBE

The neutron probe is capable of giving very precise measurements of soil moisture changes, in situ, in undisturbed soil in its natural state. Measurements are rapid and may be repeated as frequently as necessary in the same soil profile which remains unchanged except for moisture content. This is a considerable advance from the traditional gravimetric methods with their disadvantage of disturbance of the soil profile and practical limitations of time and effort required.

The Wallingford neutron probe and ratescaler used in this project is a commercially available instrument developed at the Institute of Hydrology. It satisfies the demand for an easily portable, precise yet robust instrument which would be suited to practical field investigation particularly in the context of irrigation. Nevertheless it is a sophisticated instrument which must be operated with care to ensure good results. The reader should refer to the Institute of Hydrology Report No 19 for a full discussion of the techniques involved.

Principle of Operation of the Neutron Probe

The probe contains a source of fast (high-energy) neutrons. Measurements are made at the required depths in the soil profile by lowering the probe into pre-installed 1¾" aluminium access tubes which extend downwards to the lower limit of moisture changes. Fast neutrons are emitted into the soil from the probe. There they undergo collisions with the atomic nuclei of the soil elements and in the case of hydrogen, lose energy in each collision thereby producing a cloud of slow ('thermal') neutrons in the soil around the source position. Most of the hydrogen in the soil is in the form of free water; any other is fixed giving an unchanging background effect. Thus the density of the cloud of thermal neutrons is proportional to the amount of water present. The detector, mounted in the probe, produces a pulse

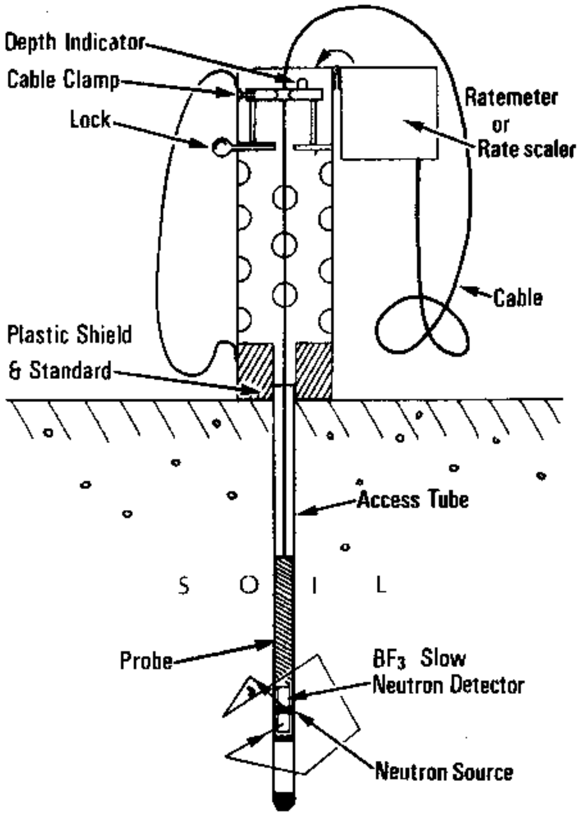
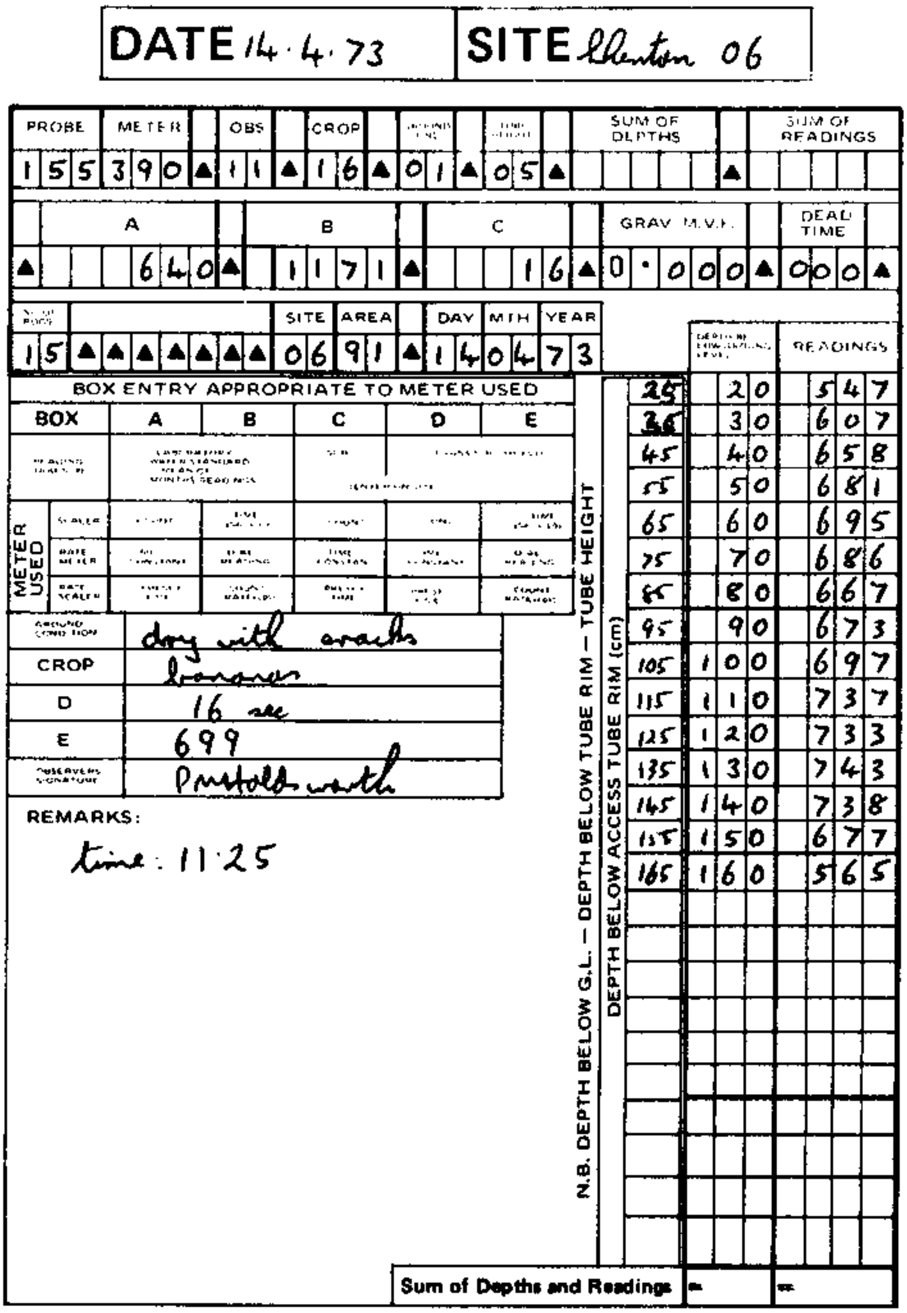


Figure 2 A Diagram of the neutron probe in use.



DATE 14.4.73 **SITE** Ilenton 06

PROBE	METER	OBS	CROP			SUM OF DEPTHS	SUM OF READINGS
155	390 ▲	11 ▲	16 ▲	01 ▲	05 ▲	▲	

A	B	C	GRAV. M.V.F.	DEAD TIME
▲ 640 ▲	1171 ▲	16 ▲	0·000 ▲	000 ▲

		SITE	AREA		DAY	MTH	YEAR
15	▲▲▲▲▲▲▲	06	91	▲	14	04	73

BOX ENTRY APPROPRIATE TO METER USED

BOX	A	B	C	D	E

METER USED

GROUND CONDITION	dry with cracks
CROP	bananas
D	16 sec
E	699

REMARKS:

time: 11·25

N.B. DEPTH BELOW G.L. – DEPTH BELOW TUBE RIM – TUBE HEIGHT

DEPTH BELOW ACCESS TUBE RIM (cm)		READINGS
25	20	547
35	30	607
45	40	658
55	50	681
65	60	695
75	70	686
85	80	667
95	90	673
105	100	697
115	110	737
125	120	733
135	130	743
145	140	738
155	150	677
165	160	565

Sum of Depths and Readings = =

Figure 2 B An example of a field record card.

for each thermal neutron that passes through it and these pulses are collected and counted by the scaler. Thus the count rate indicated by the scaler is a measure of the amount of water present in the soil.

The count rate is converted to moisture content using a calibration line derived from direct comparisons of count rate to moisture content obtained gravimetrically from core samples. The moisture content is expressed as moisture volume fraction (MVF) i.e. volume of water per unit volume of soil. Different calibrations have to be used for different soil types but in practice these can usually be simplified to a family of four lines which have been found to represent nearly all soil types. For most purposes we wish to know only the changes in soil moisture. Thus the background count rate can be ignored. It is only the slope of the calibration line which defines the change; usually this slope varies very little between one soil and another.

Because the neutrons (both fast and thermal) have a fairly large range in soil, the probe measures the moisture content of a 'sphere of influence' of soil. The radius of this sphere is dependent upon the energy of the fast-neutrons (constant for a given type of source) and the moisture content of the soil. It can vary from about 15 cm in pure water or a very wet soil to more than 30 cm in a very dry soil. For this reason measurements are made at 10 cm intervals down the profile providing an overlap between adjacent spheres of influence and ensuring that all variations in water content down the profile are monitored. This results in a 'smoothed' moisture profile, the integrated area beneath which is an accurate measure of the total moisture in the profile. One disadvantage of the neutron method is that it is not possible to achieve quite such accurate measurements in the top 20 cm of the soil profile because neutrons are lost to the atmosphere when the probe is in this zone. There are methods of overcoming this problem but in this project an *ad hoc* correction is made based on the assumption that the 0-10 cm layer of soil varies in moisture content by 0.1 MVF (10% of total volume) more than the 10-30 cm layer measured by the reading taken at 20 cm. This correction will tend to produce an overestimate of the variation in total moisture content of the profile.

Processing the data

In the field, a complete set of observations from one access tube is entered on the field card illustrated in Figure 2B. This card has been designed to facilitate computer processing of the records and it contains all the site and instrument information necessary for correct interpretation of the records.

An example of the computer line printer output is shown in Figure 3. The field records are reproduced verbatim in the first two columns. The calculation is straightforward; count rate in the field is normalised for instrument characteristics and then transformed into moisture volume fraction, MVF, by the linear calibration curve. The moisture present in each layer expressed as a depth is obtained by defining a layer as extending from midway between successive pairs of depths at which readings were taken. The integrated profile water content expressed both as a depth of water and as an average MVF is obtained by addition.

