# STUDIES OF SOIL EROSION AND SEDIMENTATION IN TANZANIA

Edited by Anders Rapp, Len Berry & Paul Temple

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# FOREWORD

BY HON. Dr. W. K. CHAGULA M. P.

Minister for Economic Affairs and Development Planning,
Chairman of Tanzania National Scientific Research Council

It is indeed a privilege for me to have been accorded this opportunity to write a short foreword to this first research monograph of the Bureau of Resource Assessment and Land Use Planning (BRALUP) of the University of Dar es Salaam on "*Studies of Soil Erosion and Sedimentation in Tanzania*" which is the result of a cooperative effort between the University of Dar es Salaam on the one hand (BRALUP, Department of Geography, and Department of Agricultural Chemistry) and Sweden (Department of Physical Geography of the University of Uppsala, the Bank of Sweden Tercentenary Fund and the Swedish International Development Authority) on the other. It is indeed a measure of the high degree of cooperation between Sweden and Tanzania that it has been agreed between the two sides that this double issue of *Geografiska Annaler* should be distributed in Tanzania as BRALUP Monograph No. 1.

Another aspect of assistance which is especially commendable has been the close cooperation between the researchers and the various Government ministries. As many of the authors in the volume have acknowledged, the cooperation has been especially noteworthy between the researchers and the Ministry of Water Development and Power and the Ministry of Agriculture, Food and Cooperatives. One hopes that these close links will continue between researchers and those who have to implement the findings.

The fifteen papers in this monograph, in my view, are of a very high academic standard, and the research methods and instrumentation used in these studies should be useful to other research workers in Tanzania and elsewhere. It is, however, my sincere hope that other scholars will continue from where the results of the Dar es Salaam/Uppsala Universities' Soil Erosion Research Project (DUSER Project) have taken us. The results of the DUSER Project should therefore be regarded as only a "bench mark" in this complex research project on soil erosion and sedimentation which should be continued for a much longer period than the 3—4 years of the DUSER Project. Indeed, I should venture to propose that the DUSER Project should continue indefinitely if its funding can be assured.

In addition to the papers in this monograph being of a very high academic standard, of even greater importance is the fact that some of the results of the DUSER Project could be applied widely in Tanzania, particularly as we are now in the process of implementing the Party's Guidelines of 1972 on modern agriculture, "*SIASA NI KILIMO*", in which the problem of soil erosion is given due prominence. I shall mention only a few of these results:

(i) The importance of tree cover in minimizing landslides; the studies recommend *how* re-afforestation for the purpose should be done.

(ii) Soil conservation measures to be acceptable to the people must bring both a demonstrable advantage to individual farmers in the short-run *and* long-term advantages to the whole community. In addition, the soil type must be identified in advance; the tribal, social, and cultural circumstances of the area must be fully taken into account; and finally adult literacy campaigns should precede the introduction of the conservation measures.

(iii) In the semi-arid central area of Tanzania, losses of water and soil can be drastically reduced by an undisturbed vegetative cover and through the prevention of over-grazing.

(iv) The water reservoirs in the semi-arid central regions of Tanzania have high rates of sedimentation and their total useful "life" can be thirty years or even shorter. This should be very useful information to the national planners for rural water supplies.

(v) Construction of new dams and reservoirs should continue however, for even a short-lived reservoir may be economically justified in areas where the need for water is so pressing as in the semi-arid areas of central Tanzania.

(vi) Wind erosion can be as serious as water erosion in certain parts of Tanzania and both can be stopped or minimized by planting trees and by controlled grazing.

(vii) The lack of hydrological data for the Luwegu and Luhombero Rivers in the Rufiji Basin makes immediate development and flood control in the Rufiji Valley difficult.

(viii) A full analysis of the probable sedimentation in the Stiegler's Gorge reservoir should be undertaken before the 600MW Stiegler's Gorge hydropower station is built.

It is my sincere hope that the relevant authorities in the Government of Tanzania will pay due attention to these practical conclusions which are some of the results of this very worth-while DUSER Project.

Finally, I should like to congratulate all those who have participated in this DUSER Project, directly or indirectly, as well as those institutions, both in Tanzania and in Sweden, which have financed the studies contained in this volume and have made their publication possible. As I have stated earlier, it is my sincere hope that this DUSER Project will be continued indefinitely.

(W. K. Chagula)

# SOIL EROSION AND SEDIMENTATION IN TANZANIA — THE PROJECT

BY ANDERS RAPP, LEN BERRY, AND PAUL H. TEMPLE

Department of Physical Geography, University of Uppsala,
Department of Geography, Clark University and
Department of Geography, University of Dar es Salaam



This double issue of Geografiska Annaler, which is distributed in Tanzania as BRALUP monograph No 1, comprises fifteen papers, all concerned with aspects of soil erosion and sedimentation in Tanzania. The majority of the papers are based on research done as part of the Dar es Salaam/Uppsala Universities Soil Erosion Research Project (DUSER Project) during the period 1968—1972.

The DUSER Project and the majority of the other studies presented below resulted from cooperation between the Department of Physical Geography of the University of Uppsala, Sweden, and the Department of Geography, the Bureau of Resource Assessment and Land Use Planning (BRALUP), and the Department of Agricultural Chemistry of the University of Dar es Salaam, Tanzania.

The main sponsor of the DUSER Project was the Bank of Sweden, Stockholm, from its Tercentenary funds. Funds made available by the Bank of Sweden covered travel, local accommodation and field expenses for the Swedish academic staff and their assistants. The University of Dar es Salaam provided funds through BRALUP and its own Research and Publications Committee for its own staff. Other valuable assistance was provided by the Tanzania Ministry of Water Development and Power and the Ministry of Agriculture and Cooperatives. The Swedish International Development Agency (SIDA) made grants towards the costs of aerial survey and part of the costs of publishing this volume.

Soil erosion and soil conservation have long been major issues in a number of tropical areas, not least in Tanzania. Much of the debate on these issues has been carried on with only superficial specific information on the types of processes at work, their relative importance and their rates of operation. The main purpose of the DUSER Project was to obtain reliable data on the types, extent and contemporary rates of soil erosion and sedimentation in Tanzania, as it was hoped that such data might form a more rational basis for future schemes of soil and water conservation in critical areas in Tanzania.

That the need for such schemes is now officially recognized is indicated by the recently published TANU party paper (TANU 1972). This paper frankly admits that agricultural efficiency in Tanzania has declined since Independence and cites as the cause of this decline the failure to change husbandry practices. One of the identified results of this is soil erosion which is said to be "very serious in many places and getting worse". The official conclusion drawn from this diagnosis is that "we are destroying the heritage our children can expect from us—which is the land itself". Later in the paper, soil conservation measures are placed among the first essentials of an improved agriculture.

