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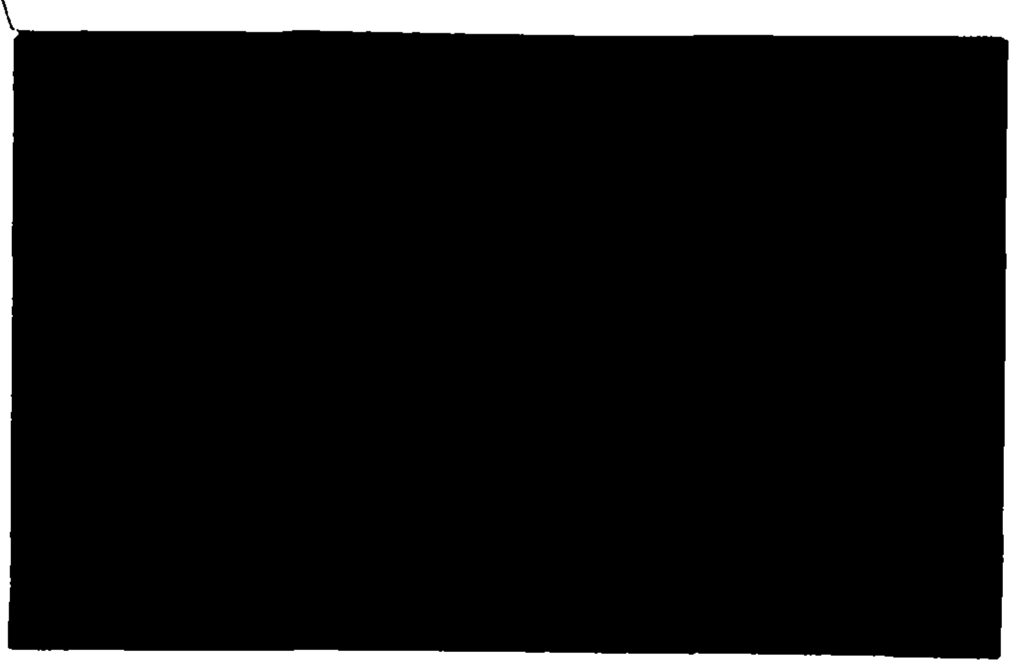

FINAL REPORT
ON THE
EAST AFRICAN CATCHMENT
RESEARCH PROJECT

(ODM R2582)

VOLUME I

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PREFACE

EXPERIMENTAL METHODS

by

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FINAL REPORT ON THE EAST AFRICAN CATCHMENT RESEARCH PROJECT (ODM R2582)

by

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PREFACE

PREFACE

Research Scheme R2582 was initiated to assist the East African Agricultural and Forestry Research Organisation in bringing to a successful conclusion the catchment experiments begun by Dr H C (Sir Charles) Pereira in 1956 and continued by the Physics Division of EAAFRO with the help of Partner States of the East African Community.

Technical assistance was first provided by a joint programme of research between EAAFRO and the UK Institute of Hydrology (then the Hydrological Research Unit). J R Blackie, H M Gunston and M H Rawlings were seconded to EAAFRO through the Overseas Development Administration and other members of IH staff also assisted in the programme for short periods. During this time, 1967 to 1971, the task of re-processing the data from the experimental catchments was begun and additional instrumentation was introduced. Prior to J R Blackie's return to the UK in 1971, a scheme for completion of these studies was formulated and submitted by EAAFRO to ODA. This scheme was implemented as R2582. Under its terms, K A Edwards, C W O Eeles and M H Rawlings were seconded to EAAFRO from 1972 and back-up was provided by IH in the form of specialist staff, instrumentation, computer facilities and technical advice as and when required. A Hill, J D Cooper, J L Hill, B A Callander, S M Cooper and G Roberts joined the project for short periods to complete specific experimental or data processing tasks. E S Waweru, a member of the original Physics Division team, continued to give invaluable assistance in supervising all the junior staff both at EAAFRO and in the catchments.

The following report is the final scientific report on the project, a summary of hydrological data having been published elsewhere. It covers the whole period of operation of the experimental catchments, 1958 to 1974, up to the time of the transfer to Kenya Government, Ministry of Water Development, of the Kimakia and Kericho catchments.

The preliminary sections deal with experimental and analytical methods and they are followed by individual sections on each of the four catchment experiments. To give as complete a picture as possible, outside contributions have been included from authors who have been associated with the project or similar work in East Africa. The report concludes with general comments on the results of the catchment experiments and recommendations for continuing research.

It is impossible to acknowledge all the advice and assistance, both direct and indirect, which has been given since the inception of the experiments. An attempt has been made, however, to acknowledge the more recent assistance received during the course of this research.

A major contribution in editing and compiling this report has come from R T Clarke of the Institute of Hydrology, Wallingford. The authors wish to express their gratitude to him for acting as a catalyst and counsellor, thereby ensuring that the report reached completion in spite of the problems which still remain in interpretation of the experimental data.

With the breaking up of the East African Community, EAAFRO has now become the Agricultural Research Department of the Kenya Agricultural Research Institute. The affiliation of some authors and references to EAAFRO in the text have not been changed.

1.1

CATCHMENT RESEARCH AS A MEANS OF ASSESSING THE EFFECTS OF LAND USE CHANGE

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INTRODUCTION

During the planning of the EAAFRO experiments, designed to assess the hydrological effects of changes in land use, it was apparent that the 'classical' method of controlled watershed experiment, such as the Wagon Wheel Gap experiments (Bates, 1911; Bates and Henry, 1928), required an experimental period of such length that the questions originally posed may have become irrelevant before such experiments were completed. Decisions were already being taken on the future development of many areas in East Africa and it remained for the scientists to monitor the effects of these land management policies, to conduct controlled experiments in certain critical areas to assess the effects of land use change, and to produce considered judgements on future policy which had a bearing on water availability and water conservation.

It was thought that experimental methods in hydrology had progressed far enough for shorter term experiments to have a good chance of measuring the effects of land use change without the lengthy calibration periods or multiple management trials that had been previously advocated for statistically valid results (Wicht, 1966). In short, it was considered that the major components of the hydrological cycle could be measured with sufficient accuracy for individual water balances, calculated for different types of catchment, to be compared. In this way, not only could the measurements be checked for internal consistency, but indirect assessments could be made of the evaporative loss from each catchment which is one of the most difficult components of the water balance to measure directly.

Accordingly, catchment studies (Pereira et al, 1962) were begun in four areas of East Africa. It was recognised that at least ten years of records would be needed to allow for a calibration period during which the catchments could be checked for major leaks, for a transition period when the land use was changed, and for a post-transition period when the new vegetation grew to maturity. In fact, the experiments were conducted over the period 1958 to 1974; in the later years, sophisticated equipment was available which gave more detailed measurements than were possible when the studies began. It was also apparent by 1969 that the multitude of measurements collected since the start of the experiments needed some form of computer processing, not only to facilitate mathematical modelling, but also to permit quality control checks to be made and to ensure rapid access to the data for routine analysis. With the change to computer processing, the ten-day analysis, which had been used to simplify the handling of catchment data, was no longer necessary and a one-day time period was used. Although the new system is more flexible, processing the data has revealed many errors which took much time to correct; it has also resulted, in some cases, in revision of previously-published data, and these corrections are discussed in later sections.

Inevitably, as the responsibility for conducting the experiments has passed on to new workers, the methods of analysis have changed also. For this reason, this introductory section sets out the basic theoretical approach to using the water balance equation including a justification for the method of paired catchment experiments. It also gives details of how later experimental work developed and how the use of conceptual catchment models allows recent theoretical concepts to be included in the interpretation of the experimental results.

THE CATCHMENT APPROACH

In recent years, this method of using paired catchments for land use experiments has been criticised heavily on the ground of cost effectiveness and the lack of precision in the results obtained (Slivitsky and Hendler, 1964; Ackerman, 1966; Reynolds and Leyton, 1967). Without doubt, it is costly both in time and money to instrument such catchments and secure measurements of good quality; on the other hand, costs can be evaluated only by comparing them with the costs of alternative methods of securing the required information (Hewlett et al, 1969) and the costs of subsequent development which relies on such data to establish suitable engineering designs.

As a means of obtaining quantitative data on the consequences of land use policy, no satisfactory alternative exists to conducting catchment experiments. As the above authors put it, ".... if we wish to manage watersheds, we shall have to study watersheds" (Hewlett et al, 1969). This statement reflects the fact that, in spite of rapid progress in micrometeorology and soil physics, a micro-scale examination of the physical processes in the hydrological cycle often leads to severe problems in extrapolating to the scale on which water resources planning decisions have to be made. One of the most recent theoretical approaches to estimating regional evaporation (Thom and Oliver, 1977) calls upon experimental verification from catchment experiments to justify the assumptions implicit in adopting physically-sound methods to heterogeneous vegetation surfaces on irregular landforms. This, in itself, demonstrates the need for careful water balance measurements from natural catchments.

Catchment research, therefore, involves large scale environmental experiments in which many complex physical processes are integrated. Although these experiments are designed primarily for the solution of practical agricultural problems, much basic knowledge of the hydrological cycle has stemmed from them. In the case of the EAAFRO experiments, the effects of particular interest caused by the land use modifications are changes in the water use of the catchments (ie the combined losses from transpiration and evaporation), changes in total volume of streamflow and its seasonal distribution, and changes in stormflow and its associated pattern of sediment yield.

When, as in the case of the experiments at Kimakia and Kericho, the land use change is from indigenous forest to another deep-rooting evergreen vegetation, it can be anticipated that the effects on the hydrological cycle will be small. Nevertheless, verification of such an expected result is as important as the measurement of the effects of more devastating land-use changes. For either purpose, the accuracy of the basic hydrological measurements must be high, and considerable emphasis has therefore been placed on precision and error in measurements in the following sections. First, however, the framework is examined within which the components of the hydrological cycle are equated and methods are described whereby systematic errors in the data can be detected.

THE WATER BALANCE

The general expression describing the water balance of a water-tight catchment over a given period is:

$$R = Q + AE + \Delta S + \Delta G \qquad (1)$$

where R,Q are precipitation and streamflow;
AE is actual evapotranspiration; and
ΔS, ΔG are changes in soil moisture and groundwater respectively.

Where no bias is present in any of the measured terms, this expression can be used to determine the value of any one term, by difference, over the stated period; for example, the term normally required to be evaluated is AE, which is given by (1) as:

$$\hat{AE} = R - Q - \Delta S - \Delta G + \varepsilon \qquad (2)$$

where $\hat{AE}$ is the true or expected value; where measured values of R, Q, ΔS and ΔG have been substituted in the right-hand side, and where ε is the random error in its determination. Whilst this expression can be used to determine $\hat{AE}$ over any time interval, the error will be dependent on the precision of the instruments, the efficiency of the sampling networks relative to this time interval, and the extent to which ΔS and ΔG can be measured.

THE WATER YEAR

The paired catchment approach calls for a comparison of values of AE over time intervals short enough to give reasonable precision so that departure trends as well as differences can be detected. In deciding on an appropriate time interval for any particular study, consideration must be given to a number of factors; these include the duration of the experiment, the time required for the new land-use to stabilise, the number of components of the water balance being measured, the precision of the measurements and the variation of this precision with interval length.

In general, the precision of any estimate of areal rainfall improves with the length of time-interval (ΔT) over which raingauge readings are accumulated. Similarly, the proportional error in streamflow will decrease with increasing ΔT, where water level recorders operate on accurately-rated structures. The precision of the soil moisture storage change, however, is not dependent on time interval but, for any given sampling network and method, on the spatial variability existing within the catchment at the sampling times. For a catchment with uniform soil type, soil depth and vegetation cover, the precision of an areal estimate of storage will normally be greatest in the dry season. At this time the estimate is not complicated by (a) the quantities of water which pass through the soil profile in shorter times than that required by the field observers to move from one soil moisture sampling site to another within the catchment, or (b) by the possibility of rain occurring between readings at different sites. For similar reasons the precision of the groundwater storage change, whether obtained from well-level readings or from using the recession curve as a storage-discharge relationship, is not dependent on the length of the time interval but is likely to be greatest between dry season sampling times.

The implication of these comments on the precision of individual terms within the water balance expression is that, where all four terms are measured, relatively long time intervals starting and ending in dry conditions will give the most precise estimates of AE. From this emerges the concept of a 'water year' - a time interval of approximately one year running from a dry season to the following equivalent dry season, as a period over which consecutive precise estimates of water use can be made for comparative purposes.

In the previous Special Issue (Pereira et al, 1962), it was not anticipated that ΔG could be measured or estimated by the means available at that time. Since then, Blackie (1972) and others have used a composite recession curve to calculate groundwater storage changes. Combined with more accurate estimates of soil moisture deficits from the neutron probe, it is now possible to minimise storage errors by selecting water years between sampling dates in the dry season.

The choice of water year, therefore, is of considerable importance. For a prescribed duration of experiment, the best choice will minimise the error in each determination of AE and, hence, give greatest precision to the description of any trend found to be present in water use.

THE USE OF THE WATER BALANCE TO DETECT BIAS

To derive accurate estimates of AE from the water balance as described above, it is necessary to detect and eliminate systematic errors or bias in the measurements of the right hand terms in Equation (2).

A detailed scrutiny of the data together with intercomparisons between catchments is generally sufficient to detect any systematic errors which have developed during the period of measurement. When such errors are present throughout the data run, however, other methods are required.

One such method which can be used to detect major systematic errors in the individual terms of the water balance of catchments, where soil moisture deficit is not a limiting factor in transpiration, is based on the assumption that annual AE totals bears a reasonably constant relationship to the annual Penman estimate of open water evaporation, EO. In the high rainfall tropical regions this assumption is valid, and if AE can be shown to be strongly correlated with R or Q, there is a suggestion that systematic errors are present in the water balance.

This method can be of considerable value in detecting 'leaks' in a supposedly water-tight catchment. The most frequently encountered example of this is when subsurface flow around a gauging structure causes an apparent overestimate of AE which is positively correlated with both rainfall and streamflow. At the same time, such a relationship does not necessarily point to a leaking catchment since errors in the storage terms (ΔS and ΔG) can also produce a strong positive correlation of AE with R as will be seen in Section 5.2.1. If it is suspected that a catchment is not watertight, all available information, particularly deep soil moisture measurements and alternative estimates of actual evaporation, must be used to determine the cause of the trend of AE with R and, if necessary, additional experimental work should be undertaken to confirm the postulated explanation.

The absence of any trends of AE with the terms of the balance, on the other hand, is strong evidence that any systematic errors present are small, although the possibility of compensating errors cannot be completely excluded.

THE WATER BALANCE OVER SHORT PERIODS

Use of the water balance expression to determine total water use, AE, over a water year and the conditions under which the AE/EO ratio can be expected to remain constant in successive water years have been discussed above. A criticism of earlier analytical work on the EAAFRO catchment data concerned the assumption made then that this ratio remained constant even over short periods throughout the water year. The work of Monteith and others, referred to in Section 1.2.2, however, has demonstrated that AE is a function of the aerodynamic resistances of the vegetation canopies and the stomatal resistances of the leaves in addition to the net radiation input and that an analysis of evaporative losses based on an energy balance approach alone can give misleading results.

Provided certain basic conditions are satisfied, experimental determinations of short-term water use can be made using soil moisture and rainfall measurements over suitable chosen periods. One condition is that after wetting, the profile drains rapidly to a 'field capacity' moisture content after which downward moisture movement is negligible in comparison with the rate of extraction by the root system. The second condition is that there should be no contact between the root system and the water table. Over the period chosen, the profile moisture content must remain below field capacity. The water balance expression then reduces to

$$AE = R - \Delta S$$

if surface runoff is insignificant, and the accuracy of AE is determined principally by the soil moisture sampling technique.

From the descriptions of the soil types and depths, rooting depth and water table behaviour in the Kericho, Kimakia and Mbeya catchments given in Pereira et al (1962), it is reasonable to assume that the above conditions are met in these catchments. Further evidence in support of this assumption comes from the soil moisture vertical flux studies described in Section 2.2.3.

