Institute of Hydrology

1976/001D

Natural Environment Research Council

FINAL REPORT
ON THE
EAST AFRICAN CATCHMENT
RESEARCH PROJECT

(ODM R2582)

VOLUME IV

THE MBEYA EXPERIMENTS
REGIONAL ANALYSIS
APPENDICES

1976

by

K A EDWARDS
J R BLACKIE
C W O EELES

5.1.1

THE MBEYA RESEARCH PROJECT

J R Blackie and K A Edwards
Institute of Hydrology, Wallingford, UK

5.1.1

THE MBEYA RESEARCH PROJECT

J R Blackie and K A Edwards
Institute of Hydrology, Wallingford, UK

INTRODUCTION

Only about four per cent of the East African land surface reliably receives a mean annual rainfall greater than mean annual potential transpiration (Russell, 1962). These areas, for the most part, are the highlands above 2000 m which were covered originally by natural montane forest. Nearly all the major rivers rise in these highlands, and it is generally accepted that their dry season flow depends upon high infiltration rates giving recharge to groundwater storage in the headwater catchments. Traditional methods of non-intensive, shifting cultivation, with fallows long enough to allow the regeneration of the natural vegetation (albeit of secondary type), caused little long-term damage to land in closed forest zones. The concentration of population in favourable areas, however, has resulted in the permanent removal of ~~the~~ most of the original forest. Intensive cultivation of steep slopes under a subsistence economy relying predominantly on annual crops has led, in turn, to severe soil erosion and a deterioration of water yields in terms of both quantity and quality (see Temple, 1972, for examples in the Uluguru Mountains, Tanzania).

The protection of forests to conserve water supplies has for many years been the cornerstone of forest policy. Despite pressure to release these areas of high agricultural potential, many countries now have legislation to prevent further clearing or encroachment on the forest reserves. Faced with expanding populations and a pressing need for increasing food supplies, there is a natural desire to use such areas for purposes more profitable ~~that~~ than protection forestry if this can be done without undue harm to water resources (Webster and Wilson, 1966). Quantitative evidence to support a rational land use policy, however, is difficult to find and, justifiably, Forest Departments have steadfastly opposed any proposals to release land until it can be shown that serious and irreversible damage will not ensue; at the same time, they have encouraged quantitative studies on the effects of land use change, and the site of one such study was at Mbeya in southern Tanzania. Participants in the study were EAAFRO, the Forest Department, and the Department of Water Development and Irrigation of the then Tanganyika Government.

With the gazetting of the Forest Reserve in the Mbeya Range, cultivation of certain areas within the boundary ceased, and the local Wasafwa people accepted monetary compensation and moved into an adjacent valley. This valley had not been cultivated for many years and was covered with regenerating bush. The opportunity presented itself, therefore, to compare the hydrological regimes of three nearby catchments under contrasting land use. One catchment was the newly occupied catchment (A), the second was the vacated catchment which now fell within the reserve and was being allowed to regenerate (B), and the third was a control catchment under the tall evergreen forest (C).

The project was discussed and principles were agreed at the East African Catchment Area Planning Conference in 1956 and, with the provision of funds by the Tanganyika Government, the experiment was started. A full account of the local problems, the contributions of co-operating bodies, and the preliminary stages of the experiment, are given in Pereira et al (1962).

DESCRIPTION OF THE EXPERIMENTAL CATCHMENTS

Comprehensive descriptions of the catchment soils and vegetation were given by Scott (in Pereira, op cit, page 112) and Kerfoot (1964). The catchments are situated on the north facing slope of the Mbeya Range (8°50'S, 33°28'E) at a mean altitude of 2500 m. Geologically, the Range is a ridge of gneiss across the line of the Great Rift Valley system but the soils are derived from an overlay of volcanic ash of variable depth; this is generally of the order of 1 m. The gneiss is deeply weathered beneath the ash soil and the mixing of these two components is largely a function of position on the slope. The higher, more level ground has an almost intact ash-derived soil, while the steeper slopes are more variable and resemble scree. The deepest and most fertile soils are found in the valley bottoms, where ashy soils are interbedded with colluvium.

Mean annual rainfall is 1800 mm (1959-1969) and falls entirely in five months of the year, December to April. Mean annual estimates of potential evaporation are about 1500 mm with relatively small seasonal variation. The climate of the region is summarised in Table I.

The forested catchment, C, is 16.3 ha in area with very steep valley sides at an average slope of 30° near the weir. There is a difference in altitude of 228 m between the weir and the highest point in the catchment. The lower two-thirds of the catchment are under dense montane evergreen forest, and the upper third under annual grasses and shrubs.

Catchment B, the regenerating catchment, was abandoned as a water balance study in 1961 following the discovery that quantities of water were bypassing the weir. Rainfall and soil moisture continued to be measured and the records were used in the analysis of soil moisture conditions under various vegetation covers (Section 5.2.1). The catchment is roughly circular, 8.4 ha in area, with steeply sloping sides and a more gently sloping lower basin containing a deep infill of fertile soil. Originally under cultivation, the vegetation in 1958 consisted largely of montane scrub and bracken but, over the course of the experiment, more woody species such as *Hagenia abyssinica* and *Pinus patula* were planted and became well established.

The cultivated catchment, A, is 20.2 ha in area with two tributaries joining just before the weir (Fig 1). The sides are very steep with an average slope of 30° and an altitudinal

TABLE I

Mean Climatological Data (1958-69)

Mbeya Range

Altitude 2428 m, Latitude 8°50'S, Longitude 33°28'E

	Rainfall	Temperature			Humidity	Wind	Radiation	Sunshine
	Monthly Total	Max		Mean	Saturation Deficit	Mean speed at 2 m	Gunn Bellani Radiometer	
	mm	°C	°C	°C	mb	km hr^{-1}	MJ m^{-2}	hr
Jan	315.3	18.0	10.4	14.2	2.3	5.6	17.9	4.0
Feb	323.8	18.2	10.3	14.2	2.2	5.8	18.1	3.8
Mar	399.0	18.1	10.5	14.3	2.1	5.4	17.6	3.8
Apr	244.0	18.1	10.3	14.2	2.3	7.2	17.8	5.3
May	28.1	17.9	8.2	13.1	3.1	6.7	20.8	7.6
Jun	2.0	16.0	6.2	11.1	3.8	7.4	20.8	8.1
Jul	0.1	17.2	6.0	11.6	4.7	8.7	23.8	9.2
Aug	0.1	18.4	7.1	12.7	5.8	9.1	24.6	9.1
Sep	7.9	20.0	9.0	14.5	7.1	9.6	24.4	8.4
Oct	25.2	21.1	10.3	15.7	8.1	8.6	23.9	7.9
Nov	100.4	20.2	10.8	15.5	5.7	6.6	20.3	5.5
Dec	287.5	18.3	10.7	14.5	3.1	5.1	17.5	4.0

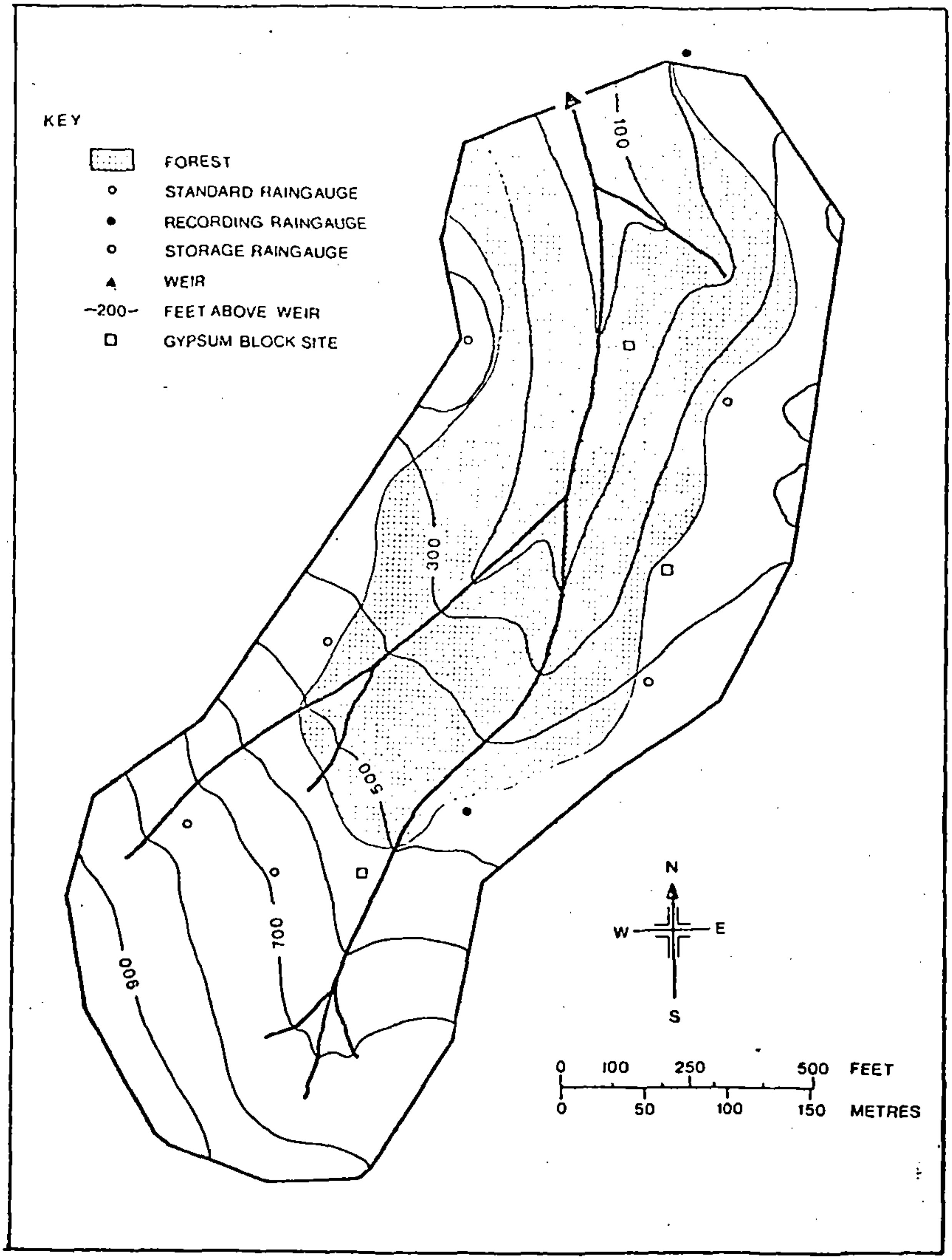


Figure 1 The forested catchment (C) at Mbeya

range of 166 m. A few trees remain in the valley bottom but the remainder is cleared with approximately 50% of the area under cultivation and the rest under annual grasses, grazed by goats and sheep. The area under cultivation changes from year to year, depending on the food requirements of the families inhabiting the valley. The local practice of cultivating across the slope is followed with no effective soil conservation measures other than the placing of 'bunds' of maize stalks approximately along the contours.

All three catchments have north-north-west to north-westerly aspects. Catchments B and C and contiguous while Catchment A lies 3 km to the north-east of B.

INSTRUMENTATION OF THE CATCHMENTS

A full account of instrumentation for streamflow measurement is given in Section 1.2.4. Briefly, Catchments B and C had 120^0 v-notch weirs as their gauging structures while Catchment A had a compound 90^0 v-notch and rectangular sharp-crested section. Lea rotary water-level recorders were installed at all three structures. A sediment trap, consisting of a 7.6 m^3 concrete-lined tank, was installed upstream of the weir in the cultivated catchment to measure part of the sediment load. Daily samples of suspended sediment were also collected at the weirs to estimate the total sediment yield in steady flow conditions.

Rainfall was measured by networks of seven gauges in Catchment ~~A~~ C, six gauges in Catchment B and six gauges in Catchment ~~C~~ A. Five of these were Dines tilting-siphon recording gauges (Fig 2). The gauges were stratified by altitude, and with the high densities used in these small catchments, the precision of estimate of annual totals is within 1%, and for individual storms about 3% (McCulloch, 1962).

Measurements of soil moisture status were obtained from monthly gravimetric sampling at three sites in each catchment.

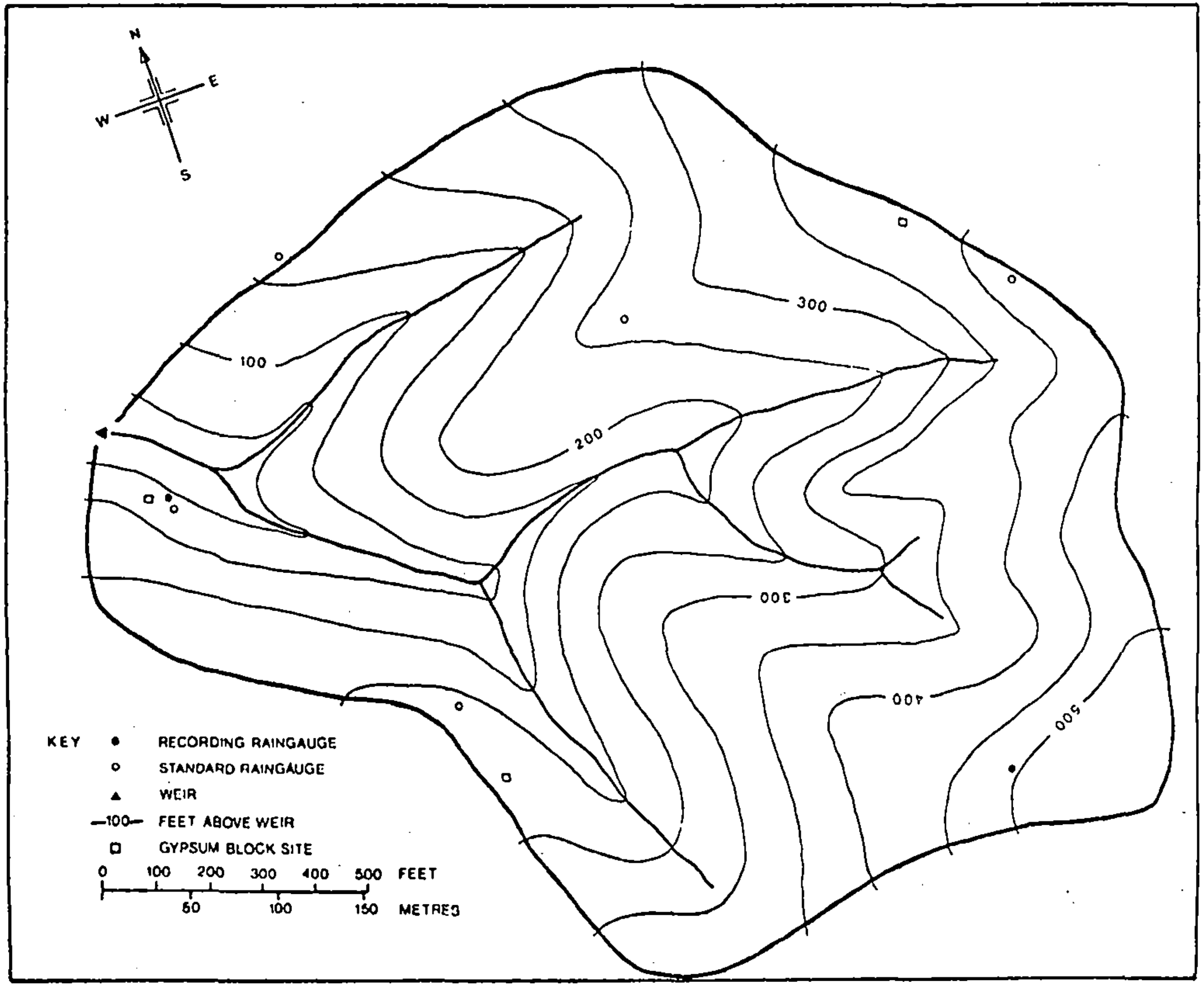


Figure 2 The cultivated catchment (A) at Mbeya

Electrical resistance units were also installed at the three sites to a depth of one metre. In 1962, the depth of profile sampled by these units was extended to two metres. All three profiles in Catchment A were extended to three metres in 1965. The blocks were read at approximately weekly intervals.

Between the catchments, a meteorological site was established, and this yielded records from which Penman estimates of open-water evaporation EO were calculated. Radiation was measured by a Gunn-Bellani radiation integrator - calibrated against a Kipp solarimeter at EAAFRO, Muguga. During the course of the experiment, the exposure of the meteorological site changed due to the growth of a stand of pines outside the enclosure; the possible effect of this on the Penman estimates is discussed in Section 5.2.1.

Attempts were made to measure the sediment yield of the cultivated catchment as described above. It was known that the methods used were unsatisfactory for monitoring the far heavier soil losses which occurred during storm runoff which might be only a few hours in duration. A device for measuring the suspended sediment during times of flood was installed in the stilling pool of the weir and operated successfully during the early part of the experiment. It proved impossible to maintain and operate this device satisfactorily, however, and results are only available for a few storms. An analysis of the sediment yields is presented in Section 5.2.2.

LIMITATIONS OF THE MBEYA EXPERIMENT

The Mbeya region is characterised by a unimodal rainfall distribution with a long dry season which precludes the continuous growth of crops. At the outset of the experiment, therefore, it could be anticipated that, in line with many other such comparisons all over the world, the deeper-rooting evergreen forest would use more water than the shallow-rooting annuals. The experimental objectives, therefore, were to determine the relative distributions of flow between wet and dry season on both catchments, to compare storm runoff volume and to estimate the rate of loss of soil from the cultivated catchment.

These catchments exhibit an unusually high rainfall acceptance due to the porous nature and good structure of the ash derived soils. It is by no means resolved how far the results from this experiment can be extrapolated to other areas; in Tanzania, for example, nearly all the major forest reserves are apparently on soils broadly similar in structure to those of Mbeya if Scott's classification of soils is accepted (see Russell, op cit, 1962). Variability in the seasonal distribution and intensity of rainfall between these areas, however, could make the Mbeya results atypical and without further regional surveys of infiltration rates and soil stability, extrapolation of results for the Mbeya study should be avoided. Furthermore, the erosion studies were never fully implemented, partly because Mbeya lies over 1600 km from Muguga by road and, as with the Atumatak experiment, supervision and maintenance of the experiment fell short of what was necessary to ensure continuous, reliable results. Despite frequent requests for more financial support to revitalize the project, it closed in 1970 without yielding firm quantitative evidence on erosion and sediment transport.

The following sections present an analysis of the ten years of rainfall, streamflow, evaporation and soil moisture data from the Mbeya study. Despite the limitations of the experimental environment, they give valuable insight into the water balance of headwater catchments, and help explain why land-use practices which would be disastrous in other regions did not produce serious erosion in Catchment A during the first five years of cultivation.

REFERENCES

KERFOOT, O, 1964. A preliminary account of the vegetation of the Mbeya Range, Tanganyika. Kirkia, 4, 191-205.

McCULLOCH, J S G, 1962. Measurement of rainfall and evaporation. E Afr agric for J, 27, Special Issue, 115-117.

PEREIRA, et al, 1962. Hydrological effects of changes in land use in some East African catchment areas. E Afr agric for J, 27, Special Issue, 131.

RUSSELL, E W, 1962. (In Pereira et al, ibid, page 1).

TEMPLE, P H, 1972. Soil and water conservation policies in the Uluguru Mountains, Tanzania, Geografiska, Annaler, 54, Ser 9A, 110-123.

WEBSTER, C C, and WILSON, P N, 1966. Agriculture in the Tropics. Longmans, London, 488.

5.2.1

THE WATER BALANCE OF THE MBEYA EXPERIMENTAL CATCHMENTS

K A Edwards
Institute of Hydrology, Wallingford, UK

5.2.1

THE WATER BALANCE OF THE MBEYA EXPERIMENTAL CATCHMENTS

K A Edwards
Institute of Hydrology, Wallingford, UK

INTRODUCTION

The two previous summaries of the interim results from the Mbeya experiment (Pereira et al, 1962, Dagg and Blackie, 1965) contain systematic errors in the streamflow records from the cultivated catchment (A) due to an erroneous transposition of stage-discharge tables at an early stage of data analysis. The resulting over-estimation of flow in Catchment A led to an exaggeration of the difference in water use between it and the forested control catchment (C). This anomaly stimulated an extensive check of the experimental data which led to major corrections to streamflow and evaporation values.

The corrected data have been published in summary form (Edwards et al, 1976) and this section deals with the water balances of the two catchments. In achieving the experimental objectives, briefly the comparison of cultivated and forested catchments on the steep volcanic soils of the Mbeya Range in southern Tanzania, the pertinent hydrological effects to be examined are the influence of the land use change on the volume and distribution of streamflow and on the rate of sediment yield from the cultivated catchment. This latter aspect is dealt with separately (Section 5.2.2).

RAINFALL

The Mbeya Range lies approximately 450 km inland from the Indian Ocean at a latitude of 8°50' south of the Equator. The rainfall pattern is related to the southerly swing of the Inter-Tropical Convergence Zone around the southern hemisphere summer solstice, which results in 98% of the rain falling between November and May. The seasonal distribution is shown by the mean monthly rainfall totals in Table I. Monthly

TABLE I

Mean and Standard Deviation of Monthly Rainfall (mm) at Mbeya Catchment C (Control: Evergreen Forest) 1958-68

Month	Mean	σ
January	328	± 152
February	313	± 54
March	436	± 122
April	271	± 103
May	34	± 31
June	4	± 8
July	0	
August	0	
September	7	± 8
October	25	± 24
November	112	± 80
December	369	± 144
Total	1899	

totals are of high reliability during the wet season and the coefficient of variation of the average annual total of 1899 mm is relatively low at 13%. This uniformity is particularly useful for water balance studies.

The experimental catchments lie on the north side of Mbeya Peak and, as expected, total rainfall varies with altitude. The forested catchment extends to some 250 m higher than the cultivated catchment and receives about 17% more rainfall on average. The rainfall networks have been described in Section 5.1.1, and their efficiency has been discussed in Section 1.2.1. With such small catchments and dense raingauge networks (Catchment A has approximately 30 gauges km^{-2}, Catchment C has 43 gauges km^{-2}), the precision of mean areal rainfall is high. The differences between mean areal rainfall estimated by the arithmetic mean and by the Thiessen polygon method are negligible and no systematic errors are thought to be present in the rainfall data.

Rainfall intensity has been discussed briefly in Section 1.2.1 also. While Mbeya, Kericho and Atumatak show similarities both in seasonal rainfall distribution and general intensity pattern, Mbeya has significantly fewer intense storms (> 100 mm hr^{-1}) than either Kericho or Atumatak (Dagg, 1958); furthermore, although Mbeya and Kimakia are similar with respect to incidence of intense falls, the Mbeya catchments lie clearly under a different regime taking into account seasonal distribution and diurnal rainfall pattern.

The low rainfall intensities and deep volcanic soils in both the Mbeya and Kimakia regions are important factors in reducing soil erosion from cultivated catchments, and this high rainfall acceptance allows land use practices which would result in widespread erosion outside the zone of Tertiary Volcanics.

EVAPORATION

The seasonal distribution of Penman EO values is shown in

Figure 1 together with the monthly rainfall totals from Catchment C; the figure shows that potential evaporation exceeds rainfall from May to November and is less than rainfall in the wet season. In contrast to the other high rainfall experimental catchments (Kimakia and Kericho), there is a long period during which soil moisture is being depleted by transpiration. Although the water that can be stored in the top metre of soil is large (185 to 225 mm), the bulk of roots are found in this zone also; furthermore, potential evaporation, which is an index of evaporative demand, is high (120 to 160 mm per month) and these two factors suggest that soil moisture stress must be such that actual evaporation is less than potential.

Although the Penman estimates of potential evaporation are known to exceed actual evaporation for several months of the year, the ratios of actual to potential evaporation (AE/EO) are of value for interpreting the water balance, and it is important to ensure that the estimates are free from bias. It was known that several difficulties had arisen with operating the meteorological site at Mbeya, so that EO values were suspect; in particular, a stand of small conifers which had been planted in 1959 eventually grew to a height at which lower wind speeds and radiation totals were being recorded because of shelter effects. There were also minor temperature anomalies which do not affect the evaporation values significantly. An examination of the annual evaporation totals showed, in fact, a steady decline throughout the 1960s.

It was considered impractical to attempt to correct the basic wind run data for the above effect, since no standard for comparison existed and the systematic error was thought to be no more than 5%. However, large corrections were made to the radiation data collected up to 1960 by comparing the relationship between radiation and sunshine for different periods and adjusting regression equations for individual Gunn-Bellani radiometers. Changing these

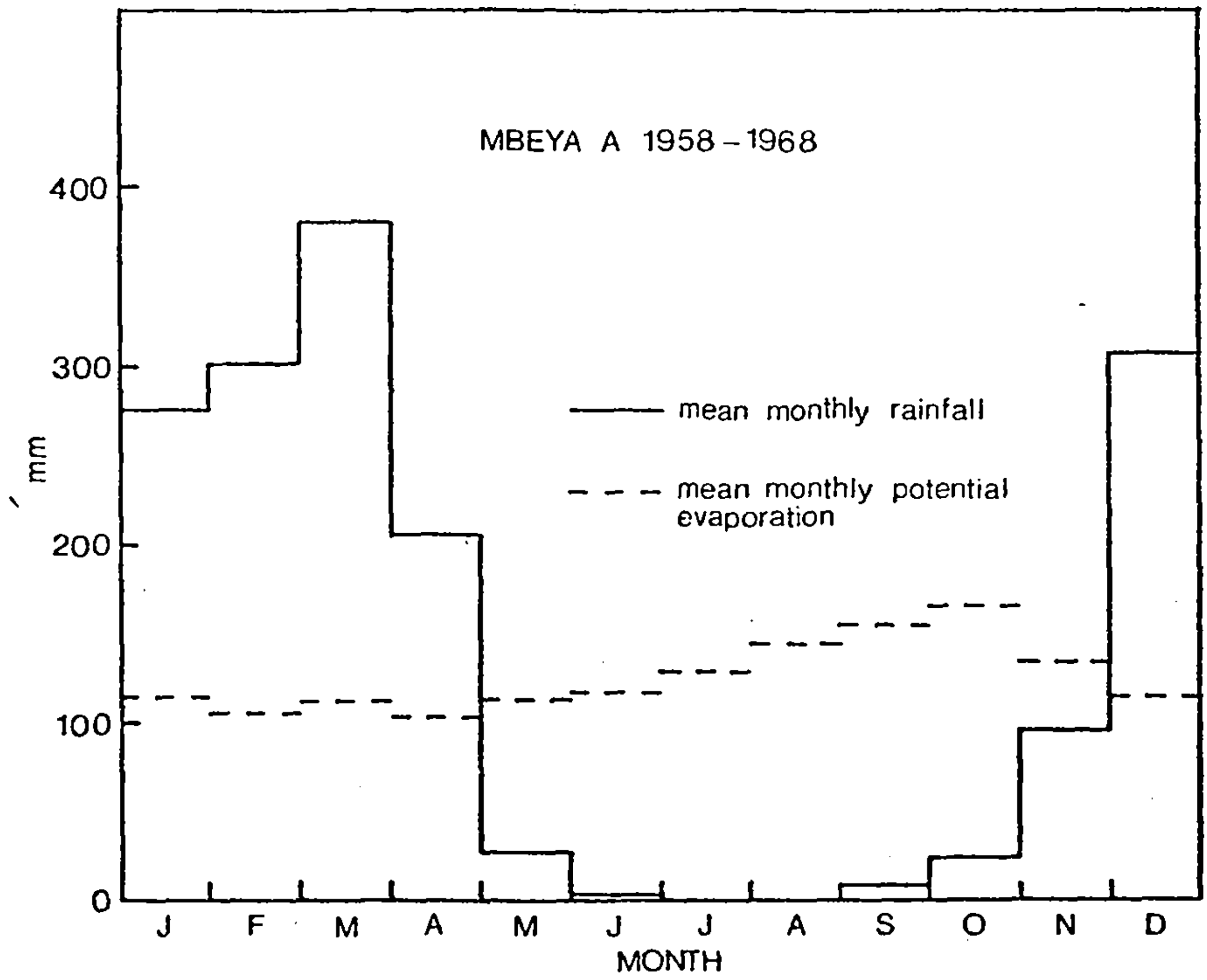


Figure 1 Mean monthly rainfall and potential evaporation at Mbeya Catchment A

high values removed much of the variation in year-to-year evaporation totals. The trend still exists, as can be seen in Fig 2, but how far any secular trend in evaporation totals can be separated from the trend due to shelter effects is a matter for conjecture. Since the likely errors are now small, they do not affect the water balance conclusions and it was considered sufficient to publish the data as they now are, with a warning as to the existence of the small systematic error.

Daily potential evaporation rates vary little throughout the November to May "wet" period, averaging 3.6 mm day^{-1}. From July onwards, the rate rises to a peak of 5.4 mm day^{-1} in October. The annual mean daily value is 4.1 mm day^{-1} over the period 1958-68. The frequency distribution of potential evaporation rates at 0.5 mm intervals is shown in Fig 3. As a result of the hot dry conditions at the end of October, some exceptionally high rates, of the order 9-10 mm day^{-1}, have been recorded.

STREAMFLOW

The two catchments have a mantle of ashy volcanic soils lying on top of weathered gneisses of the Basement Complex Series. The valley bottoms, therefore, have a varying depth of pumiceous ash mixed with gneiss-derived material which is not watertight and which posed considerable problems in siting stream gauging structures. The preliminary examination of the water balance data used the overestimates of streamflow from Catchment A (due to the incorrect rating curve, referred to in the Introduction) and in consequence the actual evaporation loss from the catchment was thought to be small[5], relative to potential evaporation; similarly, for Catchment C, the actual evaporation loss was found to be high and the conclusion drawn was that streamflow from Catchment C was probably underestimated because flow was bypassing the gauging structure. The revision of the streamflow and evaporation data now gives an entirely different picture, and although leaks around both structures cannot be ruled out, they

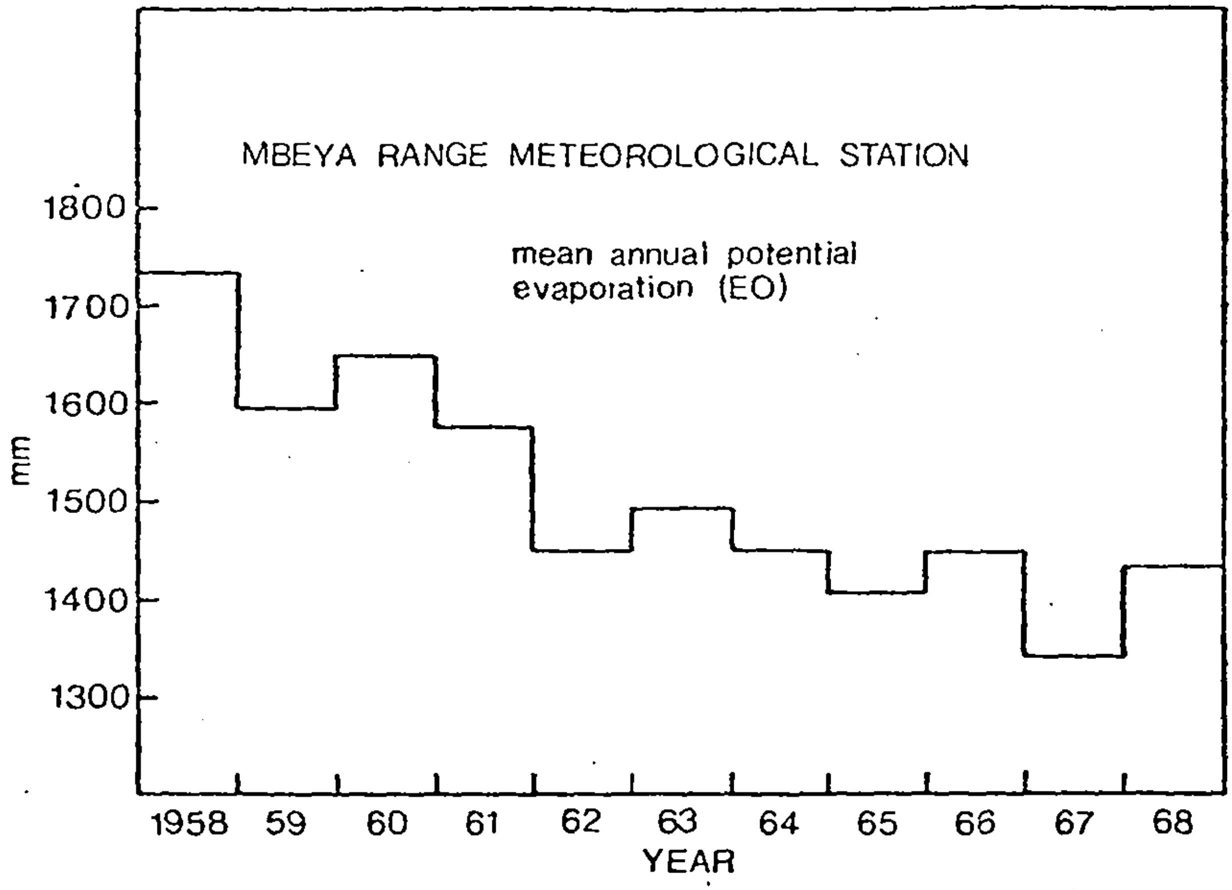


Figure 2 The trend in annual potential evaporation totals at Mbeya

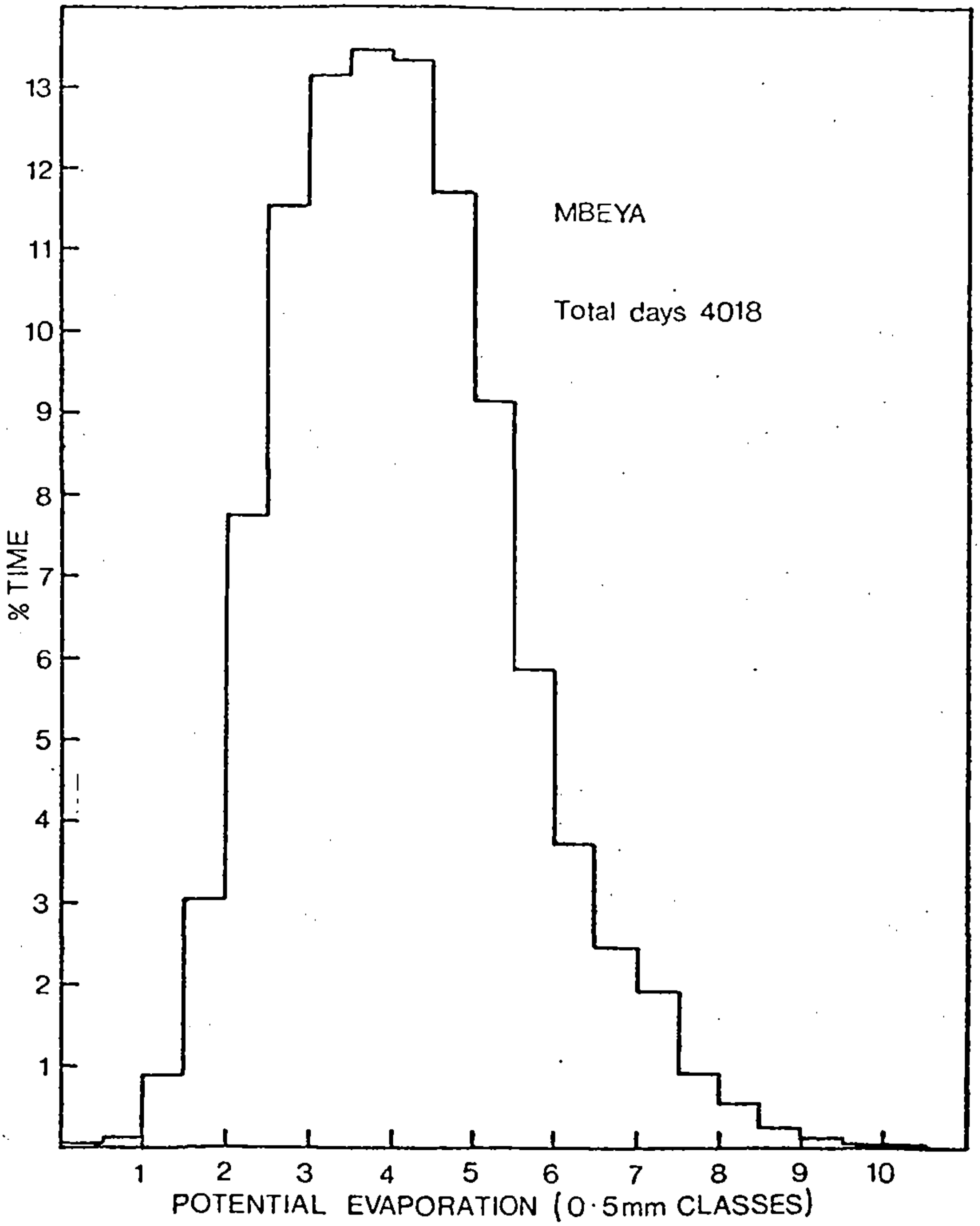


Figure 3 Frequency histogram of daily potential evaporation in 0.5 mm class intervals

are unlikely to be of great consequence.