Since the 1920s soil erosion has been an issue of growing concern among technical and administrative officers in Tanzania. In 1931 a special committe was set up to study soil erosion and its relation with crop production, animal husbandry, afforestation, tse-tse fly, irrigation, water supplies, roads, railways, and public welfare. This committe concluded "that in the absence of considerable funds for a direct attack on the problem, the endeavour should primarily be educative rather than directly ameliorative" (Harrison 1937, p. 4). The authorities decided in other words to rely on persuading the people to adopt improved land use methods rather than to carry out extensive schemes to prevent erosion or check deterioration in eroding areas. This was then the policy and practice of the 1930s and early 1940s. It was a policy which had a rational basis but was primarily conditioned by lack of finance



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during the interwar years and the impact of war in the early 1940s.

After the Second World War a change of Government and policy in Britain brought new pressures to bear on the colonial administration in Tanganyika. Grants under the Colonial Development and Welfare Act together with accumulated balances in Tanganyika removed some of the financial constraints which had operated hitherto. Remedial and ameliorative measures became possible and were given an impetus by the establishment of the ill-fated Groundnut Scheme set up in 1947, under the auspices of the Overseas Food Corporation. A soil conservation service was set up in Tanganyika in 1945 and an official review of the soil erosion problem attempted in 1951—52 (Hill & Moffett 1955). This second review following 15 years after Harrison's original memorandum reflects a changed approach. Work by Bennett in the USA (1939) and Jacks and Whyte (1939) in Britain had by then highlighted the global problems of soil erosion and the need for conservation of soil and water resources, while Gillman (1940) had summarised available data and identified problem areas in Tanganyika. By this time too there was clear evidence of resource wastage in particular areas. In other areas however the data were much less definite. The 1951—52 review outlined the general problems but listed also a series of major schemes where a new direct approach had been put into operation. Several of these projects are reviewed in papers which follow (e.g. the Uluguru Land Usage Scheme).

But 1951—52 was too early to evaluate the success of this new policy of direct action. Most of the schemes were in fact poorly implemented, and did not improve agricultural conditions. Furthermore they raised peasant resistance and were failures in the final analysis. As these land conservation schemes were firmly associated with the colonial government and with some of the more authoritarian aspects of their agricultural policy it was not surprising that policies changed after independence, when direct action was abandoned as a policy though it had been abandoned in fact some years before.

There is no uniformity of view at present among officials and scientists concerning the severity, importance and economic consequences of soil erosion in Tanzania, nor is there a defined policy or conservation service. In part this is a reflection of uncertainty resulting from the mistakes of the past, in part it results from the political aspects of previous conservation programmes. But it also reflects the lack of reliable quantitative data on erosion and sedimentation.

The collection of quantitative data on runoff and soil erosion was begun in Tanganyika in 1933 at Mpwapwa and continued over a period of 5 years by Staples (Staples 1933, 1935 & 1938). Gillman (1933 and 1934) collected the first data on reservoir sedimentation from the dams around Dodoma. Staple's work was continued and expanded by Van Rensburg (1955). These recordings were however too few and limited to provide a good picture of conditions even in limited areas. From 1956 onwards, the East African Agriculture and Forestry Research Organisation (EAAFRO) began a number of studies concerned with the water balance of catchment basins in different environments and under different types of land use. One catchment basin was selected in each East African country. In Uganda, a basin of semi-arid rangeland was selected in Karomoja. In Kenya, selected catchments were near Kericho and in the Aberdares, representing changes from rainforest to tea, and bamboo to planted softwood. In Tanzania, mountain catchments were selected near Mbeya, in order to compare the hydrology of similar catchments under forest and under peasant cultivation (Pereira 1962). These experiments have provided much valuable and detailed information on the water balance of representative East African catchment basins. Although they concentrated primarily on water balance measurements, some of the studies provided data on the high fluctuations of sediment transport for some of the streams. For example during 1959/60, four times as much soil was lost from a cultivated valley than from a forested valley in the Mbeya mountains, during conditions of steady flow (Pereira and Hosegood 1962, p. 124). However, the undoubted practical difficulties of sampling sediment concentrations in streams during flood are one reason why the EAAFRO studies only provided limited information on sediment load.

The DUSER Research Project was devised in an attempt to provide further basic quantitative information about soil erosion in Tanzania as has been noted above. Its justification can be found in part in the comments on research needs by the East African Royal Commission 1953—1955 Report (1958, p. 265):

"In the relative absence of valid statistics, of systematically collected and collated observations based on practical experience and of scientifically acquired knowledge regarding the major problems of the region, it often proves impossible to make more than a tentative approach to development planning. In these circumstances projects are sometimes inevitably based upon little more than conjecture and informed guesswork".

Some of the adverse results of previous conjectures and guesswork are reviewed below. A more substantial justification of the project will be found in the new data presented.

These data cover localities from two widely contrasted environments:

a) Mountain slopes, mostly deforested.
b) Interior plains with a long dry season and largely semi-arid.

Constraints of time, money and staff rendered it impossible to cover other environments or processes other than erosion by water. The selected environments are however of major importance to Tanzania and it was clear from information already available that they were susceptible to severe erosion and water losses under certain conditions.

The mountain areas studied form part of the very limited zones of generally heavy and reliable rainfall with perennial streams; they are thus stream source areas and zones of water surplus which supply the surrounding drier plains with stream flow. They often also maintain high agricultural population densities. The semi-arid interior plains, broadly defined, occupy by contrast some 60—70 % of the total area of the country (Peberdy 1969). Thus the first environment is important as a source region for water and a zone of dense settlement while the second environment is important because of its extent and the difficulties it poses to the development of agriculture.

In the assessment of the problems of these two critical environments, the unit of study was generally the catchment basin. Representative catchment basins for detailed study were selected on the basis of the availability of background data, including maps, air photographs, hydrological and geological information, and accessibility during most seasons. Figure 1 shows the location of the study areas.

## Deforested mountain slopes

The Uluguru mountains were selected as representative of a largely deforested mountain area. The first paper (by P. H. Temple) gives an account of the history of conservation policy and practice in this area over a period of approximately 70 years. This review forms a background to the group of four papers which follows. These papers deal with contemporary erosion processes using different approaches. The second paper (by A. Rapp, V. Axelsson, L. Berry, and D. H. Murray-Rust) analyses the loss of water and soil from the instrumented catchment of the Morogoro river valley in the northern Uluguru mountains. This catchment is steeply sloping, the uppermost slopes being covered with montane rainforest and the lower slopes under cultivation. The basic data used derive from a three year sampling programme of suspended sediment transport.

The third paper, (by P. H. Temple and A. Rapp) is a description of landslide erosion och deposition resulting from one heavy rainstorm of unusual intensity which occurred early in 1970 at Mgeta in the western Uluguru mountains. This rainstorm caused great damage to land, crops, roads, and property. The study shows the hazards involved in the cultivation of steep mountain slopes in this climate of recurring intense rainstorms.

