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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 per cent 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 minimize the uncertainties arising in the interpretation of data from a "patchwork" catchment comprising 380 ha tea estate, 130 ha forest and 190 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 minimized 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 rechecking 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 minimized by regular inspection and checking. Those arising from height of gauge above ground are considered to be lower than the 1 per cent to 4 per cent described in Appendix 7.1.2 for the site at Muguga, since windspeeds in the Kericho area are some 50 per cent 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 per cent to −6 per cent 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 per cent 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 per cent in all but three of the 16 years 1958-73. The three years in question, 1964, 1965 and 1966 had errors of 4.8 per cent, 4.1 per cent and 5.7 per cent respectively. It is notable that the latter two years were the driest on record. This level of precision is lower than the 1 per cent 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 per cent 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 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 per cent and +2.4 per cent 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).

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	2,334	33	2,325	15	+ 9
1962	2,553	28	2,516	14	+37
1963	2,209	71	2,192	14	+17
1964	2,123	13	2,092	9	+31
1965	1,520	18	18 gauges redistributed.		
1966	1,881	24	1,858	8	+23
1967	2,259	16	2,211	10	+48
1968	2,145	11	2,061	24	+84
1969	1,511	20	1,505	13	+ 7
(*b*) Theissen Means					
1961	2,328		2,352		−24
1962	2,540		2,523		+17
1963	2,185		2,217		−32
1964	2,121		2,114		+7
1965	1,520		18 gauges redistributed.		
1966	1,869		1,862		+ 7
1967	2,214		2,214		0
1968	2,139		2,070		+69
1969	1,504		1,498		+ 6

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 alongside from February to October 1974, indicated that the error was systematic and time-invariant. Corrections were duly applied using regression relationships with these two anemometers. The net effect of this correction on EO was less than 2 per cent however, inadequate to explain the downward trend.

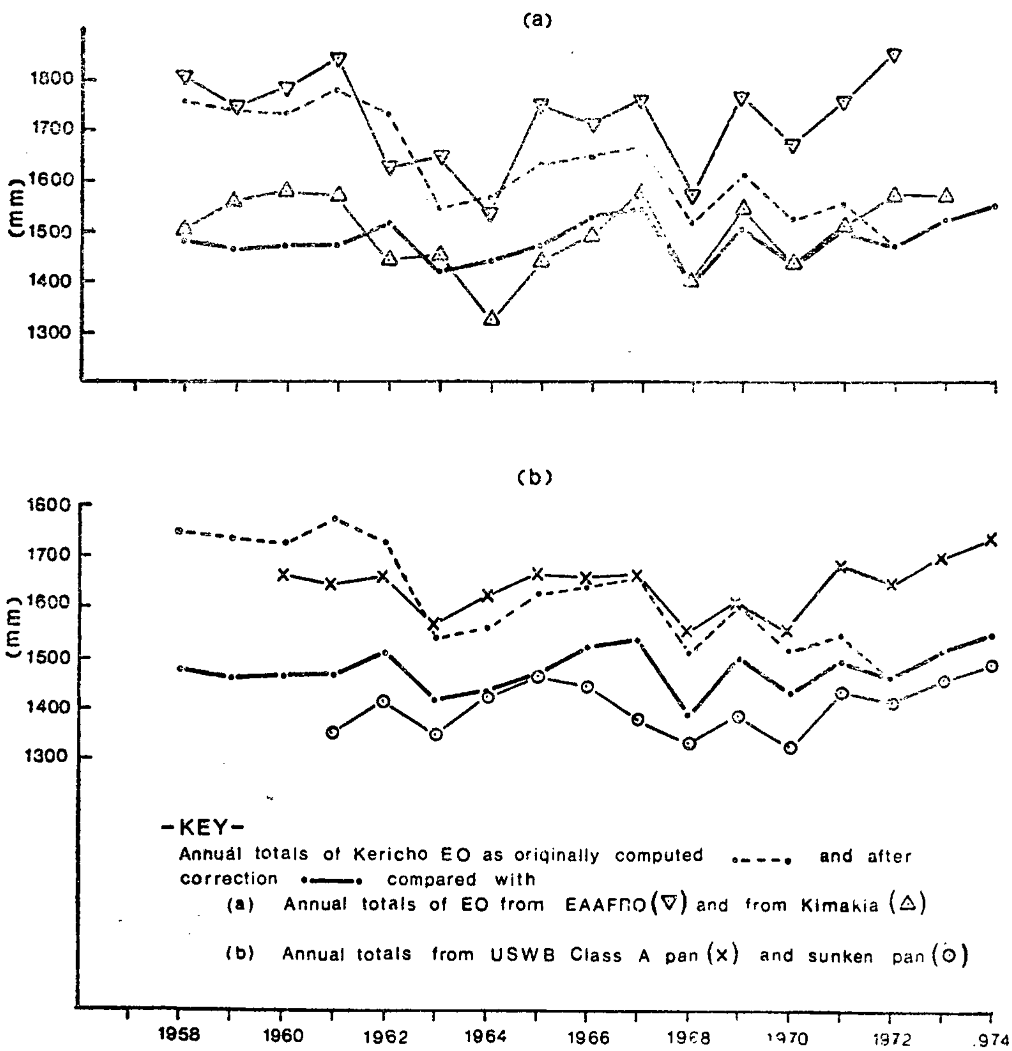


Figure 1.—Comparison of Kericho EO, before and after correction, with EO from other sites and with evaporation pan data

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—

$$R_o/R_a = a + b\,^n/N \qquad \text{......... (1)}$$

where—

R_o 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.

