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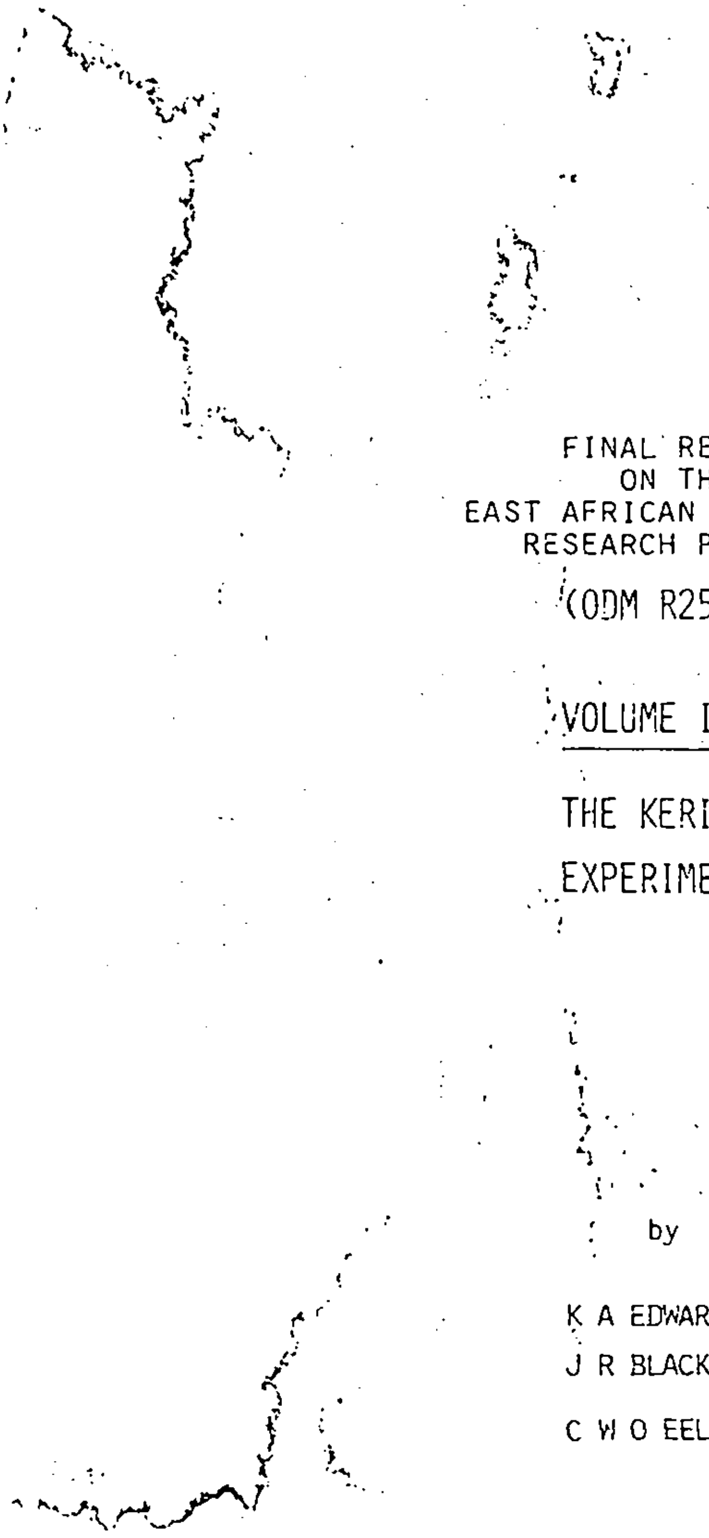

FINAL REPORT ON THE EAST AFRICAN CATCHMENT RESEARCH PROJECT

(ODM R2582)

VOLUME II

THE KERICHO EXPERIMENTS

1976

by

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2.1.1

THE KERICHO RESEARCH PROJECT

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THE KERICHO RESEARCH PROJECT

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INTRODUCTION

After the Second World War, agricultural production of many crops, and of tea in particular, expanded rapidly in East Africa. Increased tea yields due to more efficient agronomic practice led to higher returns and a consequent demand for more land suitable for tea planting, particularly in those areas experiencing the high rainfall required for optimum tea production. Large tracts of these areas are preserved as gazetted forest to conserve and regulate water supplies and, by the mid-1950s, there was opposition in Kenya to any further expansion of tea plantations because of the risk to water supplies if forest excision were allowed to continue.

At the same time, the belief was growing among water engineers that trees use more water than shorter crops and that the slow-growing indigenous forests not only gave low economic return in terms of timber yields but were costly in water losses through evaporation (Law, 1956, Ovington, 1954). This belief was, however, based on disputed scientific evidence, and opinions were voiced for and against the preservation of forests specifically for water conservation, not only in East Africa but in many parts of the world. Proponents of forests emphasized also their value for soil conservation; however, since the tea industry in Kenya has a high reputation for good soil conservation practices, tea was a possible high yielding cash crop which could be considered as an alternative to forests.

Because little was known about the water use of tea and the possible consequences of removing the forest and its associated litter layer, it was desirable that a controlled experiment be instigated to determine the effects of replacing the indigenous forest by large tea estates. Kericho, being the centre of tea production in Kenya and on the edge of one of the largest surviving tracts of tall rain forest, was a suitable location for such an experiment. In addition, the tea growers were themselves very interested in the productivity of these remaining higher areas of the Mau Forest which might or might not be economically viable for tea production due to the effects of altitude on yields.

After detailed reconnaissance of the South West Mau Forest above the existing tea belt, two suitable catchments were chosen for the experiment. One, the Sambret Valley, was excised from the Forest Reserve and leased to the Kenya Tea Company (now Brooke Bond Liebig (Kenya) Ltd) on condition that it was cleared and planted to tea in accordance with an experimental programme specified by EAAFRO. The second catchment, that of the Lagan tributary of the Saosa, remained under forest as a control.

The establishment of the experiment is described in detail in Pereira et al (1962) and in Section 2.1.2 of this report. Blackie (1972) summarized the results up to 1969 and the following sections present the full analysis of the entire 16 years of data up to the transfer of the catchments to Kenya Government in July 1974.

Since the experiment started, the emphasis in the tea industry has moved towards the development of smallholder tea production units as opposed to large estates. The land use question (that is, whether indigenous forest can be replaced by a more economic crop without detriment to soil and water resources) is still relevant, however, in the context of the future expansion of agricultural production in the higher rainfall areas of East Africa and the continuing need to balance water and soil conservation with optimum use of high potential land. In addition, the ancillary information on the water use of tea is of great interest to the tea industry which is faced with increased production costs and the necessity to maximise yields. It is anticipated that further analysis of the hydrological data obtained from the experiments will follow in view of their value to the general problem of water resources evaluation in the East African environment. At present, however, the analysis has been restricted to answering the land use question which was first posed in 1956 and which has assumed wider significance as the pressure on high potential agricultural land has increased.

DESCRIPTION OF THE EXPERIMENTAL CATCHMENTS

The catchments are situated in the South West Mau Forest Reserve in Western Kenya within the Lake Victoria drainage basin. The forest consists of tall, broad-leaved evergreen species giving way to bamboo at the higher altitudes. Lying within 0.5° south of the equator and between 2000 m and 2800 m in altitude, the forest receives an annual precipitation in the range 1500 to 2500 mm. The perennial streams which rise in this area supply first the tea estates and then the densely populated lake shores of Nyanza Province.

The catchments chosen comprise two parallel valleys at a mean altitude of 2200 m. Their relative positions are illustrated in Fig 1. Both were under unbroken forest cover at the beginning of the experiment, and are topographically similar with mean slopes of 4% (Lagan control catchment) and 4.5% (Sambret catchment, tea estates). The solid geology of the area consists of Tertiary lavas extruded in a westerly and south-westerly direction from the Rift Valley Faults in early Miocene times. They are noted for the number and thickness of their beds, their freedom from interbedded pyroclastic material and their low angle of dip (Binge, 1962). These phonolite lavas are remarkably uniform in composition and are reported to be free from fissures due to the lack of subsequent tilting. They weather into deep stonefree soils, heavily leached and uniform in physical structure to a depth of 6 m.

The Lagan (control) catchment is 544 ha entirely under moist

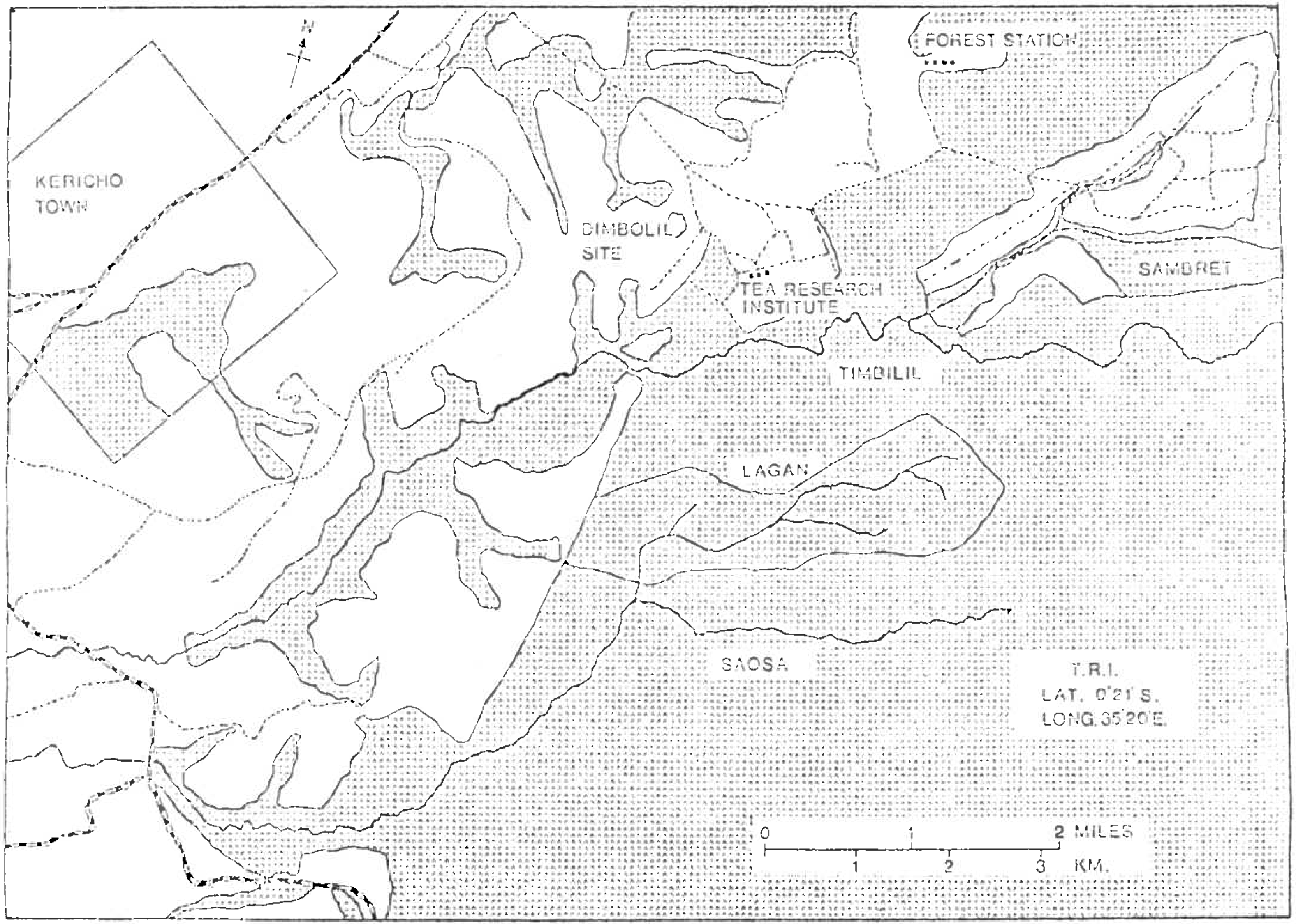

Figure 1 Relative location of the Kericho catchments

evergreen high forest. Sambret, the experimental catchment, was originally mostly evergreen forest with montane bamboo forest appearing at 2300 m. The area of the catchment is 702 ha of which 376 ha became tea estate (this area including roads and estate buildings as well as stands of tea), 128 ha are forest, and 190 ha are mixed bamboo with scattered evergreen forest elements. There is also an 8 ha, partially-enclosed drainage basin or 'vlei' in the upper part of the catchment containing grasses, sedges and geophytes; see Kerfoot (1962) for a description of the vegetation.

The climatic environment of the two catchments can be summarised by the meteorological data shown in Table I. The rainfall distribution is such that in only three months of the year is rainfall less than open water evaporation, EO, and restrictions on growth and transpiration are normally only experienced in the months of January and February. There is a marked diurnal pattern of rainfall (see Figure 1 of Section 1.2.1) which is attributed to the geographical position of Kericho. Lying on the high plateau between the Rift Valley and Lake Victoria, it is influenced by both the generally easterly airstream of the Indian Ocean Monsoons and by the large scale thermal winds of the lake. Convectional instability increases during the day until thunderstorms break in the afternoon; rainfall is intense and hail frequent. The frequency distribution of intense rainfall (see Figure 2 of Section 1.2.1) shows a higher incidence of storms with intensity greater than 100 mm hr^{-1} at Kericho than at any other EAAFRO experimental area.

EXPERIMENTAL OBJECTIVES AND METHODS

The objectives of the Kericho experiments were to investigate the effects of the change in land use on the total water yield of the catchments and on its seasonal distribution. The approach adopted was to measure the water balance components before, during and after the land use change, to determine how this change has affected evaporative water use of the two catchments and their streamflow.

TABLE I

Mean Climatological Data (1958-74)

Kericho (Tea Research Institute)

Altitude 2073 m, Latitude 0°21'S, Longitude 35°20'E

	Rainfall	Temperature			Humidity	Wind	Radiation	Sunshine
	Monthly Total	Max	Min	Mean	Saturation Deficit	Mean speed at 2 m	Gunn Bellani Radiometer	
	mm	°C	°C	°C	mb	km hr^{-1}	MJ m^{-2}	hr
Jan	92.6	23.9	9.0	16.5	7.6	5.9	24.0	8.1
Feb	104.8	24.1	9.1	16.6	7.5	5.7	23.8	7.8
Mar	171.5	24.1	9.5	16.8	7.0	5.7	23.4	7.5
Apr	264.4	22.8	10.0	16.4	4.7	4.5	18.9	5.9
May	282.8	21.9	9.8	15.8	3.6	4.6	18.0	6.0
Jun	209.8	21.3	9.1	15.2	3.9	5.3	18.7	6.5
Jul	197.0	20.5	9.2	14.9	3.8	5.4	17.2	5.6
Aug	213.2	20.8	9.1	15.0	4.1	5.7	17.7	5.7
Sep	181.8	21.9	8.6	15.3	4.6	5.8	19.1	6.1
Oct	172.3	22.3	9.1	15.7	5.0	5.6	18.6	6.0
Nov	151.0	22.3	9.7	16.0	5.3	5.4	18.6	5.8
Dec	98.2	23.0	9.1	16.1	6.4	5.7	21.9	7.3

Streamflow in the control catchment, Lagan, was measured by means of a compound rectangular sharp-crested and broad-crested weir equipped with Lea Rotary Water-Level Recorders and weekly charts. At a later stage, an additional Leupold and Stevens A35 Recorder was installed to obtain more detailed hydrographs.

In Sambret, where 376 ha of indigenous forest was replaced by tea plantation, the weir at the main outfall was of compound sharp-crested and broad-crested rectangular section. A sharp-crested weir was also incorporated in the outfall from the water supply dam, upstream of the main weir, to assist in determining the routing effect of this small dam on flood peaks. Since only half the total area was scheduled for clearing, a third weir was installed on the outfall of a subcatchment due to remain under mixed bamboo and forest cover. This was of compound v-notch sharp-crested and broad-crested design. At a later stage, a fourth weir, of v-notch design, was installed at the outfall of a subcatchment entirely under tea. As on the control catchment, a Leupold and Stevens Recorder was installed alongside the Lea Recorder on the main weir in 1970.

All weirs were designed, installed and rated by the Ministry of Water Development of the Kenya Government. Apart from the weir on the dam, all were sited on bedrock. Assessments of the possible errors in their stage-discharge relations are given in Section 1.2.4.

The raingauge network on the control catchment, Lagan, comprised three canopy-level, platform-mounted, daily-read gauges on the northern side of the catchment, two tilting-syphon recording gauges with check gauges near the upper and lower ends of the catchment on the southern side, and a post-mounted daily gauge near the middle of the south side (Fig 2). The recording gauges are in clearings with a maximum shading angle of 45° which has been shown to be adequate in the low wind speed conditions of the Kenya highlands (McCulloch, 1961).

In the experimental catchment, Sambret, the network of gauges

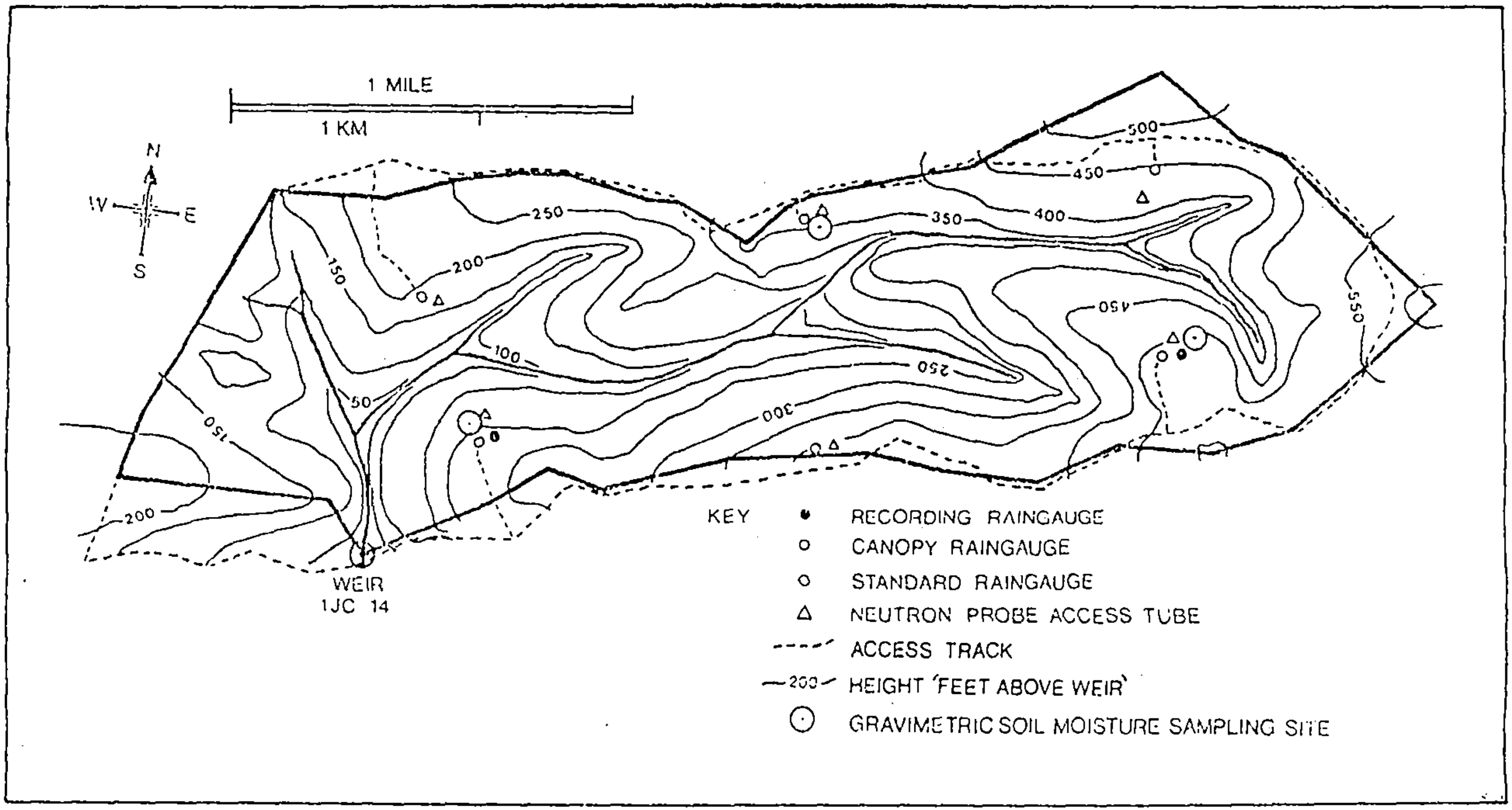

Figure 2 Lagan catchment

before land clearance consisted of three recording gauges, each with an adjacent check gauge, situated in the upper, middle and lower sectors of the catchment, and six 10-day storage gauges set in clearings around the catchment boundary. After land clearance had begun, a further network of 18 post-mounted daily-read gauges was installed with their orifices 30 cm above the level of mature tea. This network, designed to check the data from the original gauges, was redistributed in 1965 after tea planting was complete. The final network is illustrated in Fig 3.

The uniformity of the soils simplified the problem of soil moisture sampling, and three sites were chosen in each catchment representing the upper, middle and lower areas. At each site, undisturbed core profiles were taken at 30 cm intervals to a depth of 3 m, and field capacity and wilting point were determined from them. Bulk densities were used to convert the gravimetric monthly measurements of soil moisture content at replicated sites into volumetric soil moisture values. In 1968, access tubes were installed for the determination of soil moisture content using neutron probes. These results are discussed in detail in Section 2.2.5 together with the methods of estimating mean catchment soil moisture deficits. The technique of using recession curves of the hydrograph, mentioned in Section 1.1 and described by Blackie (1972), was used to obtain estimates of changes in groundwater storage.

Penman estimates of EO and ET were derived from data obtained at a meteorological site established at the Tea Research Institute of East Africa situated at the mean altitude of the catchments (2073 m) some 2 km north of Lagan and 1.5 km west of the main outfall on the Sambret catchment (see Fig 1). It has been assumed that the similarity in altitude, in rainfall amount and in rainfall distribution resulted in no major long-term differences in the Penman estimates between this meteorological site and the catchments.

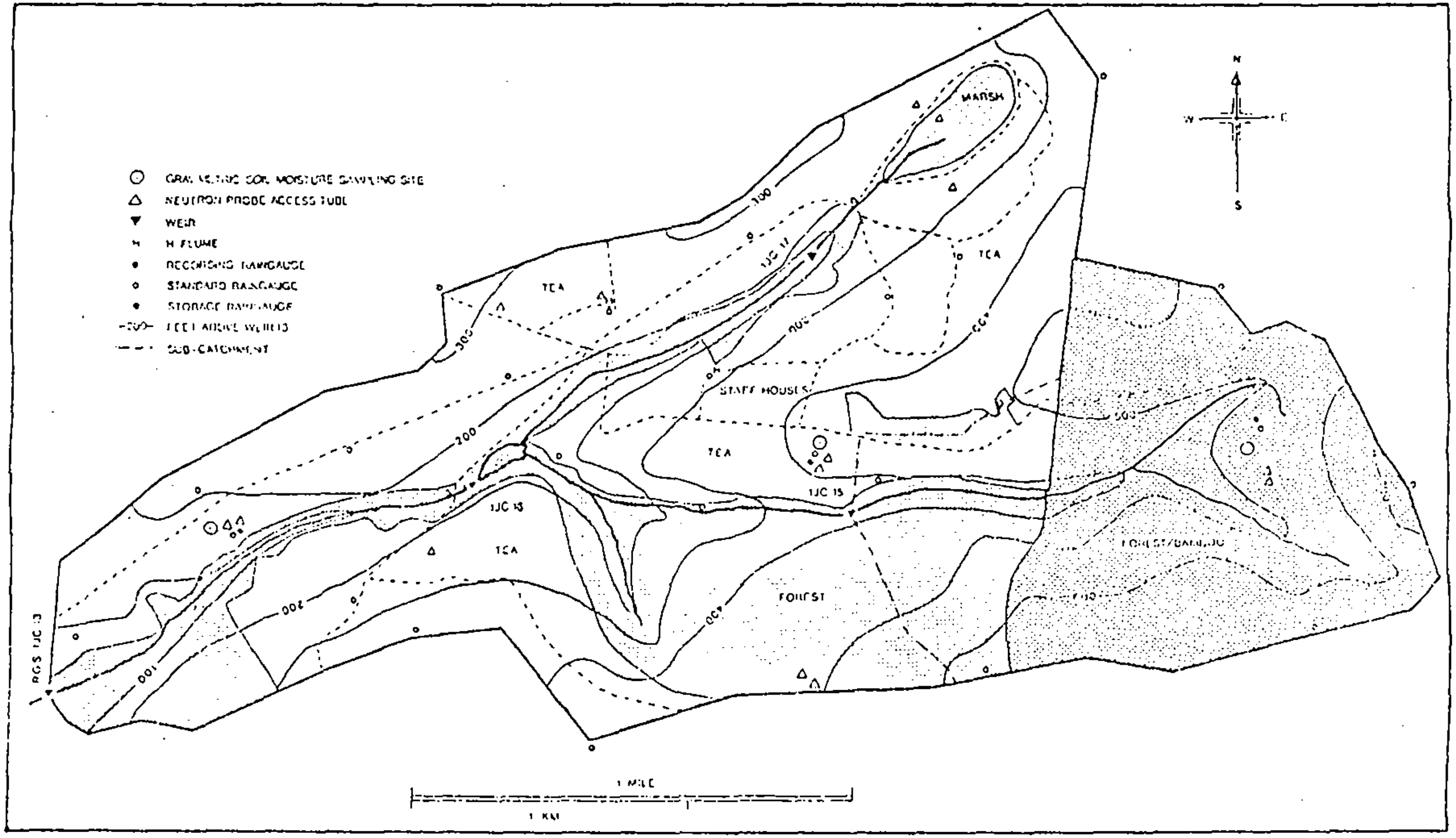

Figure 3 Sambret catchment

EXPERIMENTAL PROGRAMME

Basic instrumentation was completed by the end of 1957, and the following year is the first full year of hydrological data. The agreement with the Kenya Tea Company was that clearing would start after an 18-month control period with the final planting taking place in 1964. Details of the planting programme are included in Section 2.1.2. In this programme, the first planted tea would not reach maturity until 1967/68; it was desirable, therefore, that the experiment be continued until the entire estate was mature. The experiment was terminated in July 1974, to allow a final assessment to be made, although Kenya Government have continued to record rainfall and streamflow as part of their national water resources programme.

During the course of the experiment, a hydraulic lysimeter study of the water use of tea was conducted at the Tea Research Institute. This project provided a useful cross-check on the apparent water use figures derived from the catchment (Dagg, 1970; Wang'ati and Blackie, 1971). Short-term studies of the radiation balance over tea, bamboo and forest were carried out in 1966 (Ripley, 1967) and 1971 (Blackie, 1972). Staff of the Tea Research Institute mounted a detailed plot study of the effects of a range of conservation techniques on storm runoff and soil erosion in tea. A report on this work is presented in Section 2.2.4. This study helped to fill a gap in the original design of the catchment experiment in which the only sediment studies considered possible were the monitoring of suspended sediment by daily sampling at the catchment outfalls, and crude estimates of bedload from the frequency of cleaning of stilling pools.

More recently, as part of the participation of the UK Overseas Development Ministry in the experiment, two further field experiments were started in late 1973. These were the Fluxatron Project and the Soil Moisture Project which were both designed to obtain direct measurements of the actual water use of the tea crop. These were to be compared with the Penman estimates to check whether systematic errors had been incorporated into the water balance, and the results of these projects are presented in Sections 2.2.2 and 2.2.3 respectively.

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2.1.2

THE COMMERCIAL DEVELOPMENT OF SAMBRET ESTATE

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DECISIONS ON CHOICE OF SITE AND DEVELOPMENT PROGRAMME

During 1957, negotiations were completed between the Kenya Government, EAAFRO and the Kenya Tea Company (now Brooke Bond Liebig (Kenya) Ltd) regarding an area of forest situated 6 km south-west of the existing Cheboswa Estate at land reference No 9932 within the Western Mau Forest Reserve. The purpose of the negotiations was to make available an area suitable for a catchment study designed to evaluate the changes in total water yield and in its seasonal distribution that might result from replacing natural forest by tea estates (see Section 2.1.1). The total area to be developed was approximately 690 ha at altitudes varying between 2100 m and 2340 m; most of this area was under indigenous forest with canopies up to 15 m high, but it also included about 100 ha of bamboo. Under the agreement, the Kenya Tea Company undertook to fell, clear and plant to tea 120 ha per year up to a total of 324 ha by 1963.

EARLY DEVELOPMENT

(a) Surveying and Felling

Work started early in 1958 when an EAAFRO surveyor cut traces to determine the exact size of the area and nature of the terrain. Three rain gauges were installed as described in Section 2.1.1, and at the same time the Company planted trial plots of Assam and China hybrid tea to a total of 0.2 ha at the highest point on the proposed clearing within the bamboo belt. A weir was installed at the main outfall on the western boundary of the catchment. Senior staff included two Managers and two Assistant Managers experienced in new development to cope with the heavy clearing programme.

During the first part of 1959, an access road was completed to the proposed administrative centre of the Estate situated some

7 km from the old Tea Research Institute. Slopes in excess of 7½% were avoided where possible, but this was not easy until the forest was cleared. Staff housing was completed by the Company's Engineering Department and welfare facilities for the future labour force were laid out near the main office. These included a school, a football field, a running track and a dispensary.

Towards the end of 1959, 114 ha of forest had been felled, mostly in the month of June while a further 12.5 ha were left undisturbed to provide a control area of original forest for runoff measurements. Felling was a spectacular operation, and the Caterpillar D.8 was able to fell one hectare in approximately 7½ hours. A useful bonus emerging from this operation was the collection and distribution of 57,000 m^3 of forest firewood to six neighbouring tea factories. It was necessary at this stage to set up a field workshop to maintain and repair machinery on site.

A very small labour force was required to cut paths and assist with road building in the early stages, and those employed were local Kipsigis. Some months later, however, when the first camp housing was ready, about 100 men from the Luo and Kisii Districts became permanent residents.

(b) Clearing

Through late 1959 and early 1960, work continued on the task of preparing the 120 ha destined for planting with the break of the long rains. Tap roots were dug out and subsequently all tree stumps left by the firewood contractors were removed. Ripping followed, revealing large amounts of buried roots which were removed by hand to minimise *Armillaria mellea* infection in the newly-planted tea. A second ripping exposed the remaining roots, after which levelling and harrowing completed the operation.

(c) Soil Conservation

Before the terraces were planned, the positions of cut-off drains were sited. A chart showing lateral distances between terraces on a zero line to correspond with various vertical intervals was supplied by the Soil Conservation Service; terraces were restricted to a minimum discharge distance of 300 m in any one direction, and were on a 0.5% slope with a 0.5 m^2 cross-sectional area.

(d) Planting

The traditional method of manually preparing holes for the tea stumps was discarded after successful experiments involving the use of a tined tool bar mounted on the rear of a crawler tractor. This cut two furrows along the chosen contour, and individual holes were made at planting time in March 1960. With a planting rate of 200 stumps per man day, the 960,000 Assam plants which had all been brought in from neighbouring nurseries, had been planted by early May at a contour spacing of 1 m x 1.5 m. As a further soil conservation measure, oats were planted between all lines of tea except where terraces occurred. The red lateritic soil did not appear to be eroded as easily as the darker soils lower down the district. Broken pieces of wood formed effective trash lines.

At this stage, a temporary shade pattern of *Virgilia divaricata* was introduced and this was subsequently interplanted with permanent *Grevillea robusta* with each species planted on a 12 m grid. A change in Company policy in 1965, however, led to removal of all shade trees on Brooke Bond Estates including that at Sambret. While the main programme was continuing according to plan, the original 0.2 ha of Assam and China tea was maturing, although growth was slower than in other estates belonging to the Company because of lower temperatures at the high altitude. Labour at this stage was readily available, and an average of 250 labourers per day were employed. Further buildings, roads and a permanent water supply were installed. A shop and social hall were constructed to provide the usual amenities for employees; this was particularly important because of the distance from Kericho.

By June 1960 the first 120 ha of the new estate was completed; the cultivation methods were repeated in 1961, 1962 and 1963 to fulfil the total contract of 324 ha of tea which had been planted over 4 seasons. After the trial planting of 0.2 ha in 1958, the following areas were planted in each of the years 1960-1963 inclusive: 122.6 ha; 81.8 ha; 84.3 ha; and 35.1 ha. A further 26 ha were taken up by administrative and staff housing; there were 6 ha of fuel plantation; and major and minor roads occupied 19 ha.

During a particularly heavy rainstorm in September 1960, 88 mm fell in 70 minutes and considerable surface runoff occurred in the tea estate. It was apparent after this storm that the early care taken over soil conservation was fully justified; the cleared areas which had been carefully terraced and contour-cultivated accepted this heavy storm without damage, but steep cement-sectioned storm drains were overloaded and suffered some severe structural damage and gullying. The protection afforded to the 960,000 plants put out in 1960 by narrow based terraces, oat and soft weed lines and *eragrostis* banks controlled erosion losses to a mere 300 plants.

CULTIVATION PRACTICES ON THE MATURING ESTATE

The general principle of bringing the bushes into bearing was to tip shoot growth at 75 cm until the wood attained a thickness of 1.5 cm at a height of 22 cm. Preceding this, laterals had been removed between 12 and 32 cm. A 40 cm prune followed and the immature bush was then tipped in at 60 cm. The first mature prune took place after 7 years at 50 cm above this height.

Early manurial policies included a 28 gm dressing of double superphosphate per bush which appeared to give little response. After five years, the first planted tea received an application of 224 kg of calcium ammonium nitrate per hectare. Agricultural lime and basic slag were tried experimentally with no apparent effect in an endeavour to raise the pH of the most acid areas, which ranged between 4.0 and 5.0. Later, ammonium sulphate nitrate (26%N) and di-ammonium phosphate (18%N, 47% P_2O_5) were used. Indications of a general potash and phosphate deficiency appeared and were remedied using dressing of both double supersphosphate and sulphate of potash. After 1968, formulations of complex N-P-K became more popular in the ratio 5:1:1 or 2:1:1 and were applied as split doses during August and October, often together with sulphate of ammonia as a source of straight nitrogen.

It was extremely fortunate that the change to chemical weed control which began in 1962 coincided with the development of Sambret. In the system used, a 45 cm strip was weeded by hand on either side of the tea, leaving soft weed lines and trash as a soil conservation measure between the lines. Only these clean-weeded areas within the more mature tea were chemically sprayed using Simazine 50W pre-emergent control. Couch *(Digitaria scalarum)* and Kikuyu grass *(Pennisetum clandestinum)* were eradicated by Dalapon. Broad-bladed Dutch hoes were still used to remove sporadic and isolated outbreaks.

The Kericho plantations have been remarkably free of most serious diseases and Sambret was no exception, apart from the continuing incidence of *Armillaria mellea*. Between 1960 and 1974, it resulted in the death of over 90,000 bushes, a figure which represents some 3.5% of the total Estate and is some four times greater than in other Estates during the same development period. Scarlet Crevice Mite in 3rd and 4th year tea was the only other disease of note, but was easily controlled by Kelthane (18.5% dicofil active ingredient). A larger pest, the elephant, destroyed 800 stumps on one memorable occasion whilst in search of succulent oats!

YIELDS AND CROP LOSS

The stumps planted to 1960 produced their first crop in 1962 as tipping leaf and yields began to increase as the bushes matured. Table I traces the yield pattern up to 1974; yields

TABLE I

Yields of made tea (12 months ending 30 June)

Year	Total Yield Kg	Per Planted Ha Kg	Average Mature Estate
1958	Nil	Nil	-
1959	Nil	Nil	-
1960	Nil	Nil	-
1961	Nil	Nil	-
1962	4,232	13	1,556
1963	12,823	40	1,648
1964	44,957	139	1,729
1965	363,528	1,122	1,396
1966	374,544	1,156	1,567
1967	205,416	634*	1,211
1968	313,308	967**	1,589
1969	433,512	1,338	1,753
1970	487,620	1,505	1,987
1971	459,108	1,417	1,672
1972	559,548	1,727	2,212
1973	636,984	1,966	2,365
1974	441,996	1,362	1,900

* 1st mature prune 1960 area

** 1st mature prune 1961 area

have generally been lower than on the other Kericho Estates, almost certainly due to the higher elevation and lower night temperatures. The diurnal range of temperature is large (see Table I, Section 2.1.1) and frost damage in the lower parts of the valley has occurred on several occasions, notably in 1970 and 1974. Rainfall is generally higher than on the lower estates but exhibits a similar seasonal pattern with appreciable moisture deficits developing only in the January to March period.

One of the reasons for loss of crop has been hail. No records of hailstorms were available before the catchment area was cleared for planting, but since 1964 careful estimates have been made of the amount of crop lost (Table II).

PROFITABILITY

Profits from the Sambret Estate have been less than anticipated. Costs of production have been consistently higher than the district average because of lower yields at its high elevation. During the prolonged drought in early 1974, the Estate suffered badly; large areas were defoliated and recovery was poor, resulting in a further loss of profitability. The slow recovery has been both the cause for much concern and the origin of further investigations to determine how productivity could be increased. Possible explanations given for the poor performance include:

(a) The possible existence of a defect in soil chemistry (not, however, borne out by comparative analysis of soil samples from different areas of the Estate);

(b) A defect in soil structure;

(c) Climatic effects.

A study of soil physical properties is currently being undertaken with the assistance of the Tea Research Institute of East Africa.

TABLE II

Hail Damage - Estimated Loss Kg/ha of Made Tea

(12 months ending 30 June)

Year	Sambret	Kericho Average (Brooke Bond Estates)
1964	*7	59
1965	*Nil	101
1966	*201	75
1967	*118	58
1968	*134	83
1969	103	63
1970	167	128
1971	82	130
1972	190	100
1973	88	172
1974	128	137

* Estate largely immature

CONCLUSIONS

Despite a more rapid clearing programme than had been usual for the Company and occasional restrictions necessitated by the EAAFRO experiment, no abnormal problems were encountered. The wisdom of the geographical location selected for the investigation is now in doubt. The results of current studies will reveal whether the remedial action necessary to make Sambret a successful estate will be economic and practicable.

ACKNOWLEDGEMENTS

Credit must go to Mr D I C Hopkins, the Senior Manager of Sambret Estate during the development period for his precise organisation of the clearing programme.

Thanks are due also to Mr L A S Grumbley, now Chairman of Brooke Bond Liebig (Kenya) Ltd, for his great interest in this scheme from its inception and the encouragement and advice he has given to all concerned throughout the years.

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2.2.1

THE WATER BALANCE OF THE KERICHO CATCHMENTS

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INTRODUCTION

The background of this study has been described in detail in Section 2.1.1. Briefly, the practical objective was to determine the hydrologic effects of a change in land use from montane rainforest to tea estate. To this end, two catchments on the SW Mau above Kericho were instrumented to measure rainfall input, streamflow output and changes in soil moisture storage. A meteorological site adjacent to the catchments provided the data required to compute estimates of potential evaporation. The Lagan catchment, of 544 ha, remained under rainforest throughout the 1958-74 period of study. After a brief intercalibration period in 1958/59, clearing and planting of the Sambret experimental catchment commenced in 1959/60 and by 1964 a total of 380 ha, representing 54% of the catchment area, was under tea estate. Details of this clearing and planting programme are given in Section 2.1.2. Regrettably, the original plan to clear virtually the entire catchment was abandoned; in an attempt to minimise the uncertainties arising in the interpretation of data from a 'patchwork' catchment comprising 380 ha tea estate, 140 ha forest and 180 ha of bamboo with intermingled patches of forest, a subcatchment was instrumented within the main catchment. As shown in Figure 3 of Section 2.1.1, this subcatchment of 186 ha includes the bulk of the bamboo and mixed bamboo/forest area. Collection of rain, flow and soil moisture data from this subcatchment commenced during 1961.

A preliminary analysis of the data from the main catchments was presented by Pereira et al (1962), and subsequent analysis by Dagg and Blackie (1965) and Blackie (1972). The latter covered the period up to 1968 when the bulk of the tea in Sambret was approaching its mature level of ground cover. Since that time, co-operation with the Institute of Hydrology, and, more recently, a research project sponsored by the United Kingdom Overseas Development Ministry, has made it possible (i) to upgrade the instrumentation on the catchments, with a view to checking for systematic error in the earlier data, (ii) to transfer the accumulated data to computer tape thus making more detailed processing practical and (iii) to instigate a number of physical process studies, described in detail in Sections 2.2.2 and 2.2.3.

In this paper the major sources of systematic error detected in the data are described, together with the corrections applied. The accuracy of the resulting data is considered and a water balance analysis is presented. The problems of interpretation of these results, both in terms of the practical implications for further land use change of this type in the immediate area and in terms of extrapolation in time and space using conceptual models, are discussed and some specific conclusions drawn.

ACCURACY OF THE DATA

The instrumentation originally installed on these catchments has been described in Section 2.1.1. This comprised daily raingauge networks in each catchment supplemented by autographic gauges, sharp-crested weirs with continuous water level recording, daily meteorological observations, and measurement of soil moisture change over the bulk of the root range, initially on a monthly basis at three sites per catchment using gravimetric techniques and subsequently using neutron moisture meters on a denser network. All of these measurements have inherent possibilities of both random and systematic error.

In any real data a residual element of random error is inevitable. This can be minimised by thorough training and close supervision of the observers and by detailed checking of the data. In the present case all data were subject to additional quality control checks during the processing phase and corrections applied only after checking back through the processing sequence to the observer if necessary.

Systematic errors can arise from instrument or observer malfunction, processing errors, instrument or network design faults. Those arising at some point during the run of data can be detected by such techniques as double mass plotting or time series comparisons, but those inherent in the instrument or experimental design are much more difficult to detect. Occasionally they can be inferred indirectly from analysis of the data, but the basic safeguard must be in checking and re-checking the initial designs and calibrations.

A number of the more important sources of systematic error in the Kericho data are discussed in the following paragraphs.

Rainfall

The possible sources of systematic error in point rainfall measurement have been discussed by Rodda (1967). In the present case, those arising from instrument design and operation are considered to have been minimised by regular inspection and checking. Those arising from height of gauge above ground are considered to be lower than the 1% to 4% described in Appendix 7.1.2 for the site at Muguga, since windspeeds in the Kericho area are some 50% lower on average. The major potential sources of systematic error in the catchment rainfall estimates are, therefore, the network design in relation to the spatial variability and the exposure of the individual gauges.

The latter point is particularly relevant in the case of the Lagan forested catchment. As shown in Figure 3 of Section 2.1.1, this network comprised six gauges, the three on the northern side being mounted on tree platforms at mean canopy level and the three on the south side being post-mounted in clearings, with a maximum shading angle of 45°. Considerable practical difficulties in the operation of the canopy mounted gauges resulted in a number of missing or doubtful records.

Nevertheless, periods of continuous good record showed a relatively consistent difference of -3% to -6% between the canopy gauges and their clearing-mounted counterparts. The extent to which this difference is attributable to the exposure of either set of gauges or to genuine rainfall trend is unresolved, though the evidence available from the Sambret network indicates no equivalent north/south rainfall trend. Because of this uncertainty and the gaps in the canopy gauge records, the catchment Thiessen estimates have been based on the three clearing gauges only. As a result, the Lagan rainfall used in this paper for the 1958-68 period is higher by some 3% on average than that used by Blackie (1972). The spatial variability of rainfall in Lagan has been discussed in Section 1.2.1. As might be expected under the pattern of relatively small, high intensity afternoon convective storms, considerable variation is noted on a daily basis, reducing progressively over longer time intervals. Table I of Section 1.2.1 indicates that the standard error of the mean annual totals from the three gauges in Lagan is less than 3% in all but three of the 16 years 1958-73. The three years in question, 1964, 1965 and 1966 had errors of 4.8%, 4.1% and 5.7% respectively. It is notable that the latter two years were the driest on record. This level of precision is lower than the 1% or less obtained from the twenty-one gauge network in Sambret, and must be borne in mind when considering the implications of the water balance analysis.

As described in Section 2.1.1, the Sambret raingauge network initially comprised three gauges sited in clearings. During 1960 this was supplemented with a further eighteen gauges. When clearing and planting was completed these eighteen gauges were redistributed within the catchment during 1965. Thus the catchment estimates of rainfall input were estimated from three gauges during 1958-60, a network of twenty-one gauges during 1961-65 and a different network of twenty-one gauges from 1965 onwards. To check for possible bias resulting from these changes, the catchment annual totals from each twenty-one gauge network were compared with the original three gauge network.