The 90^0 v-notch weir on Catchment A has been extensively modified and buttressed during the course of the experiment. Its present design has many undesirable features which cast doubt on the stage-discharge relation. It has been calculated that a discharge reduction of the order of 8% might be expected due to drowning of the v-notch and rectangular sharp-crested section at stages of 30 cm or more. At higher stages, the rectangular sharp-crested weir has no provision for aeration and discharge may increase by about 3% while suffering from the same compensating drowning-out effect mentioned above. A further effect which may also occur is that of an increase in discharge due to the erection of a recorder well in the approach channel close to the weir. At high flows, therefore, discharge may be underestimated on Catchment A by perhaps 15 to 20%. Fortunately, stormflow contributes only a small percentage of the total flow (about 2%) and it is clear that these errors in discharge measurement at high stages will not seriously affect the water balance calculations.

As a direct consequence of the unreliability of the gauging structure in Catchment A, however, it was not considered worthwhile to continue the stormflow analysis begun by Dagg (Dagg and Blackie, 1965). The stormflow results published at that time were based on the faulty streamflow data and, after correction, if the stormflows are reduced by 15 to 20% as recommended above, the difference between forested and cultivated catchments decreases accordingly. Although no precise corrections can be made, it is clear that there are practically no differences in the percentages of rainfall which leave the catchments as storm runoff.

As an illustration of this, storm runoff has been calculated for storms in the 1962-63 water year and the 1965-66 water year from both catchments. Each storm has been classified according to a weighted mean intensity determined by summing the product of rainfall amount and intensity for various parts of the storm, and dividing by the total rainfall. This procedure therefore takes some account of the high intensities which may be experienced at the beginning of a storm and which may be reduced significantly when the mean intensity is calculated as storm total divided by duration.

Table II gives the storm runoff as a percentage of incident rainfall for various weighted mean intensity classes. These values have been calculated for storms falling on already wet catchments (ie rainfall occurring within the last 24 hours) and on surfaces which have been drying out for between 1 and 2 days. After 3 days, the storm runoff for practically all intensity classes is very low although these storms occur very infrequently in the two years analysed.

It can be seen that Catchment A has a slightly higher percentage of rainfall leaving the catchment as storm runoff than Catchment C, and this difference is most marked during the lower intensity storms. All the values are very low, however, and the maximum storm runoff during the two years did in fact come from Catchment C in March 1966 where 7.8% of a rainfall of 53 mm can be separated from the hydrograph as storm runoff.

Fig 4 shows the cumulative flow frequencies at 0.5 mm intervals for the two catchments. At higher flows, the patterns are identical, but significant differences can be seen at the low flows. The forested catchment has a higher percentage of very low flows (< 2 mm day^{-1}) which reflects the continuing high rate of water use during the dry season. Looking at the seasonal pattern of flow, Fig 5 gives the percentage of total streamflow in each calendar month. Bearing in mind that the cultivated catchment has a higher total streamflow, in spite of a lower rainfall, than the forested catchment (Table III), it can be seen that there is an unexpected seasonal pattern which contrasts sharply with similar experiments elsewhere (Bates and Henry, 1928, Douglass, 1967). Catchment A appears to have a moderating influence on the high runoff during the rains and yet sustains higher flows during the dry season than

TABLE II

Percentage of Storm Runoff for Various Rainfall Intensities (1962-63 and 1965-66 water years) at the Mbeya Catchments A (cultivated) and C (forest)

Time since last rain	Weighted Mean Intensity Classes			
	0 - 13 (< 0.5)	13 - 38 (0.5 - 1.5)	38 - 64 (1.5 - 2.5)	> 64 mm hr^{-1} (> 2.5 in hr^{-1})
Mbeya A				
< 1 day	0	1.0	3.3	3.6
1-2 days	0	0.5	1.9	4.2
Mbeya C				
< 1 day	0	0.8	1.6	3.8
1-2 days	0	0.5	0.4	0.8

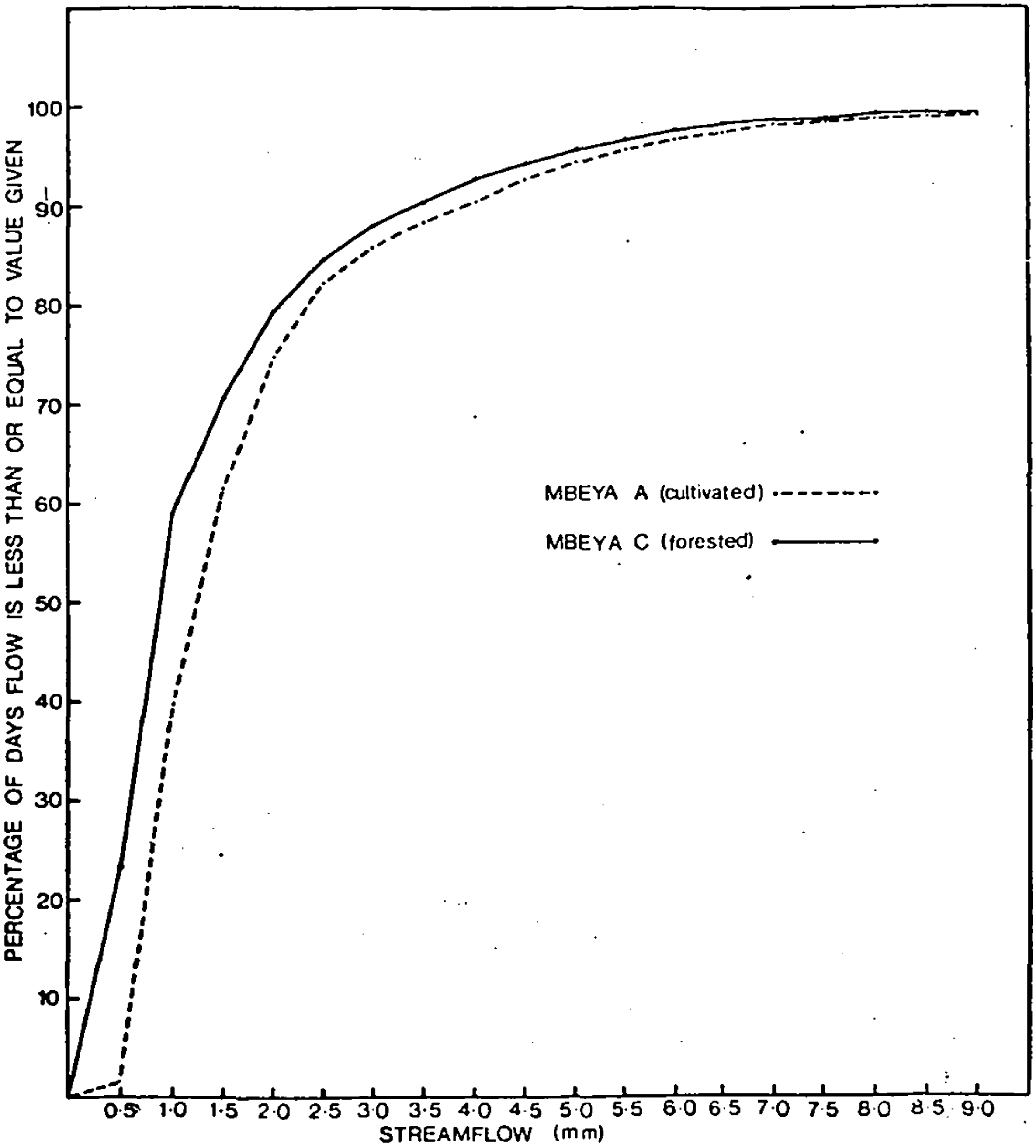


Figure 4 Cumulative flow frequencies for the Mbeya catchments

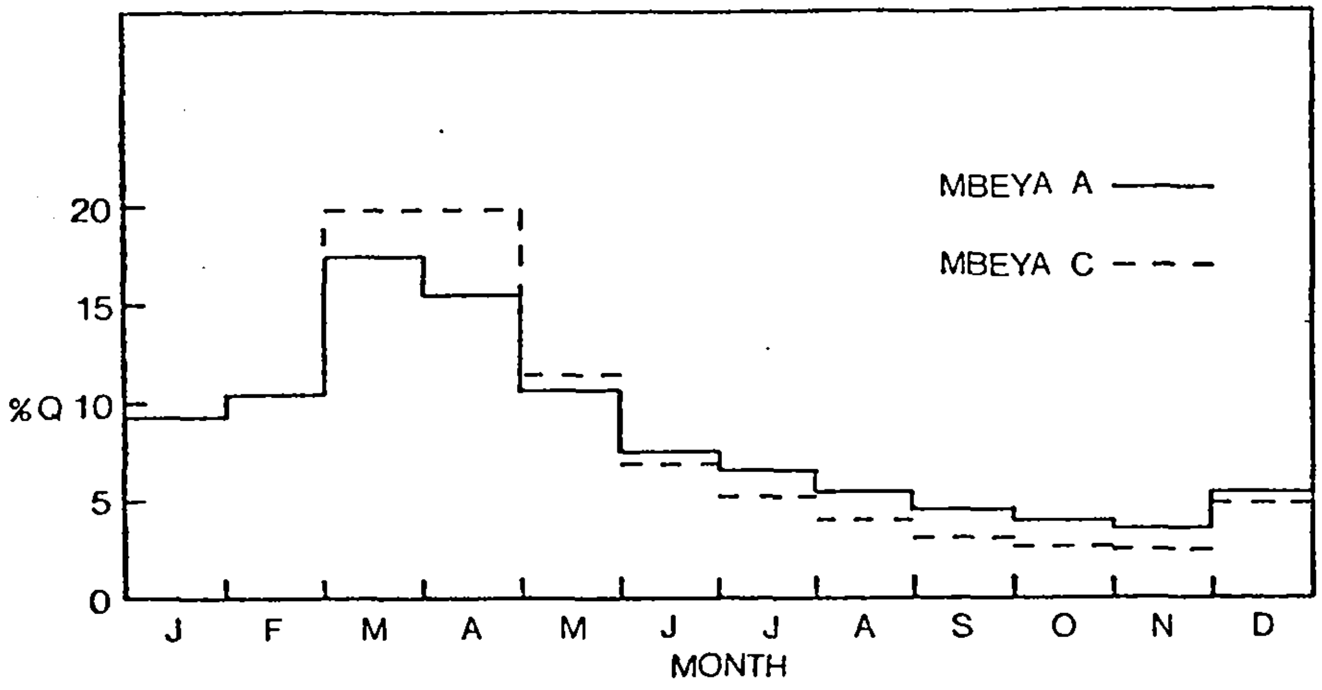


Figure 5 The seasonal pattern of streamflow at Mbeya

TABLE III

Monthly Streamflow (mm) 1958-1968

Month	Mbeya A (cultivated)	Mbeya C (forested)
January	60	48
February	68	54
March	114	104
April	102	104
May	69	60
June	46	36
July	42	27
August	36	21
September	29	16
October	26	14
November	24	13
December	36	25
Total	652	522

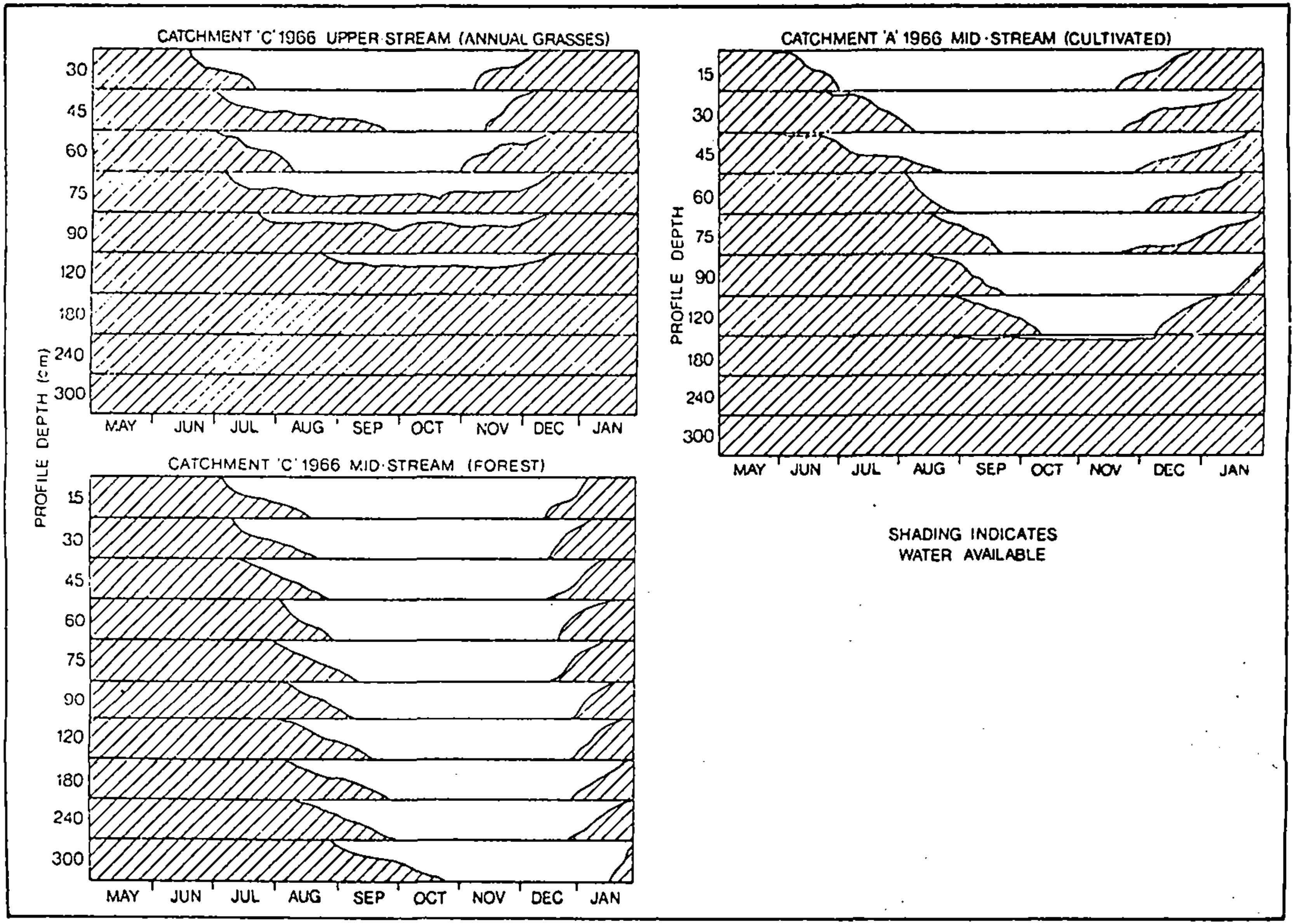
Catchment C: in other words, the behaviour of the cultivated catchment is very like that expected for a forested catchment.

How far one can attribute the higher streamflow in Catchment C in the wet season to the effect of the grassland occupying the upper third of the catchment is difficult to say, but the marked differences in dry season flow are undoubtedly due to the higher rate of water use by the trees compared with the annual crops. Confirmation of this may be obtained from the following analysis of the soil moisture records.

SOIL MOISTURE

To obtain estimates of the amount of water stored in the soil to be included in the water balance calculations, monthly gravimetric measurements of soil moisture content were made to a depth of 1.07 m (3½ ft) in both catchments. At this level, a stone layer is present which makes deeper sampling difficult, and although attempts were made to sample down to 3.05 m (10 ft) at the more favourable sites, it has not been possible to calculate soil moisture deficits accurately over the whole range of moisture extraction. In the cultivated catchment, this has not proved too severe a limitation since both the perennial grasses and the annual crops do not appear to extract water from beyond 2.5 m except in the driest years (see below). In the forested control Catchment C, however, the trees root to a depth of some 8.2 m (27 ft) into the decomposed gneiss (Kerfoot, 1964) and it is known that water is regularly extracted from beyond 3.05 m during the dry season.

Gypsum blocks were also used to indicate the pattern of seasonal moisture availability. Three sites were chosen in each catchment, and weekly measurements of block resistance were made down to 3.05 m. These qualitative indications of available moisture are useful in confirming the pattern of moisture extraction suggested by the surface gravimetric measurements. Fig 6 shows plots of the resistance block records in a typical year from the middle sites in each catchment and



CATCHMENT 'C' 1966 UPPER STREAM (ANNUAL GRASSES)

CATCHMENT 'A' 1966 MID·STREAM (CULTIVATED)

CATCHMENT 'C' 1966 MID·STREAM (FOREST)

SHADING INDICATES WATER AVAILABLE

Figure 6 Resistance block records for the Mbeya catchments (1966) from the upper site in Catchment C where the forest gives way to grassland. Ignoring the irregularities which are bound to arise occasionally from such readings, the cycles of drying and wetting throughout the soil profiles at the different sites are well defined.

At the forested site in Catchment C, the readings show rapid drying throughout the profile until wilting point is reached by the end of October at 3.05 m. It is interesting to note that this layer does not return to a fully wetted state until the end of January, and the baseflow response is accordingly affected by this lag in recharge.

At the upper site on the grass slopes of Catchment C, moisture extraction is evident down to 1.22 m (4 ft) but the indications are that the perennial grasses root to a relatively shallow depth and that the gravimetric samples give a good indication of the soil moisture deficit in this part of the catchment.

In the cultivated catchment, the pattern of water extraction varies slightly from year to year depending on the crop density and type, particularly in the immediate vicinity of the block sites. The general pattern, however, is shown in Fig 6, and it can be seen that the surface blocks are beginning to dry out at the end of May and by the end of August the soil is at wilting point to a depth of 60 cm (or more in the drier years). It is significant that the lower blocks did not dry out until the end of September in 1966, demonstrating the continued extraction by the crop until harvesting time. Although some extraction does take place from the 1.8 m (6 ft) level, the gravimetric sampling can be expected to measure most of the soil moisture deficit during the early part of the growing season. By the end of October, however, an unmeasured deficit exists below the sampling range, and this has a significant effect on the water balance calculations.

THE ANNUAL WATER BALANCE

In view of the large soil moisture deficits which develop in the two catchments, the choice of a water year is quite critical if the errors in the storage terms are to be kept to a minimum in individual years. It is known from the gypsum block readings that water is being extracted from below the soil moisture sampling range by the end of July, and by October the soils are at wilting point over most of the rooting depth. The October to September water year seems attractive at first sight because baseflow is at a minimum; the unmeasured soil moisture deficit below the depth of sampling, however, is much too large by this date to ignore, and year-to-year variations are then a significant feature of the water balance.

Equally, any water year beginning in the wet season cannot adequately account for storage changes in groundwater from year to year, because of the lag in recharge, although it is reasonable to assume that no soil moisture deficit exists. A far better water year is from July to June, by which time a soil moisture deficit has developed but not extended beyond the sampling range and, also, the groundwater recession has begun, following the end of the rains in May. Thus, soil moisture storage changes can be measured from the monthly gravimetric sampling and the groundwater storage changes can be estimated from the recession curves and baseflow measurements.

Table IV gives the unadjusted water balance figures for both catchments over the periods shown. The length of the periods varies slightly depending on the soil moisture sampling dates as shown in the Table. AE is the actual evaporation or water use in the catchments, calculated from:

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

and EO is the Penman estimate of open water evaporation. Soil moisture sampling was discontinued in Catchment C after 1964, following increased commitments on the part of the local field staff. At that time, it was felt that sampling to 1 m was not worth the considerable effort involved, particularly

TABLE IV

Unadjusted Water Balance (mm) for Mbeya Catchments A (Cultivated) and C (Forested)

Catchment A (cultivated):

Period	R	Q	ΔS	ΔG	AE	EO	AE/EO
21.6.58-21.6.59	1308	358	0	-75	1025	1748	0.59
21.6.59-11.6.60	1730	497	+33	+131	1069	1496	0.71
11.6.60-11.6.61	1181	457	-29	-112	865	1675	0.52
11.6.61-11.7.62	2257	1044	+11	+212	990	1636	0.60
11.7.62-11.6.63	1546	643	+38	-100	965	1329	0.73
11.6.63-11.6.64	1901	792	+11	+124	974	1473	0.66
11.6.64-11.6.65	1369	556	+21	-160	952	1465	0.65
11.6.65-10.6.66	1485	494	-58	0	1049	1380	0.76
10.6.66-10.6.67	1528	476	+29	+18	1005	1435	0.70
10.6.67-11.7.68	2276	1296	-13	+167	826	1442	0.57
Mean, 1958-68:	1658	661	+4	+20	972	1508	0.64
	±120	±94	±10	±42	±24	±42	±0.02

Catchment C (Forested):

Period	R	Q	ΔS	ΔG	AE	EO	AE/EO
10.6.58-10.6.59	1421	214	+18	0	1189	1722	0.69
10.6.59- 7.6.60	2043	564	-61	+70	1470	1526	0.96
7.6.60-29.6.61	1332	330	+2	-70	1070	1773	0.60
29.6.61- 5.6.62	2753	842	+42	+85	1784	1406	1.27
5.6.62- 5.6.63	1878	534	-34	-27	1405	1453	0.97
5.6.63- 6.6.64	2199	652	+4	+27	1516	1481	1.02
6.6.64-11.6.65	1512	446	0	-39	1105	1482	0.75
11.6.65-10.6.66	2013	564	0	+12	1437	1380	1.04
10.6.66-10.6.67	1681	453	0	0	1228	1435	0.86
10.6.67-11.7.68	2404	814	0	-20	1610	1442	1.12
Mean, 1958-68:	1924	541	-3	4	1381	1510	0.93
	±143	±62	±9	±15	±73	±42	±0.06

since resistance block readings showed deficits to at least 3 m depth. For the later years, the soil moisture storage term has been neglected, and the effect~~ive~~ of this omission is discussed later.

The water year figures show both wide variation from year to year within catchments, and a striking difference between catchments. The streamflow figures Q indicate that whilst approximately 40% of rainfall on Catchment A runs off, only 28% of the higher rainfall in the forested Catchment C is measured as streamflow. Expressed in a different sense, the water use estimates, AE, show that the forested Catchment C uses approximately 72% of the rainfall whilst the equivalent figure for Catchment A is 59%. Whilst these differences are moderated somewhat by the corrections to streamflow and evaporation compared with the 1965 published data, they are still very large with serious implications for land management policy. It is important, therefore, to look at each catchment in detail to see whether there is any justification for doubting the pattern of water use portrayed by Table IV.

MBEYA A, THE CULTIVATED CATCHMENT

The ratio of actual water use, AE, to the Penman estimate of open water evaporation EO is a critical guide to the consistency of the hydrological data. In the climatic regime of Mbeya, the year-to-year fluctuations are an expected response to different seasonal rainfall distributions and can also be affected by cropping patterns and densities. The ratios AE/EO calculated for each water year are the resultants of high potential evaporation rates during the wet season and decreasing rates as soil moisture deficit increases. The average ratio for the ten-year period is 0.64 with fluctuations of the order of 10% of EO.

If the annual AE/EO value is plotted against rainfall R as in Fig 7, it can be seen that a complex relationship exists for Catchment A, whilst a clear dependence of AE/EO on R is

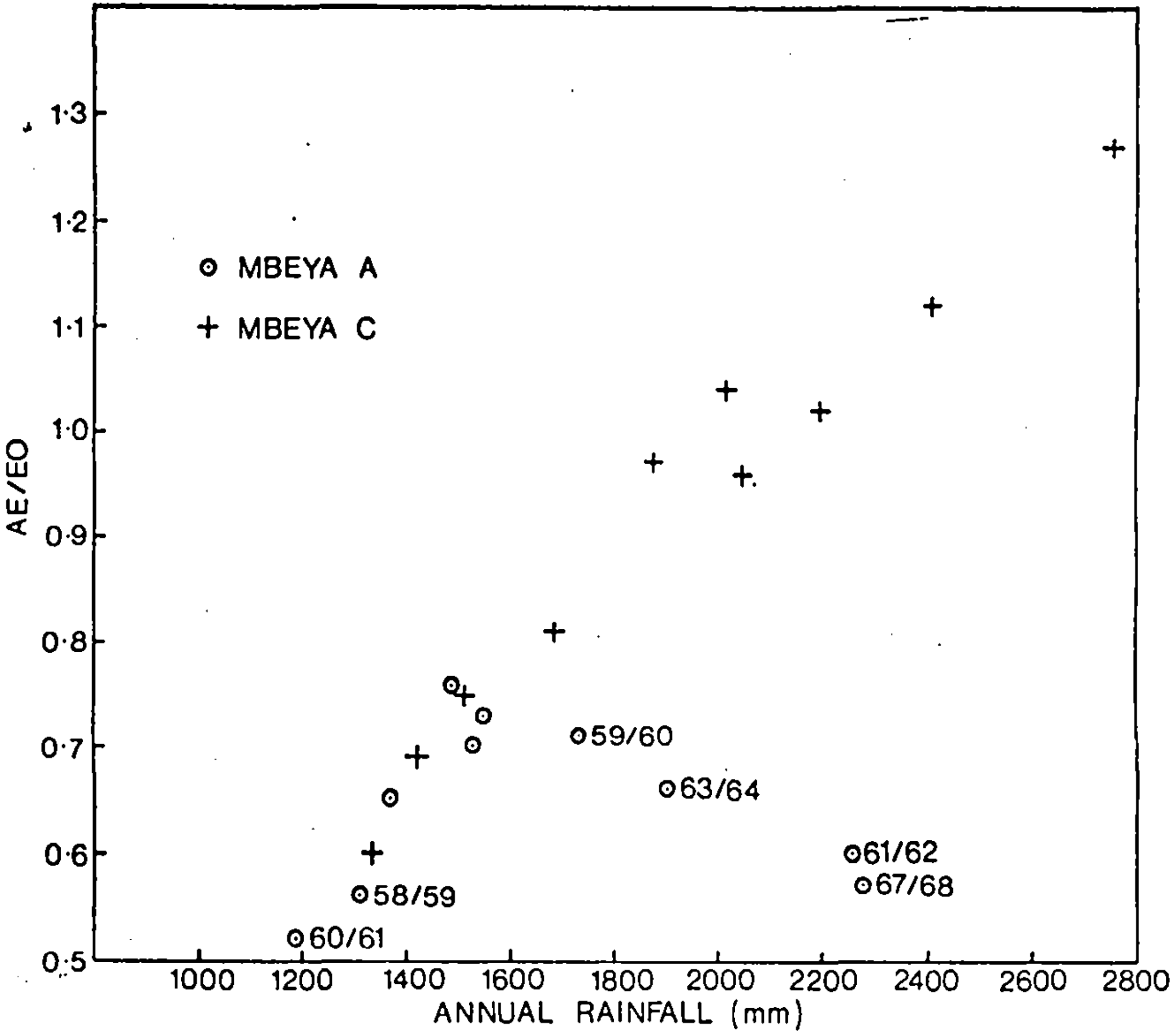


Figure 7 The annual ratio of AE/EO against rainfall for the Mbeya catchments

apparent for Catchment C. This relationship is important because it indicates a probable systematic error in the water balance of Catchment C. In the cultivated Catchment A, on the other hand, the range in AE/EO is much smaller, and two quasi-linear relationships appear to exist. One is a tendency for AE/EO to increase with R in drier years, and second is an apparent trend of decreasing AE/EO with R in wetter years. Before discussing the origin of these trends, however, it is useful to examine the seasonal data for consistency with the soil moisture measurements.

During the dry season, a surface water balance may be calculated which is simplified by the absence of rainfall sufficiently heavy to cause recharge beyond the depth to which soil moisture is measured. Changes in storage over the measured soil profile can then be equated directly to the evaporative losses at the surface, neglecting unsaturated vertical flow in the profile. Taking account of such small isolated showers, we have:

$$AE = R \pm \Delta S$$

where ΔS is the change in storage between monthly sampling dates.

Fig 8 shows such dry season water use values plotted against the mean soil moisture deficit between sampling dates. The scatter is typical of such diagrams where gravimetric soil moisture measurements form the basis of the calculated deficits. The low AE/EO rates with small deficits (shown in the bottom left hand corner of the figure) are almost always the first measurements of the dry season, when vegetation cover may be minimal and transpiration losses therefore small; the anomalously high values result from rain falling between the sampling dates and are postulated as lying on a wetting cycle. A hysteresis loop is sketched in by eye; its exact form is, of course, difficult to define from such limited data. The drying curve is more definite and has been drawn to pass through the mean AE/EO ratios and deficits derived from the

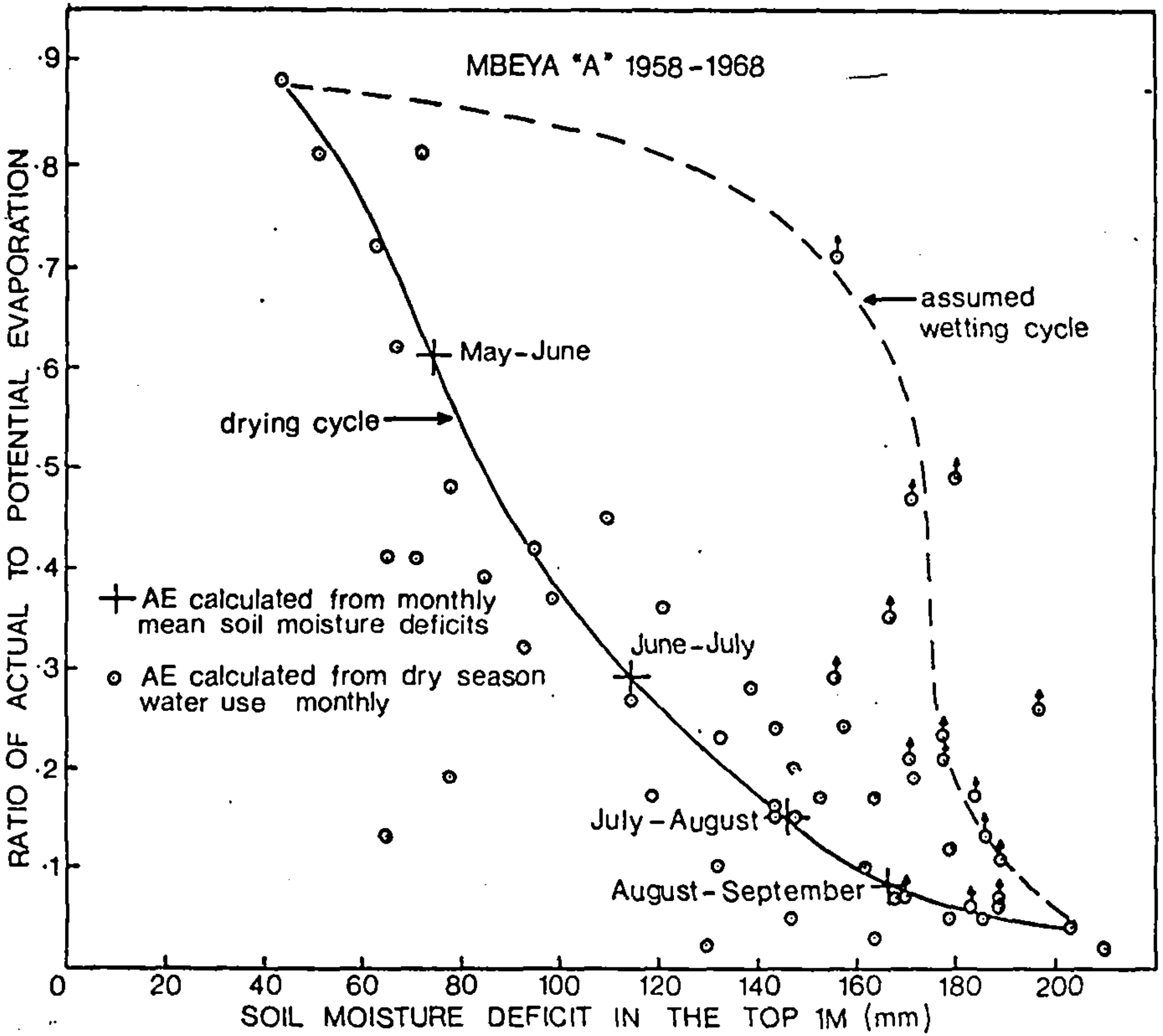


Figure 8 Estimated dry season water use as a function of soil moisture deficit, Mbeya A

monthly mean soil moisture deficits and potential evaporation, averaged over the eleven years of data (Table V).

Two points should be made about Fig 8, however, before taking the argument further. First, although the resistance block readings indicate that not much water is lost from below 1 m, the drying cycle represents the reduction to wilting point of the whole profile and the measured soil moisture deficits are an underestimate of the true deficit from July onwards. Second, the mean wet season rate shown as the upper limit of the curve has been calculated by difference assuming that the overall average AE/EO ratio of 0.64 in Table IV is correct.

An alternative method of calculating the wet season AE/EO ratio is to take each water year and sum the measured water loss from the profile. This dry season water use can be subtracted from the annual AE calculated from the water balance equation and expressed as a ratio of the measured EO during the wet months. Table VI shows these values; the mean AE/EO ratio derived in this way is higher by about 5%.

The higher value arises from the underestimate of dry season water use given by the 1 m soil moisture deficits. Using the difference between these two values as an estimate of the deficit developed below 1 m, (5% of mean EO), the extra storage term to be accounted for is approximately ± 75 mm or equivalent to the soil drying to a depth of 1.52 m (5 ft).

To summarise, therefore, the water use figures for Catchment A are consistent with a wet season water use of from 0.92 EO to 0.97 EO, and a dry season water use which varies with soil moisture deficit in the manner indicated by Fig 7. These values are much higher than previously computed figures. At the same time they agree in wet season water use with AE/EO ratios derived for broad-leaved forest at Kericho (see Section 2.2.1) and in Catchment C: they also appear to give reasonable estimates of dry season water use.

TABLE V

Estimated Mean Dry Season Water Use (mm)
by Mbeya Catchment A (Cultivated): 1958-68

	J	F	M	A	M	J	J	A	S	O	N	D
SMD	37	43	43	38	74	114	147	166	178	165	166	96
ΔS	-6	-0.3	+5	-36	-40	-32	-20	-11	-9	+21	+69	+59
R	276	300	380	206	28	2	0.1	0.2	8	22	95	309
AE	-	-	-	-	68	34	20	12	17	1.3	26	-
AE/EO					0.61	0.29	0.15	0.08	0.11	0.01	0.19	-

TABLE VI

Wet Season Water-Use Water Year Oct-Sept

Water Year	AE/EO
1958-59	0.91
1959-60	1.09
1960-61	0.81
1961-62	1.00
1962-63	1.06
1963-64	1.02
1964-65	0.81
1965-66	1.05
1966-67	1.07
1967-68	0.83
Mean	0.97 ± 0.04

MBEYA CATCHMENT C, THE FORESTED CATCHMENT

The AE/EO ratios for the control catchment are different from those for Catchment A in both mean value for the water years and in the year-to-year variation. Although the mean value of 0.91 is close to the wet season water use in Catchment A, the range 0.$\overset{6}{5}$0 to 1.27 is too large to have arisen from accidental minor storage errors or from systematic errors in EO. The year-to-year variation is also strongly correlated with rainfall and streamflow, and there is a suggestion of either systematic errors in these terms or major storage errors associated with drainage and recharge in the dry and wet years respectively.