A detailed erosion plot study (by P. H. Temple and D. H. Murray-Rust) of erosion and deposition on single cultivated slope units using different conservation methods then follows. The basic information used is on splash and sheet wash and derived from the measurement of erosion pegs at Mfumbwe in the eastern Ulugurus.

A compilation and discussion of erosion plot data from earlier experimental studies has been made by P. H. Temple and is included as the fourth paper. It provides interesting comparisons of runoff and erosion under different

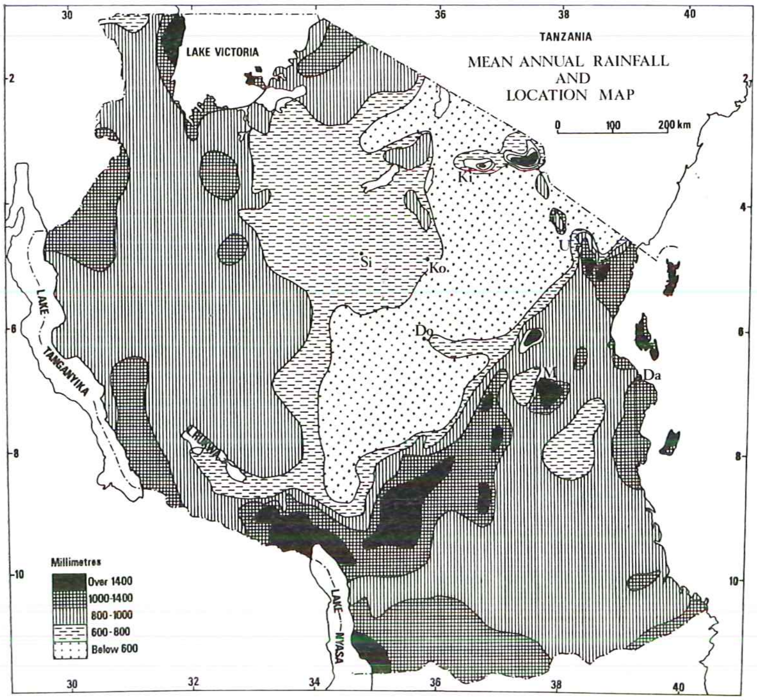


Fig. 1. Map of mean annual rainfall and field areas of DUSER catchment studies. Da = Dar es Salaam, Do = Dodoma, Ki = Kisongo, Ko = Kondoa, M = Morogoro and Mgeta, Uluguru mountains, U = Usambara mountains, Si = Singida. Rainfall map after Jackson 1972.

types of vegetation cover and slope conditions. The studies reported are from several areas in Tanzania, Rhodesia and Uganda, both mountain areas and plains.

Some comparisons from other mountains in Tanzania are provided by the following papers. They employ different methods of study. The history of conservation policy in the Usambara mountains is reconstructed and critically reviewed by J. Watson. The other paper of this group (by B. and L. Lundgren) deals with a study of soils under forest and grassland cover on Mount Meru. Mt. Meru is a youthful volcano and the soils derived from volcanic rocks are markedly different from those derived from the ancient basement rocks which form the Uluguru and Usambara mountains.

## Semi-arid interior plains

In these areas streams are ephemeral with flash floods common when they flow. No long-term gauging records in small catchments are available from the interior plains, but data can be obtained on water balance and sedimentation by other means. From the early 1950s onwards, numerous dams were constructed in these semi-arid areas for the purpose of flood control or water storage. A series of catchments with reservoirs were selected for detailed investigations. These investigations concentrated upon:

1. The measurement of sedimentation rates in the reservoirs.
2. The recording of erosion features and their relation to land use in the catchment basin feeding the reservoir.

As a general introduction to the detailed results of these catchment studies, a review is made (by L. Berry and Janet Townshend) of the numerous attempts to conserve soil and water resources in this environment. Detailed studies were made in the Dodoma area, in the plains west of Arusha and in the area of Singida and Kondoa. Four catchment basins with reservoirs near Dodoma were subjected to detailed investigations (by A. Rapp, D. H. Murray-Rust, C. Christiansson and L. Berry). A further catchment was selected west of Arusha. This catchment, although similar in climate and land use to the Dodoma catchments, differed from them in possessing soils derived from unconsolidated volcanic tuffs rather than ancient basement rocks. The paper (by D. H. Murray-Rust) is a summary of an M. A. thesis, written for the University of Dar es Salaam. Work on these reservoirs and their catchments has been greatly assisted by information (dam site maps and reservoir topography prior to dam construction, some silt survey data and water level data) supplied by the Water Development and Irrigation Division of the Ministry of Water Development and Power. All these reservoir studies provide unambiguous documentation of rapid reservoir sedimentation and intense catchment erosion. Similar studies within selected catchments in the Singida and Kondoa districts have been started (by C. Christiansson) and a preliminary report on this research, which will be continued during 1973, is included.

## Other contributions

The investigations listed so far and set out in detail below have been concerned with erosion plots and small to medium-sized catchments. By contrast, the next paper (by P. H. Temple and Å. Sundborg) presents data on the hydrology and sediment transport of the largest river of Tanzania, the Rufiji. Though concerned primarily with the relationship of sediment load and water discharge, it provides data on catchment erosion and possible sedimentation rates in large reservoirs.

The last paper in this double issue (by I. J. Jackson) portrays the variations of mean daily rainfall intensity and average number of raindays over Tanzania in four selected months. Though different from the preceding studies in approach and scope, it provides a valuable background of short time-interval climatic data of greater relevance to studies of erosion and sedimentation than the more frequently discussed monthly and annual averages.

## Conclusion

As Editors of this volume and co-workers in the DUSER Project we wish to express our hope that this series of papers will provide useful data and information for future land and water development schemes in Tanzania and other countries where similar environmental conditions prevail. We also hope that the research methods described and the areas selected for special study will be used for continued research in Tanzania. The 3—4 years of DUSER Project is really too short a period for the study of the complex inter-relationships between the physical processes of erosion and sedimentation and the range of factors which influence it.

Finally we would like to express our sincere gratitude to all persons and institutions who have helped us in the initiation, progress and completion of the work which is presented below. Acknowledgement accompanying individual papers provide further details.

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# SOIL AND WATER CONSERVATION POLICIES IN THE ULUGURU MOUNTAINS, TANZANIA

BY PAUL H. TEMPLE

Department of Geography, University of Dar es Salaam

ABSTRACT. Proper use of soil and water resources in major stream source areas is vital both for the short-term advantage of the local economy and for the long-term advantage of the whole community. This paper is a case study of official conservation policies and their impact on the partly deforested and densely settled stream-source area of the Uluguru mountains of Tanzania.