In Table I the annual rainfall for the periods 1961-64 and 1966-69, estimated from the three gauges and each twenty-one gauge network using (a) the arithmetic mean, and (b) Theissen polygon method are listed. As can be seen, the differences are small. Analyses of variance produced the following conclusions:

(a) Arithmetic mean estimates.
There was evidence of a consistent difference between three gauge and twenty-one gauge estimates of the annual rainfall but no evidence that the difference was altered by the redistribution of the twenty-one gauges.

(b) Theissen polygon estimates.
There was no evidence of consistent differences in annual rainfall estimates between three gauge and either twenty-one gauge network.

In the water balance analysis, the Theissen estimates are used. It is reasonable to assume, therefore, that no bias in the annual totals has been introduced by using the differing networks.

Streamflow

As indicated in Section 1.2.4, the ratings of the structures are considered to be accurate within 2% over the normal range of flows. The water level recorders in use until 1970 suffered from design limitations resulting in low accuracy in the short term. These errors, together with those inherent in the methods of utilizing the ratings to obtain flow in mm depth over the catchments, were essentially

TABLE I

Comparison of Sambret Rainfall from Three and Twenty-One Gauge Networks

Year	3 Gauge Annual Mean Rainfall (mm)	SEE	21 Gauge Annual Mean Rainfall (mm)	SEE	Difference (mm)
(a) Arithmetic Means					
1961	2334	33	2325	15	+ 9
1962	2553	28	2516	14	+37
1963	2209	71	2192	14	+17
1964	2123	13	2092	9	+31
1965	1520	18	18 gauges redistributed		
1966	1881	24	185~~3~~8	8	+23
1967	2259	16	2211	10	+48
1968	2145	11	2061	24	+84
1969	1511	20	1505	13	+ 7
(b) Theissen Means					
1961	2328		2352		-24
1962	2540		2523		+17
1963	2185		2217		-32
1964	2121		2114		+ 7
1965	1520		18 gauges redistributed		
1966	1869		1862		+ 7
1967	2214		2214		0
1968	2139		2070		+69
1969	1504		1498		+ 6

random however, and the annual flow figures are considered to be of an accuracy comparable with the ratings. Because of mechanical faults arising in part out of the damp locations of the recording sites, the potentially greater sensitivity of the new recorders installed in parallel with the earlier ones in 1970 was achieved only intermittently. Cross checks during these periods revealed no significant sources of systematic error. A detailed check on the catchment areas in 1968 resulted in corrections of +1.7% and +2.4% to the flows, expressed in depth, from Sambret and Lagan respectively when compared with the figures quoted by Pereira et al (1962) and Dagg and Blackie (1965). The corrected figures were used by Blackie (1972).

Penman Estimate of Evaporation

The Penman estimate of potential evaporation, EO, from the Kericho meteorological data has been computed using several versions of this well-known expression. Pereira et al (1962) used the Penman (1948) version. Dagg and Blackie (1965) used the modified version due to McCulloch (1965), whereas Blackie (1972) used a similar version incorporating the Berry (1964) polynomial expressions for the computation of saturation deficit. This latter version has been used for all EO data presented here. As the data accumulated, a downward trend in annual totals inconsistent with other stations in Kenya having comparable lengths of record was noted. This is demonstrated in Fig 1(a) whilst 1(b) shows the departure trend of EO from the Class A and sunken evaporation pans on site at Kericho.

Initially, the meteorological data from 1970 were examined in detail for systematic error. A marked decrease in the wind run from October 1972 onwards was detected. Comparison of the data with those from another meteorological site 0.5 km away, and with those from an Automatic Weather Station (AWS) operated along-side from February to October 1974, indicated that the error was systematic and time-invariant. Corrections were duly applied using regression relationships with these two

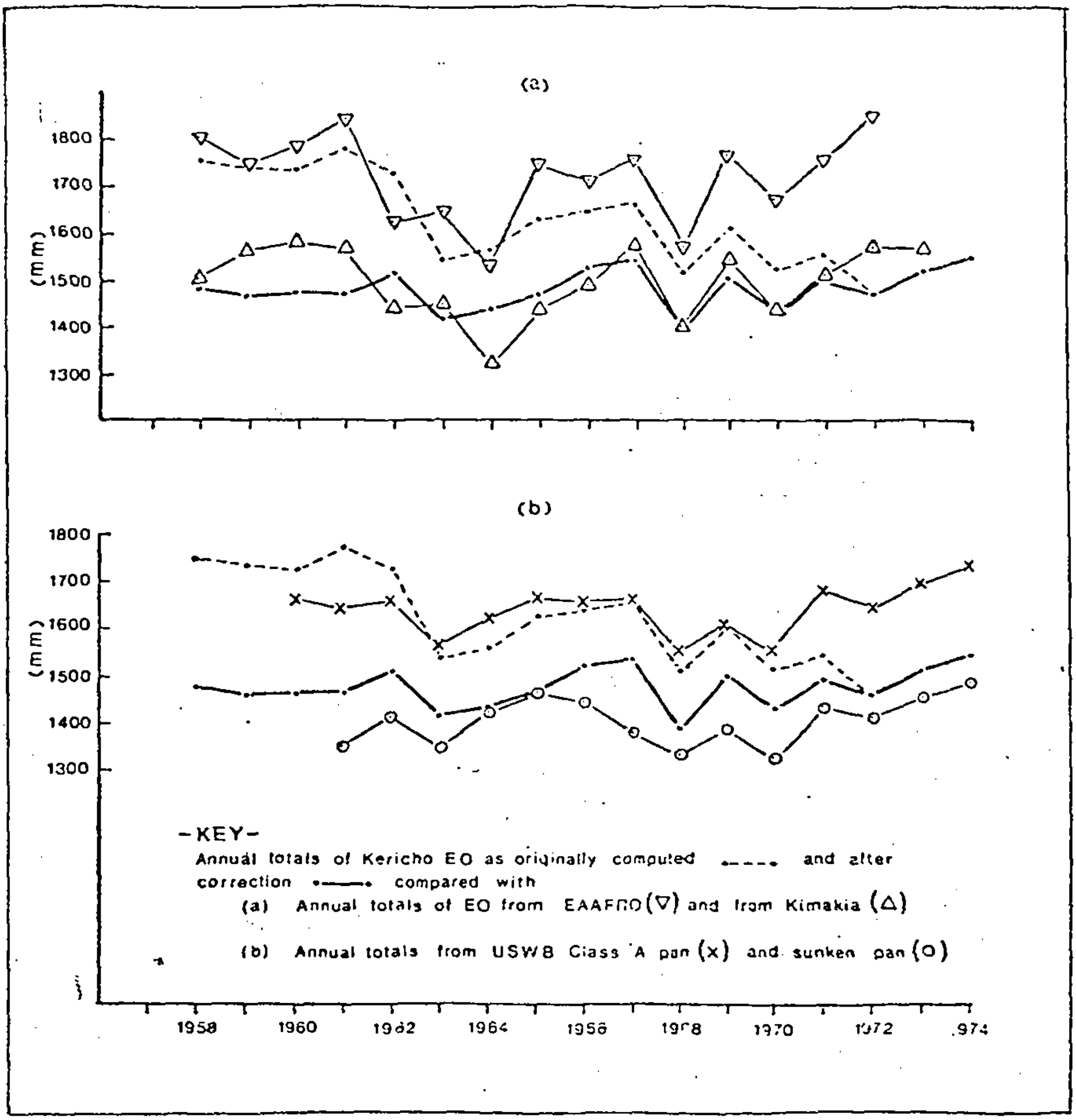


Figure 1 Comparison of Kericho EO, before and after correction, with EO from other sites and with evaporation pan data

anemometers. The net effect of this correction on EO was less than 2% however, inadequate to explain the downward trend.

Further examination of the full run of meteorological data revealed a trend in radiation similar to that in EO. Radiation measurements have been obtained throughout at Kericho using a series of Gunn Bellani radiation integrators (Pereira, 1959), each of which has been calibrated against the Kipp solarimeter at EAAFRO prior to installation in the field. Comparison of daily totals of radiation from the Gunn Bellani on site in 1974 with those from the recently calibrated Kipp on the AWS revealed remarkably close agreement, as shown in Fig 2, indicating that the Gunn Bellani had not gone off calibration. Since this Gunn Bellani has been in operation from September 1971, the implication was that some systematic error was present in the radiation data obtained from earlier Gunn Bellanis in use at Kericho. In the absence of any other local radiation records, the only check available was comparison with sunshine hours using the standard Ångström type of regression relationship

$$\frac{R_c}{R_a} = a + b\ {}^{n}/N \qquad \ldots\ldots\ (1)$$

where R_c is actual radiation;

R_a is radiation at the outer limit of the atmosphere at the time and latitude

n is actual sunshine hours

N is maximum possible sunshine hours

a,b are constants.

In general, this type of relationship, commonly used to estimate radiation from sunshine hours, exhibits a wide scatter. However, with the remarkably constant diurnal cloud

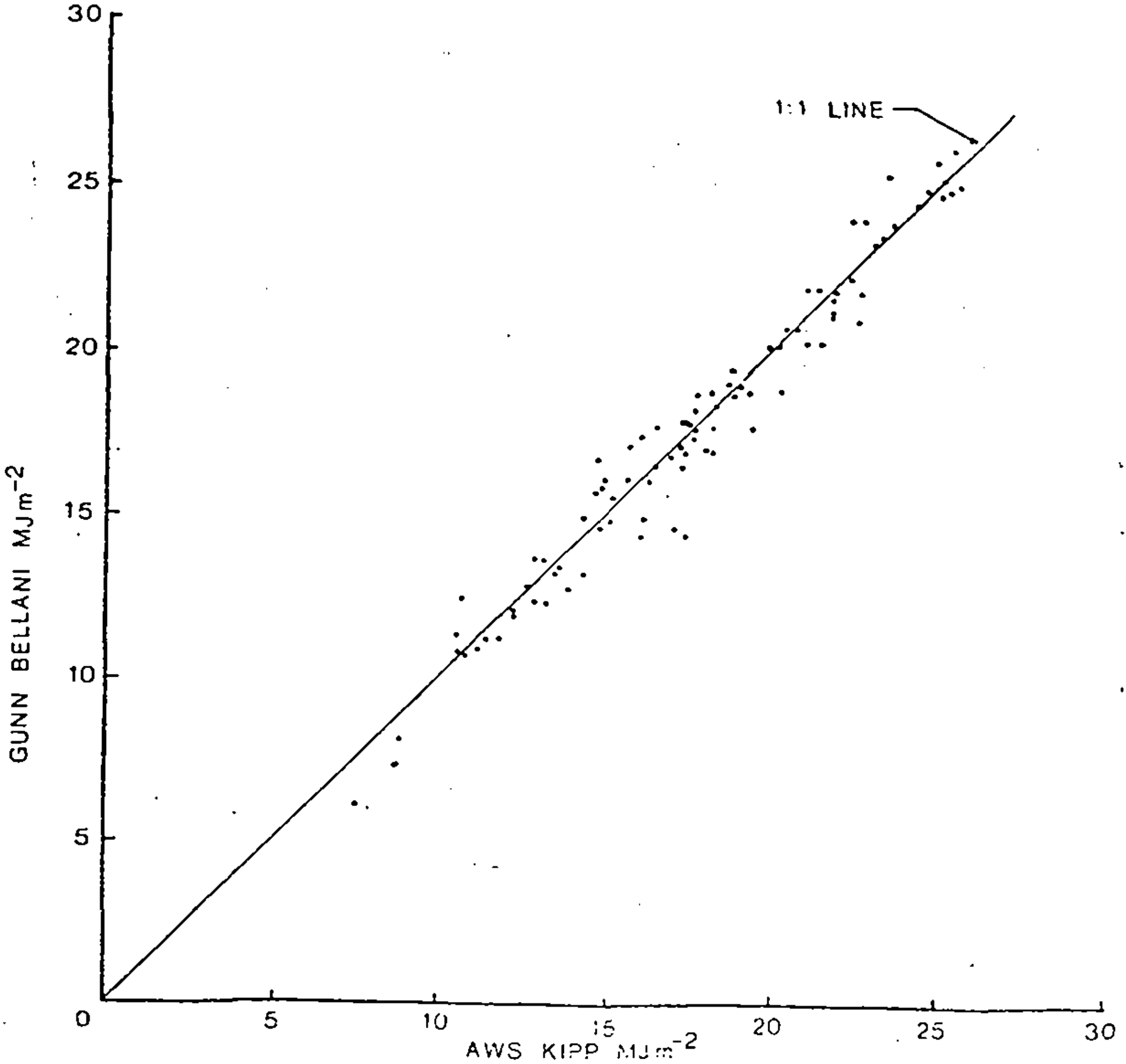


Figure 2 Kericho daily radiation, April to June 1974, as measured by Gunn Bellani radiometer and by the Automatic Weather Station Kipp solarimeter

patterns at Kericho comprising clear mornings with progressive cloud build-up through the afternoon, better than average precision could be expected.

Plotting $^{R_c}/_{R_a}$ against $^{n}/N$, using monthly means, revealed a considerable scatter as shown in Fig 3(a). However, these points could be separated into 6 groups. Groups 1, 4, 5, and 6 correspond to the periods of use of four different Gunn Bellanis, whilst a fifth had been in use throughout periods 2 and 3, but examination of the station log showed that its mounting had been altered at a time corresponding to the separation of the periods. The regressions relating to the six periods are listed in Table II. Analysis of variance revealed that the differences in the slopes, b, were not significant but, using a pooled value of slope, there was strong evidence of differences between the intercepts, a. Details of the analysis are given in Table III.

Taking the 1971-74 period 6 as the best estimate, on the evidence of the agreement of the Gunn Bellani with the AWS Kipp, gave, using the pooled slope,

$$\frac{R_c}{R_a} = 0.1547 + 0.6379\ ^{n}/N \qquad \text{..... (2)}$$

Using (2), intercept value corrections k_1 to k_5 were computed for addition to the pooled slope regression intercepts for each of the other periods. These are listed in Table III.

Since the daily radiation is obtained from measured Gunn Bellani distillation using a calibration of the form:

$$R_c = Ad + B \qquad \text{..... (3)}$$

where, for each instrument,

d is daily distillation;

A,B are constants specific to the instrument;

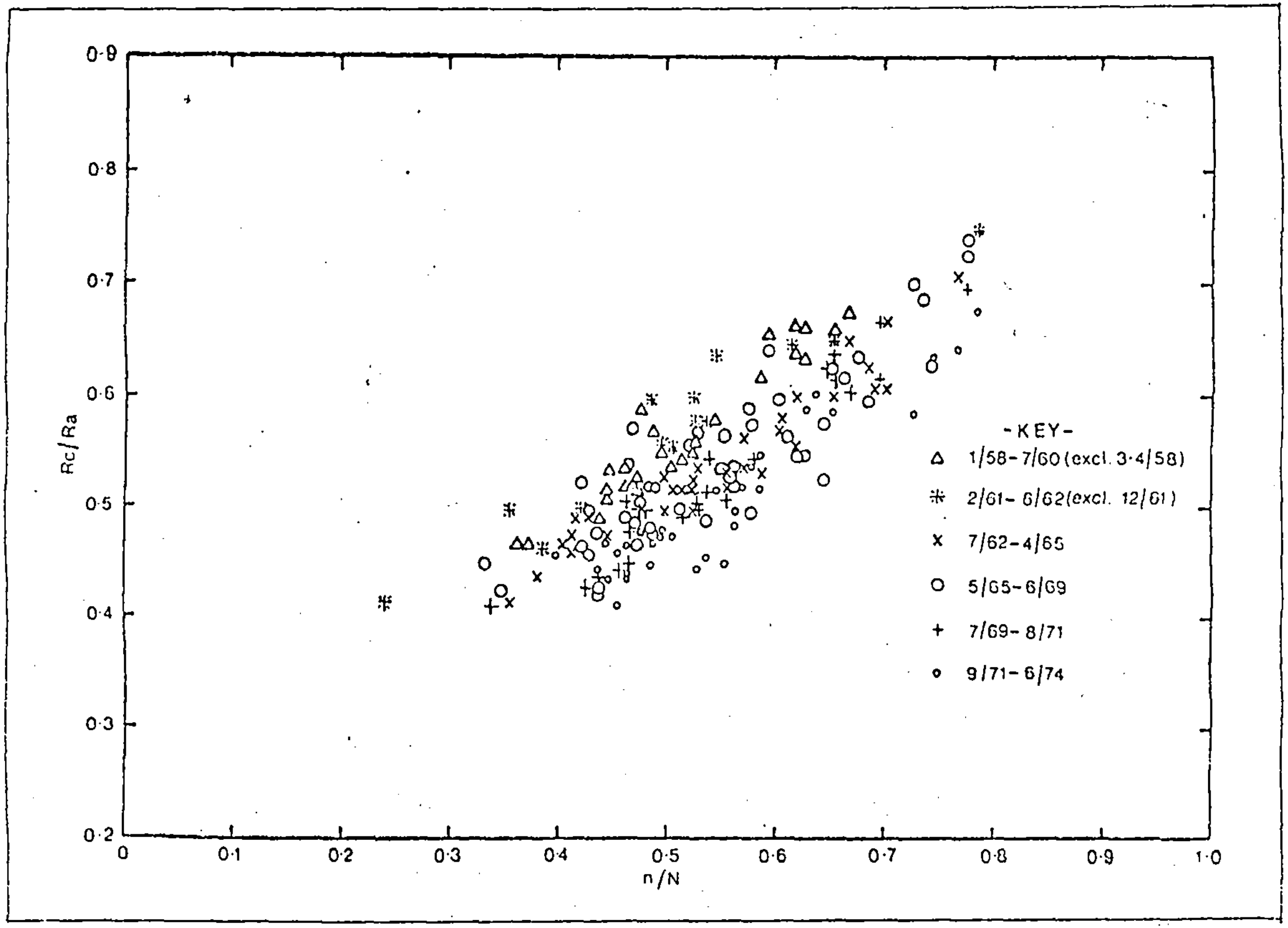


Figure 3(a) Comparison of fractional radiation, R_c/R_a, and fractional sunshine hours, n/N, showing systematic differences with each Gunn Bellani change

TABLE II

Regressions of Fractional Radiation $^{R}c/R_a$, on Fractional Sunshine Hours, $^{n}/N$, for each of Six Periods at Kericho

Period	Dates	Gunn Bellani	Regression
1	1/58 → 6/60	P10 ($R_c = 31.7d + 126$)	$^{R}c/R_a = 0.194 + 0.717\ ^{n}/N$ $n = 28,\ r^2 = 0.927$
2	2/61 → 6/62	P140 ($R_c = 27.7d + 93$)	$^{R}c/R_a = 0.261 + 0.610\ ^{n}/N$ $n = 16,\ r^2 = 0.932$
3	7/62 → 4/65	P140 ($R_c = 27.7d + 93$)	$^{R}c/R_a = 0.209 + 0.603\ ^{n}/N$ $n = 34,\ r^2\ 0.922$
4	5/65 → 6/69	P11 ($R_c = 32.4d + 93$)	$^{R}c/R_a = 0.272 + 0.628\ ^{n}/N$ $n = 47,\ r^2 = 0.786$
5	7/69 → 8/71	P1148 ($R_c = 28.2d + 70$)	$^{R}c/R_a = 0.148 + 0.696\ ^{n}/N$ $n = 26,\ r^2 = 0.935$
6	9/71 → 6/74	P723 ($R_c = 26.4d + 50$)	$^{R}c/R_a = 0.161 + 0.626\ ^{n}/N$ $n = 34,\ r^2 = 0.872$

TABLE III

Significance Tests of the Radiation v Sunshine Regressions listed in Table II ($y = {}^{R}c/R_a$, $x = {}^{n}/N$)

Period	n	Syy	Sxy	Sxx	$(Sxy)^2/Sxx$
1	28	0.109947	0.142209	0.198410	$0.1019\overset{2}{\cancel{3}}7$
2	16	0.106598	0.162943	0.267232	0.099353
3	34	0.146638	0.224135	0.371425	0.135253
4	47	0.289170	0.362187	0.577144	0.227291
5	26	0.133775	0.179703	0.258198	0.125072
6	34	0.162854	0.226996	0.362769	0.142038
All	185	0.948982	1.298173	2.035178	0.830944

Test of Significance for Difference between Slopes of Regressions

	df	SS	MS	F
Pooled slope	1	0.828061	0.828061	***
Diffs between slope	5	0.002883	0.0005766	NS
Pooled error	173	0.118038	0.0006823	

No evidence of significant differences between slopes.

Using pooled slope, $b_p = 0.6379$, the intercepts become $a_{p1} = 0.2348$, $a_{p2} = 0.2459$, $a_{p3} = 0.1900$, $a_{p4} = 0.1902$, $a_{p5} = 0.1790$ $a_{p6} = 0.1547$.

Test of Significance for Differences between Intercepts

	dF	SS	MS	F
Overall regression	1	0.772350	0.772350	
Diffs between slopes	5	0.002883		
Diffs between intercepts	5	0.148139	0.0296278	43.42***
Pooled error	173	0.118038	0.0006823	
Total	184	1.041410		

Strong evidence of differences between intercepts.

Assuming a_{p6} to be best estimate, corrections required to intercepts for periods 1 - 5 are: $k_1 = -0.0801$, $k_2 = -0.0912$, $k_3 = -0.0353$, $k_4 = -0.0355$, $k_5 = -0.0243$.

corrected daily radiation was computed as follows.

Let R_{ci} and R'_{ci} be the original and corrected radiation values for a given day in period i. Using the pooled regression slope, b_p, and the appropriate intercept a_{pi}

$$R'_{ci}/R_a = a_{pi} + k_i + b_p \, {}^n/N$$

Therefore:

$$R'_{ci} = R_{ci} + k_i R_a \qquad \ldots\ldots (4)$$

Combining (4) and (3) gives:

$$R'_{ci} = A_i d + (B_i + k_i R_a) \qquad \ldots\ldots (5)$$

For Kericho (lat 0°22'S) R_a varies seasonally from 33.1 MJ m^{-2} to 37.7 MJ m^{-2}. With the largest of the k_i values, -0.0912 in period 2, replacement of R_a with its annual mean value of 35.7 MJ m^{-2} results in a maximum error of 0.25 MJ m^{-2}, less than 2% of the mean daily radiation.

Thus, using the mean value of R_a and the appropriate k_i, daily radiation was recomputed for periods 1 to 5 from the distillation data using (5). For those months where the distillation data were incomplete, daily radiation was computed from sunshine hours using expression (2) in place of the Glover and McCulloch (1958) generalised latitude dependent expression previously used.

A plot of R'_{ci}/R_a against ${}^n/N$ is presented in Fig 3(b) and the effect of the radiation corrections on annual EO is demonstrated in Figs 1(a) and 1(b). The corrected values now show general agreement in temporal trend with other stations and with the Kericho evaporation pan data. These revised EO estimates result in differences in the interpretation of the water balance data from that in earlier papers.

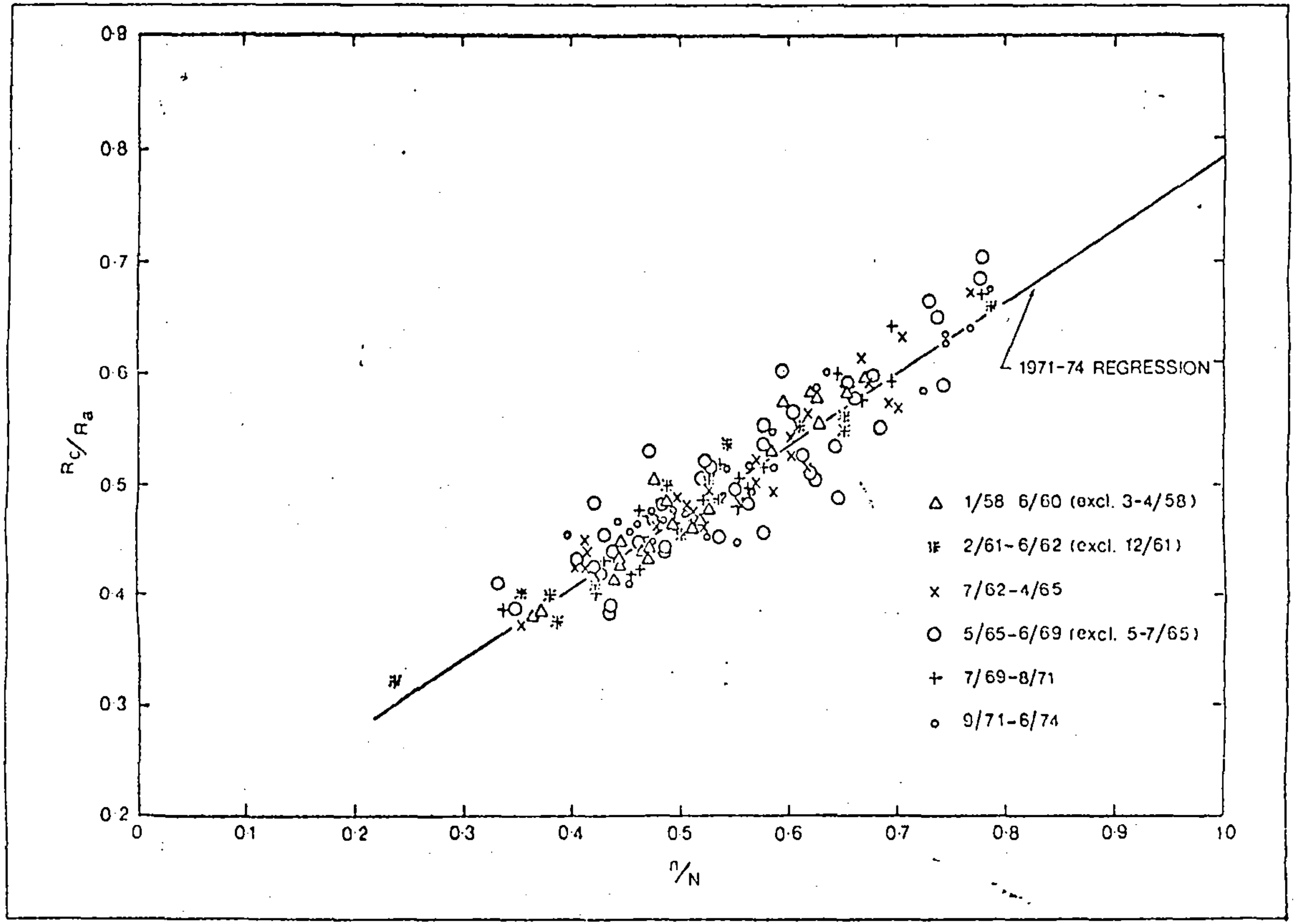


Figure 3(b) R_c/R_a v n/N, after correction of radiation using the 1971-74 regression shown as reference

The physical interpretation of these apparent systematic errors in Gunn Bellani radiation data is relevant to the many other users of these instruments in tropical areas. Each instrument used at Kericho had been calibrated first against a Kipp solarimeter at EAAFRO prior to installation. In only one case, however, was it possible to check this calibration against a Kipp on site. As reported above, this check, in 1974, showed comparable agreement to that obtained during calibration in 1971 prior to installation.

Although the above comparison with sunshine hours is not particularly sensitive in determining the reasons for departure from calibration of the earlier Gunn Bellanis, it does indicate two important features. One is that each departure was apparently constant in time, and the other is that they can be interpreted reasonably as being constants, independent of radiation intensity. Thus, the discrepancy between calibration and on site performance arose from a change in the regression intercept, B, in expression (3) and not from a change in sensitivity. The physical interpretation of B has been discussed by Pereira (1959) and McCulloch and Wang'ati (1967). In part it represents the radiation required to raise the water in the instrument to its pressure-reduced boiling point, and in part it represents any cut-off due to the shielding effect of the mounting at low solar altitudes.

Since, in this case, mean temperatures are very similar at calibration and operational sites, no major departure is likely to have arisen from the former source. A more likely explanation lies with variation in shading effect. Normally these instruments are mounted in 127 cm diameter cylindrical shields with the top of the 5 cm diameter copper sphere 1 cm below rim level. Thus they receive no direct solar radiation until a solar altitude of 9° and the entire hemisphere is not exposed until a solar altitude of 44°. If set 1 cm low in the mounting, these figures become 17° and 48°. On a clear day at Kericho total solar between 9° and 17° is of the order of 0.63 MJ m^{-2}. Thus errors of at least 1.26 MJ m^{-2} seem not unreasonable due to a variation of 1 cm in mounting height. The correction to B indicated above for the instrument in use in periods 2 and 3 provides further evidence of shield effect as the major source of error. In June 1962 this instrument was reported to have been lowered by an unspecified amount. The indicated correction changes from -3.3 MJ m^{-2} in period 2 to -1.25 MJ m^{-2} in period 3. The discontinuity in radiation readings is therefore in the correct sense of a reduction in measured radiation.

In retrospect, therefore, it would seem advisable to carry out checks on the calibration of these instruments on site or, failing that, to calibrate and install instrument and mounting as a complete unit.

Soil Moisture and Groundwater Storage

The soil moisture measurements taken on the Kericho catchments are fully described in Section 2.2.5. Comment here is restricted therefore to aspects relevant to the water balance calculations. These include the precision of the measurements and the accuracy of catchment mean deficit derived from them.

For the monthly gravimetric sampling to 320 cm operated from 1958 to 1971, the precision in terms of profile total volumetric moisture contents is remarkably good. In general, the totals from paired profiles at each site differ by less than 3%. Despite the remarkable lateral and vertical uniformity of soil structure in these catchments, variability between sites is rather greater, reflecting spatial variations in rainfall input and root abstraction as well as measurement errors. Standard errors of the estimate of the catchment mean for Lagan, based on three sites (2 profiles per site), were generally in the range 1 % to 3 % for the gravimetric sampling. Despite the increased network density used for neutron probe sampling (5 sites, 11 profiles) the corresponding range was 2 % to 3 %. In general, the greatest precision was obtained when sampling was carried out after periods of several days without rain.

No firm statement can be made on the absolute accuracy of these estimates of catchment mean storage in the profile. However, bearing in mind the long-term spatial uniformity of catchment rainfall, the uniformity of soils and of the vegetation, it is reasonable to assume that the point made by Pereira et al (ibid) remains valid: this is, that the careful choice of sites should result in mean values bearing a reasonably constant relationship to the true catchment mean. It follows from this that differences between means should closely represent differences in true moisture content between sampling times. In terms of water balance calculations, it is these differences that are of importance rather than the absolute values. This is particularly the case where the 'available' storage in the root range is of comparable magnitude to the mean annual flow (Pereira et al, ibid).

The errors attached to each estimate of the catchment mean, though small compared to the total moisture content, assume much greater proportional significance when differences are considered. Thus the soil moisture data are of value in water balance calculations only when relatively large changes of storage have occurred, or where the precision of the estimates is better than average.

A point of some concern regarding soil moisture data from the Kericho catchments is whether the sampling depth, initially 320 cms, was sufficient to encompass the total operative root system. Kerfoot (1962) found from a study of the root systems of the major forest species and of the tea in the catchments that their root systems extended to at least 600 cm depth, though the bulk of the roots in each case tended to be in the upper 300 cm. On the basis of the latter point and preliminary studies, which indicated no significant development of moisture stress beyond 180 cms, the 320 cm sampling depth was chosen. However, more detailed studies in later dry seasons, notably 1967 and 1971, and the subsequent use of neutron probes monitoring to depths of 450 cms and beyond have indicated that moisture abstraction can occur from well beyond 320 cms. A time series plot of catchment mean moisture volume fraction (MVF) at 30.5 cm intervals over the 320 cm sampled profile in Lagan during the 1967 dry season is presented in Fig 4(a). Comparison of the mean profiles early in the dry season (20.9.66), at the time of maximum deficit (20.2.67) and following recharge (19.5.67), as shown in Fig 4(b), suggests that considerable abstraction of moisture from beyond the 320 cm depth occurred. In Figs 5(a) and 5(b), the profiles at similar times under bamboo and tea in Sambret indicate that abstraction from beyond 320 cm also occurred under these vegetation types. The smaller deficits at 305 cms, relative to the rest of the profiles, suggest that abstraction by bamboo and tea from beyond 320 cms may have been less than that by the forest. The abstraction depths recorded by neutron probe measurements in the 1970-71 dry season are discussed in Section 2.2.5. The implications of this on both short and long term water use determinations are discussed later.

No attempt was made to monitor water table levels in these catchments, nor was any systematic attempt made to determine the soil depth over the catchments. Consequently, the total storage between the 320 cm sampling level and bedrock and its temporal variation have been matters for indirect estimation. From root washing observations (Kerfoot, ibid), from the moisture movement studies reported in Section 2.2.3 and from the installation of neutron access tubes to 600 cm on both catchments, it is known that the soil remains virtually uniform in structure to a depth of at least 600 cm over the area generally though, at two sites, Kerfoot reported signs of decomposing rock at this depth. A negative observation of relevance in this context is that no evidence of a general water table rise to within 600 cms of the surface has been obtained from the monthly neutron probe readings. Groundwater storage range would appear to comprise the available storage from a depth of 600 cm to bedrock.

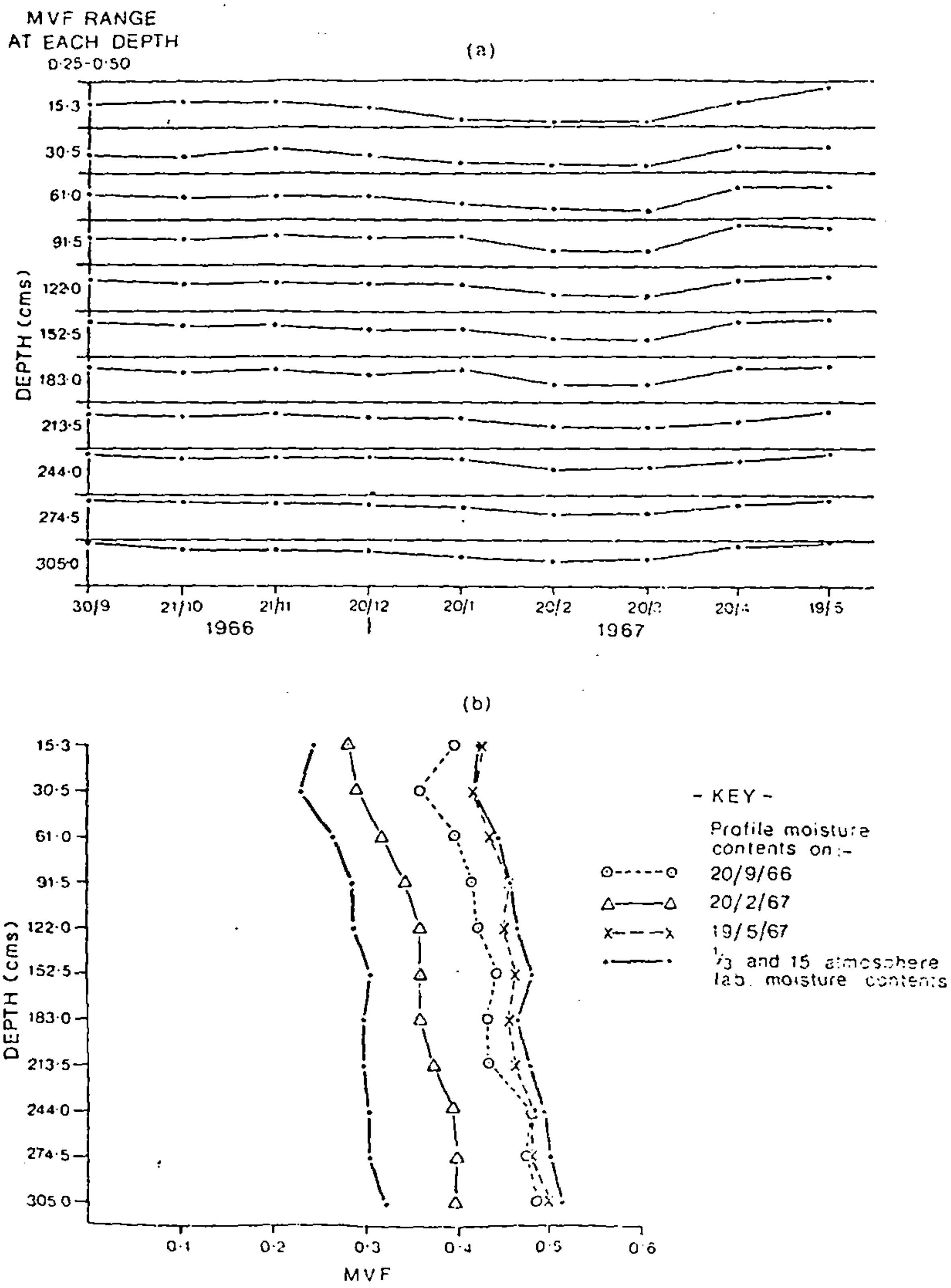
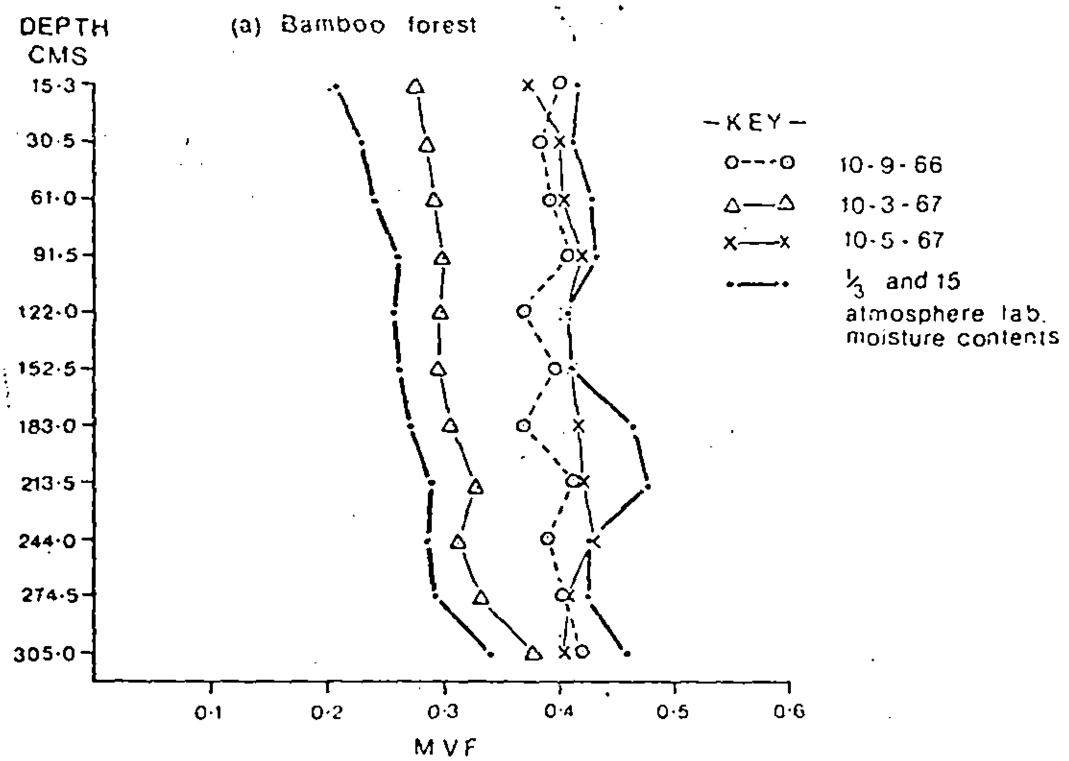


Figure 4 Mean soil moisture profiles under forest in Lagan during the 1966-67 dry season

(a) Time series plot

(b) Profiles at beginning, at maximum recorded deficit and after recharge



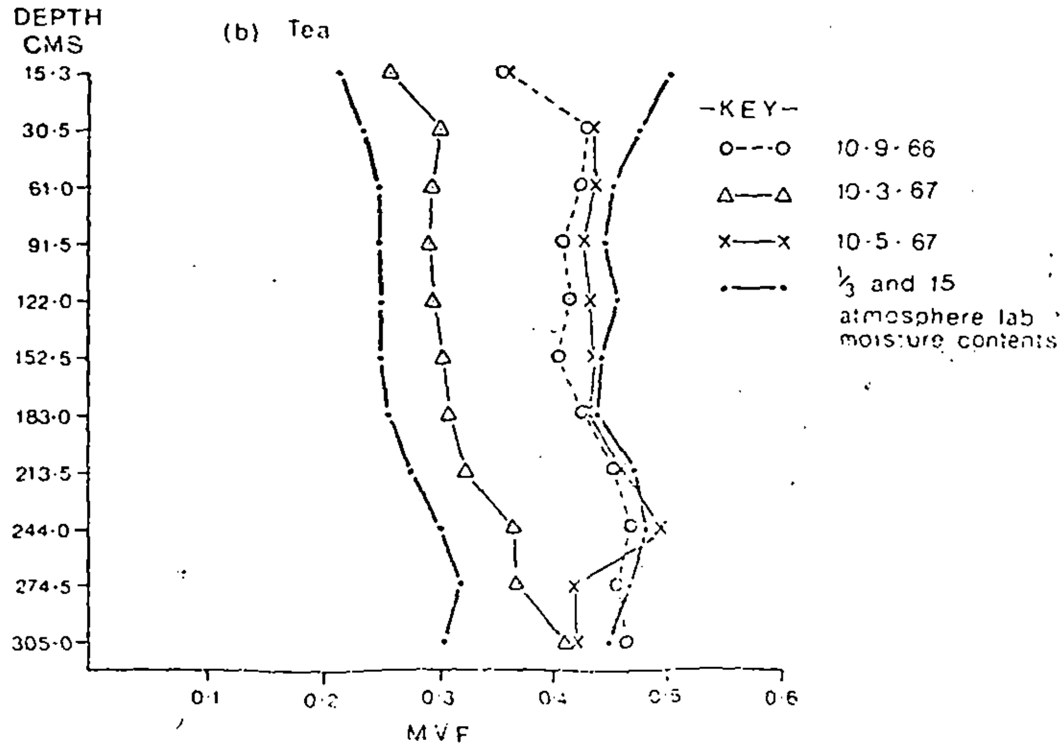


Figure 5 Profile moisture contents during the 1966-67 dry season in Sambret catchment

In the absence of direct measurements of water table fluctuations, Blackie (1972) used empirically derived baseflow recession curves to estimate groundwater storage changes in the catchments. These curves, reproduced in Fig 6, were derived from dry season flows in periods when soil moisture and rainfall measurements indicated negligible percolation to groundwater. Consequently, they cover a relatively narrow band at the lower end of the flow range. As might be expected, no simple logarithmic or power function can be fitted with consistent precision even over these narrow ranges. The development of mathematical functions to describe storage-discharge relations is discussed in Section 1.3.

From this discussion of the quality of the data it can be concluded that the precision of annual totals of rainfall in the Kericho catchments is of the order of 1% for Sambret and the bamboo sub-catchment within it, whilst those for Lagan are probably not estimated to better than 3%. Estimation of the absolute accuracy of the EO estimates is not feasible but, following the method outlined by Woodhead (1968) and bearing in mind the eradication of systematic errors as described above, it is considered that the annual totals of EO have a precision in the range 5-10%. Annual totals of streamflow are considered to be accurate to within 2% for both catchments. The precision of the catchment estimates of soil moisture are, at best, some 2% of the profile content, with severe constraints on the conditions under which this precision can be achieved. Provided these constraints are observed, however, estimates of soil moisture change over periods of 12 months will have errors similar in magnitude to those in flow and rainfall. Only the crudest estimates of storage change beyond the sampling depth are available, restricting the choice of water balance intervals to those between comparable points on the baseflow recession curve. At the chosen flow levels the errors in the estimates from the recession curve should not exceed 20 mm of flow.