Taking streamflow first, the simplest explanation at first sight would be to postulate a "leak" or a systematic bypassing of the gauging structure proportional to total flow. Given the porous topsoil and rotten gneiss beneath, it is not difficult to calculate saturated matrix flow of the required order of magnitude from the permeability values given by Pereira (Pereira et al, 1962) and the known dimensions of the valley. On the other hand, to remove the trend in Figure 7 by means of a "one-way" correction to streamflow, compensating for the leak, requires that the average annual AE/EO value for this forested catchment be reduced to about 0.60, a figure patently too low for evergreen forest.

In terms of rainfall, the quantity required to correct the trend is a smaller percentage of the annual precipitation, but bearing in mind both the high precision of the mean and the agreement between the two catchments, it is not easy to see how a large systematic underestimate in R could arise.

Perhaps the most satisfactory explanation is that a deep deficit exists which is neither measured by the soil moisture sampling, nor is it such that it affects the base flow in the stream. Such a deficit is known to develop, of course, from the resistance block readings, but it was assumed that adopting the

July to June water year would eliminate any systematic errors because the deep store would have been replenished by then. It now appears that not only is the store still in deficit by July in a dry year (in other words, it must be deeper than 3 m) but also that, in a wet year when it is contributing to the flow, it is not reflected in any significant increase in baseflow.

The magnitude of this deep storage effect can be gauged from Fig 7 as approximately half the total range in AE/EO multiplied by the mean EO value. It is estimated at approximately ± 528 mm assuming that the 1961/2 water year represents a very wet year and the preceding year an equally dry extreme. The absence of surface soil moisture deficits for the later years can now be seen to introduce insignificant errors in terms of this deep storage effect. The acceptance of this figure implies that a complete water balance of Mbeya Catchment C (the forested control) cannot be accomplished by the experimental methods adopted. It is necessary, however, to provide an independent check of the magnitude of this systematic error before it forms a basis for discussion and because of its important influence on the interpretation of the Catchment A data.

COLLECTING THE WATER BALANCE DATA

An alternative method of approaching the water balance is to assume that actual evaporation can be estimated within a small margin of error and that the unknown is now the deep storage effect introduced above. By following the recent findings on evaporation from forests (Rutter et al, 1971, Stewart and Thom, 1973, Shuttleworth, 1975) it is possible to use a Penman-Monteith type equation to calculate the wet and dry canopy evaporation rates separately. In the absence of direct measurements of aerodynamic and canopy resistances (Section 1.2.2) certain simplifying assumptions can be made, and a crude estimate of the total annual evaporation can be derived from three parameters: the interception storage of the canopy (SINT), the rate of evaporation of intercepted water as a function of EO (FW), and the rate of transpiration from the dry canopy, also expressed as a function of EO denoted by FD). In this case, SINT was taken to be 3 mm, FW was taken to be 6 EO, and FD was taken to be 0.85 EO, all values derived from the optimisation of the mathematical models of the Kericho Lagan catchment.

Using the number of raindays in which R was equal to or greater than the canopy storage as the prime variable, it is possible to calculate a new estimate of total water use, denoted by EVAP, for the water years. These values, however, apply strictly to the forested catchment, and it is necessary to reduce them to allow for the upper third of the catchment under grass. This has been done assuming that the average water use for the grass is 0.65 EO, ie equivalent to the average annual figure for Catchment A. The corrected evaporation figures, therefore, are listed in Table VII together with the revised AE/EO ratios. It can be seen that these corrections remove the trend from the AE/EO ratios by means of the effective addition of a storage term equal to (AE - corrected AE). The magnitude of this storage term is from + 454 to - 496 mm, almost identical with the previous estimate; it implies that, if the corrected AE values are approximately correct, this is the quantity which is drained from the deeper soil and rock layers in a dry year and which is recharged in the wet year.

In the case of Catchment A, it is not easy to calculate a corrected AE because of the uncertainty of the relationship between AE/EO and soil moisture deficit in the dry months. From the coincidence of the dry year's points with those of Catchment C in Fig 7 there is a strong suggestion that a deep deficit is developed in the years when annual rainfall is less than annual EO. In introducing this concept to the Catchment A data, however, it does not explain the inverse relationship of AE/EO with R in the wet years.

This negative trend of AE/EO with increasing R can be accounted for by a large apparent overestimate of flow in the wet years.

TABLE VII

Corrected Water Balance (mm) for Mbeya Catchment C (Forested)

Water Year	AE	EVAP*	EO	Corrected AE**	Corrected AE/EO	Storage Correction (≡Ae-Corrected AE)
1958-59	1189	1724	1722	1522	0.88 0.78	-333
1959-60	1470	1631	1526	1418	0.93 1.04	+52
1960-61	1070	1770	1773	1564	0.88 0.68	-494
1961-62	1784	1538	1406	1330	0.95 1.34	+454
1962-63	1405	1530	1453	1335	0.92 1.05	+70
1963-64	1516	1588	1481	1380	0.93 1.10	+136
1964-65	1105	1501	1482	1322	0.89 0.84	-217
1965-66	1437	1478	1380	1284	0.93 1.12	+153
1966-67	1228	1504	1435	1314	0.92 0.94	-86
1967-68	1610	1578	1441	1364	0.95 1.18	+246
Mean	1381	1584	1510	1383	0.92 1.01	-2
	±73	±31	±42	±29	±0.01 ±0.06	±90

* Calculated using the values 3 mm, 6, 0.85 for the parameters SINT, FW, FD, as described in text.

** Calculated at (2xEVAP+0.65EO)/3, as described in text.

For reasons stated above, with 95% of total streamflow at very low stages, it is most unlikely that errors of this magnitude can be found in Q. The remaining explanation is that the error is arising in the estimates of catchment storage from baseflow and soil moisture deficits in the top metre. Because of the time lag inherent in the recharge cycle, choosing a water year which starts too soon after the end of the rains can result in either an underestimate or an overestimate of ($\Delta S + \Delta G$). Referring to Fig 7 again, it can be seen that four years make up this apparent negative trend, and one of these lies practically on the mean AE/EO value. These years are all years in which large positive changes in groundwater have been calculated. If one assumes that the recession curve at this point is not a good indicator of groundwater storage, and water balance is recalculated for the October to September water year, the resulting water balance figures are those given in Table VIII and the corresponding graph of AE/EO against R is shown in Fig 9.

The picture which now emerges is much more satisfactory. In the first place, the wet years now all lie on or about the mean AE/EO ratio, which is slightly higher (0.66) with this particular water year. The anomaly of 1964/65 and 1965/66 is caused by having to use August soil moisture observations in the place of missing October and September data. If the two years are lumped together, the resulting value for AE/EO agrees with the mean, and fits in well with the emerging pattern. Secondly, the storage effect in the dry years still remains. Its magnitude is of the order ± 200 mm, which would represent drying out to a depth exceeding 2 m in the driest years. This is borne out by the few gypsum block observations which were made to 3 m in Catchment A during 1966; it is unfortunate that no data are available for the top 1 m of soil during the exceptional year 1960-61. Alternatively, it may be postulated that an 'interflow' store exists between the soil and groundwater stores and that changes in this store do not affect the baseflow levels. In physical terms, this storage effect could be caused by water held in the deeper soil layers,

TABLE VIII

Corrected Water Balance, Mbeva Catchment A (Cultivated)

Period	R	Q	ΔS	ΔG	AE	EO	AE/EO
20.10.58-10.10.59	1320	329	+4	0	987	1625	0.61
10.10.59-10.10.60	1718	578	+6	+90	1044	1527	0.68
10.10.60-10.10.61	1190	391	+18	-109	890	1687	0.53
10.10.61-10.10.62	2248	1112	-27	+163	1000	1462	0.68
10.10.62-10.10.63	1548	628	+14	-72	978	1488	0.66
10.10.63-13.10.64	1884	854	-3	+15	1018	1449	0.70
13.10.64-10. 8.65	1369	418	+25	-15	941	1165	0.81
10. 8.65-10.10.66	1485	548	-22	-21	980	1691	0.58
10.10.66-10.10.67	1570	485	+18	-22	1089	1368	0.80
10.10.67-10.10.68	2240	1326	+24	+114	776	1379	0.56
Mean, 1958-68:	1657	667	±6	±14	970	1484	0.66
	±116	±104	±6	±27	±28	±51	±0.03

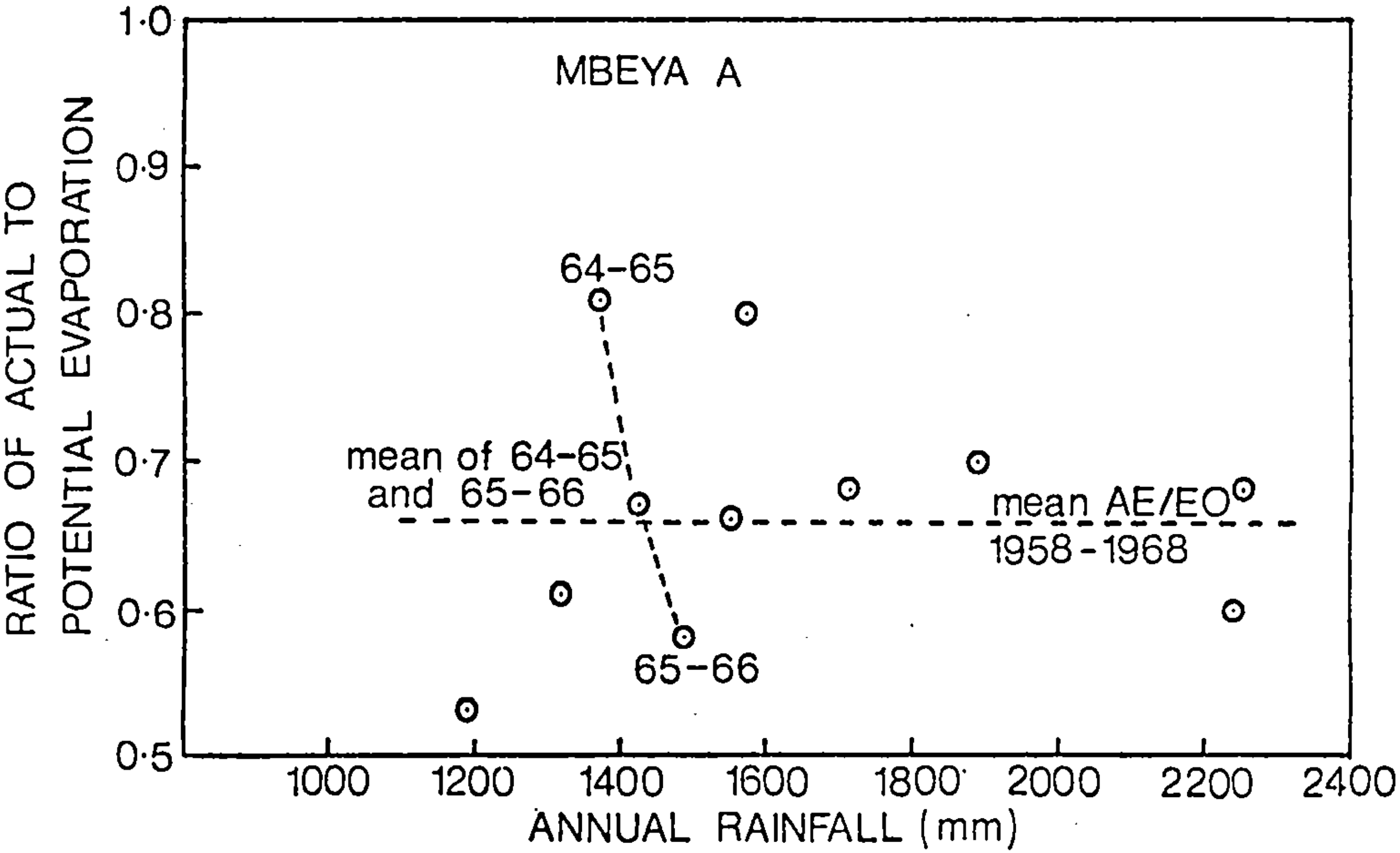


Figure 9 Annual ratios of AE/EO adjusted for different water years, Mbeya A

in the layer of decomposed gneiss or in fissures in the regolith. It is assumed that, in the drier years, this store is depleted both by lateral drainage (interflow) or by the deeper-rooting vegetation. In the wetter years, recharge is by deep percolation and interflow but there must be a hydraulic discontinuity between this store and 'groundwater' for there to be little indication of excess water in the base flow records.

IMPLICATIONS OF THE REVISIONS TO THE AE/EO RATIOS

The interpretation of the water balance figures set out above may be criticised on the grounds that it is not based on direct measurements. Given that the interpretation is based on physical concepts, however, and that the pattern which now emerges is simply a reflection of the resistance block readings, it is considered unnecessary to seek any further explanation of the water balance discrepancies, and that conclusions can now be drawn on the overall objectives.

It is evident that over the eleven years of the experiment, a sufficient range of climatic conditions has been experienced to give mean values of the water use of the two catchments which are relatively precise. In absolute terms, the AE/EO ratios may be overestimated in both catchments because of the neglect of their steeply sloping nature, which would increase the dry season EO values. In terms of the comparison of two contrasting land uses, however, the difference in water use is so marked that it cannot be affected by further corrections to the experimental data.

It is clear that the forested catchment in this climatic environment uses 12-13% more water than the cultivated catchment and that the forest trees extract moisture from depths below 3 m. Far from storing moisture in the wet season to release slowly in the dry season, the forest develops such deep storage deficits that a major part of the rainfall is used in recharging such stores, and dry season flow is actually higher in the cultivated catchment (Table III).

Normally this feature would be accompanied by increased surface runoff, soil erosion and sediment yield, yet it will be shown in Section 5.2.2 that the porous ~~moisture~~ nature of the Mbeya soils results in surprisingly low sediment losses in spite of the steep slopes.

CONCLUSIONS

The conclusions which may be drawn from the Mbeya experiment from the land management point of view are not as clear cut as might be expected.

Taking the water balance data as a bald statement that water yield will increase if forest areas are clear-felled and cultivated is not only a dangerous oversimplification but also positively misleading. The experiment was set up in the first instance because a seemingly ideal opportunity arose to monitor an example of population displacement caused by conservation legislation. However, soils of this area are so porous and permeable that the expected disastrous consequences of cultivating steep slopes did not occur. The increase in flow is to be expected, *ceteris paribus*, if trees which transpire all the year round are replaced by annual crops which grow for only six months of the year. The absence of serious erosion, however, has led to an almost stable situation where, unless the intensity of cultivation increases drastically, there appears to be no deleterious effects of the land use change. This is not to say, however, that similar land use changes on less stable soils would avoid the destruction normally associated with cultivation without soil conservation measures.

Already the pathways and tracks outside the experimental catchments are showing signs of erosion, and the fine balance between retaining the top soil with its high rainfall acceptance and beginning the irreversible process of sheet and gully erosion, may be upset by human decision making. Clearly it would be advisable for some form of terracing to be practised and to avoid the steeper slopes, but on the hydrological evidence presented here there is no immediate case for Government action.

In many ways, it is unfortunate that this particular case study has failed to provide evidence for the preservation of forests. It is a salutory reminder of how little is understood of the hydrological cycle at the extremes of the spectrum of environmental conditions which may be encountered. It has provided a valuable insight into the water balance of the areas where volcanic-derived soils exist, and shown most clearly that the problem of measuring storage terms in the water balance equation is not easy and may well confound any such experiment conducted either on less contrasting land-use types, or on heterogeneous soils.

The Mbeya experiment has been particularly difficult to run, lying over 1600 km from EAAFRO Muguga, and its successful conclusion owes much to the co-operation of the Government Departments of Tanzania and their local field officers. To a certain extent, the siting of the experiment has led to results which are of limited regional application: on the other hand, it has presented a complex hydrological problem, the solution of which has led to a better understanding of the processes of evaporation and the role of infiltration in the control of streamflow.

REFERENCES

BATES, C G, and HENRY, A J, 1928. Forest and streamflow experiments at Wagon Wheel Gap, Colorado. Final Report. Monthly Weather Review Supplement No 30; 79.

DAGG, M, 1958. EAAFRO Record of Research (see page 12).

DAGG, M, and BLACKIE, J R, 1965. Studies of the effects of changes in land-use on the hydrological cycle in East Africa by means of experimental catchment areas. Bull IASH Xe Annee No 4, 63-75.

DOUGLASS, J E, 1967. Effects of species and arrangements of forests on evapotranspiration. In Sopper and Lull (Eds) Proc Int Symp Forest Hydrology, 451-461.

EDWARDS, K A, BLACKIE, J R, COOPER, S M, ROBERTS, G, and WAWERU, E S, 1976. Summary of hydrological data from the EAAFRO Experimental Catchments.

KERFOOT, O, 1964. A preliminary account of the vegetation of the Mbeya Range, Tanganyika, Kirkia 4, 191-205.

PEREIRA ET AL, 1962. Hydrological effects of changes in land use in some East African catchment areas. E Afr agric for J Vol 27, Special Issue, 131.

RUTTER, A J, KERSHAW, K A, ROBINS, P C, and MORTON, A J, 1971. A predictive model of rainfall interception in forests. 1. Derivation of the model from observations in a plantation of Corsican pine. Agric Met 9, 367-384.

SHUTTLEWORTH, W J, 1976. A one-dimensional theoretical description of the vegetation - atmosphere interaction. Boundary Layer Met 10, 273-302.

STEWART, J B, and THOM, A S, 1973. Energy budgets in pine forest, Q J roy met Soc 99, 154-170.

5.2.2

SEDIMENT YIELDS AT MBEYA

K A Edwards
Institute of Hydrology, Wallingford, UK

5.2.2

SEDIMENT YIELDS AT MBEYA

K A Edwards
Institute of Hydrology, Wallingford, UK

INTRODUCTION

The methods used to obtain measurements of total sediment yield have been described briefly in Section 5.1.1. Suspended sediment, during periods of steady flow, was measured by taking a daily sample of 568 cc (1 pint) from the weir and bulking these into a monthly sample. The excess water was evaporated before the samples were despatched to EAAFRO for analysis. Suspended sediment during stormflow was sampled by means of the apparatus described in Pereira and Hosegood (1962), which extracted 568 cc samples at the surface and at a preset level below the surface during two stages of the rising flood. Bed load was measured by means of a silt trap, upstream of the weir, which was periodically emptied.

Approximately four years of data have been used in the analysis of results presented below. Difficulties arose in continuing the sediment sampling after 1962, and the existing data are themselves subject to uncertainties. The order of magnitude of the total yields obtained are believed to be correct, however, and the yields are presented here in spite of their shortcomings because of their relevance to the land use experiment and because of their unexpected nature.

SUSPENDED SEDIMENT IN STEADY FLOW CONDITIONS

Table I gives a summary of the suspended sediment values from the three catchments (cultivated, regenerating and forested) during the period 1958-1962. It can be seen that over twice as much sediment was carried beyond the weir in the cultivated catchment as in the forested catchment. The regenerating catchment gave sediment yields between the values of the other two but, by the end of the 1962, there were indications that the sediment yields were falling below those of the forested catchments as the woody species developed. This is most likely

TABLE I

Suspended Sediment at Mbeya (ppm)

		A (cultivation)	B (regenerating)	C (forest)
1958	J	60	36	35
	A	81	136	18
	S	30	34	10
	O	30	53	27
	N	160	89	12
	D	74	65	47
1959	J	43	11	34
	F	126	14	19
	M	54	15	40
	A	53	6	19
	M	44	10	52
	J	52	7	31
	J	48	-	22
	A	54	-	72
	S	24	-	17
	O	77	-	23
	N	106	-	72
	D	74	-	47
1960	J	289	11	11
	F	263	12	136
	M	43	13	31
	A	50	12	20
	M	17	6	17
	J	22	16	11
	J	16	1	10
	A	51	7	8
	S	16	-	3
	O	50	11	11
	N	11	8	6
	D	19	7	21
1961	J	5	57	66
	F	122	17	31
	M	33	7	4
	A	50	17	0
	M	26	16	5
	J	33	6	1
	J	19	9	3
	A	15	12	37
	S	32	6	2
	O	4	4	7
	N	7	2	1
	D	-	-	-
1962	J	28	2	10
	F	215	6	26
	M	35	-	1
	A	-	0	-
	M	45	0	7
	D	115	24	76
1963	J	641	25	41

a result of the lower mean slopes in Catchment B (regenerating) than in Catchment C (evergreen forest).

The method of bulking the samples made detailed analysis of the results impossible. Seasonal trends are shown in Fig 1, however, relative to monthly rainfall totals. In general, the pattern of suspended sediment closely follows the rainfall distribution in Catchment A. The tendency for peak suspended sediment yields in Catchment A to precede the peak rainfall months in the years 1958 and 1959 may be associated with greater agricultural activity during the month of November when maize is planted. It is not clear why this tendency was not observed in 1960 and 1961.

Overall levels of suspended sediment were very low. The mean values for the catchment averaged over the period of observation were 75 ppm for Catchment A (cultivated), 20 ppm for Catchment B (regenerating) and 24 ppm for Catchment C (evergreen forest). In terms of the quality of drinking water downstream, the effects of cultivation were apparently minimal in this area. The absolute maximum recorded was a value of 662 ppm in December 1961, following a rainfall of 485 mm in Catchment A. This corresponds to a loss of 293 kg of soil per hectare or a lowering of the surface of the soil by 0.02 mm. This is clearly a high value for a single storm, and it is unfortunate that stormflow sampler measurements were not available for the same period to allow the computation of total losses from the catchment.

STORMFLOW SEDIMENT YIELD

The 'Muguga' pattern sediment sampler worked intermittently in Catchment A (cultivated) during the period 1960 to 1962. A total of 41 samples were taken from preset levels on the rising limb of the hydrograph. These corresponded to surface and sub-surface samples at the stages shown in Table II.

Interpretation of the measurements in terms of sediment concentrations at particular discharge levels has proved difficult due to the small number of samples and lack of any

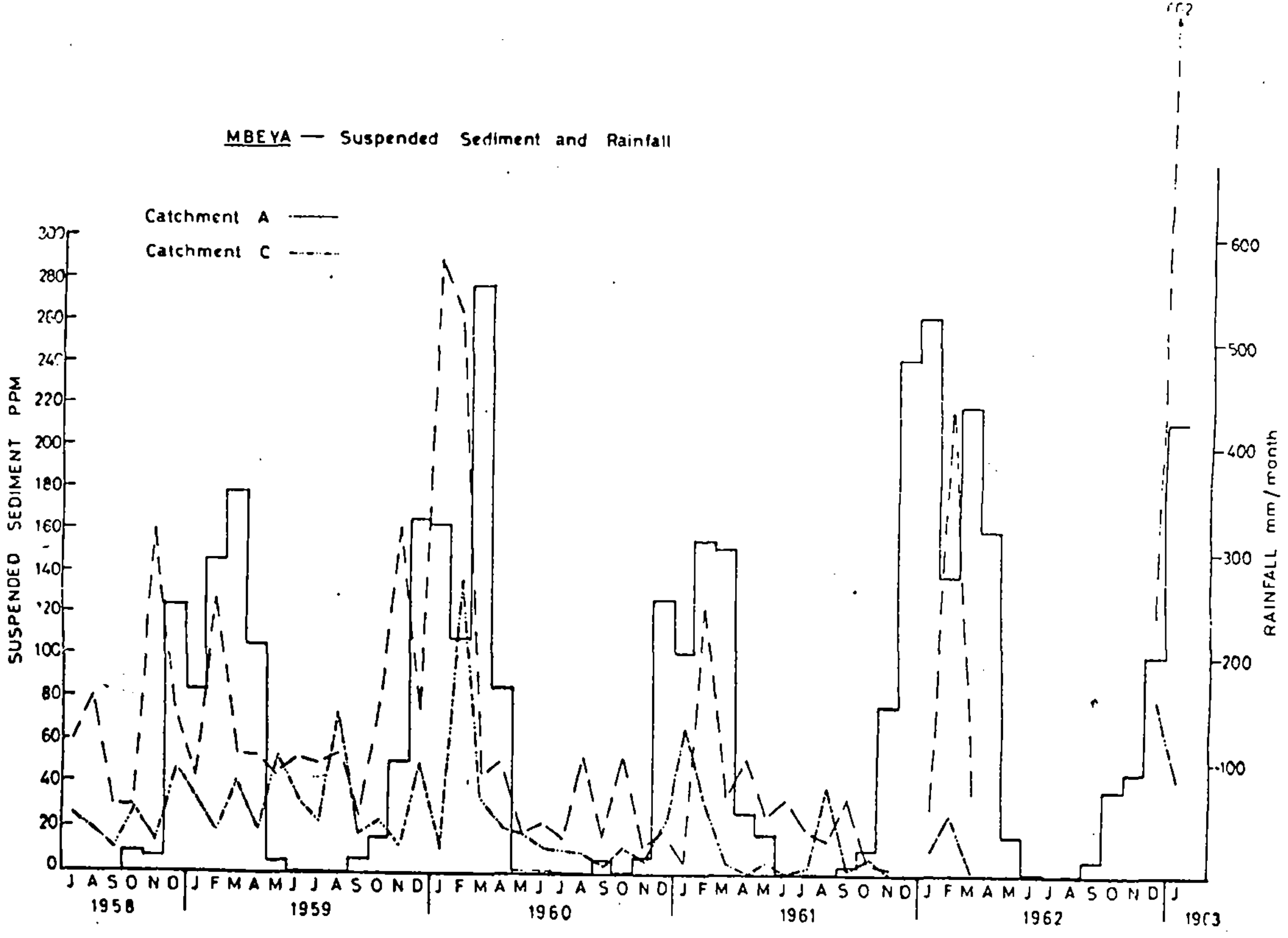


Figure 1 Monthly totals of suspended sediment and rainfall for the Mbeya catchments

systematic pattern in the values obtained. Sediment concentrations in natural channels during stormflow vary both with time and with the velocity distribution across the channel. Between storms, there were also variations due to the different rates of supply of transportable sediment particles from upstream. Accordingly, the 41 values of sediment concentrations can best be regarded as a sample from the population of sediment concentrations obtained by sampling across the profile continuously through successive storms.

The frequency distribution of this sample was expected to conform to an exponential form similar to the distributions obtained for frequencies of heavy rainfalls. Fig 2 shows the exponential curve $y = be^{cx}$ fitted by least squares to the data and giving $b = 21.4$ and $c = -0.047$. The fit was good ($r = 0.96$) in spite of the small number of data points. The first point diverges from the line in keeping with many bounded distributions of this type (Brooks and Carruthers, 1953, p 120) and may reflect the occasions when the orifice of the sample bottles became blocked by debris, giving low values of sediment concentrations.

The mean concentration of the 41 samples was 17.8 gl^{-1}. If one takes the volume of stormflow as a percentage of total streamflow (approximately 5%, 1958-1968), the average annual loss of sediment from the catchment was approximately 5.2 tonnes ha^{-1}. In years where rainfall and streamflow were high, this value rose to 10 tonnes ha^{-1} and, in low rainfall years, it fell to 3 tonnes ha^{-1}.

There are no figures available for Catchments B and C.

BED-LOAD

The silt-trap in Catchment A was 7.6 m^3 in volume and, from the weight of samples taken from the trap, the total weight of sediment was found to be approximately 9 tonnes. The frequency with which the trap was emptied depended to a large extent on the diligence of the observers and the estimates of bed-load obtained from the mean frequency of clearing are likely to be

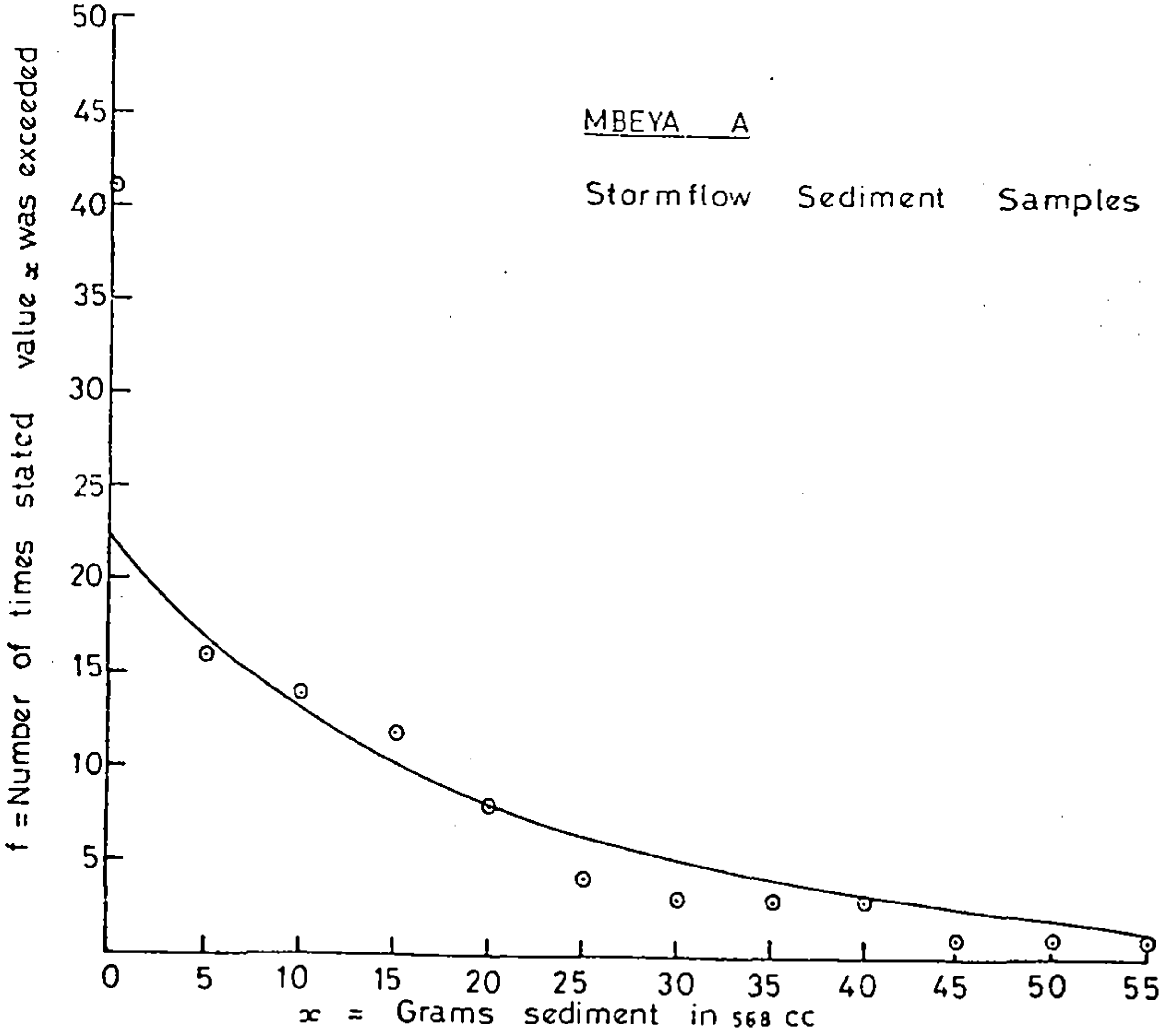


Figure 2   Frequency distribution of stormflow suspended sediment values, Mbeya A

TABLE II

Levels of Sampling for Suspended Sediment in the Stream Draining Catchment A (Cultivation), Mbeya

Bottle No	Level (cm)	Stage	Discharge ($m^3 sec^{-1}$)
1	52.7	52.7	0.444
2	37.5	52.7	0.444
3	22.2	22.2	0.032
4	7.0	22.2	0.032

TABLE III

Total Sediment Yield tonnes $ha^{-1}yr^{-1}$

	Steady-flow suspended sediment	Storm-flow suspended sediment	Bed-load	Total
	0.36	5.28	3.21	8.85
% Total	(4.1%)	(59.6%)	(36.2%)	

underestimates. Fig 3 shows the relationship between frequency of clearing and rainfall during the period 1 November to 31 October. It can be seen that only two points lie off the fitted straight line and, if it is assumed that this results from observer error, the mean frequency is 7.2 times per year. This gave an average yield of bed-load sediment in the order of 65 tonnes yr^{-1} or in Catchment A, 3.21 tonnes $ha^{-1}yr^{-1}$.

TOTAL LOAD IN CATCHMENT A

It can be seen from the average figures for the different components of the total sediment yield in Table III that their magnitudes differ greatly. The total amount of steady-flow suspended sediment was only 4.1% of the total yield. Errors in estimating this quantity were insignificant when estimating the total yield. The stormflow measurements can only be rough approximations of the actual losses from the catchment; the figures from the stormflow sampler give estimates of the average losses, but individual large storms which were not sampled could have given much higher figures. It should be noted that the quoted loss of 7.3 tons per acre for one storm (Pereira and Hosegood, op cit, p 124) was a misprint in the original report on the sediment yields; the correct figure should have been 0.73 tons per acre (1.8 tonnes ha^{-1}). This figure is still rather high due to the use of uncorrected streamflow data, but is now of the same order as the results in Table III.

Although no comparative figures were obtained for the critical measurements of stormflow and bed-load from Catchment C, it is apparent from the far less frequent clearing of the stilling pool of the weir that stormflow sediment yield is considerably less than in Catchment A. Nevertheless, the figures quoted for the total soil losses from Catchment A are very low in comparison with other small catchments in Tanzania (Temple, 1972) and represent an overall soil denudation rate of approximately 0.6 mm yr^{-1}. In view of the steep slopes and loose, friable nature of the soil, this small value is remarkable.