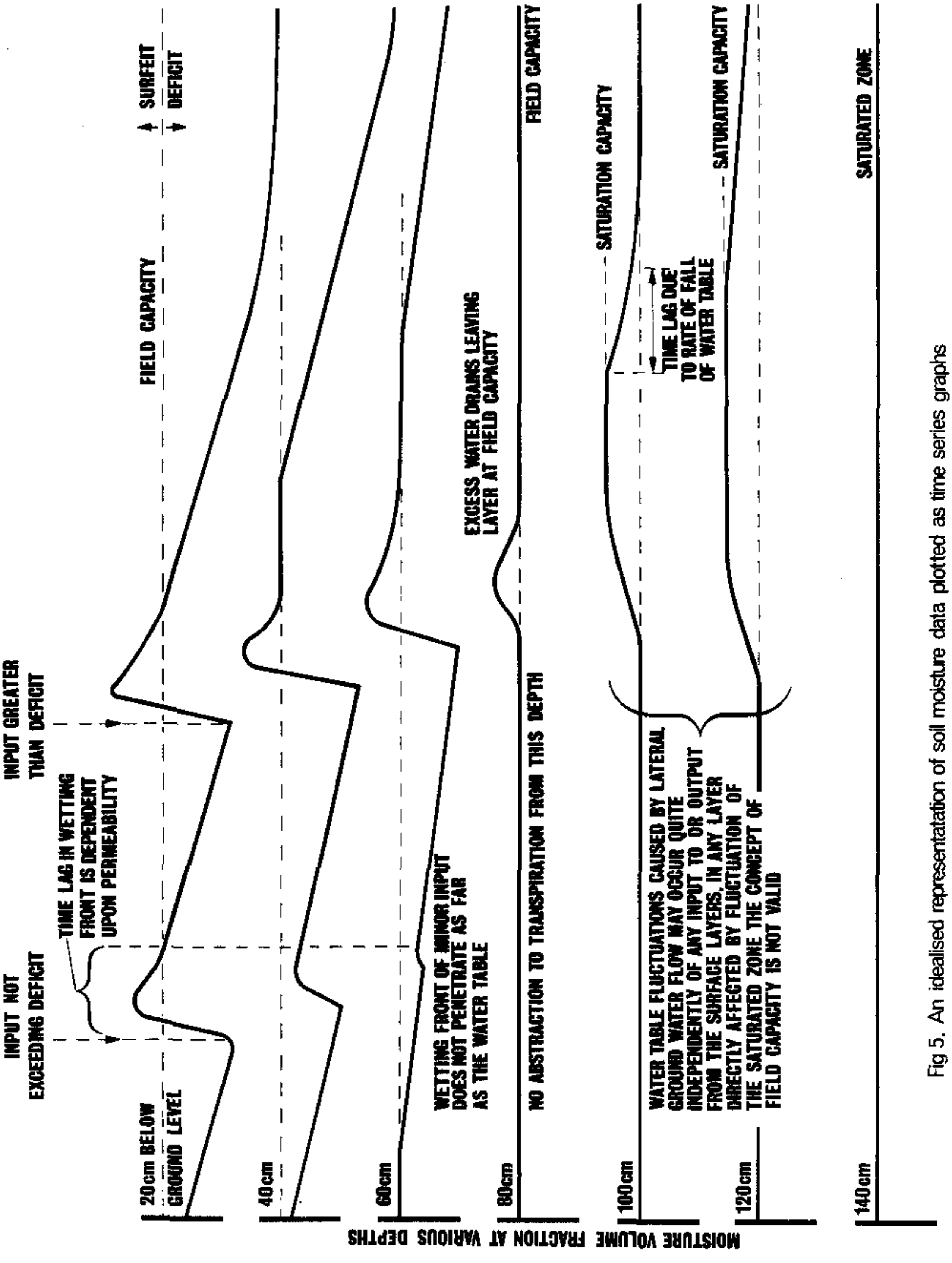


Fig 5. An idealised representation of soil moisture data plotted as time series graphs

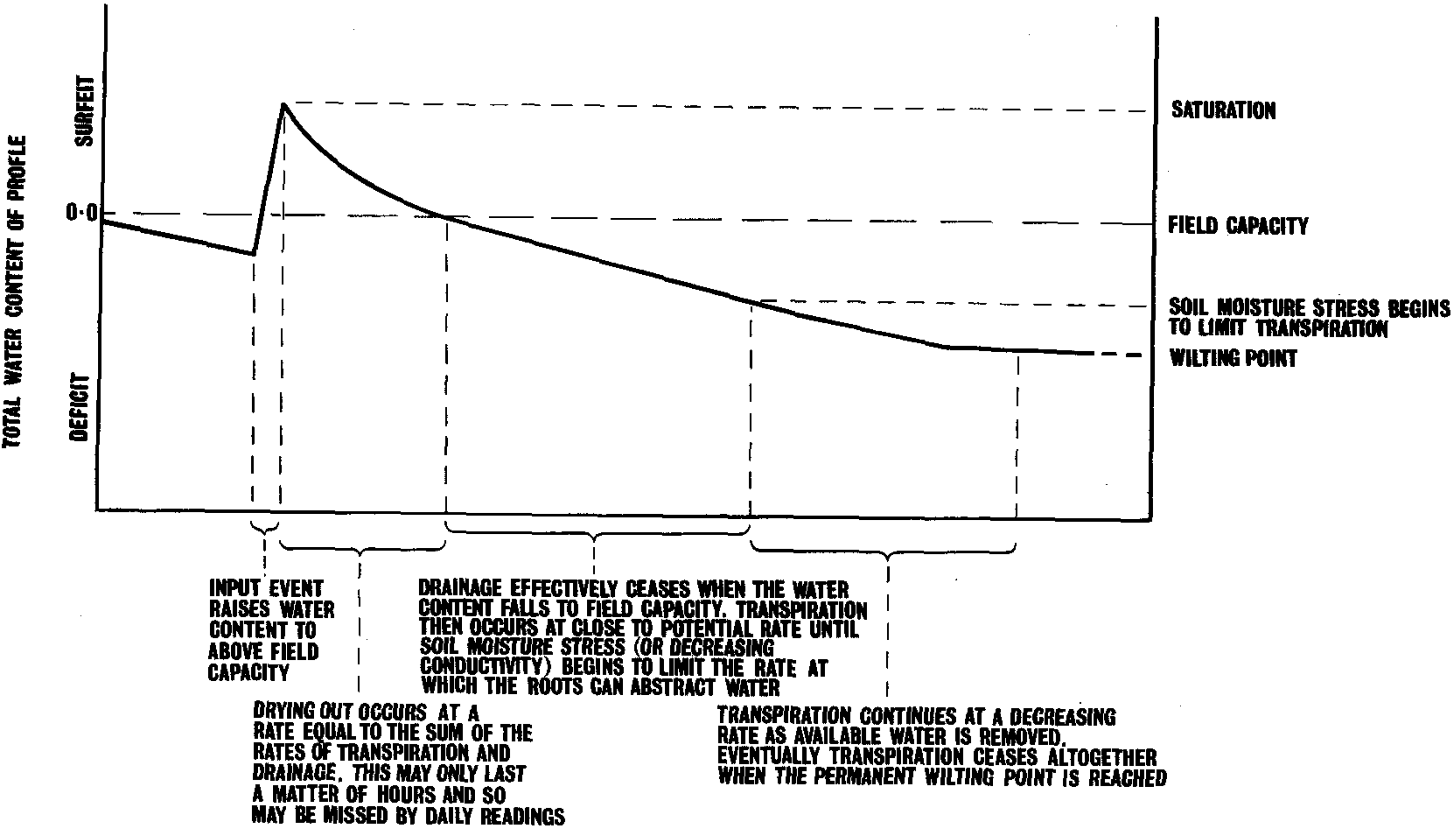


Fig 6.Soil moisture storage depletion curve (An idealised representation of variation in total water content of a soil profile))

The values quoted for standard deviation refer to the effect of a random error inherent in the use of neutron probes. Fast neutrons are emitted from the source randomly in time. Consequently any measurement of count rate of realistic duration must be subject to some departure from the true mean value. This departure is termed the random counting error. Its distribution about the mean is assumed to be normal and it can be represented by the standard deviation of the distribution. This means that the precision of the measurement is dependent upon the number of pulses accumulated during that measurement; the longer the counting time, the higher the precision.

Presentation of Data

An appreciation of moisture changes both with depth and with time is essential to any analysis of water movement in the soil and its abstraction by plants, and we have presented the data in three different graphical forms.

The first type of graph, the soil moisture profiles shown in Figure 4, has moisture content plotted against depth. Several curves can be superimposed on the same graph corresponding to sets of measurements from the same table on different dates. The area under each curve represents the total moisture content on each date.

Interpretation of superimposed soil moisture profiles can be difficult, especially when there is a fluctuating water table within the zone of measurement. However, in the simplest case the group of profiles takes the form of an inverted triangle (Figure 4a) whose maximum width depends on the moisture changes at the surface and whose apex corresponds to the depth below which no change in water content occurs. We can infer that abstraction by the plant is negligible below this point.

Where the profile is made up of layers of soil of different composition, this can be distorted (Figure 4b) by the different moisture retention characteristics of the soil layers. However, the same general form can usually be recognised. If there is interference by a fluctuating ground water level and its associated capillary fringe, changes in water content will also occur in the lower part of the profile giving a basal zone of change (Figure 4c). Where the water table is close to the surface, the zones will intersect. In this situation we cannot distinguish upward movement of water, ultimately lost by transpiration, from downward movement by infiltration and drainage, unless in addition we have measurements of soil moisture potential (tension). Where the water table never falls below the deepest part of the measured profile, no change of water content will occur below the water table and the graphs will show two zones of maximum change and two of minimum change (Figure 4d).

In the second type of graph, the variation in moisture content at each depth is plotted against time. The suite of lines illustrated in Figure 5 indicate the time scale of the moisture changes and also serve to identify any sequential vertical changes during the wetting or drying cycles.

Finally, the third type of graph shows the total water content at each site plotted against time and indicates the rate of change of storage in the profile and in particular the rate at which depletion occurs. Ideally the graph would be of a form illustrated in Figure 6.