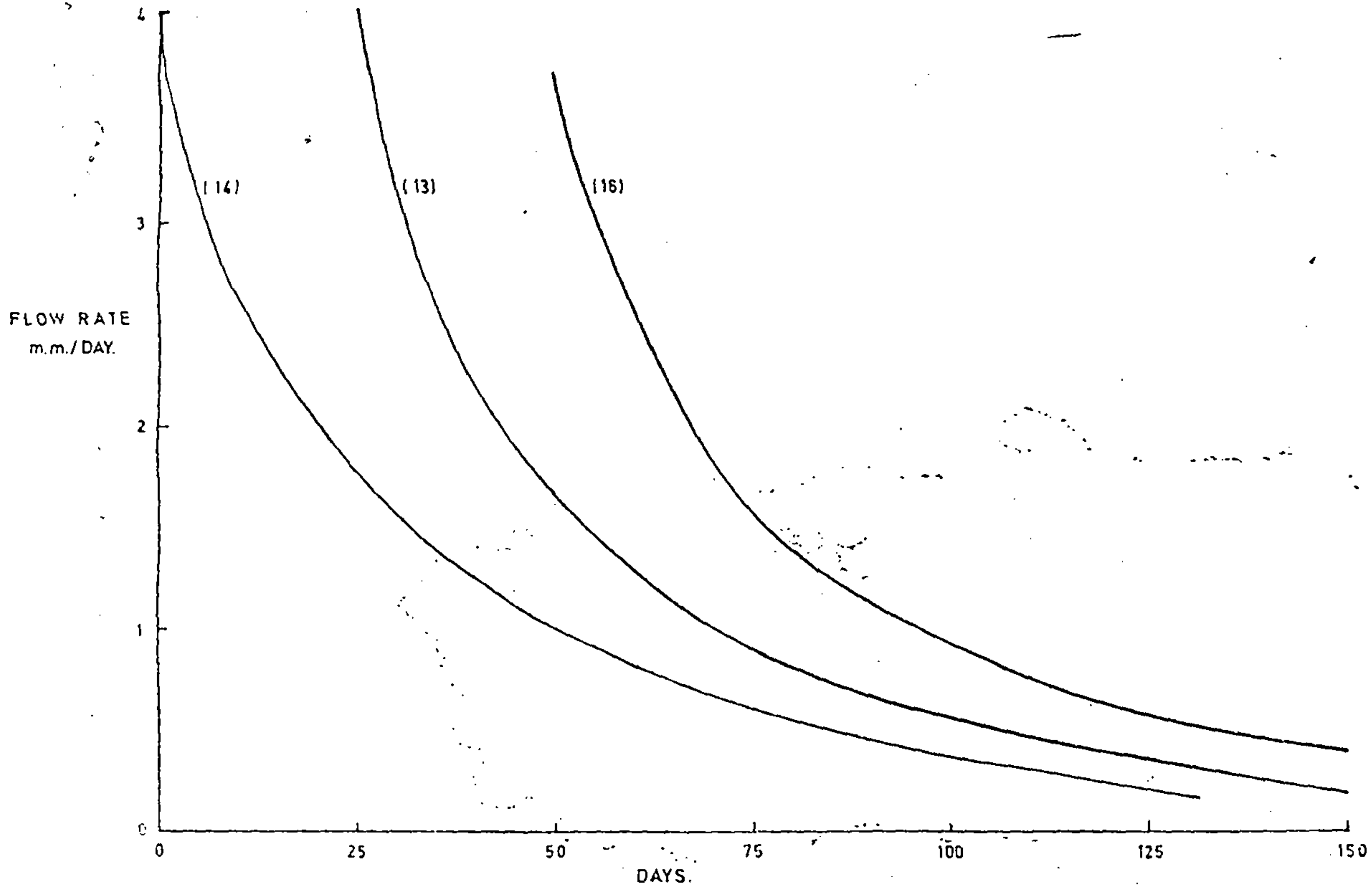


Figure 6 Composite baseflow recession curves derived from dry season flows in Lagan (14), Sambret (13) and the Sambret sub-catchment (16)

CATCHMENT DATA

The data obtained from the Kericho catchments have been made available elsewhere in the form of tabulated daily rainfall, streamflow, Penman EO and ET and monthly mean daily values of the meteorological variables (Edwards, Blackie et al, 1976). In Table IV annual totals of rainfall, streamflow and raindays (R ≥ 0.1 mm) for the 16 years are presented. Monthly means of these variables and of Penman EO for the period 1962-73 are listed in Table V, together with their standard deviations. Points which emerge immediately from these Tables are the broad similarity in historic and seasonal trends of rainfall and flow, coupled with considerable year to year variability in the totals. The standard deviations in Table V emphasise the conservative nature of Penman EO when compared with rainfall and flow.

LONG TERM WATER USE

The year to year variability in the rainfall and streamflow terms of the water balance follows essentially the same time sequence in all three catchments. This point is demonstrated in Table VI where the standard deviations on the mean annual values of rainfall minus flow (R-Q) are seen to be considerably lower than those on R and Q in Table IV. These values of R-Q provide a first estimate of water use by the vegetation in each catchment. Because of the potentially large errors introduced by ignoring the storage change terms, the annual figures can not be regarded as accurate estimates. However, the relative magnitude of the storage terms diminishes over longer periods and the 12 year and 16 year figures provide acceptable estimates of long term water use. These totals indicate that, over the entire 16 year period, the water use by the experimental catchment was lower than that of the control, forested catchment by 1968 mm or some 8.9%

In Table VII(a) the totals over each phase of development in the experimental catchment are compared. With due reservation

TABLE IV

Calendar Year Totals of Rainfall, Streamflow and Raindays

Year	Rainfall (mm)			Streamflow (mm)			Raindays		
	14	13	16	14	13	16	14	13	16
1958	1949	1785	-	307	245	-	232	233	-
1959	1841	1876	-	285	443	-	225	231	-
1960	2470	2308	-	929	977	-	263	253	-
1961	2539	2352	-	850	980	-	258	256	
1961 (Feb-Dec)		2349	2385		959	911			
1962	2488	2523	2556	1144	1348	1373	251	245	245
1963	2133	2217	2288	695	951	1014	241	239	239
1964	2020	2114	2149	901	1017	1043	274	245	245
1965	1541	1569	1523	268	275	224	214	226	226
1966	1631	1862	1889	656	635	648	186	242	242
1967	2166	2214	2238	721	904	862	242	247	247
1968	2446	2070	2115	1174	905	988	255	259	259
1969	1685	1498	1496	507	341	302	203	225	225
1970	2599	2222	2319	1027	943	979	249	262	262
1971	2363	2073	2021	973	946	840	223	237	237
1972	2181	2012	1937	708	737	614	240	231	231
1973	2013	1881	1903	696	673	684	215	218	218
<u>1958-73</u>									
Total	34065	32576	-	11841	12320	-	3777	3851	-
Mean	2129	2036	-	740	770	-	236	241	-
SD	±339	±279	-	±288	±311	-	±24	±13	-
<u>1962-73</u>									
Total	25266	24255	24433	9470	9675	9562	2799	2876	2875
Mean	2105	2021	2036	789	806	797	233	240	240
SD	±346	±287	±313	±265	±296	±324	±25	±13	±13

14 is the control, forested Lagan catchment

13 is the experimental Sambret catchment

16 is the bamboo-covered sub-catchment within Sambret

TABLE V

Means and Standard Deviations of Monthly Rainfall, Streamflow, Raindays and Penman EO for Kericho Catchments 1962-1973

Catchment	J	F	M	A	M	J	J	A	S	O	N	D	Annual
					Rainfall (mm)								
14	94	117	147	252	279	210	186	223	186	163	139	98	2105
	±86	±85	±69	±117	±83	±74	±59	±75	±67	±39	±61	±61	±346
13	87	111	136	262	267	214	209	218	157	152	121	87	2021
	±71	±86	±69	±111	±91	±63	±65	±51	±63	±49	±60	±55	±287
16	88	108	133	260	279	213	214	225	161	153	120	83	2036
	±72	±82	±71	±113	±97	±64	±64	±60	±62	±51	±57	±56	±313
						Rain Days							
14	12	13	15	23	26	23	22	24	21	24	18	13	233
	±7	±7	±5	±3	±3	±4	±5	±3	±5	±3	±4	±6	±25
13	11	12	15	22	26	24	25	26	22	23	18	14	240
	±7	±7	±6	±4	±3	±4	±3	±3	±5	±3	±4	±4	±13
					Streamflow (mm)								
14	43	27	25	39	90	85	92	93	101	77	61	55	789
	±31	±12	±10	±22	±65	±36	±47	±53	±46	±35	±23	±33	±265
13	31	22	24	42	115	104	106	105	99	64	50	43	806
	±21	±12	±19	±30	±97	±52	±55	±52	±42	±33	±25	±29	±296
16	32	23	22	38	109	96	104	110	104	68	51	41	797
	±19	±11	±12	±26	±105	±55	±55	±52	±47	±39	±22	±20	±224
					Penman EO (mm)								
	153	138	155	114	105	106	105	110	116	118	118	137	1476
	±19	±22	±18	±16	±8	±11	±8	±8	±9	±11	±15	±17	±47

TABLE VI

Calendar Year Totals of Rainfall minus Streamflow and of EO

Year	R-Q (mm)			EO (mm)
	14	13	16	
1958	1642	1540	-	1481
1959	1556	1433	-	1461
1960	1541	1331	-	1467
1961	1689	1372	-	1468
1962	1344	1175	1183	1512
1963	1438	1266	1274	1420
1964	1119	1097	1106	1439
1965	1273	1294	1299	1468
1966	975	1227	1241	1523
1967	1445	1310	1376	1540
1968	1272	1165	1127	1392
1969	1178	1157	1194	1506
1970	1572	1279	1349	1434
1971	1390	1127	1181	1495
1972	1473	1275	1323	1464
1973	1317	1208	1219	1519
1958-73				
Total	22224	20256	-	23587
Mean	1389	1266	-	1474
SD	±196	±117	-	±40
1962-73				
Total	15796	14580	14872	17710
Mean	1316	1215	1239	1476
SD	±167	±71	±86	±47

concerning possible storage errors, these indicate that the difference in water use was not great at any time, but reached its maximum during the clearing and planting phase when water use by the experimental catchment was some 14% lower. In the final phase when the tea estate, covering 5~~2~~4% of Sambret, was at or close to maturity, the water use was still marginally lower than that of the forested catchment. To determine whether the differences illustrated in Table VII derive from the partial land use change or from some other cause, it is useful to compare water use by the bamboo covered sub-catchment (catchment 16) with that from the control over the same periods. Since catchment 16 was not fully instrumented until 1961, data for only part of the clearing and planting is available. Table VII(b) demonstrates that water use by 16 did, in fact, fluctuate relative to 14 in a similar way to the complete Sambret catchment. This suggests that the water use differences evident in Table VII(a) cannot be attributed simply to the effect of the partial land use change. Indeed, the fluctuations in relative water use between control and experimental catchments could be due to variations in the control. Evidence for this is contained in Table VIII where 'crude' water use figures from all three catchments are compared with Penman EO for the periods in question. As can be seen, the variation of this ratio is greater for the control catchment than for either of the others. A more detailed investigation of the data is necessary to clarify this variability in the control catchment.

These 'crude' estimates of water use demonstrate that no major change in long term water use, and hence in water yield, was brought about by the conversion of 5$\overset{4}{2}$% of Sambret to tea estate. From the later stages of planting onwards, long term water use by Sambret was 83% of Penman EO. Water use by the bamboo sub-catchment was 84% of Penman over this period whereas that of the forested catchment was close to 90%.

TABLE VII

Comparison of Total Water Use in each phase of the Land Use Change on Sambret (13)

(a) Between Sambret and the control catchment (14).

(b) Between the bamboo covered subcatchment of Sambret and the control.

Period	Sambret Status	R-Q			Difference		
		(a)					
		13	(mm)	14	(mm)	13-14	(%14)
1958-59	Undisturbed	2973		3198	-225		-7.0
1960-63	Clearing and planting	5144		6012	-868		-14.4
1964-67	Establishment	4928		4812	+116		+2.4
1968-73	Mature tea estate	7211		8202	-991		-12.1
		(b)					
		16	(mm)	14	(mm)	16-14	(%14)
1962-63		2457		2782	-325		-11.7
1964-67		5022		4812	+210		+4.4
1968-73		7393		8202	-809		-9.9

TABLE VIII

Comparison of R-Q with Penman EO for the Periods defined in Table VII

Period		(R-Q)/EO	
	13	16	14
1958-59	1.01	-	1.09
1960-63	0.88	-	1.02
(1962-63)	(0.83	0.84	0.95)
1964-67	0.83	0.84	0.81
1968-73	0.82	0.84	0.93

COMPARISON OF WATER YEAR DATA

To obtain more precise estimates of catchment water use over shorter time intervals, it is necessary to utilise such data as are available on changes in storage. Since it is practical to estimate changes in groundwater storage using the empirically derived recession curves (Figure 6) only during periods of low flow, Table V indicates that intervals of approximately one year between successive December-March dry seasons are the shortest practical intervals. Dagg and Blackie (1965) and Blackie (1972) used a water year based on mid-February. Because of the evidence of dry season moisture abstraction from beyond the regularly sampled depth in the soil profile discussed earlier, the intervals used in this presentation are not precisely of one year's duration. The start of each interval is determined by the following criteria.

(a) The baseflow is as close as possible to the same value in a well-defined recession situation and is within the range covered by the appropriate curve in Figure 6.

(b) The catchment mean soil moisture deficit is reasonably precise and the profile plots show no indication of moisture abstraction from beyond the depth of measurement.

The application of these criteria, with the further restrictions imposed by the dates of soil moisture sampling and their differences between catchments, resulted in the definition of the intervals shown in Tables IX, X and XI. For subsequent reference, comparable intervals in each catchment have been given the same water-year reference number.

Before discussing the content of these tables, it is necessary to explain why the so-called calibration period

TABLE IX

Water Use Estimates, AE, for the Control Catchment 14

Water Year Ref No	Starting Date	Rain mm	Flow mm	ΔS mm	ΔG mm	AE mm	EO mm	AE/EO
0								
	201260							
1		2727	1040	-89	-4	1780	1791	0.99
	200262							
2		2080	916	+114	+4	1046	1066	0.98
	211162							
3		1843	582	+46	+4	1211	1199	1.01
	200963							
4		2450	1013	-55	+6	1486	1691	0.88
	211164							
5		1507	269	+69	-3	1172	1481	0.79
	201165							
6		1560	622	-172	+3	1107	1321	0.84
	211066							
7		2367	851	+23	-10	1503	1981	0.76
	190168							
8		2230	1014	+118	+16	1082	1118	0.97
	161168							
9		1581	478	-6	-3	1112	1166	0.95
	030969							
10		2840	1129	+2	-6	1716	1806	0.95
	021270							
11		2199	944	+16	-12	1251	1383	0.90
	041171							
12		2388	775	+10	+15	1589	1698	0.94
	281272							
13		1926	614	-12	0	1324	1275	1.04
	021173							
Total 1-13		27698	10247	+64	+10	17379	18976	0.92

TABLE X

Water Use Estimates, AE, for the Experimental Catchment 13

Water Year Ref No	Starting Date	Rain mm	Flow mm	ΔS mm	ΔG mm	AE mm	EO mm	AE/EO
	161059							
0		2538	1059	-34	0	1513	1683	0.90
	131260							
1		2547	1113	+39	+24	1371	1759	0.78
	100262							
2		2260	1212	+4	-27	1071	1214	0.88
	111262							
3		1908	857	+21	-3	1033	1209	0.85
	111063							
4		2419	1075	-17	+27	1334	1555	0.86
	101164							
5		1591	306	-32	-27	1344	1596	0.84
	101265							
6		1718	571	+12	+27	1108	1205	0.92
	101066							
7		2457	1012	-9	-17	1471	1978	0.74
	100168							
8		1932	837	+36	-7	1066	1163	0.92
	151168							
9		1388	324	-25	+3	1086	1282	0.85
	200969							
10		2383	984	-12	-7	1418	1699	0.83
	031270							
11		1993	912	+18	+7	1056	1366	0.77
	021171							
12		2163	794	-3	-3	1375	1705	0.81
	271272							
13		1767	615	-66	0	1218	1272	0.96
	311073							
Total 0-13		29064	11671	-68	-3	17464	20686	0.84

TABLE XI

Water Use Estimates, AE, for the Bamboo Sub-Catchment 16

Water Year Ref No	Starting Date	Rain mm	Flow mm	ΔS mm	ΔG mm	AE mm	EO mm	AE/EO
0		–	–	–	–	–	–	
1		–	–	–	–	–	–	
	100262							
2		2280	1240	-2	-31	1069	1214	0.88
	111262							
3		1975	931	-32	+9	1067	1209	0.88
	111063							
4		2468	1087	-43	+27	1311	1555	0.84
	101164							
5		1547	274	-5	-56	1334	1596	0.84
	101265							
6		1708	545	-28	+56	1135	1205	0.94
	101066							
7		2508	998	-15	-32	1557	1978	0.79
	100168							
8		1844	863	+70	+5	906	1017	0.89
	071068							
9		1504	335	-16	-10	1195	1429	0.84
	300969							
10		2496	1011	-55	-15	1525	1699	0.90
	031270							
11		1945	807	-2	-5	1141	1366	0.84
	021171							
12		2065	674	-27	-5	1393	1705	0.82
	271272							
13		1798	622	-64	0	1240	1272	0.97
	311073							
Totals 2-13		24158	9387	-75	-27	14873	17245	0.86

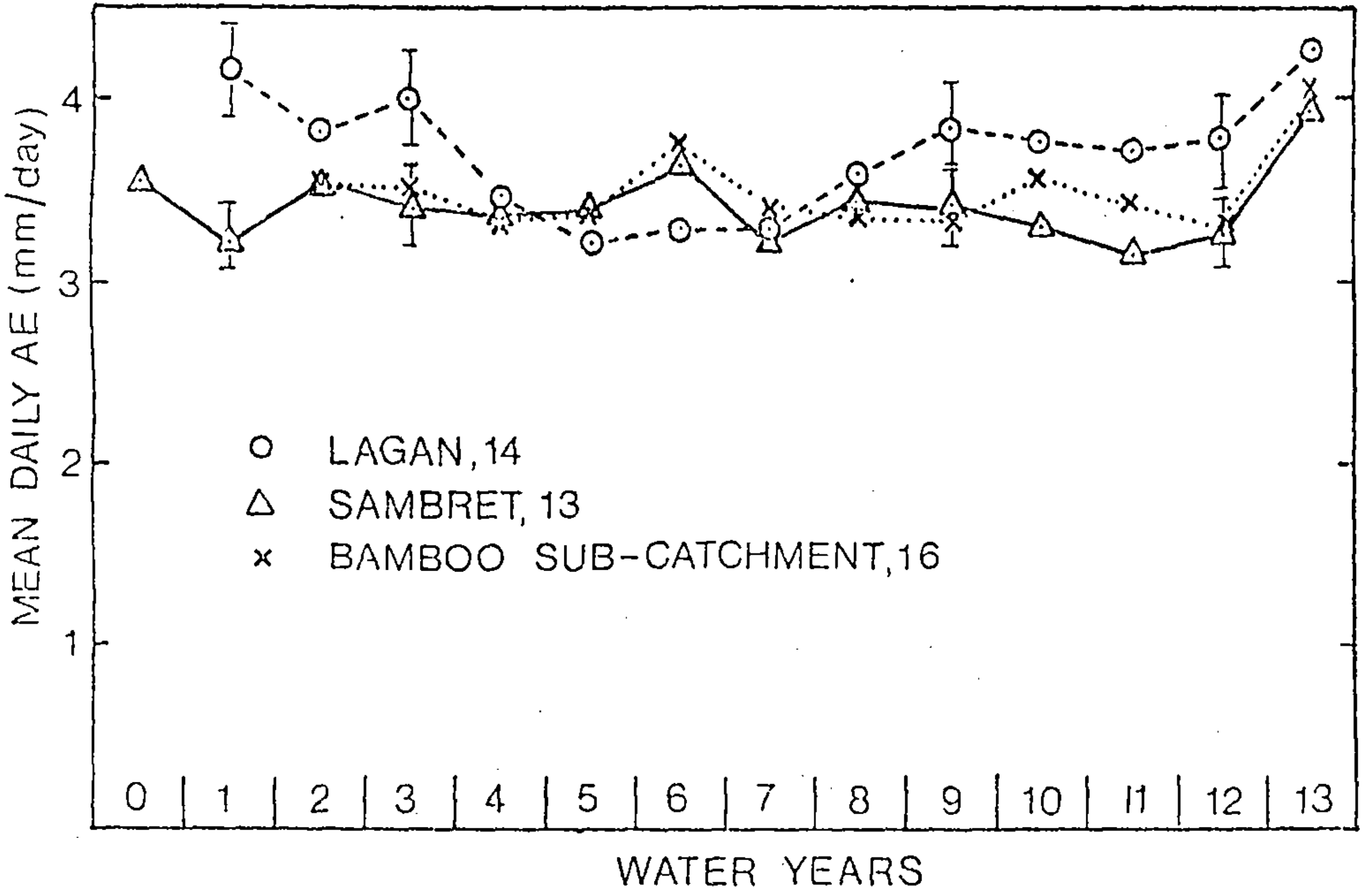


Figure 7 Mean daily water use from each catchment

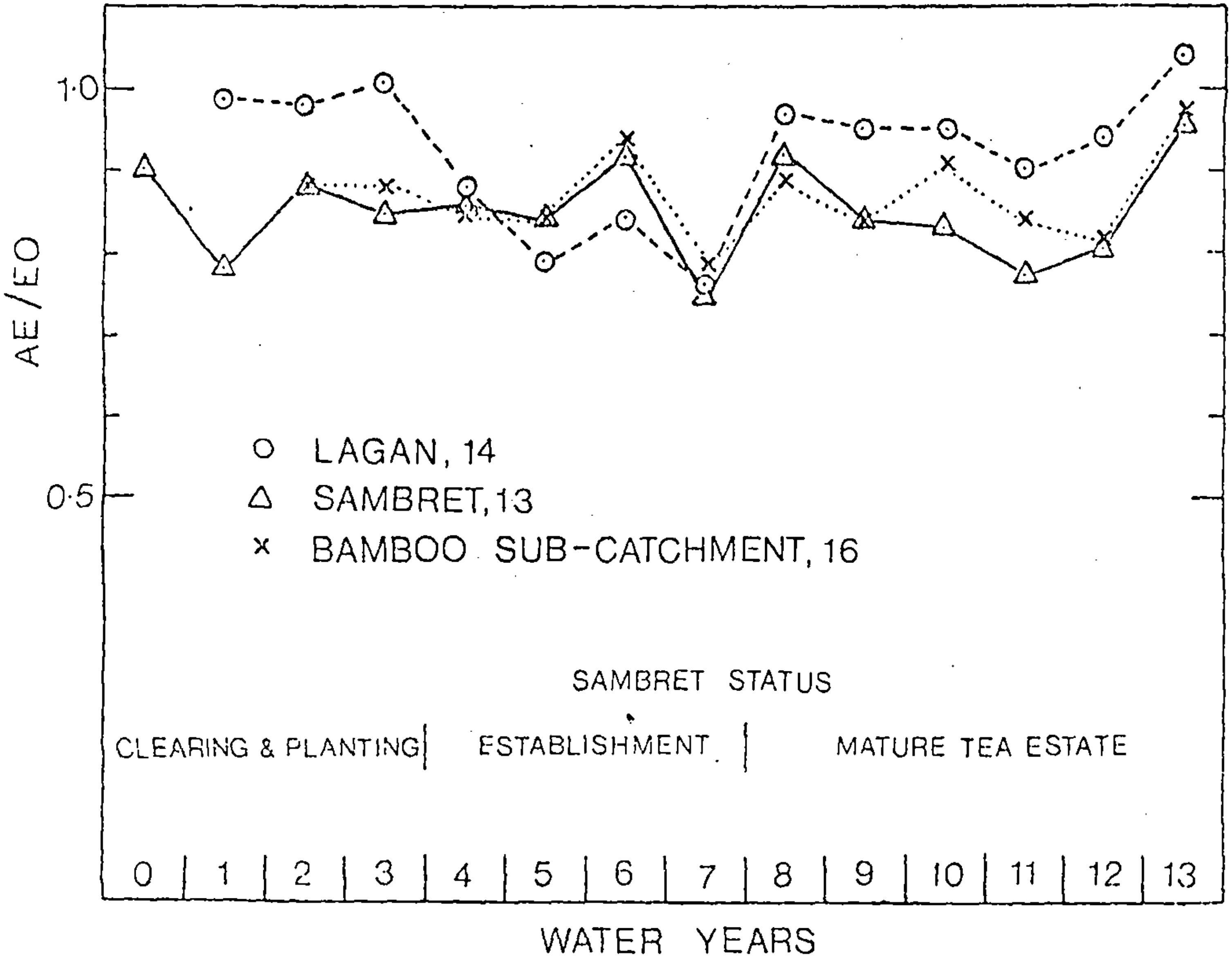


Figure 8 Water year AE/EO ratios from each catchment

AE, and of $^{AE}/EO$, is greater for Lagan than for the other catchments. Although water use by Sambret was lower than that of Lagan during the clearing and planting phases, comparison with 16, and with the Sambret values during the mature phase from period 8 onwards, suggests that the initial stages of the land use change resulted in no significant reduction of water use in the conditions existing in this area. In considering this result, the progressive nature of the clearing and planting operation must be borne in mind. The maximum area of bare soil exposed at any time was only 17% of the catchment, and that occurred only for a short period in 1960 (period 0). As soon as each area was prepared for planting, a partial vegetation cover of oats was established on it. Even under bare soil conditions, the frequency of wetting indicated by Table IV would ensure that appreciable evaporative loss would still occur.

The water-year figures for periods 8 to 13 bear out the conclusion from the long-term figures that the presence of a mature tea estate within the catchment does not significantly increase water use relative to either type of indigenous vegetation. The year to year variations in water use and in its ratio to Penman EO indicate that quantification of the results of this study for extrapolation in time or spatially presents a complex problem.

INTERPRETATION OF THE WATER BALANCE RESULTS

From Figures 7 and 8 it can be seen that variations in AE relative to EO are much smaller in catchments 13 and 16 than in 14. Bearing in mind the uncertainties in AE and the 5-10% uncertainty in EO, acceptable first estimates of water-year or annual water use are obtained for 13 and 16 by applying the mean Penman factors given in Tables X and XI, except in period 13. This applies to the clearing, planting and transition stages in Sambret as well as to the later mature state. For the forested Lagan, however, the use of the mean factor in Table IX would give less accurate estimates.

To produce better methods of predicting water use, it is necessary to establish why the variations, in 14 in particular, are present in the results. This basically requires studies of the hydrological processes operating, but in their absence, some indications can be obtained from the water balance results and from conceptual modelling.

Figure 9 demonstrates the general similarity in trend and the departures in magnitude of the catchment rainfall inputs. Of the outputs, streamflow follows the trends in rainfall more closely than water use (Figure 7) in each case. Regression of streamflow on rainfall (Figure 10) reveals similar sensitivities in 13 and 16, but a much lower sensitivity in 14. Figure 11 demonstrates an upward trend in AE/EO with rainfall amount in both 14 and 13, but the sensitivity and precision of the relationship is greater for 14. Thus, the distribution of outputs between water use and streamflow is much more dependent on rainfall in 14 than in the other catchments.

Assuming, on the basis of the evidence given earlier, that this greater sensitivity is not due to systematic error in rainfall or flow measurement, then the most obvious interpretation is in terms of the processes governing water use.

Variations in relative water use between vegetation types subject to similar rainfall and meteorological regimes can arise from two major sources, namely the canopy interception-evaporative loss process and the control on transpiration exercised by soil moisture availability. In simple terms, the contribution to total water use by the interception process is determined by the saturation capacity of the vegetation canopy, the frequency of wetting and the loss rate. The latter will be much greater for an aerodynamically rough canopy such as forest than for the smoother canopies of bamboo and tea estate. Thus, variations in annual rainfall can be expected to have a greater effect on Lagan.

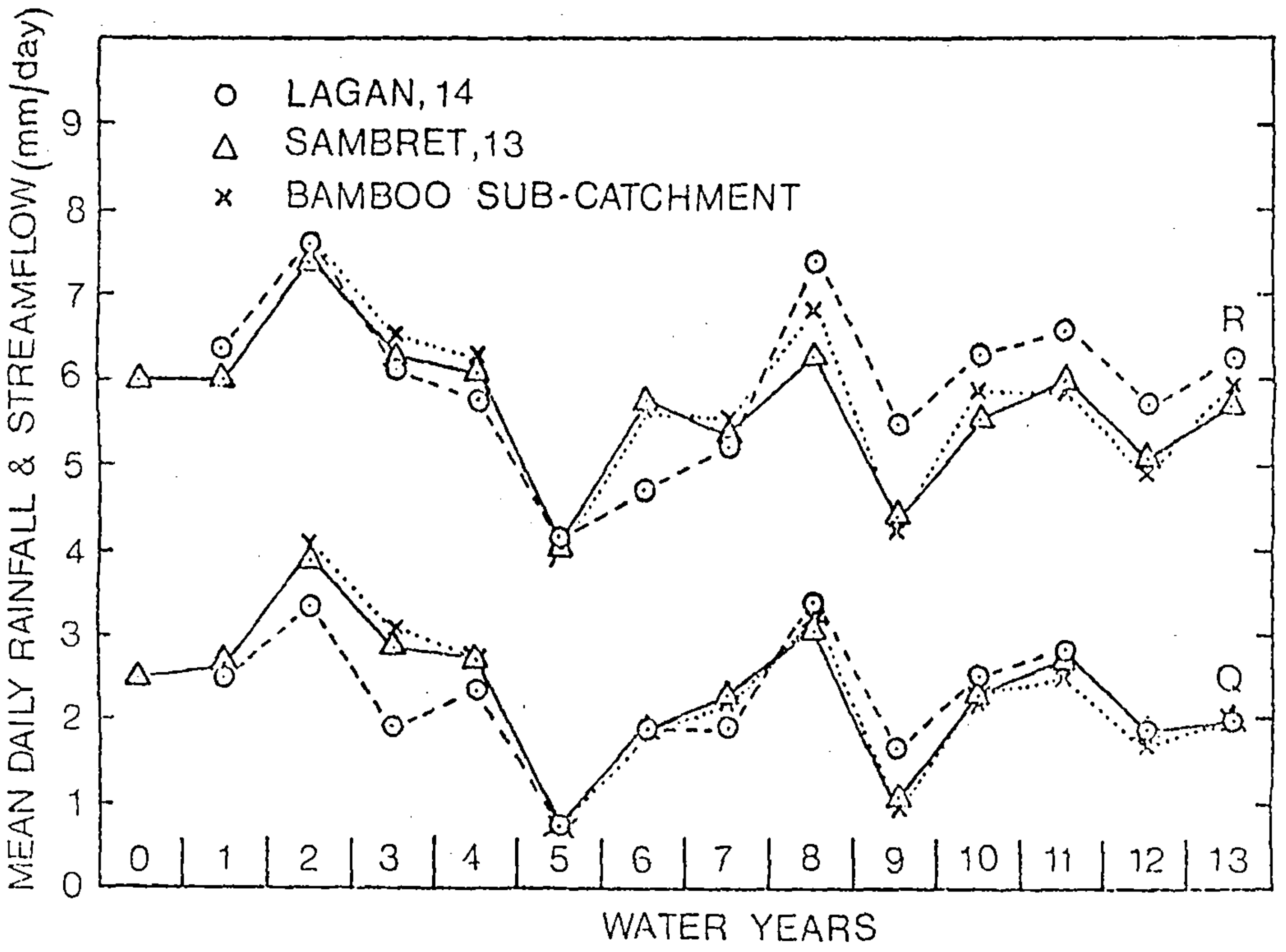


Figure 9 Mean daily rainfall and streamflow from each catchment

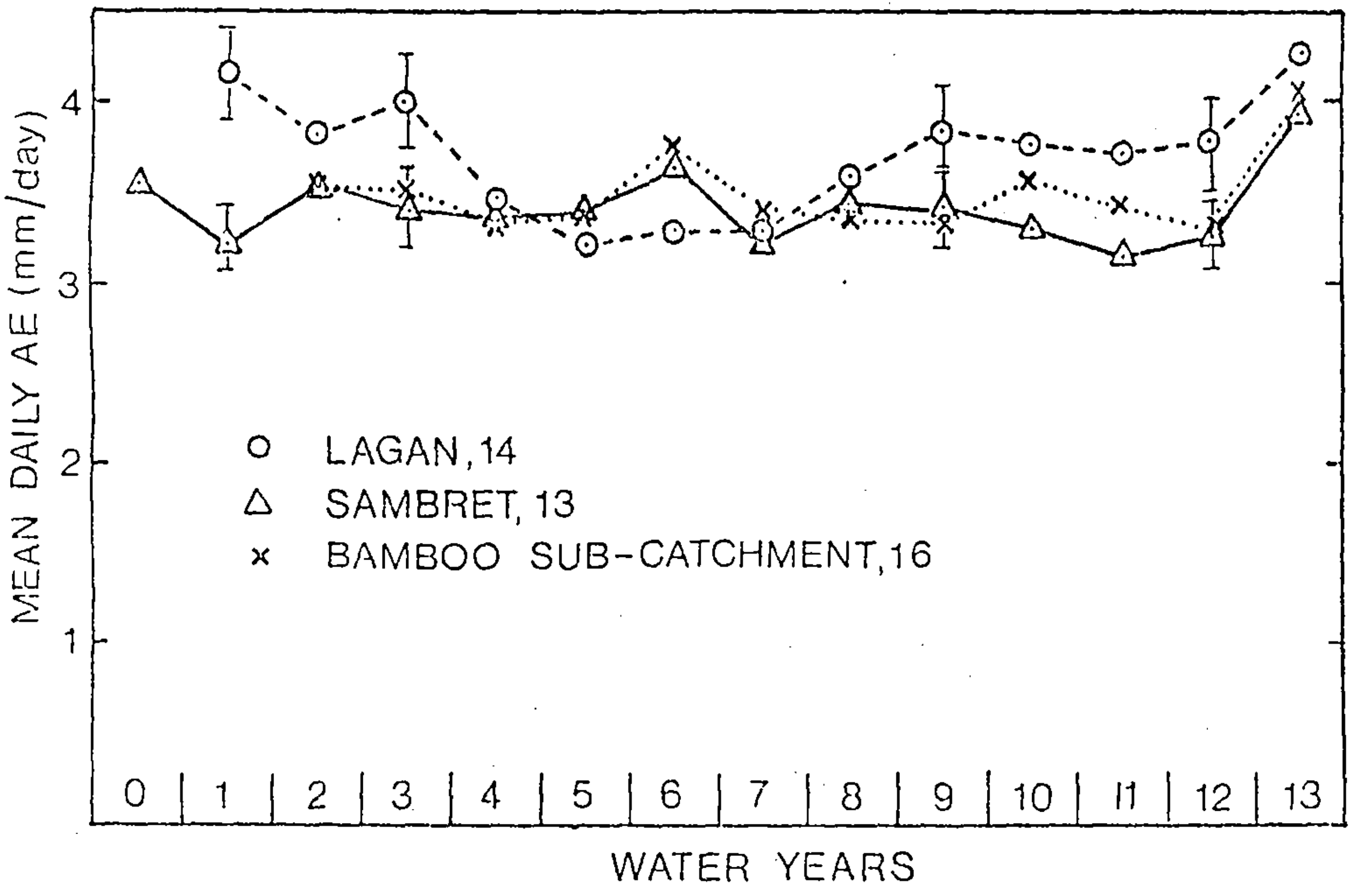


Figure 7 Mean daily water use from each catchment

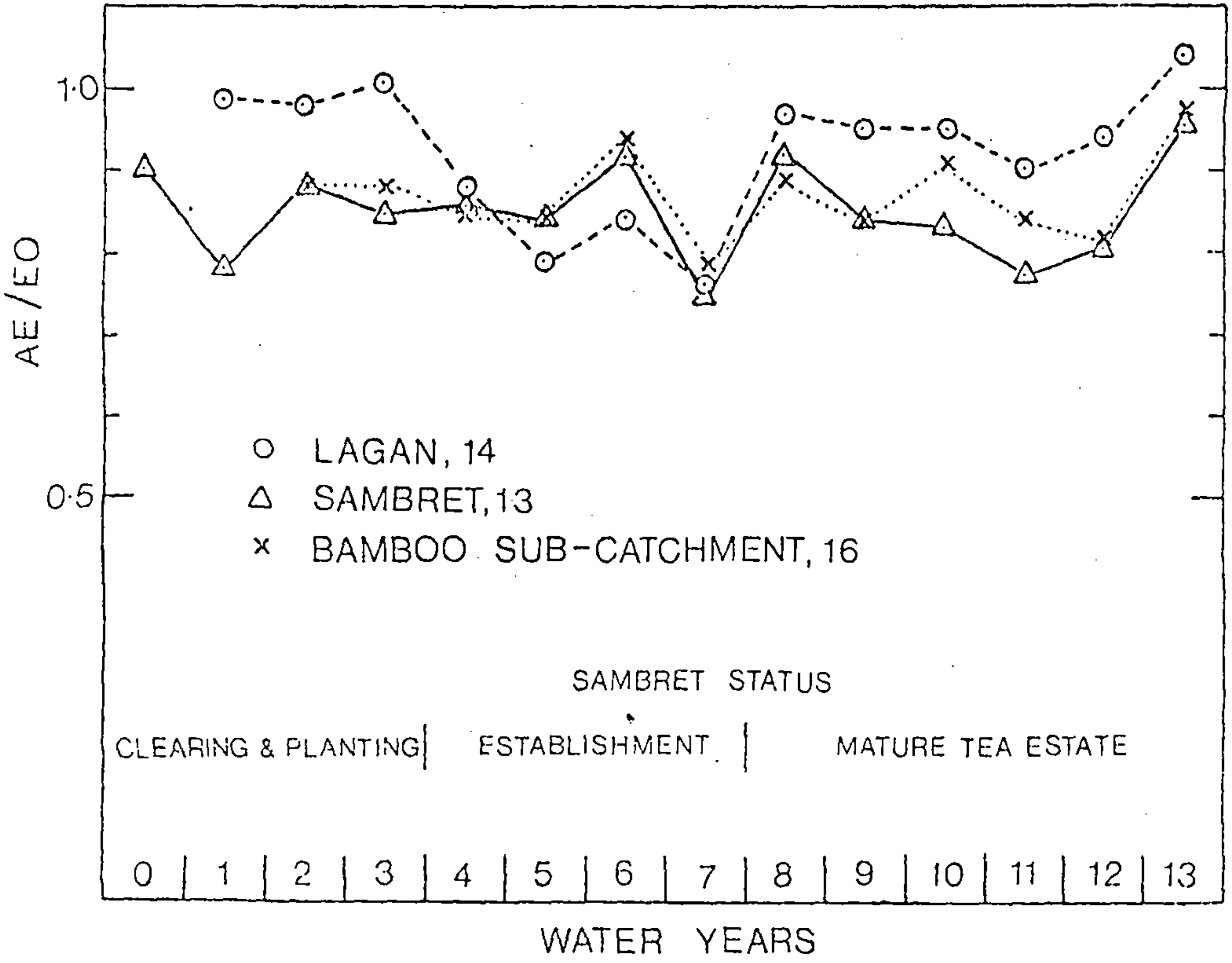


Figure 8 Water year AE/EO ratios from each catchment

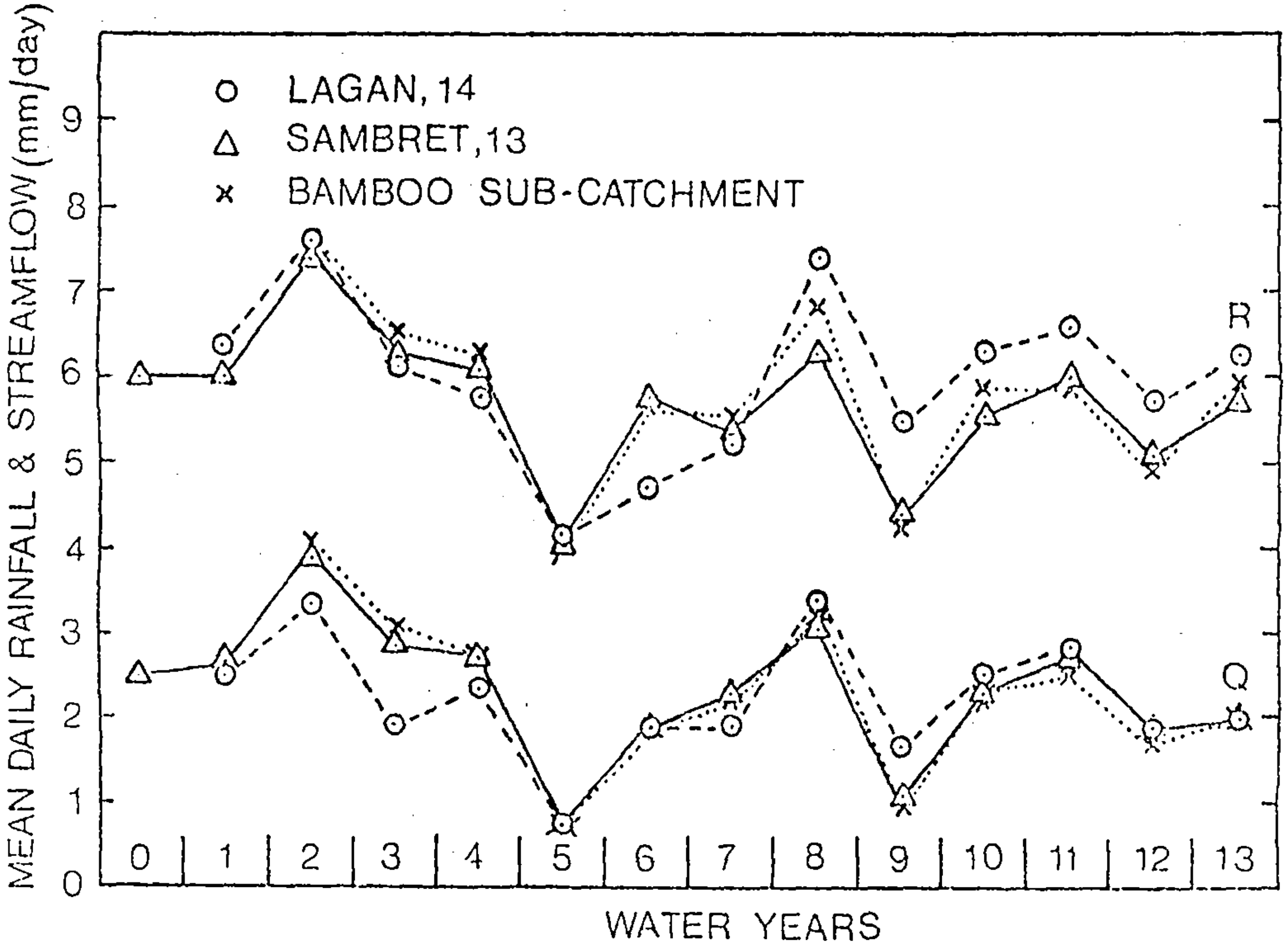


Figure 9 Mean daily rainfall and streamflow from each catchment

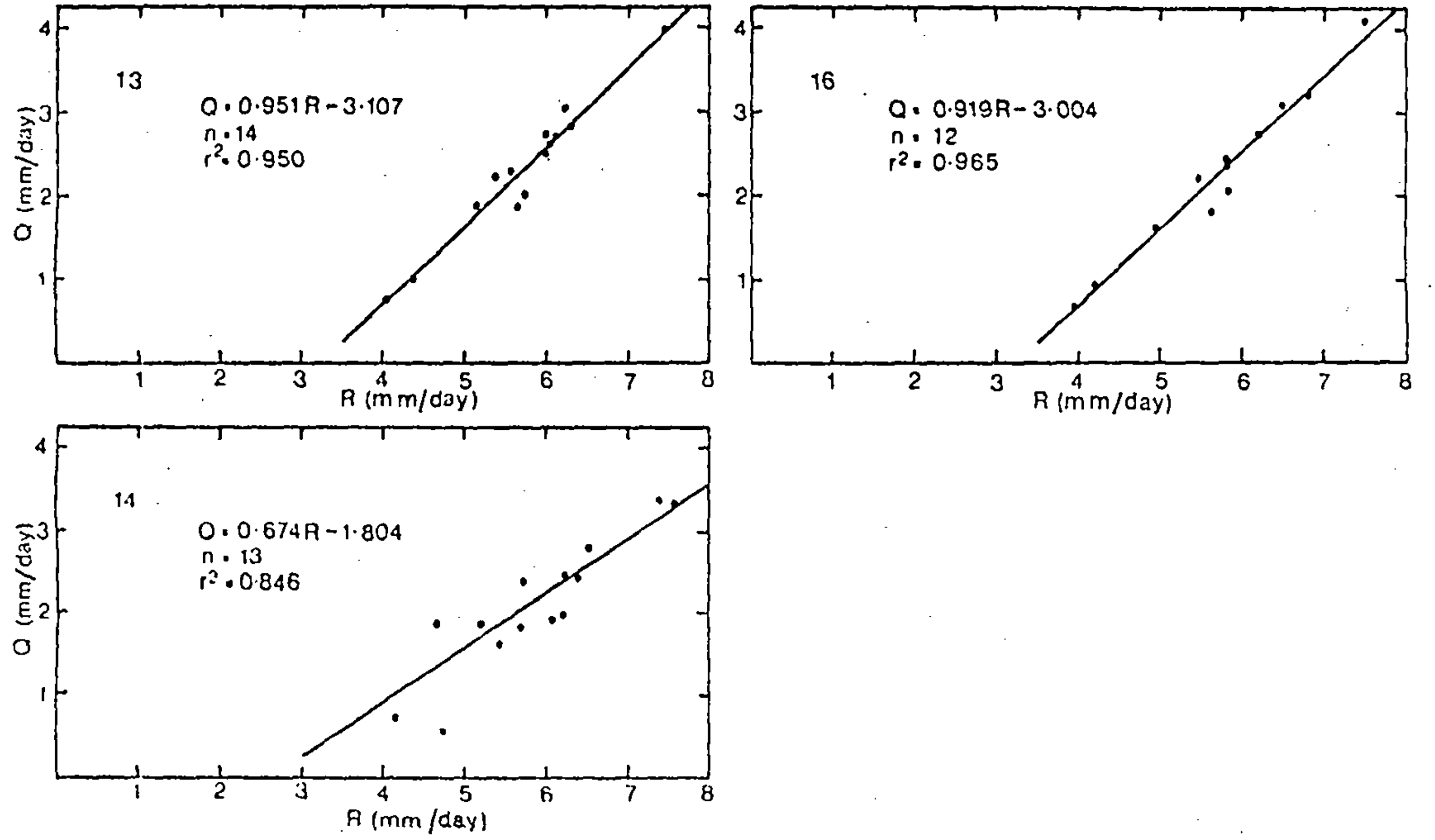


Figure 10 Plots of water year mean daily flow, Q, against mean daily rainfall, R, for catchments 13, 16 and 14

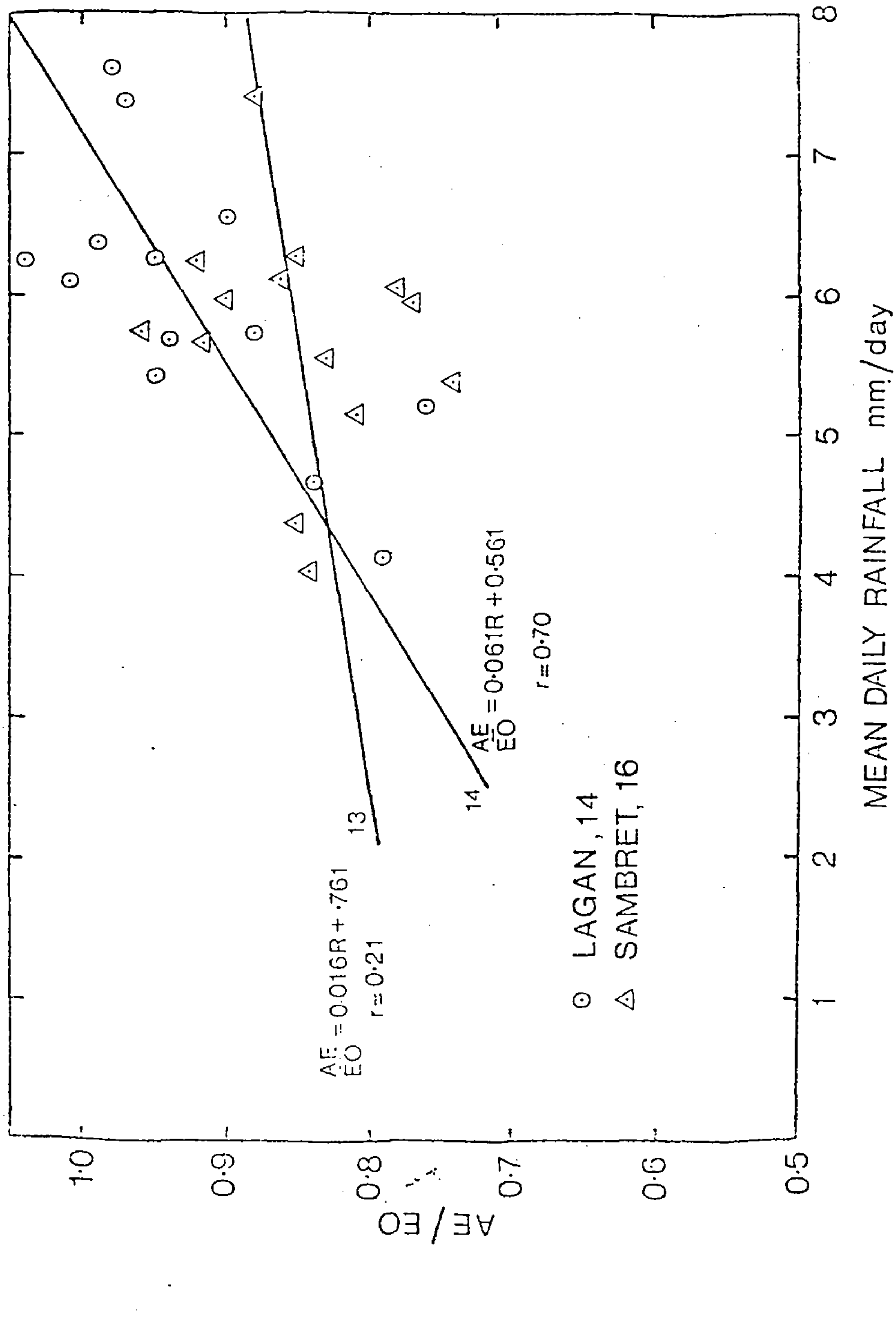


Figure 11 Regression of water year AE/EO ratios on rainfall

In Sections 2.2.2, 2.2.3 and 2.2.5 field determinations of short term transpiration from tea indicate no appreciable constraint until deficits of at least 150 mm are reached. Beyond this deficit the evidence is conflicting and inconclusive. For forest and bamboo also, the soil moisture data are inconclusive. In this context, however, it should be noted that the lowest water year $^{AE}/EO$ values for Sambret in Figure 8 occur in the water years 1, 7 and 11 containing the three most severe drought periods encountered. In all three, deficits in excess of 300 mm over the measured profile depth were recorded. Deficits were high also in periods 1 and 11 in Lagan, but there the greatest deficits recorded were in periods 5 and 7.