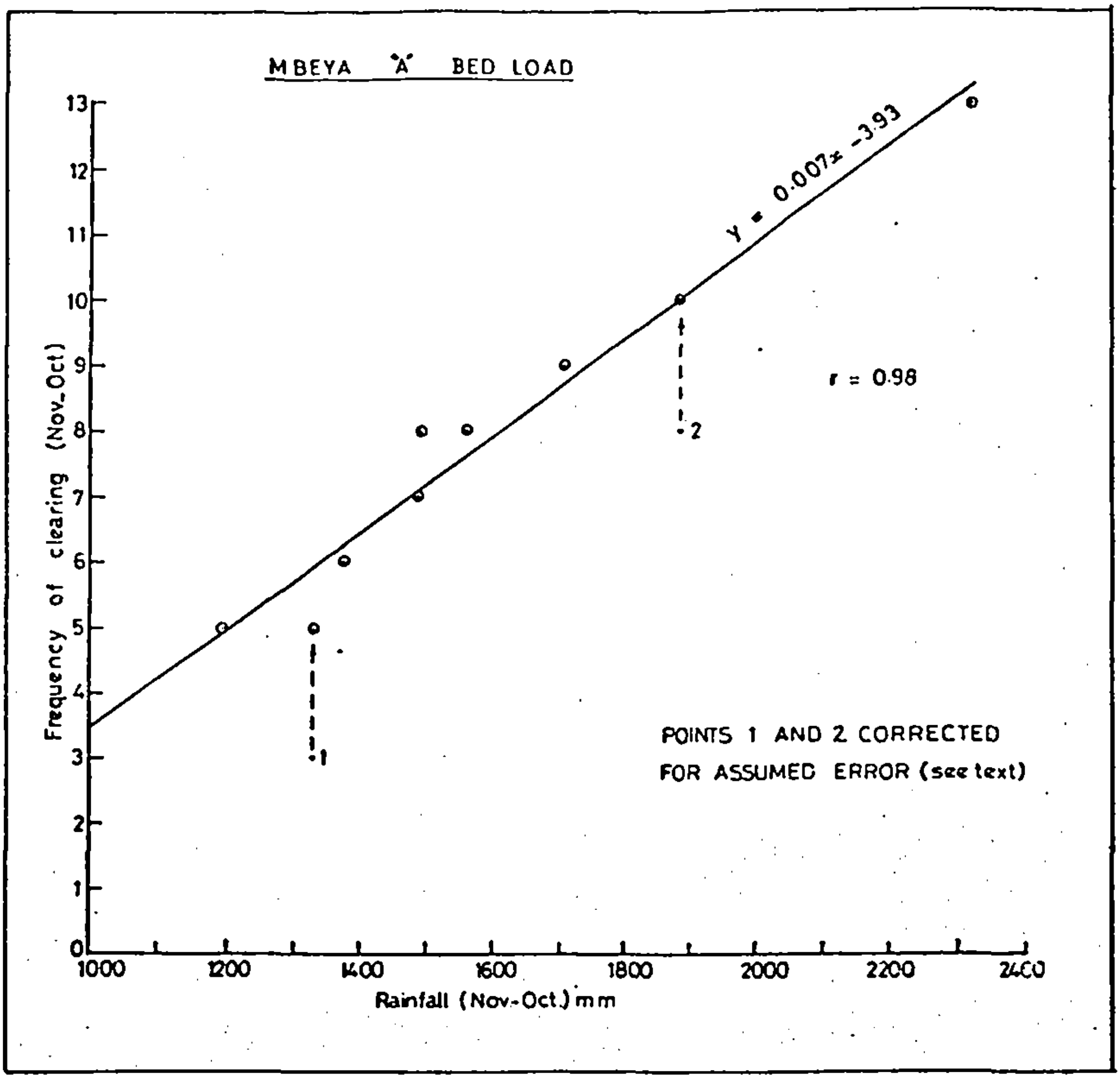


Figure 3 Frequency of clearing of the silt trap, Mbeya A

CONCLUSIONS

The representativeness of the results from the Mbeya catchments has already been commented upon (Section 5.1.1). Nevertheless, it can be stated that, irrespective of the difficulties in extrapolating results from Mbeya to other regions in Tanzania, the effects of cultivating Catchment A were unexpected. There has been less erosion than was anticipated and the rate of soil loss is not high. It is probable that the same land-use practices on basement complex derived soils would give rise to serious denudation, but, in this experiment, the land-use change has not produced erosion on a scale which should cause concern. Subjective observations in the Mbeya Range suggest that erosion from roads and track-ways, including paths to the streams used by animals, will produce sediment losses of the same order as losses from this particular cultivated catchment.

REFERENCES

BROOKS, C E P, and CARRUTHERS, N, 1959. Handbook of statistical methods in meteorology, HMSO, London, 412.

PEREIRA, H C, and HOSEGOOD, P H, 1962. Suspended sediment and bed-load sampling in the Mbeya Range Catchments. E Afr agric for J 27, Special Issue, 123-124.

TEMPLE, P H, 1972. Measurements of runoff and soil erosion at an erosion plot scale with particular reference to Tanzania. Geografiska Annaler, 54, Ser 9A, 203-220.

5.3

SUMMARY OF RESULTS FROM THE MBEYA EXPERIMENTS

K A Edwards
Institute of Hydrology, Wallingford, UK

5.3

SUMMARY OF RESULTS FROM THE MBEYA EXPERIMENTS

K A Edwards
Institute of Hydrology, Wallingford, UK

The Mbeya experiment was seen at first as an opportunity to demonstrate the beneficial effects of conservation forestry on the steep slopes of the Mbeya Range, in southern Tanzania, compared with intensive smallholder cultivation. It was anticipated that the local cultivation practices, which did not include effective soil conservation measures, would lead to accelerated soil erosion and accompanying undesirable changes in the flow regime such as a reduction in dry season flow and an increase in peak flows.

As the experiment progressed, it became clear that the expected changes in the hydrological regime of the cultivated catchment were not taking place and that the increase in total sediment loss from the catchment, although considerable, was far less than anticipated.

The reason for this response to the change in land-use was that the ash-derived soils which overlaid the Basement Complex in this locality were both stable and porous. They had very high infiltration rates which minimised surface flow (and, hence, erosion) while withstanding raindrop impact without capping. The cultivated catchment was able to absorb rainfall into storage and, because of the reduced water use of the seasonal crops compared with evergreen rain forest, was able to maintain higher flows during the dry season (Figure 5, Section 5.2.1). It was also found that the high flows during the wet season were less in the cultivated catchment than in the forested catchment.

The unusual nature of the pattern of water use in these two catchments has been elucidated by using soil moisture measurements and gypsum block records. It is apparent that much of the annual variation in water use arises from deep storage effects in the catchments and that choice of a water year is critical if errors from deep storage are to be kept to a minimum. Annual ratios of actual to potential evaporation (AE/EO) are 0.64 for the cultivated catchment and 0.92 for the forested catchment. The pattern of seasonal water use in the cultivated catchment can be deduced from the drying out of the soil profile during the dry season. Typical values have been given in Figure 8 and Table V of Section 5.2.1.

Sediment measurements were made in the cultivated catchment during the early years of the experiment and indicated that total sediment loss, ie steady-flow suspended sediment, stormflow suspended sediment and bed load, was of the order of 8.9 tonnes $ha^{-1}yr^{-1}$. During the same period, sediment losses from the forested catchment were minimal. While a significant increase in soil erosion has taken place in the cultivated catchment, the above figure is not as large as expected given the steep nature of the catchments (average slope 25%). Nevertheless, the value of protection forestry is clearly shown to lie in minimising soil erosion. On less porous soils, such as the fragile soils of the Basement Complex, the same land-use practices could well lead to widespread erosion. It would be most unwise to advocate the clearing of forests to increase water yield although this experiment and others have demonstrated predictably that evergreen rain forest will have much higher evaporation losses than annual crops which transpire for less than half the year.

6.1.1

PHYSIOGRAPHY AND SOIL TYPES IN THE HIGH RAINFALL REGION OF KENYA AND THEIR HYDROLOGICAL SIGNIFICANCE

N N Nyandat
National Agricultural Laboratories, Nairobi, Kenya

6.1.1

PHYSIOGRAPHY AND SOIL TYPES IN THE HIGH RAINFALL REGION OF KENYA AND THEIR HYDROLOGICAL SIGNIFICANCE

N N Nyandat
National Agricultural Laboratories, Nairobi, Kenya

INTRODUCTION

The importance of agriculture in Kenya is well known, since the country derives much of its revenue from the export of agricultural produce. However, as more land comes under cultivation, resources both of soil and water become threatened, since land clearance exposes the soil to heavy rain and the consequent dangers of erosion and flash flooding. Many investigators, notably Wischmeier et al (1971); Hudson and Jackson (1959); Hutchinson et al (1958); and Rensburg (1955), have found that the extent to which soil and water regime of an environment is affected by a given land use will depend on the complex interactions of climate (particularly rainfall intensity and amount), type of soil, length and degree of slope and ground cover. Experimental results generally show that most of the sediment loads of rivers in areas that are primarily agricultural and have more than 500 mm of annual precipitation, derive from sheet erosion. Catchment experiments may therefore be helpful in evaluating the extent to which soil and water regimes of an environment may be altered by a land-use change.

Such studies, however, need to be supplemented by other basic data if the results are to be extrapolated to other areas for practical use. In particular, there is a need to know the characteristics (physiography, soil, climate, etc) of the experimental site and of the region that it represents; this paper therefore outlines and discusses the relation between hydrology, land physiography and soils for that part of the country with more than 760 mm annual rainfall, and attempts to show the extent to which the results already acquired for certain catchments may be extrapolated.

PHYSIOGRAPHIC LAND UNITS OF THE AREA

Formulae exist which may be used to predict soil losses and runoff that are likely to occur on slopes of different lengths and gradients. Researchers including Wischmeier et al (op cit) and Wischmeier and Mannering (1968) have found that the capacity of runoff to transport soil particles increases approximately as the fifth power of its velocity, whereas its ability to detach them from their matrix increases approximately as the square of its velocity; this in turn increases as the slope steepens. The effect of runoff on soil removal may therefore be expected to increase when either the slope lengthens or the gradient increases.

To relate runoff to physiography, the area under consideration has been divided into several physiographical land units, which are represented in Fig 1 and explained in Table I. The material used in this paper is a modification of that given by Scott et al (1970). Examination of Fig 1 shows that, even with this broad sub-division of the landscape, the area under consideration appears complex. Various physiographic land units are categorised as narrow and broad plains, plateaux and ridges; these are also associated with a wide range of slopes which, for the purpose of this paper, have been divided into six categories: $0-0^{0}35'$ (flat); $0^{0}35' - 1^{0}45'$ (very gently undulating); $1^{0}45' - 5^{0}50'$ (gently undulating to undulating); $5^{0}50' - 17^{0}00'$ (rolling to hilly); $17^{0} - 30^{0}$ (mountainous); above 30^{0} (mountainous).

The physiographic land unit 13 occurring at the Kimakia catchment area, namely narrow ridges with 17^{0} to 30^{0} slopes, appears widespread, but by no means representative of all the major landscape units that occur. The physiographic land unit 9 (broad plateau with 17^{0} to 30^{0} slopes) on which the Kericho catchment experiment has been sited appears rather restricted in distribution.

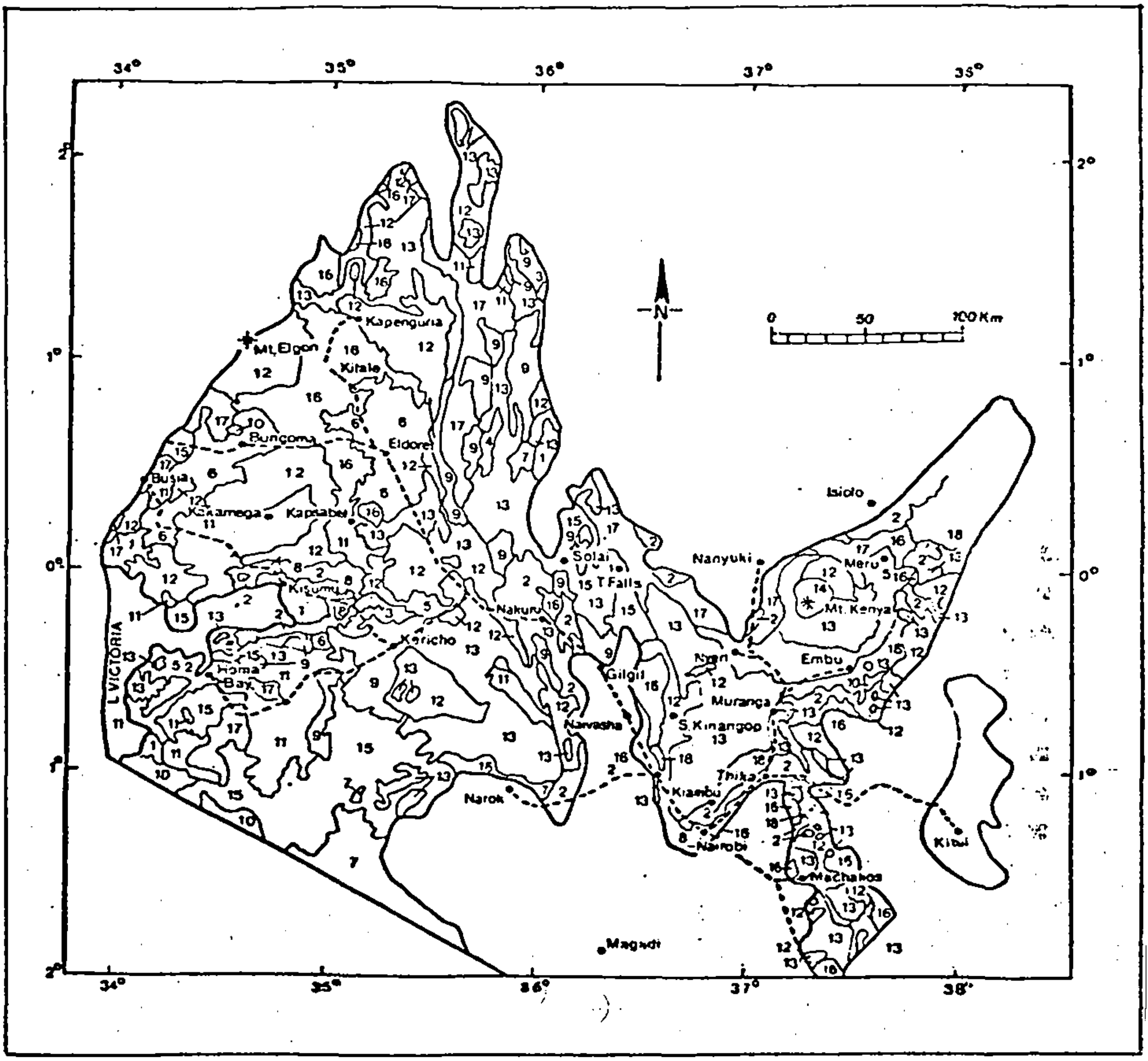


Figure 1 Physiographic land units in the parts of Kenya which receive a mean annual rainfall of more than 760 mm

TABLE I

Key to Physiographic Land Units

Unit	Description
1	Broad plain with 0° - 0°35' slope
2	Broad plain with 0°35' - 1°45' slope
3	Narrow plateau with 0°35' - 1°45' slope
4	Narrow plateau with 5°50' - 17°00' slope
5	Narrow plateau with 17°00' - 30°00' slope
6	Broad plateau with 0°35' - 1°45' slope
7	Broad plateau with 1°45' - 5°50' slope
8	Broad plateau with 5°50' - 17°00' slope
9	Broad plateau with 17°00' - 30°00' slope
10	Narrow ridges with 0°35' - 1°45' slope
11	Narrow ridges with 1°45' - 5°50' slope
12	Narrow ridges with 5°50' - 17°00' slope
13	Narrow ridges with 17°00' - 30°00' slope
14	Narrow ridges with 30°00' - 45°00' slope
15	Broad ridges with 0°35' - 1°45' slope
16	Broad ridges with 1°45' - 5°50' slope
17	Broad rigdes with 5°50' - 17°00' slope
18	Broad ridges with 17°00' - 30°00' slope

THE SOILS OF THE AREA AND THEIR HYDROLOGICAL CHARACTERISTICS

Among the soil characteristics which may have profound influence on water and sediment yield of a catchment are the texture, organic matter content, and the permeability; however, the ability of the soil surface to accept rainfall may be the most critical factor in determining the condition of a catchment. In Fig 2, an attempt has been made to show occurrence and distribution of the dominant soils of the area under consideration; the figure is greatly oversimplified, but for the broad regional treatment of the present paper, a grouping together of soils with somewhat similar characteristics should suffice. Furthermore, a correlation with the FAO/UNESCO (1973) soil units should then be possible. Using the soil map of Kenya by Gethin Jones and Scott (1959), soil units which correlate with twenty four FAO/UNESCO soil groups are identified. The key to the soils is presented in Table II.

The data in Table III illustrates the physical characteristics of some of the typical soils of the area. There are clear differences in the hydrological characteristics of these soils; Regosols (soils 22 and 23) and vertisol (soil 14) may respectively be regarded as occupying the two extreme ends of high permeability and low water holding capacity on the one hand, and low permeability and high water holding capacity on the other. The remaining soils have hydrological characteristics which lie between the two extremes, but the hydrological characteristics of the Ranker (soil 15) and Lithosol (soil 24) are much closer to those of the Regosols.

The vertisols, which are often dominated by montmorillonite type of clay, are characterised by deep vertical cracks under dry conditions which provide channels for the percolation of water during the initial stage of wetting. However, as the soil becomes wetter, the cracks close up and the permeability becomes very low. The soil holds a large volume of water, but the water is held very tightly so that only a little of it is readily available. Surface sealing is nevertheless almost absent and therefore does not contribute to the runoff and the

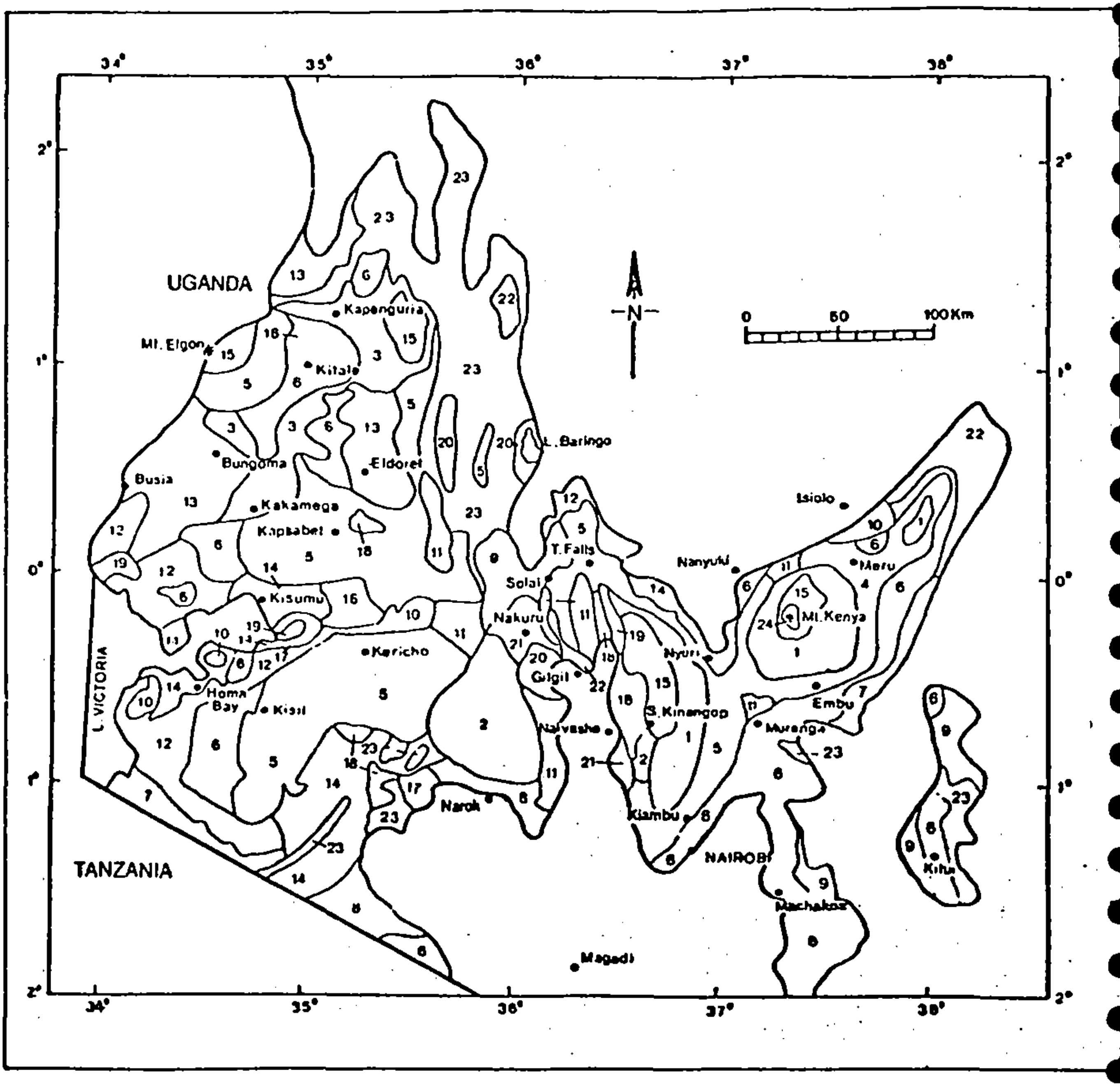


Figure 2 Dominant soils in the areas with a mean annual rainfall of more than 760 mm

TABLE II

Key to the Dominant Soils of the Area

Unit	FAO/UNESCO Description
1	Humic Andosol
2	Mollic Andosol
3	Xanthic Ferralsol
4	Eutric Nitosol
5	Humic Nitosol
6	Chromic Cambisol
7	Ferric Acrisol
8	Calcic Cambisol
9	Ferric Luvisol
10	Humic Cambisol
11	Humic Acrisol
12	Orthic Ferralsol
13	Plinthic Ferralsol
14	Pellic Vertisol
15	Ranker
16	Humic Gleysol
17	Gleyic Solonetz
18	Eutric Planosol
19	Dystric Histosol
20	Eutric Fluvisol
21	Vitric Andosol
22	Eutric Regosol
23	Dystric Regosol
24	Lithosol

TABLE III

Some of the Physical Data for Typical Soils of the Area

Soil Type	% Organic Matter	Clay		Subsoil Bulk Density gm/cc	Subsoil wt %		Topsoil Infiltration mm/min	
		Topsoil	Subsoil		Field o Capacity	Available Moisture	Dry Soil	Wet Soil
Ferralsol	3.0	68	76	0.83	38.9	11.4	12.5	8.3
Acrisol	0.7	12	46	1.31	19.5	9.5	2.5	1.5
Luvisol	0.4	8	36	1.53	18.0	7.7	9.1	5.6
Nitosol	1.4	52	64	1.10	27.0	10.5	2.0	1.2
Vertisol	1.2	59	59	1.22	39.2	10.5	-	-

low permeability.

Ferralsols (soils 3, 12 and 13) are deeply weathered and are freely draining. The soils have a very friable consistency and stable structure, tending to resist erosion. They have an excellent moisture holding capacity and availability because of the porous micro-structure and the extensive depth. Normally they have negligible surface capping, which is a characteristic contributing to the low susceptibility of these soils to erosion.

Acrisol (soils 7 and 11) and Luvisol (soil 9) unlike Ferralsols, are less deep and also contain slight cracks when dry because of the presence of appreciable quantity of illite (2:1 lattice clay mineral). The soils have weak structure and commonly form a strong surface cap and subsoil compaction. They are therefore less permeable and tend to be more susceptible to greater runoff. Luvisol however shows less surface sealing in comparison to Acrisol.

Solonetz (soil 17) and Planosol (soil 18) are soils which contain appreciable amounts of 2:1 lattice clay mineral. They also have a weak structure with a hardpan and compact subsoil. Surface sealing is often strong because of the commonly occurring silty top layer. The permeability of the soils is very slow once the soil is saturated, and water logging is a common phenomenon. The soils generally occur in rather level situations, but where slope is appreciable lateral water movement above the hardpan layer takes place.

Other soils, namely Nitosols (soils 4 and 5), Cambisols (soils 6, 8 and 10), Andosols (soils 1, 2 and 21), Fluvisol (soil 20), Histosol (soil 19) and Gleysol (soil 16), have hydrological properties which fall between those of the soils discussed above. However, they have negligible surface capping. Gleysols and Histosols are hydromorphic soils, primarily influenced by shallow groundwaters. They may be associated with permanent or seasonal swamps.

The experiment, which ran for three years (September 1970 - July 1973), on Nitosol near Embu and Vertisol near Kisumu to examine the pattern of water extraction by grass and the depth of penetration of moisture over the seasons, revealed interesting results as summarised in the paper by Wangati et al (1973). On the Nitosol, the grass (*Paspalum*) extracted moisture to a depth of 360 cm; the rainfall during the period studied did not penetrate beyond this depth. On the Vertisol at Kibos (11 km north-east of Kisumu) there was hardly any response to rainfall in the entire profile, which remained near wilting point at depths below 30 cm.

It is significant to note that the Kimakia catchment experiment falls on soil unit 1, which is also found on the slopes of Mt Kenya. Soil unit 5, which constitutes the Kericho catchment is, however, widely distributed; nevertheless, extrapolation of these results requires great caution since the runoff and sedimentation in different localities may differ both in nature and in magnitude.

REFERENCES

FAO/UNESCO, 1973. The legend of the soil map of the world. Land and Water Development Division, FAO, Rome.

GETHIN JONES, G H, and SCOTT, R M, 1959. Soil map of Kenya. Atlas of Kenya, Survey of Kenya, 3rd ed, 1970, 26-27.

HUDSON, N W, and JACKSON, D C, 1959. Results achieved in the measurement of erosion and runoff in Southern Rhodesia. 3rd Inter Afr Soils Conf Dalaba CCTA, 575-583.

HUTCHINSON, J, MANNING, M L, and FARBROTHER, H G, 1958. On the characterisation of tropical rainstorms in relation to runoff and percolation. Empire Cotton Growing Crop, Res Mem 30.

RENSBURG, H J, VAN, 1955. Runoff and soil erosion tests, Mpwapwa, Central Tanganyika, E Afr agric J 20, 228-231.

SCOTT, R M, WEBSTER, R, and LAWRANCE, C J, 1970. A land system atlas of Western Kenya, Dept of Agri University of Oxford, England.

WANGATI, F J, NYANDAT, N N, and NJIHIA, C M, 1973. Review of profile soil moisture measurements at agrometeorology stations in Kenya. Paper presented at the 5th Specialist Meeting on Applied Meteorology, Nairobi.

WISCHMEIER, W J, JOHNSON, C B, and CROSS, B V, 1971. A soil erodability monography for farmland and construction sites. J Soil and Water Conservation 26 (5), 189-192.

WISCHMEIER, W H, and MANNERING, J V, 1968. Relation of soil properties to its erodability. Soil Sci Soc Amer 33, 131-137.

6.1.2

RAINFALL INTENSITIES OF EAST AFRICAN STORMS

M E Jones
Department of Geography, King's College, London

6.1.2

RAINFALL INTENSITIES OF EAST AFRICAN STORMS

M E Jones
Department of Geography, King's College, London

INTRODUCTION

The analysis of the intensities of rainfall in tropical storms over urban areas was the major objective of the East African Rainfall Project, which was established jointly by the Transport and Road Research Laboratory, the Department of Geography, King's College, London and the East African Meteorological Department, in 1964. Three dense networks of autographic rain gauges were set out in Kampala, Nairobi and Dar es Salaam. Synchronous recordings began in late 1968, and observations were terminated in March 1973.

DATA

The Project rainfall data were derived from the autographic records of modified Dines Tropical rain gauges. These modified gauges had 30 cm (12 inch) diameter funnels. They syphoned after 5 mm (0.2 inches) rain had been received and a small tray was incorporated for temporary rainfall storage during syphoning. A clock-drive of 15 cm (6 inches) per hour was used with weekly charts. Daily and weekly time checks were added to the charts by trained observers.

The charts were sent to London for translation by a D-Mac Digitizer. This was used to record 1 minute interval trace levels onto punched paper tape. With the addition of identification code sequences, the data were copied onto magnetic tape, quality controlled, and processed to give 1 minute rainfall at each gauge on a permanent magnetic tape. Further tabulations of the data included the total fall and duration of each storm, the maximum short-period falls, and synchronous point rainfalls at all gauges through every storm.

Sites for the rain gauges in a network were dictated by the need for good exposure, rather than the need to locate them in rectangular grids. At Kampala, there were 25 gauges, sited 1 km apart, approximately, at a density of one gauge per 1.34 km^2. These gauges had reasonable exposures, with several on rooftop sites. Kampala has an annual rainfall of 1174 mm; total rainfall in 1969, 1970 and 1971 was below average, and about average in 1972. In Nairobi, there were 20 gauges, spaced at one gauge per 4 km^2, with mean distance between gauges about 2 km. Many of the gauges in the city centre had roof top sites, and the gauges at schools were mostly sited also at roof level. Nairobi has 855 mm of rainfall per year; above average falls were recorded in 1971 and 1972. At Dar es Salaam where open spaces are rare, there were 25 gauges, with one gauge per 2.5 km^2. The distribution of gauges was very uneven because sites with good exposure lay along the main roads; only two gauges were sited on tall buildings. Mean annual rainfall at Dar es Salaam is 1110 mm. Between 1969 and 1971, rainfall was below average, particularly between March and May; November was dry also, with above average falls in December. In 1972, rainfall was greater than average, particularly in the two rainy seasons.

RESULTS

The intensity and duration of the large storms which occurred between 1969 and 1972 were analysed. Large storms are defined broadly as those falls which are greater than 10 mm over short periods, or greater than 25 mm over long periods, and with an intensity of at least 0.5 mm per minute at any gauge. The ten largest storms at each network are listed in Table 1. Storms over Kampala tend to be shorter and more intense than those at Nairobi. The heaviest storms at Kampala occur in August. Storms at Dar es Salaam tend to be longer and of comparable intensity with those recorded at Kampala. Storms at Nairobi are longer and the least intense. Heavy falls were more frequent in 1971 and 1972 in Kampala and Nairobi, and the heaviest falls over all networks occurred in 1972.

TABLE I

The Ten Largest Storms Recorded at Each Network 1969-72

Date	Time of Commencement	Total Precipitation (mm)	Maximum Hourly Intensity (mm/hr)	Maximum Five Minute Intensity (mm/5 min)	Duration (mins)
Kampala					
19. 8.72	13.12	88.51	77.88	19.38	114
20. 8.71	19.50	65.57	61.71	13.07	199
23. 8.71	14.50	64.38	63.47	14.31	318
13.10.72	02.48	62.98	61.97	9.66	74
29.12.70	08.00	62.60	55.30	11.34	210
22. 8.70	15.06	62.09	47.55	9.44	253
9. 9.71	18.58	61.85	61.40	12.04	102
6.11.72	17.31	59.82	59.67	12.20	73
29. 8.71	15.22	59.66	57.34	13.55	206
10. 9.69	12.13	56.72	44.55	9.11	276
Nairobi					
3. 6.72	16.34	120.44	29.19	6.89	1249
1. 5.71	14.23	100.37	63.61	8.14	358
31.10.72	00.25	98.98	24.38	4.73	696
17. 5.71	20.04	88.71	72.09	10.72	265
16. 1.71	23.14	88.23	31.28	6.00	535
2. 5.71	14.25	84.85	41.08	8.05	594
16. 5.71	17.50	73.66	47.47	9.36	328
22. 4.70	17.13	68.92	61.75	8.62	138
15. 4.71	00.39	61.93	45.79	6.99	329
4. 5.69	16.03	59.50	22.59	5.62	295
Dar es Salaam					
18.11.72	09.15	119.27	51.80	11.41	532
1. 4.70	11.42	115.02	89.67	10.67	194
4. 5.70	10.25	66.24	29.78	5.09	636
25.12.71	03.20	66.00	36.38	6.07	418
21. 1.71	01.20	63.30	35.90	9.88	416
24.12.71	2.15	60.87	42.63	13.44	218
2. 2.69	03.12	59.18	30.33	8.34	420
19. 3.72	13.08	56.75	50.36	10.67	95
14. 3.70	11.29	55.30	54.35	12.12	124
3. 5.69	12.16	54.39	29.61	7.38	637

The number of storms with intensities of at least 10 mm per hour are classified in Table II according to the maximum hourly intensity recorded. The greatest intensity of fall was measured at Dar es Salaam, although high intensities were most frequent at Kampala. Storms were less numerous and less intense at Nairobi.

The shape of the intensity profiles of the larger storms was examined together with the overall relationship of intensity with duration. The beginning of a storm was taken as the minute when the rainfall intensity equalled or exceeded 0.05 mm per minute; the majority of the larger storms experienced their most intense precipitation and recorded the greater part of their total fall within 120 minutes.

Individual storm profiles were compared, irrespective of the total length of each storm, by examining those periods of the storm when the intensity of precipitation exceeded 2 mm in fifteen minutes at Nairobi and at Dar es Salaam, and 1.6 mm in twelve minutes at Kampala. Summing these periods gave the total effective duration of the effective precipitation of each storm. At Dar es Salaam, the mean effective duration of a storm is 60 minutes; while at Nairobi the effective duration is 75 minutes, and at Kampala 48 minutes. The very extreme precipitation usually accounts for more than fifty per cent of the total precipitation of each storm, and the low intensity fall of the 'tail' of a storm considerably less. The median values of the effective precipitation expressed as a percentage of total rainfall in each storm are 94% at Dar es Salaam and 92% at Nairobi and Kampala. Subsequently, using five-minute rainfall intensity data, it was found that at Dar es Salaam and at Kampala 64% of the storms examined received their maximum intensity of precipitation in the first half of the effective duration of the storm, while at Nairobi 70% of the storms displayed this

TABLE II

The Range of Intensities Recorded per hour between 1969-72

Network	10 - 19.99	20 - 29.99	30 - 39.99	40 - 49.99	50 - 59.99	60 - 69.99	70 - 79.99	80 - 89.99	Total Number of Storms
Kampala	114	59	28	12	5	4	1	0	223
Nairobi	100	26	10	5	0	2	1	0	144
Dar es Salaam	128	38	15	6	3	0	0	1	191

characteristic. This suggests that, in general, these storms are not symmetrical in intensity profile.

The relationship between the intensity and duration of rainfall was described by the equation

$$I = \frac{a}{(T+b)^n}$$

where I is rainfall intensity in mm per hour, T is the duration in hours and a, b and n are quasi-constant parameters. After testing, a value for b of 0.33 hours seemed most representative for all networks. An examination by the Transport and Road Research Laboratory found this value for b with many East African records (Fiddes et al, 1974). With this value for b, the equation was fitted statistically to intensities received at 1, 5, 10, 15, 30, 60 and 120 minutes through the ten heaviest storms at three representative gauges in each network. The derived values for n vary between storms. The mean value of this parameter at Kampala was 0.95, with lower mean values of 0.86 and 0.79 at Dar es Salaam and at Nairobi, respectively.

The highest mean network value of the parameter n was obtained from the Kampala data, where falls are short but very intense. Kampala storms rarely last as long as those at Dar es Salaam and Nairobi, but they often record maximum 1, 5 and 15 minute intensities which exceed those of Dar es Salaam and Nairobi (Table II). The largest storms examined at Nairobi and Dar es Salaam have small values for n (0.5 to 0.6) in association with the prolonged high intensity rainfall, with few marked peaks. These storms have return periods greater than two years; it appears that the parameter n may decrease with increasing return period at these two networks. The greatest storm at Kampala, on 19.8.72, is approximately the five-year storm; the value of the parameter n derived for this storm is near the mean value for the network. This implies that the intensities are greater with increased return period, at Kampala, rather than the greater duration of maximum intensity with increased return period at Nairobi and Dar es Salaam.

CONCLUSIONS

The major falls of large storms last less than an hour at Kampala, about an hour at Dar es Salaam, and less than two hours at Nairobi. Over 90% of the rainfall is relatively intense. The storm intensity profiles appear asymetric, reaching a peak before half of the effective duration of the storm is over. The variation of the parameter n in the intensity-duration equation between networks indicates the difference in the characteristic falls. Storms at Kampala have high intensity, short duration falls, whilst storms at Dar es Salaam and particularly at Nairobi display less well-marked peaks of intensity within them.

SUMMARY

Between 1969 and 1972, storm rainfall was obtained for each minute at Kampala, Nairobi and Dar es Salaam. Respresentative data for the largest storms are tabulated, and the intensity profiles of the heaviest falls are examined. The effective duration of the storms is found, using threshold intensities, to be 48 minutes at Kampala, 60 minutes at Dar es Salaam and 75 minutes at Nairobi. Over 90% of the total storm rainfall is effective rainfall above these threshold intensities. Over 50% of the rainfall occurs before half of the effective duration of the storms. With a constant of 0.33 hours, the rainfall intensity-duration relationship is applied to the largest storms. The derived values for n vary from 0.95 at Kampala to 0.86 and 0.79 at Dar es Salaam and Nairobi respectively.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Director, Transport and Road Research Laboratory, Crowthorne.

REFERENCES

FIDDES, D, FORSGATE, J A, and GRIGG, A O, 1974. The prediction of storm rainfall in East Africa. TRRL Report 623, Transport and Road Research Laboratory, Department of the Environment.

6.1.3

PREDICTION OF PEAK DISCHARGES FROM SMALL RURAL CATCHMENTS

D Fiddes
Transport and Road Research Laboratory
Department of the Environment
Crowthorne, Berkshire, UK

6.1.3

PREDICTION OF PEAK DISCHARGES FROM SMALL RURAL CATCHMENTS

D Fiddes
Transport and Road Research Laboratory
Department of the Environment
Crowthorne, Berkshire, UK

INTRODUCTION

Estimates of the peak discharges from catchments are required for the economic design of bridges and culverts on rural roads. However, flow measurements are sparse from small catchments in East Africa, so that design methods must frequently be based on rainfall data, which are more readily available, and catchment characteristics. This paper describes a programme of research designed to develop a suitable flood model; the programme was run jointly by the Kenya Water Department, the Uganda Water Development Department and the UK Transport and Road Research Laboratory.

