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3.7

Results of the East African Catchment Experiments 1958–1974

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3.7.1. INTRODUCTION

The expansion of agricultural activity in East Africa following the Second World War led to an increased pressure on the small percentage of the land area considered to have a high potential for agriculture. A good proportion of this land consisted of forested highlands conserved by the Forest Departments to protect water supplies. The timber yield of these indigenous forests was low and economic pressures demanded that the land they occupied should be utilized more efficiently. At the same time, a growing body of scientific evidence was indicating that forests used more water than shorter vegetation (Law, 1956). While not denying the important role of forests in soil conservation, this challenged the widely held view that forests were essential to maintaining streamflow (Nicholson, 1936). There was a clear need to evaluate, by means of controlled experiments, the hydrological effects of land use changes in forested areas which incorporated good soil conservation practices.

These questions were discussed at a Planning Committee Meeting at EAAFRO,* Muguga, in June 1956, during which it was decided that a series of experiments be initiated to investigate the hydrological effects of land use change and that they should be conducted with the strictly practical purpose of providing Government Ministers and their advisers with technical data on the consequences of land use policy decisions. In practice, however, the experiments which were established have yielded numerous results of direct scientific value (Russell, 1962) and continue to supply some of the highest quality hydrological data in Kenya for research purposes (TAMS, 1979).

The preliminary results of the experiments were published in 1962 (Pereira *et al.*,

*East African Agriculture and Forestry Research Organization—now the Agricultural Research Department of the Kenya Agricultural Research Institute.

1962) and the final report, marking the formal conclusion to the Institute of Hydrology's commitment to the programme, in 1979 (Blackie, Edwards, and Clarke, 1979). Numerous papers on individual aspects of the experiments have been published and are included in the list of references in the final report. In addition, a data summary containing daily values of rainfall, streamflow, and evaporation has been published (Edwards *et al.*, 1976). A non-technical summary of the results has also been prepared by the initiator of the original experiments, Sir Charles Pereira, for the use of officials of the respective governments who are charged with land use planning policy (Pereira, 1979).

This paper is intended as a condensation of the technical results in order to bring to the notice of a wider audience the existence of the hydrological analyses and data summaries contained in the above reports. For further reference and details of the associated research projects which lend support to the conclusions outlined here, the Special Issue of the *East African Agricultural and Forestry Journal* (Blackie *et al.*, 1979) should be consulted.

3.7.2. DESCRIPTION OF THE EXPERIMENTS

Four distinct areas in East Africa which were experiencing land-use problems were chosen as sites for the experiments (Figure 3.9). Two were in Kenya and dealt with the replacement of indigenous forest, first, by plantation tea at *Kericho* and, secondly, by exotic conifers at *Kimakia*. A third experiment was at *Mbeya* in southern Tanzania, where an opportunity arose to compare the streamflow and sediment yield in two catchments of similar physical characteristics except for land use; one being under indigenous forest cover and the other cultivated without soil conservation. The fourth experiment dealt with the serious problem of degradation of grass savanna to thorn scrubland—so common in the rangelands of East Africa. At *Atumatak* in north-east Uganda, the soil moisture regime and the streamflow of two adjacent catchments were monitored whilst bush clearing; grass recovery and subsequent controlled grazing took place on one and uncontrolled grazing continued on the other. This experiment, unlike the others, was designed to measure the beneficial effects of a controlled land management policy rather than the possibly deleterious effects of land use changes.

All the experiments were started in 1957 and 1958. Kericho and Kimakia still continue as representative basins under the Kenya Ministry of Water Development, but the detailed monitoring of the effects of the land use change was terminated in June 1974. Mbeya closed in 1969 following increased difficulties in managing the experiment from Muguga, some 1600 km away. Atumatak, the Ugandan experiment, suffered throughout its life from the difficult communications with Muguga but was finally closed in December 1970 following a renewal of stock theft in the region which left 23 people dead, the observers terrorized and all the government cattle stolen.

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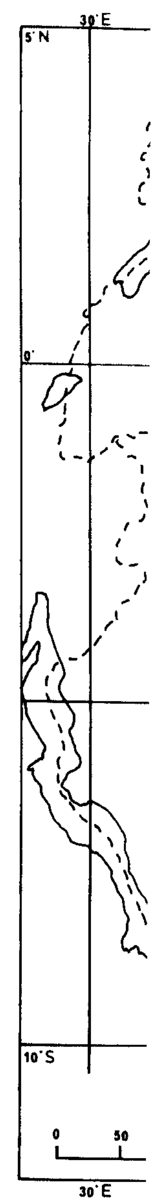

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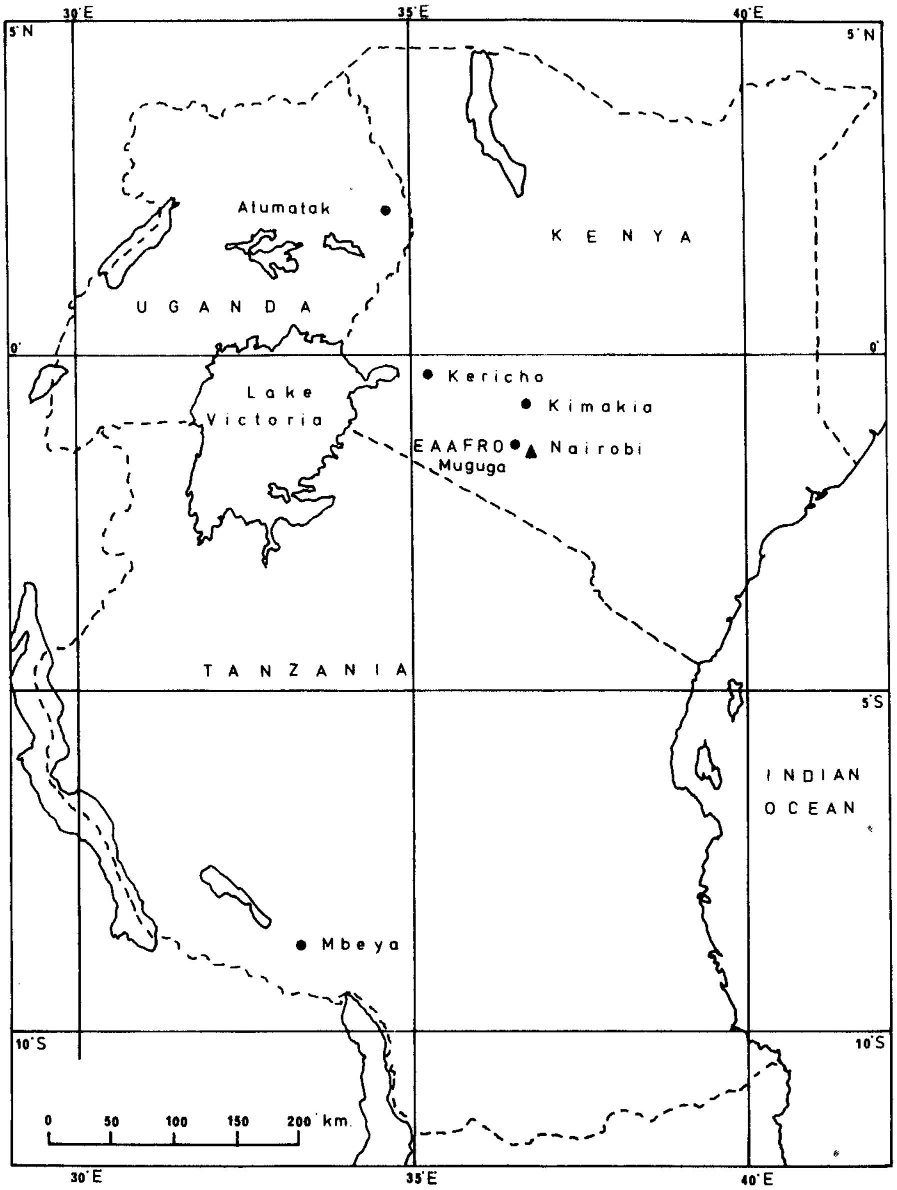

Figure 3.9 Location of the experimental catchments

Government assisted with the management of the experiments and with the task of processing the huge volume of data which had accumulated during the course of the studies. At the same time, the assembly of the data on magnetic tapes was undertaken to allow the development of mathematical models as well as making the data bank available for other users.

The following paragraphs outline the essential details of the individual experiments and the practical objectives in each case.

3.7.2.1. The Kericho Experiments

The successful introduction of tea as a plantation crop in the high rainfall areas of East Africa led to a demand for more forest to be opened up. There was some opposition to any further expansion of the plantations, however, because of the risk to water supplies if forest excision were allowed to continue. Little was known, at the time, of either the water use of tea or the consequences of removing the forest with its protective canopy and deep litter layer. It was decided, therefore, to conduct a controlled experiment near the centre of tea production in Kenya. Two similar catchments on the edge of the South West Mau Forest near Kericho were instrumented to monitor rainfall, potential evaporation, streamflow, soil moisture, and sediment yield before, during, and after a controlled change in land use from indigenous forest to tea plantation in one of them.

One catchment, the Sambret Valley, was excised from the forest and leased to Brooke-Bond Liebig (Kenya) Ltd. to be cleared and planted in accordance with an experimental programme specified by EAAFRO. The other catchment, the Lagan tributary of the Saosa river, remained as a control under broad-leaved montane rain forest.