In the sections dealing with the water balance and soil moisture sampling on Kericho, Kimakia and Mbeya, dry season water use figures derived in this way are quoted. Whilst the precision of these figures is low compared with those derived from the water year, they give some indication of the seasonal range experienced in each catchment. Of particular interest are periods in which no rain falls; from these, estimates of the rate of transpiration only, and of its variation with deficit, can be obtained. In the case of the Kericho catchments they are also compared with short-period figures from lysimeter studies, from soil moisture vertical flux measurements, from theoretical considerations and from the application of the eddy correlation techniques described in Section 2.2.2.

EXTRAPOLATION OF THE EXPERIMENTAL RESULTS

The discussion so far has centred on the continuity or water balance approach to the analysis of catchment data. It has been argued that this approach can be used both to check the consistency of the data and to check the magnitude and variability of differences in hydrological response between paired catchments. In considering how the results from such studies can be used to forecast the future response from the same catchments or to predict the response of catchments in other areas, however, the limitations of the water balance approach become apparent.

Water balance studies do not provide an insight into the reasons for any significant changes in the hydrological cycle and cannot form a basis, therefore, for extrapolating outside the environmental conditions encountered in the experimental catchments. To extrapolate the recorded results, a better understanding is needed of the physical processes and of their interactions.

At this point the relationship between conceptual modelling and physical process studies may be utilised. A conceptual model based as closely as possible on known physical processes can be fitted to the catchment data. The fitting procedure will give valuable indications as to which processes are most critical in determining catchment response and, hence, where further investigation of the physical processes will be most beneficial. The study of key processes leads to a greater understanding of why the land use modification has produced the measured change in response. In turn, this allows the development of an improved conceptual model which will reflect the behaviour of experimental catchments more closely.

Ideally, this interactive procedure should produce a model which is physically realistic and in which a minimum number of parameters has to be evaluated by optimisation. By fitting the model to data from different catchments, an operational tool becomes available for forecasting flow from either real or synthetic inputs to these catchments.

The procedure of modifying a basically empirical model in the light of a clearer understanding of the physical behaviour of the system, fitting the model to a set of data by optimisation and testing the model prior to further modification, although laborious and time consuming, does offer a logical means of combining the physical insight obtained from process studies with the quantitative information on the catchment scale obtained from the water balance studies.

Models so developed may also provide a basis for assessing the effects of applying the same form of land use change to other catchments. In this case, great caution should be exercised and every attempt should be made to determine quantitatively as many of the model parameters as possible in the new catchment. While it is accepted that complex physical processes cannot always be adequately represented by the manipulation of one or two model parameters, it is equally true that our knowledge of the mechanism of these processes and their interaction is imperfect and does not yet allow a rigorous theoretical approach to the problems of land use change. In the present state of development of the science of hydrology therefore, this semi-empirical approach offers a method of combining available knowledge in a way which allows catchment response to be predicted from known inputs when a prescribed land use is imposed.

APPLICATION TO THE EAST AFRICAN CATCHMENTS

When the four series of catchment studies were initiated by EAAFRO in the later 1950s, the instrument networks on each catchment were designed to provide accurate long-term measurements of rainfall and streamflow, estimates of potential evaporation and estimates of soil moisture storage changes which were as precise as possible within the instrumental, manpower and financial constraints of the time.

The analysis of the data as described in the previous Special Issue (Pereira et al, 1962) followed basically the lines of the water balance approach described above. In addition, a manually-computed 10-day model was used to predict soil moisture deficit and, by comparison with measured deficits, to optimise parameters describing actual evaporation and the groundwater recharge. Detailed investigations were made of the surface runoff response to different rainfall intensities and also of sediment yield from some of the catchments.

From 1961 to 1968, shortages of staff and a lack of funds limited the amount of research into the physical processes of the hydrological cycle. Emphasis was placed on maintaining a flow of good quality catchment data, in so far as this was possible with the resources available. It is a tribute to the foresight of Dr H C Pereira, Dr J S G McCulloch and their colleagues that the instrument, observer and administrative networks they designed continued to operate successfully during this period. Through a joint programme of research between EAAFRO and the UK Institute of Hydrology from 1968 onwards and subsequently by means of Technical Assistance from HM Government in the form of a Research Project sponsored by the Overseas Development Ministry, it became possible to introduce more sophisticated instrumentation, to transfer the catchment data to magnetic tapes, to initiate mathematical modelling of the data and to introduce some additional process studies.

The cost, in terms of skilled manpower needed to install, maintain, calibrate and process the data from this more accurate instrumentation, was much higher than anticipated. Information was obtained, however, which allowed a number of retrospective corrections to be made to the streamflow and meteorological data from the long-term networks.

The assembly of over 130 catchment years of data on computer tape has been one of the major tasks achieved during the Research Project period. In addition to collation and punching of hourly and daily measurements, it involved the application of the quality control and processing programmes described elsewhere (Plinston and Hill, 1974) and the detailed examination of the raw data, using a range of techniques, to detect and remove systematic errors. The resulting processed data have been published elsewhere (Edwards, Blackie et al, 1976) in accordance with the recommendations of the International Hydrological Programme.

Studies of soil moisture movement and transpiration processes in tea were undertaken during the later period to clarify the pattern of water use emerging from the water balance study.

The final results of analyses performed on these data together with descriptions of the catchments and accounts of the process studies are presented in the following chapters. The differences in water use obtained from water balance calculations are assessed quantitatively in relation to the processes giving rise to them. Where results are conclusive, the implications for land management policy and water resources planning in the regions to which they can be applied are discussed. Inevitably, there are some results where doubts still exist. The reasons for these are discussed and recommendations are made for additional studies where these are relevant to future economic planning in East Africa.

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1.2.1

RAINFALL

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RAINFALL

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INTRODUCTION

Except for the high altitude areas of Mt Kenya, Mt Kilimanjaro, Mt Elgon and the Ruwenzori range, precipitation in East Africa is almost always rainfall. Solid precipitation, in the form of hail, does fall over large parts of the highlands, particularly in the Kericho area where it frequently causes damage to growing tea. For the most part, however, the input to the hydrological cycle is rainfall, and, where not otherwise specified in the text, 'input' is to be interpreted in this restricted sense. Only one other form of precipitation may be of any significance; this is the combined total of 'occult' precipitation and mist interception which leads to the phenomenon known as 'fog drip'. The question of the relative importance of this term in the water balance is discussed below.

Rainfall in East Africa is highly variable in time and space due to its convectional or orographic (forced convectional) origin. In contrast to temperate regions, where predominantly frontal rain often produces remarkably uniform spatial patterns in rainfall, dense networks of raingauges may be required if mean areal rainfall is to be estimated with adequate precision. Being the largest component of the hydrological cycle, the estimates of mean areal rainfall must be of an accuracy comparable with, or better than, the accuracy of other water balance components. This section deals with the problems of measuring rainfall at a point, network design and the subsequent calculation of mean areal rainfall in the EAAFRO experimental catchments.

MEASUREMENT OF RAINFALL AT A POINT

The standard raingauge used throughout East Africa during the course of the catchment experiments has been the 12.7 cm

(5 inch) diameter gauge. The Dines tilting-syphon, tropical-pattern recording gauge, accompanied by a standard gauge used to check its totals, has been used also for short-period measurements and rainfall intensity studies.

Exposure of the raingauges was determined by the nature of catchment vegetation. Where vegetation was short, raingauges were exposed on posts at various heights above the vegetation canopies to avoid interference by animals. It was considered that, with the low average wind speeds typical of these latitudes (Pereira et al, 1962), exposure of the gauge above ground or canopy level was not critical, especially as much of the rainfall occurs as heavy showers with large drop size. Appendix 7.1.2 discusses the results of an experiment at EAAFRO to determine the effect of raingauge exposure on catch; this confirmed that, under the conditions experienced in the experimental catchments, no gross errors were introduced by mounting gauges on posts. This result differs from that given by similar experiments in middle latitudes (see, for example, Green and Helliwell, 1974).

Within the forested catchments, several methods were used to estimate point rainfall. At a few sites, extending steel towers which could be raised to the height of the canopy were used. The high cost of these installations, however, ruled out their use at all sites. Where possible, suitable large trees had their topmost branches removed and platforms were constructed to support the raingauges at canopy level. From these collectors, rainfall was led through PVC tubing to storage devices secured at the base of the tree. Initial tests described in the previous Special Issue (Pereira et al, 1962) suggested that no significant losses were sustained by the use of these tubes; despite their regular inspection and cleaning, however, subsequent analysis of records from one of the catchments (Lagan at Kericho) revealed systematic differences between tree gauges and neighbouring gauges in clearings. Although the tree gauge records are frequently mutually consistent, it was concluded that they were subject to systematic errors during the period 1966 to 1970. Replacement of the corroded inverted funnels, which were used to prevent water running down the outside of the PVC tubing into the storage devices, resulted in a return to more consistent records from 1970 onwards.

Elsewhere in the forested catchments, gauges were mounted on posts within clearings. The size of the clearing was determined by preliminary trials (Pereira et al, 1962) which indicated that a screening angle of 45^0 (ie the angle of elevation at the top of the nearest object from the gauge) was adequate for all practical purposes.

During the early growth of plantation forest at Kimakia, pivoted masts of 'dexion' construction were used to maintain the raingauges level with the canopy of the growing trees (Pereira et al, 1962). As the trees *(Pinus patula)* grew higher, these temporary gauges, having fulfilled their purpose, were replaced by tower gauges.

ERRORS IN RAINFALL MEASUREMENT

Apart from the systematic errors due to exposure of the gauges mentioned above, other errors may occur which must be eliminated if rainfall records are to be reliable. It is essential to use trained observers, who, in addition to their tasks of measuring rainfall amounts, regularly inspect the raingauges and take the necessary preventive action to avoid erroneous readings. Although the raingauge is essentially a simple device, its records may be unreliable for the following reasons:-

(a) The raingauge orifice is not horizontal;

(b) The funnel is partially blocked causing loss of records during periods of intense rainfall;

(c) The rain collectors, or the tubes leading rainfall from a gauge to the storage device, may leak;

(d) The orifice rim is damaged, so that the area of the gauge is altered;

(e) The raingauge is being tampered with;

(f) The exposure of the raingauge has changed due to the growth of vegetation around the gauge; or

(g) Raingauges are not being read at or about the same time.

Careful inspection and maintenance will do much to eliminate such systematic errors, which may often be detected by double mass analysis of individual gauges against the catchment mean or against gauges of known reliability; this may reveal periods when certain gauges are unreliable, which can then be omitted from subsequent calculations of mean areal rainfall. If such checks can be made soon after the data have been collected, as a standard routine, it will be possible to detect faulty gauges quickly, and correct their performance.

NETWORK DESIGN

Assuming that the difficulties of measuring rainfall at a point in a catchment can be resolved, the network of raingauges must be so designed that estimates of mean areal rainfall are of adequate accuracy and precision. For catchment experiments, where small differences in annual water balance are to be compared, estimates of mean areal rainfall are usually required to be within 5% of the true mean.

For the EAAFRO catchments, a stratified random sampling procedure was used to site the raingauges (Pereira et al, 1962). Where rainfall was known to increase with altitude, stratification was by altitude. Where there was no obvious physical basis for the stratification, as for example in the Atumatak catchments, stratification was by proximity.

Within each stratum, gauges were located at random where possible, but in practice difficulty of access and maintenance prevented strict adherence to this principle. The ruling requirement in siting gauges in the catchment networks was that no personal bias was permitted in positioning the gauges. Preliminary estimates of the precision given by the networks were reported by McCulloch (1962); in some cases, the number of gauges was subsequently reduced where the standard error of estimate of the mean was sufficiently low to justify it.

To illustrate the efficiency of the catchment networks, Table I shows annual mean rainfall, its standard error and coefficient of variation. The precision of estimation decreases for shorter time intervals; estimates for single storms were given by McCulloch (1962).

In most cases, standard errors of means are of the order of 1 or 2% with the number of gauges given (only gauges which have complete records for the year have been used in this analysis). The network at Kimakia A was reduced in Nov 1967 from 10 gauges to 6; precision was affected only in 1971 when all but three gauges had incomplete records and the standard error of the mean of these three gauges exceeded 5%.

In the Atumatak catchments, the two networks were treated as one, since several gauges were common to both catchments in the calculation of mean areal rainfall. Because rainfall is erratic in this semi-arid area, it was expected that the standard errors would be large. Table II shows the same statistics as Table I for some arbitrary-selected days at Atumatak, together with the statistics for two monthly totals: February 1964, a dry month, and April 1965, a wet month. This table shows that, even at Atumatak, the standard errors are comparable with those from other catchments and still lie within the limits specified above. The dry month February 1964 gave the worst result, illustrating the irregular and erratic nature of rainfall in the dry season.

ESTIMATING MEAN AREAL RAINFALL

In the stratified random sampling procedure, the number of gauges within each stratum was taken, where possible, as

TABLE I

Annual Mean Areal Rainfall, its Standard Error, and Coefficient of Variation
(means are arithmetic means, units are mm, and figures in brackets are numbers of gauges)

Year	Kimakia C (bamboo)		Kimakia A (pine plantation)		Kimakia M (grass)		Sambret (tea plantation)		Lagan (Indigenous forest)		Mbeya (forest)		Mbeya (cultivated)	
	Mean	CV(%)	Mean	CV(%)	Mean	CV(%)	Mean	CV(%)	Mean	CV(%)	Mean	CV(%)	Mean	CV(%)
1959	1903±27	4.2(9)	1820±26	4.8(11)	-	-	1874±37	3.4(3)	1825±55	5.2(3)	1591±11	1.7(7)	1508±17	1.8(5)
1960	1983±15	2.3(9)	1857±18	3.2(11)	-	-	2295±25	1.9(3)	2458±62	4.4(3)	1820±20	2.7(7)	1653±21	2.8(6)
1961	3292±16	1.3(8)	3231±18	1.7(10)	-	-	2326±15	3.0(21)	2532±56	3.9(3)	1894±15	1.9(7)	1568±19	2.7(6)
1962	2443±21	2.4(8)	2366±10	1.4(10)	-	-	2516±14	2.6(21)	2482±41	2.9(3)	2361±21	2.1(7)	1981±50	6.7(6)
1963	2748±16	1.8(9)	2719±31	2.8(6)	-	-	2192±14	2.8(21)	2132±28	2.3(3)	1980±21	2.6(7)	1686±21	2.8(6)
1964	2585±19	2.1(8)	2486±19	1.8(6)	-	-	2092± 9	2.0(21)	1992±95	8.3(3)	1921±17	2.1(7)	1658±26	3.1(5)
1965	2332±22	2.9(9)	2161±33	3.0(4)	-	-	1582± 8	2.5(21)	1523±62	7.0(3)	1858±24	3.1(7)	1568±32	4.6(6)
1966	2326±25	2.6(6)	2248±44	2.0(6)	2240±22	3.5(9)	1535± 3	2.0(21)	1605±92	9.9(3)	1724±22	3.0(7)	1291±33	5.7(6)
1967	2178±22	3.0(9)	2033±18	2.1(6)	2165±22	3.0(9)	2211±10	2.1(21)	2159±28	2.3(3)	2218±11	1.2(7)	2070±31	3.3(6)
1968	2627±26	3.0(9)	2498±23	1.6(3)	2571±24	2.8(9)	2060±24	5.3(20)	2443± 9	0.7(3)	1991±14	1.8(7)	1739±32	4.1(6)
1969	1591±29	5.5(9)	1529±31	4.0(4)	1518±24	4.8(9)	1505±13	4.0(21)	1678±35	3.6(3)				
1970	2232±33	4.4(9)	2084±17	1.6(4)	2161±32	3.9(9)	2224±19	4.0(21)	2583±44	2.9(3)				
1971	1987±35	5.7(9)	1696±87	8.9(3)	1874±30	4.7(9)	2107±26	5.7(20)	2353±39	2.9(3)				
1972	2493±41	5.0(9)	2311±29	1.8(2)	2428±37	4.2(8)	2035±24	5.3(21)	2174±46	3.7(3)				
1973	1906±32	5.0(9)	1754±33	3.2(3)	1843±36	5.5(8)	1873±20	2.4(21)	2000±53	4.6(3)				
1974 (6 mths)	1324±37	7.8(8)	1194±13	2.2(4)	1285±22	4.7(8)	1060±21	3.4(21)	1066±35	5.6(3)				

TABLE II

Daily and Monthly Mean Areal Rainfall at Atumatak (mm)

Date	Arithmetic mean	Thiessen mean	CV(%)
22.6.62	37±0.3	36	3.6(19)
1.4.64	35±0.4	34	4.9(23)
13.4.65	30±0.3	29	4.4(23)
24.7.67	58±0.5	58	3.4(18)
February 1964	35±0.4	35	6.0(22)
April 1965	145±0.6	143	2.0(23)

proportional to the area of that stratum (Pereira et al, 1962). In theory, therefore, the arithmetic mean should be the best estimate of the true areal mean.