Conservation policy in this area has been marked by radical shifts of emphasis and direction. These are described and analysed. Such a review of past experiences, together with newly-available technical data presented in papers which follow, forms a basis for comment concerning the future conservation measures in this area.

## Introduction

The Uluguru mountains form one of the major stream source areas of Tanzania. The rivers Ruvu, Ngerengere and Mgeta all rise in these mountains (Fig. 1). The Ruvu basin (18,389 $km^2$) drained by these rivers, is recognized as an area having considerable development potential.

Heijnen (1970) provides a bibliography of the development projects, some of which are already constructed, others being under way and yet others under active consideration. The Ruvu river supplies the water demands of urban and industrial users in Dar es Salaam. The Ngerengere river is the major water source for the numerous sisal estates in its catchment while the Morogoro river is the main water source for Morogoro town designated, under the Second Five Year Plan, for expanded industrial and urban development.

Yet the mountain sources region of these perennial streams has long been identified as prone to severe soil erosion and consequent deterioration of water yields in terms of either quantity or quality. Large areas of the mountains have been deforested over the last century and a half in the course of expansion of peasant agriculture. The rural economy is essentially subsistence-orientated, relying heavily on annual crops which provide little protection against sudden heavy rainfall on the generally steep slopes.

The agricultural economy of the mountains sustains a fairly-high population density, though out-migration is widespread. There is thus an urgent need to prevent resource deterioration within the area to sustain the existing population at least at their present level and a need for awareness of the possible repercussions such a deterioration could have on the developmental prospects of the whole Ruvu Basin.

There is indeed a long and intricate history of conservation policy and practice in the Ulugurus. It was in the Ulugurus, for example, that the British colonial government attempted one of its most ambitious and comprehensive schemes of soil conservation and land use improvement in the early 1950s.

This paper presents a critical review of past conservation policies and their impact. The paper covers environmental appraisal, policy recommendations and administrative action. It also examines the reactions of the local agricultural population to the measures adopted. It will be demonstrated that many of these measures were based upon inaccurate data and subjective assessments. While this situation was to some extent inevitable, it is certainly a major explanation of the failure of many of the conservation schemes. It will further be demonstrated that, in one classic case, conservation measures actually accelerated resource wastage.

The purpose of this review is to draw lessons for the present from the frequently painful and costly experiences of the past and to highlight the need for objective, factual technical data as the only sure basis for proper decision-taking.

## The natural environment and its early modification

The topography and geology of the Uluguru mountains is described by Sampson and Wright

(1964). Average annual rainfall, rainfall reliability and monthly rainfall data for the Ruvu basin are discussed by Jackson (1970). Hydrological data on stream flow is available for all the major rivers but this information has not yet been fully analysed (WD & ID, Yearbooks 1963 & 1967). Analysis of population density (Fig. 2) and land use has been made by Thomas (1970). Work on land systems is in progress (B. A. Datoo, personal communication).

Contrasts in natural vegetation in the Ulugurus reflect local differences in altitude, slope, soils and rainfall, but it is probably variations in the latter which are most important in explaining the pattern. Generally average annual rainfall exceeds 150 cm; on the eastern slopes annual rainfall rises to over 285 cm as at Tegetero, but on the western slopes conditions are drier due to a pronounced rain shadow effect. The main rainy season extends from late February to early May at most stations, though some show an important secondary peak from late November to early December (e.g. Bunduki and Mfumbwe).

Under natural conditions and before the heavy impact of man, the Uluguru mountains were mainly covered by forest and woodland. Only on the upper levels of the Lukwangule plateau at altitudes of above 2600 m does forest give way to a grassy scrub climax (Hill 1930). Below this summit level, montane forest extended downslope to varying elevations in response to rainfall amounts. On the northern Ulugurus, where all the detailed study areas are located, the natural lower limit of forest varied over an altitude range of 1000 m from 800 m a.s.l. on the wetter eastern slopes to 1300—1400 m above Morogoro and to 1800 m above Kienzema. On the southern Ulugurus, which are drier, the natural lower limit of forest varied between 1200 m on the eastern, seaward-facing slopes and 1800 m on the western slopes (T. Pocs, personal communication). On steeper slopes and at higher elevations, particularly in the west, a part of this forest cover still remains and is protected as Forest Reserve. Below the forest limits, woodland of various types covered the remaining slopes; most of this has been cleared for agriculture.

Various dates have been advanced for the beginnings of woodland and forest clearance and the intensive settlement of the mountains. These range between 1884 (Savile 1947), 1800 (Bagshawe 1930, Cory undated) and 13—15 generations or up to 300 years ago (Young & Fosbrooke 1960). The account of Bagshawe and Cory is the most plausible and is followed here.

According to these authors, the Luguru, who form the bulk of the African cultivators, migrated to the Ulugurus from Ubena in Iringa Region. They were originally plains people who knew little about the cultivation of steep slopes and carried their lowland crops with them into the mountains, where they were driven through pressure from the stronger pastoral Ngoni. They were a pastoral people but their cattle were decimated in this area by East Coast Fever and could not flourish on the insufficient pastures in the mountains. The Luguru settled initially in the open woodlands of the western and south-western slopes, where relics of abandoned *shambas* (small cultivated plots) can be discerned in areas of open grassland, the original vegetation of which has been almost entirely destroyed by fire and cultivation. These areas were progressively abandoned as they became impoverished (the upper Mlali valley is an example) and the tribe expanded into the more densely wooded upper slopes around Kienzema and Bunduki, and later still into the wetter eastern forested areas. It is unlikely that any conservation practices were followed in this initial phase of exploitation of a virgin environment. The land was cleared and cultivated until it became impoverished and was then abandoned.

## History of conservation policy and practice

*Pre-1945: Piecemeal measures*

This shifting cultivation was interrupted by the enforcement of the first conservation measures in 1909. These resulted from the advocacy of forest and watershed protection by Bruchhausen (reported by Cory *op. cit.*) and a report on rapid forest clearing by Stuhlmann (1895). An area of 277 km$^2$ was declared Forest Reserve and its boundary demarcated by the German colonial administration. In many areas the reserve boundary lay well within the woodland and forest zone (Cory *op. cit.*) but in some areas cultivated or cleared land was included within the Reserve boundary and