Both catchments lie less than 0.5° south of the Equator at altitudes between 2000 m and 2800 m. At the beginning of the experiment both were under unbroken forest cover. The soils are deep (6 m), stone free and physically uniform, being derived *in situ* from the phonolitic Tertiary lavas. Rainfall is over 2000 mm per annum, with only three months of the year when it is less than potential open water evaporation (EO). The climatic environment of the two catchments is summarized in Table 3.17 which shows the mean monthly climatological data from the adjacent Tea Research Institute of East Africa.

Basic instrumentation was completed by the end of 1957 and forest clearing in the Sambret catchment began in 1959. By June 1960, the first 120 ha of the new estate were completed and, by 1964, 380 ha of the 702 ha catchment had become tea plantations in accordance with the programme. Because of the presence of the substantial amount of bamboo forest in the remainder of the catchment, a sub-catchment of 186 ha which included the bulk of the bamboo and mixed-bamboo forese was also gauged. The rainfall network in the catchment consisted of 21 daily read gauges including 3 recording gauges. Soil moisture was sampled monthly to 3 m at sites representing the upper, middle, and lower parts of the catchments. From 1968 onwards, access tubes were installed at 14 sites and the neutron probe was used for soil moisture determination.

In the control catchment (544 ha), six gauges were used to sample rainfall and soil moisture access tubes were also situated at the same six sites.

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Table 3.17. Mean climatological data (1958–1974) Kericho (Tea Research Institute) altitude 2073 m, latitude 0° 21′ S, longitude 35° 20′ E

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

Apart from the major monitoring programme, a number of subsidiary projects have been carried out during the course of the experiment. During the establishment of the tea estate, storm runoff from a 12 ha administrative area was compared with a similar area of forest (Dagg and Pratt, 1962). A hydraulic lysimeter study of the water use of tea was conducted at the Tea Research Institute (Dagg, 1970; Wang'ati and Blackie, 1971). An erosion plot experiment was undertaken by the staff of the Tea Research Institute to measure the effects of different conservation techniques on soil and water loss from young tea (Othieno, 1979). In 1975, attempts were made to calculate the direct water loss from a mature tea crop by use of the eddy correlation technique (Callander and Woodhead, 1979) and by use of the Zero Flux Plane method and the Hydraulic Conductivity-Potential Gradient method (Cooper, 1979). All these projects were concerned with providing background information on the main objective, i.e. the hydrological effects of a change in land use from indigenous forest to a well-managed tea estate.

3.7.2.2. The Kimakia Experiments

In the late 1950s, the expansion of the city of Nairobi led to concern about safeguarding its water supply. The city depends heavily on the perennial streams which originate on the forested slopes of the Aberdare Mountains in Central Kenya. These streams also provide critical dry season supplies to the coffee industry and to densely populated rural areas. At the same time, the Forest Department was eager to exploit the high potential of the Aberdares for economic softwood timber production and other forms of land use, such as high density sheep grazing, were being considered. To determine whether such changes in land use would affect total streamflow yield or its seasonal distribution, catchment studies were proposed to compare the water yields from indigenous bamboo forest, softwood plantations, and sheep pasture.

The three catchments studied lie at the southern end of the Aberdares, 0.5° south of the Equator and at a mean altitude of 2440 m. The central catchment is a 65 ha tract of bamboo forest (*Arundinaria alpina*) with scattered evergreen forest species such as *Podocarpus milanjianus*. Nine raingauges, including two recording gauges, were installed in the catchment either in clearings or at canopy level on tree-mounted platforms and on telescopic masts. The experimental catchment (36 ha) was cleared of bamboo in 1956, except for a protective strip on the steep river banks, and planted with pine seedlings (*Pinus patula*) in April 1957. Following the usual Kenyan system of plantation development, vegetables and maize were grown among the pine seedlings until 1960, when the closing pine canopy inhibited interplanting. A further 37 ha valley was instrumented in 1966, partially cleared, planted to Kikuyu grass (*Pennisetum clandestinum*) and subsequently used for a high density sheep grazing trial supervised by the Ministry of Agriculture.

The three catchments are situated on Miocene basalts and agglomerates which give rise to deep, porous soils with high available water capacities (765 mm in the top 3.2 m of soil). Soil moisture was sampled at three sites in each catchment until the introduction of the neutron soil moisture meter made it possible to sample at six sites in the control and the pine catchments and three sites in the grass catchment.

A meteorological enclosure at the Forest Station serves all catchments and a summary of climatological data is given in Table 3.18. Mean annual rainfall is 2235 mm; of the same order as Kericho but with a more pronounced bi-modal distribution.

All catchments are equipped with water level recorders operating on compound sharp-crested weirs. Suspended sediment samples were taken at the weirs during the establishment of the pine plantation and during the last year of the experiment.

3.7.2.3. The Mbeya Experiment

The protection of forest to conserve water supplies has for many years been the cornerstone of forest policy. Despite pressure to release these areas of high agricultural potential, Forest Departments have opposed any proposals to allow further excision until it can be shown that serious and irreversible damage to soils and water supplies will not ensue. At the same time, they have encouraged quantitative studies on the effects of land use change such as the Mbeya experiment in southern Tanzania.

With the gazetting of the Forest Reserve in the Mbeya Range, cultivation of certain areas within the boundary ceased and the local Wasafwa people accepted monetary compensation and moved to an adjacent valley outside the Reserve. An opportunity arose, therefore, to measure the effects of cultivation on sediment and water yield and to compare the hydrological regime of a cultivated and a forested catchment.

With the assistance of the Forest Department and the Department of Water Development and Irrigation, EAAFRO instrumented the catchments and began measurements in 1957. The two catchments chosen are situated on volcanic ash which overlies weathered gneiss of the Pre-Cambrian Basement Complex. The combination of these two parent materials gives rise to a very porous but structurally stable soil. The forested catchment is 16.3 ha in area with very steep valley sides at an average slope of 30° near the weir. The cultivated catchment is as steep as the forested control and 20.2 ha in area, of which about 50 per cent is cultivated in any given season. Both catchments have compound V-notch and rectangular sharp-crested weirs with water level recorders. The cultivated catchment has a sediment trap upstream of the weir and for a time a stormflow sediment sampler was also in operation (Pereira and Hosegood, 1962). Rainfall was measured by six gauges in the forested catchment and seven in the cultivated catchment. Six raingauges were also installed in a regenerating catchment adjacent to the forested control. This catchment was later abandoned as a hydrological experiment but the rainfall network was continued. Of the 19 gauges, five were Dines tilting-syphon recording gauges.

Soil moisture monitoring in the two catchments was accomplished by gravimetric sampling and the installation of electrical resistance blocks.

Table 3.18. Mean climatological data (1958–1974) Kimakia Forest Station altitude 2438 m, latitude 0° 48′ S, longitude 36° 45′ E

	Rainfall	Temperature			Humidity	Wind	Radiation	Sunshine
	Monthly total	Max	Min	Mean	Saturation deficit	Mean speed at 2 m	Gunn Bellani radiometer	
	mm	°C	°C	°C	mb	km hr^{-1}	MJ m^{-2}	hr
Jan	90.4	20.1	6.9	13.5	3.7	9.5	26.4	8.3
Feb	118.8	20.7	7.3	14.0	4.5	9.6	26.9	8.5
Mar	195.1	20.4	8.5	14.4	4.5	10.6	26.2	8.2
Apr	435.5	19.0	9.5	14.3	3.1	9.5	22.3	6.9
May	363.9	17.8	9.1	13.4	2.2	7.6	18.5	5.3
June	126.9	16.5	7.5	12.0	2.0	6.6	17.2	4.9
Jul	86.5	14.8	7.2	11.0	1.4	5.5	13.2	3.1
Aug	85.3	15.0	7.1	11.1	1.4	5.9	9.6	3.3
Sep	78.0	17.5	6.8	12.2	2.6	7.9	21.3	6.0
Oct	226.0	18.4	8.3	13.4	3.4	9.7	23.3	7.1
Nov	306.9	18.2	8.8	13.5	2.8	10.7	21.6	6.4
Dec	121.5	19.1	7.1	13.1	3.1	8.5	24.6	7.7

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A meteorological site was positioned between the two catchments and a summary of climatological data is shown in Table 3.19. It can be seen that the mean annual rainfall of 1733 mm has a pronounced unimodal distribution with a long dry season, in contrast to the two Kenyan catchments.

3.7.2.4. The Atumatak Experiments

Large areas of potentially productive rangeland in East Africa suffer from the effects of overgrazing. The grasslands degrade into bushland and dry thicket and the removal of the protective vegetation, combined with trampling of the surface by animal hooves, leads to a rapid removal of soil, a lowering of the infiltration rate, and flash flooding. In regions of high rainfall erosivity and high soil erodibility, the cycle is self-propagating and may lead to the widespread removal of soil by sheet and gully erosion.

If the cycle can be interrupted in its early stages, however, a comparatively modest expenditure on bush clearing and fencing, together with some system of controlled grazing, can bring about a remarkable recovery of degraded grasslands. The social and economic problems of encouraging pastoralists to limit their herds are formidable and it was thought that a demonstration of the beneficial results of controlled grazing would be an effective means of introducing modern concepts of range management. By choosing two adjacent catchments, one to act as a control and remain under traditional grazing practices and the other to have a system of inexpensive treatment and management imposed, it was hoped that the effect on runoff and on soil moisture regimes could also be demonstrated.