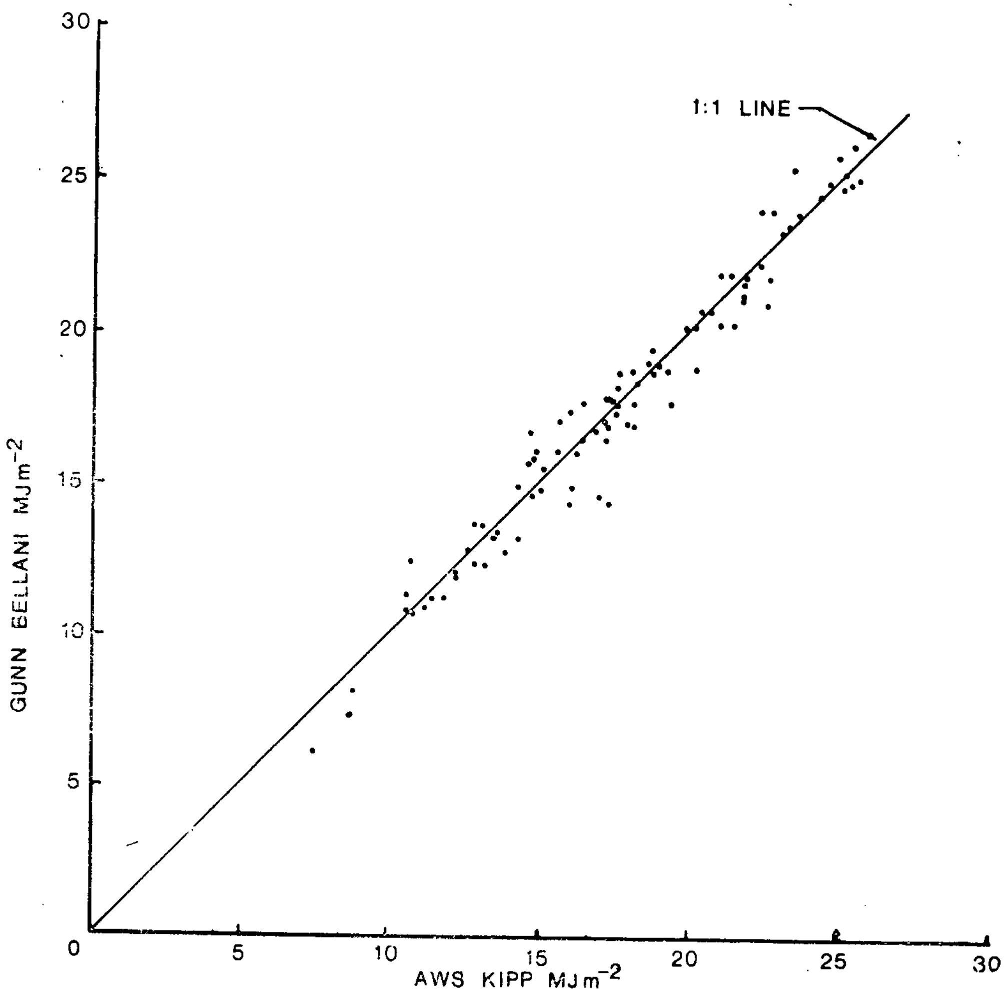
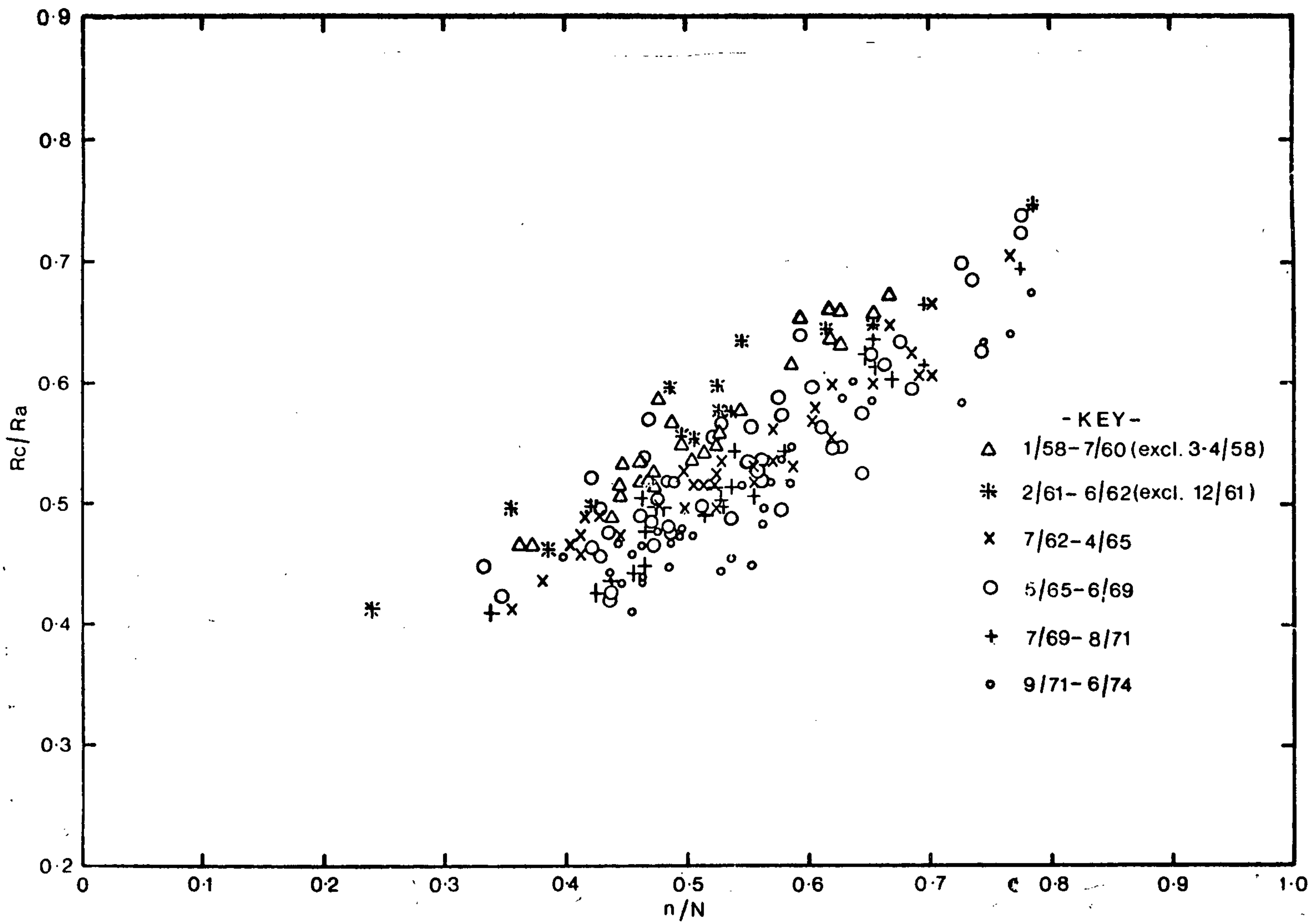


Figure 2.—Kericho daily radiation, April to June 1974, as measured by Gunn Bellani radiometer and by the Automatic Weather Station Kipp solarimeter



R

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

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 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,

$$R_c/R_a = 0.1547 + 0.6379\,^n/N \quad \ldots\ldots\ldots (2)$$

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:

$$R_c = Ad + B \quad \ldots\ldots\ldots (3)$$

where, for each instrument,
d is daily distillation;
A, B are constants specific to the instrument;

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	0·101927
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, $b_p=0{\cdot}6379$, the intercepts become $a_{p1}=0{\cdot}2348$, $a_{p2}=0{\cdot}2459$, $a_{p3}=0{\cdot}1900$, $a_{p4}=0{\cdot}1902$, $a_{p5}=0{\cdot}1790$ $a_{p6}=0{\cdot}1547$.

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: $k_1=-0{\cdot}0801, k_2=-0{\cdot}0912, k_3=-0{\cdot}0353, k_4=-0{\cdot}0355, k_5=-0{\cdot}0243$.

corrected daily radiation was computed as follows:—

Let R_{oi} 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:

$$R'_{ci} = R_{oi} + k_iR_a \qquad \text{......... (4)}$$

Combining (4) and (3) gives:

$$R'_{ci} = A_id + (B_i + k_iR_a) \qquad \text{......... (5)}$$

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 per cent 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) generalized 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.