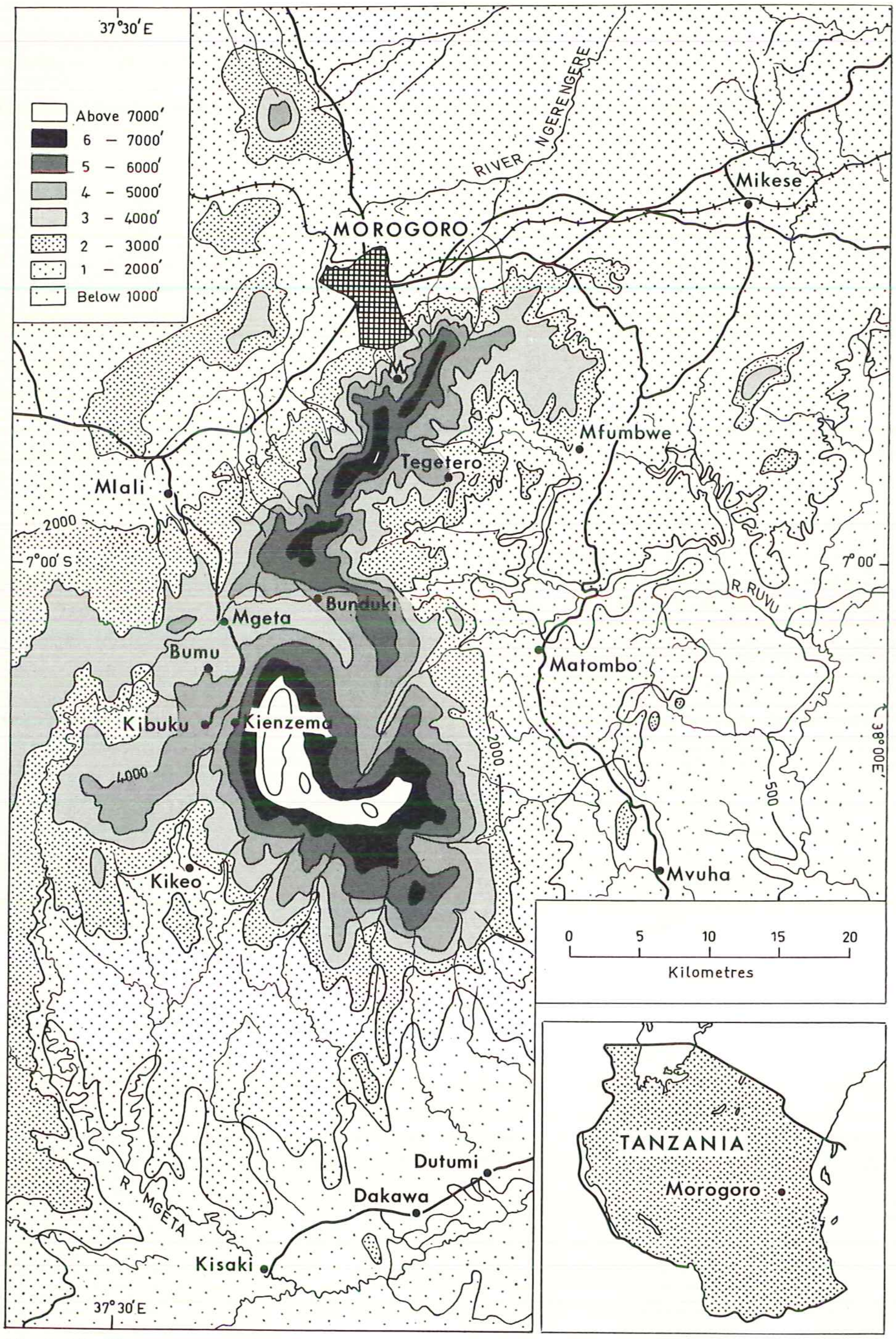


Fig. 1. The Uluguru mountains, Tanzania.
M = Morningside in the Morogoro river catchment.

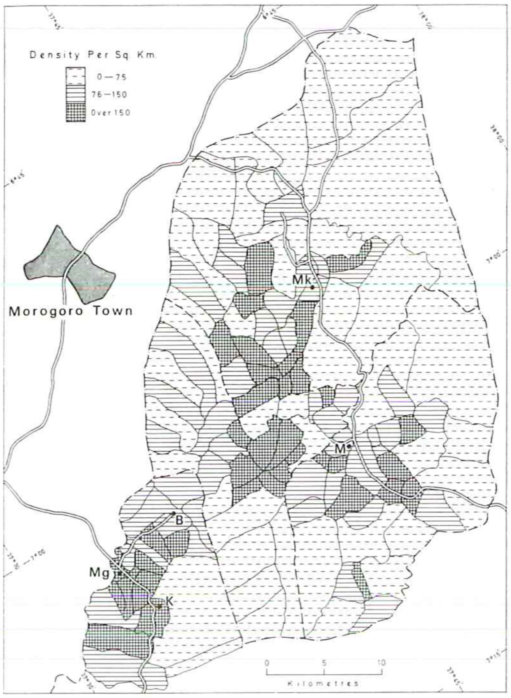


Fig. 2. Population density by enumeration areas in the Uluguru mountains (after Thomas).
B = Bunduki; K = Kienzema; M = Matombo; Mf = Mfumbwe; Mg = Mgeta; Mk = Mkuyuni.

occupants of these plots were expelled and compensated (Platt, Huggins, Savile & Parry 1945). The aim of this step was to safeguard perennial stream flow in the surrounding lowlands. In many areas the present Forest Reserve boundary follows the original demarcation but in some areas woodland cover has been pushed back beyond it as near Kienzema. The effect of this conservation measure according to Savile (1945—1946) was to intensify the exploitation of remaining non-reserved land and to accelerate its deterioration; land was cleared before vegetation regeneration had fully restored the soil fertility and a greater proportion of steep slopes were cultivated leading to increased soil erosion by sheet wash. Cultivated land of these types showed a decreased fertility and "in order to compensate ... the natives increased the area under cultivation which in turn caused a decrease in the resting period which the land received before being reopened for cultivation. Thus we have the start of a vicious circle in which sheet erosion has encouraged the natives to steadily increase the area under cultivation, thereby in turn, increasing the amount of sheet erosion that took place" (Savile *op. cit.*). This view almost certainly exaggerated the rate of soil loss through wash (for which there was no reliable data), underestimated the ability of exposed soils in this area, even on steep slopes, to resist erosion and overestimated the recovery period of soils under fallow.

During the period of the First World War, a number of those expelled from the Forest Reserve area by the Germans returned to their original *shambas* and were not expelled by the less efficient early British administration, but it is clear from later reports that these incursions were limited (Platt, Huggins, Savile & Parry *op. cit.*).

During the 1920s limited conservation measures were put into operation both by local action and through legal pressure. Around Mgeta in 1923 the local people began planting trees (mainly black wattle) in a number of small areas "with the double idea of obtaining firewood and preventing erosion" (Bagshawe *op. cit.*) though wood was also in demand for pit props for the local mica mines (Duff, personal communication). Furthermore the "Mgeta system" of laying down grass and weeds in ridges along contours as a method of counteracting sheet wash probably evolved during this period of agricultural intensification (D.O., Morogoro to P.C. 1930). This method of conservation was replaced by improved practices in the late 1930s in the Mgeta area but is still common in other areas, as for example in the Morogoro catchment. In 1929 regulations were laid down (Native Authority Orders, 1929) that no one was allowed to burn grass or bush on land other than his own without permission.