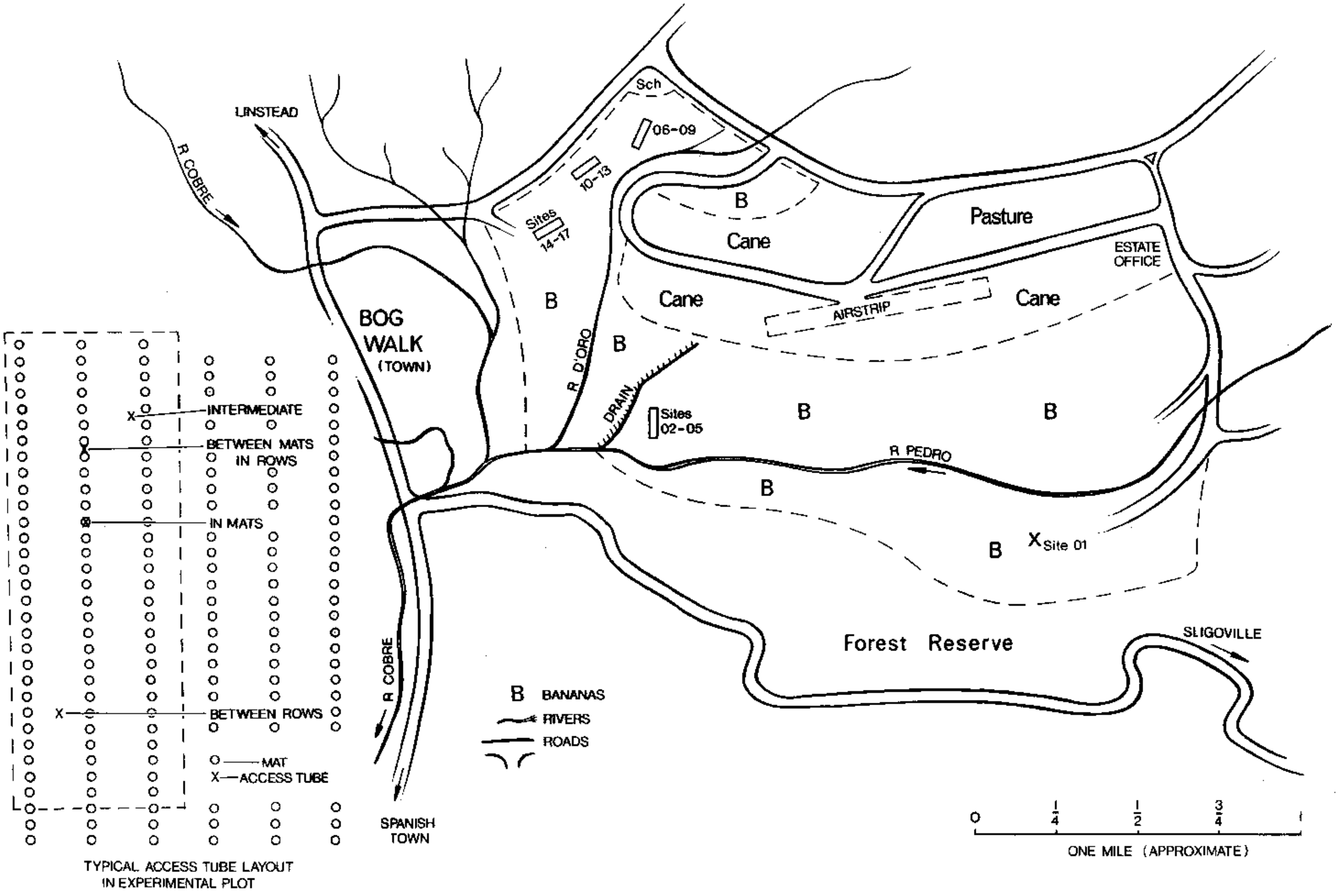


Fig.7. Sketch map of Tulloch Estate

Project 1: THE OPTIMUM IRRIGATION REQUIREMENT OF A BANANA PLANTATION

A series of experiments is being carried out by various groups of research workers from the Banana Board of Jamaica on the Tulloch Estate, Bogwalk. This experiment by W. Bond of the Banana Board and Dr L. Coke of the University of the West Indies, aims to improve yield by optimising irrigation control.

Background

The produce of the Tulloch estate is diverse with sugar, citrus, coconuts and beef, but the predominating acreage is given over to bananas. Although banana production in Jamaica has been declining for several years the demand for Jamaican fruit remains high, partly because demand generally is high and partly because of its superior quality. Typical yield per acre for Jamaica as a whole is very low (about 2 tons) while that for Tulloch is already much higher at around 10 tons per acre. It is essential that yields and profitability are improved to keep the Jamaican banana industry viable as competition from other countries increases. Mr Turner, the owner and manager of the estate, is aiming by pest control, the use of fertilizers and by irrigation to increase yield to something nearer that obtained in the most successful banana growing areas of the world (around 25 tons per acre). To this end he has installed a travelling overhead spray irrigation system to apply the optimum amount of water at optimum time intervals. It is also possible to dissolve pest and weed control chemicals and fertilizer in the irrigation water. Minimal labour is required to operate the system. Previously no irrigation was used and fertilizer was applied by hand or by aerial spray, both methods being expensive.

Annual rainfall is generally in the range 65-75 inches, falling mainly in the months October to December, May and June. However the rainfall is usually localised and heavy; a large proportion of the annual total fall will be accounted for in 30-35 days. This is one reason for the low yields as cropping rate is reduced 2-3 months after a dry spell.

Instrument Networks

In the plots used for this project the rows of plants were about 11 ft apart with 3 ft between plants in the rows. As the plots matured the plants spread to form 'mats' making it difficult to define the original plant spacing although the rows remained fairly distinct. The canopy was about 12-15 ft high and its cover was virtually complete. The soil is mainly freely draining silty-loam with some very sandy lenses and has a very low organic content. Some areas were covered with fresh silt up to 10 inches thick after floods within the last decade. There is little information concerning the position of the water table.

The experiment already planned covered four plots, each 27 mats (90 ft) long by 3 rows (20 ft) wide. One of these is to be a control plot receiving no irrigation; the other three are to receive different quantities of irrigation. Our major concern was to choose a network in each plot which would enable us to derive a reasonable estimate of water use over the whole plot. At the same time we considered it important to examine the variations in soil moisture change caused by the pattern of extraction by the root systems centred on the mats. These objectives are difficult to achieve with the number of tubes we could expect to be able to install and read on a routine basis with the manpower available.

One tube was installed at each of the sites, 4 in each plot. Within each plot the 4 tubes were positioned relative to the mats, one in a mat, one between two mats in a row, one midway between adjacent rows and one in an intermediate position. However, these tubes were not positioned in a group centred on a single mat since any variations across the plot would be missed by such an arrangement. Thus the network on each plot, shown in Figure 7, was spread across the plot. We should emphasise that this is the minimum network which can be considered as representative; more tubes are necessary to examine fully the small-scale variations around the mats themselves.

These 16 sites were all selected to be on as nearly as possible the same soil type. In addition, one tube installed during a reconnaissance visit in 1972 is in a much more sandy location and should provide an interesting contrast.

As each tube was installed, readings were taken daily; all 17 sites were read daily from 22 March until the end of April. This intensive study could not be maintained and a rate of three readings/week was selected as the best alternative. It is hoped that readings will continue at this rate until at least 12 months' records are available.

Results and analysis

Limitations of the data

Regular irrigation did not start until June 1973, after the period covered by the data presented in this report. Thus, at this stage we cannot determine the efficiency of the irrigation regime in terms of the replenishment of the soil moisture storage. We can however estimate the actual transpiration during selected periods and thereby give an indirect estimate of the gross efficiency of the proposed irrigation regime.

Shortly before the experiment started a major drainage ditch close to the control plot (sites 02-05) was cleared and dredged and we have observed that this caused a progressive permanent change in the level of the water table below that plot. This has invalidated any quantitative results from these sites. Further readings should indicate when a new equilibrium level is achieved and subsequent readings should then be valid. The situation was not fully appreciated until several months after the experiment had started. Trial runs with the irrigation equipment in the area containing site 01 invalidate results from this site before June 1973.

The whole experiment is complicated by the fact that the plantation is affected by nematodes (root destroying pests) which prevent the natural development of healthy root systems. It was initially thought that their effect was fairly uniformly distributed throughout the plantation but it is now suspected that this effect is more marked in the control plot than elsewhere.

Field capacity

The start of the experiment coincided with a period of rainfall with nearly 3 inches falling in the first two weeks of March, preceded by a total of 5 inches in January and February. Thus we can be reasonably certain that the soil was at or above field capacity at 13 March, the date of the last rain. Table 1 shows the profile water content at field capacity estimated from the readings taken during the third week of March. These results should be confirmed when the profile is next at field capacity.

TABLE 1

TULLOCH: PROFILE MOISTURE CONTENT AT FIELD CAPACITY FOR THE TOP 150 CM OF THE PROFILE

cm

Site	Moisture content	Site	Moisture content	Site	Moisture content
1	45.0	7	70.0	13	64.0
2	56.0	8	67.0	14	63.0 *
3	60.0	9	70.0	15	60.0 *
4	60.0	10	42.0	16	66.0 *
5	65.0	11	54.0	17	66.0 *
6	70.0	12	62.0		

* These values were obtained by extrapolation back to 19 March.