The catchments chosen lie at the head of the Atumatak valley near Moroto in northeastern Uganda. Together they form a well-defined 811 ha catchment draining north into the Omanimani River. The soils are derived from the Basement Complex peneplain and are in an advanced state of erosion. Soil profiles are truncated with stone mantles or erosion pavements exposed throughout the catchments. The climate of the area is summarized in Table 3.20 which shows the mean annual rainfall to be 753 mm. Potential evaporation is of the order of 2000 mm yr^{-1} but, with high wind speeds and large saturation deficits at certain times of the year, there is considerable heat advection. A dense network of 18 daily and 5 recording raingauges was installed in the two catchments. Soil moisture tension was recorded at 20 sites by means of electrical resistance blocks and a meteorological site was established. Because of the large range in discharge and the silt-laden nature of the streamflow, compound rectangular-throated flumes were used to measure discharge. Unfortunately, silt deposition during the recession of the flow was a constant problem. Although remedial measures were attempted during the course of the experiment, they were never completely successful and a considerable amount of flow data was lost.

From 1957 to 1961, the runoff patterns under typical local grazing intensities were determined and surveys of the soil and vegetation were made. In 1961 and

Table 3.19. Mean climatological data (1958–1969) Mbeya range altitude 2428 m, latitude 8° 50′ S, longitude 33° 28′ E

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

Table 3.20. Mean climatological data (1958–1974) Atumatak altitude 1524 m, latitude 2° 14′ N, longitude 34° 39′ E

	Rainfall	Temperature			Humidity	Wind	Radiation	Sunshine[a]
	Monthly total	Max	Min	Mean	Saturation deficit	Mean speed at 2 m	Gunn Bellani radiometer	
	mm	°C	°C	°C	mb	km hr^{-1}	MJ m^{-2}	hr
Jan	10.4	29.9	15.0	22.5	13.1	8.8	27.0	9.8
Feb	22.2	30.3	15.4	22.8	12.7	8.0	26.6	9.2
Mar	56.7	29.7	15.8	22.8	11.6	8.0	26.2	8.7
Apr	121.7	28.2	16.1	22.2	9.0	6.5	23.5	7.9
May	105.8	27.4	15.1	21.3	6.8	4.1	23.3	8.2
Jun	54.3	27.6	14.2	20.9	7.5	4.0	23.2	8.6
Jul	110.1	26.2	14.6	20.4	6.6	3.8	21.7	7.2
Aug	93.3	26.9	14.4	20.7	7.3	4.4	23.6	8.0
Sep	59.6	28.3	13.9	21.1	8.6	4.8	26.0	8.9
Oct	49.8	28.6	15.8	22.2	10.5	7.3	25.5	8.7
Nov	49.3	28.4	16.0	22.2	10.8	8.7	24.8	8.5
Dec	20.0	28.9	15.0	21.9	11.5	9.0	25.8	9.5

[a] Sunshine records incomplete (1971–1974)

1962, one catchment was cleared of bush and fenced to exclude cattle while the other remained under the traditional grazing system. By 1964, a grass cover had re-established itself in the cleared catchment and, having demonstrated that this minimum treatment produced good rehabilitation, the next stage was to introduce grazing on a controlled basis to determine the optimum grazing densities. Grazing started in 1965 but, because of the many difficulties experienced (including theft of fencing wire, illicit grazing, and theft of stock), the proposed rotational grazing scheme was never fully implemented.

Towards the end of the experiment, the problems of maintaining and operating instrument networks became overwhelming and the continuity and quality of the catchment data deteriorated. So little is known about the hydrology of these semi-arid areas, however, that an attempt has been made at the interpretation of the experimental data.

3.7.3. METHOD OF ANALYSIS OF EXPERIMENTAL DATA

Previous hydrological experiments of this nature required lengthy calibration periods or repeated trials to establish statistically valid results (Bates and Henry, 1928; Wicht, 1966). With the advent of better methods of estimating the evaporation from natural surfaces (Penman, 1948) and a general improvement in methods of measuring the major components of the hydrological cycle, it became possible to calculate the water balances of individual catchments with reasonable precision, to check the results with the energy balance and to produce comparative estimates of the water use of different types of vegetation. The 'paired catchment' method became the basis for the EAAFRO experiments and implicit in this method is the use of the water balance equation to evaluate the unknown components. This equation can be written in general form as:

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

where R, Q are precipitation and streamflow, AE is actual evapotranspiration and ΔS, ΔG are changes in soil moisture and groundwater storage, respectively, over whatever period is specified.

Because of the slow transfer of infiltrated water from soil moisture to groundwater and finally to base flow, the calculation of AE (actual evapotranspiration) by difference becomes most precise when the ΔS and ΔG terms are evaluated in the dry season. At this time, ΔS can be measured with great precision and ΔG can be estimated from base-flow recession curves with some confidence (Blackie, 1972). From this emerges the concept of a 'water year', a time interval of approximately one calendar year running from one dry season to the following equivalent dry season, as a period over which consecutive estimates of water use can be made with precision.

Thus the water balance equation can be used to calculate actual water use of the paired catchments over a series of water years. Similar values of water use should be obtained during the calibration period, but if the imposed land use change coincides with a major climatic fluctuation, as in the case of the Kimakia and Kericho experiments, the resulting variations in hydrological regime from very dry to very wet years may confuse the comparison of the values of *AE* derived before and after the change. If the values are consistent with theoretical estimates of evaporation of intercepted water and of transpiration, it lends confidence to the assumption that the measured changes in streamflow are entirely attributable to the land use change. If not, there will be reason to believe that the differences in streamflow are due to other factors such as the failure of the recession curve method to estimate total groundwater storage change or the presence of systematic errors in the data.

Generally speaking, the water balance equation was used initially to detect systematic errors and then when it was considered that all major errors had been corrected, the streamflow regimes were accepted as being characteristic of the respective vegetation types. To interpret these regimes, use has been made of evidence from the studies of the physical processes of evaporation and transpiration and from the application of simple conceptual models to simulate the streamflow response to changes in physical parameter values such as interception storage, the rate of evaporation of intercepted water, and crop albedo. It is not possible to enter into a detailed description of the results of either the process investigations or the mathematical modelling in this condensed report and the results presented are confined to estimates of water use of the different types of vegetation derived from the water balance and to differences in the seasonal patterns of streamflow.

It has become clear during the analysis of the 130 catchment years of data that the precise measurement of rainfall and streamflow are of paramount importance in studies of this kind. Fortunately the rainfall networks were designed with great care (McCulloch, 1962) and the precision of the areal rainfall estimates is high. The measurement of streamflow, on the other hand, has given cause for concern in some of the catchments and retrospective corrections to streamflow based on reassessments of the rating curves account for the differences between previously published values and those presented here. Throughout the analysis, the Penman method has been used to estimate open water evaporation (*EO*) for each pair of catchments and the ratio of actual water use (*AE*) to *EO* is used as the index of comparative water use.

3.7.4. RESULTS OF THE CATCHMENT EXPERIMENTS

Water balance results are presented for the Kericho, Kimakia, and Mbeya experiments. Atumatak flow data was discontinuous and did not allow water balance calculations to be made.

3.7.4.1. Annual Water Balance

Table 3.21 lists the mean water year *AE*/*EO* ratios for the years following the establishment of each new land use. These show that none of the land use changes

Table 3.21. Comparison of mean water year *AE/EO* ratios for the Kericho, Kimakia, and Mbeya catchments for the periods after each new land use was fully established

Location	Catchment	Dominant vegetation	Period	Mean rainfall (mm)	SEE	*AE/EO*	SEE
Kericho	Lagan	Montane rainforest	1967–73	2219	±149	0.93	±0.032
	Sambret sub-catchment	Bamboo		2026	±140	0.86	±0.022
	Sambret	Tea		2011	±139	0.84	±0.030
Kimakia	C	Bamboo	1967–73	2143	±158	0.76	±0.012
	A	Pines		1997	±151	0.76	±0.020
	M	33% Grass		2062	±137	0.70[a]	±0.023
Mbeya	C	Montane rainforest	1958–68	1924	±143	0.93	±0.065
	A	Cultivated crops		1658	±120	0.64	±0.025

[a] R–Q only

resulted in an increase in long-term water use. Thus, total water available to the downstream user has not been adversely affected. As indicated by the standard errors in Table 3.21, some year to year variability in the *AE/EO* ratios was observed. A detailed examination of the year to year variations (Tables 3.22–3.28) showed that most if not all of the variations could be accounted for by the enhancement of *AE* values in wet years, when evaporation of intercepted water became a more significant factor, and by the reduction of *AE* values in dry years when large soil moisture deficits brought about a reduction in transpiration.

Simulation of the evaporative process using a mathematical model indicated that the rate of evaporation of intercepted water from each tall vegetation type was considerably in excess of *EO*. Wet season water use can be expected to exceed the mean value for the year, therefore, and the annual mean itself will fluctuate from year to year with variation in rainfall amount and frequency. Similar simulation of the control exerted by soil moisture deficit on rates of transpiration showed that some of the residual variability in *AE/EO* rates could be explained for the forest and bamboo catchments at Kericho, but not for the bamboo and pines at Kimakia. This may merely be a reflection of the greater frequency of severe drought conditions at Kericho than at Kimakia. In the case of tea, both the soil sampling results and the heat flux studies indicated a significant decrease in transpiration rates with increasing soil moisture deficit.