The water year totals offer some evidence to support the hypothesis that variability in water use is due to differences in the parameters governing the interception process and to deficit effects. These hypotheses are explored in more detail through the use of the IH conceptual model in the following paragraphs.

MODELLING

As indicated in Section 1.3, data from these catchments have proved extremely valuable in testing and developing lumped conceptual models and modelling techniques at the Institute of Hydrology (IH). In the following paragraphs selected aspects of this work are described. The results obtained by using versions of the IH model to test simple functional representations of the interception process and of the interaction between deficit and transpiration are summarised.

The IH model as described in Section 1.3 has as its ultimate objective the prediction of flow, given rainfall and Penman EO data. To reach this objective it has to predict water use and the timing of movement of the remaining water over or through the soil profile to form streamflow. Since water use is the larger of the two output terms in these catchments, high precision in its prediction is necessary if acceptable accuracy in the predicted flow values is to be achieved. Logically, therefore, the first stage was to determine the best functions to represent the catchment water use processes.

WATER USE MODELLING

Three approaches to water use modelling were attempted on these catchments. In the simplest, the factor model, water use was estimated as a constant multiple ($\equiv f \times EO$) of Penman's EO. This constant factor, f, was determined from the long term water year totals of AE and EO as:

$$f = \sum AE / \sum EO$$

The second approach involved the use of a functional relationship to represent the interception/evaporation process with a constant factor applied to EO to represent transpiration. In the absence of information from studies of interception in bamboo and forest, and with the constraint of a daily time interval, it was not possible to use detailed models of the process such as that proposed by Rutter et al (1972). Some initial work was done using a daily version of the Monteith expression described in Section 1.2.2, but this presented computational problems. Subsequently, a simple function utilising the existing daily Penman data was adopted. Using the terminology defined in Section 1.3, this water use model can be expressed as

$$\hat{AE} = \sum | FC \,.\, EVAP_i + CS_i \,(1 - {}^{FC}/_{FS}) |$$

where $EVAP_i$ and CS_i are the Penman EO and the contents of the interception store on day i. The store is recharged by rainfall to a maximum value, SS. Constant rates FS and FC, relative to EVAP, of evaporation from SS and of transpiration are assumed and, together with SS, are the parameters to be evaluated.

The third approach, described in Section 1.3, incorporates the above expression with the additional condition that FC is controlled by soil moisture deficit, DC, above a threshold value DCS. This relationship is represented as

$$FC^1 = 0.5 \left|\cos\left(\frac{DC - DCS}{DCR}\right) + 1\right| . FC$$

where DCS and DCR are parameters to be optimised.

These three approaches, referred to as the factor model, the water use model and the full model, were fitted to the bamboo catchment 16, and the forested catchment 14. The predictions of AE were compared objectively with the water balance determinations using as the objective function, F, the weighted variance

$$F = \sum \frac{(\hat{AE}_j - AE_j)^2}{N_j}$$

where N_j is the number of days in water year j. In optimising the parameters initial values derived from field observation or from the literature were used. Constraints were applied to hold the values within physically realistic ranges.

The optimum parameter values attained are listed in Table XII. Because a considerable measure of interdependence exists among the parameters, their physical interpretation must be approached with caution. They imply, however, that water use of the forest is more sensitive to interception than that of the bamboo and that FC^1 for bamboo starts from a much greater deficit.

Comparisons of the variance, F, obtained by using each model in prediction mode, and of the residuals are presented in Tables XIII and XIV. Table XIII indicates a large proportional decrease in variance when the water use model is used on 14 in place of the factor model; no improvement in prediction is achieved by using the full model. For catchment 16, both

TABLE XII

Optimum Parameter Values Attained Using (a) the Factor Model, (b) the Water Use Model (c) the Full Model

Parameters	14 (Forest)	16 (Bamboo)
	(a)	
F	0.92	0.86
	(b)	
SS	3.51	2.17
FS	6.33	4.74
FC	0.49	0.61
	(c)	
SS	3.51	2.17
FS	6.33	4.74
FC	0.53	0.61
DCS	27.3	147.3
DCR	158.8	101.0

TABLE XIII

Catchment 14 Water Use Modelling Using (a) the Factor Model, (b) the Water Use Model, and (c) the Full Model

Period	AE	(a)		(b)		(c)	
		$\hat{AE}$	δ	$\hat{AE}$	δ	$\hat{AE}$	δ
1	1780	1640	-140	1628	-152	1641	-139
2	1046	977	-69	1092	+46	1133	+87
3	1211	1098	-113	1129	-82	1172	-39
4	1486	1548	+62	1597	+111	1644	+158
5	1172	1357	+184	1225	+53	1234	+62
6	1107	1210	+103	1111	+4	1157	+50
7	1503	1815	+312	1682	+179	1670	+167
8	1082	1024	-58	1182	+100	1217	+135
9	1112	1068	-44	1022	-90	1069	-43
10	1716	1654	-62	1698	-18	1754	+38
11	1251	1267	+16	1266	+15	1284	+33
12	1589	1555	-34	1587	-2	1644	+55
13	1324	1168	-156	1167	-157	1208	-116
$\sum$	17379	17379		17384		17825	
F		561		332		339	

TABLE XIV

Catchment 16 Water Use Modelling Using (a) the Factor Model, (b) the Water Use Model, and (c) the Full Model

Period	AE	(a)		(b)		(c)	
		$\hat{AE}$	δ	$\hat{AE}$	δ	$\hat{AE}$	δ
1							
2	1069	1047	-22	1084	+15	1088	+19
3	1067	1042	-25	1049	-18	1052	-15
4	1311	1341	+30	1347	+36	1347	+36
5	1334	1377	+43	1313	-21	1269	-65
6	1135	1039	-96	1054	-81	1059	-76
7	1557	1706	+149	1651	+94	1575	+18
8	906	877	-29	939	+33	941	+35
9	1195	1232	+37	1192	-3	1194	-1
10	1525	1465	-60	1512	-13	1515	-10
11	1141	1178	+37	1185	+44	1166	+25
12	1393	1471	+78	1441	+48	1442	+49
13	1240	1097	-143	1101	-139	1103	-137
$\sum$	14873	14873		14870		14751	
F		189		125		109	

water-use and full models give a reduction in variance. Proportionally, the reduction achieved by the water use model relative to the factor model is less than in 14, indicating lower sensitivity to the transpiration process. Whilst the reduction in F due to the use of the deficit control function on 16 is small, the fact that it occurs almost entirely in the periods 7 and 11 having the most prolonged droughts is significant.

The improvements achieved in water use prediction by the inclusion of functions simulating the interception process, and, in the case of the bamboo, the deficit control of transpiration, indicate that these processes play a significant role in the total water use by these vegetation types. They account for a not inconsiderable part of the variation in the observed water use within each catchment. The above model-fitting results suggest also that they account for an appreciable part of the variation between catchments.

The residuals in Tables XIII and XIV can be interpreted either as an indication of model inadequacy or of data errors. Distinguishing between these two is not easy, but two features in the tables require comment. One is the sequence of positive values through periods 4 to 7 in catchment 14 present in all versions of the model. Whilst the magnitudes are reduced by the inclusion of the interception function, this sequence is unlikely to arise from random error and may indicate inadequacy in either rainfall or streamflow data through this period. The second is the uniform underestimate of water use by all models on both catchments in period 13. The measurement common to both catchments is Penman EO and the underestimate could be the result of systematic error in it, though none can be detected. A complicating factor in this unresolved problem is the fact that, as shown in Figure 7, the highest observed AE values in all three catchments occur in this period.

STREAMFLOW MODELLING

Details of the optimisation of the parameters in the functions controlling percolation and baseflow in the IH model are not relevant in the context of this paper, since each set of parameters is specific to the catchment on which it is optimised; these parameters are of value for within-catchment estimation of streamflow given rainfall and EO, but cannot be used for inter-catchment extrapolation of streamflow prediction. The surface runoff parameters are influenced by both catchment characteristics and land use. The values of the parameter RC, controlling the volume of runoff, achieved on 16, 14 and 13 in the post-clearing period were comparable and resulted in volume predictions in the range 1-2% of the annual rainfall, in agreement with the results quoted by [illegible] ([illegible])

Obviously, cumulative error in the water-use prediction results in comparable volume errors in predicted flow. Nevertheless, the optimised version of the IH model, incorporating the full model water-use functions with the parameter values listed in Table XII, predicted total flow from catchment 16 for the period from February 1961 to June 19~~6~~74 with an error of + 0.6% and an overall efficiency on daily values of 95%. For 14, the comparable figures for the period December 1960 to June 1974 were -3.8% and 91%. Plots of the monthly values of the cumulative error in each of these prediction runs are presented in Figure 12. The catchment 14 plot demonstrates the effect of the cumulative overestimate of water use through 1964-68 (periods 4-7) discussed above. Whilst the use of the optimised interception and deficit functions have reduced the errors in flow prediction, the trend in those remaining suggests underestimates of rainfall as a possible explanation. It is noteworthy that the period in question includes the 3 years with coefficients of variation of annual rainfall nearly twice those for the rest of the data run (Section 1.2.1).

EXTRAPOLATION OF RESULTS

The results of experimental catchment studies or of detailed

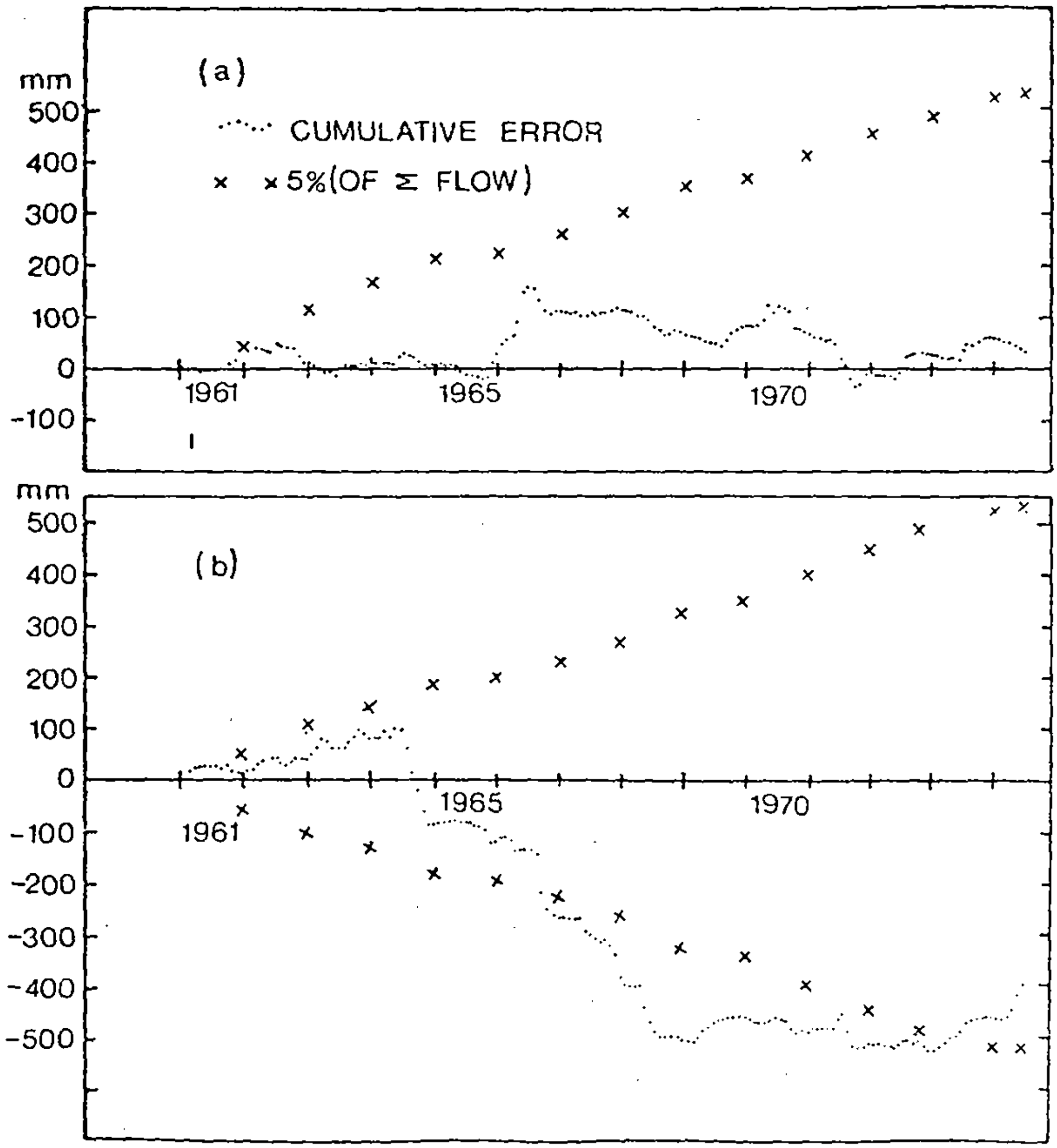


Figure 12 Cumulative error in flow prediction by the IH model on (a) catchment 16, (b) catchment 14

process studies are of scientific interest in themselves, but become of practical value only when they can be used to estimate vegetation water use or catchment streamflow at some other time, in some other place, or in some prescribed set of conditions. The practical requirement, in short, is that the results must be incorporated into a predictive model.

A lumped catchment model designed to predict short term flows is a valid model for extrapolation in time, but can be used for extrapolation in space only if sufficient data exist in the new location to re-optimise those parameters which are catchment specific. Provided the requirement is for extrapolation of water use data for a specific crop, however, then a lumped water use model such as that described above becomes a practical proposition. Ideally, the functions and their parameters should be derived from process studies, but optimisation may be adequate provided the parameters do not incorporate bias derived from the catchment data used in the optimisation.

As a practical test of the validity of the water use model described above and the parameters optimised for bamboo and forest, an attempt was made to use it to predict water use from Sambret. In addition to those for bamboo and forest, listed in Table XII, parameter values of FC, FS and SS were required for tea. Values of FC of 0.56 and SS of 2.5 mm were obtained from the process study described in Section 2.2.3 and used with various data to estimate a value for $\overset{s}{\text{FW}}$ of 3.3. Each set was then applied to the Sambret rainfall and the Penman EO, and the predicted AE values were finally combined in the ratio of tea estate, forest and bamboo cover in the catchment, ie 54%, $\overset{15\%}{26\%}$ and $\overset{35\%}{20\%}$. The results obtained are compared in Table XV with the water year AE values and with the results of using the simple factor model, in which f values of 0.84, 0.92 and 0.86 for tea, forest and bamboo were combined in the same area ratio. As can be seen, the residuals are comparable in magnitude to those in Tables XIII and XIV and the variance is less than for the factor model.

TABLE XV

Predictions of Sambret Water Use, AE, from (a) the Factor Model using Long Term Totals, (b) the Factor Model using Vegetation Area Proportioned Factors and (c) the Water Use Model Similarly Proportioned

Period	AE	(a)		(b)		(c)	
		$\hat{AE}$	δ	$\hat{AE}$	δ	$\hat{AE}$	δ
6	1108	1017	-91	1038	-70	1051	-57
7	1471	1670	+199	1704	+233	1647	+176
8	1066	982	-84	1002	-64	1079	+13
9	1086	1082	-4	1104	+18	1060	-26
10	1418	1434	+16	1463	+45	1507	+89
11	1056	1153	+97	1176	+120	1187	+131
12	1375	1439	+64	1469	+94	1436	+61
13	1218	1074		1095	-123	1101	-117
Σ	9798	9852		10051		068 10~~102~~	
F		243		267		205 ✓	

It appears, therefore, that reasonable precision can be obtained by this type of model, provided no bias exists in the available data at fitting or predicting sites and provided the climatic conditions at both sites are similar.

SEASONAL FLOW DISTRIBUTION

The effects of a land use change on the seasonal distribution of flow may also be critical. At Kericho only small differences observed were between the mean monthly flows from Sambret and Lagan (Table V). Furthermore, the pre-treatment calibration coincided with a particularly dry period, ~~so that~~ the conventional within and between catchment comparisons of long term means before and after the land use change were not feasible. [illegible] In seeking causes Observed ~~for what~~ differences ~~were observed possible contribution factors were investigated~~. [illegible]

[illegible]

Seasonal rainfall distribution and the storage discharge characteristics of the catchment groundwater aquifer are independent of land use, whilst both control of surface runoff and seasonal distribution of aquifer recharge can be influenced by it. Whilst the small differences in mean monthly rainfall (Table V) undoubtedly contribute to the differences in flow distribution, they cannot account for the more rapid rise and higher level of flow from Sambret in the early part of the rains. Indirect evidence of the effects of aquifer discharge characteristics, in the form of composite baseflow recession curves (Figure 6), indicates that catchment geometry is at least partly responsible for these differences. ~~in flow in the early rains.~~ After a short lived increase during clearing and planting, surface runoff from Sambret quickly returned to the same negligibly small level as that ~~those~~ from the forest as the tea became established (Blackie, 1972). Consequently, the seasonal flow differences do not arise from any loss of surface runoff control. On catchments with similar soils and rainfall distribution, time variations in aquifer recharge can arise from differences in the water use processes. Interception losses from tea have been shown to be lower than from forest, implying more rapid recharge, [illegible] transpiration losses are higher, implying a shorter duration of recharge. The balance between these differing land use effects depends on rainfall distribution, but the net effect at Kericho is some accentuation of the seasonal range of flow from tea.

Hence the small differences in seasonal flow distribution observed at Kericho do not arise from any increase in surface runoff from the tea. Recharge in the aquifer may well be modified by the land use change, but its effect is confounded by differences in catchment geometry and in rainfall distribution.

SEASONAL FLOW DISTRIBUTION

The effects of a land use change on the seasonal distribution of flow may also be critical. At Kericho only small differences were observed between the mean monthly flows from Sambret and Lagan (Table V). Furthermore the pre-treatment calibration coincided with a particularly dry period, the conventional within and between catchment comparisons of long-term means before and after the land use change were not feasible, and the reasons for the observed differences had to be investigated indirectly.

Of the possible contributing factors, seasonal rainfall distribution and the storage discharge characteristics of the catchment groundwater aquifer are independent of land use, whilst both control of surface runoff and seasonal distribution of aquifer recharge can be influenced by it. The small differences in mean monthly rainfall (Table V) undoubtedly contribute to the differences in flow distribution, but they cannot account for the more rapid rise and higher level of flow from Sambret in the early part of the rains. Indirect evidence of the effects of aquifer discharge characteristics, in the form of composite baseflow recession curves (Figure 6), indicates that catchment geometry is at least partly responsible for these differences. After a short lived increase during clearing and planting, surface runoff from Sambret quickly returned to the same negligibly small level as that from the forest as the tea became established (Blackie, 1972). Consequently, the seasonal flow differences do not arise from any loss of surface runoff control. On catchments with similar soils and rainfall distribution, time variations in aquifer recharge can arise from differences in the water use processes. Interception losses from tea have been shown to be lower than from forest, implying a shorter duration of recharge. The balance between these differing land use effects depends on rainfall distribution, but the net effect at Kericho is some accentuation of the

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seasonal range of flow from tea.

Hence the small differences in seasonal flow distribution observed at Kericho do not arise from any increase in surface runoff from the tea. Recharge to the aquifer may well be modified by the land use change, but its effect is confounded by differences in catchment geometry and in rainfall distribution.

Suggested addition to SI, section 2.2.1

JMS 19/10/78

JCDC 20/10/78

SEASONAL FLOW DISTRIBUTION

Whilst the effects of a land use change on annual water use, and hence on water yield, are of critical interest, any modification of the seasonal distribution of flow is also important to the downstream user. At Kericho it was not possible to use the normal technique of within catchment and between catchment comparison of long term means before and after the land use change to quantify differences in seasonal flow distribution. ~~Instead, the causes of the~~ small observed differences in mean monthly flows from Sambret and Lagan (Table V) ~~were sought by consideration of the information available on possible contributing factors~~.

[illegible]

These factors comprise seasonal rainfall distribution, the storage discharge characteristics of the catchment groundwater aquifer, surface runoff control and the seasonal distribution of aquifer recharge. Of these, the first two are independent of land use whilst both surface runoff and aquifer recharge can be influenced by it. Whilst the small differences in mean monthly rainfall (Table V) undoubtedly contribute to the differences in flow distribution they cannot account for the more rapid rise and higher level of flow from Sambret in the early part of the rains. Indirect evidence of the effects of aquifer discharge characteristics, in the form of composite baseflow recession curves (Figure 6), indicates that catchment geometry is at least partly responsible for the early rains differences in flow. Blackie (1972) has shown that, after a short lived increase during clearing and planting, surface runoff from Sambret quickly returned to the same negligibly small levels as from the forest as the tea became established. Consequently the flow differences do not arise from any loss of surface runoff control. On catchments with similar soils and rainfall distribution, time variations in aquifer recharge can arise from differences in the water use processes. In the detailed discussion of these processes it has been shown that interception losses from tea are lower than from forest, implying more rapid recharge, and that transpiration losses are higher, implying a shorter duration of recharge. The balance between these land use effects will depend on rainfall distribution, but the net effect at Kericho will be some accentuation of the seasonal range of flow from tea.

In summary therefore it can be stated that the small observed differences in seasonal flow distribution at Kericho do not arise from any increase in surface runoff from the tea. The effect of the land use change on aquifer recharge ~~may be a contributory factor~~ but its magnitude is confounded by the in catchment geometry and rainfall distribution. ~~differences.~~

SEASONAL FLOW DISTRIBUTION

Whilst the effects of a land use change on annual water use, and hence on water yield, are of critical interest, any modification of the seasonal distribution of flow is also important to the downstream user. At Kericho it was not possible to use the normal technique of within catchment and between catchment comparison of long term means before and after the land use change to quantify differences in seasonal flow distribution. Instead, the causes of the small observed differences in mean monthly flows from Sambret and Lagan (Table V) were sought by consideration of the information available on possible contributing factors.

These factors comprise seasonal rainfall distribution, the storage discharge characteristics of the catchment groundwater aquifer, surface runoff control and the seasonal distribution of aquifer recharge. Of these, the first two are independent of land use whilst both surface runoff and aquifer recharge can be influenced by it. Whilst the small differences in mean monthly rainfall (Table V) undoubtedly contribute to the differences in flow distribution they cannot account for the more rapid rise and higher level of flow from Sambret in the early part of the rains.
Indirect evidence of the effects of aquifer discharge characteristics, in the form of composite baseflow recession curves (Figure 6), indicates that catchment geometry is at least partly responsible for the early rains differences in flow. Blackie (1972) has shown that, after a short lived increase during clearing and planting, surface runoff from Sambret quickly returned to the same negligibly small levels as from the forest as the tea established. Consequently the flow differences do not arise from any loss of surface runoff control. On catchments with similar soils and rainfall distribution time variations in aquifer recharge can arise from differences in the water use processes. In the detailed discussion of these processes it has been

shown that interception losses from tea are lower than from forest, implying more rapid recharge, and that transpiration losses are higher, implying a shorter duration of recharge. The balance between these land use effects will depend on rainfall distribution, but the net effect at Kericho will be some accentuation of the seasonal range of flow from tea.

In summary therefore it can be stated that the small observed differences in seasonal flow distribution at Kericho do not arise from any increase in surface runoff from the tea. The effect of the land use change on aquifer recharge may be a contributory factor but its magnitude is confounded by the differences in catchment geometry and [illegible] rainfall distribution. ~~differences.~~

D

SEASONAL FLOW DISTRIBUTION

Whilst the effects of a land use change on annual water use, and hence on water yield, are of critical interest, any modification of the seasonal distribution of flow is also important to the downstream user. At Kericho it was not possible to use the normal technique of within catchment and between catchment comparison of long term means before and after the land use change to quantify differences in seasonal flows distribution. Instead the causes of the small observed differences in ~~[illegible]~~ mean monthly flows from Sambret and Lagan (Table V) were sought by consideration of the information available on possible contributing factors.

These factors comprise: seasonal rainfall distribution, the ~~[illegible]~~ storage discharge characteristics of the catchment groundwater aquifer, ~~surface~~ runoff ~~[illegible]~~ controls and the seasonal distribution of aquifer recharge. Of these, the first two are independent of land use whilst ~~[illegible]~~ surface runoff and aquifer recharge can be influenced by it. Whilst the small differences in mean monthly rainfall (Table V) undoubtedly contribute to the ~~higher early dry season~~ differences in flow distribution they cannot account for the more rapid rise and higher level of flow from Sambret in the early part of the rains. Instead ?

evidence of the effects of aquifer discharge characteristics, in the form of contrasting baseflow recession curves (Figure 6), indicates that catchment geometry is at least partially responsible for the early rains differences in flow. Blackie (1972) has shown that, after a short lived increase ~~in surface runoff~~ during clearing and planting, surface runoff from Sabret quickly returned to the same negligibly small levels as from the forest as the tea established. Consequently the flow differences do not arise from any loss of surface runoff control. On catchments with similar soils and rainfall distribution the variations in aquifer recharge can arise from differences in the water use processes. In the detailed discussion of these processes it has been shown that interception losses from tea are lower than from forest, implying more rapid recharge, and that transpiration losses are higher, implying a shorter duration of recharge. The balance between these land use effects will depend on rainfall distribution but the net effect at Kericho will be some accentuation of the seasonal range of flows from tea.

In summary therefore it can be stated that the observed differences in seasonal flow distribution at Kericho do not arise from any increase in surface runoff from the tea. The effect of the land use change on aquifer recharge may be

SEASONAL FLOW DISTRIBUTION

Whilst changes in annual water ~~yield~~ use and hence in water yield are of critical interest, changes in the seasonal distribution of the annual yield are also important to the downstream users.

Any such changes brought about by a land use change would normally be quantified by within catchment and between catchment comparisons of long term mean distributions before and after the land use change. ~~In absence of any~~ ~~calibration period~~ ~~sufficiently long~~. At Kericho ~~[illegible]~~ this approach was inapplicable and ~~therefore~~ it was necessary to approach the problem indirectly. ~~by considering [illegible] [illegible] land use change [illegible] affect flow distribution~~

Briefly, changes in distribution can arise from land use change brought about change in ~~surface~~ runoff characteristics or ~~[illegible]~~ on groundwater recharge patterns. ~~[illegible]~~ Account must also be taken of any differences in seasonal pattern due to factors other than land use, in particular differences in rainfall distribution and in the storage discharge characteristics of the groundwater aquifer ~~which~~ may result in differences in flow distribution.

Comparison of the 1962-73 monthly means for Sambret and Lagan (Table V) reveals small differences in seasonal figures in the sense of a greater seasonal range for Sambret. Blackie (1972) has shown that, after the clearing and planting period, surface runoff from both catchments is comparable and negligibly small, i.e. 1.5% of rainfall or 5% of flow. This surface runoff is ~~[illegible]~~ ~~[illegible]~~ the cause of ~~not contributed~~ to the observed small differences. ~~[illegible]~~. Differences in rainfall distribution may account for some, but not all, of the differences. The remainder must, therefore, arise either from catchment 'geometry' or from the effects of the land use change —

age pattern. Comparison of the composite baseflow recession curves (Figure 6) indicates that 'geometry' undoubtedly contributes to the greater baseflow range in Sulbrat. The differences in the water use processes, discussed above, are such that they may also contribute. The 3-fold, lower ~~greater~~ interception losses by the trees and [illegible] ~~forest~~ ~~in plantation~~, will ~~would~~ result in increases ~~smaller~~ in wet season ~~discharge~~ recharge and hence in baseflow. The higher ~~evaporation~~ transpiration by trees and bracken could however compensate for this increase; the balance being dependent on rainfall frequency and amount.

~~[illegible]~~

At Kirkton afforestation has not resulted in any ~~[illegible]~~ modification in seasonal flow pattern through loss of control over surface runoff. The observed small differences in ~~the~~ seasonal baseflow may arise in part from the differences in ~~water use processes~~ interception and transpiration but ~~these~~ ~~raw~~ effects of these process differences are confounded by ~~the effects of~~ differences in rainfall distribution and in catchment geometry.

SEASONAL FLOW DISTRIBUTION

B

The annual water use and hence the water yield resulting from forest, bamboo and tea estate has been analysed in detail. Another important aspect of the water balance from the downstream users viewpoint is the effect of the land use change on the seasonal distribution of the streamflow. In the Kericho ~~studies~~ catchments marked differences in seasonal distribution of rainfall between the catchments and from year to year within each catchment has precluded detailed comparisons of differences and trends in seasonal flow distribution. Nevertheless the 1962-73 monthly means in Table V reveal small differences in seasonal distribution of flow which are not fully consistent with the ~~distribution of~~ differences in distribution of rainfall. These are in the sense of a marginally greater seasonal range of flows in Sambret, and raise the question ~~of~~ whether they are due to the land use change or simply arise from the ~~[illegible]~~ differences in the 'geometry' of the two catchments.

On similar soil types a change in land use could affect seasonal distribution through changes in surface runoff or changes in the amount and timing of recharge to the groundwater aquifer. As has been shown by Blackie (1972) there was some increase in surface runoff during clearing and planting but, after establishment of the tea runoff from both catchments was comparable and at 1–2% of rainfall, representing less than 5% of the total flow, almost negligibly small. Thus no change in seasonal distribution has arisen from surface runoff.

In the discussion of water use processes it has been shown that ~~[illegible]~~ interception losses are smaller from the tea and bamboo than from the forest. Transpiration ratios from tea and bamboo are also marginally higher and remain higher with increasing soil moisture deficits. For a comparable rainfall distribution, catchments with soil moisture storage and catchment geometry the ~~[illegible]~~ effect of these process differences will be partially compensating but could result in an increase in wet season baseflow from ~~[illegible]~~ the tea-bamboo catchment.

As can be seen from Figure 6 however the catchment measurements indicate that a more rapid baseflow change can be expected from Sambret. Thus, in this study, the small observed differences in seasonal flow distribution do not arise from land use induced changes in surface runoff but from a combination of differences in rainfall distribution, differences in aquifer geometry and ~~differences~~ land use change induced differences in the water use processes. In the absence of a control period under forest in Sambret it is not possible ~~to attribute the~~ to determine whether geometry or land use is the major cause of the small differences.

A

SEASONAL FLOW DISTRIBUTION

The ~~total~~ annual water use and hence the water yield resulting from the vegetation types has been discussed in detail. ~~[illegible]~~ Another important aspect of the water balance for the downstream users important is the effect of the land use change on the ~~seasonal streamflow regime~~. Seasonal distribution of streamflow. ~~[illegible] flow is determined~~ ~~by~~ Factors determining the distribution are the surface runoff response ~~and~~, ~~by~~ the ~~[illegible]~~ groundwater aquifer geometry and ~~by~~ the seasonal distribution of rainfall and of groundwater recharge.

As was shown by Blackie (1972), surface runoff from Sambret increased during the clearing and planting period but quickly reduced to 1-2% of annual rainfall as the tea became established, a figure comparable to that from the forest and the bamboo. ~~Visual observations indicate that the greater part of this runoff was from the road system.~~ Thus no significant change in seasonal distribution has arisen from the effects of land use change on surface runoff, except during the transition phase. Any differences in distribution must result from the other factors.

Since no long term catchment under the same land use were available the only evidence available on the effects of aquifer geometry on the baseflow response is that from the composite recession curves (Figure 6). These suggest a more rapid change in ~~[illegible]~~ baseflow, at comparable flow rates in Sambret.

Though the seasonal trends in rainfall are generally similar in both Sambret and Lagan, there are marked ~~[illegible]~~ differences individual years and, within each catchment, marked departures from the ~~[illegible]~~ mean. Thus a year by year comparison of seasonal distribution is not feasible. In ~~[illegible]~~ Table V the ~~[illegible]~~ 1962-73 means distributions of rain and flows are compared. The between catchment differences are small in relation to the standard deviations but summer flow is marginally ~~slightly~~ higher during the ~~wet~~ season both in ~~[illegible]~~ absolute and proportional terms.

As has been shown ~~[illegible]~~ in the discussion of the water use processes there are significant differences between forest and grass in the sense that interception losses are higher from forest and transpiration rates are lower and decline more rapidly with increasing deficit. The net effect of these differences, when conventional rainfall distributions are applied, will be to depress the rate of soil moisture recharge in forest and to prolong the period of recharge. Thus qualitatively one would anticipate less seasonal variability in baseflow.

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2.2.2

EDDY CORRELATION MEASUREMENTS OF CONVECTIVE HEAT FLUX AND ESTIMATION OF EVAPORATIVE HEAT FLUX, OVER GROWING TEA

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2.2.2

EDDY CORRELATION MEASUREMENTS OF CONVECTIVE HEAT FLUX AND ESTIMATION OF EVAPORATIVE HEAT FLUX, OVER GROWING TEA

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INTRODUCTION

The EAAFRO catchment experiments (Pereira et al, 1962) were designed and executed to investigate the water use of different vegetative covers, including tea estates, over periods of the order of a year. The eddy correlation experiment reported here, by providing estimates of daily evaporation over several days, offers an independent check on the catchment results; another method of water use estimation, through a monitoring of soil moisture changes, is described in Section 2.2.3.

Much valuable information would be available if the changes of water use from day to day and within a day could be measured and understood. This eddy correlation experiment was therefore designed to yield additional data on the pattern of evapotranspiration from tea within a day.

The evaporative flux is difficult to measure directly, but it can be estimated as the residual in an energy balance equation when all other components have been measured. The convective, or sensible, heat flux component was measured by the eddy correlation technique using the recently developed 'Fluxatron' instrument (Hicks, 1970). Being a very compact and portable instrument, the fluxatron offered wide possibilities for short term evapotranspiration measurements in semi-arid areas, to aid both long term agricultural planning and also local crop management. A necessary prelude to this type of use was an extensive field trial in the tropics, under the conditions of the large radiative, convective and evaporative fluxes experienced near the equator. Such trials require that the measurements be made above a large expanse of crop and that laboratory and workshop facilities be accessible. These considerations, and the proximity of the catchment and soil moisture experiments, made the tea estates near Kericho, Kenya, an excellent site for this field evaluation. Furthermore, estate tea has a crop structure eminently suitable for micro-meteorological research.

THEORY

Crop Energy Balance

The energy balance of unit area of a crop can be written as:

$$R_n + \lambda E + C + G = \Delta J + M \qquad \text{..... (1a)}$$

where R_n is net irradiance;

λE is latent, or evaporative, heat flow intensity;

C is sensible, or convective, heat flow intensity;

G is soil heat flow intensity;

ΔJ is rate of change of heat stored in crop biomass and airmass, per unit horizontal area;

M is net rate of storage of chemical energy by photosynthesis, per unit horizontal area;

and where a positive flow intensity is taken as one entering the crop (defined by the surfaces of soil and canopy). The terms ΔJ and M represent the rates of storage of energy within the canopy, and it is assumed that there is no horizontal divergence of flux and no precipitation. The evaporative heat flow intensity is therefore:

$$-\lambda E = R_n + C + G - (\Delta J + M) \qquad \text{..... (1b)}$$

(This equation, by rigorous adherence to sign convention, may be confusing; it is worthwhile remembering that under normal daytime conditions, with strong sunshine, λE, C and G are usually negative quantities and $(\Delta J + M)$ usually a positive quantity).

The evaporation rate, E, is related to the evaporative heat flow intensity by the latent heat of vaporization of water;

$$\lambda = 2.26 \times 10^6 \ \mathrm{Jm^{-2}} \text{ per mm of evaporation,}$$

a figure independent, in micrometeorological situations, of the initial chemical potential of the evaporated water.

Eddy Correlation

Convection proceeds by the transport of heat along a temperature gradient (assumed vertical) by turbulent eddies. Suppose a layer of air, with mean temperature T, overlies a warmer layer with mean temperature T + T'. An eddy transporting air from the warmer to the cooler layer will convey a net amount of heat, H, through a horizontal plane at a rate:

$$\frac{dH}{dt} = \rho c_p \frac{(Sdz)}{dt} T'$$

where ρ is air density;

c_p is specific heat of air at constant pressure;

S is horizontal cross sectional area of eddy;

$\frac{dz}{dt}$ is speed of vertical movement of eddy.

Identifying $\frac{dz}{dt}$ as w', the instantaneous vertical wind speed, the instantaneous vertical heat flow intensity is:

$$C = \frac{1}{S}\frac{dH}{dt} = \rho c_p (w'T')$$

and averaging over some time interval, the mean heat flow intensity

$$\bar{C} = \rho c_p \ (\overline{w'T'}) \qquad \ldots\ldots (2)$$

Knowing the constants ρ and c_p, $\bar{C}$ is estimated by averaging, over time, the covariance w'T'.

Fetch

Measurement of the covariance w'T', and hence of the heat flow intensity, requires that observations of w' and T' be made at some height in the air above the crop. The fluxatron sensors of w' and T' require to be completely immersed in the turbulent eddy that they are measuring. This requirement is more likely to be satisfied at greater, rather than lower, heights above the crop, because the eddy size correlates positively with height above the canopy.

Conversely, the fluxes of heat, water vapour and carbon dioxide above the canopy represent the underlying crop only within a boundary layer of air whose vertical thickness depends on the distance of homogeneous canopy upwind of the point of observation - the 'fetch'. The fetch and the thickness of the boundary layer are related (Monteith, 1973), their ratio being of order of 200:1. The available fetch thus imposes an upper limit to the sensors' mounting height.

Wind Profile

When the effect of buoyancy in promoting or inhibiting the vertical movement of air is negligible, ie under near-neutral stability conditions, the relationship between horizontal windspeed, u, and height z, can be expressed as:

$$u(z) = \frac{u^*}{k} \{\ln(z-d) - \ln z_o\} \qquad \ldots\ldots (3)$$

where u^* friction velocity;

k is von Karman's constant;

d is zero plane displacement;

z_o is roughness length.

The parameters d and z_o, which describe the aerodynamic qualities of the crop canopy, are derived from measurements of the vertical wind profile under suitable conditions; however, correlation of results from a variety of crops, with canopy height, h, ranging from 0.2 m to 20 m, found the average values (Monteith, 1973):

$$d/h = 0.63 \qquad \text{..... (4a)}$$

$$z_o/h = 0.13 \qquad \text{..... (4b)}$$

INSTRUMENTATION AND CALIBRATION

Net Radiometers

Two 'Funk' type net radiometers (Model CN1 by Middleton, Melbourne) were employed, both mounted on a 2 m boom raised to 3.9 m above ground (2.7 m above crop). Calibration was by a difference method against an Eppley Pyrheliometer, the results being confirmed by later intercomparison of the radiometers in the field. Precision of calibration was 5%.