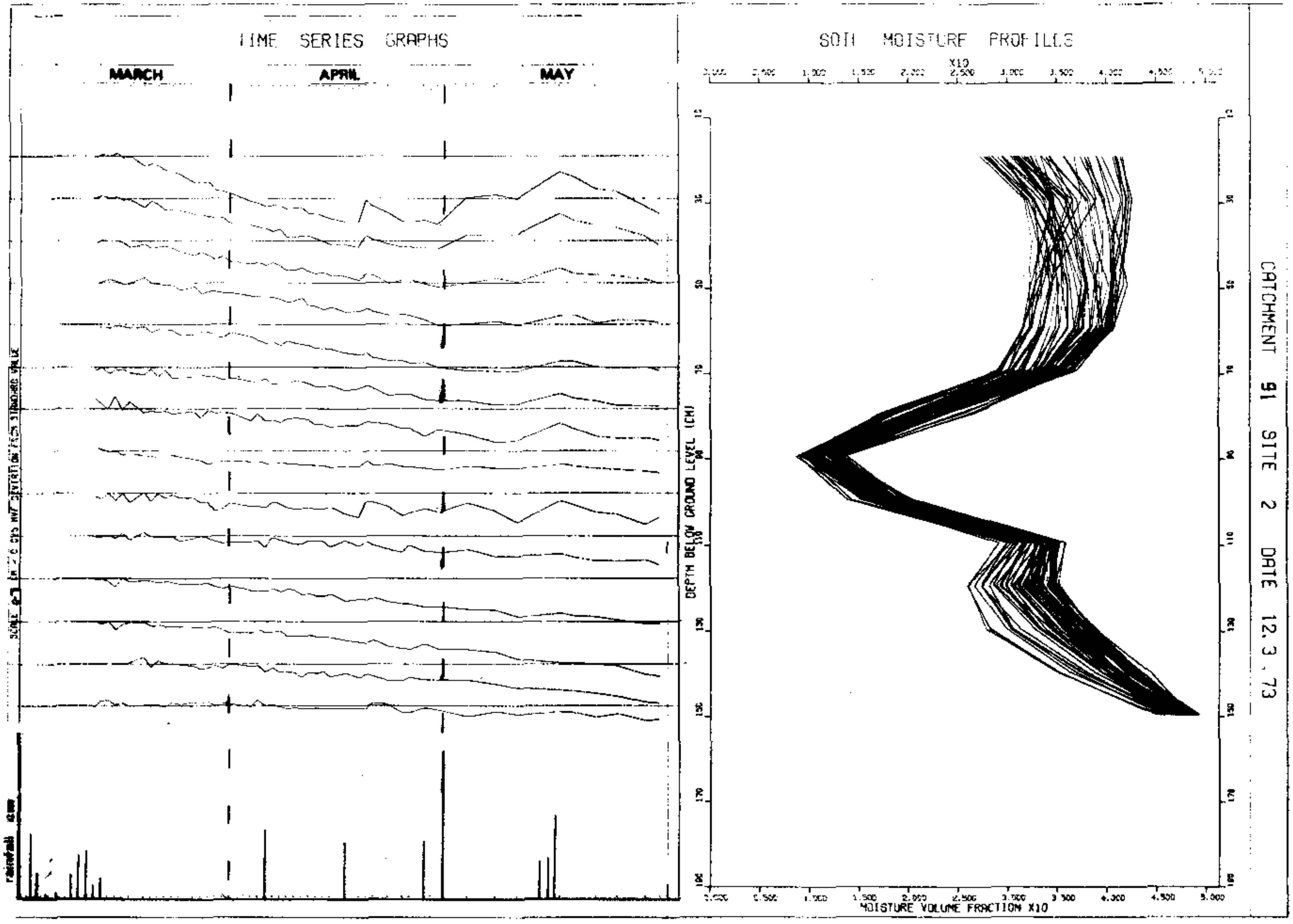


Figure 8 Tulloch site 02

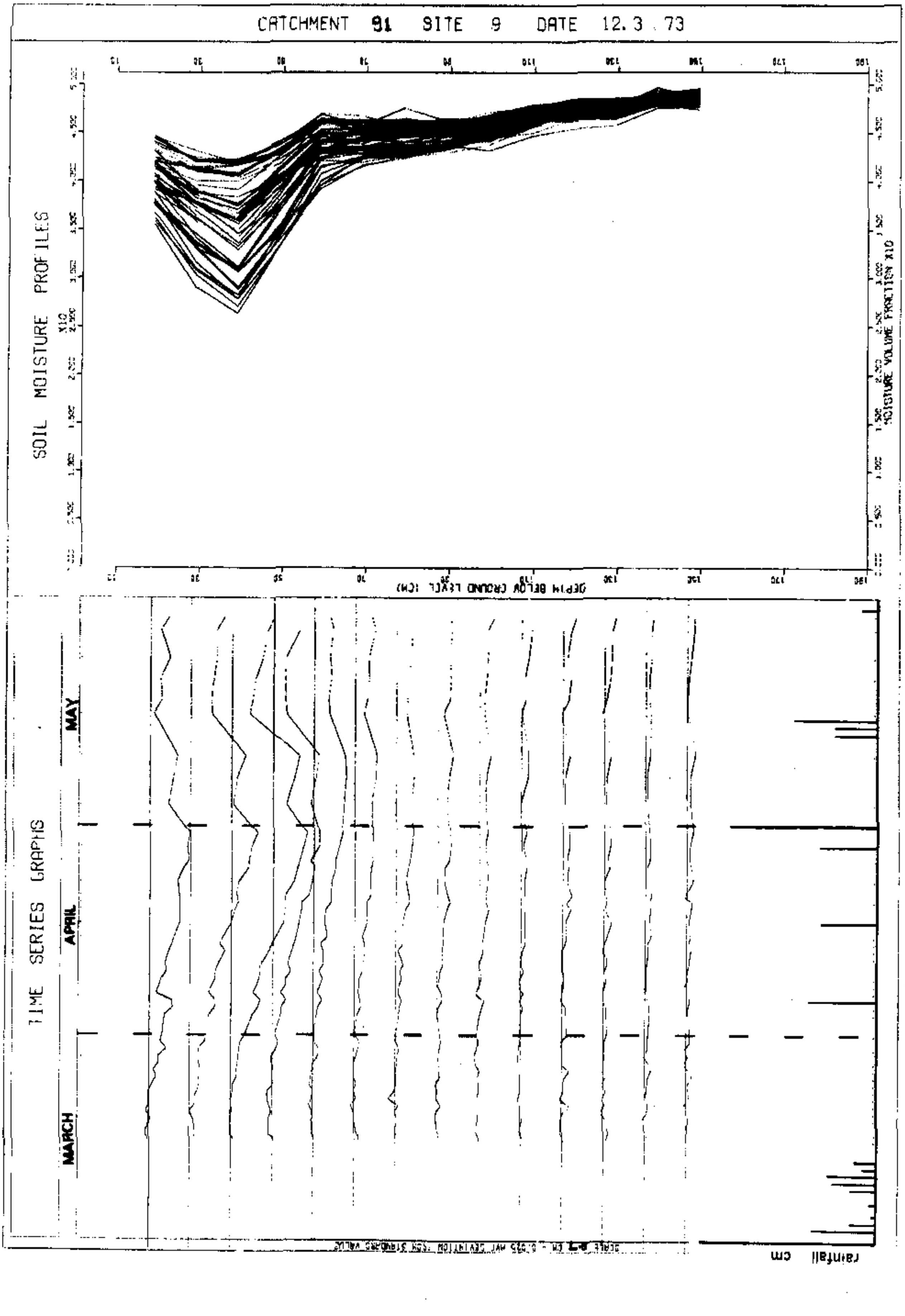


Figure 9 Tulloch site 09

Graphical presentation of the data

Figures 8 and 9 are examples of the graphs showing the variation in the soil moisture profiles and the variation with time of the moisture content at each depth. All the moisture content values are expressed as moisture volume fraction, MVF, and on the graphs showing the variation with time, the results have been normalised with respect to the MVF at field capacity at each depth.

At site 9 it is clear that most of the variation is confined to the top 80 cm of the profile and there is no significant effect which can be attributed to a water table fluctuation. This result is typical of all the experimental plots (sites 6 to 17). We have included the graph for site 2 in the control plot to illustrate the effect of lowering the water table by the drainage work noted above. In this case graphs show a substantial zone of change below 110 cm and the graph of variation with time shows this to be a continuous decline of moisture content in the zone 110 - 140 cm.

Figure 10 shows the integrated profile moisture content plotted against time for each site. Again the continuous decline shown for sites 2 - 5 is due to the lowered water table. The other sites exhibit partial recovery of moisture content levels following replenishment by rainfall. For convenience of interpretation the rainfall pattern has been plotted on the same graphs.

Identification of Processes

Following any occasion when the ground is at or above field capacity it can be assumed that transpiration will be at the potential rate for several days. Thus if the soil is initially above field capacity the rate of reduction of soil moisture storage will be the sum of the drainage rate and the potential transpiration rate. When field capacity is reached drainage ceases and there should be a period of fairly constant depletion at the potential transpiration rate. Howevever, as readily available moisture is removed and soil moisture stress begins to limit transpiration the depletion rate is correspondingly reduced. This does not apply, of course, to situations where the rooting system is able to draw water directly from a water table. Bananas are shallow rooting and are unlikely to be influenced by water table fluctuations provided that water logging of the rooting zone does not occur.

Figure 10 shows that the first phase of rapid loss of water is not apparent. It is possible that drainage was of such short duration that it was not detected by the daily neutron probe readings. It may well prove necessary to take readings at six or even three-hourly intervals during the period immediately following an irrigation (or storm) before this phenomenon can be positively identified.

By contrast, during the period of several days after rainfall there is a tendency for the measured depletion to be very slow. This is more apparent than real and is a consequence of the difficulty of measuring moisture changes in the top 20 cm of the profile. The