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 inter-

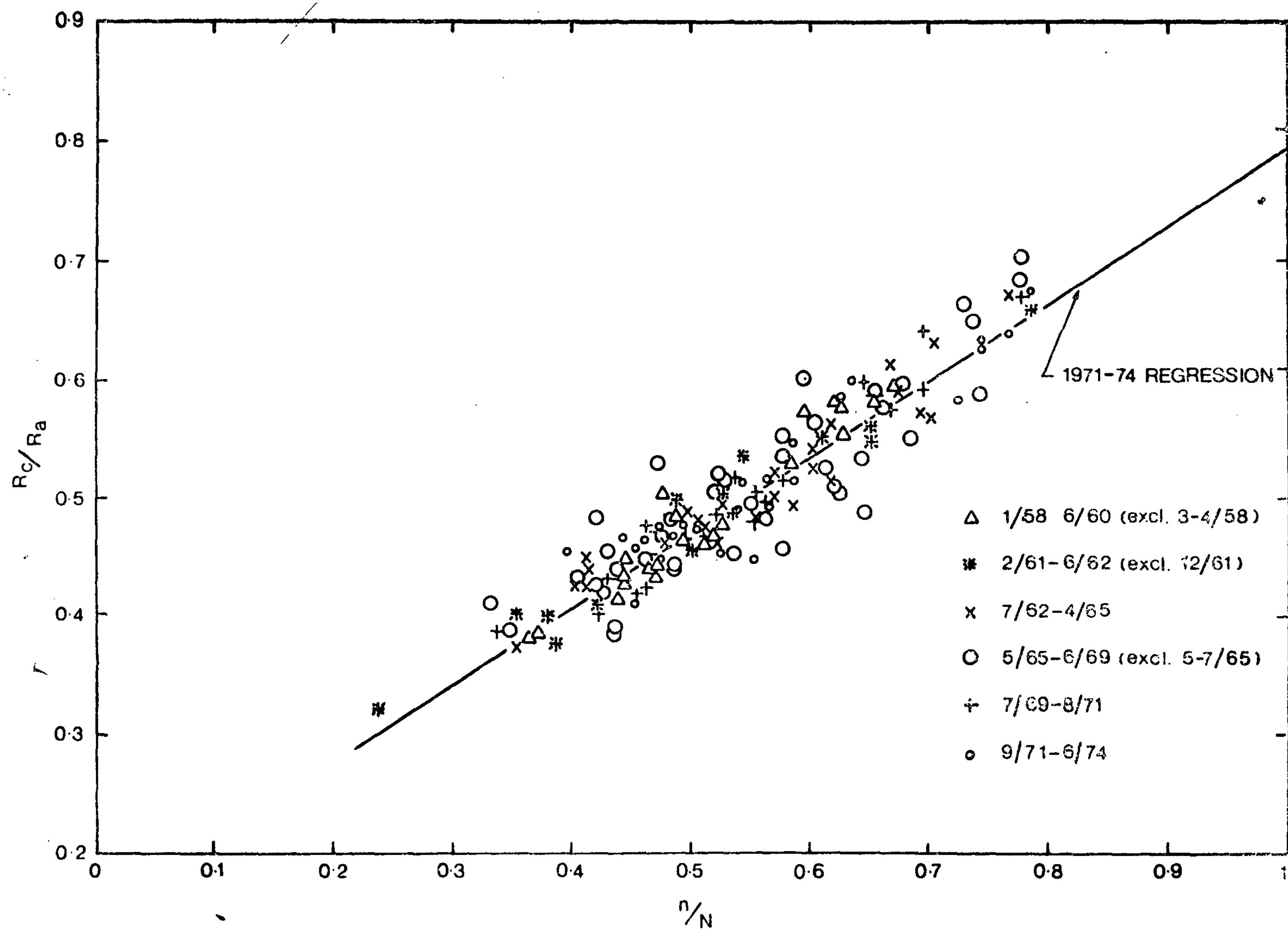


Figure 3 (b).— R_c/R_a v n/N, after correction of radiation using the 1971 to 1974 regression shown as reference preted reasonably as being constants, independent of radiation intensity. Thus, the discrepancy between calibration and on site performance arose from a change in the regression intercept, 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, threfore, 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 per cent. 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 (two profiles per site), were generally in the range 1 per cent to 3 per cent for the gravimetric sampling. Despite the increased network density used for neutron probe sampling (5 sites, 11 profiles) the corresponding range was 2 per cent to 3 per cent. 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 cm, 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 cm, 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 cm and beyond have indicated that moisture abstraction can occur from well beyond 320 cm. 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 cm 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 cm 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.

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 per cent for Sambret and the bamboo sub-catchment within it, whilst those for Lagan are probably not estimated to better than 3 per cent. 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 per cent. Annual totals of streamflow are considered to be accurate to within 2 per cent for both catchments. The precision of the catchment estimates of soil moisture are, at best, some 2 per cent 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

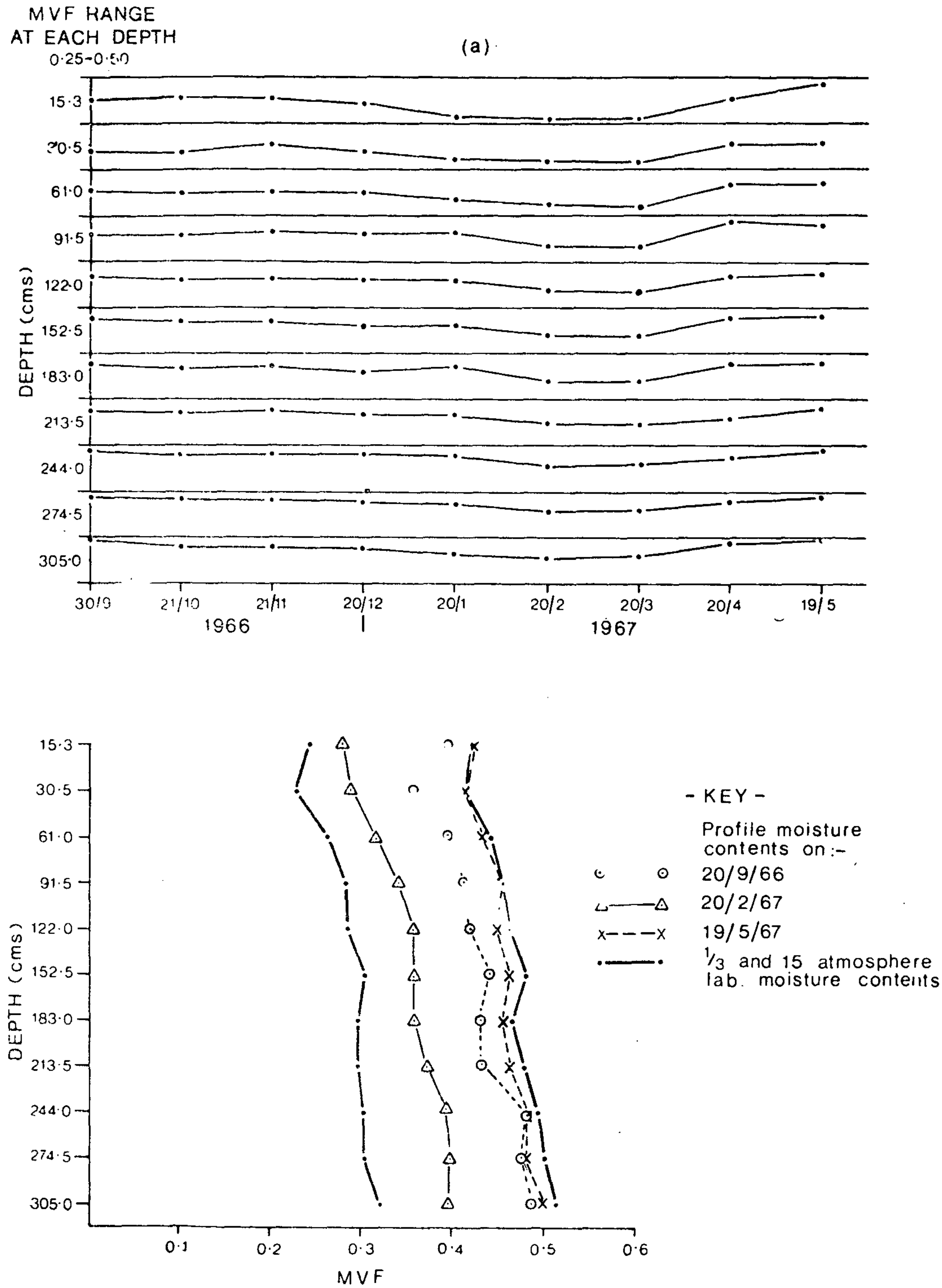


Figure 4.—Mean soil moisture profiles under forest in Lagan during the 1966-67 dry season:
(a) Time series plot
(b) Profiles at beginning, at maximum recorded deficit and after recharge