Eddy Correlation 'Fluxatron'

The fluxatron measures the sensible heat flux by measurement of the covariance w'T'. Physically, the instrument consists of a vertically mounted Gill propeller anemometer (Type 27100 by R M Young Co, Michigan, USA), to the casing of which is attached a very small ITT P25 bead thermistor (See Fig 1); these sensors are electrically connected to a remote electronic console. The lightweight polystyrene propeller, sensitive only to the vertical component of any impinging wind, drives a small dc generator; fluctuating vertical windspeed, w', is therefore converted to a voltage fluctuating both in magnitude and sign. The thermistor, forming one arm of a resistive bridge circuit, similarly converts temperature fluctuations, T', to voltage fluctuations across the bridge. The voltage signals from both sensors are amplified, filtered, and multiplied electronically in the console, to give an output voltage that is proportional to the covariance w'T'.

To calibrate the fluxatron, electrical signals which simulate

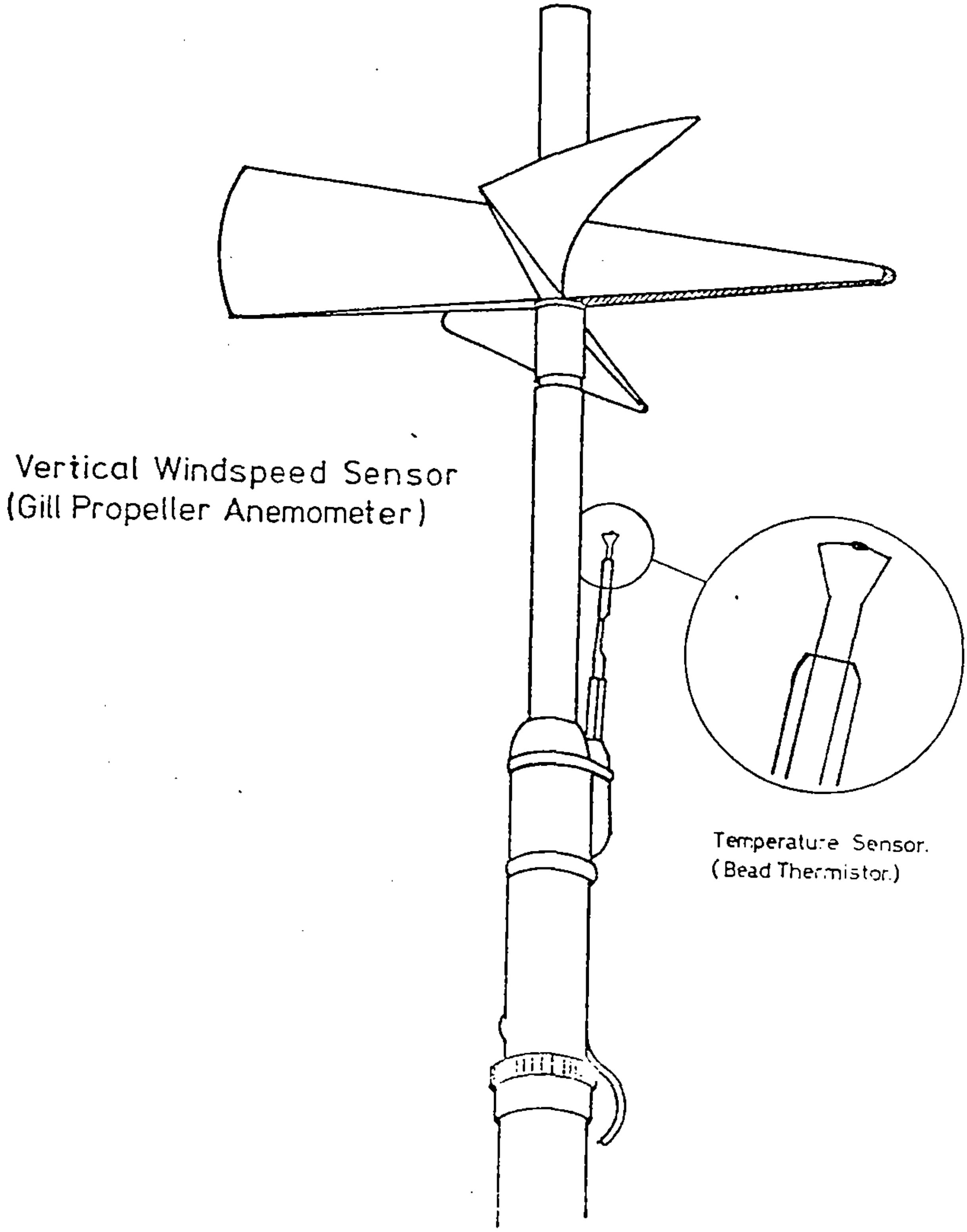

Figure 1 Fluxatron sensors

the outputs from the w' and T' sensors, and which can therefore be interpreted as a sensible heat flux, are fed into the console. The output voltage from this console can then be calibrated directly in terms of heat flux input. Precision of calibration was 5%. Taking account of the fetch in the most frequent wind directions, all eddy correlation observations were made at 4.2 m above ground (3.0 m above crop).

Soil Heat Flux Plates

Six SRI9 soil heat flux plates (Solar Radiation Instruments, Melbourne), in two series-connected groups of three, were buried immediately below the litter layer, one set in a row of bushes and the other between rows. Tea having such a dense canopy, soil heat flow intensity was expected to be relatively small, typically 10-20 Wm^{-2}, and measurement confirmed this. The manufacturer's calibration was to a precision of 5%.

Thermometry

Non-aspirated dry bulb platinum-resistance 'Thermohms' were mounted at heights of 0.5 m, 1.0 m, 1.2 m (crop height) and 4.2 m above ground. Those at canopy level and above gave information on the temperature gradients above the tea; those at canopy level and below gave data for the calculation of the stored heat term of the energy balance. At and above crop height, each thermohm was supported by perspex arms within a radiation shield made of two co-axial metal cylinders, coated with reflective 'Melinex' on the outer surface. Below-canopy thermohms were shielded from overhead radiation by double-skinned half cylinders.

All thermohms were calibrated over the range 10-30^{0}C by immersion in a constant temperature water bath. Precision of calibration was $\pm 0.2^{0}$K (ie ± 0.2 C^{0} at 20^{0}C) but calibration drift and hysteresis in the mechanism of the recorder increased this uncertainty in temperature measurements to $\pm 0.5^{0}$K. This was not a serious problem in calculation of the change of stored heat, where only increments and not absolute values of temperature were required. It did, however, preclude the alternative estimation of sensible heat flux by the aerodynamic method, since differences in air temperature between 1 m and 4 m elevations were usually smaller than the absolute uncertainty of any individual temperature measurement.

Anemometry

Wind profiles for estimating zero plane displacement and roughness length, and also for calculation of atmospheric stability, were obtained with sensitive Sheppard-type cup anemometers (Casella, London), mounted at 5 heights up to 4.2 m above ground. A calibration appropriate to the altitude of the tea estates was carried out in the University of Nairobi's wind tunnel. Precision in calibration was 0.2 ms^{-1} at the windspeeds commonly encountered (2-5 ms^{-1}).

Data Logging

The Munitalp mobile laboratory is a self-contained laboratory for the field operation of micro-meteorological experiments, and contains workshop facilities and data logging equipment. A petrol generator supplied 240 V and 110 V ac power, but low voltage electronics were supplied directly from 12 V dc accumulators.

The voltage signals from the net radiometers, and from the fluxatron console after interfacing, were fed into Lintronic Mk IV integrators (Lintronic Agromet Data Systems, London), which, with automatic printout, averaged net radiation and sensible heat fluxes over half-hour intervals.

The microvolt signal from the soil heat flux plates was amplified and displayed on a Leeds and Northrup 9835-B dc microvolt amplifier (Leeds and Northrup, Philadelphia, USA); spot readings were recorded manually every half-hour.

The anemometers operated electromagnetic counters in the laboratory, and a manual reading of these was taken every half-hour.

Finally, a Leeds and Northrup 'Speedomax G' chart recorder monitored the dry bulb temperatures, completing 12 sampling cycles every half-hour throughout the measuring periods.

EXPERIMENTAL METHOD

Three components of the energy balance (net radiation, convective, and soil heat fluxes) were directly measured. The storage term, ΔJ, was estimated from below-canopy temperature recordings, and the chemical energy storage term, M, was taken as 2% of R_n. (This was a mean estimate of M, derived from diurnal measurements of the carbon dioxide uptake of tea at Mlanje, Malawi (Squire 1974, private communication). The small size of M, relative to the main energy balance components, meant that even an error in M of 100% would have no significant effect on measured evapotranspiration).

Vertical profiles of wind speed and temperature were recorded. These would have provided alternative estimates of C by the aerodynamic method but, as explained earlier, unacceptable errors in temperature measurements precluded this. However, values of d and z_o were derived from these profiles.

To reduce possible systematic affects of instrumental uncertainties, interchanging of instruments with respect both to relative position, and also to recorder, was carried out where possible; net radiometers and fluxatrons were interchanged daily, and anemometers every two-three days.

Although three separate fluxatrons were employed at various times during the experiment, a maximum of two was used at any one time. 51% of the convective flux data was gathered with two instruments in operation, 49% with one instrument in operation.

Periods of Measurement

Measurement generally began at 07.45 h EAST and continued either until rain fell, or until sunset. The former terminated measurements because zero precipitation is one of the assumptions inherent in the energy balance theory (Eqn 1a), and the latter because after sunset, when energy fluxes became much smaller than during the rest of the day, errors of a constant absolute value caused unacceptably large fractional errors in C and, since R_n was small, in λE also.

Evapotranspiration outside the daily periods of energy balance measurements was estimated on the basis of average radiative energy losses. It was assumed that all of the heat energy stored within the crop and soil during the rest of the day was lost by radiation, and that of the remaining energy radiated - the 'residual' radiated energy - one half was supplied by the condensation of water vapour and the other half by a downward flux of sensible heat. The uncertainty attached to this assumption of a Bowen ratio of unity is discussed later.

RESULTS

404 half-hour measurements of the energy balance were made during 1974, distributed as follows:

Month	No of half-hour means
February	38 from 2 days
July	8 from 2 days
August	65 from 4 days
September	47 from 4 days
October	167 from 13 days
November	79 from 8 days
	404 from 33 days

Diurnal Patterns and their Change with Season

Fig 2 shows the typical diurnal behaviour of the energy balance components for (a) February, during a drought, when soil moisture deficits reached 37 cm of water, and (b) October, when soil water was plentiful. To account for an unavoidable loss of measured convective heat flux by the fluxatron, (see eg McNeil and Shuttleworth, 1975), a correction factor has been applied to the C figures before plotting and analysis. The

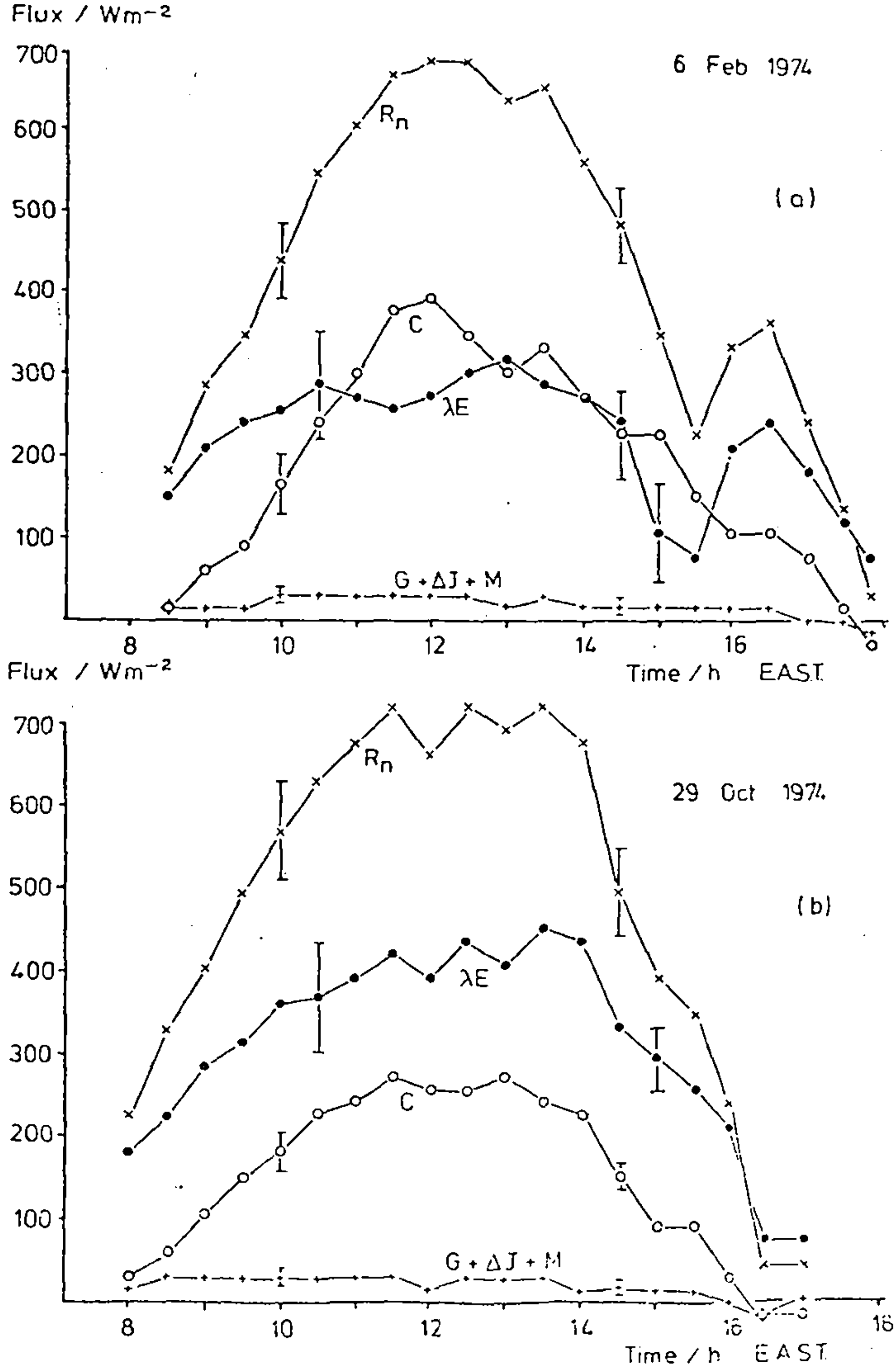

Figure 2 Diurnal pattern of energy balance: (a) when soil moisture is limited (6 February 1974), and (b) when soil moisture is plentiful (29 October 1974)

theory underlying this correction factor will be reported in a future paper. The lower morning values of net radiation in February are consistent with an increase in outgoing longwave radiation, due to the lower water vapour pressures, and a decrease in incoming solar radiation due to increased atmospheric turbidity. The term $G + \Delta J + M$ was small, as expected, and overall it was found that:

$$G + \Delta J + M = 0.04\ R_n \qquad \ldots\ldots (5)$$

with a standard deviation of $0.05\ R_n$. This implies that, for mature tea, approximating available energy A, by net radiation R_n, would involve an error generally of no more than 10%.

The higher Bowen ratios in February (Fig 3) indicate that, at least towards the end of the drought, the tea was suffering from limitations of available water, a conclusion reinforced by the absence of significant growth during this period.

Regressions of Bowen ratio, β, against available energy, A,

$$\beta = mA + c \qquad \ldots\ldots (6)$$

were calculated for data grouped by calendar month. The correlations were all statistically significant, and the regression coefficient for February differed from that for the other months (Fig 4 and Table I). An attempt will be made to relate these regression coefficients to soil moisture status.

Substituting in (6) the identity:

$$\beta = \frac{A}{\lambda E} - 1 \qquad \ldots\ldots (7)$$

yields the empirical relationship:

$$\lambda E = \frac{A}{mA + (1 + c)} \qquad \ldots\ldots (8)$$

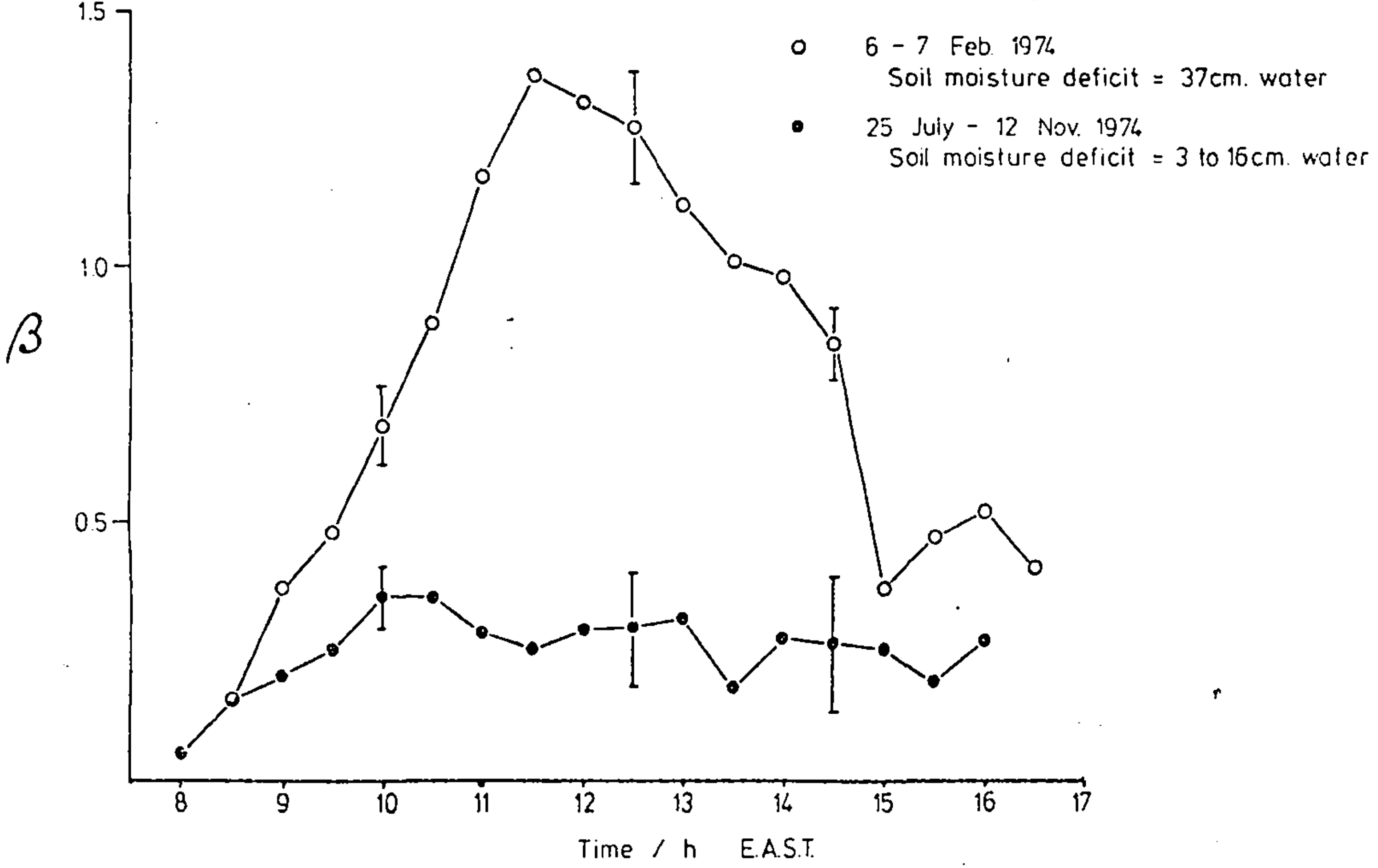

Figure 3 Diurnal pattern of mean values of Bowen ratio, β, when soil moisture is limited (open circles), and plentiful (full circles)

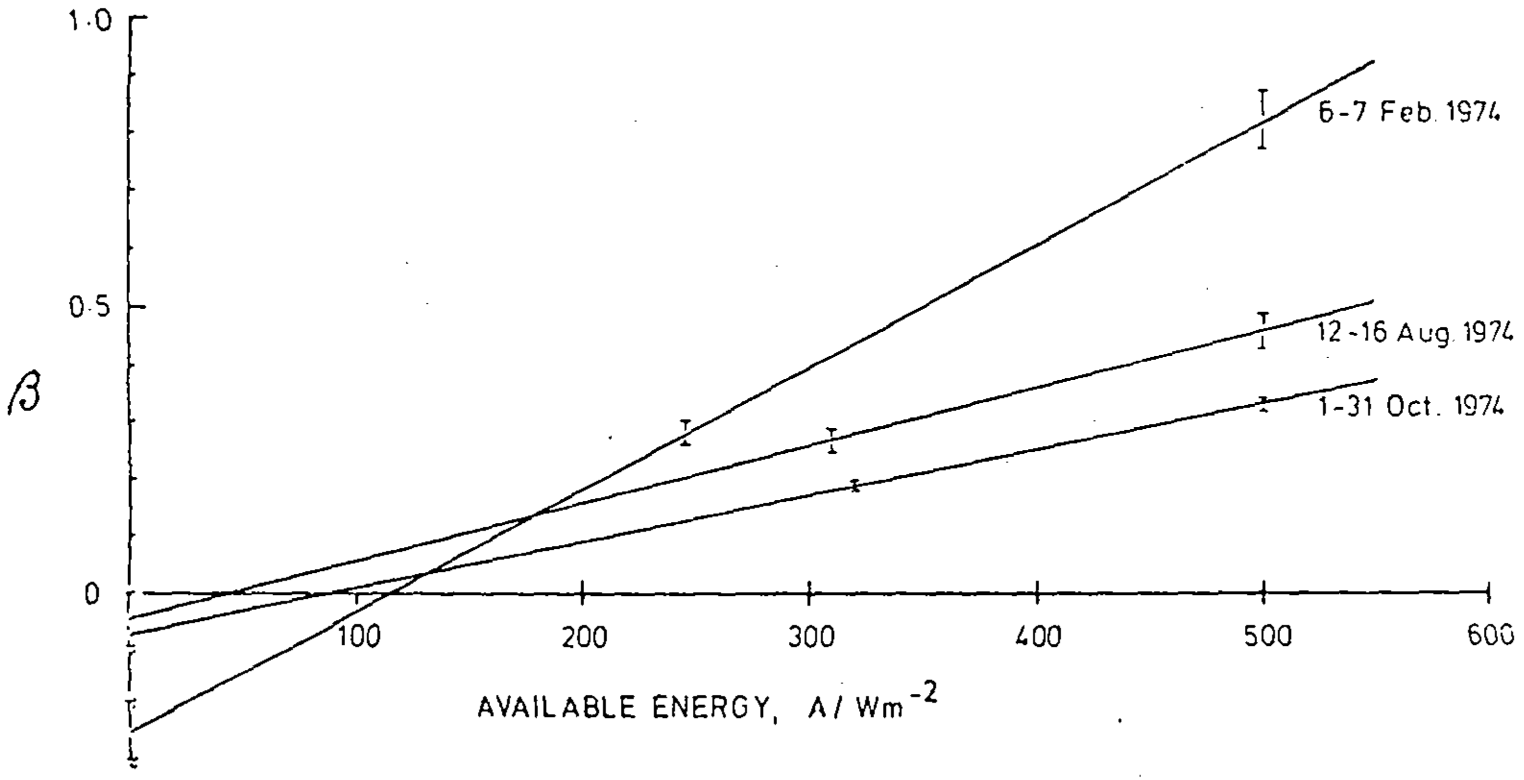

Figure 4 Results of linear regression of Bowen ratio, β, on available energy, A. Error bars are representative of the least significant difference between regression lines at the 1% level; they are not direct indications of the spread of the data

TABLE I

Derived Coefficients from Regression of Bowen Ratio on Available Energy

Month	Slope, $m \times 10^3$ ($m^2 W^{-1}$)	Intercept, c	r^2	n
February	2.1 ± 0.3	-0.24 ± 0.08	0.83	39
July	1.6 ± 0.3	-0.23 ± 0.09	0.56	9
August	1.1 ± 0.1	-0.07 ± 0.04	0.58	47
September	0.9 ± 0.1	-0.15 ± 0.02	0.67	44
October	0.7 ± 0.1	-0.06 ± 0.01	0.56	146
November	1.2 ± 0.1	-0.21 ± 0.03	0.73	64

With A measured in Wm^{-2}, m is generally of the order of 10^{-3} m^2W^{-1}, and c of the order of 10^{-1}. Fig 5 demonstrates the behaviour of equation (8) for different values of the coefficient m and c. The lowest curve, obtained from the regression of the February data, approaches a limiting value of λE with increasing A, with a limit to λE of about 300 Wm^{-2} (0.48 mm/h^{-1}) for a typical maximum available energy. The highest measured λE in February, from this energy balance experiment, was 330 ±70 Wm^{-2}. The curves corresponding to other times of the year do not exhibit a similar limitation, with λE increasing in response to increasing A, typically to a maximum of 470 ±30 Wm^{-2} (0.75 mm h^{-1}).

In the region of available energy A < 200 Wm^{-2}, the experimental data cannot distinguish any significant change in evaporation rates with month.

Effect of Wet Canopy on Bowen Ratio

There was some evidence that moisture on the surface of the tea leaves decreased the Bowen ratio. Owing to the large uncertainties associated with the generally low sensible heat flow intensities, this was not statistically significant.

Daily Evapotranspiration and Comparison with Penman Estimates

Integrating the energy balance estimates of mean latent heat flow intensity over the total daily measurement period, and allowing for an expected evaporation rate outside this period, estimated daily evapotranspiration rates, E_{EB}, could be compared with the Penman (1948) estimates E_T, calculated assuming an albedo of 0.20 (Blackie, 1976; private communication). With the energy balance measurements usually terminating at the onset of rain or near dusk, estimated evaporation during the remaining hours of daylight was of the order of tenths of a millimetre. On the basis of the observed range of net radiation at night, and taking account of the loss of that heat stored within the canopy airmass during the day, a night-time condensation of 0.2 (±0.1) mm was subtracted from the daily energy balance evapotranspiration estimates.

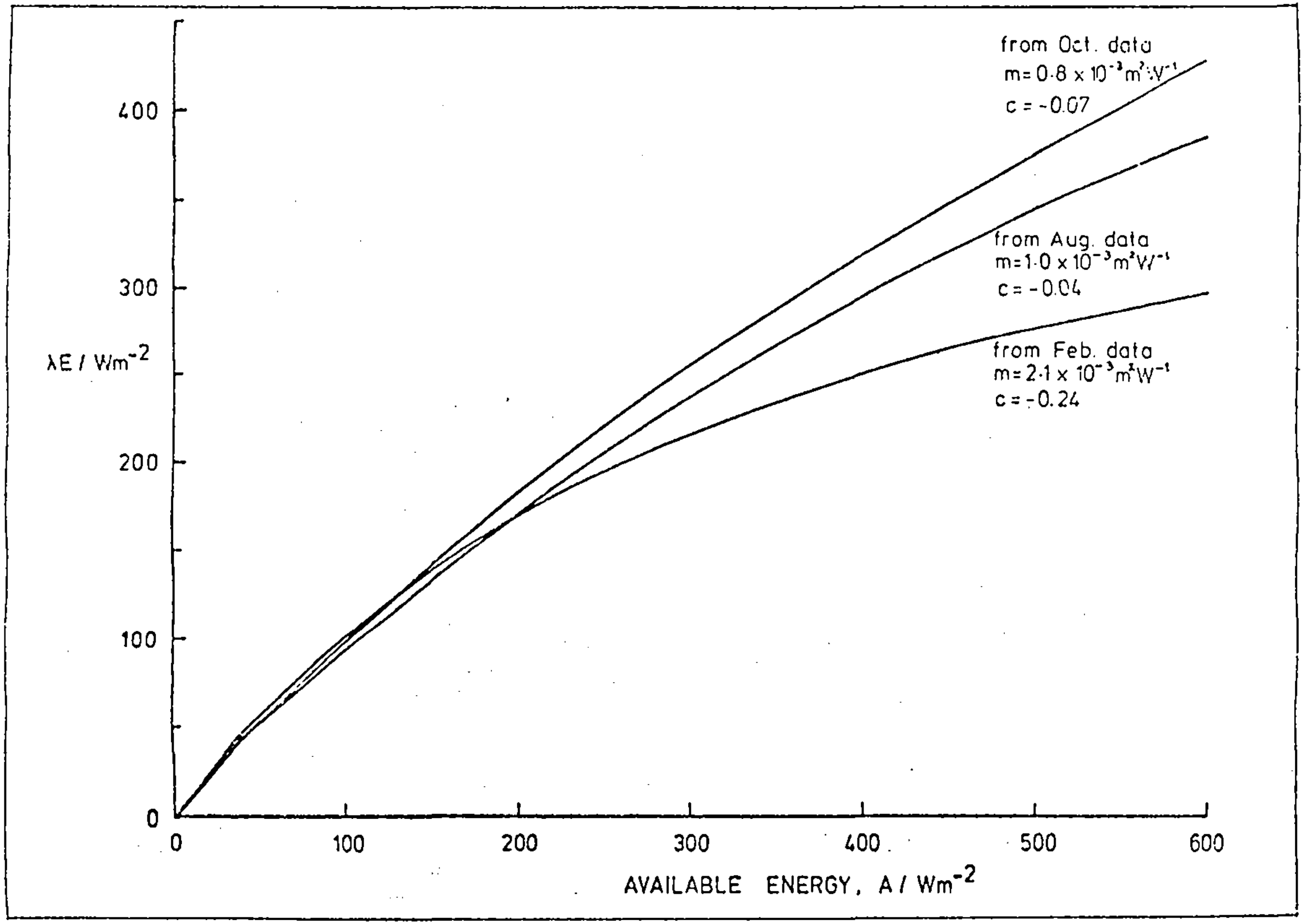

Figure 5 Behaviour of function $\lambda E = A/(mA + 1 + c)$ for different values of m and c (see Table 1)

The plot of E_{EB} versus ET is shown in Fig 6. (For the sake of clarity, the uncertainty in ET, constant at 6.5% ET is indicated only on two points.) Assuming for simplicity a regression line through the origin, weighting according to the uncertainty in E_{EB}, and ignoring for the moment the February data,

$$E_{EB} = (0.94 \pm 0.03)\ ET \qquad \ldots\ldots (9a)$$

Compared with potential open water evaporation, EO, equation (9a) is equivalent to,

$$E_{EB} = (0.76 \pm 0.02)\ EO \qquad \ldots\ldots (9b)$$

The data from which equations (9) were derived covered soil moisture deficits from 4 to 16 cm of water.

In the two measurement days in February, with a soil moisture deficit of 37 cm of water, the relationship became:

$$E_{EB} = (0.65 \pm 0.02)\ ET \qquad \ldots\ldots (10a)$$

and

$$E_{EB} = (0.52 \pm 0.02)\ E0 \qquad \ldots\ldots (10b)$$

Aerodynamic Results

Twenty-one half-hour measurements of the wind profile, up to 4.2 m above ground, were obtained during near-neutral stability conditions when the logarithmic equation (Eqn 3) is expected to hold.

Optimising the goodness of fit of the experimental points to Equation (3) by adjustment of the parameter d, led to a mean value of the zero plane displacement,

$$d = 0.66 \pm 0.14\ m$$

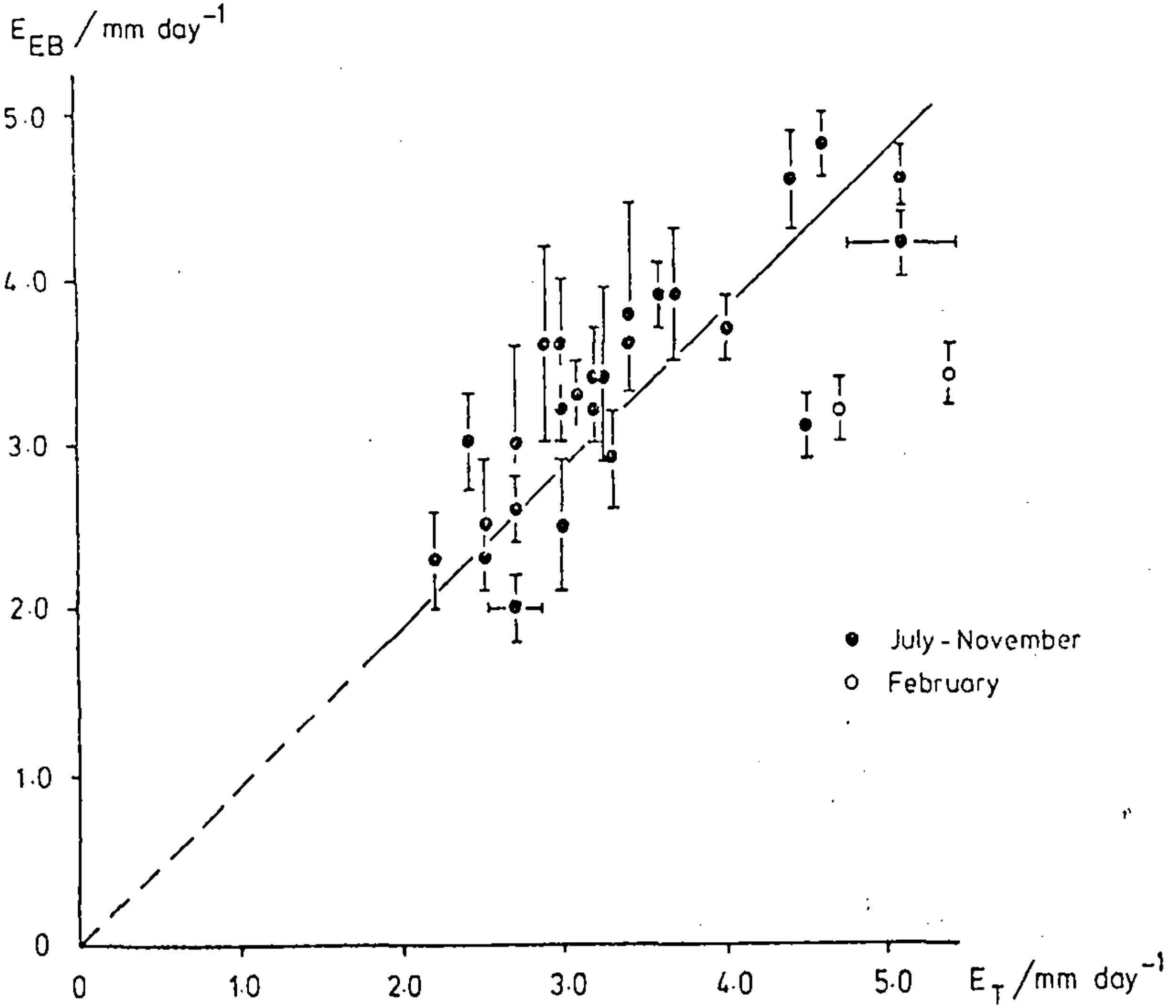

Figure 6 Comparison of energy balance, E_{EB}, and Penman, ET, estimates of evapotranspiration

and, with h = 1.2 m,

$$\frac{d}{h} = 0.55 \pm 0.12 \qquad \text{..... (11a)}$$

Using this value, further analysis of the profile measurements returned a mean value of the roughness length

$$z_o = 0.20 \pm 0.07 \text{ m}$$

and

$$z_o/h = 0.17 \pm 0.06 \qquad \text{..... (11b)}$$

UNCERTAINTIES

Convective Heat Flux, C

The calibration precision of 5% contributed relatively little to the total uncertainty in C, which was governed by two predominant sources of uncertainty.

The first was spatial variability in the canopy itself, combined with a statistical scatter in the data inherent in the technique of eddy correlation, which samples a number of randomly occurring eddies over a given time interval. A randomised block intercomparison of two fluxatrons led to the conclusion that in total these variabilities could add 10% to the uncertainty in C.

The second source of uncertainty arises because the w' and T' sensors cannot be perfect instruments: each takes a finite, and different, time to respond to a fluctuation w' or T'. The measured covariance therefore differs from the true covariance $\overline{w'T'}$. This difference can be calculated and a correction factor applied: typically, the measured heat flow intensity must be multiplied by a variable correction factor, of the order 1.4 to 1.6, to obtain the true intensity. The correction factor is itself uncertain to with ± 12%.

Compounding all percentage errors gave an uncertainty in C of 16%. However, a lower limit of ± 15 Wm^{-2} was set by uncertainties (mainly in the data logging equipment) of a constant absolute value. The overall uncertainty in C can be summarised as:

± 16% of C

or ± 15 Wm^{-2}, whichever is greater.

Net Radiation, R_n

Calibration of net radiometers was to a precision of 5%, and agreement between the radiometers during measurement was better than this. However, the intercomparison of the two fluxatrons suggested that spatial variability caused by the canopy inhomogeneities could be of the order of 10%, and this uncertainty was therefore attached to net radiation values.

Soil Heat Flow Intensity, G, Storage of Heat, ΔJ, and Net Rate of Photosynthesis, M

The measurements of soil heat flux were taken to have an uncertainty of 10%. Taking account of the range of G, this was adequately expressed by a constant uncertainty of ± 2 Wm^{-2}

The main contribution to uncertainty in ΔJ came not from errors in temperature measurements, but from the assumptions of representative specific heats and total amount of biomass taking part in heat storage below the canopy. An error of ± 3 Wm^{-2} was arbitrarily attached to ΔJ, equivalent to assuming an uncertainty in ΔJ of not less than 25%.

An uncertainty of ± 3 Wm^{-2} was ascribed to net rate of photosynthesis, M, equivalent to an assumed uncertainty in M of not less than 20%.

The overall uncertainty in the term $(G + \Delta J + M)$ was therefore ± 5 Wm^{-2}.

Anemometry

Precision of calibration of individual anemometers was ± 0.20 ms^{-1}, but this uncertainty was reduced by interchanging the anemometers, and by the effective averaging of five windspeed observations in the analysis of the wind profile. The uncertainty in the mean value of d, determined from the scatter of d values obtained from five separate anemometer configurations was ± 0.14 m. The uncertainty limit of ± 0.07 m in the calculated value of z_o was imposed by the uncertainty in d.

Latent Heat Flow Intensity, λE

The uncertainty in λE, compounded from the absolute errors in R_n, C, and $(G + \Delta J + M)$, had a minimum of ± 16 Wm^{-2}, corresponding to zero net radiation, but was typically in the range 40 to 70 Wm^{-2}.

Estimation of Evapotranspiration in the Absence of Energy Balance Measurements

In estimating evapotranspiration during those periods when the energy balance instrumentation was not deployed, the source of greatest uncertainty was in the assumption of a night-time Bowen ratio of unity. The worst cases corresponded to either: (i) all residual radiated energy being supplied by condensing water vapour, or (ii) all residual radiated energy being supplied by sensible heat flux. The former implied an isothermal boundary layer which, since condensation was occurring at some point within this layer, meant that the temperature of the whole boundary layer would be below the local dew point. This would have led to mist prevailing over the greater part of the night, but this was not commonly observed. The latter implied zero condensation, which conflicts with the observed presence of dew on most mornings. It is assumed, therefore, that latent and sensible heat fluxes each supplied (50 ± 20%) of the residual radiated energy.

Penman Potential Open Water Evaporation, E_O, and Potential Evapotranspiration, E_T

For the instruments used to measure the weather parameters, the uncertainty in EO is 6.5% (Woodhead, 1970), and this uncertainty was assumed for ET also.

DISCUSSION

The findings of several workers on the effect of soil moisture deficit (SMD) on the rates of actual evapotranspiration of tea, AE, to potential open water evaporation, E_O, are presented, along with the results of this experiment, in Table II. The experiments were conducted at different sites and on different tea varieties, and the soil moisture deficits will not therefore be directly comparable; nonetheless the data show broad agreement in two areas:-

(a) The AE : EO ratios for tea are independent of soil moisture deficit, up to deficits of at least 16 cm of water;

(b) Severe soil moisture deficits reduce AE : EO ratios considerably.

On the other hand, Cooper (Section 2.2.3) minimises the importance of soil moisture deficit in determining actual evapotranspiration rate, but emphasises the role of intercepted rainfall lying on the tea canopy; from measurements on a field adjacent to that of the energy balance experiment reported in this paper, he found that a saturated canopy could store as much as 0.25 cm of intercepted water. If this amount were stored, and subsequently re-evaporated, on each of the 240 or so rain-days per year at the Kericho site, then annual interception losses could amount to 60 cm, equivalent to about 40% of the total evapotranspirative loss. Variation of water use with season therefore becomes a reflection not of soil moisture deficit, but of the number of rain days.

The energy balance experiment undoubtedly adds weight to the

TABLE II

Determined AE : EO Ratios as a Function of Soil Water Status

Worker	Location	Method	$E_A:E_O$ Ratios when Water			
			'Freely Available'		'Limited'	
			SMD, cm water	$E_A:E_O$	SMD, cm water	$E_A:E_O$
Willat (1971)	Mlanje Malawi	Gravimetric sampling	0 - 20	0.85	35	0.36 (drying 0.13 (wetting)
Wang'ati and Blackie (1971)	Kericho Kenya	Lysimeter and water balance	-	0.8	-	0.53 (mean for February 1970)
Willat (1973)	Mlanje Malawi	Gravimetric sampling	0 - 8	0.7-0.9	38	0.30 0.56 (mean for two dry seasons)
Carr (1974)	Southern Tanzania	Gypsum blocks	-	-	up to 33	0.34 (mean for three dry seasons)
Callander and Woodhead (1976)	Kericho Kenya	Energy balance	0 - 16	0.76	37	0.52
Laycock (1964)	Mlanje Malawi	Gravimetric sampling	-	0.85	-	-

importance of interception in determining evapotranspiration; however, analysis of the diurnal pattern of the energy balance shows that on 17 days when a wet canopy occurred, due either to rain or to dew, a maximum of 0.18 cm, but an average of only 0.08 cm, was evaporated while the canopy was wet. Thus, although the energy balance experiment supports Cooper's estimate of a saturation canopy storage of about 0.2 cm, it suggests also that, on average, dew or rain only half-saturates the canopy, resulting in a yearly interception loss of 25 ± 5 cm of water; this figure is reduced if ~~no~~ transpiration also takes place whilst intercepted water is being evaporated.

Statistically, the determined ratios $d/h = 0.55$ and $z_o/h = 0.17$ were not significantly different from the representative values of 0.64 and 0.13 respectively (Equations (4)). If the differences were real, however, they would suggest that momentum absorption occurs at lower levels within the tea crop than would be expected from such an apparently smooth and dense canopy. Possible causes of this low zero plane displacement and increased roughness are, (i) the regular pattern of access paths crossing the estates, and, (ii) the occasional holes in the canopy where one or more bushes have been removed.

On the other hand, Thom (1971) argues that z_o should bear a more direct relation to (h-d), than simply to h. He proposes that $z_o = 0.36\ (h-d)$, in agreement with the data reported here, which finds $z_o = 0.4\ (h-d)$.

CONCLUSIONS

For the mature unirrigated tea of the Dimbolil estate, Kericho, the following conclusions are reached.

(i) Soil moisture is 'freely available' for evapotranspiration at soil moisture deficits up to at least 16 cm of water.

Approximating available energy, A, by net radiation, R_n, the rate of evaporation, E, when water is freely available, is given by the empirical relationship:

$$E = R_n/(0.54\ R_n + 5.8 \times 10^2) \qquad \ldots\ldots (12a)$$

where E is in mm.h^{-1}, and R_n is in Wm^{-2}. At a soil moisture deficit of 37 cm of water, the relationship became:

$$E = R_n/(1.3\ R_n + 4.8 \times 10^2) \qquad \ldots\ldots (12b)$$

Equations (12) take no explicit account of an aerodynamic term as appears in the Penman estimate of potential evapotranspiration. Derived from data collected over five months incorporating a variety of wind-runs, the aerodynamic term has contributed an increased uncertainty to the values of the constants in Equation (12). This approach is possible only because the net radiation term is considerably bigger, usually three times bigger, than the aerodynamic term in Penman's equation.

The uncertainty in E, calculated from Equations (12), is 25%.

The energy balance measurements and the Penman estimates of evapotranspiration agree to within two standard deviations when water is freely available. When water stress is severe, E_{EB} falls to about one-half ET. (In calculating these Penman estimates, a reflection coefficient of 0.20 was assumed).