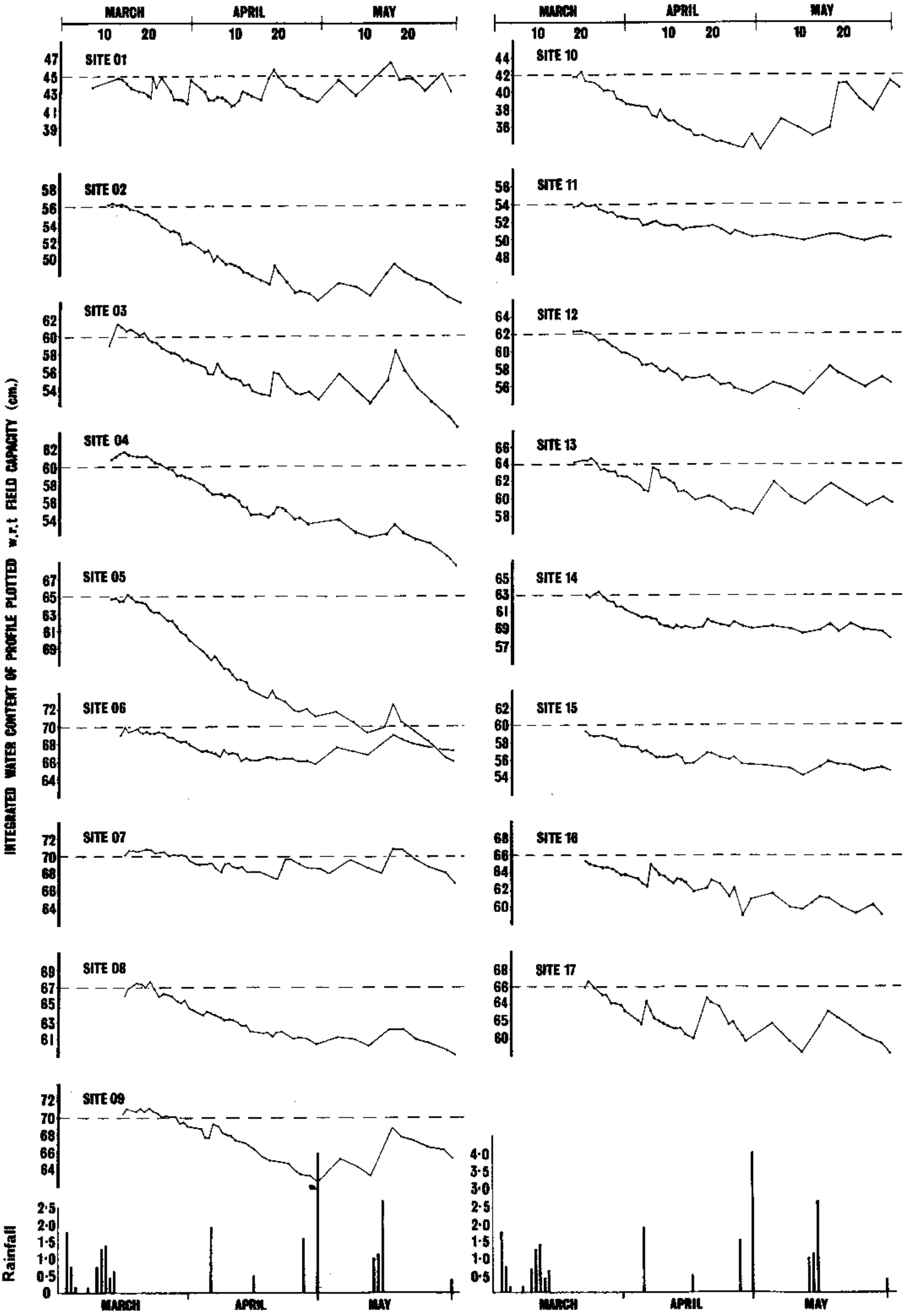


Fig 10. Water deficit of of the 0 – 150 cm. layer of the soil profile — TULLOCH — 1973

TABLE 3

DEPLETION RATE OF THE TOP 70 CM OF THE PROFILE DURING THE PERIODS 15-25 APRIL AND 2-15 MAY 1973 at CAYMANAS

Site position in field	Irrigation rate at site galls/mm	Local position R=ridge F=furrow	Daily depletion rate mm/day	Average depletion rate mm/day	
				by irrigation rate	by position in field
Top	120	1 R	- 0.3	0.8	1.2
		2 F	1.9		
		3 R	0.2		
	80	4 R	3.1	2.0	
		5 F	1.4		
		6 R	1.4		
	160	7 R	0.3	1.1	
		8 F	0.9		
		9 R	2.1		
Intermediate	120	11 R	1.8	1.4	1.1
		12 F	1.4		
		13 R	0.9		
	80	14 R	1.7	1.3	
		15 F	1.4		
		16 R	0.7		
	160	17 R	0.4	0.8	
		18 F	1.6		
		19 R	0.2		
Bottom	120	21 R	1.0	1.1	1.3
		22 F	1.3		
		23 R	1.0		
	80	24 R	1.1	1.0	
		25 F	1.0		
		26 R	0.9		
	160	27 R	1.6	1.9	
		28 F	2.3		
		29 R	1.7		
				Overall average	1.2

water in this surface layer is the first to be used by the plant so that it will be some days before any significant extraction occurs from the layers below. A correction must be made for this moisture change in the surface layer in any estimate of actual transpiration.

The second phase of fairly constant depletion lasting until early April is clearly shown in Figure 10. Following this period some sites show a decline in their depletion rates and hence in their transpiration rates. Unfortunately, at this time a heavy rainstorm occurred which makes it difficult to determine whether a substantial reduction of the depletion rate would have occurred. This stage would coincide with the first signs of stress in the healthy plant. The whole of the period to the end of May was marked by occasional showers, none sufficiently heavy to raise the soil moisture storage back to field capacity, and the interval between showers was not long enough to cause more than slight temporary wilting. Until further data are available from the control plot we can conclude that irrigation at weekly intervals would avoid any transpiration stress.

The depletion rate of the soil profile store

Within the three-month period for which data are available, we can identify five periods of at least six days duration when there was no input to the profile. The best estimate of average depletion rate for each site and period is obtained by regression of the daily values of profile moisture content against time; the slope of the regression line being the average depletion rate. This method ensures that all the available information is used and it was verified that the assumption of linearity was reasonable. In each case a standard deviation is calculated.

The calculated depletion rates are shown in Table 2 where they are grouped according to the position of the sites relative to the mats. Since irrigation had not started during these periods, it is not useful to differentiate between the different plots. Taken individually (without any averaging) the results show a marked degree of variability, greater in fact than would be expected from the standard deviations quoted. However these deviations represent only the effect of random counting error associated with the neutron probe method; they do not include variability due to differential wetting up of the profiles as a consequence of interception and channelling of rainfall by the plants or variations in soil characteristics across the plots.

If the results are considered as a statistical set stratified according to position relative to the mat, we can determine through an analysis of variance whether the differences in depletion rates are significant. Except for period 3, 19 - 25 April, this test showed that differences were not significant at the 95% confidence level. We can conclude that, with the data available, we cannot detect any systematic variation in depletion rate due to position relative to the mat. Nevertheless this analysis is not completely convincing as we can see that the lowest depletion rate in each period occurs at the 'between rows' position. This is unlikely to occur by chance in all five periods.

For a more complete study of the variation in depletion rate around the plant, it would be necessary to install additional access tubes to provide replication within plots. However for the purposes of this experiment we can take the overall mean depletion rate, discounting position and weighting only according to period length. This gives a value of 2.0 mm/day for the average depletion rate.

Correction for the surface layer

We have noted in the general introduction to the neutron probe method that it is difficult to measure moisture changes accurately in the top 20 cm of the profile. So far in the calculation of total profile moisture content it has been assumed that the top 25 cm of the profile is represented by the measurement taken at 20 cm below the surface. If we assume that over a depletion/replenishment cycle, the top 10 cm has a range of moisture content 0.1 MVF greater than that measured at the 20 cm level, then the range of moisture content in the top 25 cm of the profile is enhanced by 10 mm of water. Figure 10 indicates that the depletion rate begins to decline after about 14 days in the absence of rainfall or irrigation input. It is reasonable and fairly conservative to assume that our estimate of profile depletion rate and therefore the estimate of crop water use could have been underestimated by up to 10 mm over a 14-day period (0.7 mm per day).

Crop water use

When the correction for the surface layer is included, the estimate of crop water use is 2.7 mm/day, being the sum of the depletion rate and the surface layer correction. This is an average figure for the months March to May and in monthly terms it is 82 mm (3.2 inches) per month.

In addition it is necessary to allow for the inefficiencies of the irrigation system, including losses by spray drift and interception by the canopy. Thus we have recommended a figure of 100 - 120 mm/month as the optimum irrigation rate. It is understood that one experimental plot will receive this rate, the other two receiving more (double rate) and less (three-quarters of this rate) respectively. This irrigation input should be discounted by the amount of effective rainfall up to a limit given by the current soil moisture deficit.

Conclusions

From the results for the period March to May we have shown that an effective irrigation/rainfall input of about 80 mm/month should be sufficient to maintain the soil moisture content at a level which will sustain transpiration at the potential rate. This is likely to prove equivalent to a gross input in the range 100-120 mm/month when irrigation efficiency is measured.

The frequency of application of irrigation should be of the order of once per week although we would expect little transpiration stress to occur up to 14 days after irrigation except perhaps in particularly sandy locations.

Recommendations for future work

In making recommendations for further experimental work we would distinguish between that work required to complete the experiment as currently defined and such additional work which would lead to a greater understanding of the processes governing the abstraction of water from the soil and the efficiency of application of irrigation water.

The following work is necessary to complete the current experiments:

1. Routine readings should be continued at least twice per week at all sites through a full climatic and growth cycle to determine temporal variability of water use and requirements.

2. Continue routine readings at least until all likely extreme situations have been sampled, in particular, until a long dry spell is experienced causing significant severe wilting on the control plot. An eight-week dry period should be adequate. This should yield data on maximum extraction depth and desirable irrigation frequency.

3. Collect daily or twice daily readings for short periods (say 10 days) at selected sites following particular input events (either storm or irrigation) particularly during 'typical' climatic periods throughout the year to confirm estimates of water requirements under maximum growth conditions. This should also provide further information to refine the estimates of field capacity.

4. Ensure that both rainfall and irrigation inputs are measured daily at least in each group of sites. Rainfall areal variability is very high and therefore important if more precise conclusions are sought. An estimate of both gross and nett irrigation is desirable.

5. Compare the estimates of transpiration derived from soil moisture considerations with those obtained by evaporation pan and by the Penman equation applied to the available meteorological data.

6. The water table should be monitored at each site by means of open tube wells.

The additional work would concentrate on proving the networks as a satisfactory sampling technique and on validating the assumptions concerning field capacity and drainage. It would include:

1. Replication of the network in one of the experimental plots to investigate further the variation in soil moisture change with position relative to the mats, and position within the plot as a whole.

2. Measurements of soil moisture distribution and abstraction patterns in a selected group of mats undergoing nematode control to establish definitely whether or not the large areal variation of moisture abstraction is in fact due to poor root development. This would require a closely spaced network in the selected area and this network should be replicated in an area not under nematode control.

3. Establish moisture changes in the 0-10 cm layer either by:

   a. using surface extension trays

   b. taking gravimetric core samples on each reading occasion

   c. taking core samples under selected conditions to determine typical values for the various ground conditions.

   d. applying a special calibration specifically for measurements at 10 cm depth.

Of these alternatives, d is considered to be the best although it involves taking core samples in the first instance.

4. Measurement of vertical unsaturated soil moisture fluxes by means of simultaneous tension and moisture content measurements. This could confirm the validity of the assumptions based on the field capacity concept. This work could be done by an IH expert if sponsored, for example, by ODA.