The apparent year to year variations in *AE/EO* for the Mbeya catchments (Tables 3.27 and 3.28) are almost certainly inaccurate indications of the true variability. A stone mantle made it impossible to sample soil moisture reliably below a

Table 3.22. Water use estimates, AE, for the control catchment (indigenous forest) at Kericho

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

depth of a metre, whereas qualitative methods (gypsum block profiles) indicated that considerable deficits developed to at least 20 m under the cultivated catchment and to well below 3 m under the forest, where roots have been traced to 8 m depth. Thus the ΔS values are unreliable. Using a conceptual model (Blackie *et al.*, 1979) with parameters derived from the Kericho forest catchment an attempt has been made to estimate annual water use of the forested catchment (Table 3.27) and hence the probable error in the storage changes.

The AE/EO values given in Table 3.21 can be used to predict annual water losses from similar vegetation in similar rainfall and climatic regimes. From the preceding discussion, it is clear that the dependence of water use on the intensity and frequency of rainfall and on total water availability within the profile must be taken

Table 3.23. Water use estimates, *AE* for the experimental catchment (tea) at Kericho

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

into account if the results are to be extrapolated to markedly different climatic regimes.

3.7.4.2. Seasonal Distribution of Streamflow

The assessment of the extent to which land use changes have affected the seasonal distribution of streamflow is made particularly difficult because factors other than land use can enter into 'before and after' or ' between catchments' comparisons, making a simple analysis impossible. For instance, the change from drier-than-average conditions in the late 1950s to the unusually wet years of 1961 and 1962 coincided

Table 3.24. Water use

Water year Ref. No.	Starting date
0	
1	
	100262
2	
	111262
3	
	111063
4	
	101164
5	
	101265
6	
	101066
7	
	100168
8	
	071068
9	
	300969
10	
	031270
11	
	021171
12	
	271272
13	
	011073
Totals 2–13	

most unfortunately w
Furthermore, it has be
of forest is the frequ
catchment variations i
streamflow. In the an
that the relationship o
characteristics varied e
Rather than attemp
unwarranted conclusio
seasonal streamflow di
on the most important
off, infiltration, and gr

Table 3.24. Water use estimates, *AE* for the bamboo sub-catchment at Kericho

Water year Ref. No.	Starting date	Rain mm	Flow mm	ΔS mm	ΔG mm	*AE* mm	*EO* mm	*AE/EO*
0		—	—	—	—	—		
1		—	—	—	—	—		
	100262							
2		2280	1240	+2	−31	1069	1214	0.88
	111262							
3		1975	931	−32	+9	1067	1209	0.88
	111063							
4		2468	1087	+43	+27	1311	1555	0.84
	101164							
5		1547	274	−5	−56	1334	1596	0.84
	101265							
6		1708	545	−28	+56	1135	1205	0.94
	101066							
7		2508	998	−15	−32	1557	1978	0.79
	100168							
8		1844	863	+70	+5	906	1017	0.89
	071068							
9		1504	335	−16	−10	1195	1429	0.84
	300969							
10		2496	1011	−55	+15	1525	1699	0.90
	031270							
11		1945	807	+2	−5	1141	1366	0.84
	021171							
12		2085	674	+23	−5	1393	1705	0.82
	271272							
13		1798	622	−64	0	1240	1272	0.97
	011073							
Totals 2–13		24158	9387	−75	−27	14873	17245	0.86

most unfortunately with the major period of land use change in the catchments. Furthermore, it has been seen that a most important factor affecting the water use of forest is the frequency of canopy wetting and, hence, seasonal and between catchment variations in rainfall input can have a strong influence on the pattern of streamflow. In the analysis of seasonal streamflow data, it became apparent also that the relationship of the recession curve to inherent geometric, soil and aquifer characteristics varied even between adjacent paired catchments.

Rather than attempt to oversimplify these relationships, with the risk of drawing unwarranted conclusions, statements on the effects of the land use changes on seasonal streamflow distribution have been confined to comments on their effects on the most important processes contributing to streamflow. These are surface run-off, infiltration, and groundwater recharge.

Table 3.25. Water use estimates, AE for the control catchment (bamboo) at Kimakia

Water year Ref. No.	Starting date	Rain mm	Flow mm	ΔS mm	ΔG mm	AE mm	EO mm	AE/EO
58	260258	2322	1381	−97	−52	1090	1497	0.73
59	240259	1858	792	+49	+24	993	1404	0.71
60	280160	1966	895	−21	−16	1108	1583	0.70
61	260161	3456	2160	−57	+20	1333	1707	0.78
62	280262	2431	1246	+159	+47	979	1260	0.78
63	290163	2656	1533	−28	−28	1179	1483	0.80
64	300164	2758	1516	−83	−36	1361	1496	0.91
65	100365	2219	1043	+66	+19	1091	1256	0.87
66	270166	2253	1208	−130	−26	1202	1430	0.84
67	160167	2192	956	+70	+30	1136	1540	0.74
68	100168	2645	1502	−51	−7	1202	1467	0.82
69	210169	1875	534	+62	−10	1289	1690	0.76
70	280270	2020	1008	−55	−13	1080	1361	0.79
71	110271	2036	803	+111	+43	1079	1441	0.75
72	260172	2705	1332	+18	+38	1317	1722	0.76
73	270273	1527	706	−162	−77	1060	1477	0.72
	020274							
Totals 58–73		36919	18615	−149	−44	18497	23814	0.78
Totals 67–73		15000	6841	−7	+4	8162	10698	0.763

3.7.4.2.1. Surface Runoff and Infiltration

All the catchments at Kericho, Kimakia, and Mbeya are on volcanic soils with high infiltration rates. Surface runoff constitutes only a small percentage of total stream-flow (two to three per cent) when the indigenous forest cover is present and this

Table 3.26. Water use estimates, *AE* for the experimental catchment (pines) at Kimakia

Water year Ref. No.	Starting date	Rain mm	Flow mm	ΔS mm	ΔG mm	*AE* mm	*EO* mm	*AE/EO*
	040258							
58	060259	2416	1519	−35	+4	928	1496	0.62
59	050260	1813	874	+29	−6	916	1548	0.59
60	080261	1842	936	−34	−26	966	1619	0.60
61	140362	3319	2096	−59	+6	1276	1706	0.75
62	140363	2536	1219	+117	+20	1180	1414	0.83
63	110364	2716	1505	+8	+12	1191	1439	0.83
64	200365	2297	1551	−122	−39	907	1362	0.67
65	240266	2255	1027	+86	+4	1138	1356	0.84
66	310167	1989	1116	−109	−14	996	1368	0.73
67	240168	2029	844	+98	+23	1064	1539	0.69
68	210169	2524	1390	−32	+10	1156	1379	0.84
69	280270	1763	454	+47	−50	1312	1690	0.78
70	110271	1882	829	−60	+11	1102	1361	0.81
71	260172	1816	619	+145	+14	1038	1441	0.72
72	270273	2520	1084	+22	+62	1352	1722	0.79
73	020274	1443	604	−192	−64	1095	1477	0.74
Totals 58–73		35160	17667	−91	−33	17617	23917	0.74
Totals 67–73		13977	5824	+4	+6	8119	10609	0.765

proportion did not change materially except during the transition stages of the land use changes (Pereira *et al.*, 1962). At Kimakia this result is not so surprising since the pine plantation rapidly developed both a protective canopy and a deep litter layer. At Kericho, it was attributable to the efficiency of the soil and water conservation measures used in establishing the tea estate. Othieno (1979) demonstrated that the same soils can give higher rates of runoff when less effective measures are

Table 3.27. Water balance (mm) for Mbeya catchment C (forested)

Water year	Rain	Flow	Apparent AE	Simulated AE^{a}	EO	Apparent AE/EO	Simulated AE/EO	Estimated error in $\Delta S + \Delta G$
1958–59	1421	214	1189	1522	1722	0.69	0.88	−333
1959–60	2043	564	1470	1418	1526	0.96	0.93	+52
1960–61	1332	330	1070	1564	1773	0.60	0.88	−494
1961–62	2753	842	1784	1330	1406	1.27	0.95	+454
1962–63	1878	534	1405	1335	1453	0.97	0.92	+70
1963–64	2199	652	1516	1380	1481	1.02	0.93	+136
1964–65	1512	446	1105	1322	1482	0.75	0.89	−217
1965–66	2013	564	1437	1284	1380	1.04	0.93	+153
1966–67	1681	453	1228	1314	1435	0.86	0.92	−86
1967–68	2404	814	1610	1364	1441	1.12	0.95	+246
Mean	1924	541	1381	1383	1510	0.92	0.92	−2
	±143	±62	±73	±29	±42	±0.06	±0.01	±90

[a] Modelled using parameter values for canopy storage, interception evaporation, and transpiration for the forested area derived from the Kericho forested catchment and mean water use of 0.65 *EO* for the grass area.

Table 3.28. Water balance, Mbeya catchment A (cultivated)

Period	R	Q	ΔS^a	ΔG	AE	EO	AE/EO
20.10.58–10.10.59	1320	329	+4	0	987	1625	0.61
10.10.59–10.10.60	1718	578	+6	+90	1044	1527	0.68
10.10.60–10.10.61	1190	391	+18	−109	890	1687	0.53
10.10.61–10.10.62	2248	1112	−27	+163	1000	1462	0.68
10.10.62–10.10.63	1548	628	+14	−72	978	1488	0.66
10.10.63–13.10.64	1884	854	−3	+15	1018	1449	0.70
13.10.64–10.8.65	1369	418	+25	−15	941	1165	0.81
10.8.65–10.10.66	1485	548	−22	−21	980	1691	0.58
10.10.66–10.10.67	1570	485	+18	−22	1089	1368	0.80
10.10.67–10.10.68	2240	1326	+24	+114	776	1379	0.56
Mean 1958–68	1657	667	6	14	970	1484	0.65
	±116	±104	±6	±27	±28	±51	±0.03

[a]Measured to 1 m depth only and known to underestimate total storage change.

adopted. At Mbeya, the very small increase in surface runoff when forest gives way to smallholder cultivation incorporating no effective measures to prevent erosion is a surprising result and atypical of experience elsewhere in East Africa. This is attributed to the remarkable wet season stability of the ash-derived soils, combined with the low erosivity of rainfall in this part of Tanzania (Moore, 1978).