In 1930 the administration became alarmed by the Land Development Commissioner's Report (Bagshawe *op. cit.*). This report which, besides indicating that there was no remaining land in the mountains suitable for alienation, added that "owing to approaching congestion on the higher slopes it is necessary to stop further alienation within an area below", presumably in order to allow room for future migration of a labour force and settlers into the surrounding plains, then being developed as sisal estates. A spate of reports and recommendations for improvements followed. Among the measures proposed was the encouragement of coffee planting (D.O., Morogoro to P.C., 1930 & P.C. to D.O., Morogoro *op. cit.*), with the aim of encouraging more permanent cropping and thereby reducing sheet wash. Encouragement of the indigenous trash contour ridges was also advocated.

Reafforestation of denuded areas was proposed and improved protection of residual forest areas advocated but nothing was done. A report on local fuel and pole requirements (probably for the local mica mines) in the western and southern areas of the mountain (Baldock & Hutt 1931) noted that there were marked shortages of both commodities, and mentioned the difficulty of acquiring land for forest plantations due to population pressure. 100 hectares of forest were nonetheless set aside as Clan Forest Reserve, presumably additional to the existing Crown Forest Reserve. The report added that lines of wattle should be planted along the tops and bottoms of shambas in Mgeta, but no steps were taken to implement this sensible proposal.

The first agricultural conservation work of significance came in 1936—1937 with the establishment of trial plots and experimental bench terraces for vegetable and potatoe growing at Mgeta (Page-Jones & Soper 1955). The plots were adjudged successful and were described as the model for the ladder or step terrace. This is doubtful as ladder terraces are a completely natural and economical way of cultivating steep hillsides with a hoe, and probably evolved earlier. They also differ fundamentally from bench terraces.

The ladder or step terrace (*matuta ya ngazi*) merits some discussion here as it is still currently the most widely employed and generally accepted soil conservation method on the western side of the mountains. "When cultivating, vegetation and crop residues are spread on the top of the terraces and covered with soil cut from the face of the terrace above. This is also done when weeding and so there is a slow mechanical movement of soil downwards. But these terraces give better yields as little subsoil is dug out and organic matter is incorporated regularly". (Grant 1956). Furthermore soils cultivated in this way acquired an open and free-draining structure. "Only rarely does a terrace system of this nature break down under heavy rain and cause gully formation" (Page-Jones & Soper *op. cit.*, p. 4). Another conservation method tested at this time was the planting of live grass barriers. Stronger regulations against indiscriminate burning were put into operation, involving a metre-wide fire-break around all *shambas* in an attempt to prevent one man setting his neighbours plot alight (Native Authority Orders 1936). As a demonstration of the benefits to be derived from protection from annual fires, a small area of uncultivated hillside near Morogoro was set aside and protected (Page-Jones & Soper *op. cit.,* p. 4).

A lull in direct conservation efforts followed between 1937 and 1943 apparently due to a policy decision to concentrate on education and demonstration and not to undertake large schemes to check or prevent erosion (Harrison 1937, p. 5). This policy was based on a 6 year review of available information and lengthy discussions. But others pressed for direct action (Gillman 1938). Gillman argued that "in the wage of devegetation follows very pronounced soil erosion and a change of stream regime from permanence to intermittance which means excessive and often destructive floods in the wet and dearth of water in the dry season. With the shrinking of the forest oases ever wider regions of the surrounding lowlands are threatened with desiccation . . . and all for the sake of feeding at best a few generations". (*op. cit.,* p. 20). He reinforced this statement later when he wrote . . . "The chief function of our highlands is *not* to provide a shortlived subsistence or profit for their excessive exploiters . . . but to maintain a regular run-off from the climatically—favoured more humid heights into the thirsty surrounding arid lowlands. By fulfilling this function they will not only permit a *limited* population to continue its highland life in safety . . . but will enable an increasing number of people to till the lowlands" (1943, p. 103). Gillman's reports were a decisive influence on later policy, but they were based on inadequate quantitative data and they ignored the importance of public opinion and public reaction.

The administration responded in 1943 with new territorial regulations to prevent large-scale burning while large-scale re-afforestation and compulsory movement of population out of the Ulugurus were mooted and seriously considered in 1944 (Page-Jones & Soper *op. cit.*). Demonstrations of storm-draining, terracing and tie-ridging were set up in August 1944 at Kienzema, Kibuku and Mgeta and these plots were said to have achieved their purpose, which was identified as the prevention of runoff and increased crop yields (Platt, Huggins, Savile & Parry *op. cit.*). How rigorously these experiments were conducted is not known nor is it possible to find out whether runoff control and yield increases were significantly different from those measured on control plots (if there were any). The report suggests that many local peasants turned over to such methods without further pressure, an assertion contradicted by subsequent instructions to the Native Authority to enforce their adoption. This move set the stage for the larger-scale interference which followed.

*1945—1955: Genesis and implementation of the Uluguru Land Usage Scheme (ULUS)*

A new approach to the problems of the area was initiated with the establishment of the Committee on the rehabilitation of eroded areas in the Ulugurus in 1945. This committee made recommendations for soil and water conservation together with comments on forestry policy and administration, prefacing their report with the following remarks: "The existing advanced state of soil erosion and detereoration of water supplies warrants the immediate adoption of such physical methods of control as will effectively halt the present rate of destruction" (Platt, Huggins, Savile & Parry *op. cit.*). No evidence of either the extent or speed of soil erosion or the type of water supply detereoration observed was presented; it was presumed that soil erosion posed a serious threat and that previous conservation practice had been inadequate. No mention was made of the ladder terrace and the efficacy of live grass barriers was questioned on all but the most gentle slopes.

The administration believed that the agricultural situation in the mountains was so grave that the people were no longer self-supporting; indeed food shortages had been experienced on the northern and western slopes (Duff, personal communication). This explains their support of the conservation proposals. The alternative must have appeared to be long-term subsidies and assistance or large-scale investments in resettlement schemes. Their first step was to re-enforce the regulations against burning; "except when breaking or preparing new land, burning of grass and bush in hill country is at all times forbidden and is permitted on flat country only to destroy weeds" (Native Authority Orders 1945).

The Department of Agriculture believed that the Luguru were destroying their land due to inadequate fallowing practice and excessive burning and by exposing cultivated soil on steep slopes to sheet wash. Savile wrote that a stage had been reached "when a family has to cultivate four or five times as much land as was necessary thirty years ago" and that "sheet erosion has advanced so far that, in many cases, the natives are endeavouring to produce crops on clayey subsoil underlying a surface layer, of 2 or 3 inches of immature surface soil " (Savile 1947). He also claimed that large areas of abandonned land were common and that some did not recover even after 40 years under fallow. Another section of this report covered the supposed repercussions of these adverse changes upon the headwaters of the Ruvu system and the resulting effects on the plain. Savile's statement "was forceful and persuasive, and it formed the official rationale for establishing the Uluguru scheme" (ULUS) (Young & Fosbrooke 1960, p. 143).