5. Examine the effects of interception of irrigation water and of rainfall by the canopy in terms of the distribution of the throughfall and stemflow applied to the soil. This study would be related to item 1 above.

Project 2: PLANT WATER RELATIONSHIPS AND DEEP PERCOLATION LOSSES IN FURROW IRRIGATED SUGAR CANE

This is part of an extensive study to investigate optimum design criteria for furrow irrigation being carried out by L Ramdial of the Sugar Manufacturers Association (Jamaica) Research Department. The study is taking place on the Caymanas Estate on the coastal plain about 10 miles west of Kingston.

Background

The cane sugar industry is Jamaica's largest single employer of labour, with over four times as many people employed as in the bauxite industry. This is because of the large number of small farmers involved, although the vast majority of the annual cane crop of about 385,000 tons comes from a few large estates. These estates usually occupy the best alluvial land on the island, mostly along the south coast, and the Caymanas Estate some 10 miles west of Kingston is typical in this respect. The average annual rainfall in this area is about 35-45 inches compared with an estimated potential transpiration for cane of about 60 inches. Supplementary irrigation is therefore required, but more than might be expected as the rainfall tends to be badly distributed throughout the growing season; 70% of the annual rainfall might fall in only 25 days. Irrigation water for the Caymanas Estate is supplied under gravity head from the Rio Cobre diversion dam above Spanish Town. This is the oldest irrigation system on the island, dating back to the beginning of the century. The cost of the water is very small and water is allocated and charged on an annual contract basis although actual quantities received are not metered. This results in considerable wastage of irrigation water, as there is little incentive to save it.

Cane in Jamaica is grown as a 12-month crop and ratoons (or stand-over plants) are allowed to continue generally up to seven years before replacement by new plants. There are a number of ways in which yields and productivity in the sugar industry may be increased; with regard to irrigation, consideration is being given to the irrigation layouts being used. The traditional method of a 'chequer board' layout of furrows requires little land levelling or regrading but it is difficult to ensure that all parts of the field are wetted. Long line furrows are found to be more efficient but this system does require careful grading of the land. The irrigation experiments at Caymanas are part of a research programme to demonstrate the advantages of this system. Spray irrigation is not widely used because of the capital and maintenance costs and the need for skilled labour, but one of the largest installations on the island is situated in the Caymanas area.

Typical yields of cane in Jamaica are on average about 33 tons per acre though at Caymanas yields of up to 50 tons per acre have been reported. The sucrose content of Jamaican cane also tends to be rather low, currently about 10½ tons of cane are required to produce a ton of sugar. By way of comparison the Queensland, Australia, industry has cane yields of about 60 tons per acre requiring only 7 tons cane per ton of sugar. This is three times the sugar yield per acre of Caymanas.

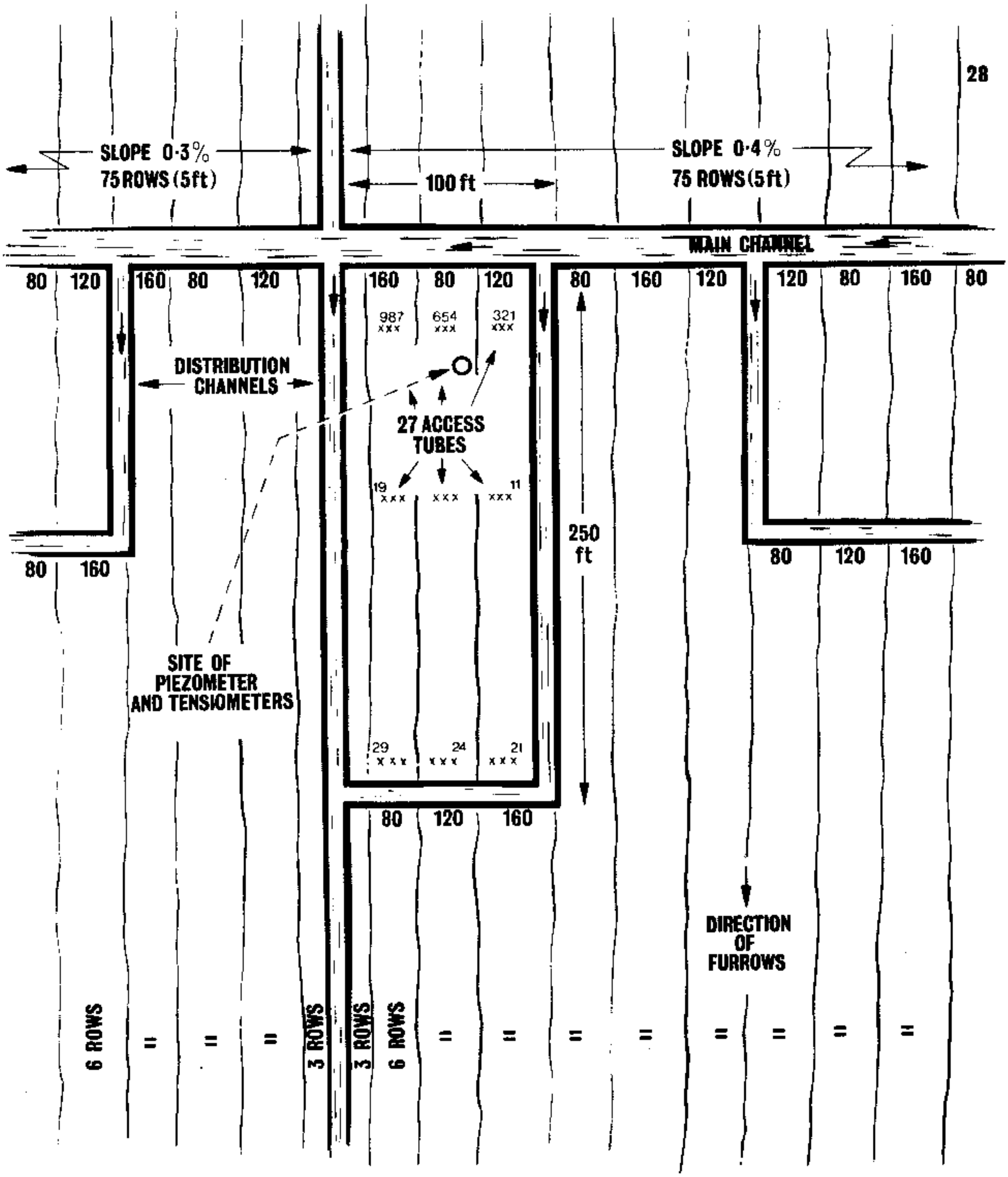


Fig 11. CAYMANAS (Cedar Grove 2) Field layout and channel system

Within the context of the extensive study, the primary aims of this project are:

1. Estimation of percolation to ground-water from the fields
2. Estimation of actual transpiration under varying conditions
3. Comparison of the effects of differing rates (not quantities) of application of irrigation water.

The field where the experiment is being performed is irrigated by a long line furrow method with close control over the layout of the furrow system, the slope of the field and the rates of application of water. It is a mature field and the start of the experiment coincided with the first irrigation of the 1973 ratoon crop. During an irrigation cycle water is allowed to flow down the furrows until the whole length of the field is wetted and water flows from the end of the furrow run.

Instrument Networks

The neutron probe access tube network consists of nine groups of three tubes, each tube being two metres deep. Three plots receive their irrigation at different rates and each contain 3 groups of access tubes shown on the sketch map, Figure 11. These are distributed so that each plot has one group close to the main irrigation channel at the top of the furrow-run, one group half-way down the field and the final group close to the end of the run. Two tubes of each group are installed in adjacent ridges and one in the furrow between them. Each plot is 6 rows (x 5 ft) wide and 44 yds long occupying about 450 sq yds (408 sq m). The plots are irrigated at rates of 80, 120 and 160 galls/min. The tubes were all installed (mainly by local unskilled labour, under supervision) during the week 2-7 April and all read for the first time on 9 April. Readings on all occasions were taken at 10 cm intervals from 20 cm to 150 cm below ground level.

Results and Analysis

Graphical presentation of the data

Again it is impracticable to show all the graphs for all sites and we have included those from just three sites to illustrate the pattern of soil moisture change over the plots. Figures 12, 13 and 14 show the soil moisture profiles and the variations with time at each reading depth for sites 5, 15, and 25 respectively. Site 5 is at the top of the field. The slope of the field containing the experimental plot is 0.4%.

It is immediately apparent that the variation in soil moisture profile is much more complicated than was the case at Tulloch. Here the range of fluctuation of moisture content in the lower half of the measured profile is large; in many cases greater than the variation near the surface. Furthermore, this range of variation is greater at the top of the field, nearer to the irrigation canal than it is at the bottom of the field which is the last area to receive irrigation. Intermediate sites show an intermediate range of fluctuation.