DESCRIPTION OF CATCHMENT NETWORK

The catchments used in the study are listed in Table I and plotted in Fig 1. They were chosen to cover, as far as possible, the ranges of catchment area, rainfall, permeability, soil type and topography found throughout Kenya and Uganda. Regarding catchment area, the range covered by the study was up to 200 km^2; most of the catchments were quite small (0-15 km^2) for reasons of economy. Regarding rainfall, several distinct zones have been recognised in Kenya and Uganda, including the following:- the coastal strip, semi-arid zone of north east Kenya, the central highlands, the northern shore of Lake Victoria, and central districts of Uganda. With the exception of north east Kenya, all these zones are covered in the study. Regarding permeability, soil type and topography, catchments of uniform soil type are rare, and soils generally vary throughout the catchment, often in a regular sequence or "catena". There is also often a close

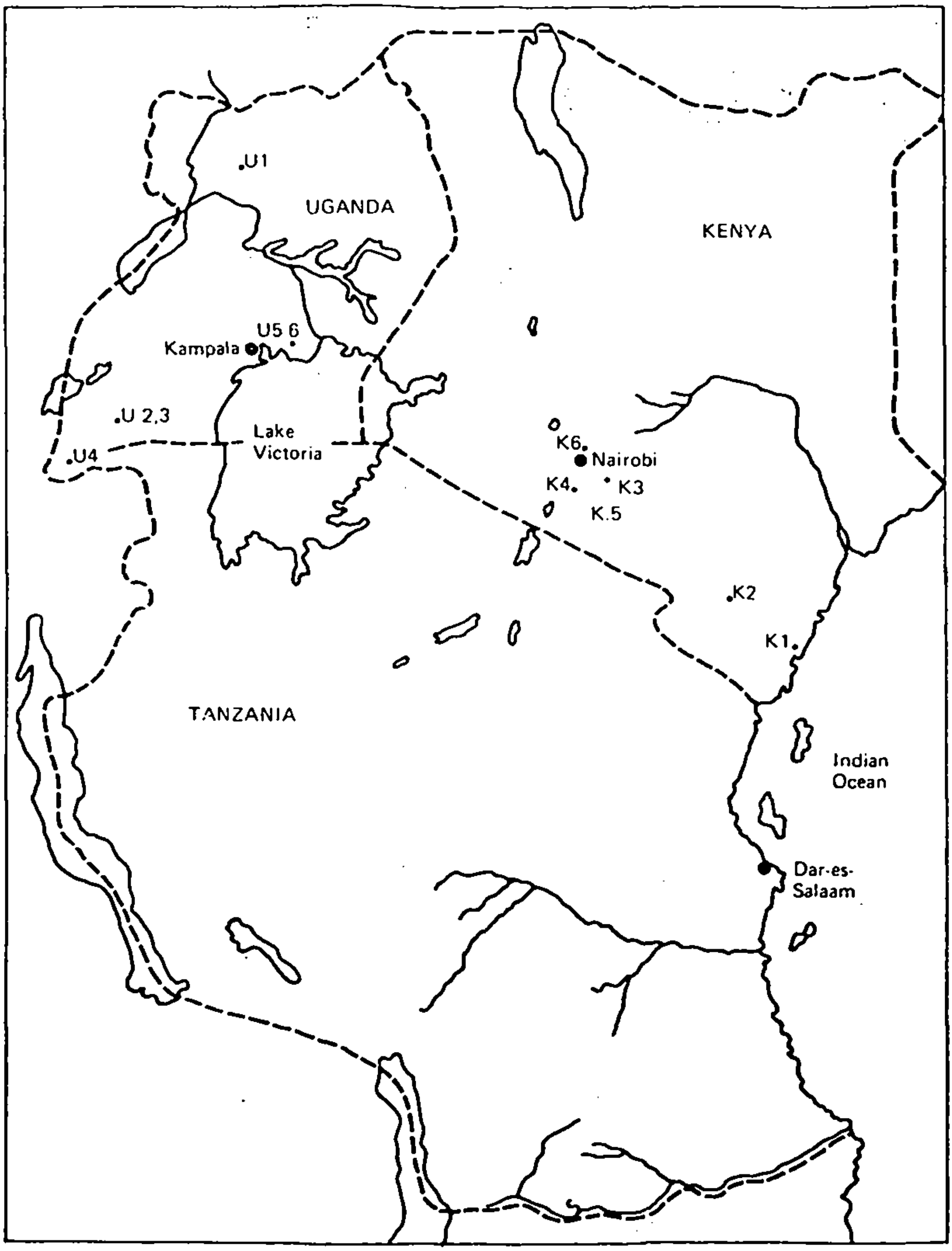


Fig.1. LOCATION OF CATCHMENTS

TABLE I

Summary of catchment details

Catchment		Rainfall zone	Topography	Land use	Area	Remarks
Ref.	Name					
	KENYA					
K1	Tiwi	750-1250 mm (Kenya coast)	Undulating	Cultivation alternating with rough grass and scrub	677 hectares	Trapezoidal flume constructed in existing box culvert. Perennial stream.
K2	Mukanda	250-500 mm	Ridge to gently undulating	Scrub	145 hectares	Catchment within Tsavo National Park. Plynlimon type flume used to avoid silting problems. Ephemeral stream.
K3	Migwani	500-750 mm	Ridge to gently undulating	Scattered cultivation and rough scrub grazing	25 km^2	Road causeway forms controls for flow measurement. Perennial stream.
K4	Kajiado	500-750 mm	Level to depressed	Savannah, rough grazing	336 hectares	Poorly drained 'black cotton' soil. Crump weir built into existing box culvert. Ephemeral stream.
K5	Kooret	500-750 mm	Ridge to gently undulating	Scrub Savannah	359 hectares	Crump weir constructed in existing box culvert. Ephemeral stream.
K6	Kiambu	750-1250 mm	Highly dissected to broad ridge	Coffee plantations	201 hectares	Trapezoidal flume Perennial stream.
	UGANDA					
U1	Barebili	1250 mm +	Gently undulating to level	'Elephant' grass and scattered trees with shifting cultivation	372 hectares	'Virginia Vee' weir upstream of existing culverts. Perennial stream.
U2	Munyere subcatchment	750-1250 mm	Highly dissected to broad ridge	Grass with cultivation on alluvial valley floor	57 hectares	Index of inflow to main swamp of U3. Perennial stream.
U3	Munyere	750-1250 mm	Highly dissected to broad ridge	Grass land and shifting cultivation with significant area of swamp in valley	145 km^2	Crump weirs in existing box culverts. Papyrus swamp 20 per cent of area Perennial stream.
U4	Rubeare	750-1250 mm	Ridge to gently undulating	Grass with shifting cultivation. No swamps	13.4 km^2	'Virginia Vee' weir upstream of existing culverts. Ill defined water course. Ephemeral stream.
U5	Sezibwa	1250 mm + (N.Shore Lake Victoria)	Redissected	Patches of dense forest permanent and shifting cultivation in woodland savannah. Significant area of swamp	170 km^2	Natural control at waterfall. Papyrus swamp 1 per cent of area. Perennial stream.
U6	Lugala	1250 mm + (N.Shore Lake Victoria)	Redissected	Woodland savannah with permanent and shifting cultivation	207 hectares	Flat Vee crump weir. Index of inflow to main swamp of U5. Perennial stream.

association between soil type and topography. With a limited number of catchments, all possible combinations could not be covered, but an attempt was made to select sites that might be representative of large areas and cover as wide a range of catchment response as possible.

INSTRUMENTATION

Rainfall and flood flow were measured, but only data from heavy storms were used in the analysis, since such storms tend to be more uniform in spatial distribution than more frequent and less intense storms. Because of the relative spatial uniformity of heavy storms, a fairly low raingauge density was possible, and daily-read gauges were installed at a density of approximately 2.5 - 5.0 per km^2 for small catchments; for larger catchments, the density was about 1/10th of this value. Sufficient recording raingauges were included to measure the uniformity and variation with time of rainfall over the area.

Wherever possible, the flow measuring structures were incorporated into existing culverts to reduce construction costs. This meant that a single design could not be used, and that each site required special treatment. The types of design used are listed in Table I. Depth measurement was by air purge recorder to minimise the effect of siltation; most of the streams were ephemeral and carried heavy bed loads.

DESCRIPTION OF ANALYSIS AND RESULTING FLOOD MODEL

For each large storm on a catchment, the mean rainfall profile and the resulting flood hydrograph were calculated.

Initially, it had been intended to prepare a unit hydrograph and a rainfall-runoff correlation for each catchment. With the small size of most of the catchments, and the limited period of research available (4 years in most cases), this proved impossible. Instead, a conceptual model of the catchment was fitted to the data. The model consisted of two components, one yielding overland flow, and the other channel flow. The overland flow hydrograph prediction required an estimate of three parameters: (i) initial retention; (ii) contributing area coefficient; and (iii) reservoir lag time. It was assumed that no runoff occurred until cumulative precipitation exceeded the initial retention, assumed to be a function of antecedent rainfall condition; subsequent runoff was assumed to be only from a limited area of the catchment (the contributing area) from which 100% runoff occurred. This runoff was routed through a linear reservoir, such that:

$$Q_t = \frac{C_A \cdot A \cdot SS_t}{K}$$

where Q_t is the surface runoff hydrograph ordinate at time t;

C_A is the contributing area coefficient;

A is the catchment area;

SS_t is surface water in storage at time t; and

K is catchment lag time.

This overland flow hydrograph for each subcatchment was routed through the stream system of the catchment using the finite difference technique of Morgali and Linsley (1965).

From the analysis of all large storms, optimum values of the lag time and contributing area coefficient were found for each catchment under flood-producing conditions. A flow diagram of the model is shown in Fig 2. The model can be used to predict the flow from any ungauged catchment, using a suitable design storm. It does, however, require considerable computer time, so that its use would be uneconomic for deriving preliminary designs at the feasibility study stage of a highway scheme. For this purpose, a simple flood model, similar in concept to the ORSTOM model for West Africa (Rodier

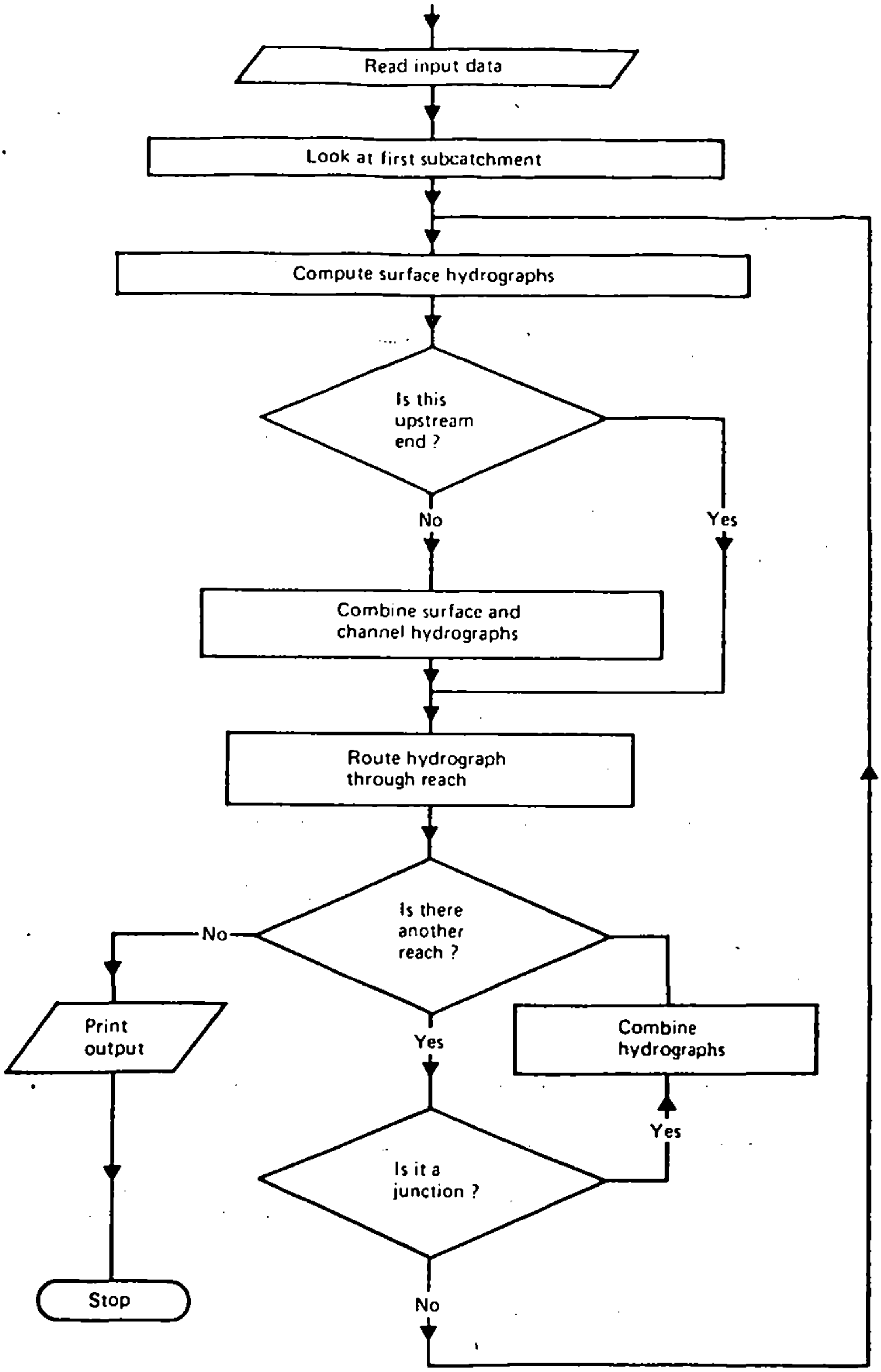


Fig.2 FLOW DIAGRAM OF MODEL

and Auvray, 1965) was developed. On each catchment, a ten-year design flood was predicted by routing an appropriate ten-year design storm through the computer model with the three parameters Y, C_A and K adjusted to their optimum values for flood-producing conditions. In many cases, this implied saturated soil conditions prior to the onset of storm rainfall; however, in some areas, particularly in western Uganda, the probability that flood-producing rainfall coincided with saturated antecedent conditions was found to be low. Appropriate parameter values for non-saturated soil were therefore selected when estimating the ten-year flood in these areas.

From these ten-year flood hydrographs, measurements were made of:

(a) The volume of storm runoff;

(b) The hydrograph base time;

(c) The ratio of peak flow to the average flow during the base time.

These three factors were related to catchment characteristics to generate a generalised flood model.

Predicting the peak flow using the model therefore involved three steps:-

(a) The total volume of runoff was calculated from:-

$$RO = (P - Y)\ C_A \ .\ A\ .\ 10^3\ (m^3)$$

where P is storm rainfall (mm) during time equal to the base time;

Y is initial retention (mm);

C_A is contributing area coefficient;

A is catchment area (km^2)

(b) If the hydrograph base time is measured to a point on the recession curve at which the flow is 1/10th of the peak flow, then the volume under the hydrograph is approximately 7% less than the total runoff. The average flow is therefore given by:

$$\overline{Q} = \frac{0.93 \; . \; RO}{3600 \; . \; TB} \quad (m^3 s^{-1})$$

where TB is hydrograph base time in hours.

(c) Peak flow (Q) is given by:

$$Q = F \; . \; \overline{Q}$$

where F is a peak flow factor.

SUMMARY OF DESIGN METHOD

Details of the derivation of the tables used to estimate the various parameters are given elsewhere (Fiddes, 1976). The following summary of the steps involved in estimating the peak flow for a design storm indicates the site measurements required and the calculations involved.

(a) Locate catchment on a large scale map and measure catchment area, land slope, channel slope (S) and channel length (L). The land slope is estimated by superimposing a grid over the catchment and measuring the minimum distance between contours at each grid point. From these, slopes are calculated and averaged to give mean catchment value. The channel slope (S) is the average slope from the bridge site to the uppermost part of the stream. Where information is sparse, this may be taken as 85% of the distance to the watershed.

(b) From site inspection, establish catchment type in

Table II, and hence lag time (K).

(c) From site inspection, or from literature, establish the soil type; using the land slope, estimate the standard contributing area coefficient (C_S) using Table III.

(d) Using the report by Fiddes (1976) check if the zone is wet, dry or semi-arid, and hence estimate catchment wetness factor from Table IV.

(e) From site inspection, decide on the type of vegetative cover, paying particular attention to areas close to the stream. Using Table V, estimate the land use factor (C_L).

(f) The contributing area coefficient C_A is given by:

$$C_A = C_S \cdot C_W \cdot C_L$$

(g) If the antecedent rainfall zone in (d) above is semi-arid or in western Uganda, the initial retention (Y) is 5 mm; for all other zones, Y = 0.

(h) Using Fig 3 and Table VI, estimate rainfall time (T_P).

(i) The initial estimate of base time is given by:

$$T_B = T_P + 2.3K$$

(j) Using an appropriate storm profile, calculate the design storm rainfall to be allowed for during the time interval T_B hours (P mm).

(k) The volume of runoff is given by:

$$RO = C_A \cdot (P - Y) \cdot A \cdot 10^3 \ (m^3)$$

TABLE II

Catchment Lag Times

Catchment Type	Lag time (K) hrs
Arid	0.1
Very steep small grassed or bare catchments (slopes > 15%)	0.1
Semi-arid scrub (large bare soil patches)	0.3
Poor pasture	0.5
Good pasture	1.5
Cultivated land (down to river bank)	3.0
Forest, overgrown valley bottom	8.0
Papyrus swamp in valley bottom	20.0

TABLE III

Standard Contributing Area Coefficients

(Wet zone catchment, short grass cover)

		Soil type	
Catchment slope	Well drained	Slightly impeded drainage	Impeded drainage
Very flat <1.0%		0.20	0.40
Moderate 1-4%	0.10	0.30	0.45
Rolling 4-10%	0.12	0.40	0.50
Hilly 10-20%	0.15	0.50	0.60
Mountainous >20%	0.20		

TABLE IV

Catchment Wetness Factor

Rainfall Zone	Catchment wetness factor (C_w)	
	Perennial streams	Ephemeral streams
Wet zones	1.0	1.0
Semi-arid zone	1.0	1.0
Dry zone (except West Uganda)	0.75	0.50
West Uganda	0.60	0.30

TABLE V

Land Use Factor (C_L)

Largely bare soil	1.50
Intense cultivation (particularly in valleys)	1.50
Grass cover	1.00
Dense vegetation (particularly in valleys)	0.50
Ephemeral stream, sand filled valley	0.50
Swamp filled valley	0.33
Forest	0.33

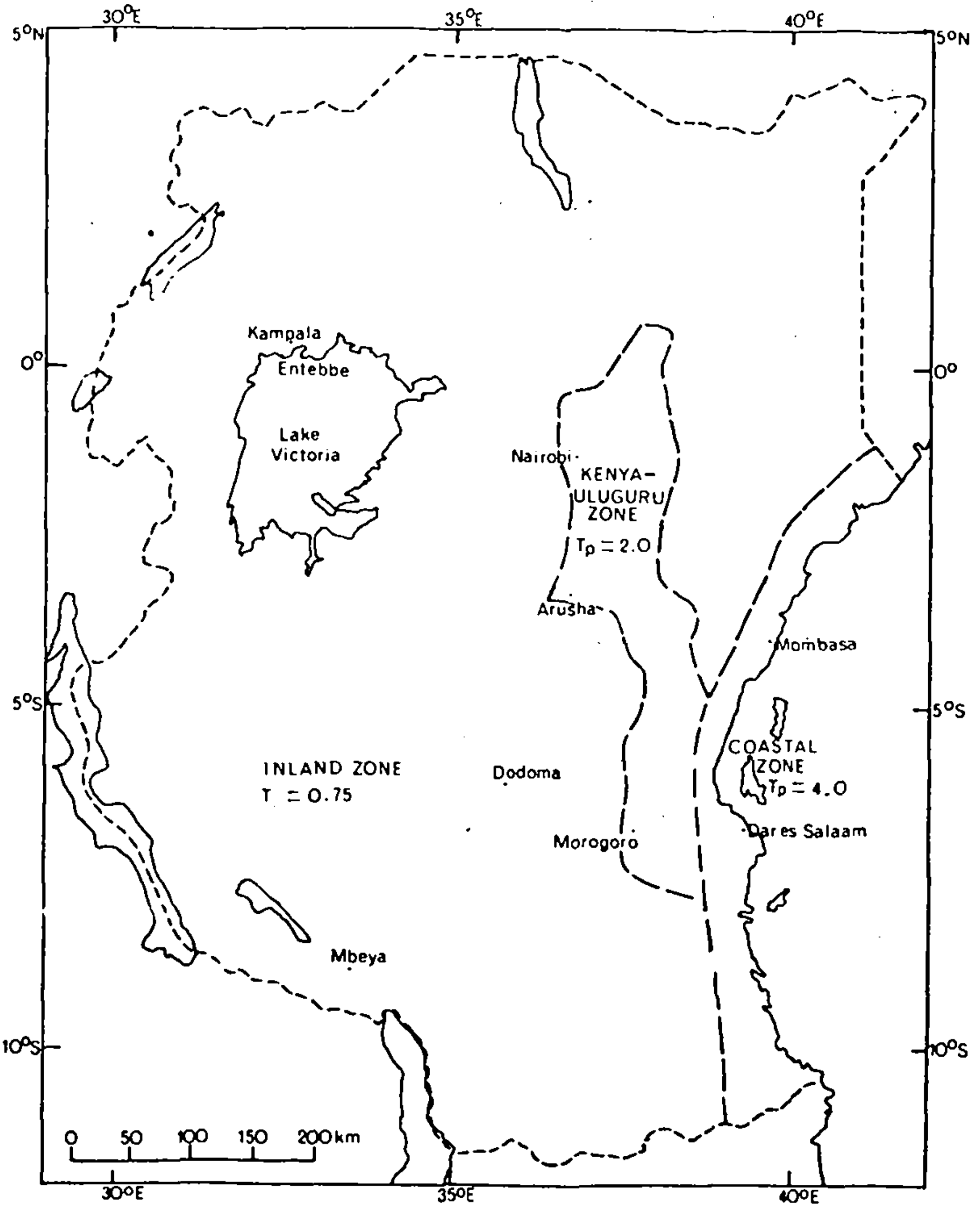


Fig. 3 RAINFALL TIME (Tp) ZONES

TABLE VI

Rainfall Time (T_p) for East African 10 Year Storms

Zone	Index "n"	Rainfall time (T_p) (h)
Inland zone	0.96	0.75
Coastal zone	0.76	4.0
Kenya-Aberdare Ulguru Zone	0.85	2.0

(l) The average flow is given by:

$$\bar{Q} = \frac{0.93 \;.\; RO}{3600 \;.\; T_B}$$

(m) Recalculate base time according to:

$$T_B = T_P + 2.3K + T_A$$

where $T_A = \dfrac{0.028\ L}{\bar{Q}^{\frac{1}{4}}\ S^{\frac{1}{2}}}$

(n) Repeat steps (j) to (m) until $\bar{Q}$ is within five per cent of the previous estimate.

(o) The design peak flow (Q) is given by:

$$Q = F \;.\; \bar{Q}$$

where the peak flood factor F is 2.8 if K is less than 0.5 hour, or F is 2.3 if K is more than 1 hour.

SUMMARY

A flood prediction method is described which was developed for the design of waterway sizes of bridges and culverts in rural highway schemes in East Africa. For detailed design, a suitable storm profile is routed through a computer model of the catchment; this model consists of a linear reservoir to simulate overload flow in each subcatchment, and a finite difference routing technique to transfer the subcatchment outflows through the stream system to the proposed culvert site. This detailed design method is supplemented with a simple synthetic design hydrograph for use in feasibility studies.

REFERENCES

MORCALI, J R, and LINSLEY, R K, 1965. Computer analysis of overland flow. Proc ASCE Hydraulics Division HT3, 81-100.

RODIER, J, and AUVRAY, C, 1965. Estimation of discharges of ten year floods for catchments with a surface area less than 200 sq km in West Africa. Inter-African Committee for Hydrologic Studies.

MORGAN, W T W, 1969. EAST AFRICA: its people and resources. Oxford University Press.

FIDDES, D, 1976. The TRRL East African Flood Model. Department of the Environment, TRRL Report LR 706.

6.1.4

GENERAL CONCLUSIONS FROM THE LAND USE EXPERIMENTS IN EAST AFRICA

J R Blackie and K A Edwards
Institute of Hydrology, Wallingford, UK

6.1.4

GENERAL CONCLUSIONS FROM THE LAND USE EXPERIMENTS IN EAST AFRICA

J R Blackie and K A Edwards
Institute of Hydrology, Wallingford, UK

INTRODUCTION

The objectives of the catchment experiments reported in this volume were to assess the hydrological effects of the following changes in land use:-

(1) From indigenous bamboo forest to plantations of exotic conifers or grassland (Kimakia);

(2) From indigenous montane forest to plantation tea (Kericho);

(3) From indigenous montane rain forest to smallholder cultivation (Mbeya); and

(4) From degraded bush to rehabilitated rangeland with bush clearing and stock control (Atumatak).

This chapter summarises results under three headings:

(i) Annual water use;

(ii) Seasonal distribution of streamflow;

(iii) Sediment yield.

In each case the extent to which the results may be extrapolated is discussed.

ANNUAL WATER USE

In the analyses of water balance results presented for the Kericho, Kimakia and Mbeya studies, the emphasis has been placed on assessing the effects of the land-use changes in terms of catchment water use, AE, rather than in terms of streamflow. This approach was adopted since water use is actively controlled by meteorological conditions and vegetation type, whereas flow can, in a sense, be regarded as a 'residual'. Meteorological control of water use is amply demonstrated in these analyses by the closer relationship between AE and Penman EO than between AE and rainfall.

In the first instance, the relationship of AE to EO, the AE/EO ratio, has been used as a means of comparing water use between different catchments. The mean water-year values of this ratio for the catchments at Kericho, Kimakia and Mbeya after each new land-use had been established are listed in Table I. These demonstrate that none of the land-use changes resulted in an increase in long-term water use. Thus, total water available to the downstream user has not been adversely affected; indeed, at Mbeya the change in land-use from rain forest to shamba cultivation has increased the annual runoff. The side effects of this increase in terms of the changes in seasonal distribution are discussed in more detail later.

As indicated by the standard errors in Table I, some year-to-year variability was present in these ratios. The variations were generally in phase with those in rainfall. Consideration of the processes which could lead to variations in water use relative to EO, namely (a) the interception of rainfall by the crop canopy and its subsequent evaporation at an enhanced rate, and (b) the reduction in transpiration brought about by the development of large soil moisture deficits, suggested that either or both could theoretically account for the phasing of the variability in AE relative to EO.

Simulation of these processes using a mathematical model (Section 1.3) indicated that the interception process accounted for a major part of this variability in forest, bamboo and pines. Field studies in tea showed that, for this crop also, interception caused considerable variability in water use relative to EO. For all four vegetation types,

TABLE I

Comparison of Mean Water Year AE/EO Ratios for the Kericho, Kimakia and Mbeya Catchments for the periods after each new land use was fully established

Location	Catchment	Dominant Vegetation	Period	Mean Rainfall	SEE	AE/EO	SEE
KERICHO	Lagan	Montane Rain Forest	1967-73	2219	±149	0.93	±0.032
	Sambret sub-catchment	Bamboo		2026	±140	0.86	±0.022
	Sambret	Tea		2011	±139	0.84	±0.030
KIMAKIA	C	Bamboo	1967-73	2143	±158	0.76	±0.012
	A	Pines		1997	±151	0.76	±0.020
	M	33% Grass		2062	±137	0.70*	±0.023
MBEYA	C	Montane Rain Forest	1958-68	1924	±143	0.93	±0.065
	A	Cultivated Crops		1658	±120	0.64	±0.025

* R-Q only

the model indicated that the rate of evaporation of the intercepted water was considerably in excess of EO. Thus the wet season AE/EO ratio can be expected to be in excess of the mean for the year and the value of this annual mean will fluctuate from year to year with variations in rainfall amount and frequency.

Model simulation of the soil moisture deficit control of transpiration rate showed that this process could account for some of the residual variability in AE/EO for the forest and bamboo catchments at Kericho but not for the bamboo and pines at Kimakia. Though the short-term field determinations of water-use of tea from soil moisture sampling must be treated with caution, they support the result, from the heat flux studies (Section 2.2.2), showing a significant decrease in transpiration from tea at high soil moisture deficits. Since moisture availability must ultimately control transpiration rates, the modelling results from Kimakia merely reflect the infrequency of drought conditions of sufficient severity to make soil moisture deficit control a significant feature there.

The mean AE/EO values quoted in Table I can be used to provide good estimates with known variability of the water use by the vegetative types studied and for the conditions in which the experiments were effected. These ratios may be applied to the same crops in other areas only if rainfall amounts, frequencies and severity of soil moisture deficits are roughly comparable with those experienced during the course of the catchment experiments; under these circumstances the ratios in Table I will provide good estimates of annual water use if Penman EO is given.

In extrapolating to markedly different climatic regimes, the dependence of water use on the intensity and frequency of rainfall, on surface infiltration, and on total water availability within the soil profile must be taken into account. For this purpose, the model described in Section 1.3

is inadequate; models of greater physical validity incorporating the physical factors listed above must be applied.

SEASONAL DISTRIBUTION OF STREAMFLOW

In assessing the effects of a change in land-use, the annual water use or water yield differences present only a part of the picture. For the domestic or irrigation user downstream, the main criterion will be the effect on the seasonal distribution of streamflow. Claims that annual total flow has not been changed will not impress this user if its distribution has been altered in a way which increases the wet season flood hazard and decreases the critically important dry season supply.

Assessment of the extent to which land-use changes in the EAAFRO catchment studies have affected seasonal flow distribution is made particularly difficult because other factors are confounded with changes in vegetation type. Temporal and spatial variations in rainfall input and differences in the inherent geometric, soil and aquifer characteristics of the catchments obscure the land-use effects in any 'before and after' or 'between catchment' comparisons. Consequently, the effects of land-use change on the individual processes contributing to total streamflow have been examined. The processes most directly affected are those governing surface runoff and infiltration and those determining groundwater recharge.

Surface Runoff and Infiltration

The catchments at Kericho, Kimakia and Mbeya are on volcanic soils with extremely high infiltration rates. As had been shown at an early stage in the studies, the changes in land-use did not materially alter the very low surface runoff response to rainfall on the catchments, except during the transition stages. That this is so on the Sambret catchment at Kericho is a tribute to the skill with which the soil and water conservation measures were designed and executed. The studies reported in Section 2.2.4 indicate that even these soils can give much higher runoff responses under tea when less effective measures are adopted. At Mbeya, the very small increase in surface runoff when forest gives way to shamba cultivation with conservation measures restricted to ineffective trash bunding is a surprising result and is atypical of experience elsewhere in East Africa. This demonstrates the high surface infiltration rates of the ash-derived soils, rates which are remarkable even by comparison with those found at Kericho and Kimakia. The wet season stability of these soils is in marked contrast to their dry season appearance.

Although no significant change in infiltration or surface runoff occurred in these catchments, it is apparent that soil structure, and the possible effect of land-use change on it, must be considered carefully in any attempt to extrapolate the results. If the change reduces the infiltration rates, wet season water yields will increase, whilst groundwater recharge, and hence dry season water yields, will be reduced. Examples of such adverse effects are all too common in East Africa and elsewhere, particularly in the change from indigenous forest to cultivation on steep slopes.

The adverse effects on surface runoff of a progressive land-use change to more intensive grazing, which may be observed over large parts of East Africa, was the raison d'être for the Atumatak study. Despite the technical and administrative problems encountered, this rangeland study demonstrated that inexpensive bush clearing and a reduction in grazing intensity lead to a re-establishment of grass cover, a recovery in infiltration rates and a consequent reduction in storm runoff, at least on relatively deep basement complex soils. The speed of recovery is largely dependent upon the extent of soil erosion prior to rehabilitation. Whereas the least-eroded soils are re-colonised rapidly, steeper or less protected slopes still show signs of a change in grass succession 12 years after clearing.

The improvement in infiltration under better grass cover is demonstrated by the ratios of storm runoff to rainfall given in Section 4.2.1. From almost equal percentages of storm rainfall discharging through the catchment outfalls before clearing, storm runoff doubled in the experimental catchment during clearing (relative to the control catchment) and fell to less than half within 5 years, as the grass cover re-established itself after clearing.

Soil moisture changes, as interpreted from the gypsum block records, also reflect the higher infiltration rates in the rehabilitated catchment. This demonstrates why recovery of moderately eroded land often proceeds rapidly. As the colonising grasses decrease surface runoff and increase infiltration, so more moisture is available in the soil to sustain plant growth when rains have ceased.

Groundwater Recharge

Recharge of catchment aquifers is not only affected by changes in the balance between surface runoff and infiltration, but also by changes in the processes governing water use by the vegetation. Replacement of one vegetation type by another may lead to:

(i) Higher dry season water use, with the result that during the following wet season a greater proportion of rainfall is required to replenish the depleted soil moisture store before recharge of groundwater can begin;

(ii) Changes in interception characteristics which may in turn affect the amount of water available for recharge.

Detailed study of the interception, soil moisture movement and transpiration processes was carried out only on tea (see Sections 2.2.2 and 2.2.3). Thus no direct evidence is available to determine whether these processes differ between the indigenous and the imposed vegetation types. Attempts were made to estimate transpiration rates, and the effect on them of increasing soil moisture deficits, from sequential dry season soil sampling. The results, reported in Sections 2.2.5 and 3.2.3 must be treated with caution, however, since the water use values obtained from soil moisture measurements include a variable proportion of interception as well as transpiration. Additional errors are introduced by unmeasured percolation losses at low deficits and the under-estimation of total abstraction by the root systems at higher deficits.

Although it was found that water use by all vegetation types decreased with increasing deficit, the differences shown require more detailed study. Some indirect evidence of the differences in interception loss, in transpiration rate, and in the sensitivity of the latter to increasing deficits, was obtained from the model simulation studies. In particular, the contribution to total water use from the interception process was found to be appreciably greater from forest than from bamboo or from tea, whereas the contributions were similar from bamboo and pines. The model optimisations also suggested that forest transpiration rates were lower than those for tea, whereas the rates were similar for bamboo and pines.

There is, clearly, a need for further study of the forest, bamboo and pines to confirm the model results. If such studies bear out the indirect evidence from modelling, the implications are as follows:-

(a) At Kericho, the replacement of forest by tea estate may have caused some changes in groundwater recharge patterns. Lower interception losses in the wet season and higher dry season transpiration by the tea may cause a greater range in seasonal flow from tea compared with that from indigenous forest.

(b) At Kimakia, the similarity in surface runoff, interception, and transpiration processes results in no major alteration in seasonal streamflow distribution arising from the replacement of bamboo with pines.

(c) At Mbeya, the change in land-use from forest to cultivation resulted in a marked increase in total streamflow. Seasonal distribution was affected particularly by the change in dry season transpiration and, to a lesser extent, by the surprisingly small increase in surface runoff. The latter accentuated the storm peaks but the absence of transpiring vegetation for most of the dry season on the cultivated catchment resulted in lower deficits, substantially greater groundwater recharge, and dry season flow nearly twice as great as that from the forested catchment.

SEDIMENT YIELD

Suspended sediment was monitored at Kimakia, Kericho and Mbeya during part of the period of study. Most of the measurements were of steady flow suspended sediment which forms only a proportion of the total sediment load. As the Mbeya results show (Section 5.2.2) steady flow suspended sediment yield may be as little as four per cent of the total load. It is not surprising, therefore, that these measurements from Kimakia and Kericho showed no significant differences in sediment yield from the various catchments. At Kimakia, more recent measurements were made with an automatic sediment sampler and no change in the pattern of sediment yield was detected. Very low concentrations of suspended sediment were found in all catchments, including one which had only recently (1973) been cleared and turned over to 'shamba' cultivation. At Kericho, the suspended sediment data from the two main catchments were variable in quality and not sufficiently reliable for publication; nevertheless, there was an indication of higher sediment yield from the tea catchment during the clearing and planting phase and a considerable reduction as the crop became established. It was then seen that the only appreciable sediment transport came in runoff from the estate road system.