The remedial action proposed by the Committee was wide-ranging as it represented a balance of departmental interests. Specific recommendations were to (a) redemarcate the forest boundary as it had been during later German times and to restore forest and woodland down to that line, (b) plant trees outside these limits to provide fuel and poles, with the aim of reducing cutting and fire damage on the margins of the reserve itself; (c) control annual burning of grass, weeds and trash in order to allow the regeneration of fallow land; (d) adopt contour tie-ridging on a large scale in order to control sheet wash. These last two measures were meant to increase infiltration and reduce surface runoff. Should these measures prove inadequate after trials, it was recommended that the whole area should be turned over to forest reserve and the people forcibly resettled on the plains. (Platt, Huggins, Savile & Parry *op. cit.*).

However there are reasons to believe that several of the arguments put forward by the committee were erroneous. Certainly the Luguru possessed a greater knowledge of their own environment and soils than the officials were prepared to concede. Witness the ladder terracing, tree planting and intercropping practiced especially around Mgeta. Furthermore both pressure on land and population growth were almost certainly overestimated due to inadequate information. Population density in the Mgeta area, according to the 1967 census reached 118.5 per km$^2$ (Tanzania: 1967 Population Census, 1969); it was estimated at 290 per km$^2$ in 1945. It was admitted in 1945 (Platt, Huggins, Savile & Parry, *op. cit.*) that the Forest Reserve, demarcated by the Germans, had not been seriously depleted though isolated forest stands were probably being rapidly reduced. The seriousness of sheet erosion was probably overestimated, for no accurate data was available, and soil regeneration in some areas at least is very rapid (see below). In assessing the changes of the hydrological regime of the Ruvu Savile made no detailed analysis either of the rainfall records or of the hydrological data but contented himself with a discussion of the increasing difficulties of paddy rice cultivation around Bagamoyo, an argument which was far from proving his case.

Nonetheless a sum of £50,000 was made available in 1947 for a 10 years rehabilitation scheme. There is however no record of any formal policy decision about the type of operations necessary (Duff 1960), presumably because it was assumed in most quarters that these would follow the 1945 recommendations. It was soon to appear otherwise for the Provincial Administration decided to concentrate effort and available money on building bench terraces and, as an after-thought, to set up demonstration plots to show how effective these bench terraces were. Removal of barren land from cultivation, tree planting, demarcation of special reserves for stream headwater protection formed the remainder of the operation. While the last two measures represented a consistent and agreed policy, the decision to concentrate primarily upon bench terracing represented a complete reversal of agreed agricultural policy which was to have tragic consequences for the whole conservation effort.

The history of the Uluguru Land Usage Scheme (ULUS) has been described by Young and Fosbrooke (*op. cit.* pp. 141—167) and Duff (*op. cit.* & 1961) and can thus be treated in summary form.

The scheme began full-scale operation in 1950 by which time the finance available had been raised to £68,000 (Notes for 1955/56 ULUS estimates, 1956). When it was abruptly dropped in July 1955 after serious riots and general disorder, over £47,000 had been spent and 5 years of the scheme were left to run (ULUS Estimates for 1953 & 1954). "By the end of 1950 monthly reports disclose that the main line of policy had somehow been established. This was to be compulsory bench-terracing in *shambas* of medium gradients, with reafforestation of steeper slopes, involving their closure to cultivation of annual crops". (Duff 1960). A basic presumption behind the whole policy was that sheet wash and flash runoff were the major problems and that large terraces were therefore the most effective method of control. No thorough investigations were conducted in advance to ascertain the rate of sheet wash or the effect of bench terracing on crop yields. On the experimental bench terraces at Kienzema some increase of yield was claimed but no firm evidence was available. Experimental terraces established in the Morningside valley had proved barren, resulting in either total or partial crop failure. No data had been collected on the heavy labour inputs necessary to build large bench terraces. Nor was any consideration given to the probability that, by holding heavy rainfall on such steep slopes by means of large terraces, other forms of soil erosion, notably landslides, might be encouraged.

Official bench terracing began at Matombo in 1950, at Mkuyuni in 1952 and later in other areas (at Mgeta in 1953). It was backed to the full by the Colonial Administration and the Native Authority. At first the Luguru appeared to accept bench terracing. At least there was initially no resistance, but the people were apathetic and had been antagonised from the start by the closing of steep land, the prohibition of burning and of the rumour of enforced migration to the plain. In mid-1952, the District Commissioner summed up progress as follows: "£20,000 spent, four field officers established in houses in the northern Ulugurus, a few areas of trees planted and out of 400 square miles of mountain under native cultivation, perhaps 5 had been put under some form of ULUS control" (quoted by Duff 1960). A lot of money was spent on a road, never properly surveyed, from Kibuku to Kisaki. Furthermore the field officers were ill-trained and uninterested. Amidst a largely Roman Catholic population, the influencial Holy Ghost Mission had been antagonised and the Fathers openly preached against the new policies (Duff 1960). When the new District Commissioner, who had no say in the operation of the most important project in his district and who came fresh from the experiences of the failing Western Usambara Land Development Scheme, dared to question the wisdom of universal bench-terracing, he was told by the Provincial Commissioner to get on with his job for the policies were "a proven success". The Provincial Commissioner, who was an influential member of the Legislative Council, played a major role in the direction of the scheme and its policies, and was much impressed by the enormous conservation projects then proving successful in the Appalachian mountains of the south-eastern U.S.A. Duff categorised his attitude with exactness; "what was good enough for the Ohio valley was good enough for the Ruvu" (1960).

From late-1952 the scheme was intensified. Competent field officers were brought in and bush-schools set up in an intensive campaign to try to secure the Scheme's acceptance by the people. Under this new impetus the programme was diversified. Fish farming, stall-feeding of cattle, soft wood and coffee planting and experiments with cloves, citrus and coconuts were introduced, though compulsory bench terracing remained the core (Hill & Moffett 1955). The administration set goals which accelerated temporarily the rate of terracing. Each household was forced to bench terrace 500 $m^2$ per year. This coersion apparently led to a seven-fold increase in bench terrace construction between 1953 and 1954, and nearly four times as many terraces were reported to have been dug in the first 6 months of 1955 as were dug in the equivalent period of 1954 (Grant *op. cit.*). The validity of these data is however in serious doubt (Kunambi, personal communication).

Other conservation methods also seemed to be succeeding. "By the end of 1954 trash bunding, live barriers, and cored ridging had become almost standard practice in fields which were not terraced, over most of the hills. *Most of these measures were successful in holding up wash during storms of rain*" (Grant, *op. cit.*) (author's italics).