At Atumatak, records from the soil moisture tension blocks demonstrated a recovery in infiltration rates (Table 3.29) following the re-establishment of grass cover in the cleared catchment. Starting from a slightly lower frequency of penetration to consecutive depths, the cleared catchment (*B*) ended up with a higher frequency of penetration at most sites down to a depth of 60 cm. A corollary to the recovery in infiltration was the reduction in storm runoff from the improved catchment. Table 3.30 shows how the runoff coefficient (Q/R per cent) increased during the clearing phase and then decreased significantly when the grass began to recover. Mean runoff coefficients can be deceptive since the actual values vary widely with antecedent soil moisture conditions and rainfall intensity. Table 3.31 shows the same data as a frequency distribution for various class intervals of runoff percentages and reinforces the striking and rapid recovery following the modest management programme.

The extent of recovery at Atumatak was very largely a function of the degree to which soil cover had been removed prior to rehabilitation. Whereas the least eroded soils recovered rapidly, steeper or less protected slopes still showed signs of a change in grass succession 12 years after clearing. The speed of recovery reflects the importance of maintaining infiltration rates on pasture land. As the colonizing grasses decreased surface runoff and increased infiltration, more moisture became available in the root range to sustain growth and facilitate propagation.

Table 3.29. Frequency of rainfall penetration at Atumatak

	Year	Mean number of readings		Depth in cm 15	30	45	60	90	120	180	240
	1959	*A*	31	38	38	10	6	13	0	0	0
		B	31	38	18	4	8	0	0	0	0
Pre-clearing	1960	*A*	48	47	43	19	11	21	14	0	0
		B	50	44	35	7	21	0	0	2	0
	1961	*A*	48	66	59	52	39	30	12	17	17
		B	49	62	48	32	38	12	12	4	4
Mean for pre-clearing phase 1959–1961		*A*		50	46	27	18	21	9	6	6
		B		48	34	14	22	4	2	2	1
Values for clearing phase 1962–1963	1962	*A*		Very few readings							
		B									
	1963	*A*	44	48	37	31	38	13	18	52	32
		B	43	50	50	38	45	35	23	14	9
	1964	*A*	48	22	15	9	13	1	3	6	3
		B	47	32	34	18	12	4	2	0	0
	1965	*A*	31	19	19	12	9	0	0	0	13
		B	31	27	18	13	17	0	0	0	0
Post-clearing	1966, 1967, 1968			Very few readings							
	1969	*A*	46	8	4	4	3	0	0	0	0
		B	43	19	19	11	15	1	0	2	0
	1970	*A*	50	20	19	16	14	1	2	0	8
		B	53	44	42	37	41	1	0	2	0
Mean for post-clearing phase 1964–1970		*A*		17	14	10	10	0	1	2	6
		B		30	26	19	21	22	1	1	0

B is the cleared catchment and *A* the control.
Figures indicate the mean percentage frequency with which available moisture was indicated by the resistance blocks.

3.7.4.2.2. Groundwater Recharge

Recharge of the catchment aquifers is governed by the amount of rainfall which infiltrates into the soil moisture store and by the rate at which this store is depleted by transpiration. For instance, changes in the interception characteristics of the vegetation will affect the amount of water available for infiltration and a higher transpiration rate will lead to a larger proportion of the infiltrated moisture being

Table 3.30. Depths of runoff and rainfall (mm) for a sample of storms (*n*) at Autumatak

		Catchment *A* (control, untreated)			Catchment *B* (bush-cleared)		
	n	*Q*	*R*	*Q/R%*	*Q*	*R*	*Q/R%*
Bush-clearing 1959–1961	59	70.73	678.8	10.4	76.02	785.9	9.7
During clearing 1962–1963	53	65.40	838.3	7.8	135.44	868.0	15.6
After clearing 1964–1968	61	160.09	1109.1	14.4	74.86	1092.8	6.8

Table 3.31. Number of occurrences of *Q/R%* values fitting in percentage classes at Atumatak

		Percentage						
		0–4.9	5.0–9.9	10.0–14.9	15.0–19.9	20.0–29.9	30.0–39.9	40 and over
1959–1961	*A*	32	11	3	8	3	2	5
	B	30	11	9	5	3	3	3
1962–1963	*A*	34	6	3	4	4	1	0
	B	22	9	3	3	7	4	4
1964–1968	*A*	21	8	13	5	8	5	1
	B	40	9	2	5	2	2	1

A and *B* are respectively the control and treated catchments

required to replenish the soil moisture store before groundwater recharge may begin.

Direct measurements of interception storage, soil moisture movement, and rates of transpiration were carried out only on the tea catchment at Kericho. In the other catchments, these processes were simulated in the mathematical modelling. At Kericho the process and modelling studies implied some change in groundwater recharge and hence in seasonal baseflow distribution due to lower interception losses and higher transpiration rates from the tea. In the particular environment at Kericho, however, these effects were small enough to be obscured by between-catchment differences in rainfall distribution and aquifer characteristics. In the change from bamboo to pines at Kimakia no significant differences in these processes were detected by the modelling; it may be concluded that there was no significant modification to baseflow. Thus whilst the catchment studies gave the practical answer of no change in seasonal streamflow distribution at Kericho and Kimakia, the data were sufficiently detailed to support modelling of the processes; this, in turn, identified the need for further investigation of interception and transpiration before global predictions can be made.

At Mbeya the change from evergreen forest to cultivation resulted in a marked decrease in interception and in dry season transpiration in the cultivated catchment, giving an overall increase in baseflow; observed baseflow levels were, on average, twice as high in the cultivated catchment. In the Atumatak study the marked increase in infiltration resulted in a substantial improvement in the grass cover, the enhanced transpiration of which did not permit any significant groundwater recharge and hence any significant base flow.

3.7.4.3. Sediment Yield

In the Kimakia and Kericho experiments steady-flow suspended sediment data were collected and, apart from some inconsequential increases during the transition phases, no significant differences in sediment yield from the different catchments could be detected. In all catchments, the sediment concentrations were low and more recent measurements at Kimakia, made with an automatic sediment sampler, confirmed the low sediment yields even in a catchment which had only recently (1973) been partly cleared and converted to smallholder cultivation.

At Kericho, once the tea crop had become established, the only appreciable sediment movement was a direct result of runoff from the estate roads.

At Mbeya, more detailed measurements were made. A stormflow sediment sampler was installed at the weir in the cultivated catchment and a bed-load trap was constructed just upstream. The results suggest that by far the largest percentage of total sediment load was contributed by stormflow (60 per cent). Bed load constituted some 36 per cent and the steady-flow suspended sediment was about four per cent. The total load was estimated as 9 t ha^{-1} yr^{-1} in the cultivated catchment compared with practically nil in the forested catchment. This quantity is surprisingly small considering the steepness of the cultivated land (*c*. 30°) and the absence of any conservation measures, apart from ineffective bunds of maize stalks.

3.7.5. CONCLUSIONS

The conclusion of these land use studies may be summarized as follows.

(a) Replacement of rain forest by tea estate at Kericho resulted in an overall reduction in water use, combined with no significant increase in surface runoff or of sediment loss. This result will apply on similar soils experiencing similar rainfall distribution provided only that equally efficient soil conservation measures are adopted. Whilst, at Kericho, no significant change in seasonal flows was observed, process and modelling studies revealed differences in interception and transpiration which, in other environments, might alter the seasonal distribution of streamflow.

(b) Replacement of bamboo forest by pine softwood plantations at Kimakia initially decreased the water use; once the pine canopy had closed, no significant differences in water or sediment yield could be detected. The modelling suggested that this result could be applicable in a wide range of climatic conditions, provided only that the soils are equally stable. The effects of the felling phase remain to be investigated.

(c) At Mbeya, the replacement of evergreen forest by smallholder cultivation on very steep slopes resulted in a large increase in water yield. Because of the remarkably stable, porous nature of the ash-derived soils, only marginal increases in surface runoff and sediment loss were recorded but the dry season baseflow was doubled. Whilst a similar increase in water yield can be expected following this land use change in other unimodal rainfall areas, maintenance of seasonal flow patterns and of water quality is critically dependent on soil type.

(d) Bush clearing followed by several years of cattle exclusion resulted in a remarkable grass recolonization of the severely overgrazed rangeland at Atumatak. This recolonization increased infiltration rates and drastically reduced the peak flows. Subsequent controlled grazing did not affect the hydrological stability of the improved regime.

The scientific and practical results outlined above, together with the pointers to further areas of necessary research, prove the value of well designed and executed catchment studies. Apart from producing answers to important local practical questions, they also provide the quality of data necessary to test theories or models of how the processes controlling the hydrological cycle work and interact.