In practice, due to instrument failure over certain periods, a strict adherence to the above rule might have led to slight bias, and it became more satisfactory when the catchment data were reprocessed by computer to use the Thiessen polygon method of mean rainfall estimation. Since network densities were high, and good areal cover was achieved by the stratification, the arithmetic mean and the Thiessen polygon mean agreed very closely when all gauges functioned correctly, the percentage difference being less than the coefficient of variation shown in Table I (eg see Table II and Section 2.2.1).

The Thiessen method is more cumbersome to calculate than the arithmetic mean, since new gauge weights must be calculated whenever the network changes. Once weights are calculated, however, previously calculated means can be rapidly corrected if certain gauges are subsequently shown to be suspect. The adoption of the Thiessen estimate also allowed the use of the Institute of Hydrology's standard data processing programmes (Plinston and Hill, 1974) which simplified the task of handling the large quantity of hydrological data resulting from the experiments.

CHARACTERISTICS OF RAINFALL IN THE EXPERIMENTAL CATCHMENTS

The principal instrument in most rainfall networks is the daily gauge read at a set time each day by observers. Since rainfall records from the East African catchments were collected by a small number of observers on foot, it was impossible to read all gauges simultaneously and it became clear that errors in daily areal estimates might be introduced if storms occurred over the period during which gauges were read. Figure 1 shows the diurnal distribution of rainfall in each of the four sets of catchments; it can be seen that the set time of 0900 East African Standard Time coincides with the diurnal minimum. In the case of Kericho and Mbeya, it was desirable that readings

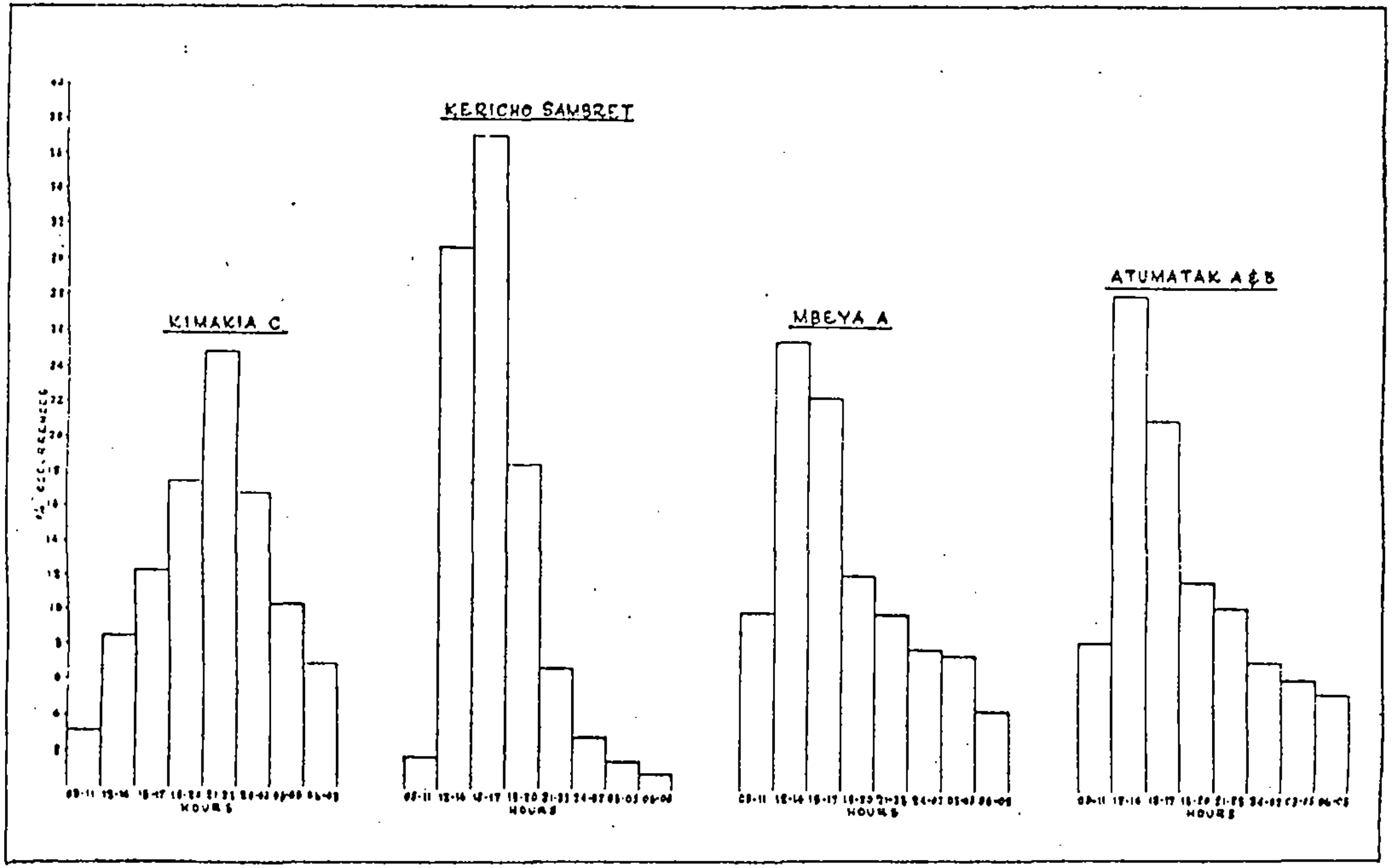

Figure 1 Diurnal rainfall distribution

should be completed by 0900, whilst at Kimakia it was preferable to start the collection round at 0900. On occasions, where storms have occurred during the collection round, corrections were made to the rainfall data to ensure that daily gauge readings were recorded on the same hydrological day as indicated by the recording gauge trace. This was accomplished by the rainfall processing programme which included a check during the quality control procedure to ensure that recording gauge and daily gauges agree within acceptable limits.

Figure 1 also brings out the difference between the pattern of rainfall at Kimakia compared with other areas. Whereas Kericho, Mbeya and Atumatak exhibit the classic instability pattern of cloud build-up in the early afternoon, Kimakia shows a pronounced rainfall maximum between 2100 and 2400 hours EAST; a pattern which varies only slightly through the year. This reflects the predominantly orographic character of rainfall in the Aberdares.

The seasonal distribution of rainfall in the four areas is generally consistent with the movement of the Inter-Tropical Convergence Zone across the Equator following changes in the Upper Air Circulation over the Indian Ocean (Findlater, 1971). In coastal East Africa and central Kenya, the bi-modal rainfall distribution can be described most simply in terms of the 'monsoonal' pattern of surface winds; since there is a close relationship between low level airflow in East Africa and the northern Indian Ocean, this simplification is not without physical foundation. Kimakia exhibits this bi-modal distribution most clearly (Figure 2) with the so-called 'long rains' in April-May and the 'short rains' in October-November. Further south, away from the Equator, Mbeya shows a bi-modal pattern with the two maxima compressed around the southern hemisphere summer solstice and separated by a long dry season during which the ITCZ moves north. Atumatak, on the other hand, lying north of the Equator, comes under the influence of ITCZ around the northern hemisphere summer solstice, and is

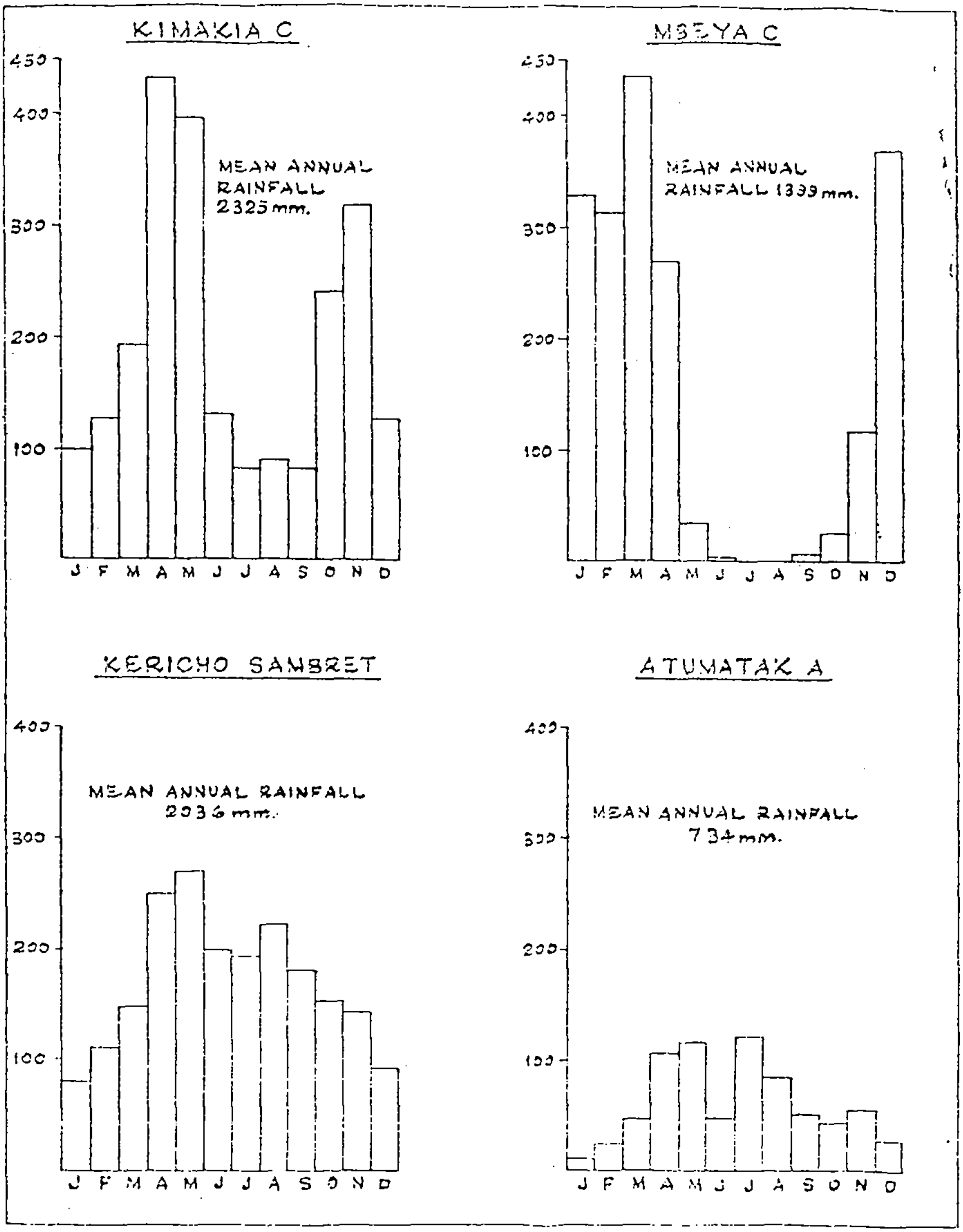

Figure 2 Seasonal rainfall distribution

altogether drier due to its lower altitude and longer overland fetch. Kericho, lying on the highlands to the east of Lake Victoria, is influenced by both the general easterly airstream and the lake itself. The seasonal distribution pattern is that of one long rainy season in contrast to the long and short rains pattern east of the Rift Valley (Kenworthy, 1964).

The contrast in rainfall distribution between the two Kenyan catchment areas was brought out further by the rainfall intensity diagrams published in the previous Special Issue (McCulloch, 1962). Kericho was found to have some 20% of all falls at intensities greater than 100 mm hr^{-1} whereas Kimakia had no falls of this intensity in the same period (1958-62). Very few storms were available for analysis from Atumatak at that time, and the pattern given from the quarter-hour rainfall intensities indicated that the frequency of storms in the class interval greater than 100 mm hr^{-1} was higher than at Mbeya and Kimakia but lower than at Kericho. Further analysis of the frequency of hourly falls of given amounts (Figure 3) shows that the above pattern disappears and that the Mbeya and Atumatak distributions are almost identical in shape, although different in the total number of hours of rainfall observed.

Exploiting the depth-duration-frequency analyses performed by the Transport and Road Research Laboratory in their East African representative catchment project (see Section 6.1.3) it is possible to examine these observed differences further. It is recognized that intensity and duration of a storm are not independent, and for a given recurrence interval, a curve of the following type relating depth (or intensity) and duration can be fitted (Fiddes, 1975):-

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

where I is intensity in mm hr^{-1};

T is duration in hours; and

a, b and n are constants.

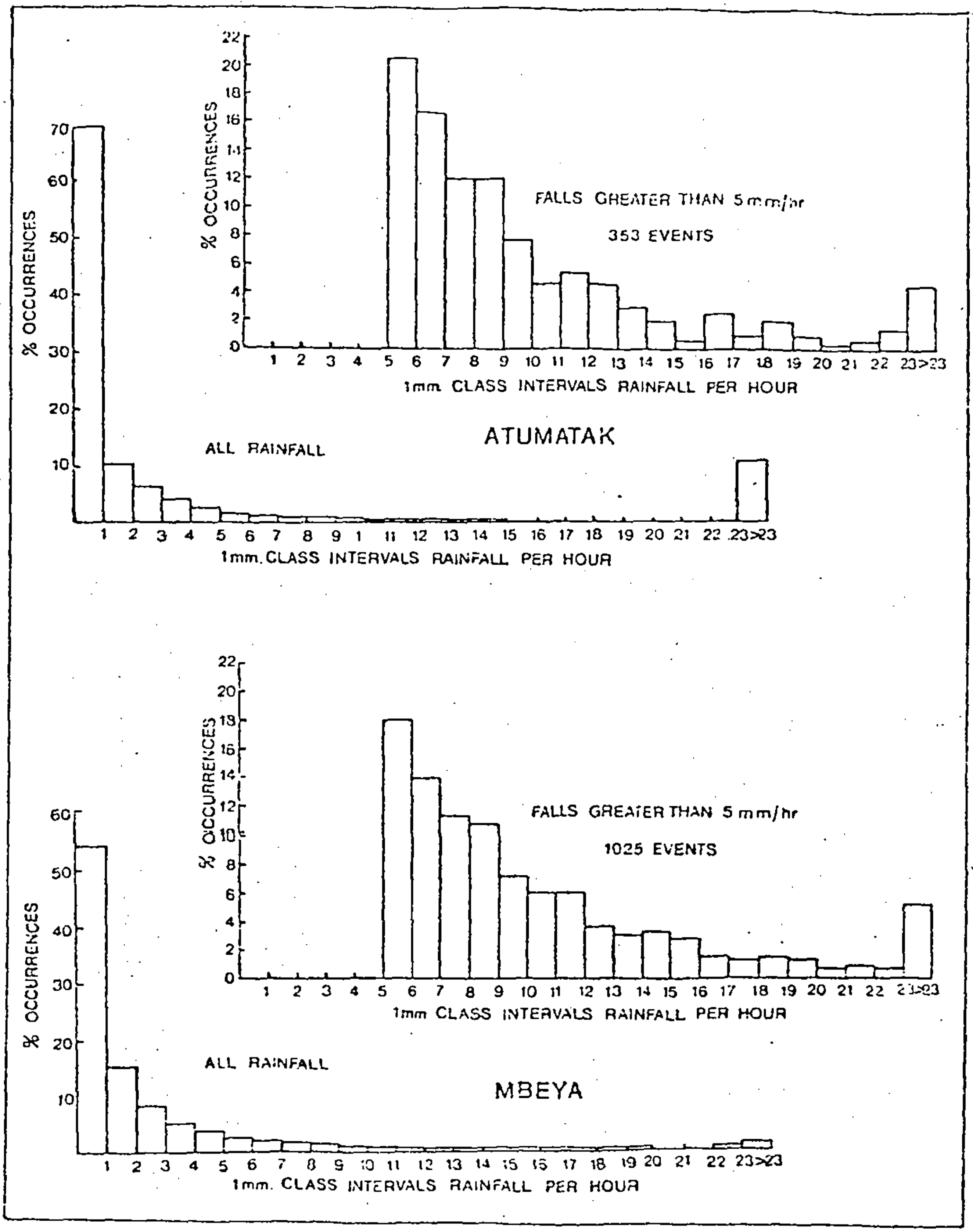

Figure 3 Frequency histograms of hourly rainfall intensities

If b is taken as 0.33 hrs, then a is the intensity of a 40 minute storm. When values of a and n were calculated for the East African catchments, significant regional differences were found as shown in Table III. With these values of a and n, the probable duration of a fall of 100 mm hr^{-1} intensity can be calculated, as shown in Table IV. It can be seen from this Table that both Atumatak and Kericho are likely to record falls of this intensity in any analysis of ten-minute events (Dagg, 1958) but, since such high intensities occur at Mbeya for a very short duration within any 10-minute period, mean intensities for such storms would be much lower. This accounts for the small number of events with intensities greater than 4 inch hr^{-1} given in Pereira et al (1962) for the Mbeya Range.