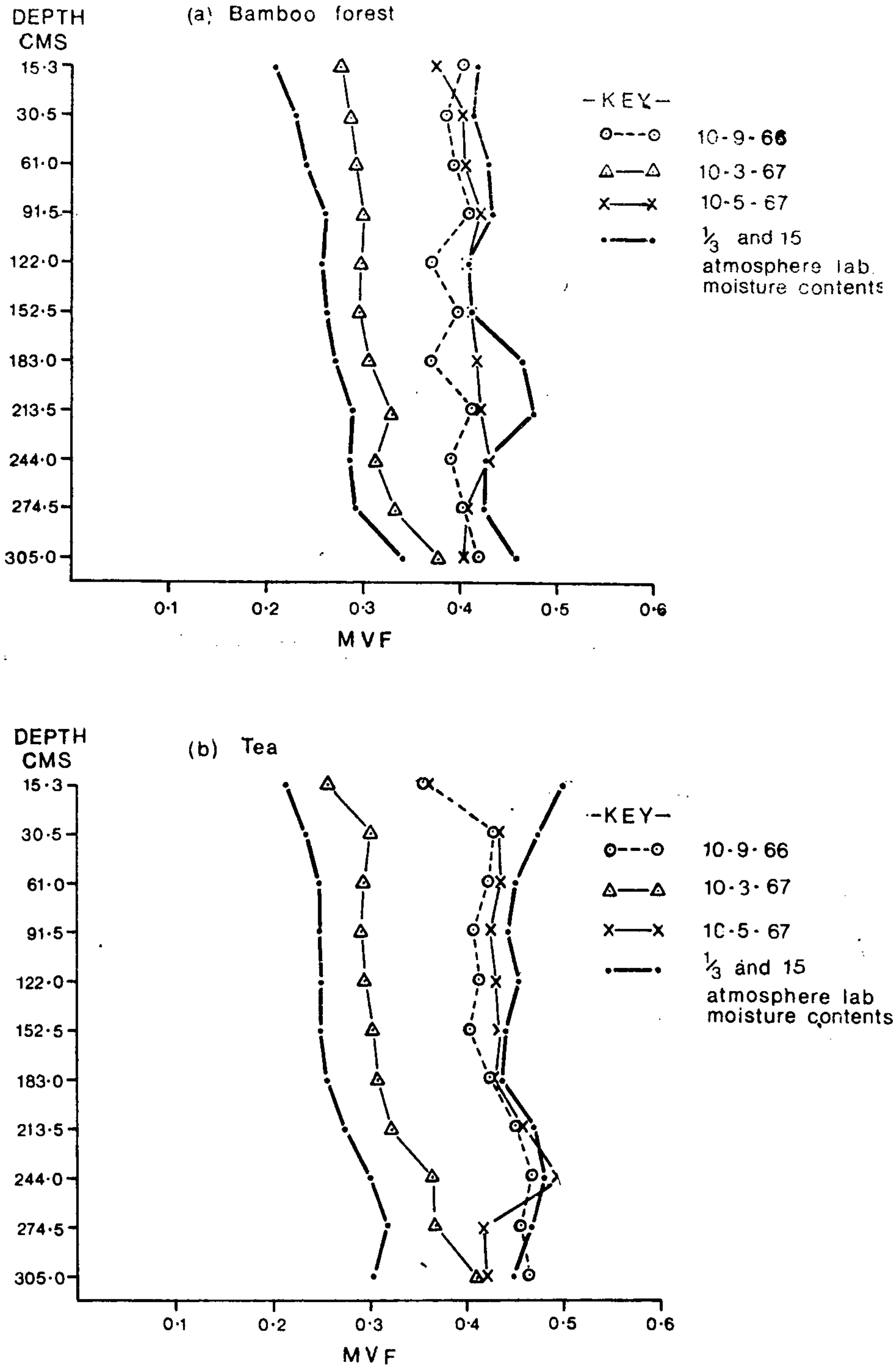


Figure 5.—Profile moisture contents during the 1966-67 dry season in Sambret catchment

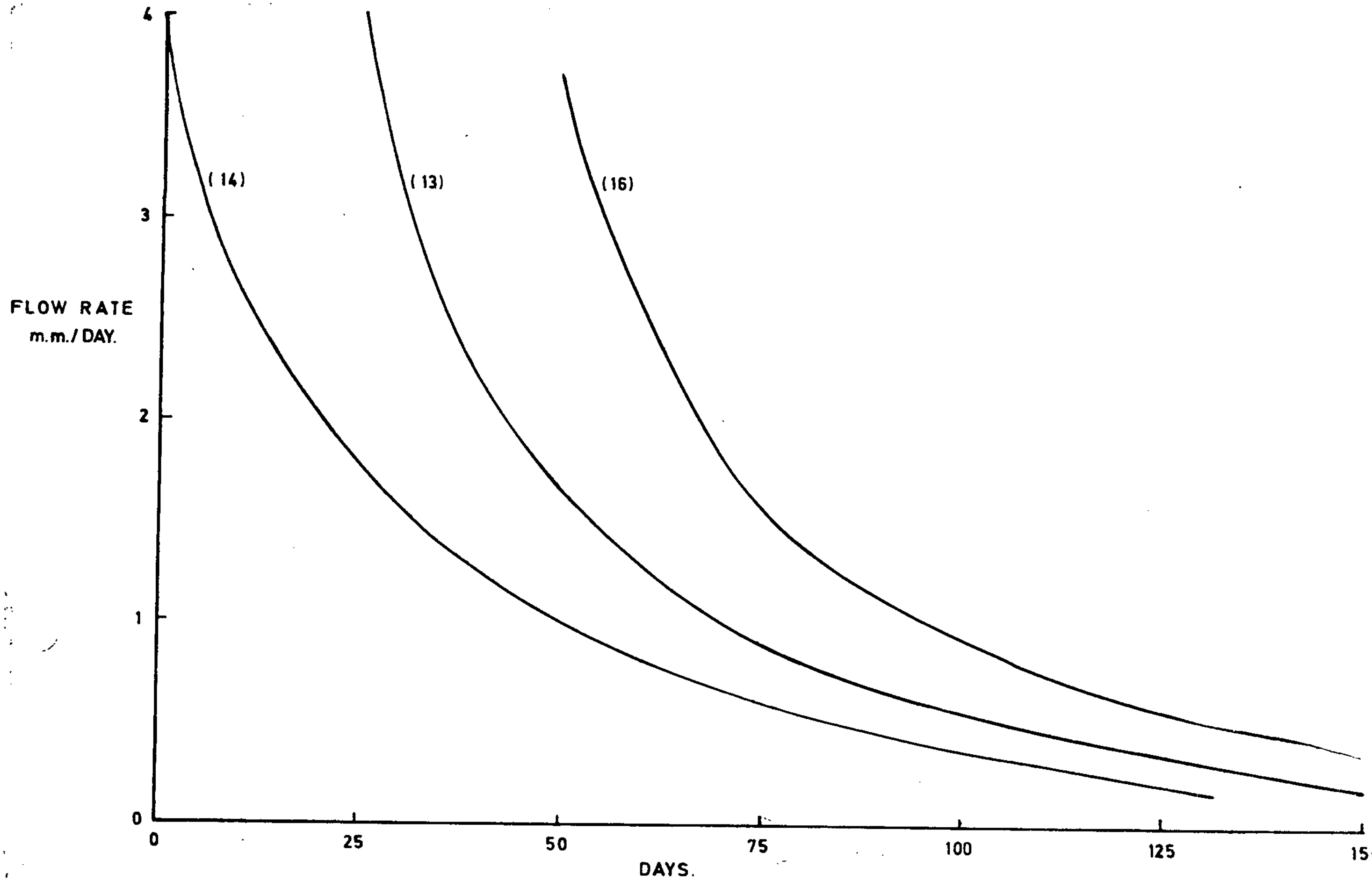


Figure 6.—Composite baseflow recession curves derived from dry season flows in Lagan (14), Sambret (13) and the Sambret sub-catchment (16)

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.