(ii) The zero plane displacement, d, was determined as

$$d = (0.66 \pm 0.14)\ \text{m}$$

which corresponds to

$$d/h = (0.55 \pm 0.12)$$

The roughness length, z_o, was determined as

$$z_o = (0.20 \pm 0.07)\ \text{m}$$

(iii) The fluxatron has many advantages: it is portable, has minimal data logging requirements, and its raw data may readily be converted to estimates of heat flow intensity. These advantages are offset by the need to multiply the estimates of sensible heat flow intensity by a sizeable correction factor: a factor which can vary with both wind speed and atmospheric stability, and whose value is to some extent uncertain. The departures from ideal performance that necessitate this correction (mainly inadequately rapid response times), lie almost entirely with the w' and T' sensors, and the future routine use of the fluxatron depends on the satisfactory solution of these instrumental problems. Further development of these sensors is being carried out by the Institute of Hydrology, UK.

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SYMBOLS

			SI units
A	:	available energy flow intensity	Wm^{-2}
C	:	convective, or sensible, heat flow intensity	Wm^{-2}
E	:	evaporation rate	$kg.m^{-2}s^{-1}$
AE	:	estimated actual evapotranspiration rate	"
E_{EB}	:	energy balance estimate of evapotranspiration rate	"
EO	:	Penman potential open water evaporation rate	"
ET	:	Penman potential evapotranspiration rate	"
G	:	soil heat flow intensity	Wm^{-2}
ΔJ	:	rate of change of heat stored in crop biomass and airmass, per unit horizontal area	Wm^{-2}
M	:	net rate of storage of chemical energy by photosynthesis, per unit horizontal area	Wm^{-2}
R_n	:	net irradiance	Wm^{-2}
S	:	horizontal cross-sectional area	m^2
T'	:	fluctuation from mean temperature	K
c_p	:	specific heat of air at constant pressure	$JK^{-1}kg^{-1}$
d	:	zero plane displacement	m
h	:	mean height of canopy	m
k	:	Von Karman's constant = 0.41	–
t	:	time	s
u	:	horizontal wind speed	ms^{-1}
u_*	:	friction velocity	ms^{-1}
w'	:	fluctuation in vertical wind speed	ms^{-1}

			SI units
z	:	height above ground	m
z_o	:	roughness length	m
β	:	Bowen ratio = $C/\lambda E$	–
λ	:	latent heat of vaporization water	Jkg^{-1}
ρ	:	density of air	kgm^{-3}

2.2.3

WATER USE OF A TEA ESTATE FROM SOIL MOISTURE MEASUREMENTS

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2.2.3

WATER USE OF A TEA ESTATE FROM SOIL MOISTURE MEASUREMENTS

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INTRODUCTION

The objective of the experiments reported in this paper was the direct measurement of water balance components in a small area of tea estate; the study complimented the catchment study described in Section 2.1.1. Measurements were made from February 1974 until August 1975; the present report concentrates on the dry period from early December 1974 until mid March 1975, when the tea was pruned.

There have been relatively few previous publications on water use of the tea crop, and even fewer where estimation of the variable has been a primary aim. On the basis of gravimetric soil moisture sampling and gypsum block readings, Laycock (1964) found that in Malawi total evaporation by mature tea, E, was related to the Penman estimate of open water evaporation EO by E = 0.85 EO. This was later modified by Willatt (1971), also working in Malawi and using gravimetric sampling, who found a hysteretic relation between the ratio E/EO and soil moisture deficit. E/EO was in the region 0.85 - 0.90 until the deficits exceeded about 200 mm of water, when the ratio fell sharply. On rewetting, the water use recovered more slowly than it had fallen. In a later paper, Willatt (1973) found that for mature, unirrigated tea moisture use during a hot dry period averaged 0.56 EO, falling to about 0.30 EO when deficits of 380 mm had built up. Carr (1974) has estimated evaporation by mature, unirrigated tea in Southern Tanzania during the dry season as about 0.36 EO, on average, for soil moisture deficits up to 330 mm. Dagg (1970) has presented results from a large hydraulic lysimeter at the Tea Research Institute of East Africa, about 1 km from the site of the present experiment; he found that the equation:-

$$E = 0.9\ EO\ |a + (1 - a)\ n\ |$$

described the results well for young tea, where a is the fraction of soil covered by the crop at noon and n is the fractional number of raindays per month. Later, however, Wang'ati and Blackie (1971) found that the factor 0.9 was too high and replaced it by 0.8 for a crop with 100% cover such as mature tea.

SITE DESCRIPTION

The experiment was sited in Field No 9 of Dimbolil Estate, African Highlands Produce Company at Kericho, latitude 35° 20'E, longitude 0° 20'S. The site was approximately level, lying on a ridge running roughly E-W at an altitude of 2150 m. The Fluxatron experiments reported in Section 2.2.2 were in the same field. The field had been planted in 1957 with seedling tea at a spacing of 1.5 m x 0.6 m (5 ft x 2 ft) and by the time of the experiment, roots had penetrated to more than 6 m.

The soil at the site is volcanic in origin (see Section 2.1.1), is at least 11 m deep, and shows no obvious horizons. Bulk densities are in the region of 0.9 over most of the profile, with very high (> 80%) clay content. Mean annual rainfall at the Tea Research Institute, some 1 km away from the site, is 2146 mm; mean annual open-water evaporation EO, calculated by the methods described in Section 1.2.2, is 1474 mm. Details of the seasonal variations in climate are presented in Table I of Section 2.1.1 of this Issue. Of particular relevance to this paper is the relatively dry period with high evaporation rates extending from mid-November until mid-March. The weather during this experiment was, in fact, quite unusually dry.

PRINCIPLES OF MEASUREMENT

Changes in soil moisture storage result from precipitation, evaporation (both as transpiration by plants and from the soil surface) and drainage from the profile. If surface runoff can be neglected, the water balance of a soil profile may be written as:-

$$\Delta S = T - E - D \qquad (1)$$

where ΔS is the change in soil moisture storage; T is the part of the precipitation reaching the ground surface, ie the net rainfall (throughfall plus stemflow); E is transpiration by the crop (excluding evaporation of intercepted water); and D is drainage from the profile.

It is assumed that lateral inflow into the profile and outflow from it are both negligible.

Well-established methods exist for the measurement of rainfall, throughfall and stemflow. The neutron probe method (eg Bell, 1976) has become established as a precise and non-destructive method for measuring soil moisture changes. The sum E + D can be derived, therefore, with little trouble and the problem reduces to separating the two. Two methods have recently been introduced to measure these components separately; they are the Zero Flux Plane method and the Hydraulic Conductivity-Potential Gradient method.

ZERO FLUX PLANE (ZFP) METHOD

The rate of change of moisture content of a volume of soil is given by the difference between the rates of inflow and outflow. If flow is everywhere assumed vertical, and using the convention that positive is downward, this may be written as:

$$v(z_1) - v(z_2) = \frac{d\, S(z_1, z_2)}{dt} = \int_{z_1}^{z_2} \frac{\partial\theta}{\partial t}\, dz \qquad (2)$$

where z is depth below soil surface; v is volume flux of water; t is time; and θ is volumetric water content.

This may be rearranged to give:

$$v(z_2) = v(z_1) - \int_{z_1}^{z_2} \frac{\partial\theta}{\partial t}\, dz \qquad (3)$$

Given the flow rate at a depth z_1 and the change in moisture content between z_1 and z_2, the flow at z_2 may be calculated from equation (3). In the ZFP method, use is made of Darcy's Law:-

$$v = -K \frac{\partial \phi}{\partial z} \qquad (4)$$

where K is unsaturated hydraulic conductivity of the soil and ϕ is total hydraulic potential.

If a depth z_o, at which the flux v is zero owing to a zero potential gradient, can be identified, equation (3) then gives (with slight change in notation):-

$$v(Z) = - \int_{z_o}^{Z} \frac{\partial \theta}{\partial t} \, dz. \qquad (5)$$

Integration of equation (5) gives, for the accumulated flux F(Z) from time t_1 to t_2:-

$$F(Z) = \int_{z_o(t_1)}^{Z} \theta(t_1) dz - \int_{z_o(t_2)}^{Z} \theta(t_2) dz - \int_{z_o(t_1)}^{z_o(t_2)} \theta(z_o) dz \qquad (6)$$

In the special case where z_o does not change with time, equation (6) reduces to:-

$$F(Z) = \int_{z_o}^{Z} |\theta(t_1) - \theta(t_2)| dz \qquad (7)$$

During dry periods, evaporation is likely to produce an upward movement of water in the upper parts of the profile, while drainage downwards may continue in the lower part below the ZFP. Since movement within roots is, on average, upwards, this method can be used only if the root system is confined effectively to that part of the profile above the deepest ZFP.

Evaporation and drainage over any specified period are equal to the accumulated fluxes across the soil surface and the base of the profile respectively. In the case of evaporation, the flux is upward, and hence negative with the convention adopted; furthermore, equation (6) gives the net flux, and allowance must be made for any rain which may have fallen during the period. The expressions for evaporation and drainage are thus:-

$$\begin{aligned} E &= T - F(0) \\ &= T + \int_{0}^{z_o(t_1)} \theta(t_1)dz - \int_{0}^{z_o(t_2)} \theta(t_2)dz + \int_{z_o(t_1)}^{z_o(t_2)} \theta(z_o)dz \end{aligned} \qquad (8)$$

$$\begin{aligned} D &= F(Z=z_{max}) \\ &= \int_{z_o(t_1)}^{z_{max}} \theta(t_1)dz - \int_{z_o(t_2)}^{z_{max}} \theta(t_2)\, dz - \int_{z_o(t_1)}^{z_o(t_2)} \theta(z_o)dz \end{aligned} \qquad (9)$$

HYDRAULIC CONDUCTIVITY - POTENTIAL GRADIENT METHOD

In principle, this method is not restricted by the necessity for the presence of a zero flux plane below the root range of the crop. It does, however, require a knowledge of unsaturated hydraulic conductivity of the soil over the range of moisture contents found in the field.

Darcy's Law, equation (4), indicates that if the unsaturated hydraulic conductivity of the soil, K, is known for any depth, then the flux v at that depth can be calculated from measurements of the potential gradient, provided this is below the rooting range (Rose and Sterne, 1965). If it is only possible to calculate fluxes over a part of the profile by this means, equation (3) can be used to compute fluxes at other depths.

MEASUREMENT OF SOIL HYDRAULIC CONDUCTIVITY

Methods for measurement of the hydraulic conductivity of soil have been reviewed by Klute (1972). When considering the properties of soil in the field, it should be borne in mind that the conductivity may vary by a factor of 10^5 or more over the range of moisture contents commonly encountered (Hillel, 1971, p 105) and that, as a consequence, the unsaturated conductivity is very sensitive even to small changes in moisture content. A second factor to be considered is soil heterogeneity; even with the very homogeneous soil at the experimental site, the heterogeneity is sufficient to make it difficult to apply results obtained at one point to another only a few metres away, without correction (Nielsen *et al*, 1973). Ideally, hydraulic conductivity should be measured at the same point as where it is used for calculating fluxes beneath a crop, as was done by Van Bavel *et al* (1968); in this study, however, this was not possible, as the crop was already established at the beginning of the experiment and it was necessary to measure both fluxes and conductivity simultaneously.

Methods for measuring unsaturated conductivity rely on Darcy's Law, equation (4). A known moisture flux is imposed on the soil and the soil moisture potential gradient, $\frac{\partial \phi}{\partial z}$ is measured so that K may be calculated. Differences in methods arise in the means used to determine v; Youngs (1964) applied a constant flux of water at the surface, and when a steady state was reached this flux was assumed constant throughout the profile. The more widely used method is the instantaneous profile method (Watson, 1966; Van Bavel *et al*, 1968) where transient fluxes in a freely draining profile are calculated from measurements of moisture content changes according to equation (3). The known flux is normally zero at the soil surface (Rose *et al*, 1965), though the ZFP method has also been used (Richards *et al*, 1956). In the present experiment, a combination of the two methods has been used, similar to the experiment of Poulovassilis *et al* (1974).

EXPERIMENTAL METHODS

The experiment consisted of two parts: (a) measurements of rainfall, throughfall, stemflow, soil moisture content, and tension associated with the growing tea crop; and (b) measurement of the hydraulic conductivity of the soil. In addition, a neutron probe calibration curve was derived by methods described by Bell (1976) and in Section 1.2.3 of this issue. The calibration curve used is given by the equation:-

$$\theta = 1.0\ (R_s/R_w) - 0.03 \qquad (10)$$

where R_s/R_w is the ratio of slow neutron count rate in the soil to count rate recorded when the probe is inserted in a large drum of water.

In what follows, Site 1 is the area used for measurements beneath the growing tea; Site 2 is that used for measurement of hydraulic conductivity.

MEASUREMENTS BENEATH THE GROWING TEA CROP

The two methods of measurement described in the last section both use (a) measurements of soil moisture content and potential down the profile, and (b) measurements of the water input to the soil surface.

Rainfall was measured by three 127 mm (5 in) diameter storage gauges spaced some 50 m apart in a triangle around the experimental area. Throughfall measurements utilised the fact that the crop was regularly spaced; a wooden frame was made covering an area of one quarter of an average tea bush (ie 0.75 m x 0.30 m) which held 18 empty tin cans each of 84 mm diameter in a 6 x 3 rectangular array. This was placed with one corner adjacent to a bush and aligned with the rows. After each storm it was moved to a different bush, so that over a period of time sampling over many different storms and different bushes has permitted a good estimate of mean throughfall.

Measurement of stemflow was difficult because most bushes (approximately 98%) possessed multiple stems; it was therefore decided to concentrate on the small proportion of bushes having single stems, and to hope to avoid serious bias by selecting bushes whose top hamper conformed as nearly as possible in size and shape to the average bush. A polyethylene funnel of about 200 mm diameter was cut and sealed onto the stem as a collar using bituminous mastic; stemflow caught by this collar was led to a 22 litre container where it was measured either with a measuring cylinder (for small amounts) or dipping for larger volumes. Eight stemflow gauges were installed.

Measurements of rainfall, throughfall and stemflow were made daily. Soil moisture content was measured from five 50 mm (2 in) diameter aluminium access tubes by a Wallingford neutron probe (Bell 1969) and ratescaler set at 64-second integration times. Two of the access tubes penetrated to 5.7 m depth and the others to 2.7 m. Daily readings were taken at depths of 0.10, 0.20, 0.30, 0.45, 0.60 and then at 0.30 m intervals to the maximum depth of the tube. The access tubes were distributed over an area of some 200 m^2.

It was assumed that thermal and osmotic components of soil moisture potential were negligible (Hillel, 1971, p 119) so that the potential could be expressed as the sum of the matric (suction) and gravitational potentials. In units of equivalent water head, this is:-

$$\phi = -(\psi + z) \tag{11}$$

where ϕ is the total potential and ψ the soil moisture tension.

In order to measure this potential to a depth of 5.7 m (which was the practical limit for access) a pit was dug 3 m long x 1.5 m wide x 6 m deep. Tensiometers were installed almost horizontally from one face of this pit in holes punched into the soil using a mild steel tube 22 mm ($\frac{7}{8}$ inches) od, the same diameter as the tensiometers. The tensiometers sloped slightly downwards to facilitate purging of air, and each tensiometer cup was installed approximately 2 m from the wall of the pit. There were 41 tensiometers in all, at depths of 0.15, 0.30, 0.45, 0.60 and then at 0.30 m intervals to 5.70 m. At some depths three tensiometers were installed 0.50 m apart, at others 2, and at some 1 only. The top five levels all had three tensiometers. The tensiometer cups were close to one of the deep neutron probe access tubes.

Each tensiometer was connected by nylon tubing to a glass capillary tube mercury manometer mounted on one of four measuring boards at various depths down the pit to avoid hanging too long a water column on each manometer. During the period covered in this paper, tensiometers were purged once a week or so. The tensiometers were read daily, early in the morning, to minimise thermal disturbance of the mercury levels.

After the end of January 1975, soil moisture tensions had exceeded the tensiometer range over much of the profile, although the lower 2 m always remained at tensions lower than 0.5 bar.

MEASUREMENT OF HYDRAULIC CONDUCTIVITY

To measure the unsaturated hydraulic conductivity of the soil, a convenient area of 200 m^2 was selected about 30 m from Site 1. The tea bushes on this area were pruned and kept defoliated manually for the duration of the experiment. A second pit, similar to the first except of 2 m width, was dug on this site, and tensiometers emplaced as in the first pit. Five neutron probe access tubes were installed, two at the centre of the area close to the tensiometer cups, with the others between this and one edge of the cleared plot.

In the centre of the plot, a 10 m square shed was erected with a corrugated iron roof and polythene sides to keep out rain and to cut down evaporation as much as possible. To reduce evaporation further, a 50 mm layer of grass mulch was applied to the soil surface.

In the first stages of the experiment, a constant rate of infiltration spread evenly over the centre 100 m^2 of soil was attempted. The area was divided into 25 squares with 2 m sides; in the centre of each square a nozzle delivered a constant trickle of water. The middle nine of these 2 m squares were each subdivided into four squares of 1 m side. Water was delivered to the centres of these smaller squares from the main nozzle via a manifold which split the water into four equal amounts. In the centre 2 m square, four secondary manifolds divided the water yet again so that equal quantities were delivered to sixteen squares of side 0.5 m. Figure 1 is a plan of the plot showing the position of the covered area, the pit, the access tubes and the irrigation nozzles.

To achieve a constant flow rate, water was pumped by a small petrol-driven pump from a 3,200-litre reservoir tank to a constant head tank 3 m above ground level. This supplied the nozzles via 25 mm diameter polythene pipe. The overflow from the tank ran back into the reservoir. The initial rate of application was nominally 25 mm d^{-1} and nozzles made from 2.6 m of 3 mm o.d. nylon tube were used to achieve the desired flow rate. The flow from each primary nozzle was measured daily, and the rate adjusted by altering the length of nylon tube. In addition, water was collected over extended periods of time from one extra primary nozzle and from the two spare secondary nozzles, which would otherwise have been allocated to the odd half 2 m square occupied by the pit.

It was found that there was quite a large change in flow rate due to the effect of the diurnal temperature variation on the viscosity of the water. The average rate of application was 23.4 mm d^{-1}. The soil moisture content became constant after 21 days, indicating that a steady state had been achieved; the nylon tubes were then replaced by 100 mm lengths of glass

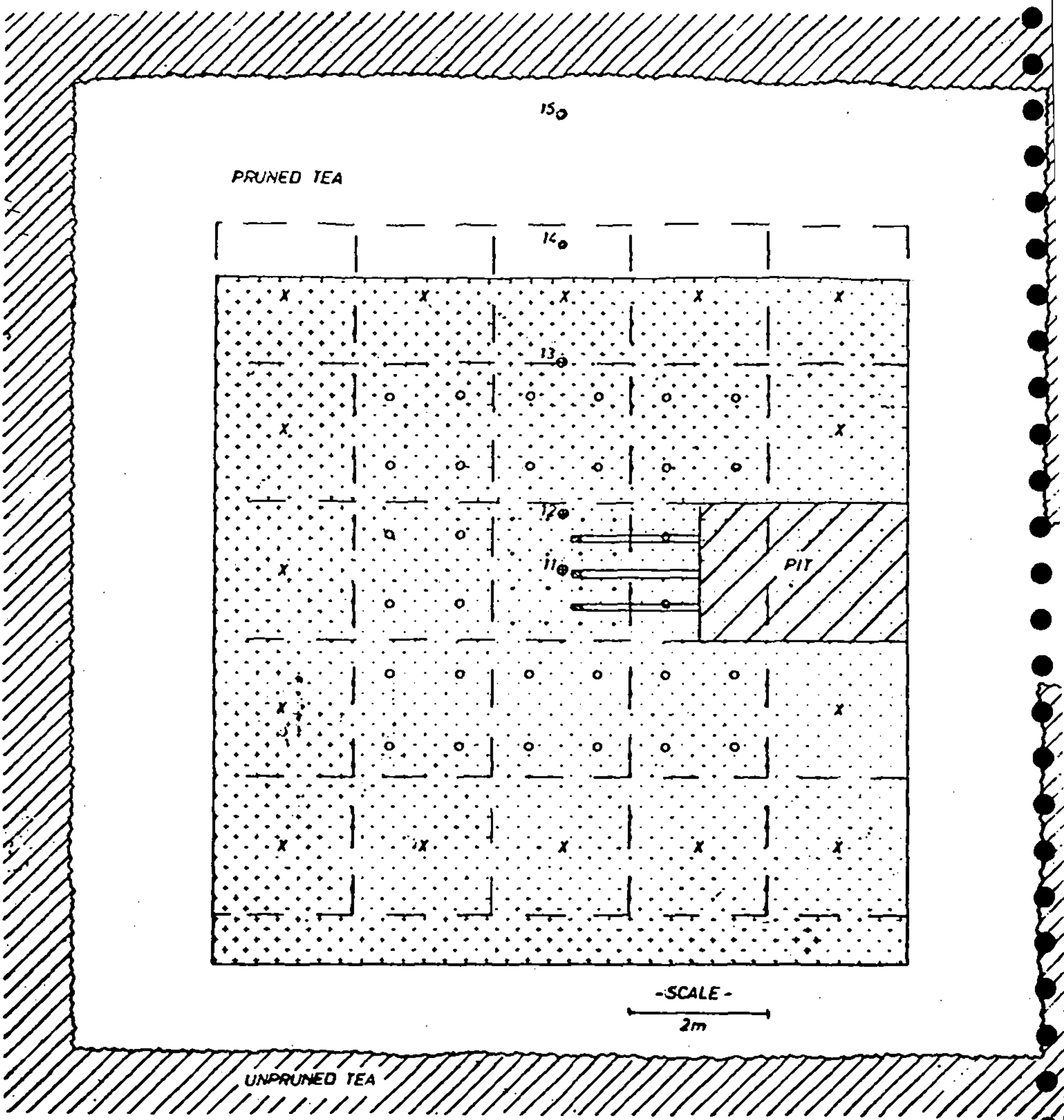

Figure 1 Plan of area used for measurements of soil hydraulic conductivity. The area beneath the shed is shaded. Broken lines represent the boundaries of the 2 m squares used as the basis for irrigation. The positions of the primary, secondary and tertiary irrigation nozzles are marked X, O and . respectively. Neutron probe access tubes are shown as ⊕ and tensiometer positions are shown at one end of the pit.

capillary tube which decreased the application rate to approximately 5.8 mm d^{-1}. Irrigation was stopped after a further ten days when a steady state had been re-established. Neutron probe and tensiometer readings were made twice daily during the period of irrigation.

After irrigation had ceased, readings were continued twice daily for seven days, then daily for 14 days; thereafter, the tensiometers were read daily, whilst soil moisture was measured by neutron probe twice a week for 24 weeks.

RESULTS AND DISCUSSION

Measurements Beneath the Tea (Site 1)

Moisture content and potential profiles are shown in Figs 2 and 3 for a number of occasions. The ZFP depths are indicated in Fig 3.

The progress of the ZFP depth with time is shown in Fig 4. As stated above, the experiment was carried out at a time of unusually severe drought; this, and the deep-rooting habit of the tea may explain why the position of the ZFP fell to a depth of 4.6 m by the end of the experiment.

The results of calculations using the ZFP depths represented by the solid line of Fig 4 with equations (8) and (9) to derive evaporation and drainage from the profile, are represented in Fig 6 as accumulated values from 10 December 1974. A mean water content for all five access tubes has been used.

Total evaporation, taking into account evaporation of intercepted water (T = rainfall in equation (8)) and net evaporation excluding interception (T = throughfall + stemflow) are shown in Fig 6. Also shown, for comparison, is accumulated Penman potential evaporation EO.

Interception (defined as the difference between rainfall and the sum of stemflow and throughfall) is plotted as a function

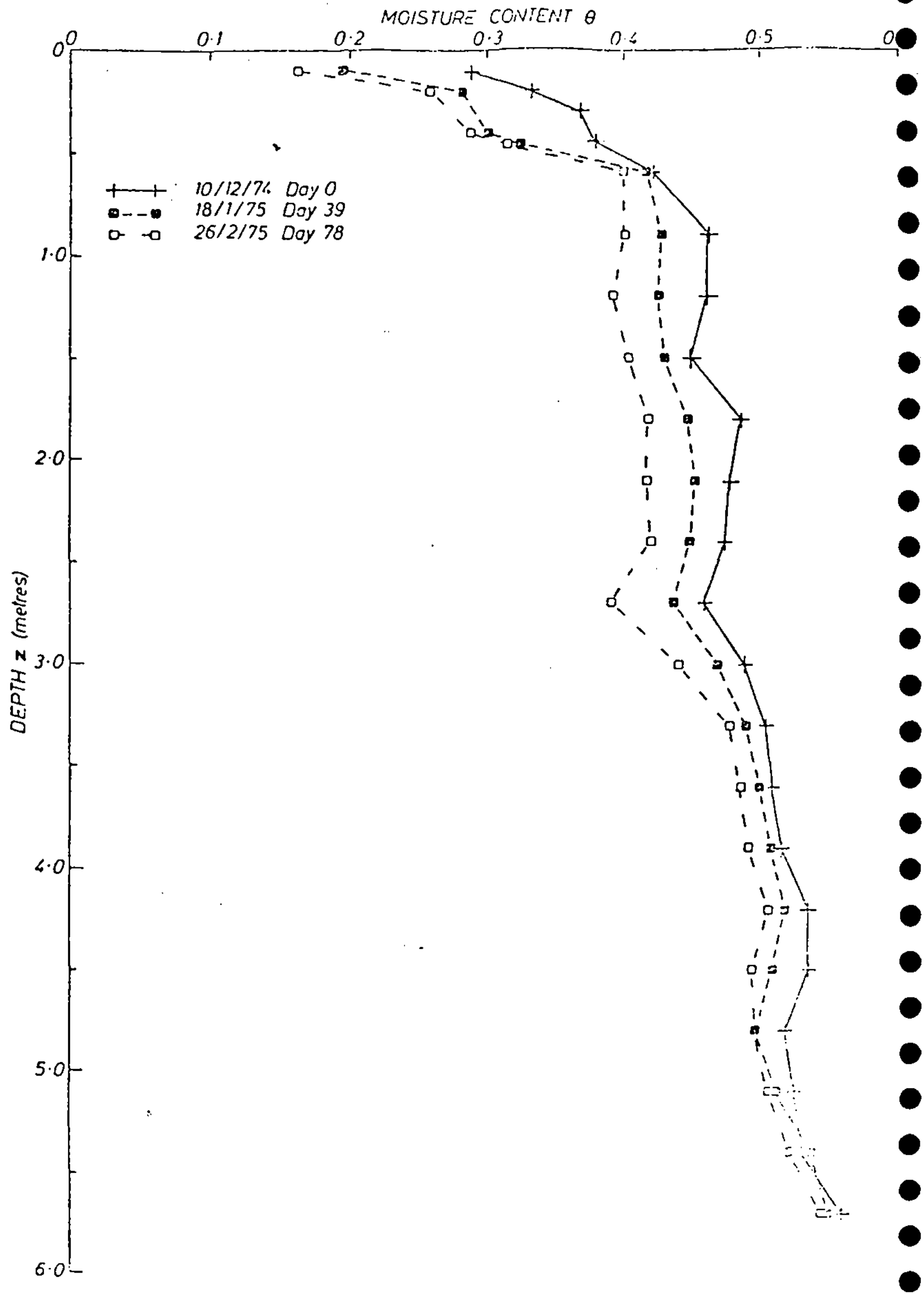

Figure 2 Soil moisture content profiles beneath the tea (Site 1) on three days during the experiment. Each profile is made up of the mean of readings from five neutron probe access tubes down to 2.7 m and from two tubes below this depth

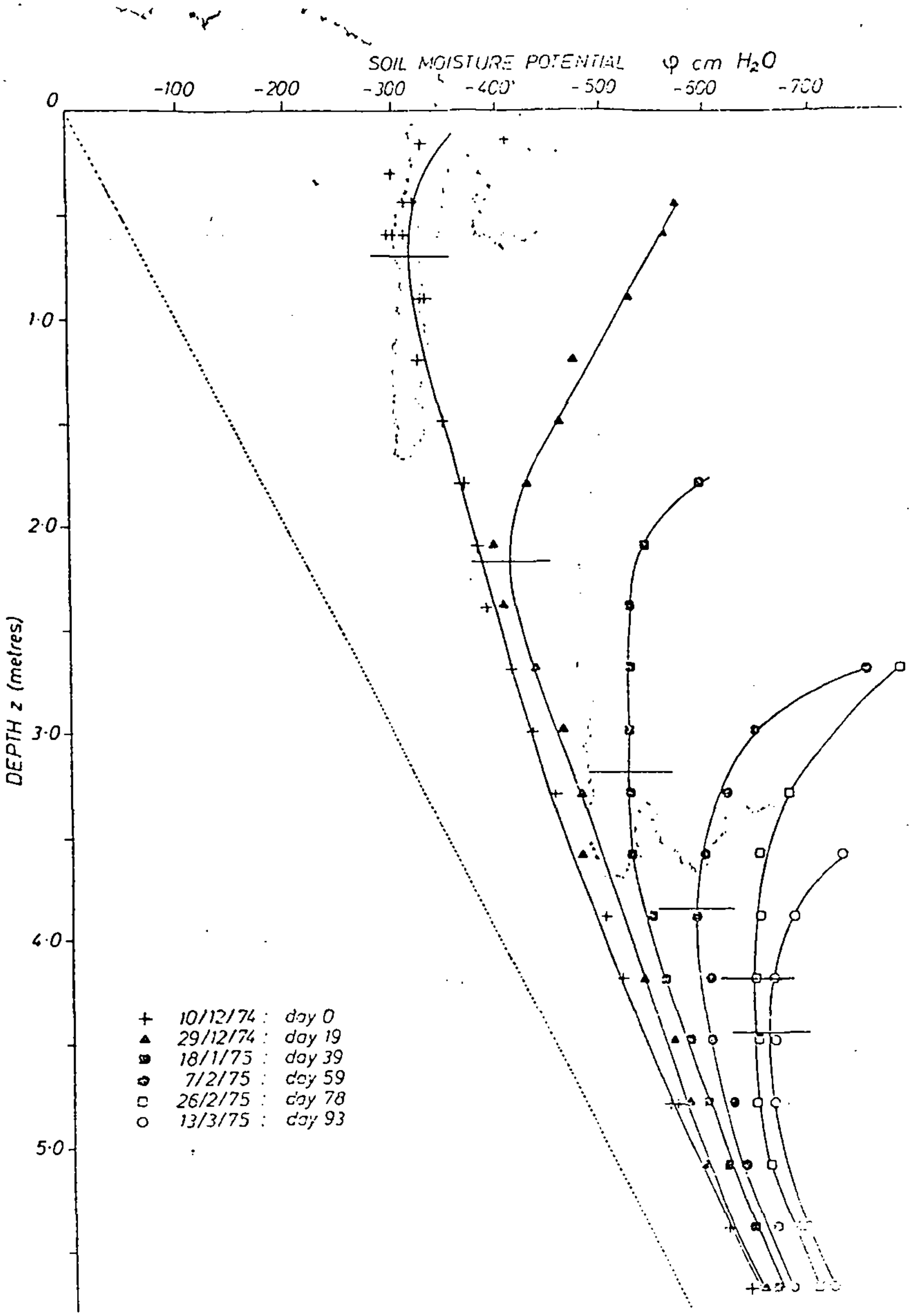

Figure 3 Soil moisture potential profiles beneath the tea (Site 1) on six days during the experiment. For the first day readings from all tensiometers installed are plotted, but only those from one tensiometer at each depth are shown for subsequent days. ZFP depths are indicated by horizontal lines

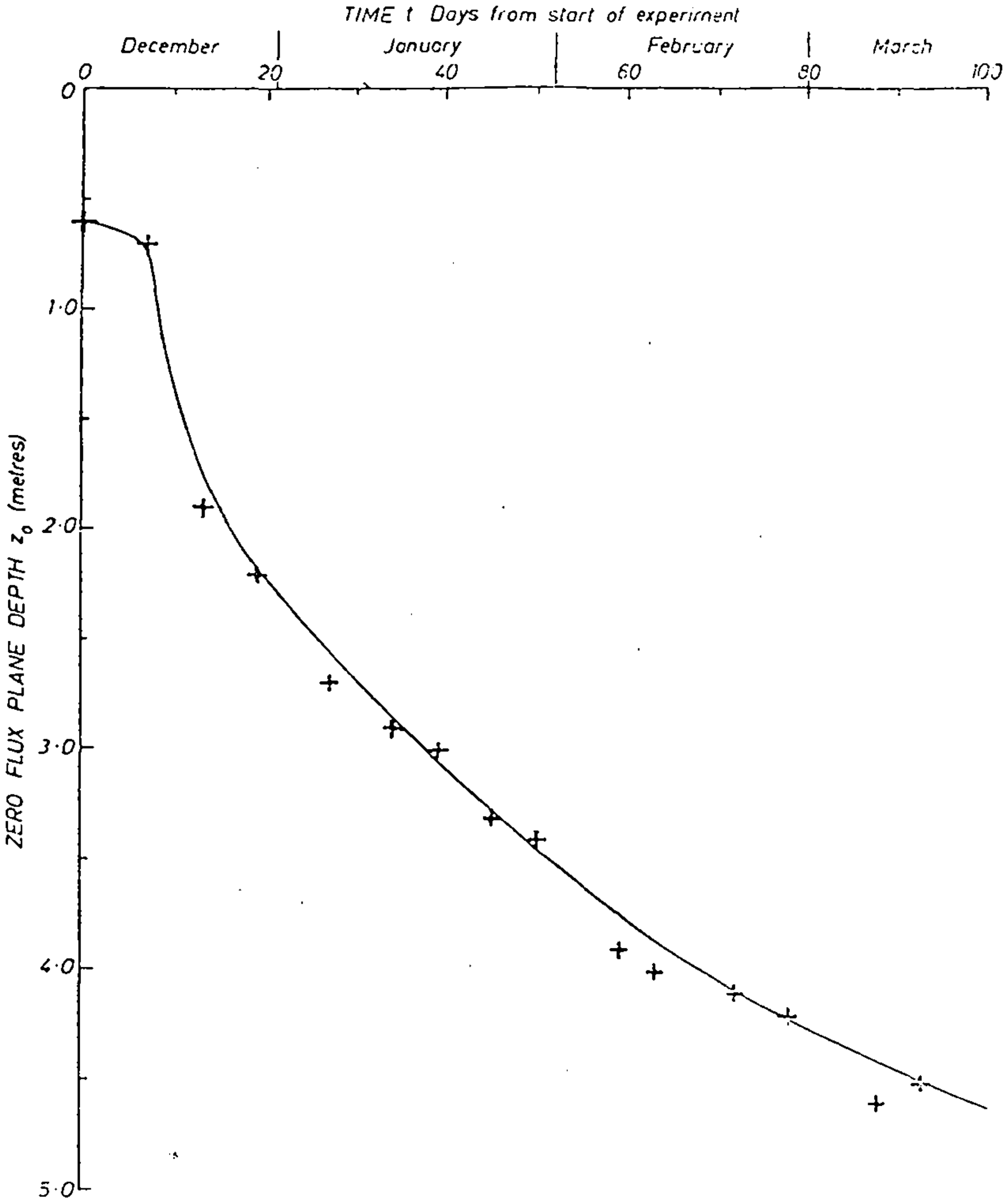

Figure 4 ZFP as a function of time. The solid line represents the values used in the subsequent analysis

of rainfall in Fig 5. The relationship defined by the solid line has been used to make interception estimates for individual days. Further details of the interception and throughfall measurements will be published elsewhere.

The evaporation and drainage results of Fig 6 inevitably show a certain amount of scatter. This arises largely from the following causes:-

(a) Random counting errors. The effect of these on neutron probe measurements has been described by Bell (1976). They arise because of the random nature of disintegration within the neutron source and of collisions in the soil. In the present experiment, the standard error associated with this source of error is equivalent to about ± 3.5 mm of water for a single profile determination using 64 second integration times in a 5.7 m deep profile containing about 2600 mm of water (Bell, 1976).

(b) Probe placement errors. These are difficult to quantify with any accuracy, but appear to be of the same order as errors due to (a) above.

(c) Uneven throughfall. This will affect the evaporation results, though not the drainage. Because of the way the bushes modify the areal distribution of water input an access tube may fortuitously be placed at a point receiving markedly more or less throughfall than the average; in this case, an abnormally low (sometimes negative) or high estimate of evaporation will be derived from the application of equation (8). This effect will, however, be temporary since over a sufficient time equation (8) can be expected to be correct for all positions beneath the bushes. This can just be discerned in Fig 6.

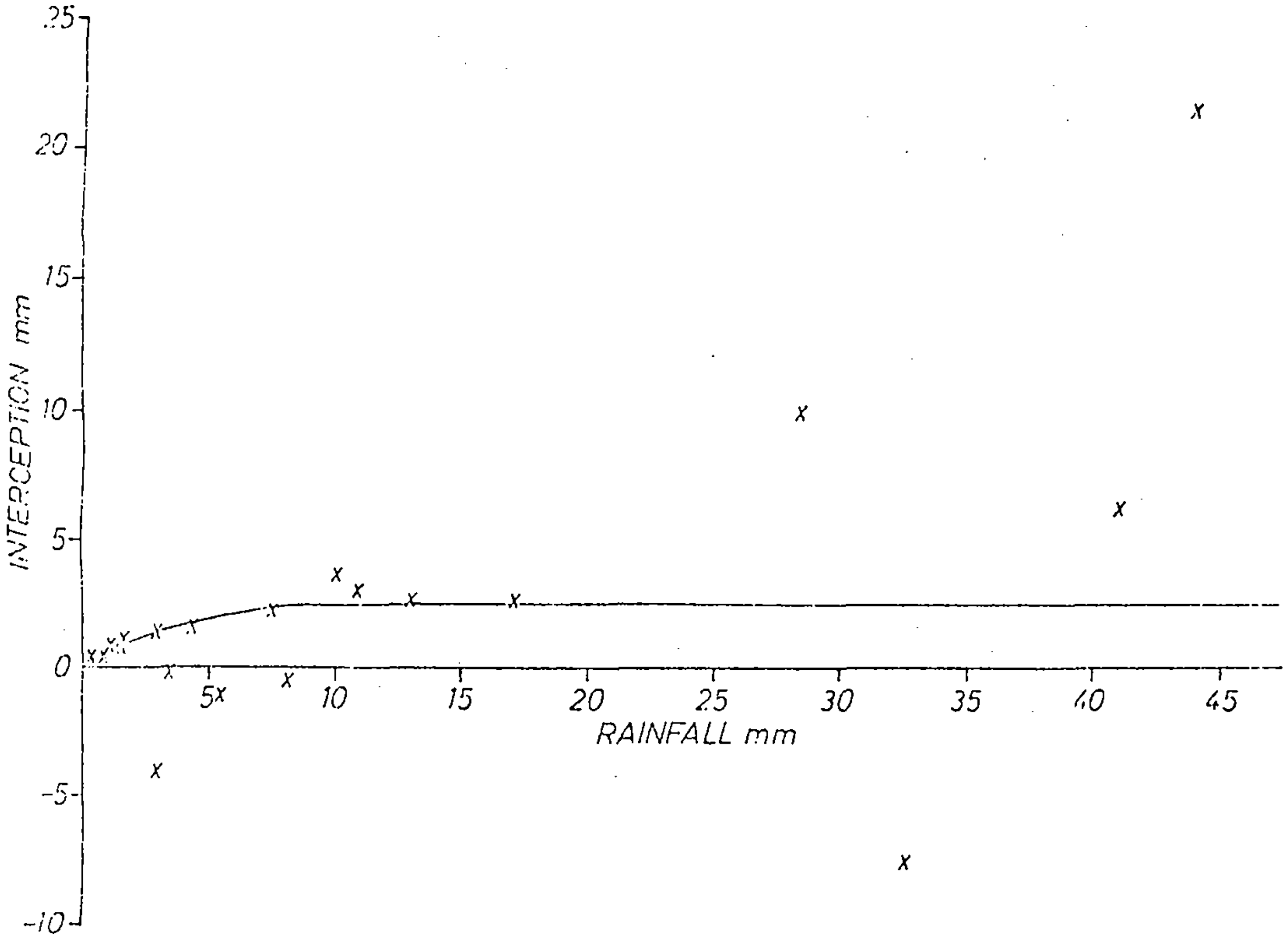

Figure 5 Daily interception values as a function of daily rainfall. The assumed relation is shown by the solid line

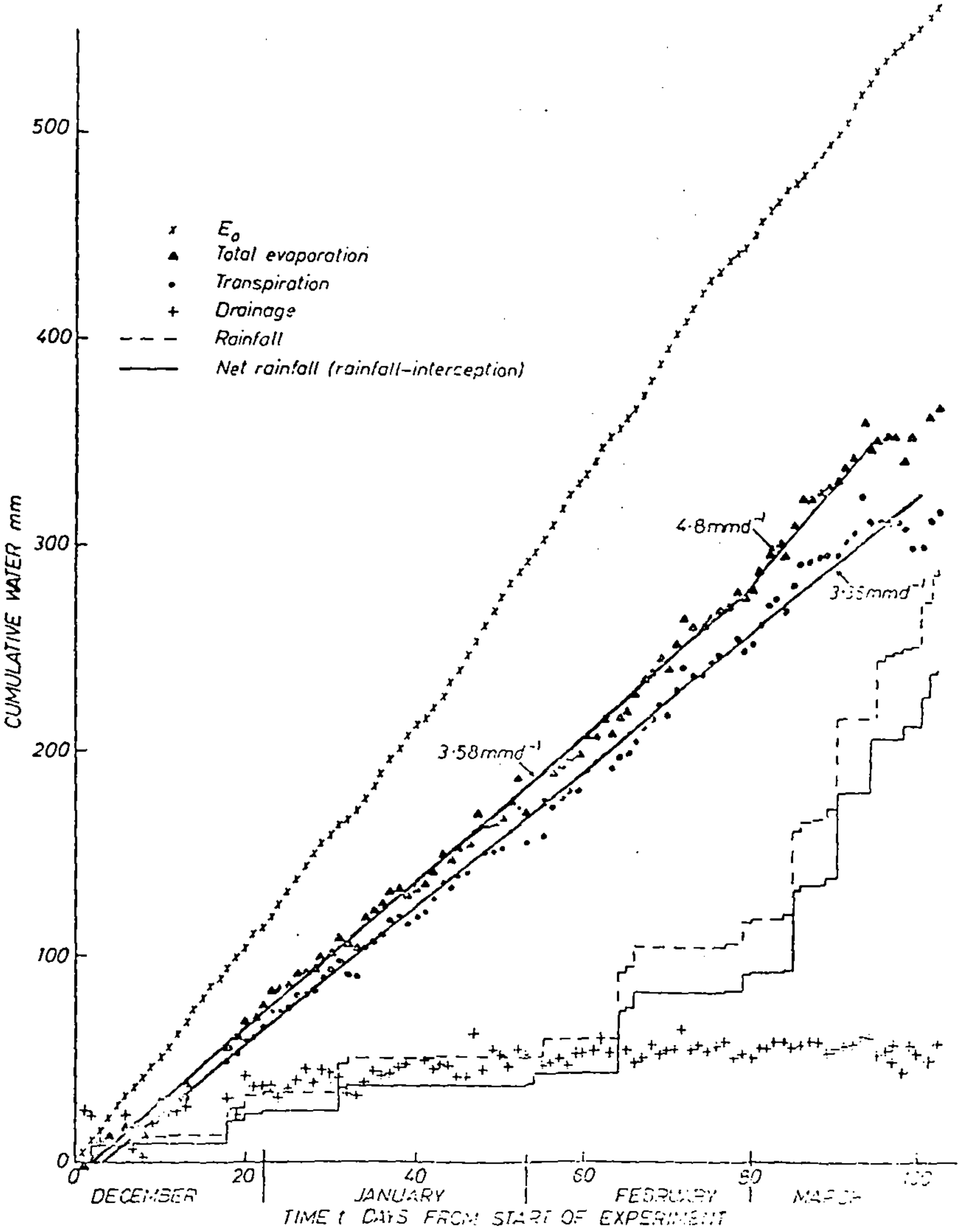

Figure 6 Cumulative values of total evaporation, transpiration and drainage for Site 1 derived by the ZFP technique. Values of cumulative rainfall, net rainfall and calculated EO are also shown

Despite (c) above, scatter in the drainage results is greater than in the evaporation estimates. This is partly because the results of Fig 6 are derived from a mean of five access tubes for the upper 2.7 m and only two from 2.7 m to 5.7 m. Furthermore, probe placement and random counting errors are larger near the bottom of the profile, the latter because of higher count rates due to greater water content there.