It may be concluded, therefore, that whereas the overall patterns of rainfall frequency west of the Rift Valley are similar, short period intensities can vary significantly. For further discussion on the regional variations in rainfall intensity, reference should be made to Section 6.1.2 and Jones (1975).

OCCULT PRECIPITATION AND MIST PRECIPITATION

Visual observation of stemflow and fog drip in many of the forested highlands of East Africa has led to speculation about the influence of forests on the water balance. Nicholson (1936), in particular, believed that forests increased net precipitation by up to 25% under favourable conditions both by condensing water vapour from the moisture-laden air (occult precipitation) and by acting as an efficient mechanical collector in physically capturing small water droplets (mist precipitation). Kerfoot (1968) has reviewed much of the international literature on this topic and has shown that while the weight of evidence certainly supports the view that forests do produce a net addition to precipitation when no rainfall would otherwise be recorded, instrumental difficulties have frequently marred the attempts to measure the magnitude of this effect. His own measurements (Kerfoot and McCulloch, 1962) were inconclusive, and no other experimental results are available from East Africa at the

TABLE III

Value of Constants in the Intensity-Duration Model (after Fiddes 1975)

Zone	Station	a	n
Inland	Atumatak	51.06	1.01
	Sambret	56.61	1.00
	Mbeya	42.20	0.97
Central	Kabete*	42.17	0.78

* The nearest station to Kimakia in the TRRL analysis

TABLE IV

Probable Duration of a Fall of 100 mm hr^{-1} Intensity
(Recurrence interval constant = 2 yr)

	T minutes
Atumatak	11
Kericho (Sambret)	14
Mbeya	5
Kabete	Less than 1 minute

present time. Hursh and Pereira (1953) have commented on the importance of preserving forest remnants in the Shimba Hills in coastal Kenya as a water conservation measure, but the argument is based on scanty field data and on indirect evidence such as the existence of forest species which normally are found in areas receiving 2000 mm of rainfall or more (ie areas receiving twice or three times the mean annual rainfall of the Shimba Hills).

In the EAAFRO catchment experiments, the area most likely to be affected by mist precipitation is Kimakia where low cloud persists over much of the months of July and August. During this period, normal precipitation is low, and if any addition to rainfall were evident, it should be most marked at this season. At Kimakia, three catchments are fully instrumented for rainfall, streamflow and soil moisture measurement; these are catchment 10, which is the control catchment under bamboo, Catchment 11 under pine plantation, and Catchment 17 (Makiama) under Kikuyu grass sheep pasture. If the contributions from occult precipitation and mist precipitation were significant, this could manifest itself either in greater runoff from the forested catchments, or in greater soil moisture storage within those catchments; we now examine whether there is evidence for either of these alternatives.

To examine first whether any significant differences in runoff are present, the calendar year totals of rainfall and streamflow, and the percentage of rainfall input leaving the catchments as streamflow were compared. Table V shows these data for 1967-1973 when all three Kimakia catchments were under study. It can be seen that streamflow, when expressed as a percentage of rainfall, is higher in the grass catchment that in either of the forested catchments and, in fact, the differences in apparent water use between the three catchments (R-Q) can be accounted for almost entirely by the differences in albedo between the vegetation types. It therefore appears that any addition to rainfall from occult and mist precipitation sources is balanced by the increased evaporation of intercepted water and the

TABLE V

Totals, for Calendar Years, of Rainfall and Streamflow at Kimakia

(Rainfall totals are Thiessen Estimates)

Year	Bamboo			Pines			Grass		
	10			11			17		
	R	Q	Q/R%	R	Q	Q/R%	R	Q	Q/R%
1967	2190	953	43.5	2024	834	41.2	2158	1040	48.3
1968	2637	1488	56.4	2521	1389	55.1	2559	1560	61.0
1969	1583	511	32.3	1499	454	30.3	1507	542	36.0
1970	2221	1027	46.2	2085	833	40.0	2142	1029	48.0
1971	1988	790	39.7	1746	630	36.1	1861	789	42.4
1972	2484	1268	51.0	2291	1015	44.3	2396	1235	51.5
1973	1874	786	41.9	1788	658	36.8	1815	863	47.5
67-73 MEAN	2140	975	45.6	1993	830	41.6	2063	1008	48.9

decreased albedo of the forest relative to that for short grass.

If the addition to rainfall from occult and mist precipitation were such as to give significantly greater amounts of soil water in the forested catchments, this would be revealed by an examination of soil moisture deficits measured by neutron probes in the three catchments. Table VI shows the deficits developed in the five years from 1969 to 1973; the Table shows that, in spite of considerable differences in measured changes in soil moisture storage from month to month, the grassland catchment (17) has the smallest deficit and hence the wettest soil in 11 of the 15 months. Any possible addition to the soil moisture store in either forested catchment is therefore not sufficient to cancel out the significantly higher water use of forest relative to grass.

More detailed discussions of the relative water balances of the Kimakia catchment will be found in Section 3.2.1. The above comments suggests that occult and mist precipitation are unlikely to be significant factors in the comparison of different land uses in the Aberdare Range; this is not to say however that they are unimportant factors in drier areas.

TABLE VI

Soil Moisture Deficits in the Top 270 cm at Kimakia during June, July and August (cm water)

Year	Month	Catchment land use: Bamboo	Pine Plantation	Grass
1969	June	4.7	2.9	1.6
	July	-12.0	2.0	-3.3
	August	2.6	1.5	0.0
1970	June	9.1	-1.4	9.1
	July	5.6	1.5	0.3
	August	4.4	2.3	-3.8
1971	June	-0.1	-4.1	-7.7
	July	-1.5	-4.6	-12.2
	August	1.7	-1.2	-3.1
1972	June	-5.6	-4.3	-9.6
	July	-2.0	-2.7	-8.8
	August	1.8	-0.4	8.9
1973	June	12.2	0.4	2.3
	July	7.1	6.6	-5.0
	August	4.9	3.6	-3.2

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1.2.2

EVAPORATION

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1.2.2

EVAPORATION

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INTRODUCTION

The problem of measuring evaporation from open water surfaces and transpiration from different types of vegetation is central to most applications of hydrological research. For many years, difficulties experienced in understanding the physical nature of the evaporation process together with the ambiguous results obtained from various types of instrument designed to measure evaporation directly (such as evaporation pans and evaporimeters) led to the development of empirical techniques for estimating water use from climatic data (eg Thornthwaite 1948, Blaney and Criddle 1950, Turc 1955). These techniques were known to give only approximate estimates but, in the absence of simple, more theoretically sound methods, they provided a useful basis for calculating irrigation need and consumptive water use of various crops.

Even now, following the advance in micrometeorological methods over the past twenty-five years, most physically sound techniques require more elaborate instrumentation and experimentation than is normally available. Although these essentially research techniques have led to a greater understanding of the evaporation process, their simplification to methods which can be readily used by water engineers or agronomists working in terrain which is far from ideal in terms of uniformity of cover and adequate fetch, cannot be achieved without loss of accuracy.

For the hydrologist, the best compromise is the physically-based, semi-empirical formula of Penman (1948, 1952, 1956, 1963) which relies on generally available agro-meteorological data. This embodies the concepts of potential transpiration (ET) from vegetation plentifully supplied with water and of evaporation from an extensive open water surface (EO). Potential transpiration is less spatially variable than actual transpiration so that spatial sampling is simplified. For short green crops, completely covering the ground and plentifully supplied with water, the method can be expected to give (and in practice does give) estimates of water use within the accuracy of the other components of the hydrological cycle (Penman 1956 op cit, Edwards and Rodda, 1970).

There are, however, two cases when actual evaporation AE and the Penman estimate ET may be expected to differ; the first occurs when water supply to the roots is limiting, with the result that transpiration may be at a rate considerably less than potential. The second occurs where the vegetation is tall forest that is both frequently wetted by rainfall and well-ventilated, when the combined loss from both transpiration and evaporation of intercepted water may considerably exceed the Penman open-water evaporation EO.

In the EAAFRO series of catchment experiments, the Penman formula has formed the basis of estimates of mean catchment water use. Evaporation pans have been maintained (raised and sunken Kenya type pans and Class A) and have helped to complete missing data in the radiation and sunshine records. Since the results from the evaporation pans are not always easy to interpret and pan factors are a function of individual pan exposure and type, they are not to be recommended as other than standby instruments for work in experimental catchments. In view of their wide use as an index of evaporation where other data are lacking, a comparison of the catchment pans with the Penman estimates is given in Appendix 7.1.3.

THE PENMAN FORMULA

Although the Penman formula is well known in East Africa (McCulloch, 1965) and has been used for regional analysis (Woodhead 1968, 1969, Rijks, Owen and Hanna, 1970), the physical basis of the formula is frequently not appreciated particularly in relation to its modification as the Monteith development of the Penman formula (Monteith, 1965). There is frequently confusion as to which version of the Penman formula is being used and why different computational methods give different results. The following brief description of the derivation of the formula is intended as a guide to the evaporation data produced from the experimental catchments. For a more complete discussion, reference should be made to the papers of Penman and Monteith cited in the text.

The original formula (Penman, 1948 op cit) is a combination of the energy balance and aerodynamic methods of measuring evaporation. If the energy quantities available for evaporation and heating the soil-plant-atmosphere system are equated:-

$$R_n = \lambda E + K + G \qquad \ldots\ldots (1)$$

where R_n is net radiation; λE is the latent heat flux; K is the sensible heat transferred to the air; and G is the sensible heat transferred to the soil and plant.

Over a day in equatorial regions, G becomes small in relation to R_n and may be neglected. R_n can be measured and the problem becomes that of partitioning R_n between sensible heating of the air (K) and the latent heat flux (λE). The ratio $\frac{K}{\lambda E}$ is known as the Bowen ratio (β).

Penman derived an expression for β by introducing an empirical aerodynamic term Ea and eliminating the need to measure surface temperatures. Evaporation from an open-water surface is then given by:-

$$EO = \frac{\Delta H + \gamma Ea}{\Delta + \gamma} \qquad \ldots\ldots (2)$$

where $Ea = f(u)(1 + u_2/100)(e_a - e_d)$;

$H = (Rn - G)/\lambda$, is the 'available' radiant energy in the same units as EO;

Δ is the slope of the curve, at mean air temperature T, relating saturated vapour pressure e_s to air temperature;

γ is the psychrometric constant;

f(u) is an empirical constant;

u_2 is the run of wind at 2 m altitude; and

e_a, e_d are saturation vapour pressure at air temperature and dew point respectively.

On the basis of the Lake Hefner results (US Navy, 1952), Penman modified the aerodynamic term to:-

$$Ea = f(u)(0.5 + u_2/100)(e_a - e_d) \qquad \ldots\ldots (3)$$

justifying the adjustment on the grounds that the exact form of Ea was not critical and that the new term gave better agreement with evaporation from a large open water surface. His Ea had been derived from an evaporation tank (Penman, 1956 op cit).

To estimate potential transpiration, Penman advocated a reduction factor which varied seasonally but which, on an annual basis for Western Europe, averaged 0.75. At a later stage, making use of measurements of the albedo of grass and reinstating the original aerodynamic term to take into account the extra roughness of a crop, Penman introduced a one-step potential transpiration formula:-

$$ET = \frac{\Delta H + \gamma Ea}{\Delta + \gamma} \quad \text{(Penman, 1963)} \qquad \ldots\ldots (4)$$

where $Ea = f(u)(1 + u_2/100)(e_a - e_d)$;

and $H = (R_n - G)/\lambda$ with R_n now measured over grass

If net radiation is not measured, it has to be estimated from a further empirical formula:-

$$R_n = (1 - r)\ R_c - \sigma T_a^{\,4}\ (0.56 - 0.09 \sqrt{e_d})(0.10 + 0.9\ n/_N) \qquad \ldots\ldots (5)$$

where R_c is total incoming short-wave radiation;

r is the reflection coefficient of the surface in question (r = 0.25 for short grass);

$n/_N$ is the ratio of actual to maximum possible hours of bright sunshine at a given latitude;

σ is the Stefan-Bolzman constant; and

T_a is mean air temperature in ^{0}K.

If the total incoming short-wave radiation is not measured, it can be estimated from:-

$$R_c = R_a \; (a + b \; n/_N) \qquad \ldots\ldots (6)$$

where R_a is total short-wave radiation received at the top of the atmosphere; and

a,b are empirical constants (see Glover and McCulloch, 1958).

The use of (6) has given rise to doubts about the use of the Penman formula over periods of less than one week. Given good measurements of R_c, however, there is no reason why ET should not be calculated for time intervals of one day.

There are three common versions of the Penman formula, therefore, and in published papers it is often difficult to determine which has been used. These are the original open-water evaporation formula (Equation (2) above), the modified open-water formula using Equation (3) and the one-stage potential transpiration formula (Equation (4)). The version most commonly used in East Africa is the original formula for EO (Equation (2)) as in McCulloch (op cit) and Woodhead (op cit); this forms a convenient measure for the comparison of potential water use in different areas.

For some applications, however, alternative measures to EO (1948) are recommended. Penman suggests that for large open-water surfaces (lakes or irrigated areas), Equation (3) is a better estimate of water loss if advection effects are not dominant. Furthermore, for a variety of short, green crops with albedos similar to grass, the combined ET formula (Equation (4)) gives a very close approximation to actual water use where soil moisture is not limiting.

An additional source of confusion between Penman estimates lies in the choice of computational method and time interval. Small differences will arise if McCulloch's tables are used in preference to the original formula due to the inclusion in the former of terms to compensate for altitudinal effects. The methods of estimating Ta and $(e_a - e_d)$ differ (cf Berry 1964 and McCulloch op cit) and give rise to small discrepancies. The non-linear nature of some of the terms in the Penman formula also leads to small differences between, say, monthly totals calculated as the sum of daily values and monthly totals calculated from the monthly mean meteorological data.

It can be seen, therefore, that the version of the formula used should be that most appropriate to the problem in hand. The method of computation will be constrained by the meteorological data and computational aids available. Every effort should be made, however, to ensure that the best possible estimates of radiation, daily mean temperature, saturation deficit and windrun are derived from the data and that appropriate altitudinal corrections are applied. Above all, the version used, the method of deriving the input data and the computational method should be specified when quoting the results.

THE MONTEITH-PENMAN FORMULA

From physical principles, Monteith derived the following formula for transpiration from a vegetative canopy:-

$$\lambda E = \frac{\Delta H + \rho c \{e_s(T_z) - e\} / r_a}{\Delta + \gamma (1 + r_s/r_a)} \qquad \ldots\ldots (7)$$

In the formula, H is the available energy (R_n - G); ρ, c are the density and specific heat of air; $e_s(T_a)$ is the saturated vapour pressure at temperature T_z; e is measured vapour pressure; Δ, γ are as already defined; r_a is the resistance to water vapour transfer between the canopy and reference height z and is a function of windspeed and plant canopy parameters; and r_s is the resistance to water vapour transfer through leaf stomata. If leaf surfaces are wet from intercepted precipitation, r_s is zero.

The Monteith formula allows a combined treatment of wet and dry canopies of aerodynamically rough vegetation to give estimates of both transpiration from dry leaves and evaporation of intercepted precipitation from wet leaves. As an indication of the relative magnitude of the differences, Monteith (op cit) quotes Baumgartner's (1956) results from a pine forest and shows that with the ratio r_s/r_a = 15 the evaporation of intercepted water is about 5 times the transpiration rate of dry leaves exposed to the same weather conditions.