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 $\geq$ 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 emphasize 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 cannot be regarded as accurate estimates. However, the relative magnitude of the storage terms

Table IV—Calendar Year Totals of Rainfall, Streamflow and Raindays

Year	Rainfall (mm) 14	13	16	Streamflow (mm) 14	13	16	Raindays 14	13	16
1958	1,949	1,785	—	307	245	—	232	233	—
1959	1,841	1,876	—	285	443	—	225	231	—
1960	2,470	2,308	—	929	977	—	263	253	—
1961	2,539	2,352	—	850	980	—	258	258	—
1961 (February—December)	—	2,349	2,385	—	959	911	—	—	—
1962	2,488	2,523	2,556	1,144	1,348	1,373	251	245	245
1963	2,133	2,217	2,288	695	951	1,014	241	239	239
1964	2,020	2,114	2,149	901	1,017	1,043	274	245	245
1965	1,541	1,569	1,523	268	275	224	214	226	226
1966	1,631	1,862	1,889	656	635	648	186	242	242
1967	2,166	2,214	2,238	721	904	862	242	247	247
1968	2,446	2,070	2,115	1,174	905	988	255	259	259
1969	1,685	1,498	1,496	507	341	302	203	225	225
1970	2,599	2,222	2,319	1,027	943	970	249	262	262
1971	2,363	2,073	2,021	973	946	840	223	237	237
1972	2,181	2,012	1,937	708	737	614	240	231	231
1973	2,013	1,881	1,903	696	673	684	215	218	218
1958–73									
Total	34,065	32,576	—	11,841	12,320	—	3,777	3,851	—
Mean	2,129	2,036	—	740	770	—	236	241	—
SD	±339	±279	—	±288	±311	—	±24	±13	—
1962–73									
Total	25,266	24,255	24,433	9,470	9,675	9,562	2,799	2,876	2,876
Mean	2,105	2,021	2,036	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	2,105
	±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	2,021
	±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	2,036
	±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	±324
						Penman EO (mm)							
	153	138	155	114	105	106	105	110	116	118	118	137	1,476
	±19	±22	±18	±16	±8	±11	±8	±8	±9	±11	±15	±17	±47

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 1,968 mm or some 8.9 per cent.

In Table VII (*a*) the totals over each phase of development in the experimental catchment are compared. With due reservation 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 per cent lower. In the final phase when the tea estate, covering 54 per cent 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.

TABLE VI—CALENDAR YEAR TOTALS OF RAINFALL MINUS STREAMFLOW AND OF EO

Year	R–Q (mm) 14	13	16	EO (mm)
1958 ..	1,642	1,540	—	1,481
1959 ..	1,556	1,433	—	1,461
1960 ..	1,541	1,331	—	1,467
1961 ..	1,689	1,372	—	1,468
1962 ..	1,344	1,175	1,183	1,512
1963 ..	1,438	1,266	1,274	1,420
1964 ..	1,119	1,097	1,106	1,439
1965 ..	1,273	1,294	1,299	1,468
1966 ..	975	1,227	1,241	1,523
1967 ..	1,445	1,310	1,376	1,540
1968 ..	1,272	1,165	1,127	1,392
1969 ..	1,178	1,157	1,194	1,506
1970 ..	1,572	1,279	1,349	1,434
1971 ..	1,390	1,127	1,181	1,495
1972 ..	1,473	1,275	1,323	1,464
1973 ..	1,317	1,208	1,219	1,519
1958–73				
Total ..	22,224	20,256	—	23,587
Mean ..	1,389	1,266	—	1,474
SD ..	±196	±117	—	±40
1962–73				
Total ..	15,796	14,580	14,872	17,710
Mean ..	1,316	1,215	1,239	1,476
SD ..	±167	±71	±86	±47

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 54 per cent of Sambret to tea estate. From the later stages of planting onwards, long term water use by Sambret was 83 per cent of Penman EO. Water use by the bamboo sub-catchment was 84 per cent of Penman over this period whereas that of the forested catchment was close to 90 per cent.

COMPARISON OF WATER YEAR DATA

To obtain more precise estimates of catchment water use over shorter time intervals, it is necessary to utilize 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 dis-

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 sub-catchment of Sambret and the control.

Period	Sambret Status	R–Q		Difference	
		(*a*) *13* (mm)	*14*	(mm) *13–14*	(%4)
1958–59	Undisturbed	2,973	3,198	−225	−7·0
1960–63	Clearing and planting ..	5,144	6,012	−868	−14·4
1964–67	Establishment	4,928	4,812	+116	+2·4
1968–73	Mature tea estate	7,211	8,202	−991	−12·1
		(*b*) *16* (mm)	*14*	(mm) *16–14*	(%14)
1962–63		2,457	2,782	−325	−11·7
1964–67		5,022	4,812	+210	+4·4
1968–73		7,393	8,202	−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

cussed 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 1958-59 does not appear in them. In both catchments baseflow levels were

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	200262	2,727	1,040	−89	−4	1,780	1,791	0·99
2	211162	2,080	916	+114	+4	1,046	1,066	0·98
3	200963	1,843	582	+46	+4	1,211	1,199	1·01
4	211164	2,450	1,013	−55	+6	1,486	1,691	0·88
5	201165	1,507	269	+69	−3	1,172	1,481	0·79
6	211066	1,560	622	−172	+3	1,107	1,321	0·84
7	190168	2,367	851	+23	−10	1,503	1,981	0·76
8	161168	2,230	1,014	+118	+16	1,082	1,118	0·97
9	030969	1,581	478	−6	−3	1,112	1,166	0·95
10	021270	2,840	1,129	+2	−6	1,716	1,806	0·95
11	041171	2,199	944	+16	−12	1,251	1,383	0·90
12	281272	2,388	755	+10	+15	1,589	1,698	0·94
13	021173	1,926	614	−12	0	1,324	1,275	1·04
Total 1-13 ..		27,698	10,247	+64	+10	17,379	18,976	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		2,538	1,059	−34	0	1,513	1,683	0·90
	131260							
1		2,547	1,113	+39	+24	1,371	1,759	0·78
	100262							
2		2,260	1,212	+4	−27	1,071	1,214	0·88
	111262							
3		1,908	857	+21	−3	1,033	1,209	0·85
	111063							
4		2,419	1,075	−17	+27	1,334	1,555	0·86
	101164							
5		1,591	306	−32	−27	1,344	1,596	0·84
	101265							
6		1,718	571	+12	+27	1,108	1,205	0·92
	101066							
7		2,457	1,012	−9	−17	1,471	1,978	0·74
	100168							
8		1,932	837	+36	−7	1,066	1,163	0·92
	151168							
9		1,388	324	−25	+3	1,086	1,282	0·85
	200969							
10		2,383	984	−12	−7	1,418	1,699	0·83
	031270							
11		1,993	912	+18	+7	1,056	1,366	0·77
	021171							
12		2,163	794	−3	−3	1,375	1,705	0·81
	271272							
13		1,767	615	−66	0	1,218	1,272	0·96
	311073							
Total 0–13		29,064	11,671	−68	−3	17,464	20,686	0·84

lower in the first four months of 1958 than at any subsequent time in the period of study, indicating that groundwater storage was extremely low. This is consistent with the long mid-1950's dry spell in East Africa generally and specifically in the Lake Victoria drainage basin, as indicated by the steadily falling lake level over this period. Using the baseflow as an indicator, only minimal recharge occurred in either catchment during 1958. The baseflow in Lagan did not rise beyond the value used as a reference under criterion (*a*) above until April 1960, giving the first usable water year starting point in December 1960. In Catchment 13 significant recharge occurred somewhat earlier. Though Sambret rainfall was only 2 per cent greater than Lagan in 1959, the seasonal distribution was markedly different, with a much greater concentration occurring in the April through August period. Rainfall in this period was 998 mm, exceeding that in Lagan by some 23 per cent. This resulted in a proportionately greater groundwater recharge and the subsequent recession made possible a water year starting point in October 1959.