At Mbeya, a storm flow sediment sampler was installed at the weir, and operated for several years. The results from this sampler suggests that stormflow contributed by far the largest percentage of the total sediment load (60%). Bed load was also measured during this period by a sediment trap upstream of the weir; 36% of the total load was bed load deposited in this trap.

In general, the rise in sediment levels attributable to the changes in land use investigated by the EAAFRO studies was low except for Mbeya, where a total load of approximately 9 tonnes ha^{-1} yr^{-1} was measured in the cultivated catchment compared with practically nil in the forested catchment. There is a need to investigate the sediment yields from cultivated catchments more fully, in view of the high suspended sediment concentrations of many of the larger rivers in East Africa. It is unfortunate that neither funds nor personnel were available to expand the sediment studies in this series of experiments.

To the authors of this report, the conclusions which can be stated unequivocally and with confidence in this section appear few in number when set against the sixteen years of field work and the subsequent years of analysis. Nevertheless, they form a basis for prediction of the effects of land-use changes in broadly similar environments. The importance of interception and the key role of soil characteristics in the seasonal runoff and transpiration processes have been demonstrated. The next stage in the development of prediction methods must be the quantification of these processes so that extrapolation to radically different environments can be accomplished.

6.2

ACKNOWLEDGEMENTS

ACKNOWLEDGEMENTS

This series of experiments was planned and initiated by the Physics Division of EAAFRO under the successive direction of Dr H C (Sir Charles) Pereira, Dr J S G McCulloch, Mr M Dagg and Dr F J Wang'ati. In the interim report published in 1962, acknowledgement was given by Dr H C Pereira to the considerable assistance he had received from government departments, supporting organisations and individuals.

The successful completion of the experimental programme is a tribute to the foresight and planning of the original EAAFRO team who laid firm foundations for the continuation of the work after they ceased to be directly involved in it.

At the same time, the research programme has been consistently supported by the Directors of EAAFRO, Dr E W Russell, Dr O Starnes and Dr B A Majisu even through difficult times. Special thanks must also be given to the Director of the Institute of Hydrology, Dr J S G McCulloch, whose continuing interest in the project led first to the Joint Programme of Research between IH and EAAFRO through the Technical Co-operation Programme of the UK Overseas Development Ministry.

Financial and technical assistance has been provided by the following government departments in recent years:-

Kenya	Ministry of Water Development Ministry of Natural Resources, Forest Department
Tanzania	Ministry of Water Development and Power Ministry for Natural Resources and Tourism, Forest Department
Uganda	Office of the Commissioner for Water Development Office of the Commissioner for Agriculture
East African Community	East African Meteorological Department

Technical advice has been received from the Kenya Research Committee for the International Hydrological Programme.

The successive Directors of the Tea Research Institute at Kericho, Dr E Chenery, Mr E Hainsworth and Mr D H Laycock, also provided considerable support and assistance to the programme, including accommodation for catchment observers and visiting research workers.

Thanks are due to the staff of the Physics Division of EAAFRO who have collected, collated, abstracted and checked the catchment data over the course of the experiments. Particular mention should be made of the assistance from:-

E S Waweru
J N Kuria
J H Waweru
N O Alose
N N Gathiro
F N Charles
J E Kahumbe
D L Mkimbo
E N Kago
D N Mugunu
W G Michobo
T J Ngumi

The costs of processing the data by computer and developing the mathematical models have been borne by the Institute of Hydrology and by the Overseas Development Ministry. Assistance in processing and correcting the data by the following members of the Institute of Hydrology staff is gratefully acknowledged:-

D T Plinston
A Hill
A N Mandeville
J R Douglas
S M Cooper
M H Rawlings
J L Hill
G Roberts
H M Gunston

Special thanks for assistance in preparing this report are due to Mrs S Yaxley and Miss S Batten of the Institute of Hydrology.

APPENDIX 7.1.1

CALIBRATION OF THE ATUMATAK FLUMES

K A Edwards
Institute of Hydrology, Wallingford, UK

Appendix 7.1.1

CALIBRATION OF THE ATUMATAK FLUMES

K A Edwards
Institute of Hydrology, Wallingford, UK

INTRODUCTION

Section 4.1.1 referred to the difficulties experienced in obtaining a satisfactory stage-discharge relationship for the structures at Atumatak. Initial design faults (see below) caused errors in theoretical calibrations, whilst the severe silting experienced in the first year of operation, and subsequent modifications to the approach channel necessitated independent checks on the flume's performance. Initially, current meters were used in the approach section to obtain discharge measurements, but the influence of the moving silt bed coupled with the rapid rise and fall in stage during floods led to an unacceptable scatter in the rating curve.

In 1965, a scale model (1:12) of the flumes was built at EAAFRO and tested in the Hydraulics Laboratory of the University of Nairobi. Although these tests were carried out with great care, the limitation of the discharge measuring device restricted these calibrations to the range of high flows. Whilst conducting the tests, Dr Vivian, of the Department of Civil Engineering, discovered a further source of error: since the deposited silt tended to block the inlet to the float well, perforated pipes had been laid across the forecourt and down the throat of the central flume section, and whilst this modification would reduce the complications due to blocked tapping points, it would produce drawdown effects of unknown magnitude in the float wells.

Following the model tests, the inlets to the wells were modified and the perforated pipe removed from one flume. The pipe was retained in the other flume, but an additional water-level recorder was installed so that the two measured stages could be compared, in the hope that a retrospective correction to the past records would be possible.

The new recorder well was erroneously installed not behind the flume walls but in the approach section; doubt arose as to the effect of this obstruction and, in 1969, the model was again tested at the Hydraulics Research Station, Wallingford, UK. The results of these tests have allowed stage-discharge curves to be derived over the whole range of flows. The following paragraphs summarise the results of the model tests and describe how the final rating curves were obtained.

THE MODEL TESTS

At the University of Nairobi, the model was tested for both silted and unsilted conditions. To simulate the stabilised silt bed, a false wooden floor was constructed to the height of the low weir. It was not thought necessary to test with a moving sediment bed as the flume should have been self-cleaning in the throat sections. A venturi-flow meter was used to measure the quantity of flow and, hence, errors in the prototype discharge below 3 m^3s^{-1} are likely to be in excess of ±5%. The results obtained from the tests, however, are remarkably consistent and it is considered that errors above this level are very small.

At the Hydraulics Research Station, the model was tested in a tilting flume at a slope of 1:100. Discharge was measured by a 90^0 v-notch weir conforming to British Standard 3680, Part 4A (1965). Four tests were performed with different combinations of the moveable parts as shown in Table I. Test 1 does not conform exactly to the unsilted test at the University of Nairobi because the low weir was in place; Test 2, however, was carried out under the same conditions as the silted test at Nairobi.

Figure 1 shows the results of both of the above series of tests. It can be seen that, apart from a gradual divergence over the low range of flows, the silted tests are in good agreement. The unsilted tests show small discrepancies which may be due to the presence of the low weir in the HRS tests.

TABLE I

Combinations of Moveable Parts Tested by HRS in their Model of the Atumatak Flume

Test No	Weir	Sediment	Stilling Well
1	Present	Absent	Absent
2	Present	Present	Absent
3	Present	Present	Present
4	Absent	Absent	Present

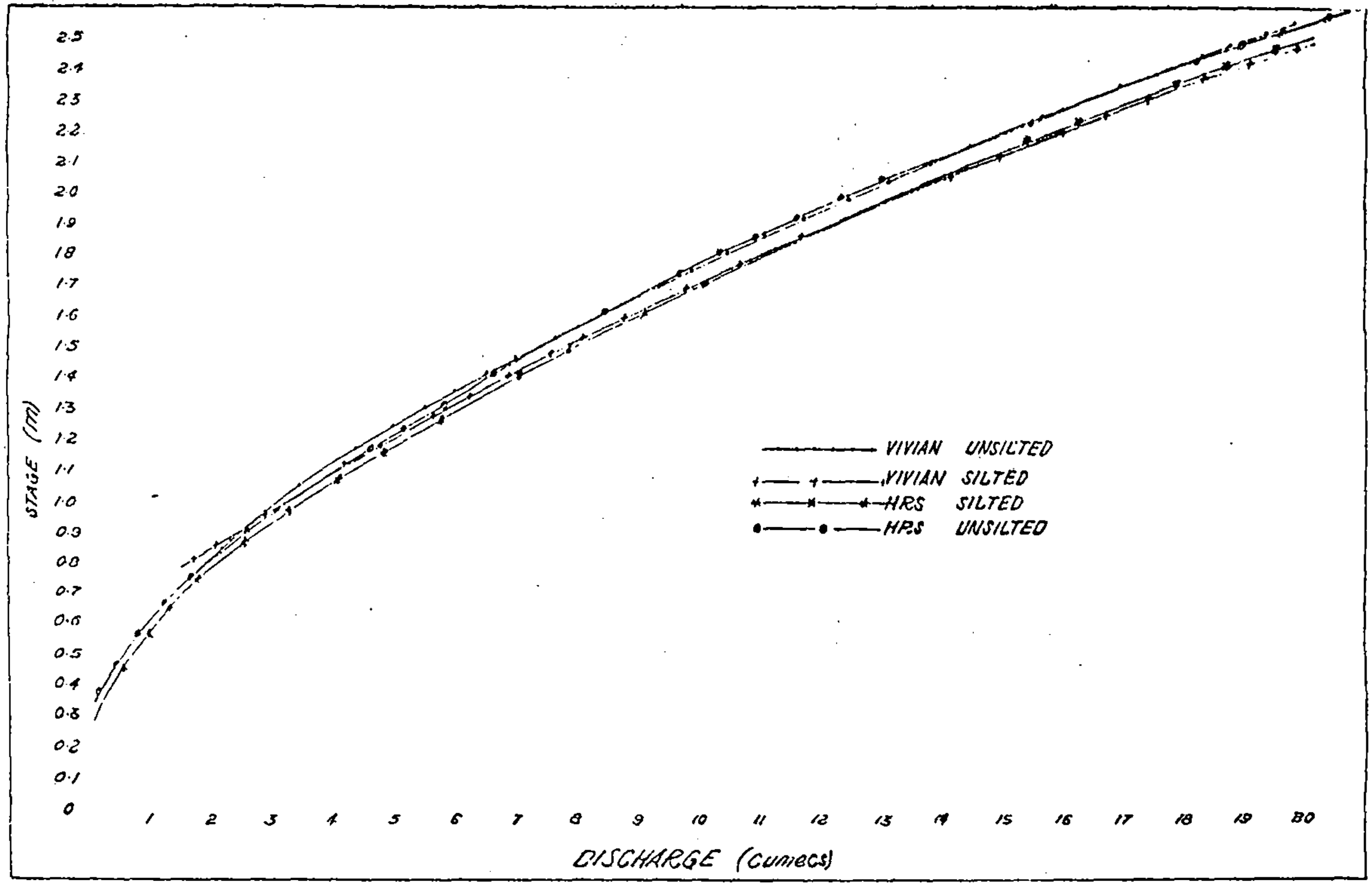


Figure 1 Model stage/discharge relationships derived by the University of Nairobi and by the Hydraulics Research Station

On the basis of the good agreement, however, the calibration tests were taken as the best available representation of the behaviour of the prototypes. After adjusting for differences between the model dimensions and the 'as built' dimensions of the flumes, a theoretical stage-discharge relationship was used to produce rating tables by adjusting empirically the non-dimensional coefficients of velocity (C_v) and discharge (C_D) (see below). HRS Test 3 included the effects of the extra stilling well; these were found to be variable but small, and were included in the rating tables as described in the next Section.

THEORETICAL RATING

British Standard 3680, Part 4A 1 was used to obtain a theoretical rating of the model. The flumes consists of a compound rectangular-throated flume with side contractions in the centre, flanked by rectangular flumes with bottom contraction (raised humps) of different elevations.

The theoretical formula relating discharge to stage for rectangular flumes is:-

$$Q = \sqrt{\tfrac{2}{3}g} \, . \, C_v \, C_D \, b \, h^{\frac{3}{2}}$$

where g is the gravitational acceleration;

b the flume width;

h the recorded stage in the approach channel relative to the flume invert;

C_v a coefficient of velocity depending on the velocity distribution in the approach channel; and

C_D is a coefficient of discharge depending on frictional and turbulence losses.

If the flumes conform to the standard, C_v and C_D are given by formulae dependent upon channel geometry. In the case of the Atumatak flumes, not only were the throat lengths insufficient to avoid inaccuracies due to flow curvature (ie L, the throat length, was less than the 1.5 h specified by Ackers and Harrison, 1963, p 13, and British Standard, op cit p 48) but the presence of the low weir affected the velocity distribution in the approach section to an unknown extent.

Accordingly, C_D and C_v were combined into a single empirical coefficient which could be determined from the model tests and then applied to the prototype dimensions using the above formula.

Table II shows the values of computed (theoretical) and measured (model) discharge for given stages with $C_D . C_v$ obtained from HRS tests 2 and 3. It can be seen that excellent agreement exists over the range of prototype discharges from 1 to 20 m^3s^{-1}; below 1 m^3s^{-1}, the theoretical formula overestimates discharge by increasing amounts as stage decreases. This range of stage, however, is outside the limits of application of the theoretical formula for the v-notch weir used in the tests (British Standard, op cit p 36). There is uncertainty, therefore, about the accuracy of the model discharges below a stage of 0.05 m.

On the other hand, it is over this range that the influence of the weir and sediment would be most marked. There is little further evidence to support either rating as being the more correct. The conclusions from the whole series of HRS tests were that discharge was increased at low flows as a result of raising the level of the forecourt. The available current meter measurements, although subject to errors as stated above, also suggest that the higher flows given by the theoretical rating are correct.

If the flumes were operating in a wetter region where low flows were a significant proportion of the total (as at Kimakia

TABLE II

Comparison of Model and Theoretical Ratings for the Atumatak Flume

(a) Silted				(b) Silted with Additional Well			
Stage	Model Discharge	Theoretical Discharge	% Theor Model	Stage	Model Discharge	Theoretical Discharge	% Theor Model
mm	m^3s^{-1}	m^3s^{-1}		mm	m^3s^{-1}	m^3s^{-1}	
323	0.14	0.17	+21.4	329	0.14	0.18	+28.6
335	0.18	0.20	+11.1	347	0.18	0.22	+22.2
393	0.30	0.31	+ 3.3	381	0.25	0.29	+16.0
418	0.35	0.37	+ 5.7	415	0.34	0.37	+ 8.8
448	0.49	0.45	- 4.3	475	0.50	0.53	+ 6.0
524	0.72	0.71	- 1.4	524	0.71	0.72	+ 1.4
573	0.92	0.92	0	573	0.92	0.93	+ 1.1
643	1.27	1.26	- 0.8	674	1.43	1.43	0
750	1.76	1.85	+ 4.5	732	1.74	1.76	+ 1.1
963	3.25	3.27	+ 0.6	753	1.90	1.89	- 0.5
1082	4.05	4.17	+ 3.0	972	3.31	3.36	+ 1.5
1274	5.76	5.78	+ 0.3	1094	4.32	4.30	- 0.5
1457	7.49	7.47	- 0.3	1241	5.53	5.53	0
1459	7.54	7.59	+ 0.7	1402	6.95	7.00	+ 0.7
1960	12.57	12.82	+ 2.0	1701	9.95	10.03	+ 0.8
2085	14.55	14.29	- 1.8	1847	11.72	11.63	- 0.8
2356	17.93	17.66	- 1.5	1957	12.81	12.89	+ 0.6
2448	19.20	18.86	- 1.8	2167	15.66	15.41	- 1.6
2509	20.18			2313	17.50	17.25	- 1.4
				2438	20.04	18.88	- 5.8
$C_D \cdot C_V = 1.10$				$C_D \cdot C_V = 1.11$			

NB All stages below 600 mm are equivalent to stages below 50 mm on the model.

or Kericho), it would be important to resolve this problem; the Atumatak study, however, is concerned with total storm flow and peak flows and it is considered that the remaining errors in the low flows will have only minor effects.

Figure 2 shows the stage-discharge curves for the two flumes and the model together with the original Uganda Water Department rating. The differences between the two flumes and the model arise from the differences in dimensions which are summarised in Table III.

CONCLUSIONS

Theoretical ratings have been derived from the Atumatak flumes from the laboratory tests on the model. The effects of various modifications to the original design were incorporated in the model tests, and values of C_D and C_V were derived empirically from the tests. In spite of uncertainties in the lower range of flows, it is considered that the errors arising in the stage measurements due to silting and faulty operation of the water level recorders are of greater magnitude. The presence of the perforated pipe leads to drawdown effects which cannot easily be detected. The records between June 1960 and August 1965, therefore, are all subject to error and this has been taken into account in the analysis presented in Section 4.2.1.

REFERENCES

ACKERS, P, and HARRISON, A J M, 1963. Critical depth flumes for flow measurement in open channels. Hydraulics Research Paper 5, HMSO.

British Standard, 1965. Thin plate weirs and venturi flumes, BS 3680 Part 4A, British Standards Institute, London, 92.

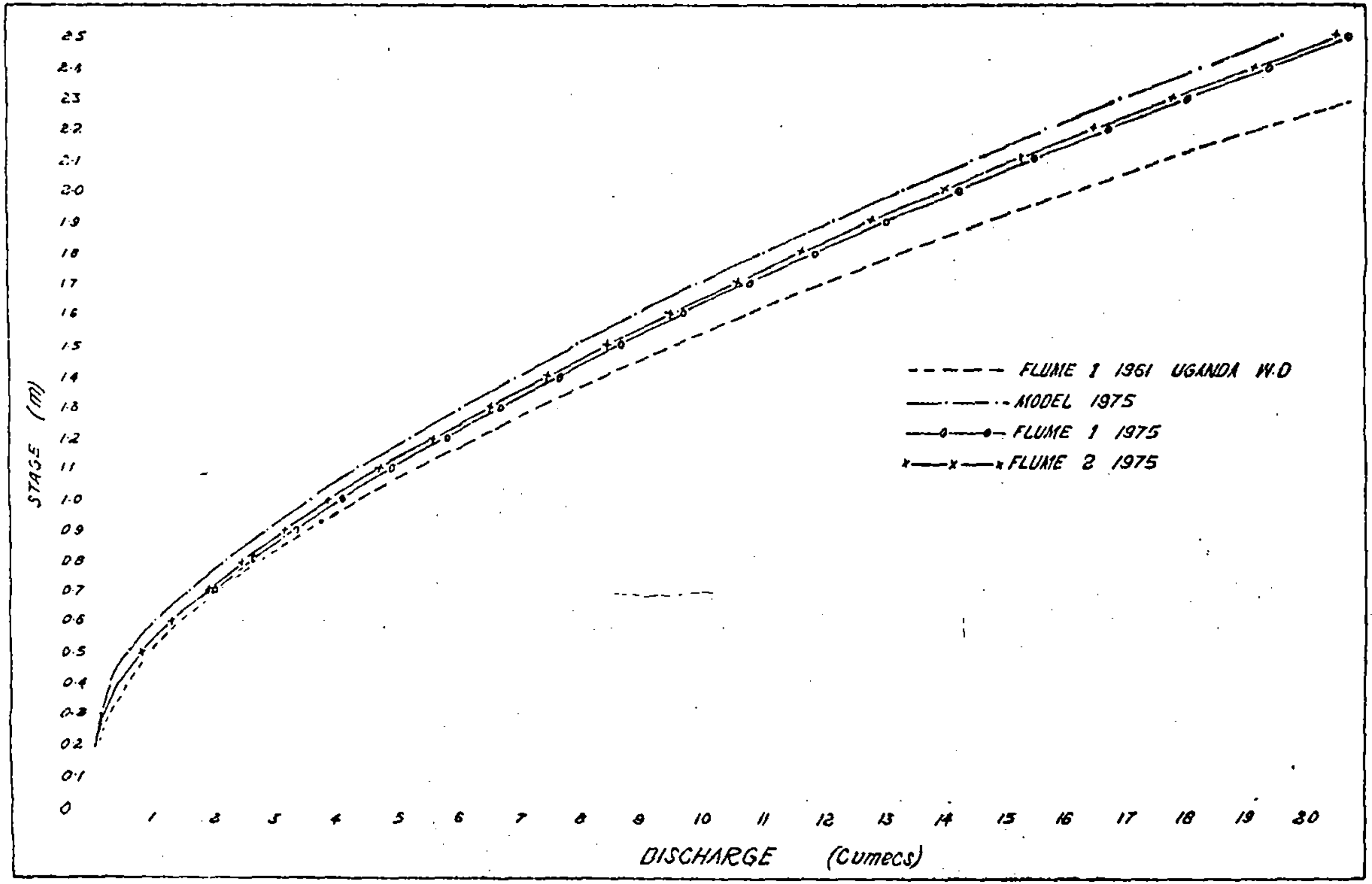


Figure 2 Prototype and model stage/discharge curves for the Atumatak flume

TABLE III

Flume Dimensions (m) for the Two Atumatak Flumes and for the Model Flume

Flume Width	Model	Flume A	Flume B
b centre	0.240	0.286	0.292
b right	1.584	1.499	1.524
b left	1.404	1.524	1.473

Elevation of hump	Model	Flume A	Flume B
Right hump	0.216	0.178	0.735
Left hump	0.444	0.406	0.389

APPENDIX 7.1.2

THE EFFECT OF RAINGAUGE EXPOSURE ON CATCH

K A Edwards and H M Gunston
Institute of Hydrology, Wallingford, UK

and

E S Waweru
East African Agricultural and Forestry Research Organisation
Muguga, Kenya

Appendix 7.1.2

THE EFFECT OF RAINGAUGE EXPOSURE ON CATCH

K A Edwards and H M Gunston
Institute of Hydrology, Wallingford, UK

and

E S Waweru
East African Agricultural and Forestry Research
Organisation, Muguga, Kenya

INTRODUCTION

Numerous authors have shown that the amount of rainfall caught in a raingauge is related to its exposure to high wind speeds (Abbe 1893, Horton 1919, Brooks 1938, Hamilton 1949, Kurtyka 1953, Corbett 1967 and Rodda 1967). Very few measurements have been made, however, of the percentage loss in catch in relation to wind speed and drop size and it is not possible to predict the amount by which a given network may be underestimating rainfall when exposed to certain wind conditions.

In East Africa, the generally low wind speeds are considered to minimise the loss in catch due to the above effect (Pereira et al, 1962, p 8). Since errors in the estimation of catchment rainfall are of vital importance to water balance studies, however, an experiment was started on the EAAFRO Meteorological Site at Muguga to investigate the magnitude of the exposure effects on the standard raingauges used in the catchments.

THE GROUND-LEVEL GAUGE

The standard raingauge in East Africa has been for many years the 127 mm diameter (5 inch) gauge mounted with its rim 30.5 cm (1 ft) above the ground. At the Institute of Hydrology, Wallingford, Rodda (op cit), following Koschmieder (1934), Riesbol (1938) and Storey and Hamilton (1943), found that these gauges caught on average 6% less rainfall than identical gauges mounted in a pit with their rim level with the ground surface and surrounded by a non-splash grid. The Wallingford meteorological site is located in a region of relatively low average wind speeds and the magnitude of this loss in catch has serious implications for water resources assessments in more windy regions, particularly highland areas which are important water catchments.

Ground-level raingauges are now widely used as an approximation to "true" point rainfall and a number of comparisons have been undertaken with different types of raingauges (Struzer et al, 1968).

Wind tunnel tests have also been carried out to investigate how gauge dimensions and shape affect their performance (Helliwell and Green, 1974).

THE MUGUGA EXPERIMENT

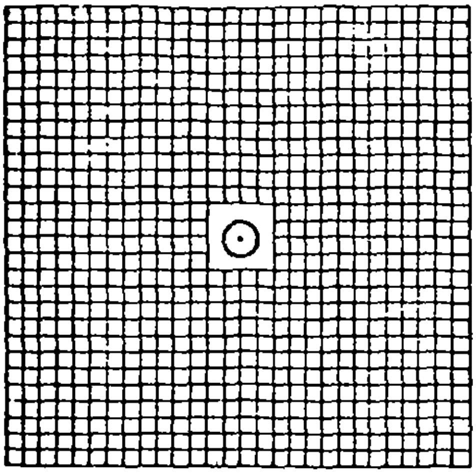
As a simple check on the magnitude of losses in catch, six gauges were exposed at different heights on the meteorological site at Muguga. These were at 1.83 m (6 ft), 91 cm (3 ft), 61 cm (2 ft) and 30.5 cm (1 ft) with two gauges at ground-level in different types of non-splash surround (Fig 1).

One of the ground-level gauges was mounted in the centre of a square pit (143 cm x 143 cm x 51 cm) surrounded by a plastic "egg-crate louvre" grid of 50 mm unit squares of a design developed at the Institute of Hydrology, Wallingford.

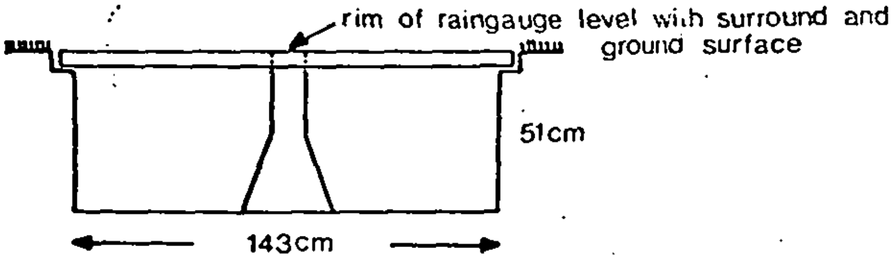
The other was placed in a circular pit (86 cm in diameter, 42 cm deep) in which concentric aluminium open-ended cylinders (15 cm deep) were spaced 8, 20 and 36 cm from the rim of the gauge. This design had been developed at Muguga.

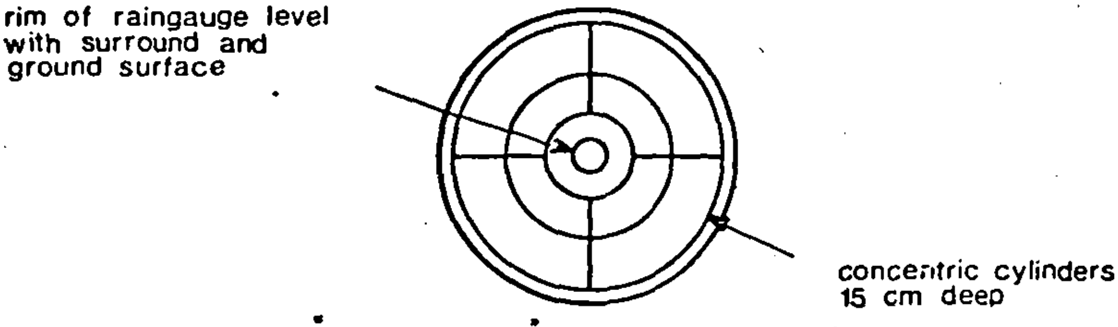
The Wallingford design was referred to as the new ground-level gauge (NGL) and the Muguga design as the old ground-level gauge (OGL).

The six gauges were placed so that no gauge was sheltered by



"Egg-crate louvre" non-splash surround





"Muguga pattern" non-splash surround

Figure 1 Ground level raingauges used at the Mbeya meteorological site

another gauge in the direction of the prevailing wind. They covered an area of 50 m^2 and, for most of the course of the experiment, no major obstructions were up wind of the site. The exception was that in one year (1973) maize *(Zea mays)* was grown in a field adjacent to the meteorological site: the effects of this on the raingauge performance are discussed below.

THE EXPERIMENTAL METHOD

Facilities were not available to weigh the catch in each gauge, which would have been desirable for high precision, and daily readings at 0900 hours were taken with a standard measuring cylinder. Experienced observers took the readings and the experiment was continued for six years to obtain a large sample of different storm sizes.

The areas of raingauge orifices differ and, in studies of this type, the errors in assuming each gauge to be precisely circular and exactly 127 mm in diameter are significant. Each gauge was carefully measured and corrections were applied to the readings.

RESULTS

Total rainfall catches for each gauge are listed by year in Table 1. It can be seen that a similar pattern is repeated in each year except 1973 with appreciable losses in the higher gauges (183 cm, 91 cm and 61 cm). The standard gauge, however, differs by only 1% from the new ground-level gauge and the two ground-level gauges have almost identical catches.

In attempting to correlate wind speed with catch, a comparison was made between the percentage loss in each gauge and the run-of-wind at 2 m and 30 cm. No obvious relationship was apparent due to the unsuitability of 24 hour run-of-wind as a measure of actual wind speed during a storm which lasts for not more than a few hours.

TABLE I

Total Catch in Raingauges Exposed at Different Heights and Percentage Loss in Catch Relative to a Ground-Level Gauge

Gauge	6 ft	3 ft	2 ft	1 ft	OGL	NGL
Year	mm	mm	mm	mm	mm	mm
1969	592.0	594.4	610.8	614.0	629.0	635.0
% loss	6.8	6.4	3.8	3.3	0.9	
1970	867.9	876.1	883.6	887.3	891.6	902.4
% loss	3.8	2.9	2.1	1.7	1.2	
1971	747.2	758.5	758.3	775.6	778.5	780.2
% loss	4.2	2.8	2.8	0.6	0.2	
1972	887.1	884.3	892.1	910.6	925.1	910.8
% loss	2.6	2.9	2.0	0.0	-1.6	
1973	712.9	720.4	707.2	723.7	728.3	718.9
% loss	0.8	0.2	1.6	0.7	-1.3	
1974	831.0	845.2	823.5	858.0	857.3	858.8
% loss	3.2	1.6	3.1	0.1	0.2	
Total* Catch	3 ~~5~~925.4	3958.5	3977.3	4045.5	4081.5	4087.2
% loss	4.0	3.2	2.7	1.0	0.1	

* Total excluding 1973)
OGL - Muguga pattern ground-level gauge) see text
NGL - Wallingford pattern ground-level gauge)

Since the loss in catch is also related to drop size, the daily rainfall totals were grouped into classes of 0 to 5 mm, 5 to 10 mm, 10 to 20 mm, 20 to 30 mm, 30 to 40 mm and over 40 mm. On the crude assumption that drop size is related to storm amount, it was expected that loss in catch would be greatest with the lower rainfall totals. Fig 2 summarises the results of this analysis for the years 1969-1974, excluding 1973.

It can be seen that the above assumption is valid under the range of wind speeds and intensities found at Muguga. Furthermore, although the average loss in catch for all storms is as given in Table I, the actual losses for low intensity, small drop-size storms are considerably higher. With storms in the range 0 to 5 mm day^{-1}, the raingauge exposed 6 ft above the ground loses more than 10% of the rainfall compared with the ground-level raingauge.

EFFECT OF CHANGES IN EXPOSURE

As stated above, maize was grown upwind of the meteorological site during 1973. Planted at the start of the long rains in March and harvested in September, the maize grew to an effective height of 2.5 to 3.0 m and sheltered the raingauges for a major part of the year. No attempt was made to analyse the readings month by month because of the small sample sizes involved, but the effects on both loss in total catch (Table I) and loss in relation to storm size (Fig 3) are marked.

Large decreases in percentage loss in catch are observed with all gauges. In fact, only the 183 cm and 61 cm gauges record losses which could be significant in a water balance context and only with the smallest storm size. The 61 cm gauge figures appear anomalously high, and it is possible that the gauge may have been disturbed and exposed with its rim not parallel to the ground surface during this period. On the other hand, it may be a feature of the wind distribution in this part of the meteorological enclosure and without further evidence no firm conclusions can be reached.

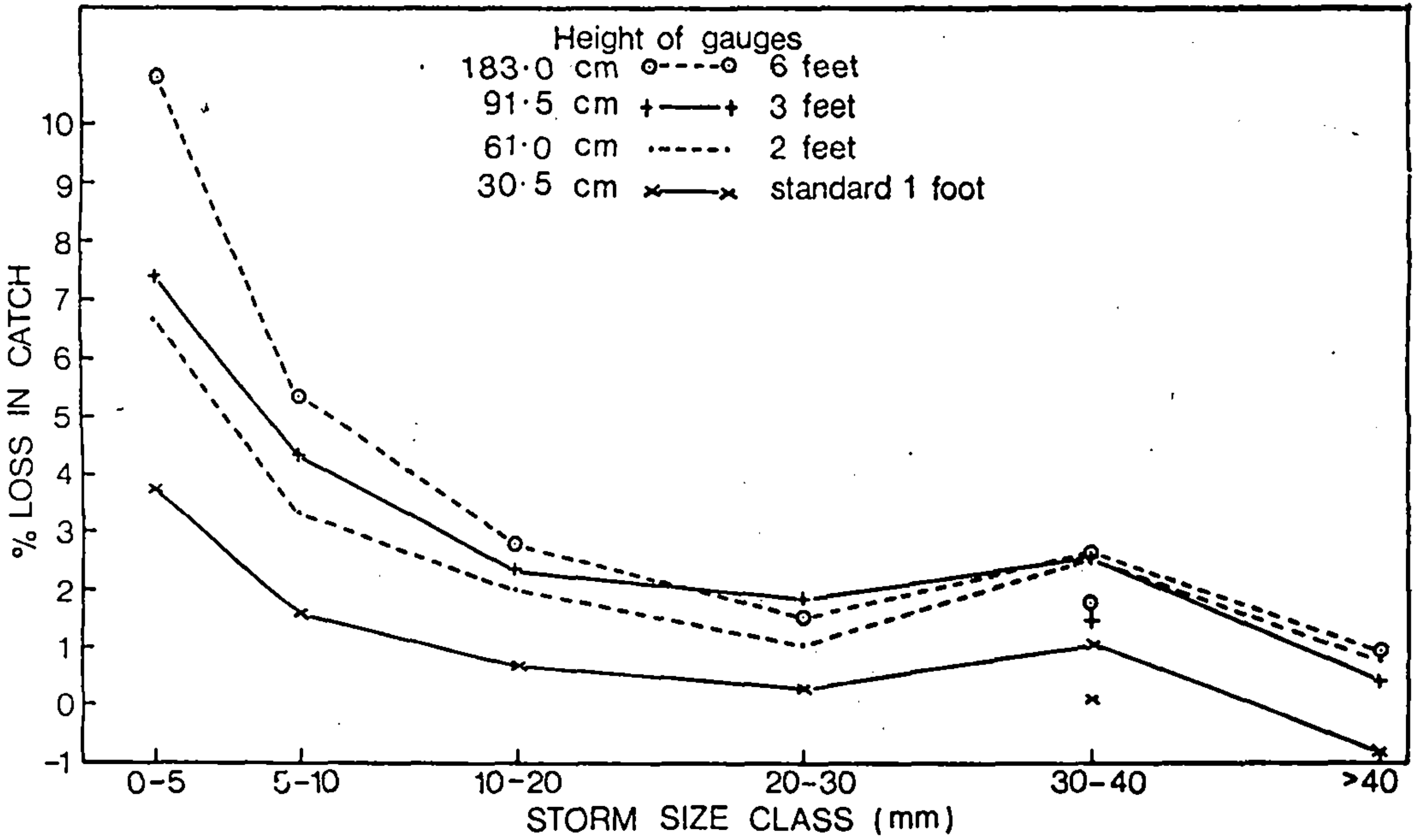


Figure 2 Percentage loss in catch for different storm size classes and for different heights of raingauge (1969-1974 excluding 1973)

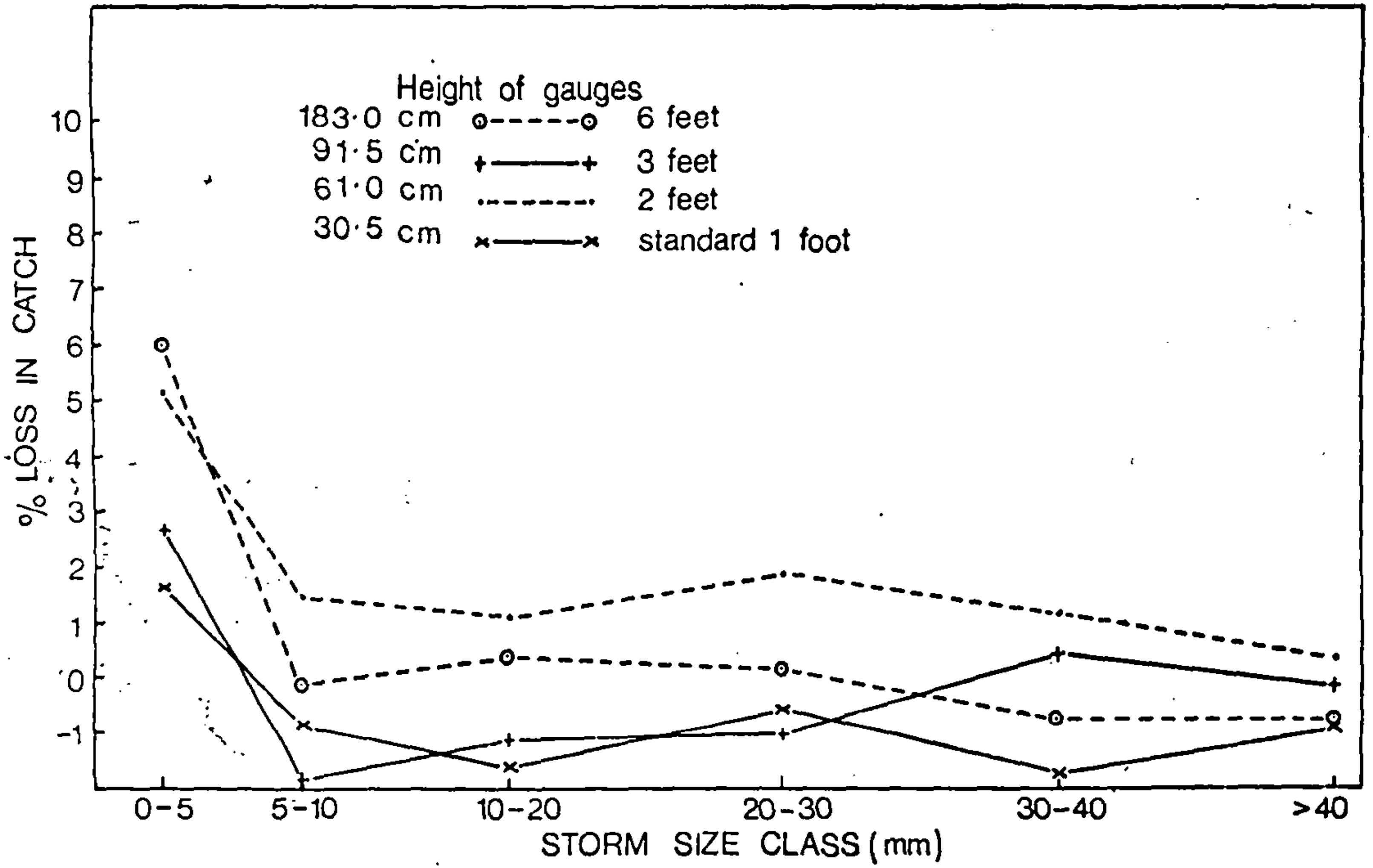


Figure 3 Percentage loss in catch for different storm size classes and for different heights of raingauge (1973 only)

CONCLUSIONS

It can be seen from the preceding discussion that the expected loss on total annual catch due to exposure of raingauges above the ground are small with gauges exposed less than 1 m above the ground in conditions similar to those found at Muguga.