Despite its physical realism, the Monteith formula is difficult to use where, as is commonly the case, estimates of r_s, r_a are not available to the hydrologist. Where they are available, their incorporation is likely to yield better estimates of water losses in forested catchments where the canopies are frequently wet. This development of the water balance is discussed in Section 2.2.1 and the hydrological implications are examined.

For short crops and extensive open water surfaces, the Penman formula is adequate. Where soil moisture stress affects stomatal opening, however, and where aerodynamically rough crops are being considered, the Monteith formula presents the possibility of estimating actual transpiration more accurately.

METEOROLOGICAL EQUIPMENT USED IN THE EXPERIMENTAL CATCHMENTS

The basic data used in computing Penman estimates for the East African catchments were obtained from manually read agro-meteorological sites containing a standard East African Meteorological Department temperature screen, run of wind anemometer at 2 m, Gunn Bellani radiometer (Pereira, 1959) and Campbell Stokes sunshine recorder. From twice daily readings on these sites daily values of Ta, R_c, n/N, N_2 and $(e_a - e_d)$ were computed. Ta was determined as the mean of observed maximum and minimum temperatures. All Gunn Bellani radiometers were calibrated individually against a Kipp solarimeter to give daily R_c from daily observed distillation. Saturation deficit was computed from twice daily wet and dry bulb temperature readings. Originally this was done using pressure corrected dewpoint tables and the McCulloch (op cit) tables, but all except the Atumatak data (Section 4.2.1) were subsequently recalculated using the Berry (op cit) formulae embodied in a computer program.

In addition to the above instrumentation USWB Class A and Kenya evaporation pans were installed on each site (see Appendix 7.1.3). From 1967 onwards Lintronic solarimeters, which are a modification of the Monteith Thermopile, were installed on the Kericho and Kimakia meteorological sites. These inexpensive instruments with their battery powered integrators recorded daily radiation with an accuracy comparable to the Kipp (Blackie, 1968), but proved unreliable at these wet sites. Consequently, they did not replace the Gunn Bellani as 'front line' radiation equipment but provided useful cross checks on their calibrations.

From 1972 onwards testing and evaluation of the Institute of Hydrology designed 'Epsylon' automatic weather station was carried out on the Kericho and Kimakia catchments. These battery operated instruments, which log 5 minute readings of temperature, wet bulb depression, radiation (using Kipp sensors), wind run, wind direction and rainfall on magnetic tape, were designed primarily for unattended operation in remote areas (McCulloch and Strangeways, 1966). Though various 'teething' problems resulted in relatively short runs of data being collected on the catchments, these proved extremely useful in checking for bias in the manually read data, as indicated in Sections 2.2.1 and 3.2.1.

CONCLUSIONS

An account has been given of the methods of estimating open-water evaporation (EO) and potential transpiration (ET) from the Penman formula, and the relation between this formula and that of Monteith has been demonstrated.

In following sections comparisons are made between water balance estimates of water use and Penman estimates derived as described above. These indicate that, when appropriate albedos (Equation (4)) are used or appropriate reduction factors are applied to EO, the Penman estimates give a useful first approximation in predicting water use. Although the data necessary for a rigorous application of the Monteith formula were not available, the incorporation of an approximation to the concepts embodied in it in the conceptual models used resulted in a significant improvement in their ability to predict streamflow from rainfall and meteorological inputs.

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1.2.3

SOIL MOISTURE

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1.2.3

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INTRODUCTION

Soil moisture is important for at least two reasons: first, because part of it is the water available to vegetation for plant growth and evapotranspiration, and second, because the moisture status of the surface soil influences the response of a catchment to rainfall. It is convenient to regard soil moisture as divided between three 'stores': the surface store, the storage to the depth reached by roots, and storage between this depth and the water table.

The surface store moisture content influences the partition, between infiltration and surface runoff, of that rain which reaches the soil surface; the storage within the rooting depth contains the 'available water', which is that available to a plant between 'field capacity' and 'wilting point'. The soil below the rooting depth provides a store through which the soil moisture is redistributed in response to gravitational potential and the matric potentials developed in the root zone. Alterations to these complex processes caused by land-use change could seriously affect catchment water yield in quantity and distribution in time; an experimental programme was therefore set up to observe any differences in the soil moisture regime associated with the different land uses.

SURVEY OF THE SOIL MOISTURE EXPERIMENTAL PROGRAMME

The role of differing vegetation types in the control of streamflow was the basis of the experimental design for the four groups of catchments. The effect of the land use changes on the distribution of rainfall input between transpiration, stormflow and baseflow outputs was to be determined together with soil erosion. The importance of the soil to this distribution process was emphasised when it became apparent during the initial analysis that the potential retention of water in the vegetation rooting depth could be greater than the total annual streamflow.

At the start of the experiments, sites were selected in each catchment using the results of soil and vegetation surveys, and pits were dug from which the rooting depth within and the physical characteristics of the soil profiles were determined. Sampling sites were established for the weekly qualitative measurement of soil moisture tension and for monthly gravimetric sampling. These sites were near raingauges and representative of the upstream, middle and downstream areas of the catchments. Due to the lack of laboratory facilities, no routine gravimetric moisture content measurements were taken at Atumatak.

By 1969, the soils field work has been completed at Mbeya and Atumatak. Analysis had been carried out on the early results, but still had to be completed for the whole period. Field work was continuing on the Kenya catchments using the more sophisticated neutron probe soil moisture measurement. The main purpose of this was to compare the results already obtained by gravimetric techniques with those from more precise equipment used at a greater number of sites over a catchment.

These observations also provided a test of the new neutron equipment under East African conditions, and provided a useful record of operational and analytical experience for future water resources investigations. An extension of the original work was the examination of the vertical moisture flux under tea bushes as a measure of deep percolation and actual evaporation (see Section 2.2.3). Finally, the use of more sophisticated equipment also provided the opportunity to train local staff in its operation and the recording of results.

TECHNIQUES AND EQUIPMENT

The determination of the physical characteristics of the catchment soils were made on volumetric cores taken with the

'Muguga' sampler (Dagg and Hosegood, 1962). This was used in pits dug to the rooting depth. Measurements made on these cores gave bulk density, free draining and field capacity pore space, relative percolation rates and an estimate of plant available water, taken as that yielded when soil moisture tension increased from 1/3 to 15 atmospheres. Mechanical and chemical analyses were also carried out, and an estimation of wilting point made using disturbed soil samples. A full discussion of these techniques and results is given in Pereira et al (1962) under the sections specifically dealing with soils and in the hydrological analysis sections for the catchments.

The Australian 'Jarrett' auger was used for the routine soil moisture sampling. Samples were normally taken at monthly intervals, with replicated samples taken at each site throughout the profile. The disturbed samples taken were processed on a dry weight basis and the results converted to moisture volume fraction using dry bulk densities previously determined as conversion factors. This auger was most effective when used in moist soils, but recovery of a sample proved difficult when some soils approached wilting point deficits.

The moisture tension readings were taken by measuring the resistance of Gypsum plaster blocks using a hand operated AC ohm-meter. The blocks and meter were at first commercially available, but these were later replaced with new designs developed by the EAAFRO Physics Division. The range of resistance of the blocks was usually from logohm 2.5 at saturation to 5.5 at the dry end of the scale. The original blocks had concentric anodes, but it was found that parallel anodes performed as well when the gypsum had the optimum consistency. Ideally the soil characteristic of moisture retention against log tension (pF) should match that of the block, or else sensitivity can be lost over the range when drying is rapid. Above about 2.8 pF these blocks usually have a linear relationship between log resistance and pF, although the actual measurement represents the moisture distribution in the block between the anodes. At lower values of pF the calibration is complicated by hysteresis both of soil and block pore structure. There are further difficulties because contact between block and soil varies with soil shrinkage and swelling, and because soil fine particles can obstruct the block surface pores.

The soil moisture blocks were usually installed when the soil was at field capacity, and blocks were saturated beforehand. A separate hole was augered out to place each block at the required depth. Soil from the depth at which the block was sited was sprinkled and firmly tamped around each block to ensure good hydraulic contact between the block and hole wall; the hole itself was very firmly backfilled to minimise vertical percolation. The block wires were led out from the side of the hole below ground level to a terminal board placed a sufficient distance away to prevent field staff trampling the surface vegetation and destroying the soil surface structure when taking readings.

The useful life of soil moisture blocks is determined by soil chemical properties; in Kenya, blocks had a life of five to ten years before insulation of the wires deteriorated. In operation, observations were taken quickly using the voltmeter on the resistance meter as a null detector, and the log resistance to balance the bridge was read from the potentiometer scale. The reading was made as quickly as possible to prevent any polarisation bias from the low frequency given by the hand cranked AC generator. The power output was not sufficient to produce any heating effect.

The whole system was simple and robust in operation and provided a good qualitative picture of moisture changes. The log resistance at each depth was plotted against time without attempting to convert readings either to moisture content or tension and the resulting plots were quite sufficient to indicate periods of infiltration, moisture abstraction and wilting conditions. A seasonal plot of moisture changes could be established when block readings were taken together with gravimetric data.

NEUTRON SOIL MOISTURE PROBES

The great advantage of this method is that many readings can be taken in the same volume of soil; once the sites and calibration curves have been established, the method is not as labour-intensive as gravimetric sampling. The equipment consists of a probe containing a radio-active source of high energy neutrons together with a detector, and a pulse counter. The probe is lowered down an access tube into the soil to the required depth. The high energy neutrons pass through the wall of the access tube and are then moderated by interactions with the nuclei of the elements in the soil matrix. At the most only about two interactions with a hydrogen nucleus are required to reduce the neutron's energy to that at ambient temperature. The reduction in energy resulting from interactions with hydrogen nuclei is so much greater than the reduction in energy resulting from interactions with nuclei of atoms of other elements, that the density of the 'cloud' of thermal neutrons formed is almost a direct measure of the water molecules present. The thermal neutrons activate the detector and the pulses are counted.

A full description of the neutron moisture meter equipment and operational experience in the Kenya catchments is given in Appendix 7.1.5. The equipment was only used in these catchments, and not in those at Mbeya or Atumatak.

The count rate recorded by the probe when inserted in the soil depends on both equipment and soil factors as well as the soil moisture content. Equipment factors include the nature of the probe source and neutron detector, and their geometry; system electronic stability and 'dead time' during which neutron events are not counted; and size of access tube and the material from which it is made. Soil factors include matrix chemistry, dry bulk density and proximity to interfaces. The random decay process of the source radio-activity also sets a limit to the precision of any soil moisture measurement given by the neutron probe; full details of the theory and procedure for calculating this limit are given by Bell and Eeles (1967).

CALIBRATION OF NEUTRON MOISTURE METERS

Field calibrations were carried out by EAAFRO Physics Division at the same time as the routine observations in the catchments were continuing. Over four hundred calibration points were obtained at different sites and depths in the catchments. The method was basically the same as that given in Eeles (1969). A special access tube was inserted near to a network site but not closer than three metres. Counts were then taken at 30 cm intervals, and two profiles of volumetric cores were taken close to the tube centred on the same depths. The moisture content of the samples was found by weighing, heating the sample for 48 hours at 105°C, and reweighing to obtain the dry weight. The results were expressed as moisture volume fraction (MVF). From the range of MVF values and count rates obtained, calibrations for each soil type were computed.

To add to the complication of the calibration work, by the end of the project eight equipments had been used in the field; five EAL probes with scalers, and three 'Wallingford' probes with ratescalers and a ratemeter. All the initial calibration work was carried out with EAL equipment using shield counts to normalise the readings. Intercalibration of the EAL with the 'Wallingford' probes using laboratory standards and field sites showed no significant differences.

ANALYSIS OF FIELD CALIBRATION DATA

The collation and analysis of this large number of calibration points proved difficult, and was complicated by errors stemming from the method of soil sampling. This became apparent when points were considered in classes defined by dry bulk densities in steps of 0.1 gm cm^{-3}, and then in wider groups appropriate to each catchment. The effect of this soil parameter on calibration curves for this type of equipment is well established by theoretical as well as experimental work (Jensen and Somer, 1967). When considering the larger groups of points it became obvious that in spite of the care taken, the small volumetric soil sampler used to take cores from the lowest parts of the profiles had produced compressed cores, and, in some cases, had also dislodged soil when lowered into the augered holes giving samples with very low densities. These failings gave points widely separated from the appropriate density class, and in some cases formed a group with suspect density.

From this general scatter of points and the absence of points at low MVF values, use of regression analysis to give a calibration curve would have been unsatisfactory. However, it would appear from linear calibrations derived theoretically (as in the last reference quoted) that they could be considered as a family of lines radiating from a common node, the envelope of the lines being defined by the one with the highest dry bulk density (DBD) and the air/water line (that obtained by joining two points, one of which is the reading in air, and the other the reading in a large drum of water). A line of DBD 1.67 gm cm^{-3} had been established by laboratory drum calibration on Thetford sand at the Institute of Hydrology. This provided one of the two lines:-

Sand $\quad MVF = 0.790\ (R/R_W) - 0.024$

Air/Water $\quad MVF = 1.006\ (R/R_W) - 0.006$

where R, R_W are count-rates within the appropriate medium, and within a large drum of water, respectively.

The intersection of these two lines provided a nodal point (-0.083, -0.090), and this was used with the centroids of the different DBD classes of field points to give the following equations:-

$$\text{Calibration line coefficient} = \frac{(MVF)_c + 0.090}{(R/R_W)_c + 0.083} \quad \ldots\ldots (1)$$

$$\text{Calibration line constant} = \frac{0.083(MVF)_c - 0.090(R/R_W)_c}{(R/R_W)_c + 0.083} \quad \ldots (2)$$

The suffix c indicates centroid value.

It was possible to use a linear regression to give calibration lines for six sets of data, and a comparison of these with the lines produced using equations (1) and (2) is given in Table I. For the catchments the absolute difference between the two methods at maximum and minimum observed values of soil moisture is less than 1%; if moisture differences are considered the bias is 4% or less.

The table also shows the differences between field, node, and theoretical calibration using the Ølgaard MOPSIIc computer program (1967). The latter required a chemical soil analysis for twelve elements, and produced a slightly curved line due to the source/detector geometry used in the program. However, using a linear regression over the observed moisture range produced the good agreement shown with the two field methods. The agreement is also good between the catchment DBD profiles established from representatives pits in 1960 and the average DBD of gravimetric samples taken for the calibrations shown in Table II. The 1960 samples were taken with the most accurate of the Muguga soil corers, which takes the largest core volume of 618 cm^3, and this agreement shows that the rejection of some neutron probe calibration samples because of doubts about their DBD did not bias this

TABLE I

Comparison of Neutron Moisture Meter Calibration Curve with Regressions on Field Calibration Data and MOPSIIC Theoretical Data

Catchment	Depth (cm)	Dry Bulk Density (gm/cc)	Calibration* Coefficient	Calibration* Constant	Regression** Coefficient	Regression** Constant	Regression** Correlation	Soil Moisture Difference Bias %
Kimakia 10	90	0.60	0.9314	-0.0127	0.9119	-0.0019	0.975	+2.2
Kimakia 11	120	0.57	0.9432	-0.0117	0.9721	-0.0275	0.839	-3.0
Kimakia 17	90	0.61	0.9265	-0.0376	0.9665	-0.0376	0.896	-4.1
Kericho 13	All Depths	0.83	0.7788	-0.0254	0.7798	-0.0259	0.838	-0.1
Mwea	All Depths	0.98	0.9132	-0.0142	0.8715	+0.0007	0.859	+4.8
Muguga	60	0.97	0.9307	-0.0128	0.8815	+0.0023	0.969	+5.6
MOPSIIC Theoretical Calibrations:***								
Muguga 2	60	0.97	0.9264	-0.0131	0.9209	-0.0117	0.994	+0.6
Muguga 4	120	1.00	0.7819	-0.0251	0.7895	-0.0270	0.995	-1.0
Muguga 6	150	0.96	0.7453	-0.0281	0.7174	-0.0205	0.995	+3.9

* Actual calibration lines used which were derived using a line through a common point of intersection and the centroid of field calibration points for each depth.

** Regression through field calibration points.

*** Calibration lines derived from a line through the common intersection point used above and centroid of MOPSIIc theoretical calibration points. These are compared with regressions through the same theoretical points.