The interpretation of the data as indicating substantial recharge in 1958-59 would explain qualitatively the anomalously high R−Q values relative to EO for 1958-1960 in Table VI and Table VIII. These "crude" estimates of water use would include, in this period, a substantial element of groundwater recharge. Unfortunately the gaps between early 1958 baseflow levels and the lowest subsequently recorded are such that the empirical recession curves (Figure 6) cannot be extended to give quantitative estimates of these recharges. Though soil moisture measurements were made from January 1958 onwards, examination of the profile moisture distribution reveals substantial deficits at the 300 cm (10 ft) level which did not disappear until

TABLE XI—WATER USE ESTIMATES, AE, FOR THE BAMBOO SUB-CATCHMENT 16

Water Year Ref. No.	Starting Date	Rain mm	Flow mm	*WS* mm	*WG* mm	AE mm	EO mm	AE/EO
0		—	—	—	—	—	—	
1		—	—	—	—	—	—	
2	100262	2,280	1,240	+2	−31	1,069	1,214	0·88
3	111262	1,975	931	−32	+9	1,067	1,209	0·88
4	111063	2,468	1,087	+43	+27	1,311	1,555	0·84
5	101164	1,547	274	−5	−56	1,334	1,596	0·84
6	101265	1,708	545	−28	+56	1,135	1,205	0·94
7	101066	2,508	998	−15	−32	1,557	1,978	0·79
8	100168	1,844	863	+70	+5	906	1,017	0·89
9	071068	1,504	335	−16	−10	1,195	1,429	0·84
10	300969	2,496	1,011	−55	+15	1,525	1,699	0·90
11	031270	1,945	807	+2	−5	1,141	1,366	0·84
12	021171	2,085	674	−23	−5	1,393	1,705	0·82
13	271272	1,798	622	−64	0	1,240	1,272	0·97
Totals 2–13 ..	311073	24,158	9,387	−75	−27	14,873	17,245	0·86

July 1958. Thus accurate estimates of changes in neither storage term can be made for this period.

Nevertheless, an indication of the magnitude of the recharge required by the hypothesis can be obtained by assuming water use at mean rates of 0.92 EO and 0.84 EO for 14 and 13 and using the water balance expression in the form:

$$\Delta S + \Delta G = R - Q - AE$$

This gives the following estimates of total recharge:—

Period	Catchment	R-Q	Est AE	Est $\Delta S+\Delta G$
010158–191260	14	4,742	3,998	+744
010158–151059	13	2,799	2,208	+591

These estimates may appear large, but, using the best-fit non-linear storage-discharge relationships discussed in the following modelling section, the estimated groundwater storage changes between the recorded flow levels on these dates are +520 mm for Lagan and +430 mm for Sambret. Since the residual values of ΔS are entirely feasible, there appears to be some indirect justification for this interpretation of the 1958-59 data.

Returning to the "water-year" water balances in Tables IX, X and XI, they can be seen to bear out the magnitudes and trends indicated by the R−Q values in Table VIII. For ease of comparison, water year mean daily values of AE for each catchment are plotted as a time series in Figure 7, and the AE/EO ratios in Figure 8. As an indication of the "noise" level, error bars computed from the error estimates discussed earlier are given for Lagan and Sambret in Figure 7. Those

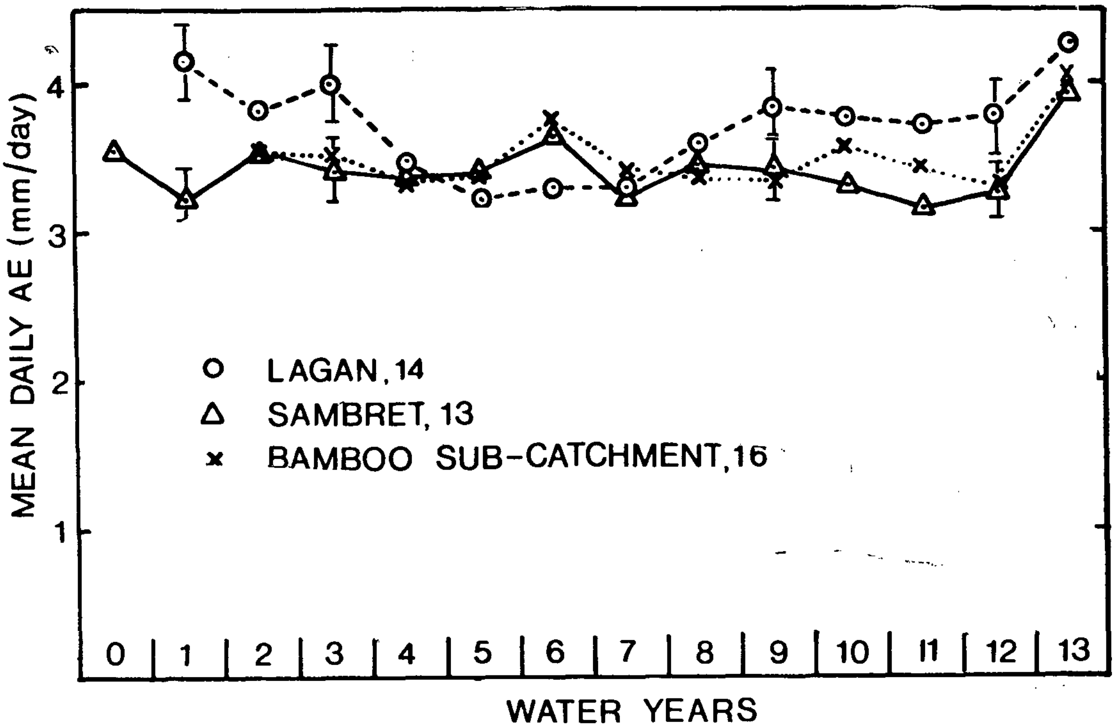


Figure 7.—Mean daily water use from each catchment

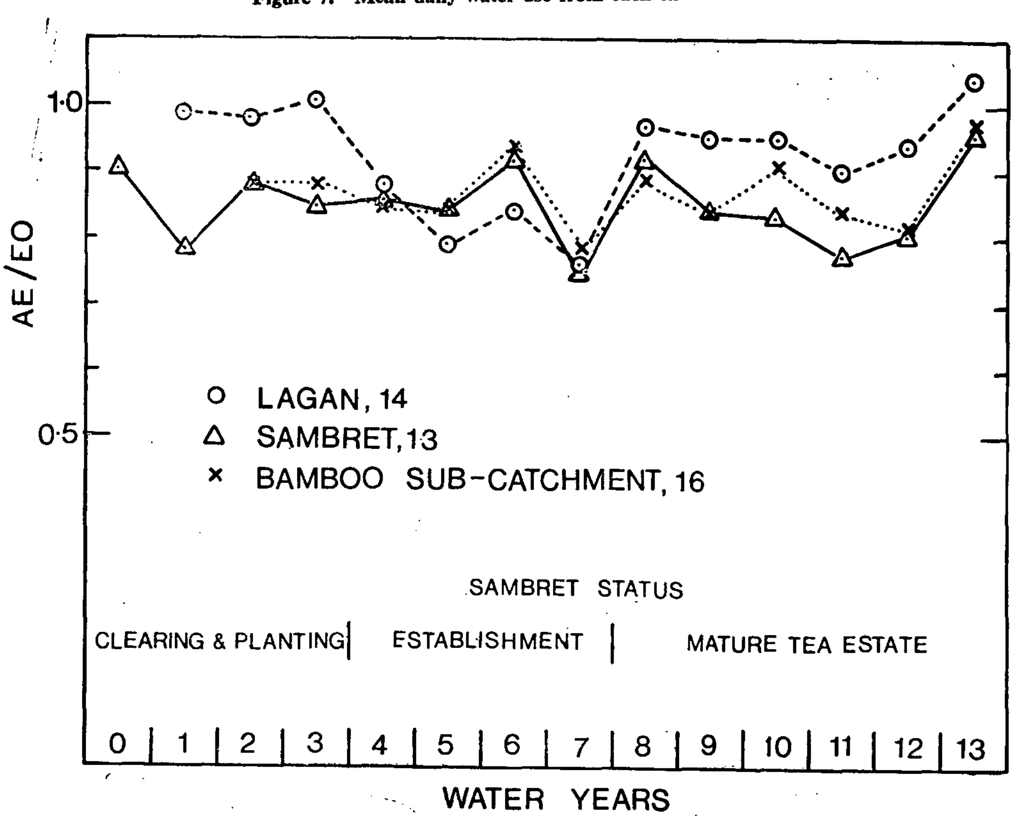


Figure 8.—Water year AE/EO ratios from each catchment

for 16 are similar in magnitude to Sambret. These plots emphasize the close agreement in magnitude and trend of the water use by the bamboo sub-catchment and the complete Sambret catchment, except for periods 10 and 11, and the marked differences in trend between Sambret and Lagan. Water use by Lagan is consistently higher than Sambret during periods 1-3 and periods 8-13, but the difference is small, or in the opposite sense, during periods 4-7. The range of values of 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 per cent 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 per cent 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 conceptional 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.