For certain uses, the measurements just described are needed in a form which can be related to climatic and other environmental variables. Fig 6 has therefore been replotted using Penman's cumulative EO instead of time as the independent variable; the result is shown as Fig 7. Within limits imposed by scatter of the data, Figs 6 and 7 both give acceptably straight lines with transpiration rates of 3.36 mm d^{-1} or 0.56 EO. The latter figure is in excellent agreement with that of 0.56 EO found by Willatt (1973) for a hot dry period in Malawi.

Care is necessary when interpreting the departure of the cumulative transpiration curve from the straight line in Fig 7 near the end of the experiment. This occurred during a period of fairly high rainfall (170 mm in 19 days) and examination of equation (8) shows that transpiration is calculated essentially as the difference between net rainfall and change in soil moisture above the ZFP. When these components are much larger than their difference, relatively minor errors in one or other of them can cause large discrepancies in the transpiration estimate. The reconvergence of the transpiration curve to the straight line after the subsequent drier spell suggests that this may indeed be what is happening. Apart from this there is no evidence of the effects of water stress on transpiration rate.

Previous work on water use of tea in the Kericho area (Dagg, 1970; Wang'ati and Blackie, 1971; and Laycock, 1976) have all considered total evaporation as a function of EO and have found values ranging between 0.8 and 0.9 EO. Before late

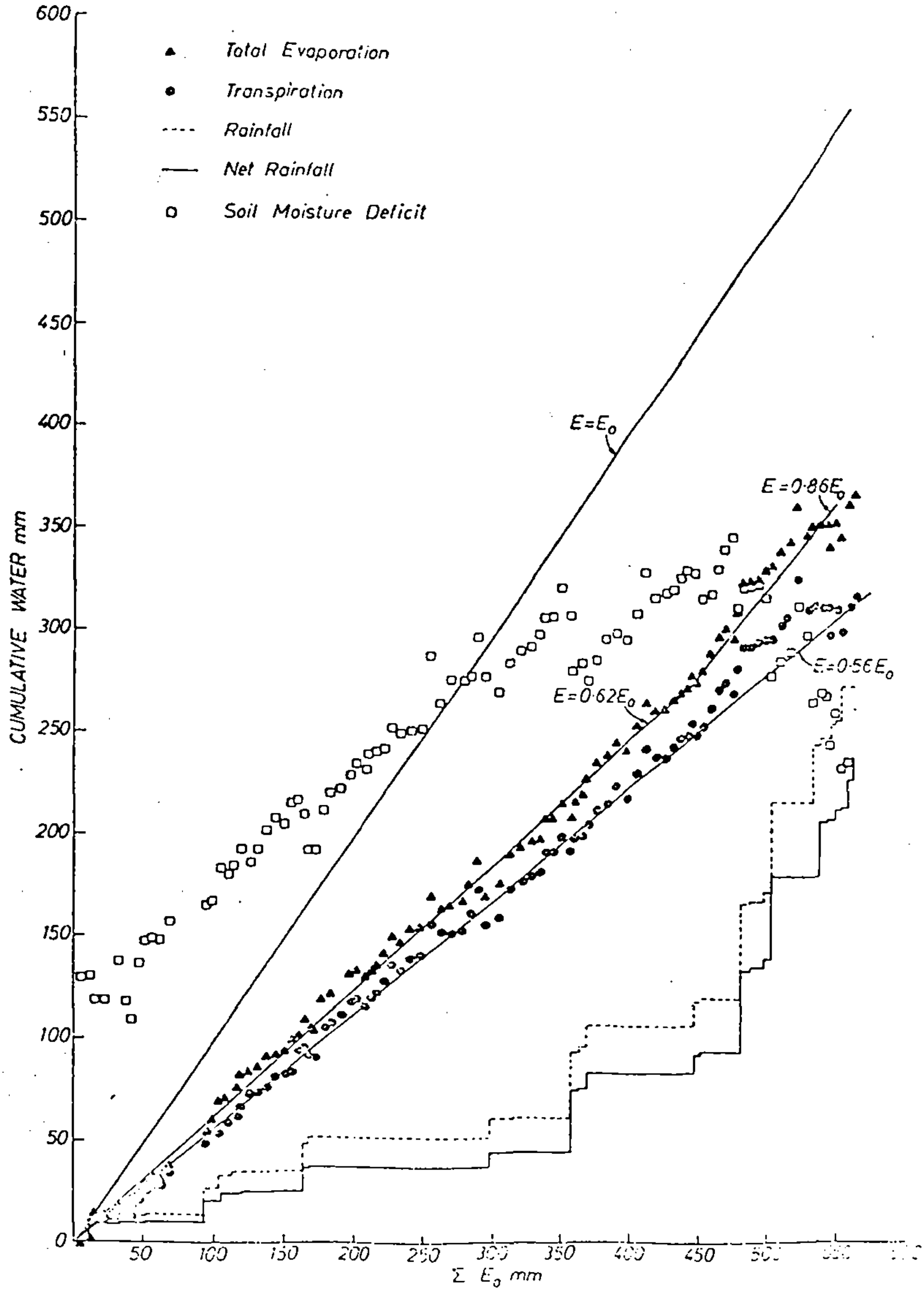

Figure 7 Cumulative total evaporation, transpiration, drainage, rainfall and net rainfall as shown in Figure 6 plotted as a function of cumulative EO. Soil moisture deficits are also shown.

February in the present experiment, rates of 3.58 mm d^{-1} and 0.62 EO were recorded (Figs 6 and 7); however, after the end of February, the total evaporation rate increased to about 0.93 EO. Examination of Figs 6 and 7 suggests that this increase in evaporation is almost entirely due to the evaporation of intercepted water, with only a small increase, if any, by transpiration. It therefore appears that evaporation of intercepted water is not at the expense of transpiration at this time of year.

The number of rain days at Kericho is, on average, about 240 per year, which represents a total of approximately 600 mm per year of interception. If it is assumed that transpiration proceeds at 0.56 EO, this gives a total for transpired water of 825 mm from a cumulative mean EO of 1474 mm, and a total evaporative loss of 1425 mm or 0.97 EO. Clearly a figure of 0.56 EO for the transpired water cannot hold for the year as a whole, probably because transpiration is suppressed at times when intercepted water is being evaporated during those months when the tea canopy is frequently wet and evaporative demand is much lower.

The apparent lack of any significant response of transpiration to water stress is at variance with the findings of Willatt and others (1971 and references quoted therein), who found quite significant reductions in total evaporation rate as soil moisture deficits increased beyond about 200 mm. There will be, however, a correlation between moisture deficit and rainfall and hence interception. Thus, when deficits are high, interception is expected to be low, so that total evaporation will be reduced significantly from this cause alone.

The validity of the foregoing measurements rests partly on the accuracy of the neutron probe measurements and partly on the validity of the ZFP method. The accuracy of moisture content changes is as accurate as the gradient of the neutron probe calibration curve. This is believed to be accurate to about 10%, and drainage estimates will be in error by the same amount.

For the evaporation, on the other hand, 216 mm from a total of 347 mm evaporation over the period has come from rainfall (equation (8)); if the rainfall is assumed accurate, therefore, the error in evaporation resulting from a 10% inaccuracy in the calibration curve would be 3.8%. In practice, of course, the rainfall measurements will not be completely accurate, though this error will not necessarily be in the same direction.

For its success, the ZFP method requires that there be no extraction of water by roots beneath the ZFP, since all losses of water in this region are assumed to be due to drainage. Given that roots are known to penetrate to at least 6 m, this is unlikely to be strictly fulfilled. However, the following points make it probable that extraction from below the ZFP is at most relatively small:-

(a) Although no quantitative information is available on the distribution of roots within the profile, the overwhelming majority have been observed within the upper metre of soil. Provided that water is fairly readily available it is expected that these roots will extract most of the water with only a tiny proportion coming from lower in the profile.

(b) As the ZFP gets deeper, the fraction of roots below it becomes steadily less.

(c) There is, at all times, at least one metre of soil above the ZFP at a tension of less than one bar. Drying within the upper 2 m, where potentials reach several bars, proceeds quite steadily to the end of the experiment, so that water must be available even at these tensions.

Measurement of Soil Hydraulic Conductivity (Site 2)

Potential profiles measured during the steady state period for the two irrigation rates and for a number of occasions during the subsequent drainage, appear in Fig 8.

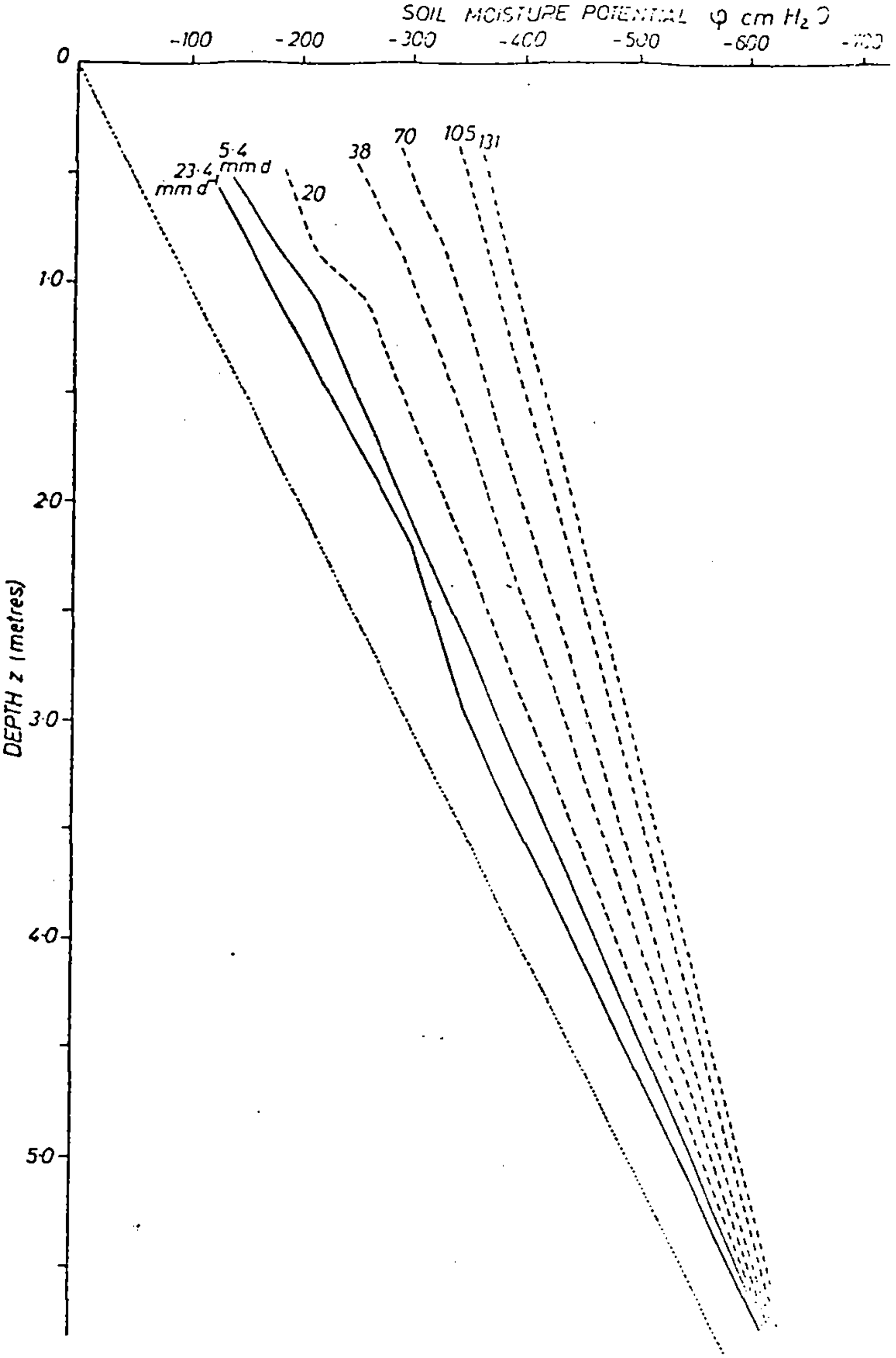

Figure 8 Soil moisture potential profiles for Site 2 during the hydraulic conductivity measurement. The solid lines are from measurements made at steady state during infiltration at the two rates, while broken lines represent data taken during the period of subsequent drainage. The figure by each broken line is the number of days since irrigation was stopped.

Cumulative drainage fluxes at the centre of the measurement plot, for the period of free drainage after irrigation had ceased, are shown for various depths in Fig 9. These were calculated by the instantaneous profile method (Watson, 1966). These data were smoothed by least squares, taking as the fitted curve an exponential plus a fifth order polynomial; the fitted curves are shown as solid lines. From the smoothed fluxes and the measured potential gradients, the conductivity can be calculated at each depth and expressed as a function of water content or suction; these are presented in Figs 10 and 11. It should be emphasised that these curves have been derived for a period of steady drying of the soil; it is expected that hysteresis would destroy the single-valued nature of these relationships if both wetting and drying cycles occur. This should be especially true of the K (ψ) relation.

The problem now arises of how to apply these measurements to the sites beneath the tea. It seems reasonable to take the curve corresponding to 5.7 m depth at Site 2 as the most likely to correspond to the same depth beneath the bushes at Site 1. Since the precision of moisture content measurements is less than that of the tensiometer readings, the K (ψ) relationship has been used.

Unfortunately, the range of soil tensions recorded at this depth beneath the tea ranged from 68 to 134 cm of water, whereas in the conductivity measurement experiment it did not exceed 66 cm of water. However, at Site 2 the ratio of conductivities at the same tension for different depths is quite impressively constant; this allowed the use of the K (ψ) relation found for the 3.9 m depth, which has been measured over the required tension range, multiplied by 0.075. Table I gives values of the ratio of conductivity at 5.7 m and 3.9 m.

In Fig 12, the cumulative drainage flux at 5.7 m depth at Site 1, using conductivity derived by the above procedure, has been plotted together with the drainage estimate from the ZFP method. Although the actual magnitudes of the drainage found using the

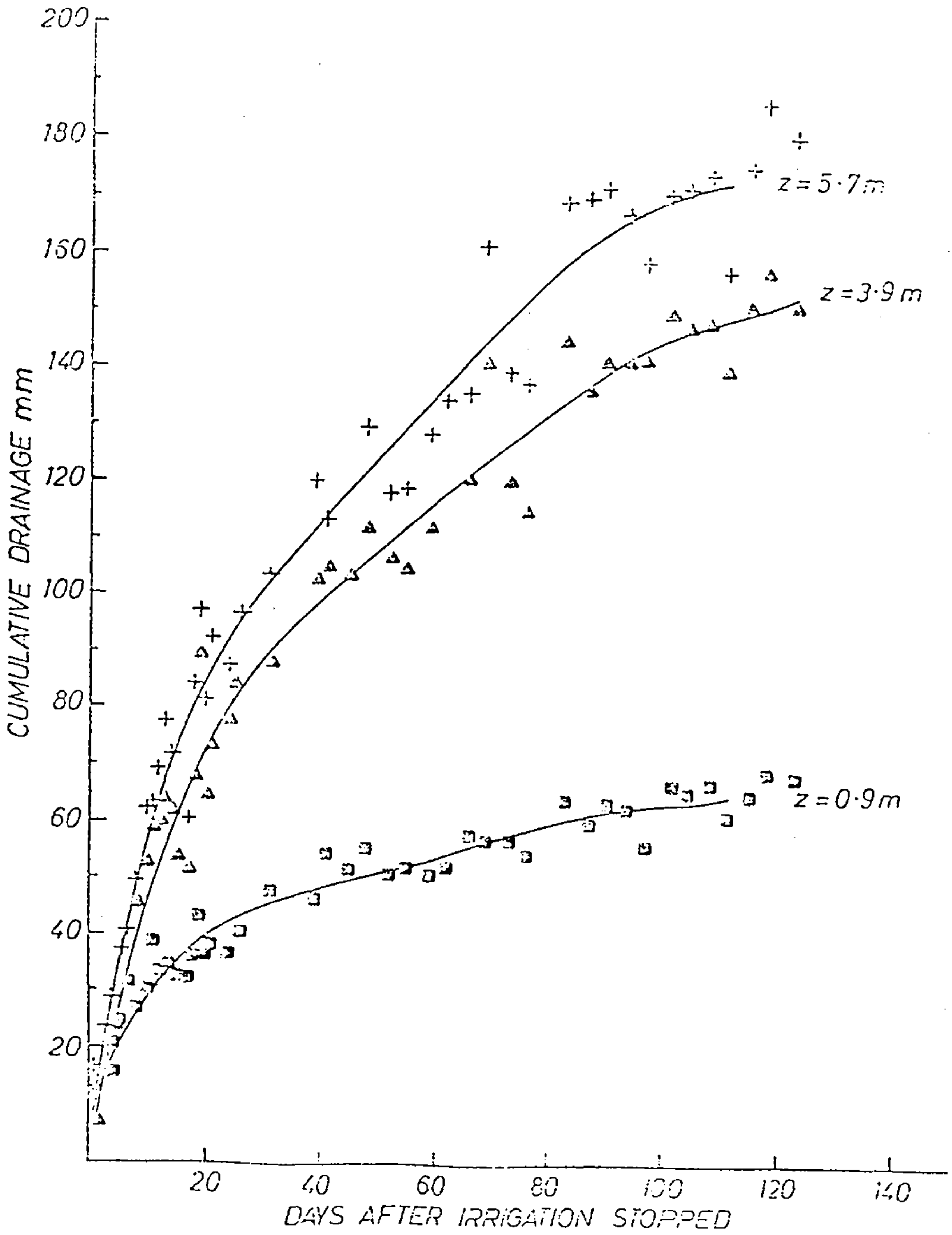

Figure 9 Cumulative drainage from the profile at three depths for Site 2. The solid lines show the fitted curves

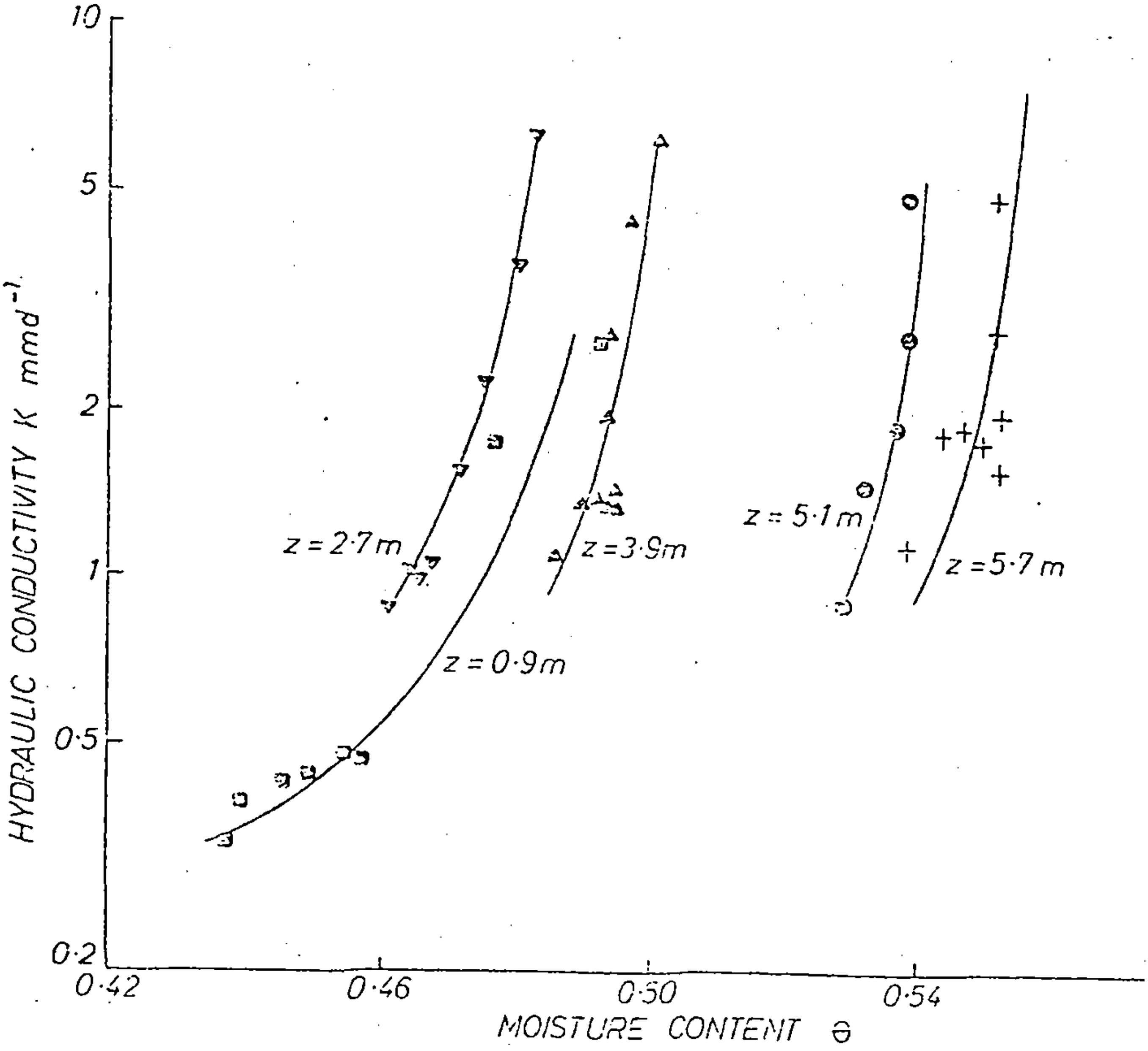

Figure 10 Hydraulic conductivity of the profile at Site 2 as a function of moisture content at five depths

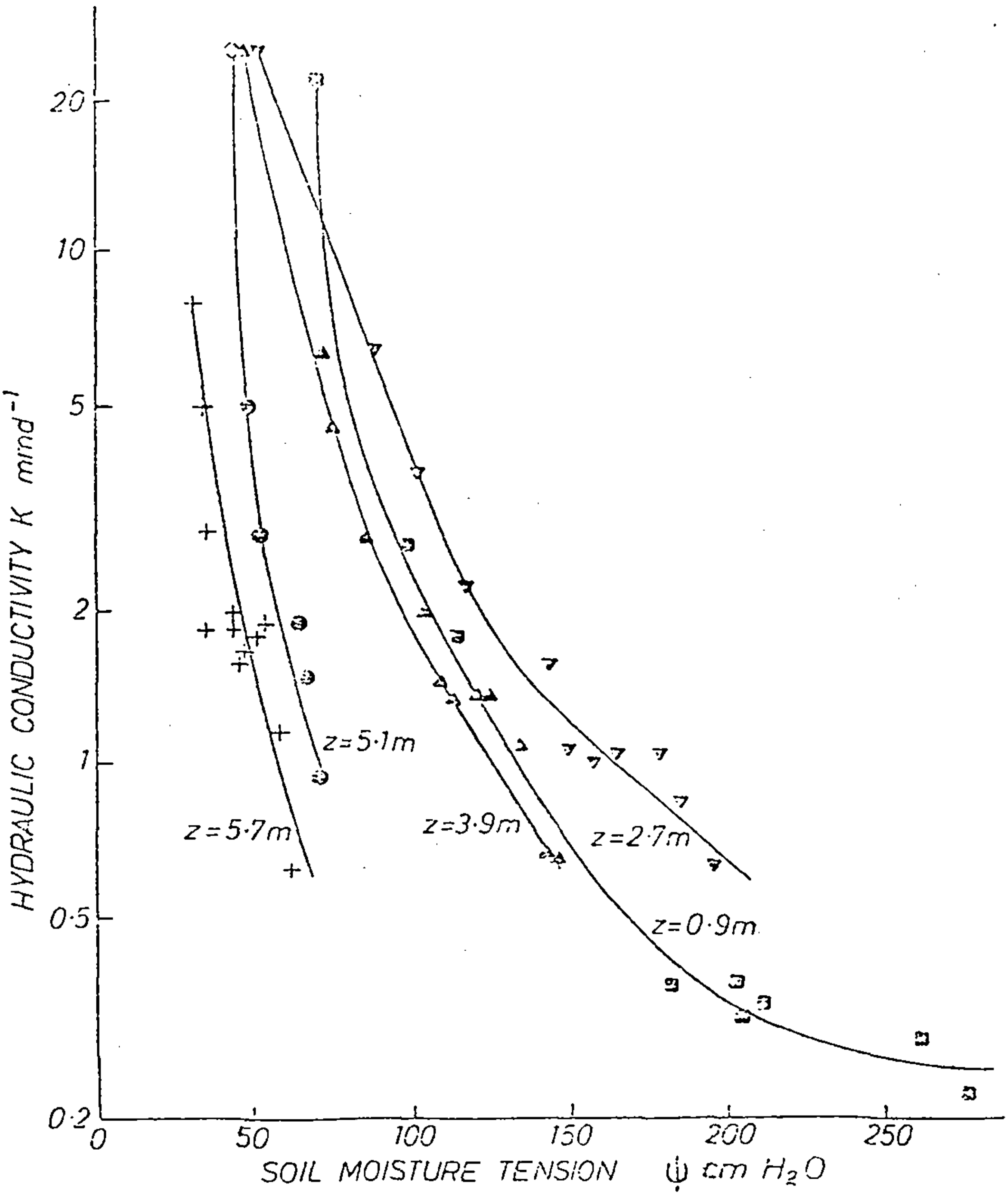

Figure 11 Hydraulic conductivity of the profile at Site 2 as a function of tension at five depths

TABLE I

Ratios of Unsaturated Conductivity at Two Depths Measured from Access Tube II Site 2

Tension ψ cm H_2O	Conductivity at 3.9 m K_{390} mm d^{-1}	Conductivity at 5.7 m K_{570} mm d^{-1}	Ratio K_{570}/K_{390}
47	24.5	1.80	0.0735
50	20.7	1.52	0.0734
55	15.5	1.15	0.0742
60	11.4	0.87	0.0763
65	8.6	0.65	0.0756

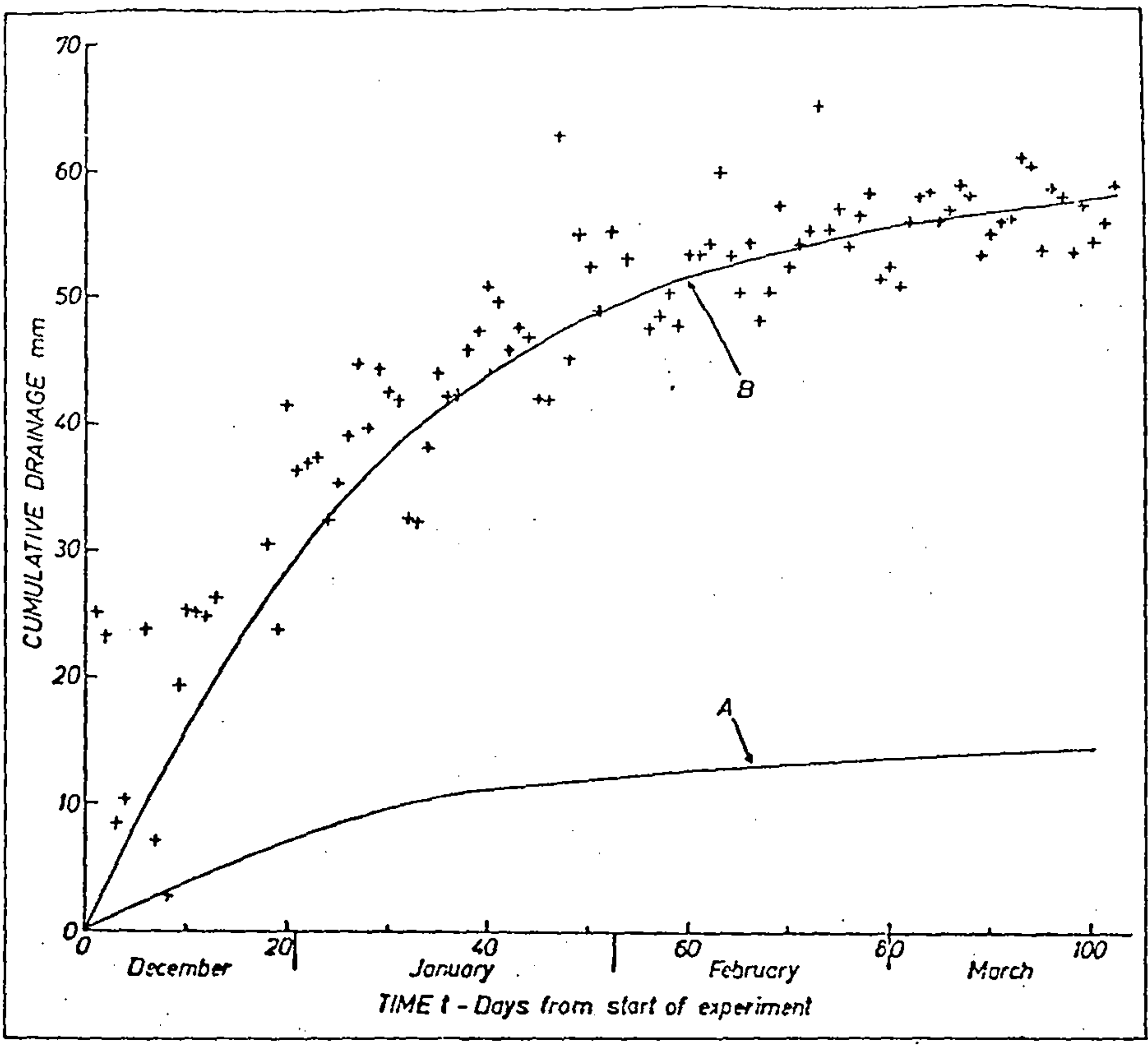

Figure 12 Comparison of drainage at 5.7 m from Site 1 derived using the ZFP technique and the hydraulic conductivity-potential gradient method. Curve A shows the drainage derived using hydraulic conductivity for the 5.7 m depth at Site 2. Curve B is the similar curve obtained by multiplying the conductivity by a factor of four. Crosses represent drainage estimates by the ZFP method

two methods do not agree well, the shapes of the curves are similar, as may be seen by comparing the ZFP-derived points with the curve obtained by scaling the conductivity up by a factor of four.

There are, then, two possible explanations for the discrepancy in Fig 12:-

(a) Root abstraction below the ZFP may make up all or part of the difference;

(b) The conductivity relation used for the 5.7 m depth beneath the tea is too low by a factor of about four. This would correspond to using the conductivity found for the 5.1 m depth at Site 2. The two sites are separated by some 30 m, and although the ground surface is almost level, the assumption that the conductivity values correspond at the same depths at different sites is not necessarily justified.

Since the shape of the ZFP drainage curve is well-described by the conductivity-potential gradient method, even though the magnitude is not, it is possible, but by no means certain, that explanation (b) holds; in any event, the drainage rate is fairly small except near the beginning of the experiment, so that even if the whole of the drainage flux were to be added to the evaporation, the latter would be increased by about 17% overall and by only 8% for the period from 10 January.

CONCLUSION

Over an unusually dry period from 10 December 1974 to 14 March 1975, transpiration from a site on a tea estate near Kericho, Kenya, was measured as 3.36 mm d^{-1}. This represented approximately 0.56 of open water evaporation calculated from Penman's formula. Total evaporation was somewhat higher, the difference being accounted for by interception. The amount of water intercepted by the tea bushes is approximately 2.5 mm for storms of more than 8 mm; a rough calculation shows that evaporation of intercepted water alone over the year amounts to about 0.4 EO.

Adding the evaporation of intercepted water to that from transpiration, and assuming that the former will occur at a rate significantly greater than the latter, plausible agreement with previous estimates of total evaporation in the region 0.8 - 0.9 EO is obtained.

There appears to be little, if any, effect of water stress on the transpiration rate. It is suggested that where such large effects have been reported previously, the cause may have been a reduction in interception during periods of large soil moisture deficits.

Measurements *in situ* of unsaturated hydraulic conductivity have been made close to the experimental site to a depth of 5.7 m. Despite a particularly homogeneous soil, it was difficult to extrapolate conductivity values from one site to another because:-

(a) The moisture range at the lowest depths at two sites for which data are available did not overlap;

(b) Hydraulic conductivity was found to be a strong function of depth.

Using crude assumptions about the function relating hydraulic conductivity to depth, drainage rates beneath the tea have been estimated using the hydraulic conductivity-potential gradient method. Although the pattern, of cumulative totals over time, of these estimated drainage rates is similar to the pattern of those estimated drainage rates derived by the ZFP method, their absolute values differ by a factor of 4.

The good correspondence between the shapes of the two curves is taken as evidence that the ZFP method gives reliable drainage estimates. Given the strong dependence of hydraulic conductivity on depth, a discrepancy by a factor of four does not seem unreasonable, but further work is clearly needed on this problem.

Drainage was small, but not insignificant, over the period, amounting to 17% of total evaporation, or approximately 60 mm.

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2.2.4

AN ASSESSMENT OF SOIL EROSION ON A FIELD OF TEA UNDER DIFFERENT SOIL MANAGEMENT PROCEDURES

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2.2.4

AN ASSESSMENT OF SOIL EROSION ON A FIELD OF TEA UNDER DIFFERENT SOIL MANAGEMENT PROCEDURES

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INTRODUCTION

In East Africa, tea is usually grown on land of undulating topography formerly covered with primary or secondary forest. After forest clearance, land is very vulnerable to soil erosion until the newly planted tea has an established canopy cover; this paper reports measurements of soil erosion recorded on a soil conservation experiment designed to give quantitative information on run-off and soil erosion from a tea field.

EXPERIMENTAL DESIGN AND TREATMENTS

The experiment was sited on land excised from the Western Mau Forest Reserve, as described in Section 2.1.2. Sixteen plots, each of size 18.3 m x 3.7 m (60' x 12') were marked out on land cleared in 1970 by heavy crawler tractor; the sixteen plots were divided into four blocks of four plots each in a randomised block design. After clearance, the land was planted immediately with oats as a cover crop; wooden planks were used to demarcate the upper and lower edges of each plot. In September 1971, the area was planted with clonal sleeved tea plants at 1.22 m x 0.9 m (4' x 3') spacing.

At the lower boundary of each plot, a concrete trough served to channel both runoff and eroded soil through asbestos pipes 10 cm in diameter into pits, which contained separate collecting tanks for two adjacent plots. Past rainfall records showed that daily rainfall was unlikely to exceed 150 mm, and the size of the tanks was calculated on the assumption that about 80 per cent of the storm rainfall would run off when the soil moisture content was at or above field capacity. For each plot, all the runoff and eroded soil was collected in Tank A where most of the soil settled; the overflow, mostly runoff with very little soil in suspension, was passed through a divisor and the fraction thus obtained collected in a second tank B (see Fig 1). Once installed, the collecting tanks were calibrated using a dip stick. The experimental design and the runoff and erosion collecting system was adapted from those used by Hudson (1957) and Hendrickson et al (1963).

In November 1971, the following soil management treatments were applied to the newly planted tea in four-fold replication:-

(1) Bare soil between tea plants; weeds controlled manually by hoeing and hand-pulling (tillage);

(2) Bare soil; weeds controlled by herbicides and hand-pulling (non-tillage);

(3) Oats planted between the rows of tea; weeds controlled by herbicides and hand-pulling;

(4) Soil surface covered by a mulch of *Eragrostis curvulla*; weeds controlled by herbicides and hand-pulling.

The manual (tillage) treatment was expected to create, at the surface, a loose soil cap which would serve to dissipate the energy of raindrops; this treatment simulated the method of weed control still widely used by small-scale growers. Most large-scale growers now use herbicide (non-tillage) weed control simulated by the second treatment above. Oats were planted and maintained as recommended in the Tea Grower's Handbook (1969). Mulch was applied at the rate of 15 tonnes ha^{-1} (dry weight) in a split application in the first year of treatment and as a single application in the years thereafter.

Runoff and eroded soil were measured once a day after storms.

RESULTS

Table I summarises three years' results from the four different soil management treatments.

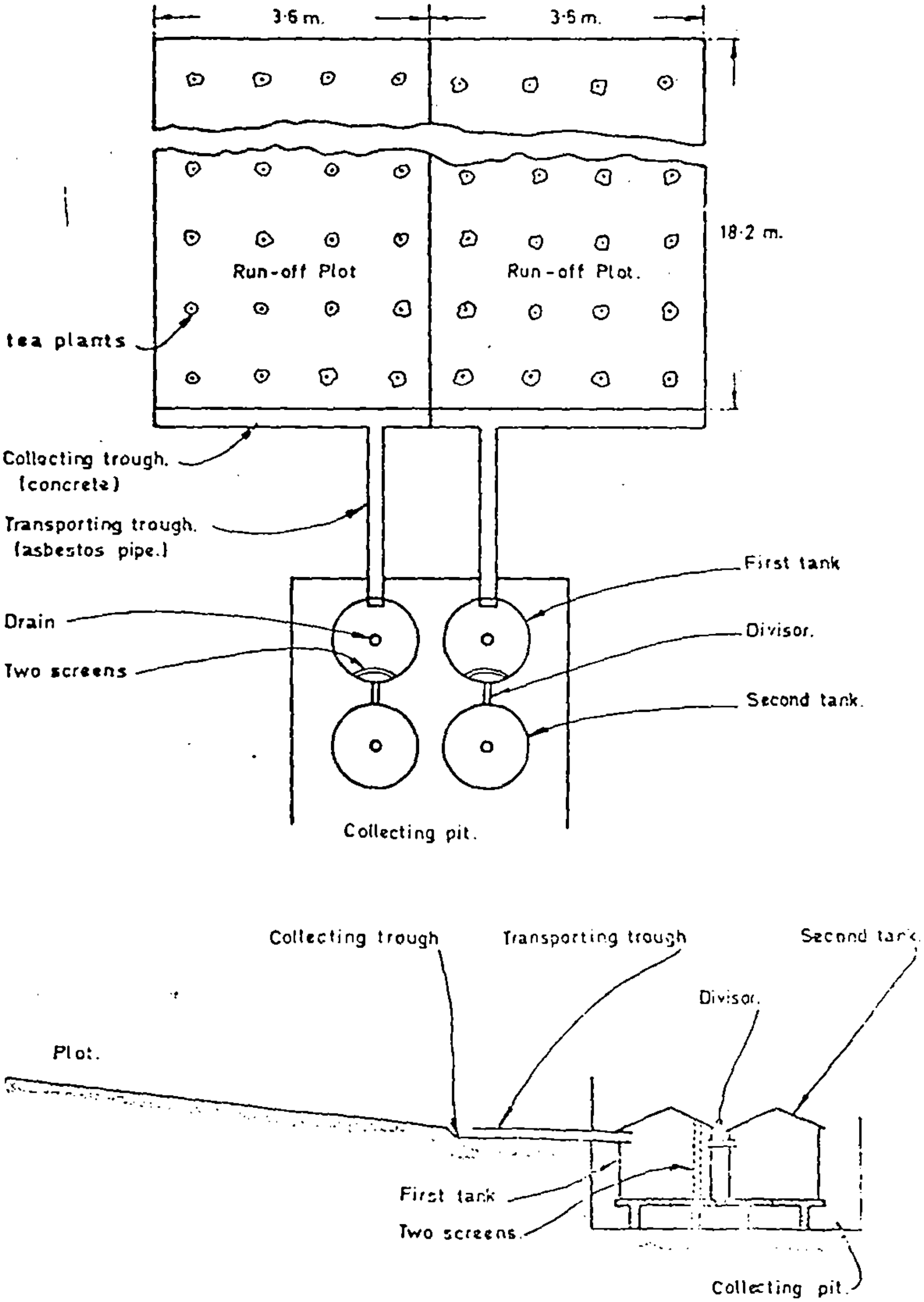

Figure 1 Runoff plots at the Tea Research Institute, Kericho

TABLE I

Soil Erosion (tonnes ha^{-1}) and Rainfall (mm)

	Year			Total
	1971/72	1972/73	1973/74	1971 to 1974
Soil Erosion				
Manual (tillage)	161.28	48.28	1.23	210.79
Herbicide (non-tillage)	168.08	80.71	6.09	254.88
Oats	34.90	4.31	0.42	39.63
Mulch	0.46	0.14	0.08	0.68
SE	±5.32	±6.14	±0.73	±11.68
Rainfall	2083	2045	1985	6113

(a) First Year

For all the treatments, soil loss was greatest in the first year following planting. The manual (tillage) and herbicide (non-tillage) treatments showed the greatest soil loss. In this first year, the tillage treatment (1) was incorrectly applied in that hoeing was unintentionally omitted from the sequence of field operations; because of the minimal soil disturbance which resulted, the first year's soil erosion from the tillage treatment was very similar to that from the non-tillage treatment.

Soil loss from the oats treatment, in the month immediately following planting, amounted to 33.52 tonnes ha^{-1} out of a total of 34.90 tonnes ha^{-1} for the year; the very large loss in the first month resulted from a delay in establishing oats caused by three consecutive storms which washed away the seeds each time. Soil erosion was reduced considerably, however, once the oats were established. Excluding the replantings necessitated by heavy storms, there were two replantings of oats and three cuttings in the first year.

As stated above, mulch was applied at the rate of 15 tonnes ha^{-1} (dry weight) split into two equal applications. Its effectiveness in controlling soil erosion was marked, with soil losses of less than one tonne ha^{-1} compared with 161 and 168 tonnes ha^{-1} for the tillage and non-tillage treatments respectively.

(b) Second Year

Both hand-pulling and hoeing were used to control weeds in the tillage treatment in the second and third years of the experiment. In this second year, a total of seven weeding operations were performed; these were at monthly intervals during rainy periods and less frequently during dry periods.

The non-tillage treatment lost 80.71 tonnes ha^{-1} of soil compared with 48.28 tonnes ha^{-1} from the tillage treatment. This large difference is ascribed to the hoeing operation and the formation of a loose soil cap at the surface.

Once again, oats were very effective in controlling soil erosion; 4.31 tonnes ha^{-1} of soil were lost on average from plots planted into oats. Of this amount, 2.18 tonnes ha^{-1} were lost in the month of June 1973 following a replanting operation before the rows had been properly established. One other replant of oats was necessary during the year.

Mulch continued to be the most effective treatment against soil erosion. Only 0.14 tonnes ha^{-1} was lost on average from plots receiving the mulch treatments, compared with 48.28 and 80.71 tonnes ha^{-1} from plots given the tillage and non-tillage treatments respectively. Mulch was given as a single application at the rate of 15 tonnes ha^{-1}.

(c) Third Year

Soil erosion in the third year was greatly reduced under all treatments. Although the amount of eroded soil was less than in the second year, the pattern of erosion was similar. On average, plots under the tillage treatment lost 1.23 tonnes ha^{-1} of soil compared with 6.09 tonnes ha^{-1} for the non-tillage treatment; this difference is again attributable to the energy-absorbing effect of the loose soil cap at the surface.

The average soil loss from the oats and mulch treatments dropped from 4.31 and 0.14 to 0.42 and 0.08 tonnes ha^{-1} respectively. Mulch, at the rate of 15 tonnes ha^{-1} was applied once; the oats crop was successively established from a single planting.

DISCUSSION

Soil erosion was greatest during the first year from both tillage and non-tillage treatments. For the oats treatment, over 90% of the soil loss occurred during the first month of the experiment before the rows were established. Soil loss from the mulch treatment was negligible.

During the first year, when the canopy cover increased from about 1 per cent to 30 per cent, the soil eroded from plots receiving the tillage, non-tillage and oats treatments were respectively 76.5%, 66.0% and 88.1% of the total losses for the three-year period. During the second year, during which the canopy cover developed from about 30% to 60%, the losses were 22.9%, 31.6% and 10.9% of the three year totals for the same treatments. During the third year, when the canopy cover had increased to about 60% to 70%, the soil loss had reduced to 0.6%, 2.4% and 1.0% of the three year total (Fig 2). The importance of canopy cover in controlling soil erosion by reducing the impact of raindrops on soil surface is therefore well illustrated.

The fact that soil erosion was reduced both by loosely capping the soil surface, which thereby acted as an energy dissipator, and also by increased canopy cover, strongly suggests that the impact of rain causes most of the soil erosion in the Kericho district. Alternatively, it could be argued that the increased infiltration associated with the tillage treatment, rather than the energy absorbing nature of the surface, was contributory to the reduction in soil loss; however, the runoff data (Table II) do not support this argument for the following reasons. First, the ratios of annual runoff to total runoff for the three year period do not follow the same pattern as that observed for the corresponding ratios calculated from the soil losses. Thus, in the first year, runoff was 53.2%, 38.7% and 35.4% of the total three-year runoff for the tillage, non-tillage and oats treatments, respectively; in the second year, the runoff was 37.3%, 39.4% and 43.4% of the three year total, and in the third year it was 9.5%, 21.9% and 21.2%. Second, the effect of canopy cover on soil erosion was obvious. For instance, runoff in the non-tillage treatment in the first and second year was about the same, whilst 168.08 tonnes ha^{-1} of soil was lost in the first year compared with 80.71 tonnes ha^{-1} in the second year. The reduced soil loss in the second year, despite roughly equal volumes of runoff, can mainly be ascribed to the dissipation of raindrop energy.