TABLE II

Catchment Gravimetric Average Dry Bulk Density (DBD) Profiles (gm/cc)

Depth (cm)	Kimakia 'A'		Kimakia 'C'		Sambret		Lagan	
	Grav*	NS**	Grav	NS	Grav	NS	Grav	NS
30	0.55		0.57		0.79		0.74	0.70
60	0.65	0.57	0.60	0.60	0.81		0.79	
90	0.61		0.69		0.81	0.78	0.82	0.79
120	0.64		0.82	0.84	0.82		0.82	
150	0.76		0.96		0.84		0.89	
180	0.80	0.82	0.99	1.01	0.87		0.86	
210	0.83		1.08		0.90	0.90	0.89	0.90
240	0.90	0.91	1.11	1.15	0.93		0.92	
270	0.99	1.00	1.11		0.91		0.90	
300	1.03		1.16		0.95		0.92	
Layer weighted average DBD for profile to 270 cm	0.72	0.73	0.85	0.84	0.85	0.83	0.84	0.83

* Grav - Gravimetric samples taken in 1960 to determine average profile DBD for catchment (gm/cm³)

** NS - Gravimetric samples taken 1968-69 to calibrate neutron probes and grouped in the DBD classes for each calibration line.

important calibration parameter. It also shows that the three soil sampling sites in each catchment were as representative as the larger neutron networks in terms of soil physical characteristics.

Errors due to the calibration are difficult to assess, particularly when the absolute comparison is made with the gravimetric sampling method which has a very high variance. The use made of an artificial node means that the calibrations are least accurate at the extremes of the moisture range, with the same bias if working in terms of differences over the whole range. The error is then proportional to the ratio of the two line coefficients. From Table I it can be seen that the node calibration produced a bias ranging from 0.1% to 4.1% on the catchment field regressions available. It is interesting to compare the Ølgaard regression curve with the 60 cm depth field calibration for Kikuyu red loam at Muguga, which gave a bias of 4.5%. The relative bias between the empirical node and the theoretical curve was 0.6%, which may be a comment on the gravimetric calibration errors! None of the node line coefficients lay outside the standard errors of those found by the linear regressions on the field points, so in order to be consistent, the former method was used for all calibrations. Due to the scatter of field points, if only those sets capable of producing a regression were used, less than 40% of the profile soil zones could have been calibrated. The number of calibration lines used was reduced to four, covering all catchments, sites and reading depths (see Fig I).

NETWORK DESIGN

For soil moisture sampling this is always a compromise between what is desirable and what is operationally possible in terms of expense and time. Over a catchment it is

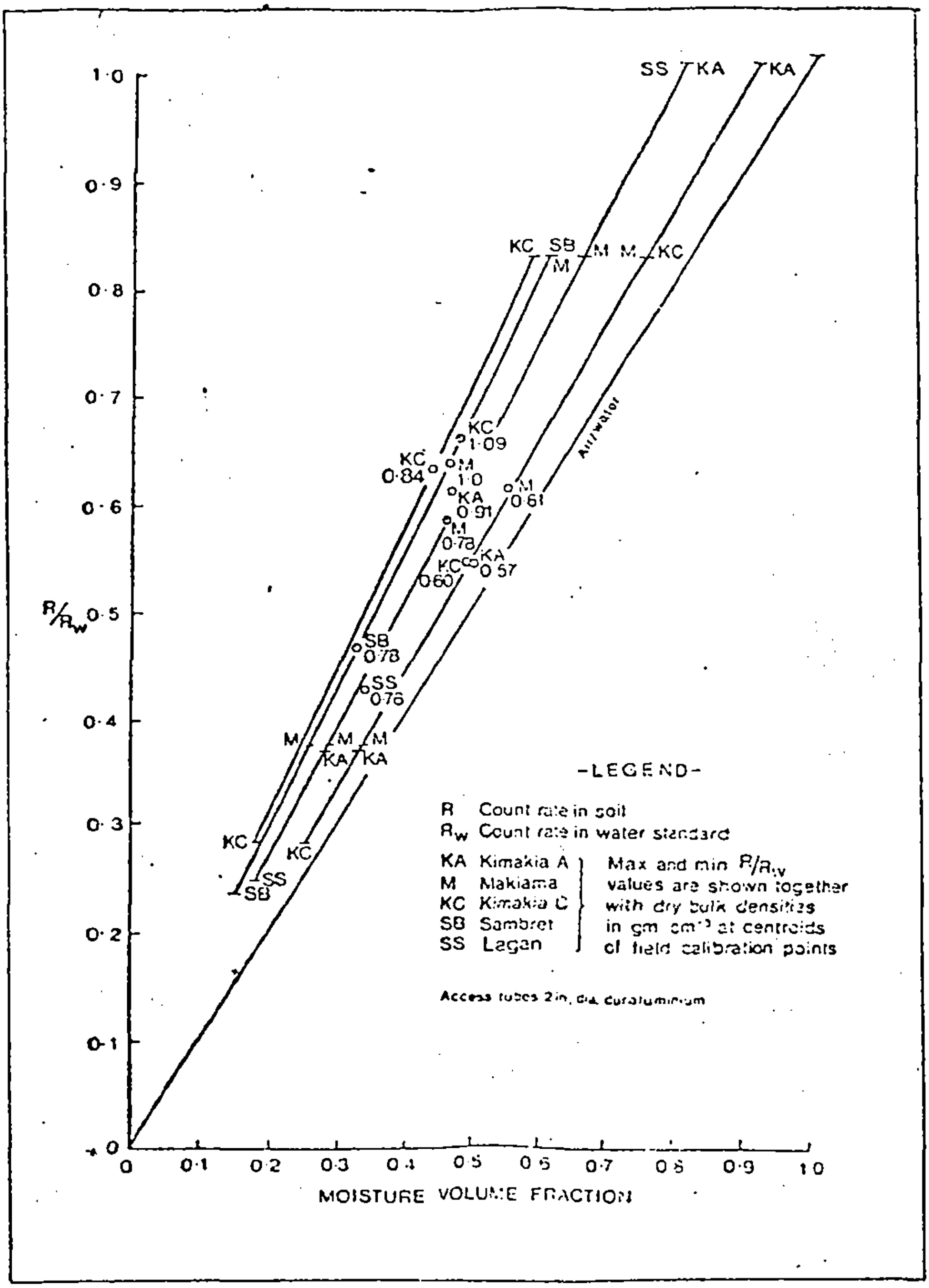

Figure 1 Neutron moisture meter calibration curves

usually required to sample as many points as possible within at the most four or five hours. Ideally, all the readings should be taken simultaneously! The sites chosen have to be easily accessible and representative of an area of catchment rather than sites selected at random within strata. Unless the catchment is very small and homogeneous, a representative area usually has to include several strata defined on uniform topography, vegetation and soil type.

The catchment gravimetric sites were selected to represent the upstream, middle and downstream areas of the catchments based on the results of soil and vegetation surveys. The neutron access tube networks were installed on a similar basis, but representing smaller areas. Tubes of length 300 and up to 600 cm were installed on some sites at Kericho so that an estimate could be made of the profile variance at a site to the depth containing the profile zone of greatest change. The depth of 300 cm included the bulk of vegetation roots on all catchments at Kimakia and Kericho according to an earlier root distribution investigation, Pereira et al (1962).

DATA PROCESSING AND ANALYSIS

The large quantity of data produced by the neutron method was processed by computer, and the details of this are given by Roberts (1972). The precision of the computed results is that given by statistics of the radio-active decay process, and does not take into account operational or calibration errors.

The total soil moisture in the profile to a depth of 270 cm was computed for all sites and used in an analysis of the processed data by catchments. To remove consistent differences between sites which were then apparent, the data were expressed as soil moisture deficits (SMD). These consistent differences bore some relation to the height of site above the stream on the line of greatest slope; however, no consistent trend was apparent, possibly because of interflow or the presence of perched aquifers at certain sites.

The use of SMD values effectively removed any bias present in the absolute soil moisture contents, and changes in soil moisture storage were used in the hydrological analysis. A field capacity was obtained for each site by averaging the moisture contents after recharge had taken place and the profile had drained; the month at the end of the long rains usually provided suitable data for this purpose.

Linear regression on the harmonic equation given below gave a good description of the variability in soil moisture deficit with time, and the regressions were used to test for differences between sites, differences between SMD as given by gravimetric sampling and neutron moisture meter, and differences between estimated SMD for catchments.

The harmonic equation related the soil moisture deficit (SMD) to the observation day of the year (T) as follows:

$$SMD = b_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 \qquad \ldots\ldots (3)$$

$$\text{where } X_1 = \cos (2\pi T/365)$$
$$X_2 = \sin (2\pi T/365)$$
$$X_3 = \cos (4\pi T/365)$$
$$X_4 = \sin (4\pi T/365)$$

Analysis of variance showed that all regressions were significant, although they seldom explained more than 70% of the observed variance in SMD.

The gravimetric soil moisture data ran from 1958 to 1971 inclusive, and divided in periods 1958-61, 1962-68, and 1969-71. The first period had sampling dates which varied from month to month and with site, whilst the middle period had sampling for all sites on the same day of the month in each catchment. The last period had the latter sampling routine still, but the sites had been used so much that the results were suspect. The neutron data ran from 1968 to 1974, and similar tests of significance were made together with a comparison of regressions for each sampling method in the period of overlap 1968-71. These significance tests appeared to be robust, and were surprisingly sensitive. One of the neutron access tube sites was affected by calibration holes too close to the main tube, and the change in response was detected through the sites' regression comparison.

CONCLUSION

The relative usefulness of the gravimetric and neutron probe methods of soil moisture measurement depends on the care and knowledge used in making the measurements and the analysis of the results. The gravimetric sampling, combined with gypsum tension blocks used in the first phase of the catchment experiments, gave a good record of changes in soil moisture measurements. The tension blocks provide a qualitative record which can be referred to the quantatitive gravimetric measurements at longer intervals. The great advantage of these two methods is the simplicity of the direct measurement and robust equipment. With care, the useful life of a gravimetric soil sampling site is probably the same as that of a profile of gypsum blocks in East African soils. However, the great drawback to this system is the limit to the length of time the same site can be used, and the large stratum which it has to represent.

The neutron moisture meter system is much easier to use and has the advantages that (a) repeated observations can be made at the same point to any required frequency; and (b) the speed of operation allows more sites to be sampled over a catchment. The calibration and interpretation of observations from a neutron probe is difficult as the readings do not apply to a point but are averaged over a varying volume of soil. The use of integrated circuits and modular construction leads to greater reliability and ease of servicing, but there are

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scales for the intended analysis.

3. The recorder should be zeroed frequently by an experienced field assistant and should not be altered by the observers except under supervision.

4. Time marks should be made every day, without disturbing the chart or punched tape, and a system of notifying the supervising department in case of breakdown should be strictly observed.

5. Where possible, two water-level recorders should be installed to minimise loss of data.

6. Analysis of the streamflow records should be kept up to date and, if doubts arise about the validity of the stage-discharge relationship, this should be checked by whichever method (chemical dilution, current metering) is appropriate.

Because of the importance of streamflow records in catchment research, every effort should be made to preserve accuracy. Systematic errors will affect the estimation of water balance components, and are extremely difficult to differentiate from effects of land use change. Furthermore, accurate streamflow measurements are themselves of great value to future water resources planners, and amply justify time and effort spent in their collection.

The severe difficulties involved in measuring runoff in seasonal streams were increased by the remoteness of the catchments, the unpredictability of the rainfall (so that flow through the flumes was but rarely observed) and the adoption of several unsatisfactory remedies for the silting problems. Nevertheless, records from catchments in semi-arid rangelands are extremely rare, so that such records as do exist from Atumatak have considerable value; furthermore, the lessons learned from the Atumatak experiment are valuable guides to future work in these areas.

MBEYA

The Mbeya catchments are on deeply weathered gneiss overlain by shallow layers of volcanic ash. Difficulties were experienced, therefore, in ensuring that the structures were water-tight. As with the Kimakia experiment, one of the original catchments had to be abandoned because of suspected leaks past the weir.

The two catchments had sharp-crested weirs; Catchment A, under shamba cultivation, had a 90° v-notch set in a rectangular plate, and Catchment C, under indigenous forest, had a 120° v-notch. Silting of the approach channel was a problem with the structure in Catchment A and a sediment tank was installed to contain the sediment and facilitate its measurement. Subsequent modifications to the weir on Catchment A have altered its theoretical rating and a correction has been applied to the streamflow record.

RECOMMENDATIONS

As a guide to future work, the experience of this series of experiments suggests that the following code of practice should be observed.

1. The gauging structures should be standard weirs or flumes conforming as far as possible to British Standard 3680 or an equivalent.

2. The water-level recorder should be reliable, easy to maintain and should have adequate time and water-level

water-level recorder housings to dry out. Silt has had to be removed periodically from the Sambret main weir (see Section 1.2.5).

ATUMATAK

Because of the high sediment loads of the Atumatak streams in spate, the type of structure chosen to measure flows was a compound critical depth rectangular-throated flume, the centre section having side contractions only and the flanking flumes having bottom contractions only. In practice it was found that sediment accumulated to considerable depths on the concrete apron of the approach section and steps were taken to stabilize the sand bed and to re-arrange the intakes of the water-level recorder wells. These modifications, coupled with the unstable approach conditions, have cast doubt on the validity of the theoretical ratings, and attempts were made to check the performance of the structures by current meter. These attempts met with limited success, and a model of the flumes was laboratory-calibrated at both the University of Nairobi and the UK Hydraulics Research Station.

Errors in water-level as measured in the float wells arose from the system of connecting the float well to the flume by means of a perforated pipe laid down the centre of the throat as well as the direct connections through the forecourt wall. To correct these errors retrospectively, a second water-level recorder was installed in an independent float well in one of the structures while the perforated pipe was still in position. The difference in recorded levels allows a correction factor to be applied to the original records. A detailed discussion of the calibration of these flumes is given in Appendix 7.1.1.

As a result of the above errors and the uncertain quantities of deposited silt, it has not been possible to use the runoff data from Atumatak for any water balance calculations. Analysis has concentrated on the peak flows generated by the two catchments and the soil moisture conditions under controlled and uncontrolled grazing (see Section 4.2.1).

TABLE II

Comparison of Kericho Weir Ratings with BS 3680

	Stage (Ft)	Rating (Ft^3/s)	BS 3680 (Ft^3/s)	Possible Error %	Comment
(a) 1JC13					
	0.2	0.89	0.890	-	
	0.4	2.51	2.509	-	
	0.6	4.61	4.625	-0.3	
	0.8	7.40	7.496	-1.2	
	1.0	13.25	13.360	-0.8	
	1.25	23.29	23.611	-1.4	
	1.50	35.53	36.198	-1.8	
(b) 1JC14					
	0.2	1.19	1.195	-	
	0.4	3.37	3.368	-	
	0.6	6.19	6.208	-0.3	
	0.8	9.53	9.627	-1.0	
	1.0	13.32	13.562	-1.8	
	1.25	18.52	19.113	-3.1	
	1.50	24.47	25.380	-3.6	

KERICHO

The three main weirs at Kericho are as follows.

Number:	Catchment; and its Land Use
1JC13	Sambret (main outfall) tea
1JC15	Sambret (sub-catchment) bamboo
1JC14	Lagan (main outfall) indigenous forest

The structures IJC13 and IJC14 at the main outfalls of the catchments are compound, rectangular sharp-crested and broad-crested weirs with end contractions fully suppressed by vertical sidewalls on the sharp crested sections. 1JC13 has two sharp-crested sections 91 cm and 2.44 m wide. The base of the wider section is 23 cm above that of the narrower, low flow section. 1JC14 has a single section 1.22 m wide. At both sites the sharp-crested sections extend to 45 cm stage. Water levels have extended above this stage into the broad-crested sections in one storm only at 1JC13 and not at all in 1JC14. 1JC15 is of generally similar construction with two sharp-crested sections 91 cm and 213 cm wide, the base of the latter being 32 cm above the former. To improve sensitivity at very low flows a 90^0 v-notch is set into the narrower section and covers the stage range to 15 cm. The total stage range in the sharp-crested sections is 107 cm and this has never been overtopped.