Such models are necessary for the global prediction of the effects of land use changes. The individual components may be constructed on the basis of the results of process studies but, to achieve acceptability, the complete model must be shown to work on long runs of high quality catchment data. These data must achieve an accuracy, particularly in areal estimates of input and output far exceeding that normally expected from a national hydrometeorological network.

3.7.6. ACKNOWLEDGEMENTS

The success of the experiments, which continued while very great changes were taking place in the structure of government in the three countries involved, is a tribute to the foresight of the instigator of the experiments, Sir Charles Pereira, and to the willingness of the various government departments as well as the UK Ministry of Overseas Development to sponsor and to staff the project. The quality of the data bank which is now available from the Institute of Hydrology and the Kenya Agricultural Research Institute, is also a tribute to the diligence of the observers, some of whom worked for seventeen years in the same catchment.

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3.8

Recent Studies on Soil Erosion, Sediment Transport, and Reservoir Sedimentation in Semi-arid Central Tanzania

L. STROMQUIST

3.8.1. INTRODUCTION

Tanzania is situated between latitudes 1° and 12° S. It covers an area of 884,000 square kilometres. The estimated population is 16 million out of which more than 93 per cent live in rural areas. Broadly speaking Tanzania has two types of environments with a high soil erosion hazard: the humid mountains with steep cultivated slopes and the semi-arid plains (cf. Figure 3.10 and 3.11). The semi-arid region is defined by the Tanzania government (1977) as the area included within the 800 mm yearly rainfall isohyet, thus covering most of the central provinces and the new national capital at Dodoma. Approximately 3 million people live within this area, from time to time affected by water shortage and local human starvation.

The aim of this paper is to give a brief presentation of some recent studies of soil erosion made within the country, with an emphasis on those from the dry lands. An excellent survey of the past and present erosion rates and processes was presented in fifteen papers published as *Studies of Soil Erosion and Sedimentation in Tanzania* (Rapp, Berry, and Temple, eds., 1972a). The study was made within the Dar-es-Salaam–Uppsala Soil Erosion Research project (DUSER) jointly managed by the universitities in Dar-es-Salaam and Uppsala. These papers form an integrated geographical study of erosion and sedimentation in some tropical environments under heavy human influence. The main approach to the project was geomorphological and hydrological as surface runoff, erosion and sedimentation were documented in a number of catchment areas. The studies of the watersheds were supplemented by earlier data from various erosion plots, etc. Hence the DUSER-project included types of environments sensitive to severe soil erosion: the semi arid savannas and the humid mountains. The project was carried out between 1968 and 1972. In two

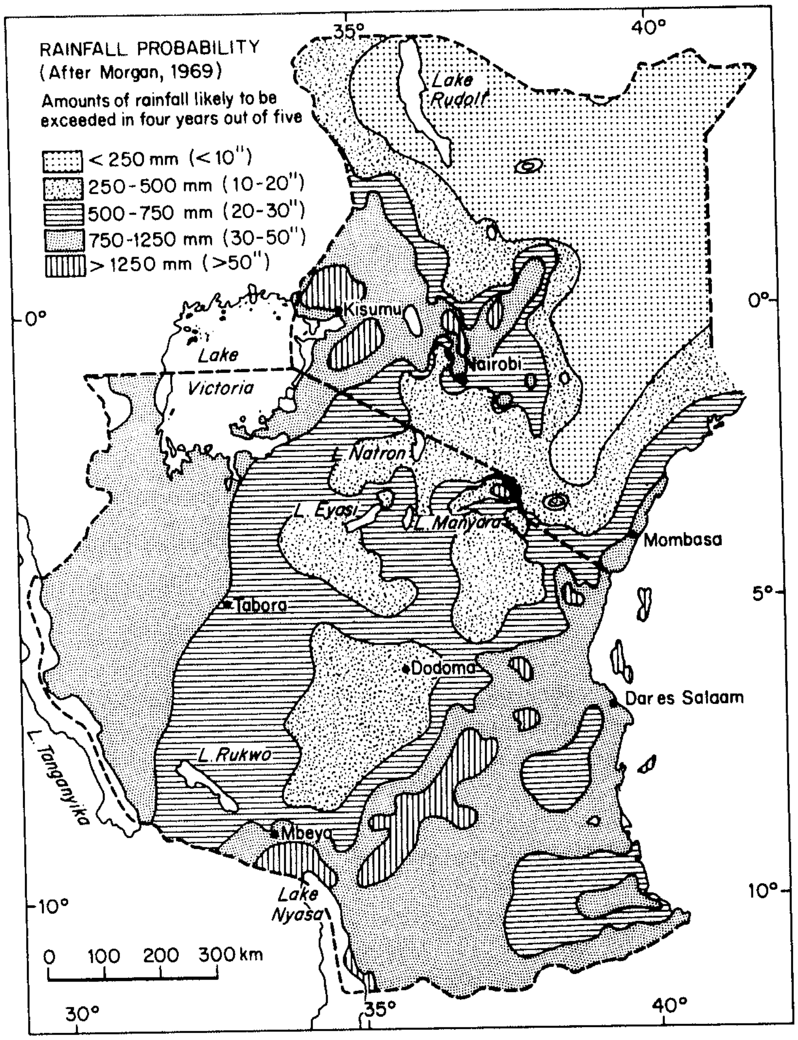

Figure 3.10 Rainfall probability in Kenya–Tanzania

of the studied areas further investigations have been made: by Christiansson (1978) in the Dodoma area and by Lundgren (1975; 1978) in the Ulugure mountains (cf. Figure 3.11).

One of the largest development schemes in semi arid Tanzania, is the Kidatu hydroelectric power plant in the Great Ruaha river and the river storage reservoirs at Kidatu and Mtera, a site 1975 km upstream from the plant. The main environmental impact in the river basin will be caused by the Mtera storage reservoir, which after the impoundment in 1980 will cover some 600 km^2 of land close to the con-

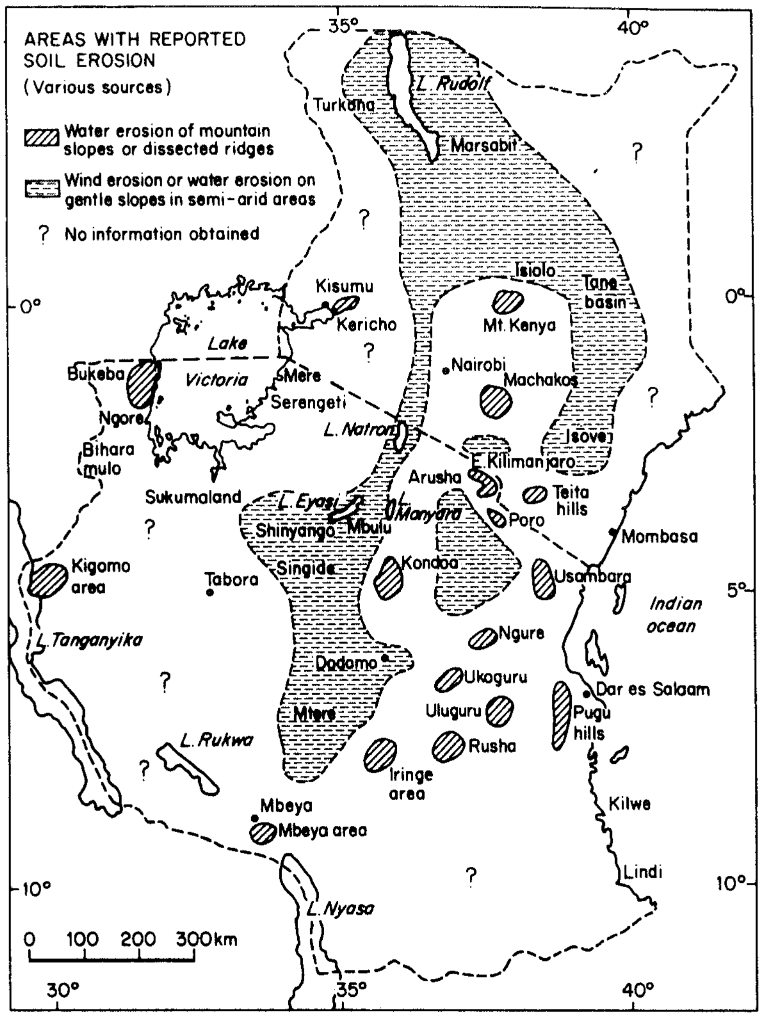

Figure 3.11 Areas in Kenya-Tanzania with reported soil erosion (From Lundgren, ed., 1975)

fluence of Great Ruaha, Little Ruaha, and Kisigo rivers. Mtera is situated about 120 km to the south of the Dodoma area. An ecological study of the area within the power development scheme (Johansson, ed., 1976). These studies included surveys based on LANDSAT-1 on the extent of soil erosion in the catchment area (65,000 km^2) upstream from the reservoir (Stromquist, 1976) and in the reservoir region (cf. Stromquist and Johansson, 1978).

Studies of soil erosion and land management planning have also been made in conjunction with various regional development schemes, water master plans, etc. A good example is the Mwanza Region Integrated Planning Project in western Tanzania (cf. Rapp, 1976). The geomorphological part of the study focused on the changed land use and erosion pattern caused by the formation of the new 'ujamaa' village.

Two case-studies from the semi-arid area are described below. The first is the DUSER studies at Dodoma using mostly air-photo interpretation, field surveys, and reservoir sedimentation as means of estimating and monitoring the soil erosion. The second is the SWECO-project (Swedish Consulting Group) in the Mtera area using satelite image interpretation, dendrochronological measures, fluvial-tile transport and vegetative patterns to quantify and describe the actual erosion.