Although the experimental data did not allow a relationship to be established between loss in catch and wind speed (vide Helliwell and Green, 1974), a clear indication of the variation in losses in relation to storm size has been obtained. With the smallest storm size class (0 to 5 mm day^{-1}), the losses in catch are unacceptably large with gauges higher than 30 cm and, in catchments where such storms form a high proportion of the total, the average annual loss in catch will be higher than those shown in Table I.

For greatest accuracy in representative point measurement of rainfall, therefore, it is desirable that raingauges should be exposed not more than 30 cm above the ground or canopy level. Where it is suspected that high wind speeds or small drop sizes predominate, steps should be taken to shelter the gauge or maintain the airflow lines parallel to the orifice of the gauge.

Further indications of the effects of exposure have been obtained from the 1973 results when the fortuitous change in upwind shelter decreased the losses in all gauges relative to the ground-level gauge. While it is accepted that sheltering a raingauge reduces the losses due to exposure, it is easier to standardise exposure by using the ground-level gauge than to determine criteria of shelter in different wind speeds and rainfall intensities.

Conditions in the tropics do not usually warrant the expense of establishing networks of ground-level raingauges. In highland areas, however, underestimation of rainfall due to

wind effects is an observable and significant feature and, where accuracy in rainfall measurement is important, over-exposure of raingauges should be avoided.

ACKNOWLEDGEMENTS

The consistency of the results presented here is a tribute to the diligence of the EAAFRO meteorological observers in taking the rainfall measurements and maintaining the gauges.

REFERENCES

ABBE, C, 1893. Determination of the true amount of precipitation and its bearing on theories of forest influences, US For Serv Bull 7, 175-186.

BROOKS, C F, 1938. Wind-shields for precipitation gauges. Trans Amer Geophys Union (1), 539-542.

CORBETT, E S, 1967. Measurement of precipitation on experimental watersheds. In Sopper and Lull (Ed) Forest Hydrology, Pergamon, Oxford, 107-129.

HELLIWELL, P R, and GREEN, M J, 1974. Raingauge performance studies. Final report to NERC on contract no F60/5/2. University of Southampton, Department of Civil Engineering.

HAMILTON, E L, 1949. The problem of sampling rainfall in mountainous areas, Proc Berkeley Symp on Maths, Statistics and Probability, Univ Calif Press, 469-475.

HORTON, R E, 1919. The measurement of rainfall and snow. J New England Water Works Assoc, 33, 14-65.

KOSCHMIEDER, H, 1934. Methods and results of definite rain measurements. III Danzig Report. Mon Weath Rev 65, 5-7.

KURTYKA, J C, 1953. Precipitation measurements study. Dept of Investigation No 20, Illinois State Water Survey Div, 178.

PEREIRA et al, 1962. Hydrological effects of changes in land use in some East African catchment areas. E Afr agric for J, 27, Special Issue, 131.

RIESBOL, H S, 1938. Results from experimental raingauges at Coshocton, Ohio. Trans Amer Geophys Union (1), 542-550.

RODDA, J C, 1967. The rainfall measurement problem, Proc genl Assemb IAHS Berne, Publ 78, 215-231.

STOREY, H C, and HAMILTON, E L, 1943. A comparative study of raingauges. Trans Amer Geophys Union, 24, 133-141.

STRUZLER, L R, D'JACHKOVA, T V, KULAGIN, V F, and ZAJCEV, A S, 1968. Errors in precipitation measurements by ground raingauges in the presence of wind, Proc Cent Geophys Obs, 215, 135-152.

APPENDIX 7.1.3

THE PERFORMANCE OF EVAPORATION PANS IN THE EXPERIMENTAL CATCHMENTS

K A Edwards
Institute of Hydrology, Wallingford, UK

and

E S Waweru
East African Agricultural Forestry Research Organisation
Muguga, Kenya

Appendix 7.1.3

THE PERFORMANCE OF EVAPORATION PANS IN THE EXPERIMENTAL CATCHMENTS

K A Edwards
Institute of Hydrology, Wallingford, UK

and

E S Waweru
East African Agricultural Forestry Research Organisation
Muguga, Kenya

INTRODUCTION

Because of low installation and maintenance costs, evaporation pans are widely used to estimate evaporation from lakes and reservoirs (WMO, 1966). They were introduced into East Africa following the Second World War, and a considerable body of data is now available for analysis. However, the interpretation and use of such data is made difficult because evaporation pan records tend to be confounded with other factors such as pan location, site, exposure, dimensions, colour and general condition (Dagg, 1970).

Following attempts to interpret evaporation data from pans dissimilar in size and exposure (McCulloch, 1961) it was concluded that regional estimates of potential evaporation could be more reliably obtained from measurements of meteorological variables recorded in standard exposures on well-maintained meteorological sites (Dagg, Woodhead and Rijks, 1970). The Penman formula was adopted as that giving the best comparative index of potential evaporation EO. Tables for the rapid computation of EO (McCulloch, 1965) simplified the task of obtaining evaporation values and many meteorological stations were equipped with simple inexpensive distillation-type radiometers (Pereira, 1959). Maps of potential evaporation have been produced from Penman estimates (Woodhead, 1968a, 1968b, Rijks, Owen and Hanna, 1970) and they have also formed the basis for calculating indices of available water (Woodhead, 1969).

Despite the greater merit of Penman's EO as an index of

evaporative loss, well-maintained evaporation pans can yield consistent results and are of considerable value for checking radiation or sunshine data for systematic errors, and for filling gaps in meteorological data records. Evaporation pan records are of little value, however, for interpolating estimates of evaporation at sites without record, because of their sensitivity to the factors mentioned above; each evaporation pan record is applicable to a particular site and geographical location.

The following paragraphs discuss the consistency of the pan data from the experimental catchments and their usefulness for estimating EO. Using the latest available measurements of evaporation from large surfaces of open water in East Africa, it is possible to make general comments on the comparative performance of East African pans relative to those in more temperate latitudes as a means of assessing lake evaporation.

DESCRIPTION OF THE PANS

Two types of pan were in general use in the EAAFRO catchments. One is the US Weather Bureau Class A pan, 1.22 m in diameter and 25 cm deep; the other was the Kenya type of pan, of the same diameter but 36 cm deep. To prevent birds and small animals drinking from the pans, some were covered by a wire mesh grid (25 mm); all pans are painted with black bitumastic paint inside and aluminium paint outside.

The Kenya pans were exposed either above ground, in the same manner as the Class A pan, or sunken in a revetted pit allowing an insulating air space between the sides of the pan and the wall of the pit (about 5 cm) and with only the lip of the pan protruding above the ground.

There are four basic combinations of pans, grid and exposure found in the catchments: (i) Class A pan, screened; (ii) Class A pan, unscreened; (iii) Kenya type pan, screened and raised; (iv) Kenya type pan, unscreened and sunken. Not all pans are

found in each catchment and the sunken, Kenya-type is the only pan common to all. For this reason, direct comparisons of the pans in different environments is not possible. Before discussing the effects of the pan characteristics, however, the overall consistency of the pan data is examined.

CONSISTENCY OF THE PAN DATA

Lacking an absolute standard for comparison, only two possibilities exist: the records from the pans, which are usually in pairs in the catchments, can be examined either for mutual consistency or compared with another index of evaporation such as the calculated Penman EO. Where good water balance data are available, a direct comparison with actual water use from vegetation is possible, but this is only useful where transpiration continues throughout the year at or near the potential rate.

Evaporation from a pan is measured as the loss or gain in any 24 hour period, suitably adjusted if any rain has fallen. Rainfall is measured in a standard gauge exposed 30.5 cm above the ground in the same meteorological enclosure. Loss or gain to the pan is measured by adding or subtracting known amounts of water (equivalent to 0.5 mm or 0.02 inches in depth). Provided that systematic errors are not introduced by assuming that the rainfall in the pan is identical to the rainfall in the standard gauge, the precision of the method is adequate for ten-day or monthly periods.

Sources of error can be summarised as follows: (i) observer errors (such as miscounting the number of containers of water added to or subtracted from the pan); (ii) splash out of the raised pans, and splash both into and out of the sunken pans; (iii) losses from unscreened pans due to birds and animals; (iv) leaks; (v) discolouration of water and pans, causing changes in albedo and pan heat balance. If these errors can be eliminated, evaporation totals from pans in the same meteorological enclosure should bear a constant relationship

to each other. Fig 1, giving the ratio of sunken pan evaporation to evaporation from raised pans of various types at four locations, shows that the ratio of annual evaporation totals is reasonably constant, although some discrepancies are apparent. Tracing and correcting individual errors retrospectively, however, is difficult and doubtful years have therefore been omitted from the subsequent analysis. The most common source of error was leakage from the pan, and such errors account for most of the missing years in the Atumatak and Mbeya records.

A second test is to compare the pan totals with the Penman estimates, and Fig 2 shows the ratios of annual totals of raised pans to Penman EO. Two unusual features emerge from this comparison; first, Kericho shows a progressive increase in the ratio Pan/EO from 1958-60, thereafter becoming stable; second, Kimakia shows a similar increase and a steady decrease from 1961 onwards. Fig 2 also shows the annual totals from the raised pans, and it can be seen that the ratios Pan/EO reflect trends in the evaporation totals from the raised pans over this period.

There is no obvious physical explanation for the low totals recorded in the first two or three years of operation. Splash may have been more marked until the grass surface established itself in the (then) new meteorological enclosures, but the raised pan should not have been affected; on the other hand, a great deal of forest clearing was in progress at both locations during this period, so that it is possible that the totals record a change in general exposure resulting from large scale forest clearing. In the case of Kimakia, the return to generally lower values may be associated with the growth of the plantation forest; at Kericho, however, the establishment of the much shorter crop (tea) over a wide area surrounding the meteorological site may have resulted in higher evaporation rates being maintained.

Similarly, the Mbeya meteorological site was not sheltered in

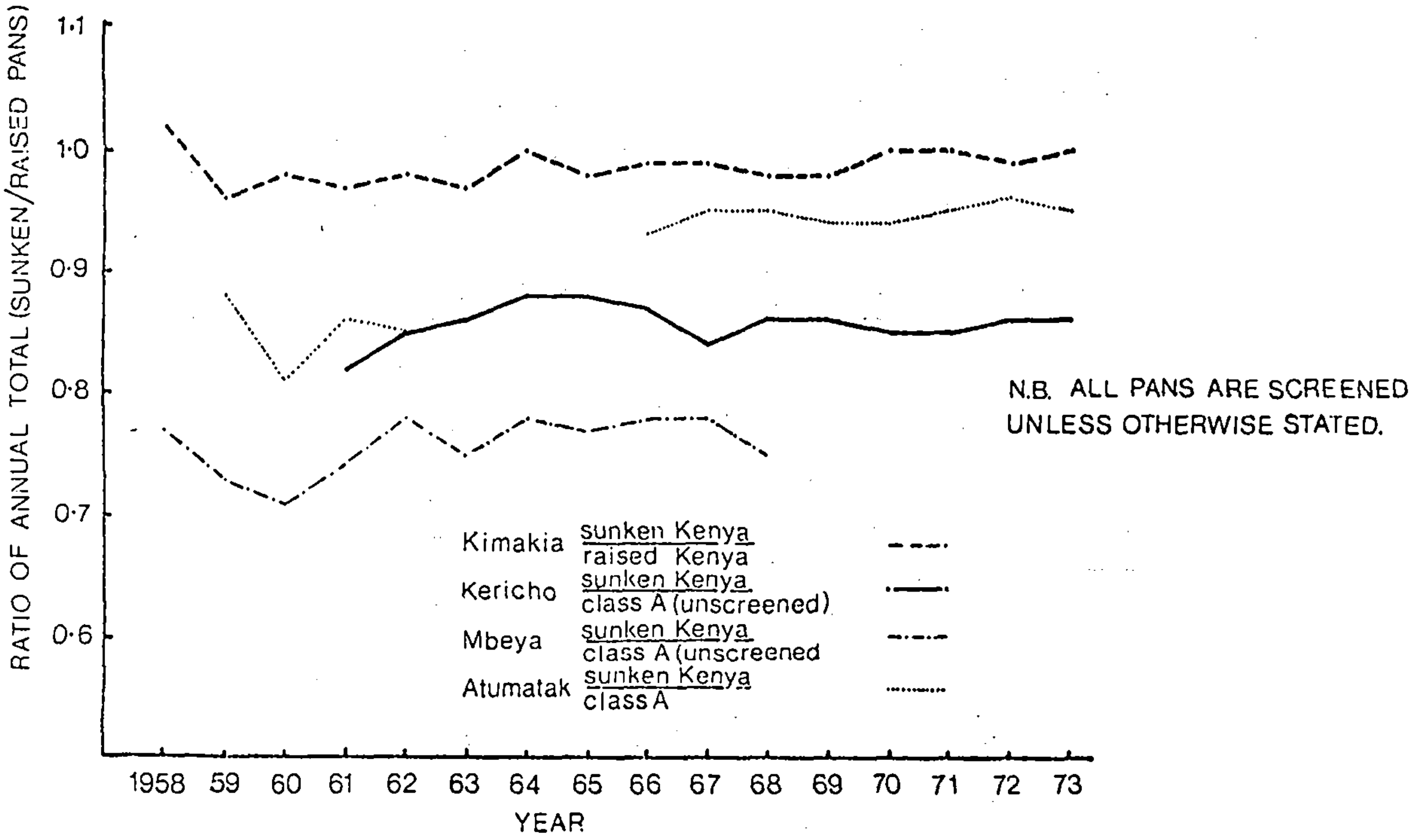


Figure 1 The ratio of evaporation from sunken pans to evaporation from raised pans of different types at four locations

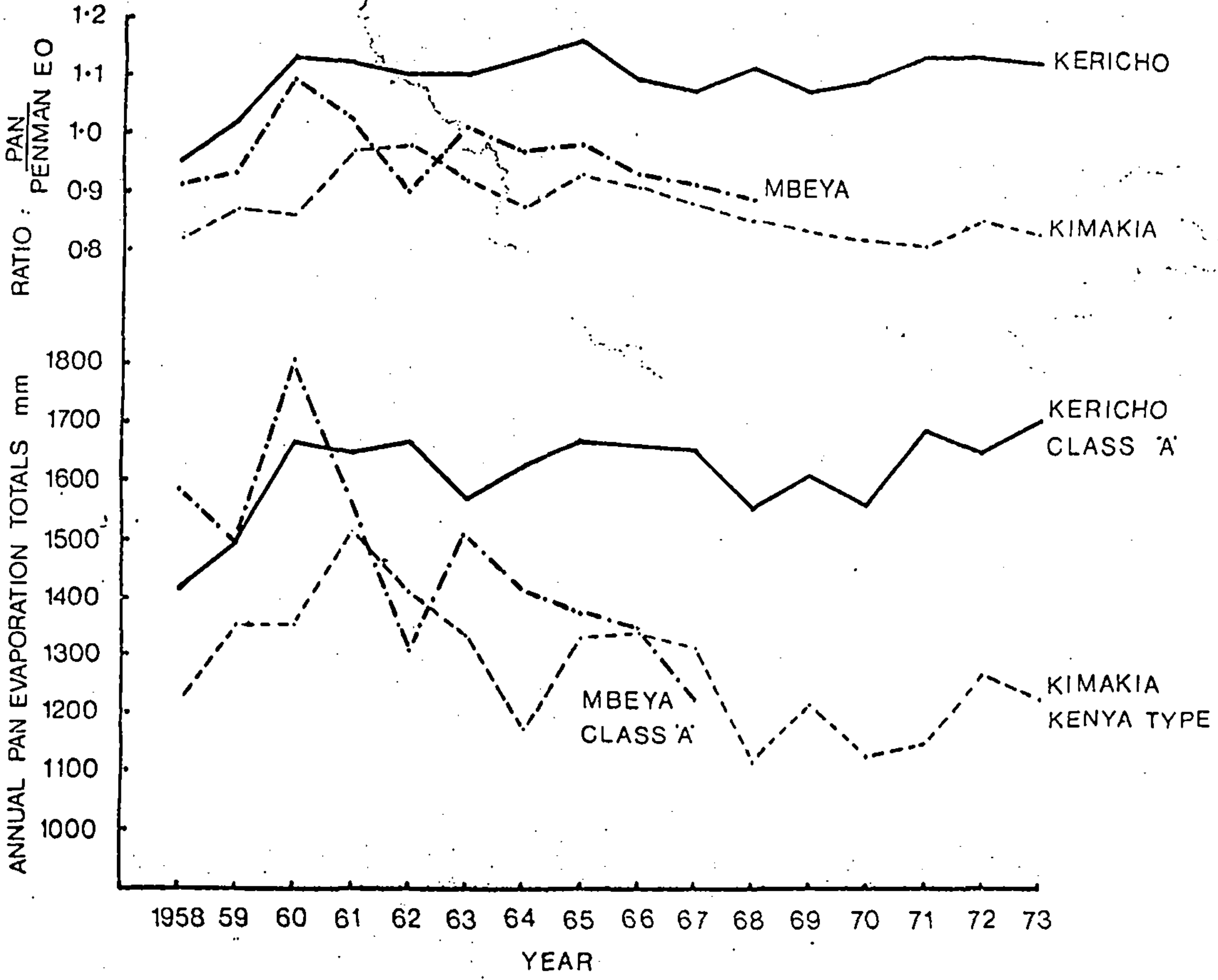


Figure 2 The ratio of annual totals of raised pan evaporation to Penman EO

1959, but by 1970 trees had grown up from one side of the enclosure; this may be associated with the decrease in evaporation rate from the pans. There is only a partial record due to leakage and other errors during this period, but the trend shown by the complete years is repeated by the Penman EO values indicating that the shelter effect, if it be the cause, is not confined to the evaporation pans but also influences the records from the other meteorological instruments.

RELATIONSHIP BETWEEN PAN EVAPORATION AND PENMAN EO

From the preceding section, it is clear that although the pan data are mutually consistent, there are variations in the ratios Pan/EO which probably result from changes in the environmental conditions and which make the derivation of universal 'pan factors' questionable. Even if it is assumed that an evaporation pan measures the same 'evaporation index' as the Penman formula, the lower exposure of the evaporation pan compared with a Stevenson Screen (1.2 m) and an anemometer (2 m) makes it more sensitive to shelter effects.

Table I shows the ratios of annual totals of pan evaporation to Penman EO over the whole of the period of reliable records. The variations in the ratios at the four stations are a feature of the differences in the seasonal energy balance. Atumatak, for example, has high ratio Pan/EO, probably because of the influence of advective heat energy in its semi-arid location. On the other hand, Kimakia has low ratios showing that no 'oasis effect' is evident at this station. Kericho has higher ratios than expected, suggesting that advection may be an important factor while the anomalously low sunken Pan/EO ratio at Mbeya is suspect because of possible sheltering.

To a certain extent the mean annual Pan/EO ratios are misleading as considerable seasonal variations are present at all stations; Fig 3 shows the monthly sunken Pan/EO ratios averaged over a number of years, and it is clear from this diagram that the range of values together with the absence of any clear pattern common to the four stations precludes any generalisation about

TABLE I

Means of Ratios of Annual Totals of Evaporation from Pans to Potential Evaporation EO

Station	Period	Type of Pan	Ratio Pan/EO
Kericho	1958-1973 (16)	Unscreened, Class A	1.09
	1958-1973 (16)	Sunken, Unscreened, Kenya	0.95
Kimakia	1958-1973 (16)	Raised, Screened Kenya	0.88
	1958-1973 (16)	Sunken, Unscreened, Kenya	0.86
Mbeya	1958-1967 (11)	Unscreened, Class A	0.96
	1958-1967 (11)	Sunken, Unscreened, Kenya	0.73
Atumatak	1962-1973 (10) (excluding 1964-1965)	Screened, Class A	1.13
	1962-1973 (9) (excluding 1963-1965)	Sunken, Unscreened, Kenya	1.05

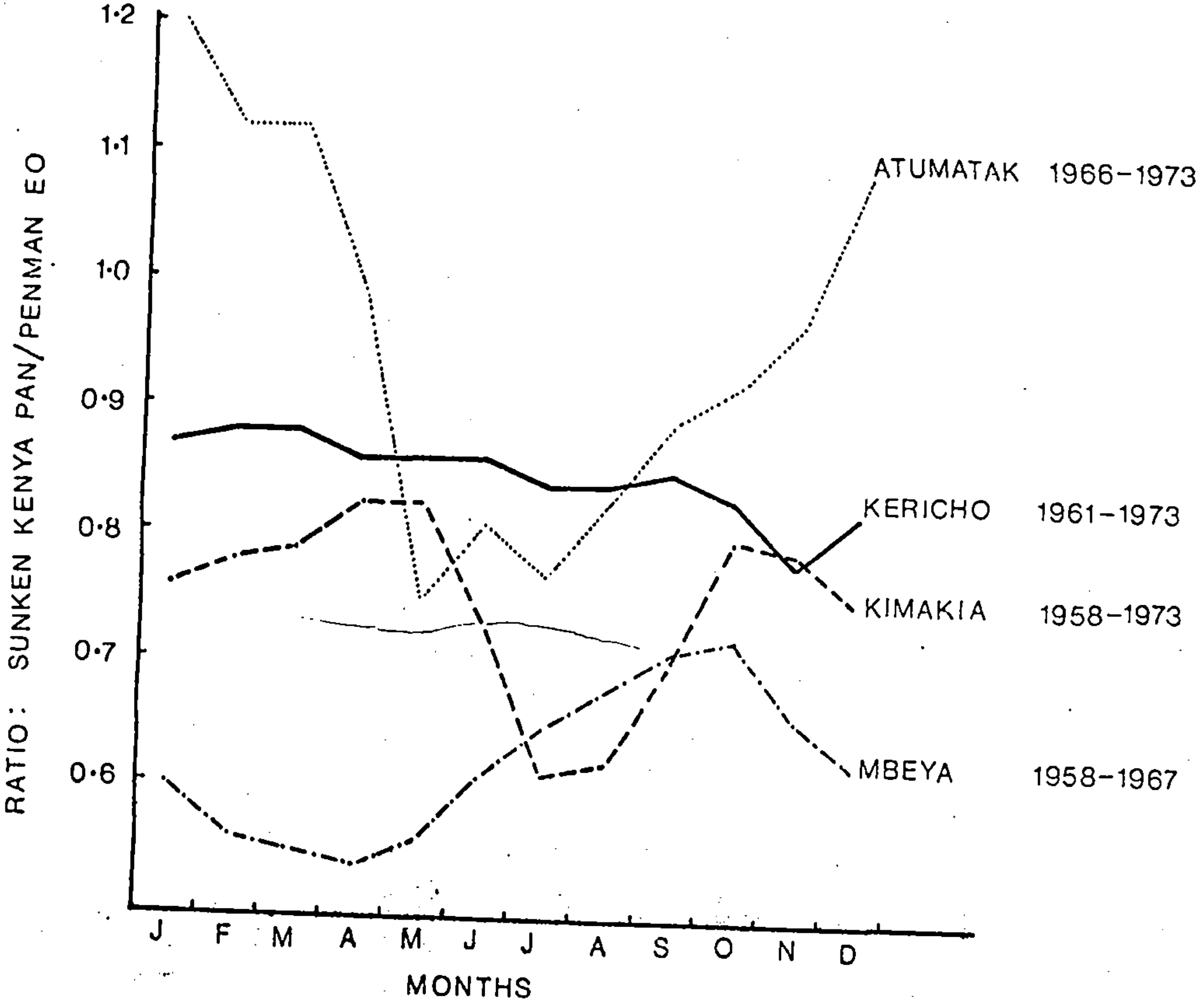


Figure 3 Monthly ratios of sunken pan evaporation to Penman EO

pan factors. Some features of the annual cycles deserve comment. Atumatak, clearly, experiences strong advection for the six months November to April. From May to August, the sunken pan/EO ratios are of the same order as those of the other stations. Mbeya also has a pronounced seasonal pattern, with low values following the rains and advection becoming more important as the soil moisture is depleted. Kericho, on the other hand, exhibits only a slight seasonal pattern, with a suggestion that some advection is present for much of the year but notably in January, February and March. Kimakia has very low values in July and August, when mist and low cloud persist for much of the day at this altitude on the eastern slopes of the Aberdares. It is possible that condensation on the surface of the evaporation pans is a measurable quantity during this period and depresses the evaporation totals.

Whatever the physical explanation for the seasonal fluctuations, the above cases illustrate the unique character of each evaporation pan site. Clearly, each evaporation pan record must be carefully scrutinized and, if possible, compared with an independent evaporation index. Even then, it would be impossible to extrapolate to other sites without a knowledge of the energy balance of the sites in question; under these circumstances, it would be preferable to extend that knowledge to a consideration of the actual evaporation from the sites rather than rely on the evaporation pan records.

USE OF EVAPORATION PAN DATA TO ESTIMATE EO

Figs 4 and 5 show the monthly pan evaporation totals plotted against Penman EO. Apart from the Atumatak pans, which reflect the conditions of high advection mentioned previously, and the sunken Kenya type pan at Mbeya, there is a surprising similarity in the distribution from all the other pans; this consistency of the monthly pan data allows them to be used to fill gaps in meteorological records at a given site, bearing in mind that the relationship between daily pan data and daily potential evaporation will be much more variable. As a means

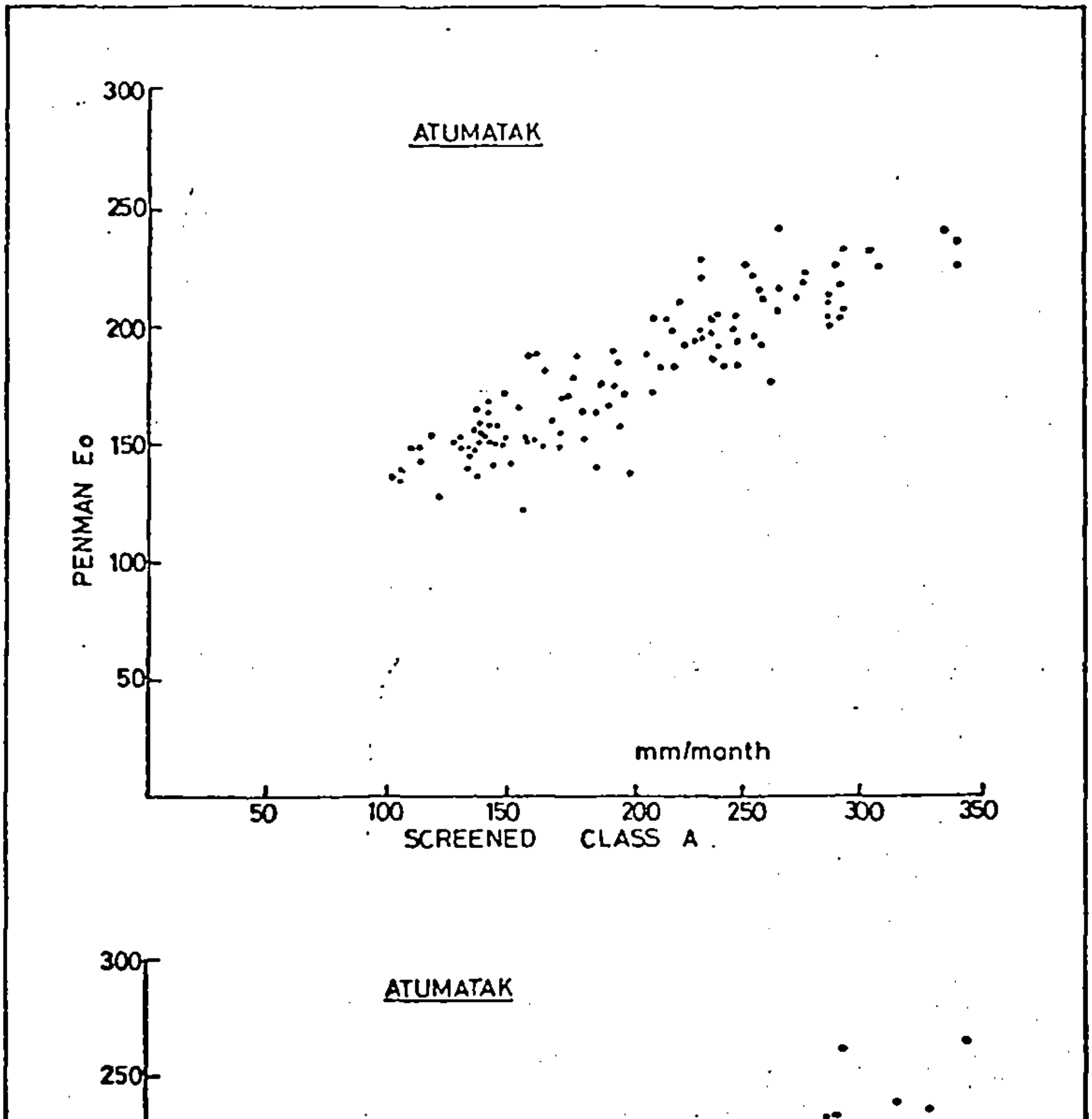


Figure 4 Monthly pan evaporation totals against Penman EO

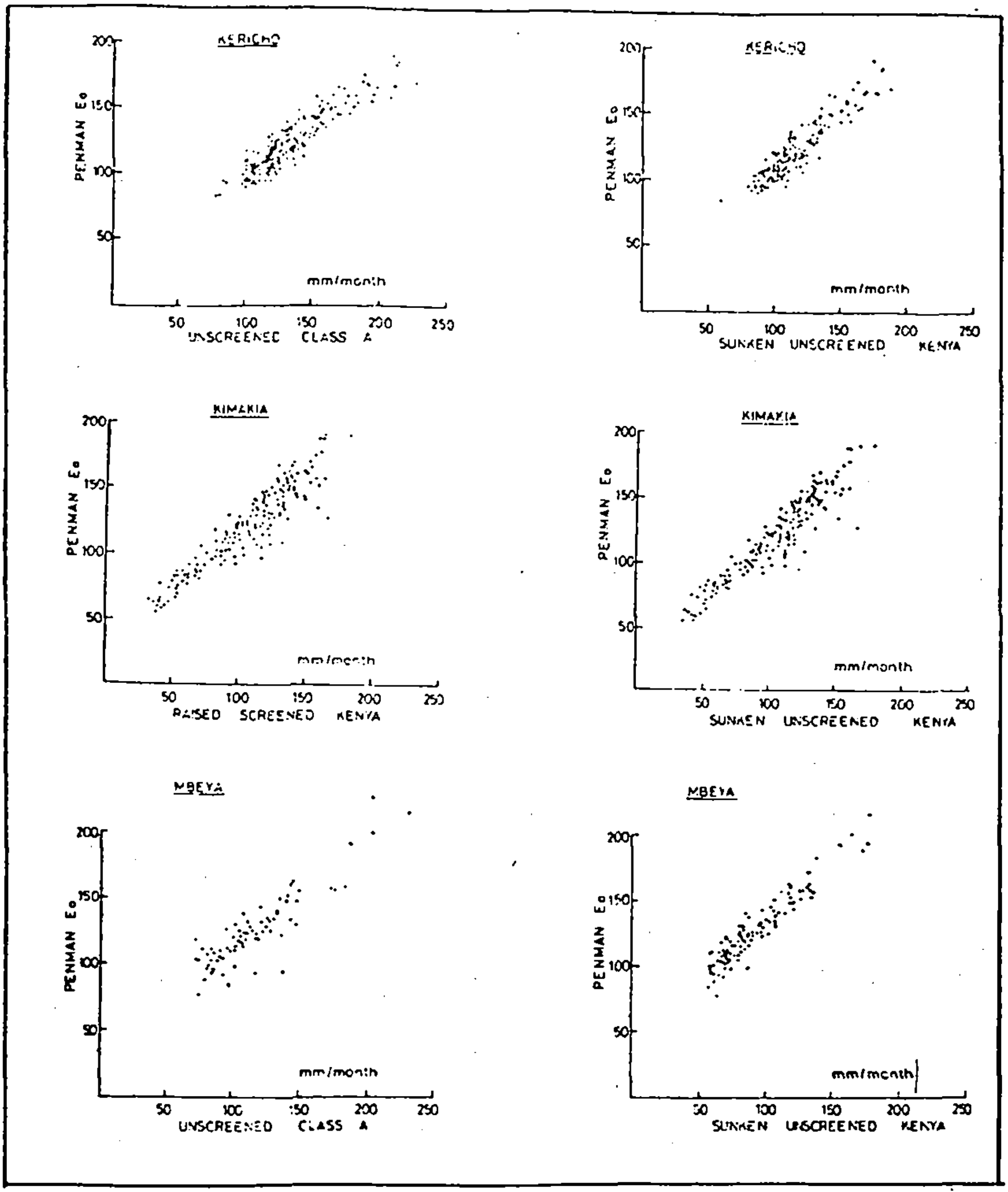


Figure 5 Monthly pan evaporation totals against Penman EO

of interpolating between stations however, the use of pan data requires considerable care and may be misleading due to the variable influence of advective heat energy. In addition, it has been pointed out previously (Dagg, 1970) that the evaporation pans in the East African catchments appear to bear a different relationship to lake evaporation than in more temperate climates; for illustration, if the assertion is adopted (WMO, op cit) that lake evaporation is 0.7 times Class A pan evaporation, then the questionable conclusion follows that the Penman formula greatly overestimates open water evaporation (see Table II). Although factors such as screening of the pan, use of the Kenya-type pan (Kimakia), excessive shelter (Mbeya) and the retention of the orginal aerodynamic term in the Penman formula all contribute to inflating the ratios in Table II, it can be see that the wide variation in performance of the evaporation pans at different geographical locations precludes the use of pan data to extrapolate between meteorological stations.