Comparison of the theoretical ratings of 1JC13 and 1JC14 with British Standard 3680 (Table II) suggests that both weirs tend to under-estimate discharge by about 2% at stages above 25 cm. Considering the errors in stage recording and abstraction from the charts, these errors are considered acceptable.

All the structures had Lea Rotary Recorders; at structure 1JC13 and 1JC14, these were later supplemented by Leupold and Stevens A35 Recorders, which experienced difficulties similar to those noted for Kimakia gauging sites. These were partly resolved by clearing the trees around the weirs, thereby allowing the problems in rugged field conditions (see Appendix 7.1.5). The large capital outlay on sophisticated electronic equipment has to be compared with the labour intensive gravimetric method in the context of finance for a research project. However, the use of the neutron probe does allow the number of sampled strata to be greatly increased within an experimental catchment.

A full discussion of the soil moisture sampling results from 1958 to 1974 for the Kenya catchment is given in Sections 2.2.5 and 3.2.3. There is remarkably little difference between the different vegetation of the catchments when the amplitude and phase of fluctuations of soil moisture deficits are considered; the significant difference is in the mean moisture deficit. When land use changes are considered, this indicates that by changing the vegetation, the annual water yield will be altered but not its distribution in time if soil moisture is the only variable considered.

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1.2.4

STREAMFLOW

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1.2.4

STREAMFLOW

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INTRODUCTION

All the weirs and flumes in the experimental catchments were built by the respective Departments of Water Development in the three countries as part of the joint programme. An account of their construction, and the people taking part, is given in the previous Special Issue (Pereira et al, 1962). Apart from routine maintenance, the only major work involving the gauging structures has been the installation of improved water-level recorders in the Kimakia and Kericho catchments and the laboratory calibration of the Atumatak flumes at the University of Nairobi and at the Hydraulics Research Station, Wallingford, UK. A brief description of the structures follows, with some discussion of the difficulties experienced in their operation.

KIMAKIA

The following four operational gauging structures were maintained by EAAFRO and the Ministry of Water Development.

Regular Gauging Station Number:	Catchment:	Catchment Land Use:
4CA9	Catchment A	Pine plantation
4CA11	Catchment C	Bamboo; control
4CA20	Catchment M (Makiama)	Kikuyu Grass with sheep
4CA14	Catchment D	Bamboo with some small-holder cultivation

All the structures are compound rectangular, sharp-crested and broad-crested weirs, with 90° v-notches set into sharp-crested plates to cover the lowest range of flows. 4CA14 has a conversion plate which bolts over the v-notch to avoid calibration difficulties during months of high flow. Up to

1974, the peak flows on all weirs except 4CA14 did not exceed the capacity of the sharp-crested sections and the theoretical stage-discharge relationships have been derived without the need to consider the hydraulic behaviour of compound sharp and broad-crested structures.

A comparison of the rating tables supplied by Kenya Government with the British Standard 3680 shows (Table I) that possible errors in the theoretical calibration of structures 4CA9 and 4CA11 due to the use of a different discharge coefficient are negligible over the stage range 6-35 cm experienced during more than 90% of the year. At higher stages, the flow might be under-estimated by approximately 2%. The rating table of structure 4CA20 incorporates a different discharge coefficient, and the possible error could lead to an over-estimate of from 1% to 3% when the stage is less than 24.3 cm.

Structure 4CA20 was fitted with a scour value to enable accumulated silt to be removed from the approach channel. Unfortunately, structure 4CA9 was not fitted with such a valve; because of erosion from the road which passed through the catchment, silt was removed at frequent intervals to avoid measurement errors.

Originally, the weirs had Lea Rotary Chart Recorders for water-level monitoring, with staff gauges read daily to provide checks on the setting of the charts. In 1970, Leupold and Stevens A35 Recorders were installed to give more information on the shape of the discharge hydrograph and to permit more detailed analysis of the flow records. In the conditions of high humidity within the forest areas, corrosion of the recorders produced a high incidence of failure until a more rigorous system of checks and maintenance was introduced. Other difficulties experienced have included the sinking of the staff gauge on structure 4CA11 discussed in Section 3.2.1 and the abandonment of one of the original experimental catchments due to seepage under the gauging structure (4CA10).

TABLE I

Comparison of Kimakia Weir Ratings with BS 3680

Stage (Ft)	Rating (Ft^3/s)	BS 3680 (Ft^3/s)	Possible Error %	Comment
(a) 4CA9 and 4CA11				
0.2	0.046	0.046	-	BS v-notch range
0.4	0.256	0.255	-0.4	
0.8	1.426	1.432	-0.4	
1.0	2.480	2.503	-0.9	
1.25	4.313	4.378	-1.5	
1.5	6.779	6.906+		
				Installed v-notch limit
1.6	8.36	8.523- 8.538+*	-1.9 to -2.1	
2.0	17.99	18.323-18.508+*	-1.8 to -2.8	
3.0	54.31	55.438-56.366+*	-2.0 to -3.6	
(b) 4CA20				
0.2	0.047	0.046	+2.1	
0.4	0.262	0.255	+2.7	
0.8	1.452	1.432	+1.4	
1.0	2.520	2.503	+0.7	
1.25	4.373	4.378	+0.1	

\+ using BS 1.25 Ft discharge coefficient

* range depending on method used to combine v-notch and rectangular section discharges

SEDIMENT YIELD

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INTRODUCTION

Two important effects of land-use change are (a) modification to the streamflow volume and its distribution in time, and (b) change in the amount of sediment carried by the river. This transported sediment may be either fine material carried in suspension, or coarser material remaining near the stream bed and moved by a combination of buoyancy, gravity and fluid forces. Accurate measurement of sediment transport, particularly of the bed-load component, is extremely difficult and the intensive sampling scheme necessary for a detailed study was far beyond the resources of the original EAAFRO experiments; nevertheless, attempts were made to utilize such resources as did exist to monitor suspended sediment, and to estimate bedload on one catchment.

Suspended sediment may be collected in a sample of water provided that the method of collection does not separate out the suspended material from the fluid. Since the sediment concentration varies with depth and position across the stream section, it is usually necessary to obtain a series of vertical concentration profiles. Alternatively, a sample can be taken at a point where mixing of the flow ensures uniform concentration of the suspended material. An approximate estimate of the bed load movement can be obtained by means of a sediment trap or pool where the decrease in velocity is sufficient to cause the coarse material to be deposited.

In the case of the experimental catchments with weirs at the stream outfalls, the approach channels formed good sediment traps and the material not deposited could be sampled at the weir. Such a procedure may be satisfactory for long period assessment of total sediment transported, but will not be suitable for the derivation of sediment-discharge rating curves.

The amount of sediment removed from the approach channel, and/or the frequency of clearing are good comparative measures of the material transported as bedload. To estimate material carried in suspension, a daily sample of 568 cc (1 pint) was collected. These samples were pooled over a month, and the solid content of the bulk sample obtained by evaporation. However, one daily sample was insufficient to represent the range of sediment concentrations found under stormflow conditions. As sediment yield is proportional to the square of the discharge for a large number of Kenyan streams as a first approximation (Dunne, 1974), it is important to sample the peak flows. With storms of limited duration and short 'times to peak' which are characteristic of small catchments, the probability that a single daily sample is taken at the hydrograph peak is small.

To obtain more representative samples, a stormflow suspended sediment sampler was built at EAAFRO and used at Mbeya. This consisted of two pairs of surface and subsurface sampling bottles designed to operate at different stages of the rising flood (Pereira and Hosegood, 1962). The sampler proved difficult to maintain as a routine instrument and it was not used after 1962. In 1972, a different type of stormflow sampler was introduced which takes samples every hour for 24 hours after triggering at a chosen stage; in this way a composite picture of the sediment yield-discharge curve could be built up.

Because of financial and administrative difficulties, sediment data are fragmentary and incomplete; however, a discussion of such sediment yields as were obtained is given in Section 3.2.2 and 5.2.2. Sediment transport remains an area of study of these catchments which needs to be continued, particularly in view of the widespread concern about increasing sediment loads in major rivers following the preliminary analysis of sediment records in Kenya up to 1965 by Dunne (op cit).

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1.3

THE USE OF CONCEPTUAL MODELS IN CATCHMENT RESEARCH

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INTRODUCTION

Conceptual models, as described below, have become an increasingly important tool in hydrology, and are widely used (a) for estimating streamflow, where the period of rainfall record exceeds that for streamflow record, and (b) for forecasting response to estimated future rainfall or a design storm. They may also form an important part of a real-time management system for river regulation (CWPU, 1977) as for the River Dee in the United Kingdom. Conceptual models are less satisfactory for predicting the effects of changes in vegetation type or cultivation or drainage methods; such problems require the use of more sophisticated models which are, nevertheless, being used increasingly by consultants and planning agencies. A number of such applications are reviewed by Fleming (1975). In the research catchment context, the interactive relationship between catchment modelling, data collection and studies of the physical processes has been referred to in Section 1.1.

A primary requirement for the development and testing of conceptual models is the availability of long, continuous runs of good quality data from catchments with well-documented characteristics. As a result of the bilateral co-operation between the Institute of Hydrology (IH) and EAAFRO from 1967, and the subsequent ODM Research Project, runs of data of some 16 years are available from the EAAFRO catchments at Kericho and Kimakia. These runs, together with similar records from research catchments in the UK, have provided an extremely useful basis for developing, fitting and testing models at IH. The technical aspects of this work are not described here, but details are given of the version of the IH lumped conceptual model (that is, a model in which both precipitation and the processes by which it becomes streamflow have been averaged over the catchment area) which has been fitted to the Kericho and Kimakia catchments and used to investigate possible interpretations of the water balance data. Results of these applications are discussed in Sections 2.2.1 and 3.2.1.

CONCEPTUAL MODELLING

The term 'conceptual model' became widely used in hydrology in the 1960s to describe the transformation of precipitation, possibly together with some index of evaporative demand such as Penman's EO, to streamflow; it was convenient to adopt the terminology of systems theory, in which the catchment is the 'system' which transforms 'inputs' (precipitation, EO) to an 'output' (streamflow). The approach was not new, but the advent of more powerful computers at this time enabled hydrologists to explore the use of more complex functions for describing the transformation, and to apply them to longer runs of data. In particular, the term 'conceptual model' has become associated with the type of lumped, deterministic model pioneered by Crawford and Linsley (1962) in which the catchment is represented by a series of stores; precipitation is then separated into components which are passed from one store to another, and thence either back to the atmosphere as evaporation or to the river channel as streamflow. The transfers of water from one store to another are determined by plausible functional approximations to the physical laws controlling flow through and over porous media and those determining evapotranspiration rates. Where possible, the parameter values in these models are determined from experimental studies; where this is not possible, optimum values are obtained by repeatedly computing the model output using a range of possible values of the parameters in question and comparing the predicted output with that observed. An objective criterion of fit, such as the sum of squared deviations between measured and predicted streamflows, is used to determine when the best fit has been found; parameter values giving this best fit are then 'optimum'. A number of computer methods for calculating optimum parameter values have been reviewed by Clarke (1973).

When fitting the model to catchment records of precipitation, EO and streamflow, the period of record is commonly divided into two parts, one for model calibration (parameter estimation), the other for testing the fitted model by predicting streamflow, assumed unknown, given the precipitation and EO; provided the predicted streamflow agrees sufficiently well with measured values, the model can then be used to estimate streamflow either from estimated future rainfall, or from design storms.

CHOICE OF MODEL

Conceptual models are used in hydrology to estimate certain quantities, and the major consideration governing the choice of design of model for a particular application is that it should yield estimates of acceptable accuracy. Cost considerations obviously dictate that it should be as simple as possible to fit and use. The type of model adopted will depend also on the data available and the time interval ΔT (hourly, daily) over which rainfall and streamflow are accumulated; if the primary requirement is to predict the fine structure of the surface runoff hydrograph from a small catchment, the model type and value of ΔT will be very different from those used to estimate monthly or annual water yield. Choice is further limited by the information available on the physical processes particular to the catchment under study.

The model structure used to describe the hydrological responses of the Kericho and Kimakia catchments was determined by the following considerations.

(a) The streamflow record consisted of a sequence of values of equivalent depth of runoff from the area of the catchment over successive hourly intervals (ΔT = 1 hour); the rainfall record consisted of a sequence of areal means for successive 3-hour intervals (ΔT = 3 hours);

and Penman's EO was calculated for successive daily intervals (ΔT = 1 day).

(b) The surface runoff component of flow was known to be very small (Dagg and Blackie, 1965, Blackie, 1972) so that the model was required to give good estimates of the baseflow component.

(c) Information on soil physical characteristics and monthly sample values of soil moisture deficit were available, although the latter were of limited accuracy.

(d) No field experimental values were available for the parameters required if actual evaporation were to be estimated using the Penman-Monteith formula.

(e) No field experimental values were available for the parameters determining interception by the vegetation, except for the work on tea reported in Section 2.2.3.

Because baseflow is a major component of water yield for the catchments, daily totals of streamflow and mean areal rainfall were derived from the sequences of one-hour and three-hour totals, and this use of a daily time-interval influenced the form of the functional relations used to describe mathematically the transfers of water from one store to another. These functions are described below, together with a brief statement of reasons for the choice.

INSTITUTE OF HYDROLOGY MODEL

Using this computer package, lumped conceptual models may be fitted that (a) use any time interval ΔT for the rainfall, streamflow and EO records; (b) have several choices of functional representations of the store-to-store transfers; and (c) can use any of several parameter optimisation techniques and methods for presenting the model output (Douglas, 1974). The package is being updated continually.

The basic structure of the model used is illustrated in Figure 1. It comprises four stores, representing the canopy interception, the 'surface' storage, the soil moisture storage within the root range, and storage in the groundwater aquifer. The functional representations of the movement of water in this sequence of stores are described below.

Interception Store

Rainfall, RAIN, increases the contents, CS, of this store until its capacity, SS, is reached. Excess rainfall, ERAIN, then 'overflows' to the surface store. Evapotranspiration output, ES, is determined by a parameter FS and Penman EO, written here as EVAP.

$$ES = FS \cdot EVAP$$

The residual evaporative demand, EEVAP, after the store is empty, is applied to the surface store.

This representation of the interception and evaporation process in the canopy is crude by comparison with the model developed by Rutter et al (1972). Justification for its use in these catchments in a daily time interval model comes from the observation that the majority of daily rainfalls derive from single, relatively short duration, high intensity storms. It is reasonable to assume minimal evaporation during the storm and hence constant interception capacity.

Parameters to be optimised or otherwise quantified in this function are FS and SS.

Surface Store

The input, ERAIN, increases the contents, CST, until the store capacity, SST, is reached after which the excess, EERAIN, overflows to the soil moisture store. Output, ECC, from the store occurs as transpiration at the potential rate, FC, relative to Penman EO.