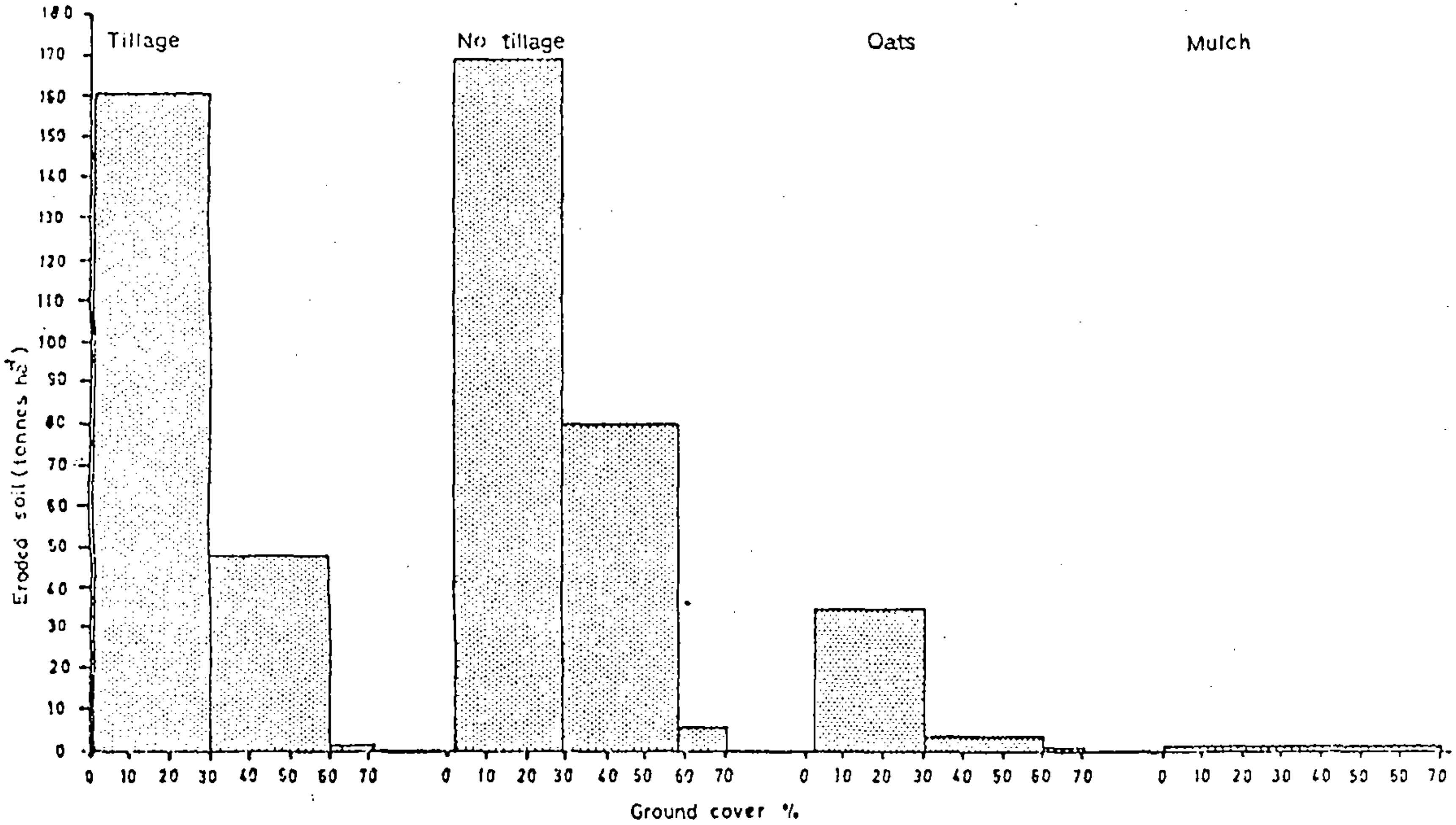

Figure 2 Relationships between soil erosion and percentage ground cover

TABLE II

Runoff (mm) and Rainfall (mm)

	Year			Total
	1971/72	1972/73	1973/74	1971 to 1974
Runoff				
Manual (tillage)	180.9	126.7	32.4	340.0
Herbicide (non-tillage)	159.5	162.3	90.2	412.0
Oats	65.1	79.8	38.9	183.8
Mulch	53.7	26.7	21.5	102.0
SE	±6.94	±4.60	±4.91	±13.31
Rainfall	2083	2045	1985	6113

Mulch was found to be the most effective treatment in the control of soil erosion, followed by oats. The action of mulch was to intercept raindrops and absorb their energy before their impact upon the soil surface; rows of oats, on the other hand, prevented the excessive movement of detached soil particles after heavy rain.

SUMMARY AND CONCLUSIONS

An experiment in the Kericho district on land with a 10% slope demonstrated that grass mulch gave best control of soil erosion, followed by a treatment in which oats were interplanted between rows of tea. Hand weeding and hoeing, which produced a surface cap of loose soil, was found to give better erosion control than the non-tillage treatment; however, hoeing is undesirable in tea fields because of potential damage to tea feeder roots.

The very large amounts of soil lost, 211 and 255 tonnes ha^{-1} in the tillage and non-tillage treatments respectively during the three years following planting, demonstrates very strongly the need for proper and adequate soil erosion control measures when land is prepared for planting and immediately after it.

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2.2.5

SOIL MOISTURE DEFICITS UNDER MONTANE RAIN FOREST AND TEA

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2.2.5

SOIL MOISTURE DEFICITS UNDER MONTANE RAIN FOREST AND TEA

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INTRODUCTION

The main objectives of the catchment research into changes of land use at Kericho have been fully set out in Section 2.1.1, and the importance of possible changes in the soil moisture regime in this experiment requires no further emphasis. The Lagan catchment, with its relatively undisturbed montane rain forest, provides the pattern of water use in the natural environment, whilst the Sambret catchment provides a comparison when land use is changed to tea. However, differences in seasonal rainfall distribution for the two catchments complicate the comparison of their soil moisture regime; this difference in rainfall is fully discussed in Section 2.2.1. Nevertheless, differences in soil moisture depletion can be compared between the two catchments under dry conditions such as the drought in 1971, and the effects of the 54% land use change on Sambret can be compared with the natural soil moisture regime under the uncleared forest which covers the rest of the catchment. This residual forest comprises 180 ha of bamboo and 140 ha of montane rain forest as shown in Figure 3 of Section 2.1.1.

CATCHMENT SOILS

The forest latosol was weathered *in situ* from the deep layer of phonolite covering the Kericho area. An 8 to 13 cm deep, dark-brown humic layer overlies the deep red friable clay below, which varies in depth of colour and texture over the catchments but shows little difference in physical characteristics. This soil is remarkably uniform and is developed to depths greater than 6 m in places. Geological sources suggest that a layer of volcanic ash approximately 60 cm deep at one time buried the humic layer, but this eroded and only survives as the top section of the soil profile in sheltered parts of the catchments. This layer has survived the erosion process rather better in the Lagan catchment, and is the only noticeable difference in soils between these catchments. The soils on Sambret are shallower at the downstream soil survey pits, and decomposed rock was found at 3 m depth. The homogeneous nature of the soils on the two catchments is shown by Table II, Section 1.2.3, which gives the average dry bulk density (DBD) profiles to 3 m depth. The lower DBD of the surface layers on Lagan is caused by the survival of a greater ash layer on this catchment.

CATCHMENT SOIL MOISTURE SAMPLING NETWORKS

As a result of the soil and vegetation surveys in both catchments, three sites were chosen to represent the upstream, middle and downstream areas of each catchment as shown on the catchment maps: Figures 2 and 3 of Section 2.1.1. At these sites the field capacities, wilting points and dry bulk densities were determined from profile soil cores taken to a depth of 3.2 m in pits. Monthly soil samples were taken by auger, also to 3.2 m, from two profiles in each pit, and these were converted to a volumetric basis using an equation valid for soils which have little change in sample volume on drying:

$$\mathrm{MVF} = \mathrm{DBD} \times \mathrm{MD}$$

where MVF is moisture volume fraction;

DBD is dry bulk density; and

MD is weight of water lost by sample divided by dry weight of sample.

At the same sites, gypsum blocks were installed through the profile to the same depth (3.2 m) and readings were taken twice weekly. The neutron soil moisture probe came into routine use in 1968, and the sites sampled in each catchment network are shown on the maps mentioned above. On Sambret, two access tubes were installed near each of the three sites where soil samples were taken by auger; one of the two extended to a depth that allowed readings to be taken to 4.5 m and the other to 2.7 m. The shallow tube was to allow the examination of spatial variability of observations in the zone of greatest moisture change.

Another pair of deep and shallow tubes was installed at a site in the forest shown on Figure 3, Section 2.1.1; other tubes were installed to the 2.7 m depth in the tea, and the latter network was extended after the long rains in 1972 when the shallow tube readings were discontinued at the upstream, middle and downstream representative sites. The Sambret network operated satisfactorily with very few changes; two access tubes were replaced due to the removal of diseased tea bushes, and one which had a 'dry' layer in the profile due either to a cavity or root was also replaced.

The soil gravimetric sampling sites and the neutron access tube network on Lagan are shown in Figure 2, Section 2.1.1. All sites, except the one nearest to the tree raingauge site at the upper end of the catchment has two tubes at each site; these were longer tubes, 4.5 to 6.0 m, than in Sambret, and observations were taken from additional tubes of 3 m depth to estimate site-to-site variation. Unfortunately, the only 6 m tube gave unreliable readings after June 1972, because the site soil regime was affected by removal of sample cores taken for calibration purposes. Beyond this, no trouble was experienced with this network other than the difficulty of negotiating the catchment perimeter access track after rain.

Both montane rain forest and tea have been shown by Kerfoot (1961, 1962) to root to depths greater than 6 m, whereas no bamboo roots were found below 2.5 m in the soil investigation pits dug in Sambret. The soil moisture observations were not taken to rooting depths, but to a depth which contained the bulk of the roots and in which the greatest changes in moisture content were considered likely to occur. The validity of the choice of 3 m as the observation depth is further discussed in Section 2.2.1, together with its effect on the catchment water balance.

Table I shows, for a year (1969) without prolonged drought conditions, the SMD calculated using data from (i) readings taken to 2.7 m; (ii) readings taken to 4.5 m, and the table shows that the differences between soil moisture deficits estimated from the two sampling depths were small. However, the differences in SMD were not negligible during an extended drought period such as the 1971 drought discussed below. The effect of this drought is demonstrated by the depletion rates at particular depths and total rates throughout the sampled profile, shown in Table IV.

ANALYSIS OF SMD DATA

Statistical analysis of soil moisture deficit observations from both catchments used the multiple regression equation of Section 1.2.3 with harmonic functions of time as independent variables. These regressions were compared using the analysis of variance method described by Williams (1964). The analysis of variance confirmed that the difference of amplitude and phase of seasonal SMD fluctuations between the Sambret and Lagan catchments was significant. The difference in seasonal distribution of rainfall between the two catchments is discussed in Section 2.2.1, and this difference confounds the interpretation of the two soil moisture regimes; however, both cleared and uncleared areas of Sambret experienced the same rainfall distribution and so, in the following paragraphs, data from these two areas have been used to assess the effects of the change in land use on the soil moisture regime.

In the soil sampling period up to 1968, deficits in the uncleared area of Sambret were sampled under bamboo only. When neutron measurement started in 1968, both bamboo and forest areas of the catchment were sampled; a comparison between forest and bamboo over the period 1968-74 showed that deficit fluctuations did not differ significantly but that annual mean SMD values were significantly different ($P < 0.1$).

During the period 1959 to 1961, the middle and lower sites

TABLE I

Sambret Soil Moisture Deficits 1969 in mm

Date	Forest Site 1		Tea Site 3		Bamboo Site 5	
	4.5 m	2.7 m	4.5 m	2.7 m	4.5 m	2.7 m
3. 1.69	42	74	122	107	119	145
21. 1.69	104	117	160	142	131	155
1. 2.69	81	82	194	155	141	161
11. 2.69	208	63	161	121	138	154
22. 2.69	77	63	170	121	156	164
3. 3.69	100	76	192	133	179	177
10. 3.69	133	104	212	154	192	189
21. 3.69	166	133	220	161	195	187
31. 3.69	108	71	160	111	148	139
10. 4.69	71	49	140	99	145	156
1. 5.69	22	6	220	149	8	71
15. 5.69	-25	27	61	17	29	41
23. 5.69	-41	18	39	12	37	40
29. 5.69	10	0	68	39	43	42
1. 7.69	-35	-14	-	-	24	45
6. 8.69	34	5	-19	-8	4	20
2. 9.69	-17	11	20	15	-7	29
1.10.69	15	35	87	70	24	67
4.11.69	59	53	47	45	95	125
4.12.69	90	66	47	39	164	167
30.12.69	179	185	117	131	176	211
Average SMD	66	56	121	91	102	118
±	15	11	16	13	15	14
SD	70	52	73	56	70	63
CV (%)	107	94	60	62	69	53

shown on Figure 3 of Section 2.1.1 were cleared and planted with tea, and showed a significant difference in amplitude and phase of annual SMD fluctuations when compared with the bamboo. Mean annual SMD also differed in this period.

In the following years, 1962-68, the tea bushes were maturing and the canopy was linked along the rows by 1968. Annual fluctuations in SMD under tea and bamboo did not differ significantly during this period, but again the average deficits were significantly different.

From 1968 onwards, the data were obtained by sampling up to 14 sites instead of 3, and it then became possible to look at the contrast between the tea and uncleared part of the catchment on an annual basis. The results from this period are summarised in Table II by years from 1968 to 1973. The low rainfall between the end of 1970 and April 1971 produced the worst drought in the period 1968-1974, and the significantly different regressions for 1970 and 1971 in Table II give an indication of the difference in response to stress conditions between the tea and forest.

For 1972, the significant difference between annual SMD fluctuations under Sambret (tea) and Sambret (uncleared part) cannot be explained by an extended drought, since that year was relatively wet; a more likely explanation arises from the fact that several heavy storms missed the upper, uncleared area of Sambret. Consequently, the seasonal pattern in SMD fluctuations was altered and the mean annual SMD under tea was appreciably lower, as shown in Table II. In Table IV of Section 2.2.1 it can be seen that these storms resulted in the 1972 rainfall on the bamboo sub-catchment, being appreciably and atypically lower than that for the complete catchment.

In Table III the mean annual SMD are shown for four periods

TABLE II

Significance Table of the Comparison of Phase and Amplitude of SMD Fluctuations and Mean SMD Levels for Tea and the Uncleared Areas of Sambret 1968-73

Year	SMD Phase and Amplitude	Mean SMD Level	SMD+ % Difference	% Difference Max SMD+
1968	NS**	Sig ($P<0.01$)	-19.3	32.8
1969	NS	NS	- 4.3	40.0
1970	Sig ($P<0.1$)	NT*	1.0	26.9
1971	Sig ($P<0.01$)	NT*	29.8	49.3
1972	Sig ($P<0.01$)	NT*	54.3	- 1.2
1973	NS	Sig ($P<0.01$)	33.0	-51.6

* NT : not tested (test unnecessary)

** NS : not significant

\+ (Uncleared area - tea value) ÷ uncleared area value expressed as a percentage

TABLE III

Sambret Catchment Mean Annual Soil Moisture Deficits to 2.7 m Depth

Year	Bamboo Site 1 (mm)	Tea Site 2 (mm)	Tea Site 3 (mm)	Tea/ Bamboo
Gravimetric sampling:				
1958-61	152 ± 16	164 ± 11	64 ± 11	0.75
1962-68	134 ± 9	161 ± 8	82 ± 8	0.91
1969-71	160 ± 14	195 ± 11	133 ± 15	1.03
Neutron moisture meter sampling:				
1969-71	159 ± 12	195 ± 10	136 ± 11	1.02
1972-73	134 ± 17	168 ± 14	122 ± 14	1.08

in the Sambret data: clearing and planting with tea (1958-61), completion of planting and maturing tea (1962-68), mature tea with an extended drought period (1969-71), and mature tea (1972-73). The sites shown are the upper, middle and lower sites originally used for gravimetric sampling and the neutron data are adjusted to the gravimetric basis to remove differences in estimates of field capacity and sampling frequency. The difference between the tea sites is greater than between the middle tea site and bamboo; however, the ratio of the mean values from the tea sites to the deficit under bamboo (shown in the last column) is greater when the tea reaches maturity than in the clearing phase. This increasing deficit ratio may represent the increasing water use of the tea relative to bamboo.

THE 1971 DROUGHT

This was the most significant drought which developed during the period in which the neutron moisture meter was used. An earlier drought which occurred in 1967 is discussed in Section 2.2.1; using data from gravimetric sampling to a depth of 3.2 m.

The deficits in moisture volume fraction (MVF) at 30 cm intervals to 4.5 m depth are shown for the sites in forest, bamboo and two sites in tea on Sambret in Figures 1 to 4. The plots are for the period August 1970 to July 1971.

All sites are at or about field capacity level in August or September 1970, and the forest site has the two lowest sampling depths approximately at saturation of 0.67 MVF indicating the presence of a water table. Marked depletion occurs under the bamboo to the beginning of January 1971, and the other sites are also in deficit by this time with the exception of the lower

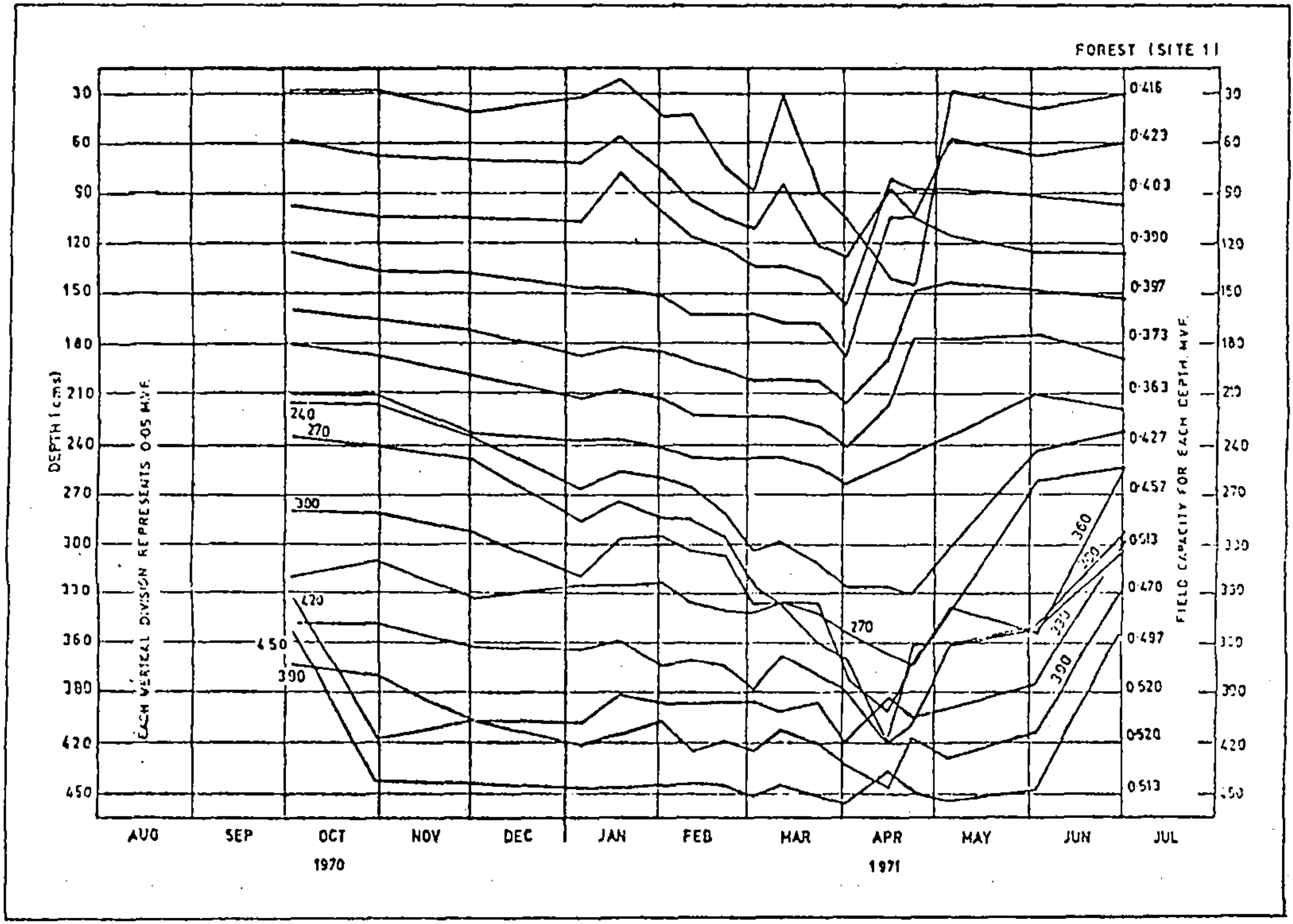

Figure 1 Soil moisture deficits under Sambret forest during 1970-71 drought

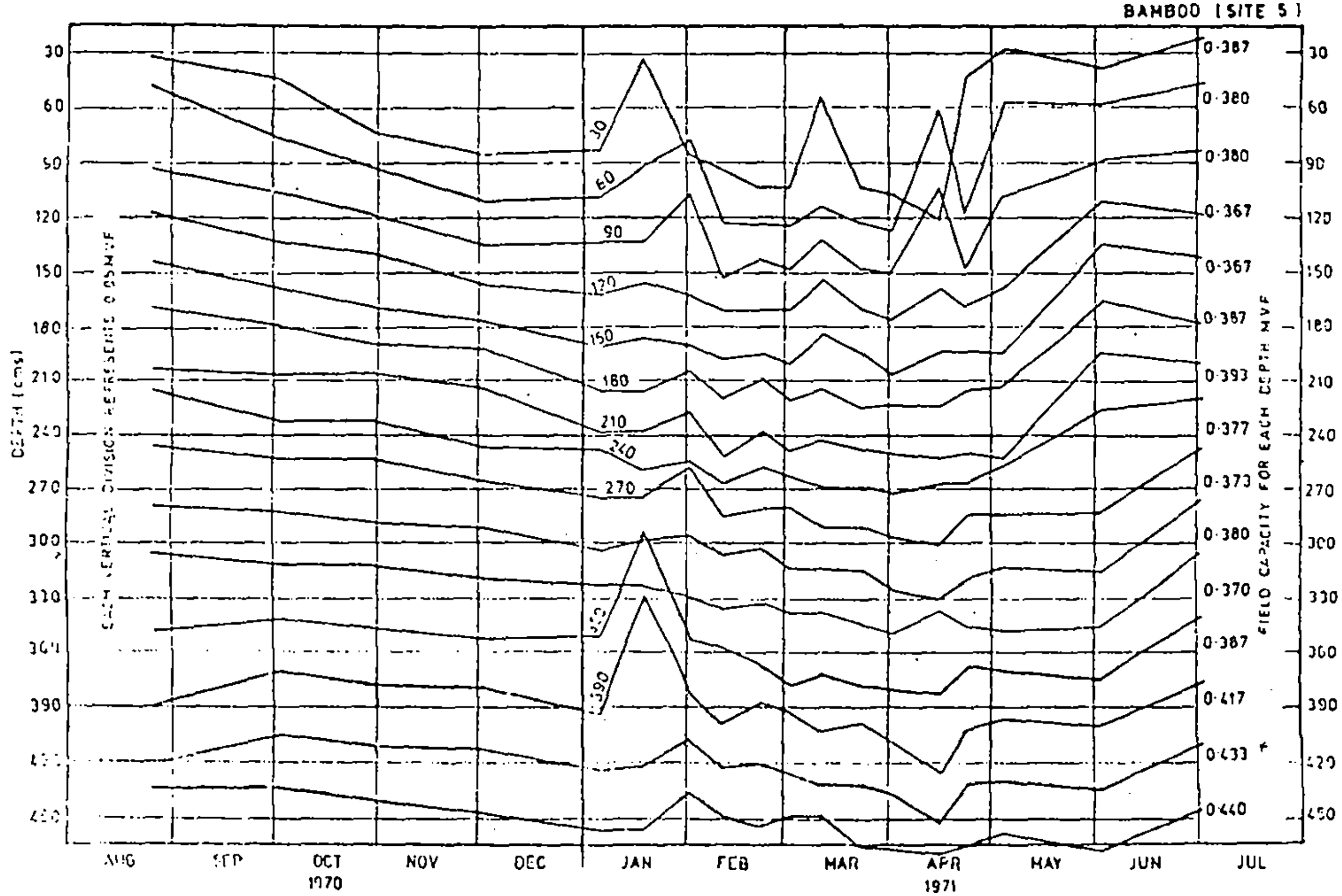

Figure 2 Soil moisture deficits under Sambret bamboo during 1970-71 drought

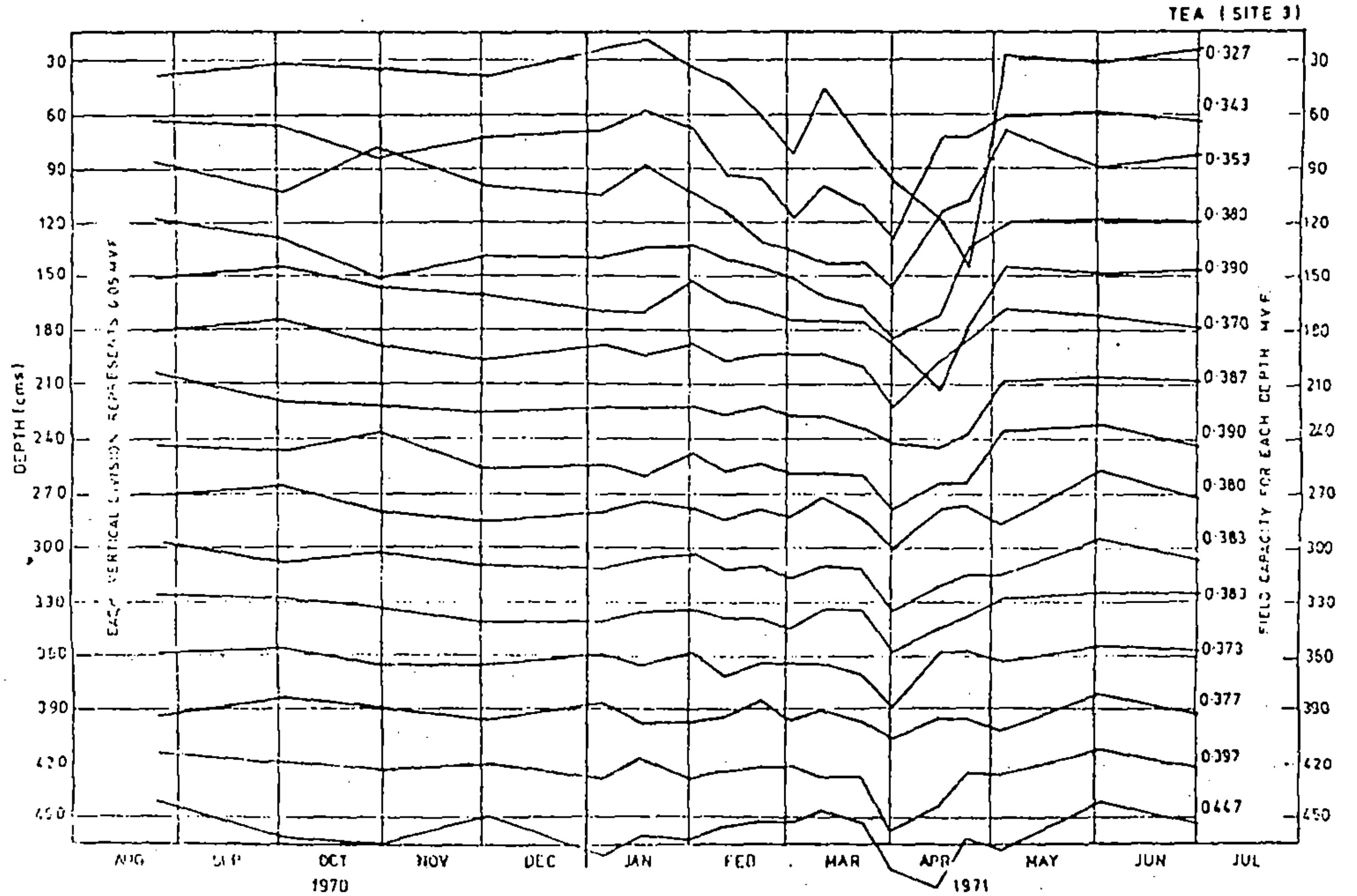

Figure 3 , Soil moisture deficits under tea (Site 3) during 1970-71 drought

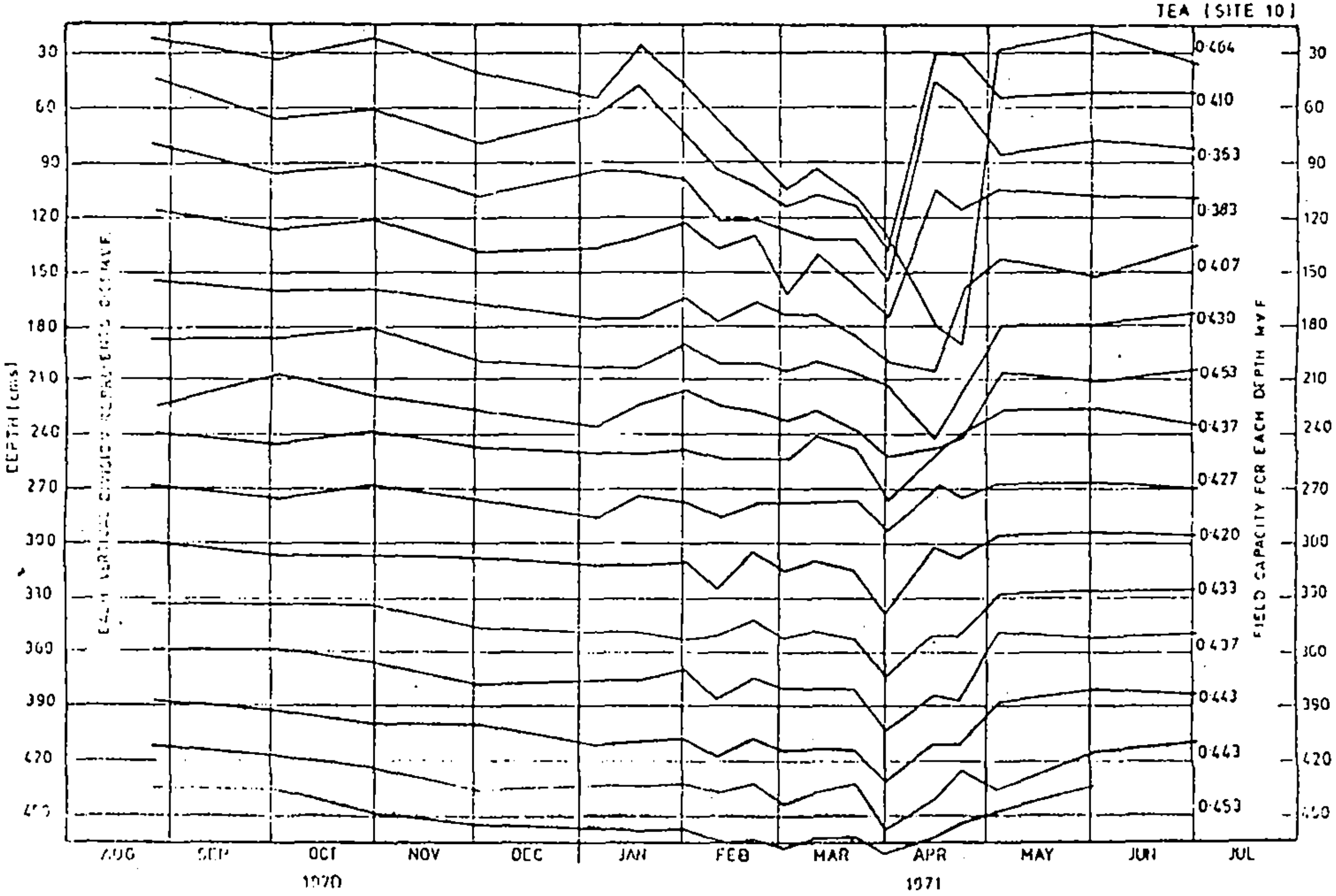

Figure 4 Soil moisture deficits under tea (Site 4) during 1970-71 drought

depths at the forest site. From the slight recharge in some depths at the beginning of January, the development of the drought deficit is very different from site to site and evidently varies with vegetation cover; the depletion rates for each depth as the drought develops are shown for each site in Table IV. The forest site on Sambret responded very similarly to those on Lagan, except that there is no evidence of the saturated zone found at the former at the bottom of profiles. The difference in root activity at each depth shows clearly in the table.

The problem of the depth to which observations should be taken, relative to the rooting depth, is clearly demonstrated by this table. The total depletion rate to a depth of 2.7 m forms the greater part of the total depletion rate to a depth of 4.5 m, but the errors that would have resulted from not measuring the lower depths are: forest 32%; bamboo 51%; and, for the two sites under tea, 27% and 24% respectively. However, the observed rooting depth in bamboo was only 2.5 m and nearly 50% of the profile depletion occurs below that depth.

For the site observed to 6 m on the Lagan catchment, there was little deficit below 3 m until the 1971 drought was at the extreme of its severity. However, even then no deficit developed below 4.8 m in the observed profile.

On Sambret during the drought the 4.5 m profile deficits did not reach those associated with wilting point (WPD). The highest deficit under the forest on Sambret reached 64% of WPD; the tea reached 47% and bamboo 57%. The Lagan forest suffered least at 43% of WPD. The surface 45 cm of soil under tea at the lower end of Sambret went above WPD as did the 3 m level under the forested part of the catchment.

CATCHMENT INFILTRATION RATES

Over the drought period, an estimate of infiltration rate can be made from an analysis of the profile response to those small

TABLE IV

Average Depletion Rates on Sambret Catchment 18.1-1.4.71 in mm day^{-1} for 30-450 cm Depths

Depth (cm)	Forest (Site 1)	Bamboo (Site 5)	Tea (Middle Catchment Site 3)	Tea (Lower Catchment Site 10)
30	0.85	0.75	0.82	1.05
60	0.50	0.24	0.48	0.62
90	0.53	0.11	0.46	0.41
120	0.27	0.14	0.34	0.30
150	0.23	0.15	0.12	0.17
180	0.22	0.05	0.19	0.07
210	0.17	0.08	0.13	0.20
240	0.48	0.09 (Observed rooting depth)	0.12	0.19
270	0.54	0.15	0.18	0.14
300	0.50	0.18	0.20	0.19
330	0.31	0.19	0.15	0.17
360	0.20	0.59	0.16	0.19
390	0.20	0.56	0.06	0.15
420	0.13	0.10	0.27	0.16
450	0.07	0.08	0.12	0.09
Total 4.5 m	5.14	3.40	3.73	4.04
Total 2.7 m	3.52	1.68	2.74	3.07

rainfalls that occur but which are insufficient to recharge the profile; the distance through the profile travelled by the wetting front then gives the water movement per day. From this analysis, the Sambret catchment infiltration rate is estimated to be 78 ± 7 cm day^{-1} which appears to be independent of the surface layer moisture content. The surface rate for tea is 70 ± 17 cm day^{-1} and that for the forest area is 83 ± 6 cm day^{-1}. The litter and humic layers of the forest give the higher rate of infiltration. Average percolation figures for the Sambret catchment profiles below the surface layers are, for MVF range between 0.29 and 0.35, 40 ± 14 cm day^{-1}; for MVF range between 0.35 to 0.42, 55 ± 8 cm day^{-1}. The great scatter at low moisture contents is possibly related to the depth and intensity of rainfall.

Hydraulic conductivity is difficult to estimate on Lagan catchment as the response of profiles to dry-season rainfall is less clear. The surface infiltration appears to be of the order of 90 cm day^{-1} and for profiles in the range 0.30 to 0.35 MVF, the percolation rate is in the region of 36 cm day^{-1}.

WATER USE OF VEGETATION

An estimate of water use of catchment vegetation can be made by taking a water balance when the soil profile can be considered to have ceased draining after rain ($AE = R - \Delta S$, where Q, ΔG in the water balance equation have been set to zero). The method is crude but the free draining soils of Kericho give the figures shown in Table V as a ratio to Penman's EO and in mm day^{-1}. The two results are shown as mean values, and the ratio to EO is divided into classes on an interval of 100 mm SMD for each type of vegetation. Further figures for the ratio of water depletion to EO are shown in Table VI; these values are obtained from water depletion to 2.7 m and 4.5 m in the same profile between the same dates. They are arranged in classes by SMD to 2.7 m, and show that although depletion in the top half of the profile was decreasing, it was not so over the whole 4.5 m profile. Taking all the data available to each depth separately and

TABLE V

Soil Moisture Depletion Rates to 2.7 m

	Mean SMDR* (mm day^{-1})	Soil Moisture Depletion as a Ratio to Penman EO				
		Mean	0 - 100 mm SMD	100 - 200 mm SMD	200 - 300 mm SMD	300 - 400 mm SMD
Tea	3.53 ± 0.23	0.64 ± 0.05	0.75 ± 0.10	0.67 ± 0.07	0.56 ± 0.09	0.38 ± 0.18
Mean SMD		128 ± 12	66 ± 14	129 ± 8	221 ± 20	313 ± 22
Bamboo	3.64 ± 0.26	0.74 ± 0.06	1.01 ± 0.12	0.82 ± 0.07	0.63 ± 0.10	0.47 -
Mean SMD		163 ± 14	62 ± 19	154 ± 10	227 ± 10	335 ± 18
Forest	3.98 ± 0.50	0.79 ± 0.07	0.87 ± 0.09	0.69 ± 0.12	0.61 ± 0.16	0.40
Mean SMD		97 ± 18	49 ± 11	139 ± 16	247 ± 42	312 ± 7

* Soil moisture depletion rate

TABLE VI

Soil Moisture Depletion as a Ratio to Penman EO for 2.7/4.5 m Profiles on the Same Site and Sampling Data

Range of SMD to 2.7 m (mm)	Depth of Profiles (mm)	Tea	Forest	Bamboo
0-100 m	450	0.77 ± 0.12	0.94 ± 0.06	1.29 ± 0.23
	270	0.79 ± 0.14	0.79 ± 0.04	1.23 ± 0.18
100-200 m	450	0.79 ± 0.08	0.98 ± 0.13	0.89 ± 0.07
	270	0.69 ± 0.08	0.77 ± 0.08	0.90 ± 0.09
200-300 m	450	-*	-*	0.86 ± 0.10
	270	0.56**	-*	0.45 ± 0.14

* No comparison possible

** One determination only

arranging by MVF deficit gives the results in Table VII; these show a trend with increasing MVF deficit for decreasing water use at higher deficits whether the shallow or deep profile is considered.

SUMMARY AND CONCLUSIONS

The problems of comparing data obtained by the use of gravimetric sampling and the neutron moisture meter in spatially different networks with variable sampling frequencies have been solved by using soil moisture deficits with 'field capacity' as reference levels; regression analysis, with harmonic functions of time as independent variables, was used in the analysis of data to 2.7 m depth.

This analysis showed that there was no significant difference between mature tea plantation and the adjacent bamboo and montane rain forest sites in phase and amplitude of annual soil moisture deficit fluctuations, except in drought periods. The significant difference found in 1972 could be explained by a difference in rainfall between upper and lower parts of Sambret and a higher recharge to depths below 2.7 m under tea. The deficiencies of SMD observations taken only to this depth,which includes the bulk of the vegetation roots become apparent in the considerable underestimation of water use during periods of drought.

TABLE VII

Soil Water Depletion Expressed as a Ratio to Penman EO

MVF Deficit	Profile Depth (m)	Range of SMD throughout profile (mm)	Tea	Forest	Bamboo
0.011	4.5	0-100	0.95 ± 0.10	0.88 ± 0.05	1.13 ± 0.10
0.019	2.7	0-100	0.75 ± 0.10	0.87 ± 0.09	1.01 ± 0.12
0.033	4.5	100-200	0.81 ± 0.10	0.79 ± 0.06	0.77 ± 0.11
0.056	2.7	100-200	0.67 ± 0.07	0.69 ± 0.12	0.82 ± 0.07
0.056	4.5	200-300	0.57 ± 0.05	0.78 ± 0.07	0.73 ± 0.11
0.078	4.5	300-400	-	0.73 -	-
0.093	2.7	200-300	0.56 ± 0.09	0.61 ± 0.16	0.63 ± 0.09
0.100	4.5	400-500	-	-	0.54
0.130	2.7	300-400	0.38 ± 0.18	0.40	0.47

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2.3

SUMMARY OF RESULTS OF THE KERICHO EXPERIMENTS

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2.3

SUMMARY OF RESULTS OF THE KERICHO EXPERIMENTS

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The objective of the study at Kericho was to determine the effects of a land-use change from indigenous forest to tea estate by monitoring and comparing the hydrological responses to similar rainfall inputs of two adjacent catchments, one under forest and one converted to tea estates. Progressive conversion to tea estate was carried out on 54% only of the experimental catchment. This, combined with the subsequent discovery that the brief initial calibration period had coincided with conditions of extremely low flow, limited the value of direct comparison as a means of detecting changes in response. To assist in the interpretation of the data from the partially converted catchment, a sub-catchment within it, almost entirely under bamboo, was instrumented in 1961.

The 16 years of rainfall, streamflow and soil moisture and meteorological data from the catchments have been processed and quality controlled. Detailed examination revealed a number of systematic errors for which corrections have been applied. The data have been analysed to give estimates of long-term water use by each catchment and to determine, using the water balance techniques described in Section 1.1, the year-to-year variations about these long-term means.

The long-term mean value of water use by the forest was found to be 92% of Penman EO compared to 84% for the partially converted catchment. The annual variability in water use was greater for the forested than for the experimental catchment. Mean water use and its variability for the bamboo sub-catchment was closely comparable with that from the experimental catchment as a whole. Trends in annual water use were found to follow those in rainfall more closely in the forested catchment. Modelling of the water use by the forest and bamboo catchments using empirical functions to represent the interception and transpiration components of water use demonstrated that much of the variability described above could be accounted for in terms of these components.

Detailed studies in tea using zero flux plane and energy balance techniques showed that dry season water use was substantially lower than that derived from the annual water balance and that the rate relative to EO decreased at soil moisture deficits greater than 300 mm. Determinations of dry season water use in tea from the routine soil moisture measurements were in broad agreement in both magnitude and trend with the detailed studies. (These, and the similar determinations for bamboo and forest could well be biassed, however, because they include the effects of variable amounts of interception, percolation at low deficits and under-estimation of soil moisture change at very high deficits).

Interception capacity of the tea canopy was about 2.5 mm and water stored in it evaporated at a rate much higher than the transpiration rate (Section 2.2.3). Model simulation suggested that the interception process in bamboo resulted in loss rates comparable with those from tea, but that such losses from both tea and bamboo were smaller than those from the indigenous forest. The modelling study also indicated that the rates of transpiration from bamboo were broadly similar to those determined from tea in the process studies; rates of transpiration from forest were significantly lower than those from tea and bamboo.

These differences in the component processes contributing to total water use largely explained the variability in annual water use in each catchment and also accounted for the greater part of the differences in water use between catchments. Whilst the model functions used and the parameters optimised for each vegetation type need not necessarily apply in other catchment areas, it was shown that they could be used to predict water use by the patchwork of tea, bamboo and forest cover on the experimental catchment with reasonable precision.

This study has established that, in the conditions pertaining at Kericho, the replacement of forest by tea estate has not resulted in a long-term reduction in water yield from the catchments. The evidence from model simulation and process studies suggests that total water use by tea may be lower than that by forest under wet conditions and comparable or higher under dry conditions. This implies some increase in the range of seasonal flows from the tea. On the soil type at Kericho and with the soil and water conservation measures adopted, surface runoff from the tea does not exceed that from the forest. The extent to which similar results would be obtained elsewhere will be dependent on the rainfall frequency and soil type. The importance of the differences in the interception and transpiration processes in each vegetation type has been established and points to the need for detailed studies of these processes before the effects of similar land use changes in other environments can be quantified.

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