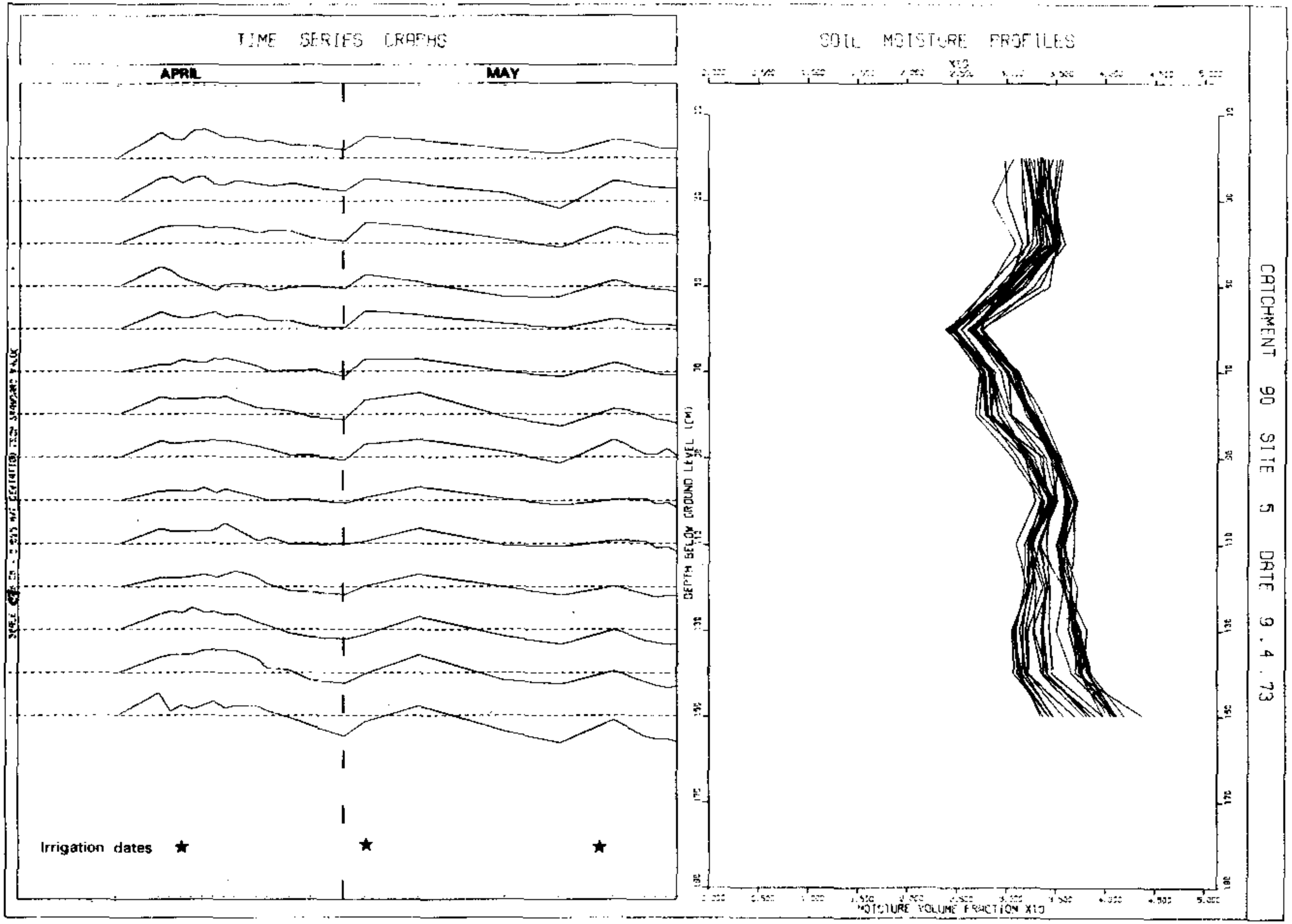


Figure 12 Caymanas site 05

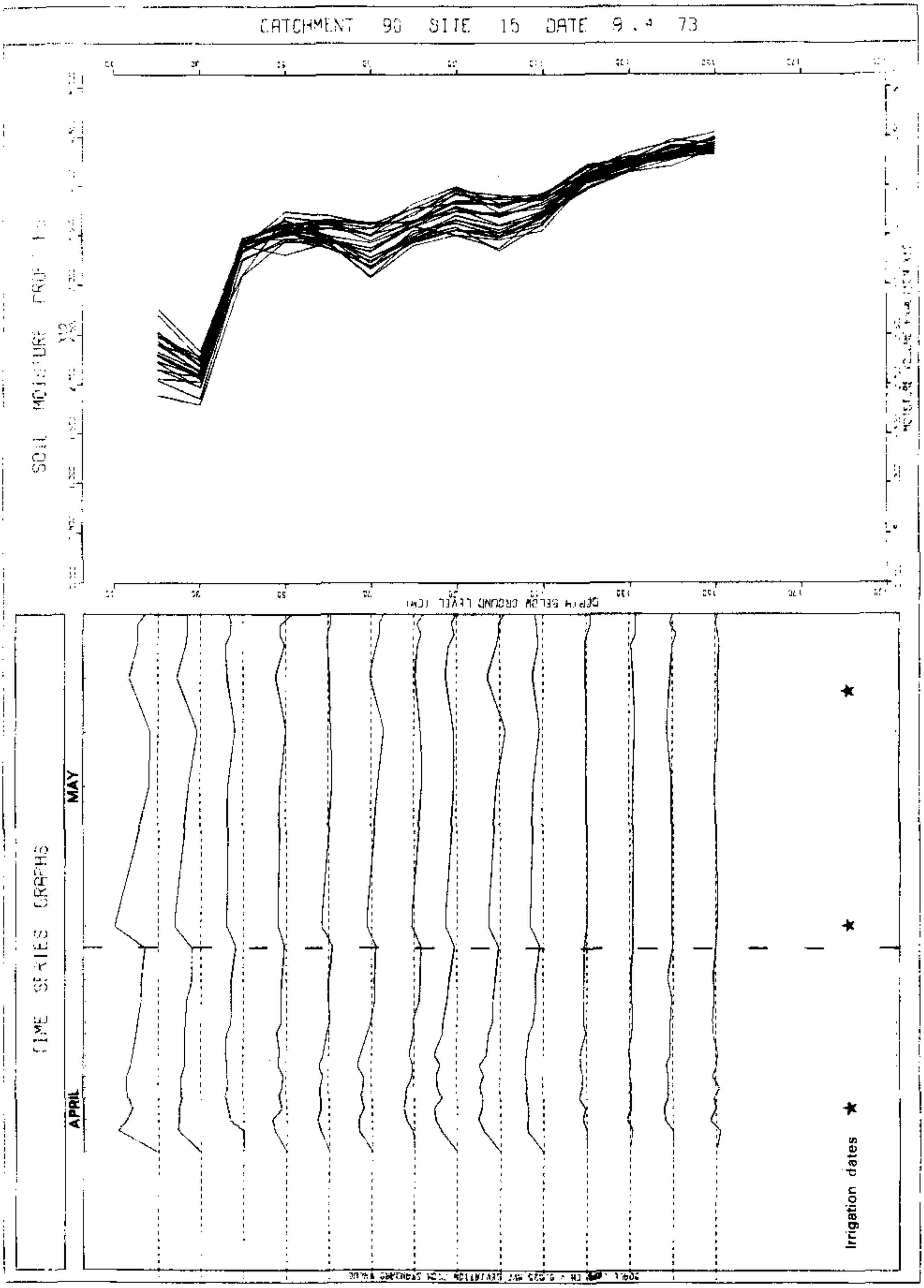


Figure 13 Caymanas site 15

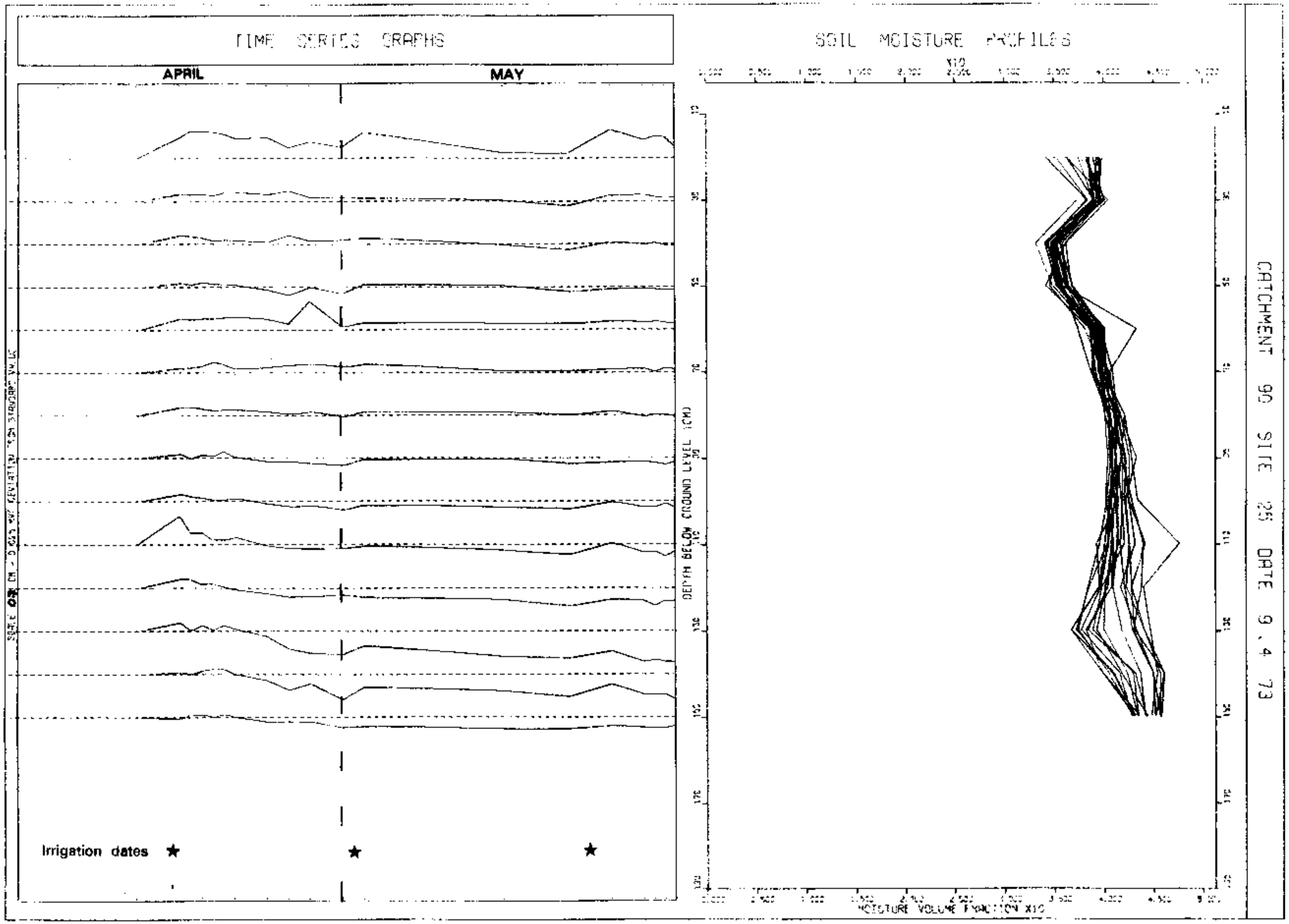


Figure 14 Caymanas site 25

This pattern shows the considerable influence of the water table. The evidence available suggests that it probably rises to the surface at the top of the field; and to within 90 cm of the surface at the lower end of the field. At site 15 the water table does not fall below 120 cm while at sites 5 and 25 the lowest water table level lies below the 150 cm monitored by the neutron probe. In these circumstances the application of the concept of field capacity is not valid and we cannot separate upward and downward fluxes of moisture using soil moisture measurements alone. Although we can hazard an estimate of transpiration by attempting to identify a level of zero flux from these data, measurements of soil moisture potential would be necessary to achieve an acceptable accuracy. In addition to the problem of identifying the direction of vertical movements, we suspect that there are significant lateral movements in the saturated zone resulting from high water table levels beneath the unlined canals. These canals are often flowing full to irrigate other areas so there is likely to be some lateral input to the experimental plot even when it is not being irrigated directly.