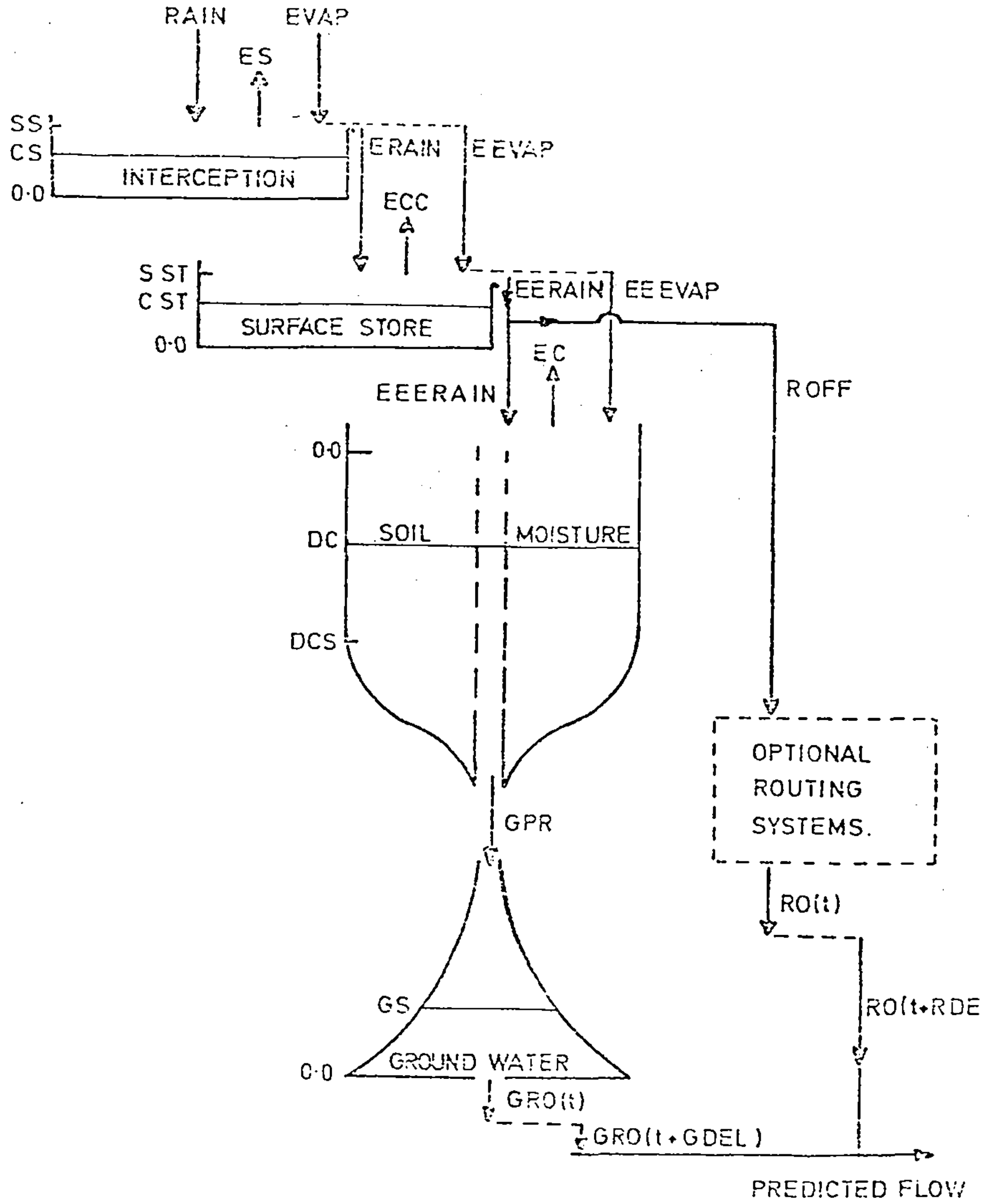

Figure 1 Institute of Hydrology four-store conceptual model

$$ECC = FC \cdot EEVAP$$

The residual evaporative demand, EEEVAP, is applied to the soil moisture store.

Basically, this store represents the detention capacity of surface depressions and the organic litter layer which must be satisfied before lateral flow can occur. In lieu of a drainage function it is allowed to deplete at potential transpiration rate on the basis that this is the rate at which the drainage, representing moisture available at low tension to the root system, would be extracted by the vegetation from the upper layers of the soil moisture store. The parameter to be optimised is SST.

Surface Runoff Function

In this model the surface runoff, ROFF, is quantified explicitly, leaving the infiltration, EEERAIN, as the implicit component of the effective rainfall. From earlier work on these catchments, the magnitude of the surface runoff component of flow was known to be small and essentially intensity dependent (Dagg and Blackie, ibid). Since it was not feasible to include storm intensity in the daily input data, a crude representation of the runoff volume is obtained from

$$ROFF = RC \cdot EERAIN$$

where the parameter RC represents the mean fraction of effective rainfall transformed to surface flow. The volume, ROFF, may be added directly to the daily estimate of baseflow or subjected to a delay, RDEL, or routed through either a linear or non-linear reservoir representation of the flow hydrograph. Routing and delaying produced a marginally better time distribution of this component of flow. The function used was:

$$RO\ (t + RDEL) = RK\ .\ (RSTORE(t))^{RX}$$

The parameters to be optimised are RC, to determine volume, and the routing parameters RK, RX and RDEL.

Soil Moisture Store

Input to this store is the infiltration EEERAIN and outputs are transpiration, EC, and percolation, GPR, to groundwater. Transpiration is determined by the residual evaporative demand, EEEVAP, and the deficit, DC, within the store. The relationship is of the form:

$$EC = FC\ .\ EEEVAP$$

until DC reaches a critical value DCS. Thereafter, the value of FC is decreased progressively using a cosine function of the form:

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

as illustrated in Figure 2. It should be noted that in dry conditions, when the contents of the interception and surface stores are zero, EEEVAP will assume the full Penman EO value EVAP.

A variety of representations of the percolation to groundwater have been explored. That used in this version of the model is a constrained hyperbola relating percolation rate, GPR, to deficit, DC. Within the constraints, the slope of this hyperbola is controlled by a single parameter, AA, as illustrated in Figure 3.

Although the validity of the above cosine and hyperbolic functions can be queried, they nevertheless describe reasonably well the observed relations between EC and DC, and between GPR and DC.

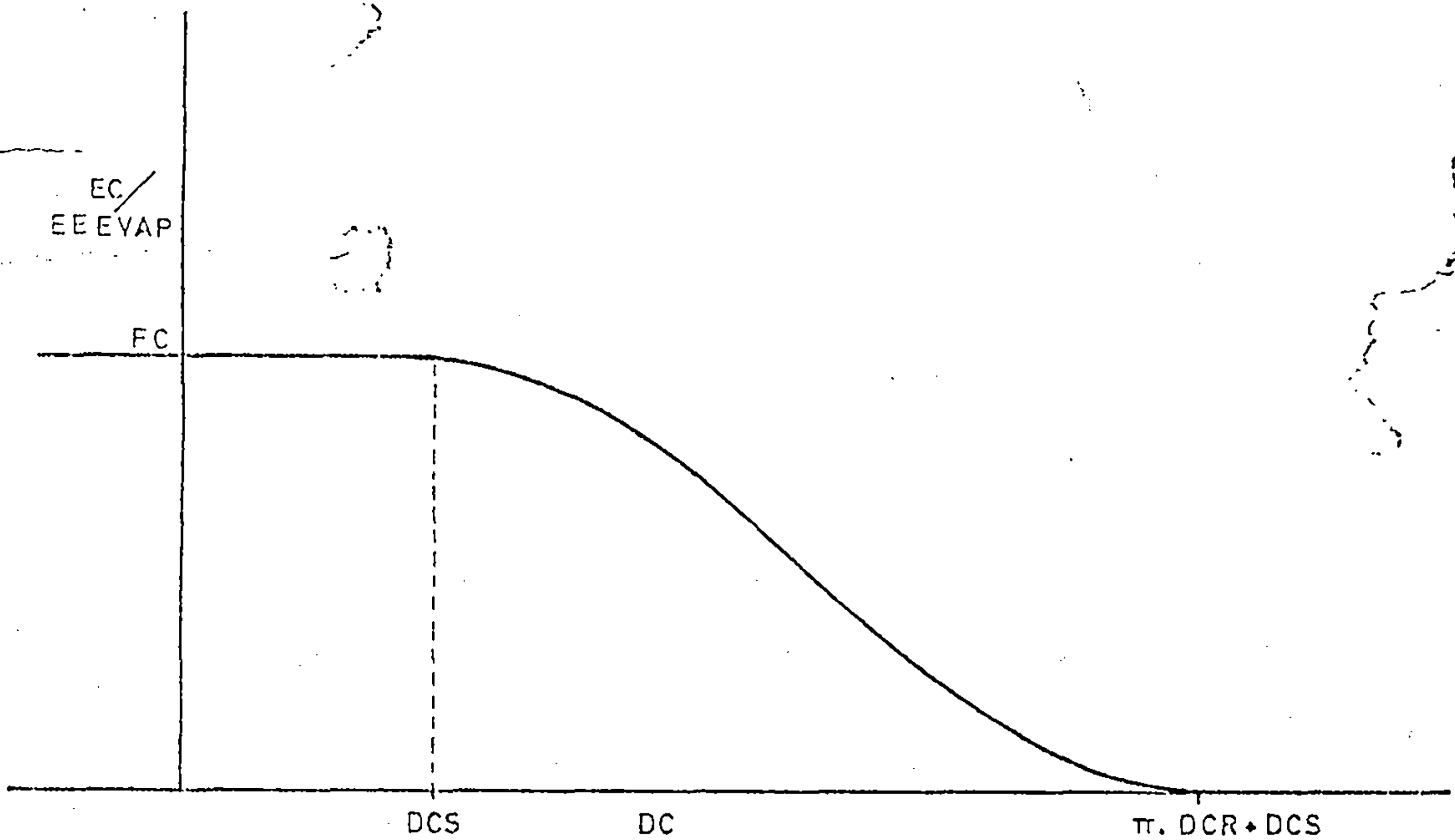

Figure 2   Function used in the model to relate the water use rate, relative to EO, to soil moisture deficit, DC

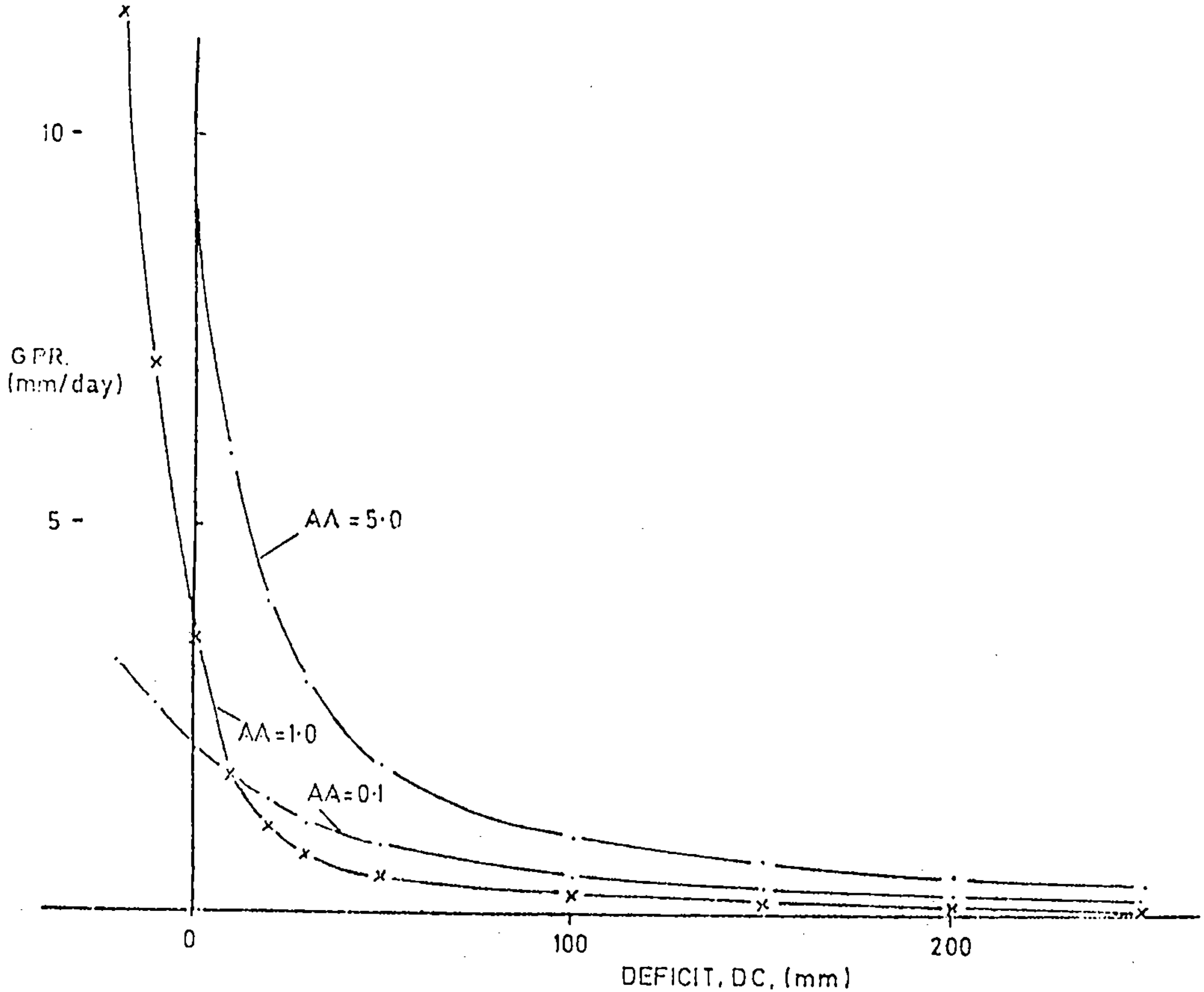

Figure 3 Hyperbolic function used to relate percolation rate, GPR, to soil moisture deficit, DC

The parameters to be optimised or otherwise quantified are FC, DCS and DCR in the transpiration function and AA in the percolation function.

Groundwater Store

Input, GPR, increases the content, GS, of this store which is depleted at a rate GRO, determined by the non-linear reservoir function

$$GRO = (GS/GSU)^{GSP}$$

The output GRO is then delayed by GDEL time units to give the baseflow prediction.

Earlier work on modelling the Kimakia data (Blackie, 1972) showed that this type of non-linear function gave a reasonable representation of the complex baseflow response of these small catchments. With no field observations of the storage changes or knowledge of the aquifer characteristics, baseflow response is determined by optimising parameters GS, GSU and GDEL in the above, together with the parameter AA governing the percolation input.

Input and Output Sequences

For each application of the model, decisions have to be made on the order in which increments to each store, and depletions from it, are to occur within each time interval. In the case of the Kimakia and Kericho catchments, it was decided, on the basis of the diurnal rainfall distributions discussed in Section 1.2.1, that evapotranspiration outputs would precede rainfall inputs in the interception, surface and soil moisture stores. Percolation leaves the soil moisture store after rainfall is input but is not added to the groundwater store until after the output has been computed.

PARAMETER EVALUATION

The model as described includes a total of 14 parameters to be evaluated, whilst starting values must also be attributed to four stores. Given the inevitable degree of interdependence amongst the parameters, it is unrealistic to expect any optimisation technique to evaluate all of them simultaneously; furthermore, a degree of manual intervention became necessary to establish 'best fit' values of certain parameters. In making these essentially subjective adjustments, guidance was obtained (a) from comparison of the predicted deficits, DC, with the field observations; (b) from detailed comparison of the trends in the deviations with those in the field measurements; (c) from comparison of the predicted water use with the water year totals from the water balance. Ideally, deviations between observed and predicted values should be statistically independent; any departure from this ideal indicates either model inadequacy or errors in the data .

MODEL EFFICIENCY

Efficiency of the model in prediction mode was determined objectively by the expression:

$$\text{EFFCY} = (\text{FO} - \text{F}) / _{\text{FO}}$$

$$\text{where FO} = \sum(\text{observed flow} - \text{mean flow})^2$$

$$\text{and} \quad \text{F} = \sum(\text{observed flow} - \text{predicted flow})^2$$

and subjectively by study of any trends in the deviations in flow, soil moisture deficit and annual water use predictions. Details of the results obtained are given in Sections 2.2.1 and 3.2.1.

DATA ERRORS

When dealing with real data, the presence of errors in either the inputs or the observed values creates problems in model fitting and in assessing its validity in prediction mode. Objective methods for distinguishing between departure trends due to model inadequacy and those due to random or systematic data errors are difficult to specify. If a systematic error exists throughout the data run, it will be compensated for in the optimised parameter values. Major random errors or short periods of large systematic error can usually be distinguished by abrupt departure trends not present for similar conditions elsewhere in the run. Models of this type can in fact perform a valuable secondary role as data quality control tools when used by an experienced operator.

EXTRAPOLATION OF RESULTS

Theoretically, it is possible to use models of this type to extrapolate results obtained from land use studies. For example, the parameters determining interception and transpiration by one vegetation type could be applied in another catchment to give estimates of the flow which would result from a change in land use to that vegetation type. This presupposes that the catchment specific parameters such as those determining interstore movement and time distribution of flow can be evaluated for the new catchment.

Great caution must be exercised, however, in this use of lumped models. As mentioned above, if the parameters in question have been determined by optimisation, there is always the possibility that they incorporate the effects of systematic error. Interdependence between parameters may also give rise to errors in prediction if the optimised values are applied elsewhere.

To be of real value in this role, the functions and parameters in question must have their values firmly established from process studies. The model, once the remaining parameters have been optimised in the new catchment, then becomes a suitable method of application of the results of process studies.

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