3.8.2. TWO CASE STUDIES–THE DODOMA AND MTERA AREAS

3.8.2.1. The Dodoma Area

The Dodoma region is characterized by inselberg plains developed in a Precambrian bedrock with late faulting and fracturing. The altitude is about 1,100 m and the relative relief about 200 to 300 m. The dominating climatic features are a long dry season and a short intense rainy season. The dry season lasts for about 7–8 months, generally beginning in April. The mean annual rainfall is 573 mm during an average 54 rain days. The potential evaporation is 2,123 mm yr^{-1}. The natural vegetation is woodland, which remains only in small parts. Man and his domestic animals have transformed the woodland into farmland, bushland, or thicket. The bushland is composed of shrubs 3 to 4 m high and occasional trees, and has a poorly developed ground cover (cf. Johansson and Stromquist, 1978a). The soils form a catena sequence and the rivers are all intermittent.

The DUSER research project on the rate of soil erosion and reservoir sedimentation was carried out during 1968–72. The water sheds and reservoirs of Ikowa, Matambula, Msalatu and Imagi near Dodoma were surveyed. The catchment areas are under intense land use and subject to severe soil erosion due to over cultivation, overgrazing, and a high rate of extraction of firewood. The rate of sedimentation in each reservoir was determined by repeated surveys of cross profiles. Inventories of erosion features within the catchments were based on air-photo interpretation and field checks. Christiansson (1978), who is a continuator of the studies in the area, also use LANDSAT-satelite images for monitoring the extent of eroded land.

Within the drainage basins (cf. Rapp *et al.*, 1972a, b; Christiansson, 1978) gullying is the most striking form of erosion as gullies appear in distinct zones on the upper pediment slopes. However the gully erosion is of less quantitative importance than splash and wash erosion.

The investigated reservoirs have very high rates of sedimentation (Table 3.32). Two will be filled with sediments only about 25 to 30 years after construction, which also indicates the severe erosion within the drainage basins. An example of a catchment area inventory map is shown on Figure 3.12 (From Rapp *et al.*, 1972).

Table 3.32. Reservoir data, sedimentation and soil denudation rate for five catchments in semi-arid areas of Tanzania

Table 3.32. Reservoir data, sedimentation and soil denudation rate for five catchments in semi-arid areas of Tanzania

Catchment	Catchment area (km2)	Relief ratio ($m\ km^{-1}$)	Annual sediment yield ($m^3\ km^{-2}$)	Soil denudation rate ($mm\ yr^{-1}$)	Reservoir completed (sediment survey) year	Capacity m^3	Percentage of original volume	Annual loss of capacity through sedimentation[a] (%)	Expected total life of reservoir years
Ikowa	640	730/50	1957–74 191	0.1–0.36	1957	3,807,000	100.0	1957–74 2.8	30–40
			1957–60 362		(1960)	3,110,000	81.6	1957–69 6.13	
			1960–63 193		(1963)	2,740,000	71.9	1960–63 3.23	
			1963–69 111		(1969)	2,315,000	60.8	1963–69 1.85	
			1969–74 99		(1974)	2,000,000	52.5	1969–74 1.66	
Matumbulu	(18.1) effective 15.0	257/4.4	1962–74 581	0.44–0.63	1962 (–60)[b]	333,000	100.0	1962–74 2.6	35–45
			1962–71 626		(1971)	248,500	74.6	1962–71 2.8	
			1971–74 445		(1974)	228,500	68.6	1971–74 2.0	
Msalatu	8.7	183/4.1	1944–74 556	0.44–0.62	1944 (theor)	421,000[c]	100.0	1944–74 1.15	80–90
			1944–50 623		(1950)	388,500	92.3	1944–50 1.3	
			1950–60 443		(1960)	358,000[d]	85.0	1950–60 0.9	
			1960–71 622		(1971)	298,000	70.8	1960–71 1.3	
			1971–74 536		(1974) (theor)	284,000[c]	67.4	1971–74 1.1	
Imagi	2.2	122/1.6	1934–71 610	0.52–0.70	1934 (–29)[e]	171,500	100.0	1934–71 0.8	120–130
			1934–50 521		(1950)	152,000	88.6	1934–50 0.67	
			1950–60 659		(1960)	146,500[d]	85.4	1950–60 0.85	
			1960–71 703		(1971)	129,500	75.5	1960–71 0.90	
Kisongo[f]	0.3	225/5.7	1960–71 481	0.45–0.64	1960	121,000	100.0	1960–71 3.7	25–30[g]
			1960–69 447		(1969)	83,600	69.1	1960–69 3.3	
			1969–71 640		(1971)	71,700	59.3	1969–71 4.7	

[a] Changes in capacity due to raised spillway and excavations have not been accounted for in this column.
[b] Katumbulu reservoir was completed in 1960. In February 1961 a part of the embankment was washed away. The embankment was repaired in 1962.
[c] The spillway of Msalatu reservoir was raised by 2 feet in 1950 and by 1 foot in 1972. The spillway of Imagi reservoir was raised by 4 feet in 1932–33 and by 2 feet in 1972.
[d] Both Msalatu and Imagi reservoirs have been subject to sediment excavations. Imagi in 1952 (9000 m^3) and Msalatu in 1953 (8000 m^3).
[e] Imagi reservoir was completed in 1929. However, the first proper survey of the total volume of the reservoir was not undertaken until 1934.
[f] Data from Rapp, Murray-Rust, and Christiansson (1972b).
[g] In early 1974 the embankment gave way. By the end of 1974 it had not yet been repaired.

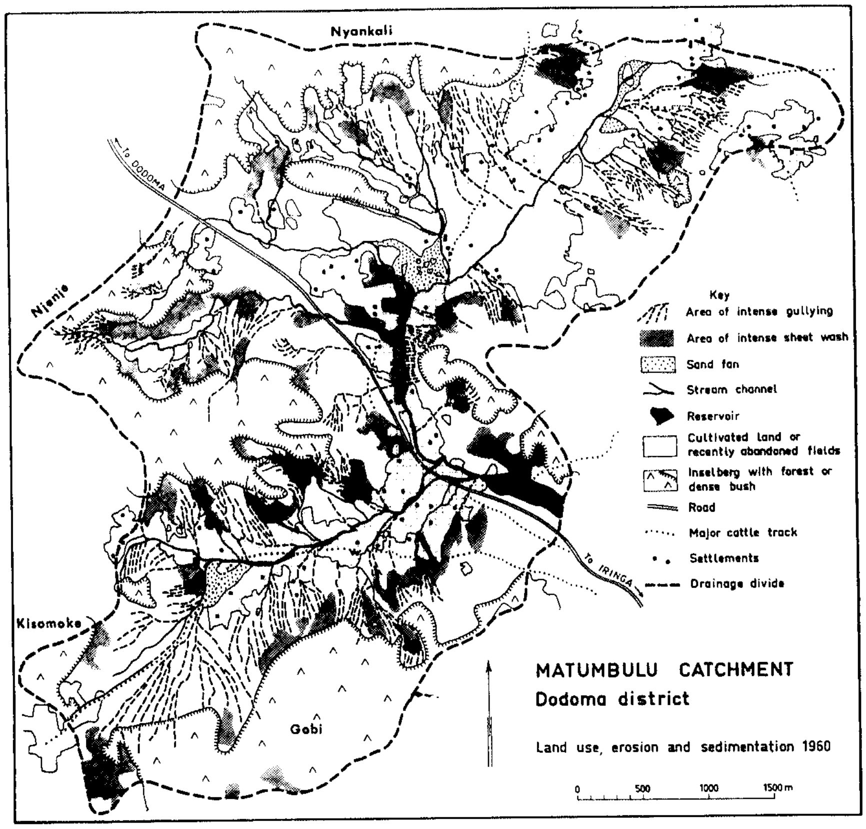

Figure 3.12 Map of land use, erosion, and sedimentation, Matumbulu catchment, Tanzania. Based on air photographs from 1960 and field checking during 1969–1971. Note the zones of erosion and deposition: gullied upper pediments with intense sheet wash, cultivated lower pediments, stream channels with three sand fans and reservoir with heavy sedimentation. Map by C. Christiansson (After Rapp, Murray-Rust, Christiansson, and Berry 1972)

According to a recent paper by Christiansson (1978) the annual sediment yield corresponding the reservoir sedimentation is about 200 to 600 $m^3 km^{-2}$ (or 300 to 1,000 $t km^{-2}$). He and Rapp and Hellden (1979) recommend a reduction in stock numbers and rangeland burning as a useful means of increasing biological production, soil water infiltration, and life span of the reservoirs. However, the formation of a reservoir in a grazing area is likely to lead to an increase in stock numbers due to an improved water supply, which will lead to increased grazing pressure in the area and an acceleration in the rate of erosion and reservoir sedimentation. This illustrates the need for integrated planning of the rural development in the country.

3.8.2.2. The Mtera Area

The Mtera reservoir will be situated in the central part of the east African rift valley. The geomorphology is characterized by steep rift valley scarps and series of tilted and inclined plateaux below which extensive pediments, wide flood plains, and large areas of 'mbuga' (playa) clays are dominating elements of the landscape (Figure 3.13) The reservoir will cover most of the flood-plains and 'mbuga' deposits, hence its shorelines will develop on the gentle, in parts severely eroded, pediments.