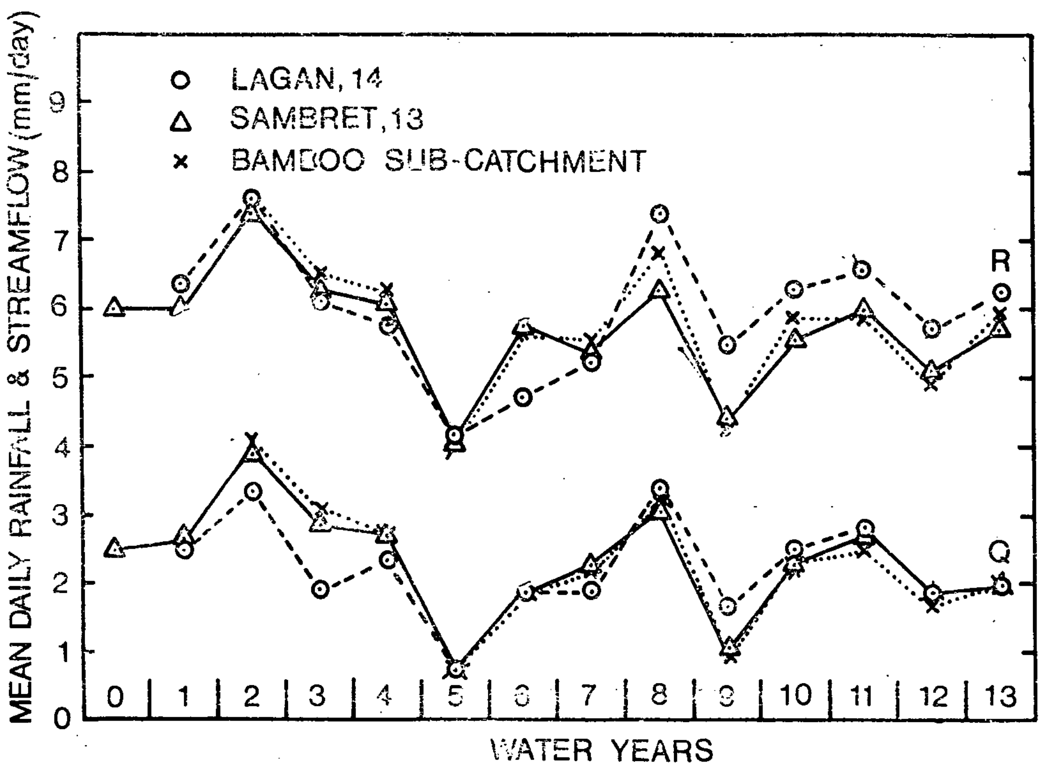


Figure 9.—Mean daily fainfall and streamflow from each catchment

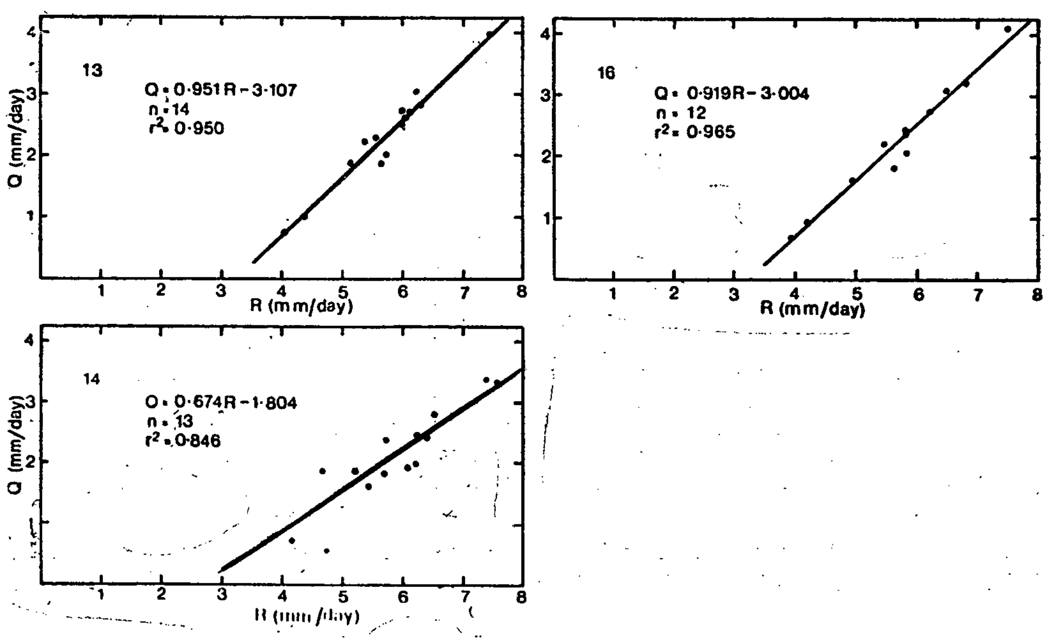


Figure 10.—Plots of water year mean daily flow, Q, against mean daily rainfall, R, for catchments 13, 16 and 14

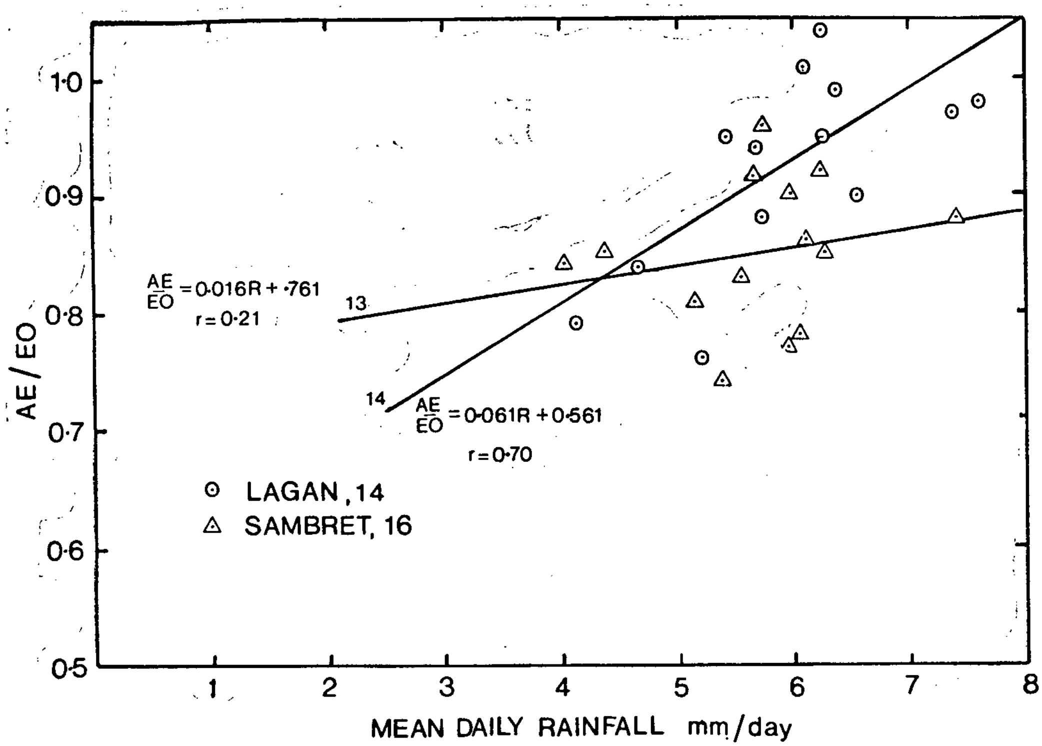


Figure 11.—Regression of water year AE/EO ratios on rainfall

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 summarized.