The time-series graph, Figure 15, shows the variation of the integrated profile moisture content with time for all 27 sites. The three irrigation periods are clearly shown with two periods of depletion between them.

Crop water use

In order to estimate the rate of transpiration we have to make gross assumptions concerning the time after irrigation when drainage from the upper profile effectively ceases. That is, we must define the extent of this upper part of the profile whose depletion rate can be attributed to transpiration alone. From Figures 12 to 14 we estimate that from a time two days after irrigation, transpiration is met by losses from the top 70 cm of the profile.

Table 3 shows the depletion rates of this zone arranged according to position in the field and irrigation rate. As would be expected, the results are very variable although more so at the top of the field than lower down. However, averaging according to irrigation rate and position in the field yields more consistent figures, which show that these factors cannot be shown to be significant with the results available. Nor does the position in ridge or furrow have any consistent effect.

The average estimate of transpiration is about 1.2 mm/day to which we must add a correction for the surface layer. If we assume that the top 10 cm of the profile has a moisture change, over a 21-day irrigation cycle, of 0.1 MVF greater than the measured change at 20 cm depth, then the total transpiration over the period is 21 x 1.2 + 10 mm = 35 mm. It should be noted that this refers to the early stages of a second ratoon crop when the measurements were made and that we would anticipate higher levels of transpiration from the mature crop, probably 3-4 mm/day and possibly considerably more.

An upper limit can be put upon this estimate by assuming that the increase in storage following an irrigation is entirely used up by transpiration with no loss to percolation. Thus, from the 9 sites

TABLE 3

DEPLETION RATE OF THE TOP 70 CM OF THE PROFILE DURING THE PERIODS 15-25 APRIL AND 2-15 MAY 1973 at CAYMANAS

Site position in field	Irrigation rate at site galls/mm	Local position R=ridge F=furrow	Daily depletion rate mm/day	Average depletion rate mm/day	
				by irrigation rate	by position in field
Top	120	1 R	- 0.3	0.8	1.2
		2 F	1.9		
		3 R	0.2		
	80	4 R	3.1	2.0	
		5 F	1.4		
		6 R	1.4		
	160	7 R	0.3	1.1	
		8 F	0.9		
		9 R	2.1		
Intermediate	120	11 R	1.8	1.4	1.1
		12 F	1.4		
		13 R	0.9		
	80	14 R	1.7	1.3	
		15 F	1.4		
		16 R	0.7		
	160	17 R	0.4	0.8	
		18 F	1.6		
		19 R	0.2		
Bottom	120	21 R	1.0	1.1	1.3
		22 F	1.3		
		23 R	1.0		
	80	24 R	1.1	1.0	
		25 F	1.0		
		26 R	0.9		
	160	27 R	1.6	1.9	
		28 F	2.3		
		29 R	1.7		
				Overall average	1.2

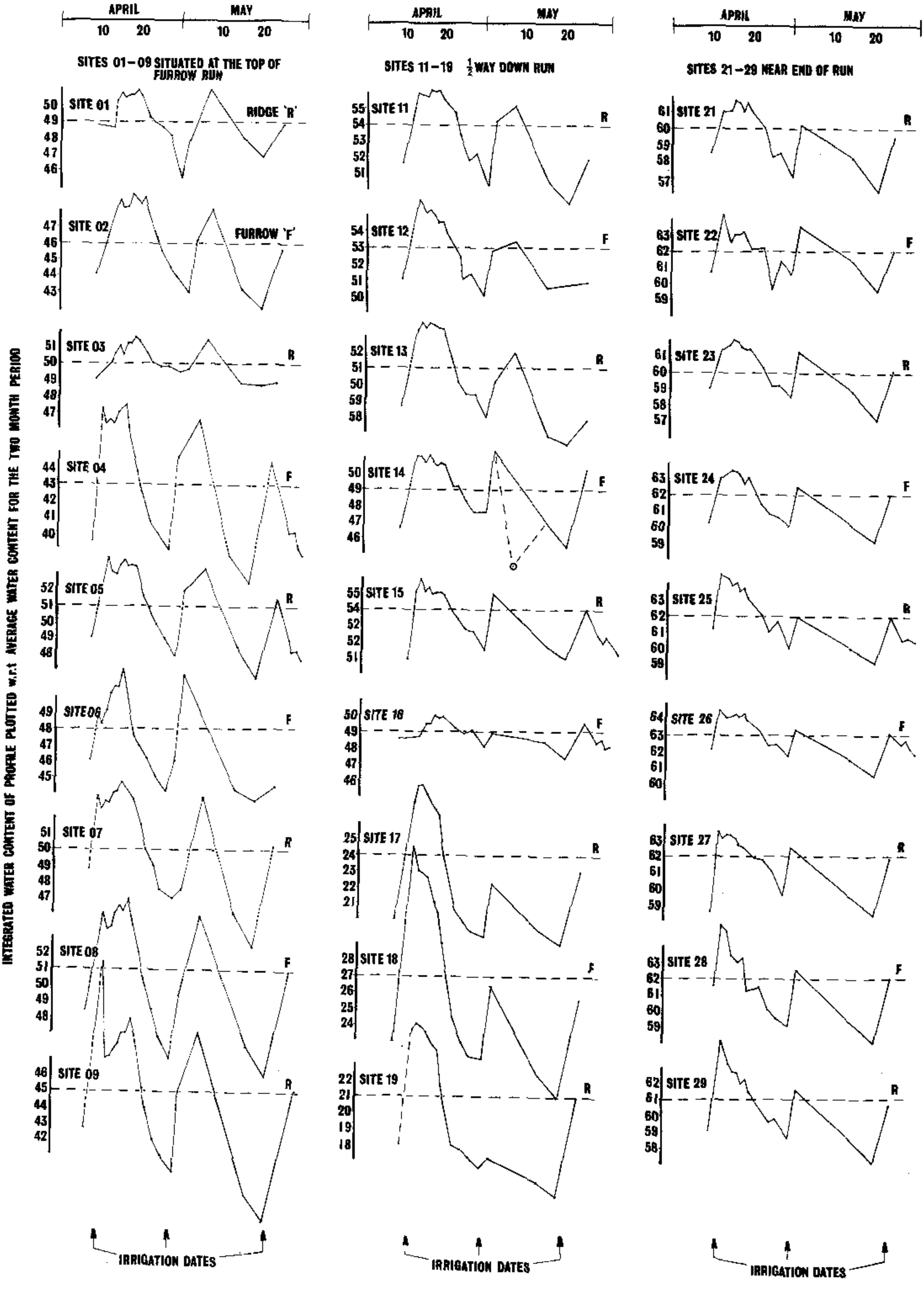


Fig 15. Water deficit of the 0 - 150 cm layer of the soil profile - CAYMANAS - 1973

in the plot receiving irrigation at the 80 gallons/min rate, the average increase in total soil moisture storage was 53 mm. Adding the correction for the 10 cm surface layer, this gives a figure of about 63 mm (3 mm/day). The true figure would therefore not exceed 63 mm and would probably be much closer to the 35 mm estimate.

Percolation losses

Control over the total quantity of irrigation water applied to the experimental area was poor. Although the rate of application was known, the duration of the period of irrigation was not recorded. We cannot therefore make a direct estimate of the percolation loss to groundwater.

However we can consider the minimum irrigation period to be three hours. At a rate of 120 galls/min on a 400 m^2 plot, the minimum application is thus 240 mm in the three-hour period. We have estimated the transpiration loss over the interval between irrigations to be about 35 mm. Thus the percolation loss is at least 200 mm or 80% of the water applied. This water is lost directly to groundwater and is of no benefit to the crop. This conclusion is not altered significantly even if we allow for a large underestimate of transpiration.

Processes leading to wastage

With long line furrow irrigation it is inevitable that there is a tendency to apply more water at the top of the field than further down the field. In well draining soils percolation losses at the top of the field can be very high. Unfortunately the optimum choice of furrow slope and application rate is not simple. The infiltration rate of the soil both in its saturated and unsaturated state is important. But so too are the constraints governing the position of the water table and it is these constraints which are often very difficult to establish especially when the main distribution canals are unlined.

Although the soil is wetted to saturation, the only water available to the plants is that which remains after excess has drained away and the soil approaches field capacity. As the soil in this area is freely draining this available storage is not high, of the order of 60-70 mm in the top 100 cm layer. For the maturing crop this could well be inadequate over a 21-day period if transpiration is 4 mm/day or more. The immature crop with an undeveloped root system will be unable to obtain water from even the top 100 cm of soil and so available water will be exhausted sooner. The ideal interval between irrigations could therefore be one week or even less.

Conclusions

At Caymanas the problem of determining transpiration rates and percolation losses is complicated by the presence of a highly fluctuating water table close to the surface. The measurement of soil moisture alone is insufficient to determine the upward and downward fluxes of moisture following irrigation. Thus we are not able to separate with any accuracy the losses due to transpiration and percolation.

It is possible that less water applied more frequently would result in a more stable water table. In this situation we could expect to be more successful in applying the field capacity concept.

Recommendations for further work

The main cause for concern in this project is the wastage of water. The amounts applied are very much in excess of the available storage capacity of the soil and this capacity would be better utilised by more frequent and smaller applications. The latter could perhaps be achieved by increasing the application rate, the field gradient or both. The measurement of crop water use by the techniques described in this report cannot be improved until changes are made in the operation of the irrigation network.

Thus we would recommend that the present network of tubes be read no more than twice weekly until the full growth cycle has been sampled with perhaps daily readings for a few days after each irrigation. It is essential that a record is kept of the quantity of water applied in each irrigation.

Some additional work would be useful to augment our knowledge of the processes involved.

1. Monitor the water table level in a network of tube wells or piezometers, particularly close to main feeder channels that may be providing lateral groundwater input to the plots.
2. Install porous pot tensiometers down the profile in each plot to be read at the same time as the access tubes.
3. Install at least one recording raingauge at canopy level.

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