Using the only available data on lake evaporation from East Africa (WMO, 1974), Table III shows a comparison of estimated evaporation from Lake Victoria and EO from Kericho. The estimate labelled 'Mass Transfer' was calculated from several stations using a Dalton equation of the form:-

$$E_D = a\ (b + \frac{u}{100})\ (e_s - e_a)$$

where u is run of wind; e_s is saturation vapour pressure at lake surface temperature; e_a is vapour pressure at 2 m; and a, b are empirical constants.

Although it is not suggested that the Penman estimates for Kericho bear any special relationship to evaporation from Lake Victoria, the close agreement between the values in Table III support the use of EO rather than 0.70 x PAN evaporation for estimating losses from large open water surfaces.

TABLE II

Comparison of Penman's EO with Published Estimates of Lake Evaporation Derived from Evaporation Pan Data

Station	(i) 0.70xClass A	(ii) Penman EO	Ratio,(ii)/(i)
Kericho (unscreened)	1129	1474	1.31
Kimakia (unscreened, Kenya)	994	1459	1.46 7
Mbeya (unscreened)	977	1492	1.53
Atumatak (screened)	1715	2173	1.27

TABLE III

Comparison of Alternative Estimates of Evaporation (mm) from Lake Victoria

	Normal Year*	1969	1970
Water Balance	1473	1602	1399
Mass Transfer	1481	1526	1442
Penman EO (Kericho)	1474**	1506	1434

* Averaged for five stations using 19 to 34 years of data (see WMO op cit page 469)

** Average value 1958 to 1972

CONCLUSION

The evaporation pan data from the EAAFRO experimental catchments has been examined and found to be variable in quality. If doubtful records are discarded, however, remarkable consistency between different types of pans in different locations is observed. Even at Atumatak, where advected heat energy is likely to contribute greatly to the net radiation, thereby producing an 'oasis' effect, the two pans at this site give mutually consistent results for the years when the data record is complete. Nevertheless, seasonal differences in the ratios of Penman evaporation to pan evaporation are apparent, and would make the task of deriving a universal pan factor extremely difficult.

In addition, the observed values of pan evaporation in the experimental catchments are lower than can be expected from comparable results obtained in more temperate latitudes.

The consistency of the results from the experimental catchments, however, and the high proportion of variance accounted for by a linear regression of pan evaporation on Penman EO estimates, confirms that good pan data can be used to fill gaps in records.

REFERENCES

DAGG, M, 1970. Factors affecting the use of evaporation pan data in East Africa. E Afr agric for J 35 (2), 203-210.

DAGG, M, WOODHEAD, T, and RIJKS, D A, 1970. Evaporation in East Africa, Bull IASH, 15(1), 61-67.

McCULLOCH, J S G, 1961. Evaporation pans in East and Central Africa. Inter Afr Conf on Hydrology, CCTA, Nairobi, 159-162.

McCULLOCH, J S G, 1965. Tables for the rapid computation of the Penman estimate of evaporation. E Afr agric for J 30 (3), 286-295.

PEREIRA, H C, 1959. Practical field instruments for estimation of radiation and of evaporation. Q J roy Met Soc 85, 253-261.

RIJKS, D A, OWEN, W G, and HANNA, L W, 1970. Potential evaporation in Uganda. Min Mineral and Water Resources, Uganda Government, Entebbe, 41.

WOODHEAD, T, 1968a. Studies of potential evaporation in Kenya. Min of Natural Resources, Kenya Government, Nairobi, 69.

WOODHEAD, T, 1968b. Studies of potential evaporation in Tanzania, Min of Lands, Settlement and Water Development. Tanzania Government, Dar es Salaam, 60.

WOODHEAD, T, 1969. A classification of East African rangeland. II. J Appl Ecol. 6.

World Meteorological Organisation, 1966. Measurement and estimation of evaporation and evapotranspiration. Tech Note No 83, 121.

World Meteorological Organisation, 1974. Hydrometeorological survey of the catchments of Lakes Victoria, Kyoga and Albert. Vol I, Part I, RAF 66-025 Technical Report 1, Geneva, 509.

APPENDIX 7.1.4

DATA PREPARATION AND PROCESSING

J R Blackie and S M Cooper
Institute of Hydrology, Wallingford, UK

Appendix 7.1.4

DATA PREPARATION AND PROCESSING

J R Blackie and S M Cooper
Institute of Hydrology, Wallingford, UK

INTRODUCTION

The volume of data collected from the four series of catchment studies in East Africa presented a formidable task in computation and checking to bring it to the processed stage where analysis could begin. Initially, this work was undertaken by a team of dedicated observers using desk calculators; from 1968 onwards it became possible to mount the data in computer compatible form and carry out much of the routine calculation and checking automatically. Even then, however, a high level of manual inspection and intervention was necessary to ensure consistently good quality of processed data. The aim initially was to process the data to produce 10 day totals of streamflow, of catchment mean rainfall and of Penman EO together with monthly estimates of soil moisture. When computer-aided processing became possible, the basic time unit was changed to 1 day, and the first 11 years of data were re-processed accordingly. For some specialist purposes, 3 hourly catchment rainfall was produced, together with hourly values of streamflow. In this appendix the philosophy underlying the checking and processing systems used is outlined and its application to streamflow, rainfall and Penman EO described.

GENERAL APPROACH

In experiments which rely on collecting data of consistently high quality over a decade or more, it is essential to establish field routines of instrument checking, of observation and of data recording which will continue despite changes in observer and in management. The observers were fully trained in such routines, and were aware of the necessity to report any departure from them. Given this basis of consistent observation, the data were then subjected to standardised forms of inspection and arithmetical cross-checking at each

catchments, manual abstraction and conversion was replaced with automatic chart reading and computer processing to give the hourly flows. Similar cross-checks against staff gauge readings and inspection for discontinuities were applied. For both types of recorder regular checks on the instrument, the float well inlet and the structure were an integral part of the observer's routine.

A further check was made for discontinuities in the hourly-processed data using the time distribution of rainfall as a guide; these data were then summed to give daily flow.

Intercomparison of the processed data with rainfall and flow in adjacent catchments was used to check for systematic error. This led to the detection of seepage under a structure at Kimakia, and work in that catchment was subsequently discontinued (Dagg and Blackie, 1965). It also revealed a systematic error in the weir calibration on one Mbeya catchment (Section 5.2.1) and an apparent trend in flow at Kimakia which was subsequently found to be caused by subsidence of the concrete plinth carrying the reference level (Section 3.2.1).

RAINFALL

Each raingauge was checked regularly for leakage, for any distortion of the funnel and for any change in exposure. In addition, the calibration of each autographic gauge was checked monthly and the accuracy of the clock noted. Transcriptions of readings from observer's notebook to monthly record sheet were cross-checked by the senior observer. Any large differences between gauges in the network were investigated immediately and the findings noted for subsequent action. Long term double mass plotting was employed to evaluate each raingauge record.

Both Thiessen polygon and the arithmetic mean methods of estimating catchment rainfall were applied. Since not all gauges in the network could be read simultaneously, the time

distribution of the total recorded over several days was calculated from the time distribution obtained from the nearest autographic gauge. For the 3 hourly catchment rainfall a similar processing programme using the autographic records was used. Missing records of a few days duration were infilled using the double mass plot relationships prior to computing catchment means. For longer gaps the gauge in question was omitted and the Thiessen areas changed accordingly.

Comparison of the processed catchment rainfall with streamflow and with the records from adjacent sites was a standard procedure. Additional checks for systematic error due to network design on exposure change were carried out by the computation of catchment means from different combinations of gauges. The results of applying these techniques are discussed in Section 1.2.1 and in the water balance papers.

EVAPORATION

The meteorological data required to compute Penman EO were obtained from manually read meteorological sites. The observations were daily distillation from a Gunn Bellani radiometer, daily windrun from a cup counter anemometer, daily sunshine hours read from Campbell Stokes sunshine recorder cards, twice daily wet and dry bulb temperatures and maximum and minimum temperatures. Standard methods of checking all of these instruments and recording the findings were prescribed as were methods of cross-checking the readings obtained.

Manual processing comprised the calculation of 10 day mean values of air temperature, dew point, solar radiation, fractional sunshine hours and windrun. The McCulloch (1965) tables were then used to calculate 10 day mean EO from these inputs. From 1968 onwards, computer programs were used to check the daily readings and to calculate daily EO from them. These programs were also applied retrospectively to the first 11 years of data.

The processed EO data were subjected to close scrutiny using intercomparison with evaporation pans on the sites and with EO from other sites to detect any trends or differences in magnitude indicative of systematic error. Where positive indications were present, similar techniques were applied to each input to the Penman calculation. Details are given in Sections 2.2.1, 3.2.1 and 5.2.1 of systematic errors in radiation and windrun detected by these techniques and of the corrective action taken.

REFERENCES

DAGG, M, and BLACKIE, J R, 1965. Studies of the effects of changes in land use on the hydrological cycle in East Africa by means of experimental catchment areas. IAHS Bull, 10, 63-75.

McCULLOCH, J S G, 1965. Tables for the rapid computation of the Penman estimate of evaporation. E Afr agric for J, XXX, 286-296.

PLINSTON, D T, and HILL, A, 1974. A system for the quality control and processing of streamflow, rainfall and evaporation data. Institute of Hydrology Report No 15, Wallingford, UK, 159.

APPENDIX 7.1.5

OPERATIONAL EXPERIENCE WITH NEUTRON MOISTURE METER EQUIPMENT IN KENYA

H M Gunston and C W O Eeles
Institute of Hydrology, Wallingford, UK

APPENDIX 7.1.5

OPERATIONAL EXPERIENCE WITH NEUTRON MOISTURE METER EQUIPMENT IN KENYA

H M Gunston and C W O Eeles
Institute of Hydrology, Wallingford, UK

In the hydrological study of catchment areas it is essential to attempt accurate measurement of changes in soil moisture storage. When the Kericho and Kimakia catchment studies were set up in the late 1950s, routine gravimetric soil moisture sampling programmes were started; disturbed soil samples were taken with a 102 mm (4 inch) Jarrett auger, and the volumetric moisture content was calculated using 'standard' dry bulk density figures taken at the start of the studies using a large volume core sampler (Dagg and Hosegood, 1962). The procedure was simple enough to be readily followed by resident catchment staff, and the deep, stone-free soil made sampling easy. However, the accuracy of estimated soil moisture contents was not high, and in 1968, neutron soil moisture meters came into use in the catchment studies (and other soil moisture studies based at Muguga). Soil moisture could then be measured at a greater number of sites within each catchment and estimates were free of complications caused by the cumulative destructive sampling of the gravimetric method; they were therefore likely to be of greater precision.

THE NEUTRON SCATTER METHOD FOR SOIL MOISTURE MEASUREMENT

Neutron moisture meters have now been widely used for some time, so no more than an outline is required of the principle of their operation. For soil moisture measurement, the meter comprises a probe which is lowered into a lined access hole in the soil by means of a cable; the access tube is usually of aluminium with 4-5 cm internal diameter and with length up to 6 metres; once it is installed, soil moisture is read by lowering the neutron meter probe down the access tube to predetermined depths. The soil is therefore not disturbed further once the access tube has been installed. The neutron meter probe contains a source of fast (high energy) neutrons

and a gas filled detector tube which is sensitive to slow (low energy) neutrons. In colliding with other particles in the soil, the fast neutrons lose most energy from their interaction with hydrogen nucleii, most of which are bound in water molecules; these interactions form a 'cloud' of slow neutrons around the source, with cloud density a function of the hydrogen content and thus indirectly of the water content in the soil surrounding the source. The detector, a gas proportional counter tube, produces electrical pulses at a rate dependent on cloud density, and these pulses pass up the cable to the scaler or ratemeter.

To calibrate the neutron meter in the field, an access hole was cut near (but not too near; ∿ 3 m) the site selected for study, and this hole was lined with aluminium tubing. Duplicate readings were then taken with the meter at 0.3 m depth intervals in the temporary access tube, and two or more profiles of volumetric core samples were taken within 0.3 to 0.5 m of the temporary tube, using the soil core sampling technique described below. Moisture volume fraction values for each depth were then calculated from the core samples and plotted against neutron meter count rates from the same depth in the soil. By repeating this process for various sites at periods when the soil was at different moisture contents, a calibration curve was produced for each particular combination of site, depth and meter. In practice, many curves were found to lie so closely together that a single curve could be produced for a range of soil depths within one catchment or even for two or three catchments. In routine operation, the appropriate calibration curve was used to convert the field neutron soil moisture readings into moisture volume fraction values for each access tube soil profile.

EQUIPMENT

Two types of moisture meter were used; the 'EAL' type, and the 'Wallingford' type which has superceded it. Both were developed by the Institute of Hydrology in collaboration with

manufacturers, and field experience with prototypes led to improvements in design in later production models.

The earlier EAL type consisted of a short probe containing a 50 mCi Americium Beryllium (fast) neutron source encapsulated in an annular ring which fitted round a boron trifluoride gas (slow) neutron counting tube of sensitive length 9 cm. This probe geometry was shown by field and laboratory calibrations to produce a linear response to moisture over the range of interest. The short sensitive half length provided an interface resolution comparable to that of a scintillator, which was the closest approximation obtained to a point detector (Bell and McCulloch, 1969). A coaxial cable supported the probe and carried both the output signal from the BF_3 tube and the 2.5 kv supply necessary to operate it. The probe itself was carried in a polyproylene transport shield.

The scaler unit was mounted in a modified ammunition box, and consisted of an electronic clock and circuitry for amplifying and counting signals from the BF_3 tube, together with a 12 v power pack of rechargable DEAC cells from which the various supply voltages, including the 2.5 kv to operate the gas tube, were generated.

The 'Wallingford' meter consisted of a longer probe (1 m) which contained the Am-Be source of 50 mCi and detector tube (with sensitive length 13 cm) together with the amplifier and other circuits necessary to produce and shape suitable output pulses for counting. The support cable carried only the 12 v supply voltage, and both the EHT voltage and output pulses were generated in the probe itself. These pulses were passed up the support cable either into a simple rate-meter or a rate-scaler which integrated the counts over a pre-set period and produced a digital display of the mean count rate. The 'Wallingford' probe was carried in a tubular frame which incorporates a polypropylene safety shield as well as a depth counter. In later models, the ratemeter or ratescaler was mounted in the lid.

ACCESS TUBE INSTALLATION

It is desirable that the access hole used for neutron meter sampling should be as small as possible. The probe diameters of both types of meter used were 38 mm (1.5 inches) and it is common in Britain to use 44 mm (1.75 inches) external diameter aluminium alloy tube of wall thickness 1.6 mm (0.064 inches), this material being nearly 'transparent' to neutrons, as well as convenient to handle. However, as 44 mm (1.75 inches) od alloy tubing is not easily available in East Africa, the nearest equivalent was used: this was 51 mm (2 inches) od aluminium alloy irrigation pipe, obtainable in lengths of 6.1 m (20 feet). The slightly larger air gap round the probes is important, but as all neutron meters were recalibrated on arrival at Muguga, this was only a minor difficulty. On both types of meter, the polypropylene safety shields were bored originally to fit into 44 mm (1.75 inches) od tube, but the extra boring necessary to make them clear 51 mm (2 inches) tube was easily carried out by a local engineering firm.
As the soils encountered on the catchments were virtually stone-free and very friable, a 51 mm (2 inches) Jarrett auger was used to open the access holes into which the tubes were installed. Every possible care was taken over the installation of each access tube, as cavities within the soil immediately adjacent to a tube can bias neutron meter readings; a special tripod frame was used to make sure that the start and first metre or so of the cut was truly vertical, and particular care was taken to prevent the shaft of the auger 'belling out' the top of the hole. This particular method was felt to be quite satisfactory for the deep red loams. The access tubes were sealed at the bottom and simple pressed aluminium caps, stamped with the code number of the site, were used to close the top of the tube.

SOIL SAMPLING FOR CALIBRATION

To take volumetric core samples for calibration, a hole was first opened up roughly 0.3 m to 0.5 m from the temporary access tube with the 51 mm Jarrett auger. When the depth of

the hole was about 28 cm the auger was carefully removed and the sampler lowered into the hole on the end of its shaft. The sampler consisted of a cylindrical steel body within which were two 51 mm (2 inches) od aluminium alloy rings. The body was screwed into a strong tubular shaft and driven into the ground by means of an annular hammer, the principle being similar to the use of a post-driving hammer. By measurement and 'feel' the sampler was driven until the flange came into contact with the soil surface. The sampler was then removed, the bottom section of the body unscrewed, and the aluminium rings carefully slid out.

Using a broad spatula, a cut was made between the rings and the bottom of the lower ring, which contained the final sample, was also trimmed off square with the spatula. The soil of this ring was then transferred to an air-tight tin, whilst the contents of the upper ring, which included loose soil from the auger cuts and sides of the hole, were rejected. The sampler body and rings were then thoroughly cleaned whilst another 30 cm cut was taken with the 51 mm Jarrett auger and the sampling process was then repeated. In the deep red loams at Kericho, this technique was used successfully down to 6 m.

Two sample profiles were taken at each site, and fresh weighings carried out within 24 hours of sampling. As mentioned earlier, care was taken that temporary access tubes for sampling were not installed too close to the access hole sites selected for long-term reading. Due to the freely draining nature of the soils concerned, 3 m was felt to be far enough away, but in poorly draining soils it would be advisable to install temporary access tubes at an even greater distance.

OPERATIONAL EXPERIENCE

Five members of the catchment research team based in Muguga were trained in the use of the meters, and two people usually

undertook each field trip. Kimakia, some 110 kilometres from Muguga, required a one-day trip, but the Kericho catchments (260 kilometres) required two days. Two EAL-type meters were used from the start of the routine readings, as use of a single meter would have proved impossible during periods when both sites were recorded at 10-day intervals.

It is difficult to assess the reliability of the meters in any entirely quantitative way, but very few sets of monthly readings were lost completely. However, there were at least three periods of a week to ten days each when both senior members of staff attached to the project spent all their time in meter servicing to the detriment of other essential work. The newer 'Wallingford' meter introduced in February 1970 behaved well after an early period of minor but annoying troubles in the field, and was better able than its predecessors to stand the inevitable punishment of travelling over rough roads. Subsequent versions of the 'Wallingford' meter have incorporated further improvements, and it can now be regarded as a very reliable field instrument.

FIELD USE OF NEUTRON METERS

In field use, operating routines were well established and consistently followed by probe users. At first, all readings taken in the soil were expressed as a ratio to the count taken in the transport shield; it was then found that the temperature of the shield could affect the count-rate significantly, but that a count taken in a drum of water was independent of water temperature. This count was also important as a check on any changes in the electronic components with time. Before and after a series of readings, ten water counts were made at the centre of a drum of water some 60 cm in radius and 122 cm in depth. These were then averaged to obtain a denominator for the count ratios of the observations.

When approaching the access tube, care was taken to prevent damage to the surface vegetation and soil structure. With the

ease of taking repeat readings, this simple precaution was essential to prevent sites from ceasing to represent the surrounding area.

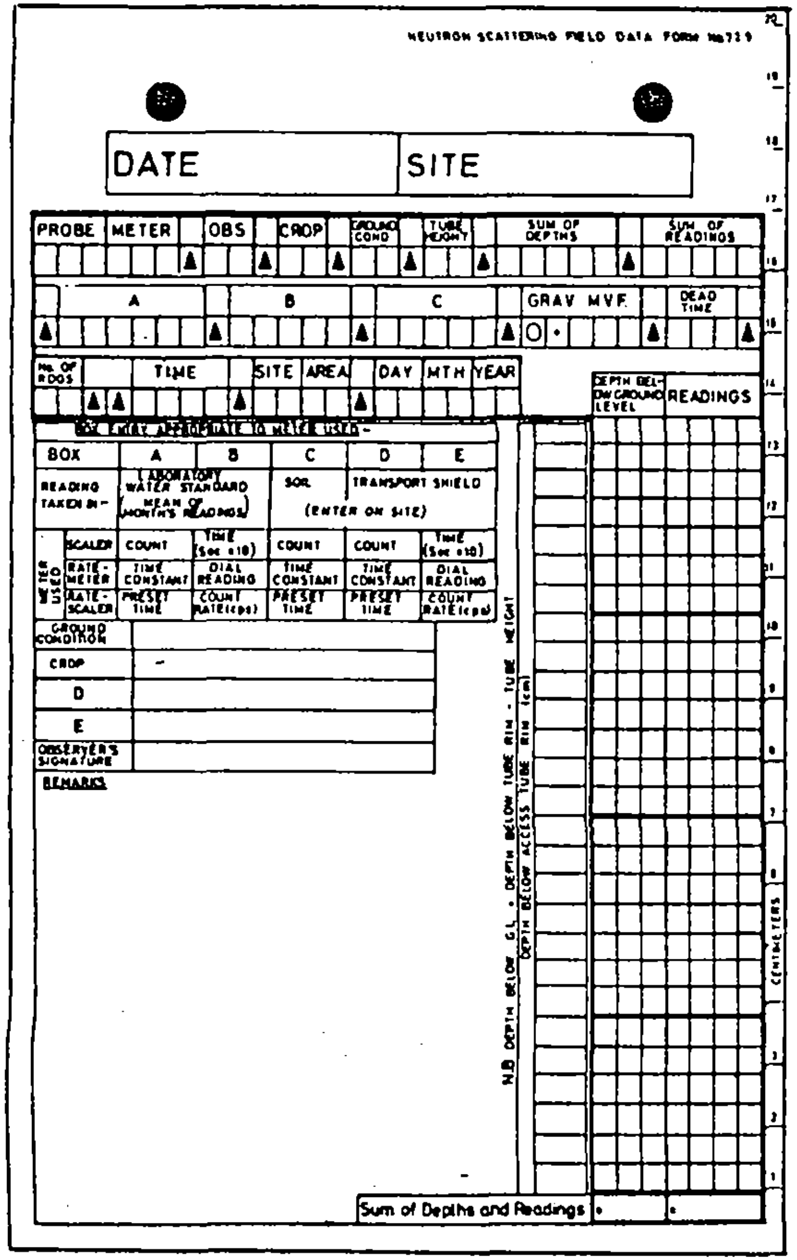
The field use of the 'Wallingford' system was less tiring than other types of equipment as the shield lock, lowering mechanism and ratescaler are all at waist level. The first reading taken was one with the probe locked in the shield to check that the equipment operated within the statistical limits set by the source radio-active decay process. The radius of the zone of influence in water is approximately 17 cm according to Ølgaard (1965), and it was therefore decided to take readings at less than twice this interval so that zones overlapped. In the earlier programme of gravimetric soil sampling, samples had been taken at 30 cm intervals, and this was continued with the neutron readings.

Readings and site data were entered on field sheets as shown in Figure 1. The sheets were then coded and the data were directly transferred to punched cards for computer processing. This processing was carried out initially at the Institute; later, the program was modified to run on the University of Nairobi computer.

RADIOLOGICAL SAFETY

Although only of low strength, the radio-active neutron sources used in the moisture meters are potentially dangerous and certain simple safety rules should be followed. International recommendations for radiological safety have been drawn up, but although a background knowledge of this subject is essential before working with neutron moisture meters, the necessity for these regulations to cover the many and varied uses of radio-isotopes makes them appear very complicated. In practice, a simple set of rules relating to the particular moisture meters used has been found sufficient.

These include locking the probe within its polypropylene safety



NEUTRON SCATTERING FIELD DATA FORM No.719

DATE
SITE

PROBE	METER	OBS	CROP	GROUND COND	TUBE HEIGHT	SUM OF DEPTHS	SUM OF READINGS
A	B	C	GRAV MVF	DEAD TIME			
No. OF RDGS	TIME	SITE	AREA	DAY	MTH	YEAR	

BOX ENTRY APPROPRIATE TO METER USED -

BOX		A	B	C	D	E
READING TAKEN IN -		LABORATORY WATER STANDARD (MEAN OF MONTH'S READINGS)		SOIL	TRANSPORT SHIELD (ENTER ON SITE)	
METER USED	SCALER	COUNT	TIME (Sec ×10)	COUNT	COUNT	TIME (Sec ×10)
	RATE-METER	TIME CONSTANT	DIAL READING	TIME CONSTANT	TIME CONSTANT	DIAL READING
	RATE-SCALER	PRESET TIME	COUNT RATE (cps)	PRESET TIME	PRESET TIME	COUNT RATE (cps)

GROUND CONDITION
CROP
D
E
OBSERVER'S SIGNATURE

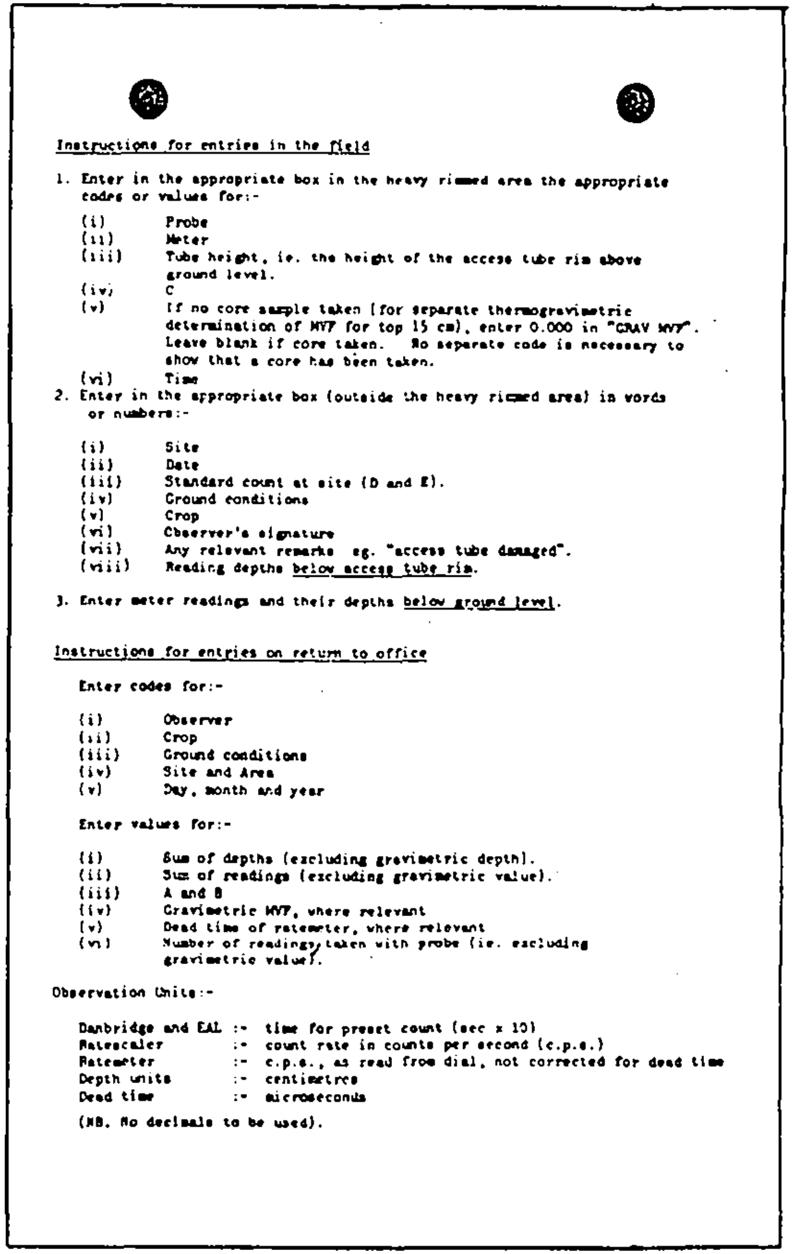
REMARKS

N.B. DEPTH BELOW G.L. = DEPTH BELOW TUBE RIM - TUBE HEIGHT

DEPTH BELOW ACCESS TUBE RIM (cm)

DEPTH BELOW GROUND LEVEL | READINGS

Sum of Depths and Readings



Instructions for entries in the field

1. Enter in the appropriate box in the heavy rimmed area the appropriate codes or values for:-
   - (i) Probe
   - (ii) Meter
   - (iii) Tube height, ie. the height of the access tube rim above ground level.
   - (iv) C
   - (v) If no core sample taken (for separate thermogravimetric determination of MVF for top 15 cm), enter 0.000 in "GRAV MVF". Leave blank if core taken. No separate code is necessary to show that a core has been taken.
   - (vi) Time
2. Enter in the appropriate box (outside the heavy rimmed area) in words or numbers:-
   - (i) Site
   - (ii) Date
   - (iii) Standard count at site (D and E).
   - (iv) Ground conditions
   - (v) Crop
   - (vi) Observer's signature
   - (vii) Any relevant remarks eg. "access tube damaged".
   - (viii) Reading depths below access tube rim.
3. Enter meter readings and their depths below ground level.

Instructions for entries on return to office

Enter codes for:-

- (i) Observer
- (ii) Crop
- (iii) Ground conditions
- (iv) Site and Area
- (v) Day, month and year

Enter values for:-

- (i) Sum of depths (excluding gravimetric depth).
- (ii) Sum of readings (excluding gravimetric value).
- (iii) A and B
- (iv) Gravimetric MVF, where relevant
- (v) Dead time of ratemeter, where relevant
- (vi) Number of readings taken with probe (ie. excluding gravimetric value).

Observation Units:-

Danbridge and EAL	:- time for preset count (sec x 10)
Ratescaler	:- count rate in counts per second (c.p.s.)
Ratemeter	:- c.p.s., as read from dial, not corrected for dead time
Depth units	:- centimetres
Dead time	:- microseconds

(NB. No decimals to be used).

Figure 1 Neutron moisture meter field data card

shield when in transit, locking the equipment when not in use in a store at base or in a vehicle when on safari, and ensuring that the probe is never handled directly in the area of the source; indeed, that the source is never handled at all.

As neutrons lose most energy in interactions with hydrogen nucleii, polypropylene which is rich in hydrogen is used as a shielding material. Since the shields are tubular, the ends of the tube are unprotected and unskilled staff must be prevented from carrying the equipment in such a way as to expose themselves or others to radio-activity from the source.

It was not possible to use radiation detector film badges in East Africa, but experience in the United Kingdom of radiation limits expected at certain distances from sources, and of times of exposure, suggested that the risk to staff was minimal and that the lack of monitoring devices was not critical.

CURRENT NEUTRON PROBE PRACTICE

For a current review of the practical application of British Radiological Safety regulations, the reader is referred to 'Neutron Probe Practice' by J P Bell (IH Report No 19, 1976 Edition) which also gives details of recent developments in neutron probe design and operational techniques which have been adopted at the Institute of Hydrology.

APPENDIX 7.1.6

NOTES ON ACCESS TO HYDROLOGICAL DATA FROM THE EAAFRO CATCHMENTS

S M Cooper
Institute of Hydrology, Wallingford, UK

Appendix 7.1.6

NOTES OF ACCESS TO HYDROLOGICAL DATA FROM THE EAAFRO CATCHMENTS

S M Cooper
Institute of Hydrology, Wallingford, UK

INTRODUCTION

The main bulk of the data from the catchment experiments described in this journal has been published separately (Edwards et al, 1976). This summary contains daily values of streamflow, rainfall, potential evaporation and selected meteorological variables for the catchments at Kericho, Kimakia, Mbeya and Atumatak. There are details of the formats of computerised data stored on magnetic tapes and information about the instrument networks in the catchments and the methods of collection of data.

Data from the catchments are stored either at EAAFRO Kenya, or at the Institute of Hydrology, UK (IH). This paper is intended as a guide to their availability and the forms in which they exist; this may range from field data sheets to magnetic tapes.

STREAMFLOW

Stage in the Kimakia, Kericho and Mbeya catchments was recorded on charts from Lea Rotary water level recorders from 1958 to mid-1970. Values of flow in inches x 10^{-5} over the catchment were extracted from these charts at hourly intervals by means of templates and summarised on a ten-day basis. The hourly values have also been punched on computer cards, two cards per day in monthly batches. These constitute the 'raw' data for computer processing. The processed streamflow results are hourly values of flow in mm over the catchment stored on magnetic tapes. Computer printouts are available giving summaries of daily and monthly values.

The Lea recorder charts and ten-day summaries are held at EAAFRO. Raw and processed computer data are at both EAAFRO and IH.

Charts produced by the Leupold and Stevens A35 recorders installed at Kimakia and Kericho in 1970 were sent direct to IH for stage abstraction using a pencil follower. The computer processing progressed in the same way as for earlier data.

Atumatak flumes had Ott C43 water level recorders. The flows there are normally zero with sharp peaks after storms. Values of streamflow have therefore been manually abstracted in inches x 10^{-5} over the catchment at half-hourly intervals. These are held at EAAFRO.

RAINFALL

Rainfall was measured by daily gauges read at 0900 hours and recording gauges (Dines tilting-syphon recorders with daily or weekly charts). These charts are held at EAAFRO as are their hourly (Mbeya and Atumatak) or three-hourly (Kericho and Kimakia) abstracted values on weekly sheets and the daily rainfall figures on monthly summary sheets.

Both types of rainfall information have been punched in monthly batches on computer cards. Values are in inches for the early years; latterly they have been in millimetres. The cards themselves are held at EAAFRO but IH has copies of the raw rainfall data stored on magnetic tapes.

The processed data, stored on magnetic tapes at IH and EAAFRO consist of hourly or three-hourly rainfall in mm over the catchment.

METEOROLOGICAL AND EVAPORATION DATA

The following measurements are recorded daily.

> maximum, minimum, wet and dry bulb temperature, run of wind, sunshine hours and distillation measured by Gunn Bellani radiometers.

calculated and plotted. The resultant computer printouts are also held at IH.

Readings were originally taken at roughly ten-day intervals and latterly at monthly intervals. Two profiles were sampled from each of three different places in each catchment. Usually twelve samples were taken down the profile.

(iii) Neutron probe readings were taken at Kericho and Kimakia from 1967 to 1974.

Again, readings were initially taken at ten-day intervals and latterly at monthly intervals. The data were transferred to punched cards and processed in accordance with the IH neutron data processing system (Roberts, 1972). The data are stored on magnetic tape at IH.

More detailed and frequent soil moisture measurements were obtained from the experiment on Water Use of a Tea Estate from Soil Moisture Measurements (see Section 2.2.3). Neutron probe readings were taken almost daily for a period of 19 months. This information was also punched and processed under the IH system and is stored there. Daily tensiometer readings were also taken at the same sites, and these are stored in raw and processed form at IH.

ACCESS TO DATA

The above data are available to users at either IH or EAAFRO and requests to use the data should be sent to the respective Directors.

REFERENCES

EDWARDS, K A, BLACKIE, J R, COOPER, S M, ROBERTS, G, and WAWERU, E S, 1976. Summary of hydrological data from the EAAFRO experimental catchments. E A Community (CPS) Printer, Nairobi, 283.

ROBERTS, G, 1972. The processing of soil moisture data, IH Report 18, 86.

Natural
Environment
Research
Council