The yearly rainfall at Mtera is very low (450 mm yr^{-1}) and concentrated in a rainy season between November and April. Most of the rain falls in December and January. January is the month which shows the least variation in number of rain days and the highest daily rainfall intensitites, hence making it the month with most erosive rainfall (cf. Stromquist, 1976; Johansson and Stromquist, 1977a; Stromquist and Johansson, 1978). The potential evaporation is 3,261 mm yr^{-1}. The vegetation can be divided into three major types: woodland, bushland, and grassland. The vegetation as we see it today is a result of an interaction of both natural and cultural processes. The very large number of domestic grazing animals, mainly cattle and goats, have severely depleted and locally exterminated the perennial grasses and palatable herbs leaving only short-lived annual grasses and unpalatable shrub with large areas of bare ground. The soil (and vegetation) types of the Mtera basin often form a marked catena sequence. Figure 3.13 (from Stromquist 1976) illustrates the geomorphological variation in the area interpreted from LANDSAT-1 images and Table 3.33 summarizes the relation between geomorphology, vegetation, and soils.

The reports by Johansson (1976) and Johansson and Stromquist (1977b, p. 19) draw attention to the need for monitoring and control of the land use of the basin after the impoundment: 'After the creation of the Mtera reservoir a rational land use policy has to consider how best to obtain an optimal and continuous yield from both farming and grazing without causing increased soil erosion and subsequent sedimentation in the reservoir. Agriculture will include both the use of traditional methods on the land above the highest shoreline as well as new methods on the land which is flooded annually.'

At present (cf. Figure 3.13, symbol 4) the southern pediment close to the perennial Great Ruaha River is severely affected by soil erosion and a similar evolution can be expected on the other pediments after the impoundment.

The ecology study made by SWECO (cf. Johansson, 1976) includes studies of geomorphology, vegetation, forestry, limnology, disease ecology, sociology, and planning. The geomorpholical studies have included:

(a) A land systems map with a description of the catchment area upstream from the reservoir (based on LANDSAT-1 satellite images, aerial survey, and limited field checks), stressing the extent of soil erosion (Stromquist, 1976).
(b) A study of land use, soils and conservation potential of the reservoir region

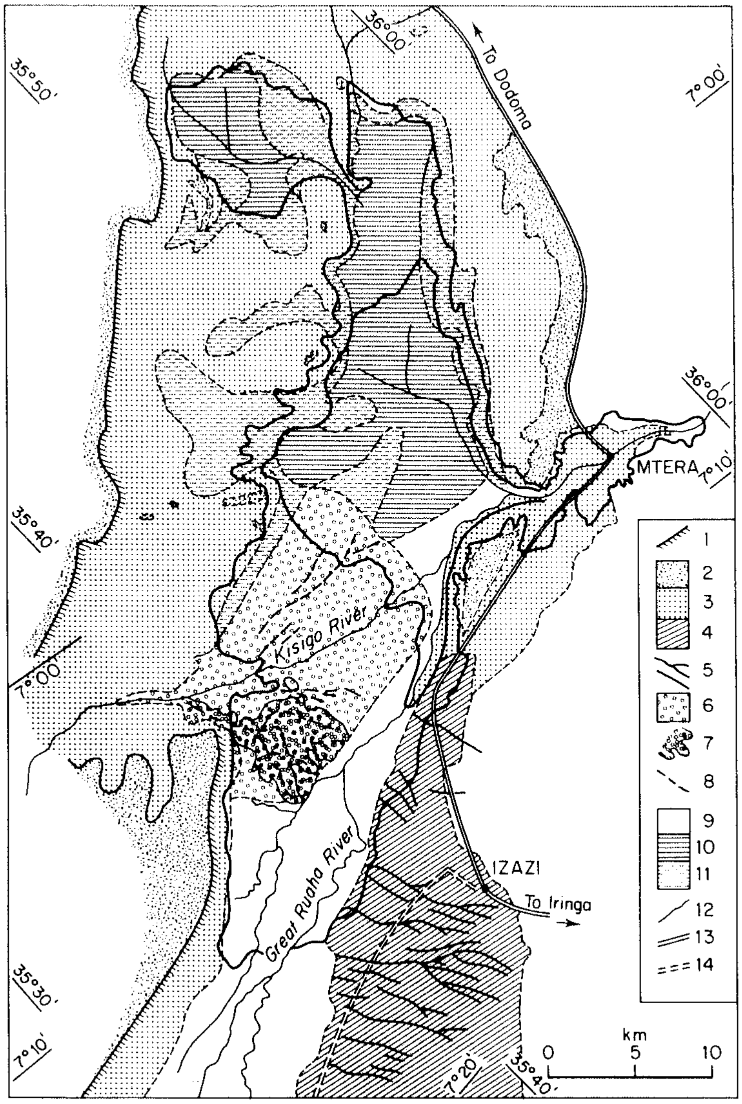

Figure 3.13. Landforms, erosion, and sedimentation in Mtera area

based on conventional air-photo interpretation (cf. Johansson and Stromquist, 1977b).

(c) A study of soil erosion and fluvial transport (cf. Johnasson and Stromquist, 1978a).

(d) An investigation of the expected environmental changes below the Mtera reservoir (cf. Johansson and Stromquist, 1978b).

Table 3.33. The correlation between soils and vegetation of the land facets in the Mtera basin

Land facet	Soils	Vegetation
(1) Rift escarpment and	Red, coarse grained acidic soils	Brachystegia woodland (miombo) (1)
(2) tectonic Hills		Acacia bushland (2)
(3) Pediments	Brown-grey sandy silts (upper parts), hardpan soils in certain areas, silty sands (upper parts)	Open bushland of mixed Acacia species (*A. tortilis* and *A. drepanolobium*)
(4) Seasonal streams	Well-sorted sand	Gallery forest on the bluffs
(5) Alluvial fan	Well-sorted sand, silt and clay	Riparian forest and ground-water bushland
(6) Floodplains	Well-sorted, sandy-to-clay grey soils	Riparian forest and ground-water bushlands
(7) Mbugas	Alkaline clay	Grasslands intersected by Acacia bushlands (*A. seyal* and *A. Stuhlmannii*)

The LANDSAT-1 satellite images have more recently been evaluated for mapping the geomorphology and vegetation in semi-arid Tanzania (cf. Johansson and Stromquist, 1978c).

Experiments were carried out to examine the feasibility of using growth rings of trees for calculating the annual soil erosion (Johansson and Stromquist, 1978a; Stromquist and Johansson, 1978). A variety of trees and shrubs were used initially for testing the method; it is suggested, however, that future studies should deal with only a few species within each area studied. *Acacia drepanolobium* which is a short shrubby tree and *Combretum hereroense*, a shrub, proved to be very useful because of both they have distinct growth rings and because of their ability to protect the ground from splash erosion. The rate of erosion was calculated from the difference in level between the ground protected by the canopy of the shrubs and that of the surrounding area. This method estimated the yearly soil loss as about 2,900 t km^{-2} or nearly three times as much as in the Dodoma area (cf. Christiansson, 1978; and Table 3.32). Combining the air-photo and satellite image interpretation with the soil loss estimated by dendrochronology the yearly transport into the reservoir from the surrounding pediments will be 0.8–1 million t yr^{-1}.

A study of the suspended sediment transport by the three main rivers was made during the 1976–1977 rainy season. The water sampling programme was made flexible as regards sampling intervals, which were shorter during the flood periods than during the recession stages. This procedure was adopted because of the discharge regime which is characterized by flash floods responsible for the bulk of sediments (cf. Table 3.34). Previous studies of sediment transport in the Great Ruaha River only used a weekly sampling programme, which often may have excluded the flashy peak floods and high sediment concentrations. This new procedure gave estimates for the total suspended sediment load four times greater than those obtained by the previous study. This clearly illustrates the need for a sediment sampling programme that takes into account the wide variation in magnitude and frequency of the erosion processes within the catchment area.

To simplify a future control programme of soil erosion, erosion rods (pegs) have been installed at different sites, each site representing a different situation in terms of soil vegetation and present land use. These results will be combined with a renewed air-photo-satellite image interpretation programme to quantify the amount and extent of future soil erosion around the reservoir.

3.8.3. CONCLUSIONS

Summarizing the main results from the recent Tanzanian studies on soil erosion, the most important result is the illustration of the necessity to observe the environmental reactions of exploitation and to draw rational conclusions for a better land use and planning from these observations. 'Every land development scheme should to some extent also be a research project' (Rapp, 1972), as land degradation is a common phenomenon but there is no common solution of the problem.

Table 3.34. Discharge and sediment concentration at Mawande, Little Ruaha River, Tanzania, 21 December 1976

Time (hr):	6 00	9 00	12 00	12 30	13 45	14 25	15 00	18 25
Discharge (m^3 sec^{-1})	9.5	10.0	12.5	15.0	20.0	23.0	26.0	12.0
Concentration (mg l^{-1})	39	7640	5784	6110	3290	3491	2143	1707
Sediment load (t hr^{-1})	4	275	258	330	237	289	200	74

The studies have to be tailored to the local physical conditions and man. That has been illustrated by SWECO studies at Mtera as well as by the DUSER project from various parts of the country.

The two studies from semi-arid Tanzania clearly illustrate the importance of remote sensing methods but also the need for a good basic knowledge of the landscape and its process activity.

The different methods to quantify soil erosion described in this paper also illustrate the need of an adaptation of field techniques to the local environment and processes.

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