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 x EO) of Penman's EO. This constant factor, f, was determined from the long term water year totals of AE and EO as:

$$f = \Sigma AE / \Sigma EO$$

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 utilizing the existing daily Penman data was adopted. Using the terminology defined in Section 1.3, this water use model can be expressed as:

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

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 optimized.

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:

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

where N_j is the number of days in water year j. In optimizing the parameters initial values derived from field osbervation 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.

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

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 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.

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	1,780	1,640	−140	1,628	−152	1,641	−139
2	1,046	977	−69	1,092	+46	1,133	+87
3	1,211	1,098	−113	1,129	−82	1,172	−39
4	1,486	1,548	+62	1,597	+111	1,644	+158
5	1,172	1,357	+184	1,225	+53	1,234	+62
6	1,107	1,210	+103	1,111	+4	1,157	+50
7	1,503	1,815	+312	1,682	+179	1,670	+167
8	1,082	1,024	−58	1,182	+100	1,217	+135
9	1,112	1,068	−44	1,022	−90	1,069	−43
10	1,716	1,654	−62	1,698	−18	1,754	+38
11	1,251	1,267	+16	1,266	+15	1,284	+33
12	1,589	1,555	−34	1,587	−2	1,644	+55
13	1,324	1,168	−156	1,167	−157	1,208	−116
Σ	17,379	17,379		17,384		17,825	
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	1,069	1,047	−22	1,084	+15	1,088	+19
3	1,067	1,042	−55	1,049	−18	1,052	−15
4	1,311	1,341	+30	1,347	+36	1,347	+36
5	1,334	1,377	+43	1,313	−21	1,269	−65
6	1,135	1,039	−96	1,054	−81	1,059	−76
7	1,557	1,706	+149	1,651	+94	1,575	+18
8	906	877	−29	939	+33	941	+35
9	1,195	1,232	+37	1,192	−3	1,194	−1
10	1 525	1 465	−60	1,512	−13	1,515	−10
11	1,141	1,178	+37	1,185	+44	1,166	+25
12	1,393	1,471	+78	1,441	+48	1,442	+49
13	1,240	1,097	−143	1,101	−139	1,103	−137
Σ	14,873	14,873		14,870		14,751	
F		189		125		109	

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 optimization 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 optimized; 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 per cent of the annual rainfall, in agreement with the results quoted by Blackie (1972).

Obviously, cumulative error in the water-use prediction results in comparable volume errors in predicted flow. Nevertheless, the optimized 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 1974 with an error of +0.6 per cent and an overall efficiency on daily values of 95 per cent. For 14, the comparable figures for the period December 1960 to June 1974 were −3.8 per cent and 91 per cent. 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 optimized 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 three 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 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-optimize 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 optimization may be adequate provided the parameters do not incorporate bias derived from the catchment data used in the optimization.

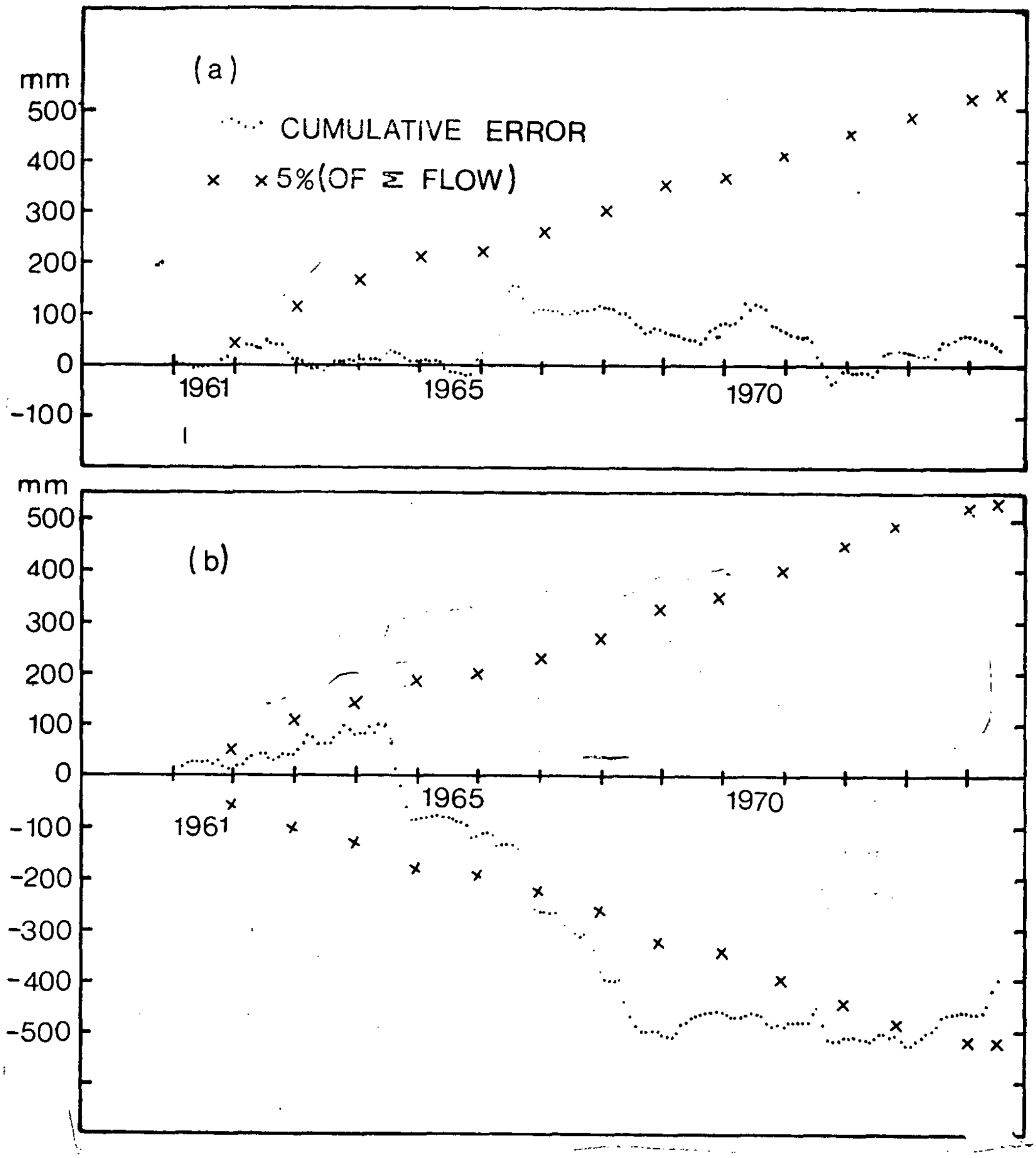


Figure 12.—Cumulative error in flow prediction by the IH model on (a) catchment 16, (b) catchment 14

As a practical test of the validity of the water use model described above and the parameters optimized 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 FS 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, i.e. 54 per cent, 19 per cent and

27 per cent. 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.

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 were observed between the mean monthly flows from Sambret and Lagan (Table V). Since 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 more rapid recharge, whilst 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 to the aquifer may well be modified by the land use change, but this effect is confounded by differences in catchment geometry and in rainfall distribution.

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	1,108	1,017	−91	1,038	−70	1,051	−57
7	1,471	1,670	+199	1,704	+233	1,647	+176
8	1,066	982	−84	1,002	−64	1,079	+13
9	1,086	1,082	−4	1,104	+18	1,060	−26
10	1,418	1,434	+16	1,463	+45	1,507	+89
11	1,056	1,153	+97	1,176	+120	1,187	+131
12	1,375	1,439	+64	1,469	+94	1,436	+61
13	1,218	1,074		1,995	−123	1,101	−117
Σ	9,798	9,852		10,051		10,068	
F		243		267		205	

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