A stringent control on bush fires was enforced and this was particularly effective in 1954: "the effect of this protection over a number of years was to be seen in the flow of the streams along the northern face of the Ulugurus. During the heavy rains experienced in February and April the streams feeding the Ngerengere did not flood as in former years and the water remained comparatively clear" (Grant *op. cit.*, p. 6).

But "as time went on, a hostile reaction developed to the new agricultural techniques, or to their implications; the hostility was expressed through unauthorised political channels and eventually led to intimidation, open violence and the use of force" (Young & Fosbrook, *op. cit.*, p. 146). Except in the Mgeta area, where the ladder terrace system largely obviated the burning of trash, the people complained bitterly over the prohibition of fires. In the east, where terracing of any type was unknown before ULUS, they also complained about terracing. The amount of work done on bench terrace construction declined rapidly and a successful strike was organised in June 1955; within a fortnight all bench terracing work had ceased throughout the area. Fires were lit all over the mountain in July to signal defiance of the land use rules. ULUS collapsed, a classic example of attempted innovation and its resistance.

Various reasons were advanced to explain the scheme's failure. Page-Jones, the Provincial Commissioner, and Soper (*op. cit.*) in their departmental enquiry stressed the general multiplicity of orders and rules, the widespread corruption of headmen and instructors, who could ignore breaches of rules and permit burning if bribed. On the northern and eastern slopes the heavy labour of terracing was considered a main factor, while in the east in particular, yields were bad, and field officers and instructors incompetent.

Young and Fosbrooke (*op. cit.*) identified much more fundamental causes, pointing out that ULUS had threatened the traditional social and cultural system of Lurugu particularly over the authority to allocate the land. They also reemphasised the deficiencies of administration. They also drew attention to the inadequacy of the technical recommendations, a fact inexcusably glossed over in the Page-Jones-Soper report, and showed how discontent engendered by all these deficiencies was used by emerging national political groups for their own purposes, which were not essentially the undermining of ULUS but the discrediting of the conservative Native Authority, and its replacement (Cliffe 1970).

The technical shortcomings were identified by Young and Fosbrooke as the incomplete nature of the initial plans which lacked clear and agreed objectives, and the lack of experimental work, demonstration plots, or adequate extension services. They noted the fact that no study of the possible impact of, and reaction to, the proposals had been made. Duff (1961) largely supported these judgements, but he argued that "these technical short-comings were less important than a general opposition to a lot of hard work under the direction of outsiders" and the disorganisation of the traditional cultivation patterns and institutions. He identified the chief fault as the unequivocal administrative directive from the Provincial Commissioner which forced the local officials into an impossible position just as it did the peasant cultivators. Bench terraces were dug to order in the knowledge that they were useless; the Luguru deliberately chose sterile sites for bench terraces in order to avoid damaging fertile land (Duff 1960).

As bench terraces were again proposed as an appropriate measure to prevent erosion in the Mgeta area in 1970, some further comment on the technical problems involved seems desirable. "An easy method of digging in crop residues and grass with a hoe without pulling down soil from the face of the terrace above was not found and this is the chief difficulty involved in cultivating with a hoe . . . when the grass is left on the terrace faces and crop residues and vegetation must not be burnt" (Grant *op. cit.*, p. 5). Secondly bench terraces construction on steep slopes with a thin soil cover invariably exposed infertile subsoil: this was a serious drawback when it was important to show improved results to justify the extra labour involved. Only on fair depths of good soil where slopes were not too steep (i.e. on areas not seriously endangered by soil wash) had maize done better on terraced land. In most areas the terraces had proved barren. "The best that could be hoped for was no diminution of yield but the chances were that there would be a loss" (Page-Jones & Soper *op. cit.*, p. 11).

*1955—present: Non-interference*

The civil disturbances were brought to an end at the price of scuttling ULUS. New regulations were brought out in July 1955 and cultivators were given the choice of what conservation method they wished to use (Grant *op. cit.*, p. 6). They mostly chose to employ none at all. Bench terracing was abandoned. People complained about barrier hedges and they were abandoned. Contour ridges and trash bunds had never been fully accepted and their use was not enforced. Permission was given to burn fields with "safeguards" against fire spreading (Grant *op. cit.*, p. 3). What these safeguards were and how they were to be enforced was discretely glossed over; in fact they were never put into practice because of opposition. All pressure towards soil conservation measures was withdrawn as a matter of policy for two years following the advice of Page-Jones and Soper (*op. cit.*, p. 34).

Only in the Mgeta area did anti-erosion methods continue while "on the eastern and southern parts of the Uluguru no soil conservation measures of any sort have been observed . . . Long established live barriers have actually been dug up. There has been a general tilling of the banks of water courses with annual crops and a re-opening of steep land which had been closed (Grant *op. cit.*, p. 6). ULUS had discredited all conservation efforts and its longterm effect was to reduce the area over which any form of conservation was practiced.

With their conservation policy in ruins, the colonial administration began belatedly to establish a series of experimental trials. Experimental plots were set up to measure sheetwash and to observe crop yields under different managements (Mfumbwe) (Temple & Murray-Rust 1972) and experimental trials were made with a wide range of crops. Other projects concentrated on methods of improving the productivity of individual holdings, on catchment area experiments, and on establishing an irrigation scheme on the plain (Mlali). This enforced change was financed by the saving which the failure of ULUS had brought about. By 1958 enthusiasm for direct action had waned. In most cases the experimental plots and crop trials were allowed to revert to bush. Mfumbwe was abandoned in 1960 and none of the results obtained were properly analysed or made available (see below).

After independence in 1961, only the Mlali resettlement and irrigation project continued while in the mountains a new phase of forest clearance began. The more accessible parts of the Forest Reserve were plundered of timber and in some areas planted forests were felled and burned to provide new agricultural land (e.g. at Bunduki). In other areas relic rain forest was cleared by fire and cultivation extended into areas never before under agricultural use e.g. south of Kienzema. The total extent of these incursions is difficult to assess but they may be seen as a logical extension of the systematic resource wastage set in motion by the failure of ULUS.

Repercussions of this apparently increasing devegetation, though locally variable, were soon remarked upon. By 1963 flood damage, bank erosion and silting had become serious problems even within the township of Morogoro itself due to the condition of catchments on the northern face of the mountains (Little 1963). Large differences between wet season high flows and dry season low flows were said to be increasingly apparent while severe short-duration flash floods of high sediment content were causing considerable damage. Little argued from an analysis of 10 years of hydrological records that the situation was deteriorating.

According to Little's analysis, the river Ngerengere was drying up completely in the dry season with increasing frequency. First recorded in 1930, this phenomenon was repeated in 1934, 1943, 1949, 1953, 1955, 1958 and 1960. For the first time in 1960, and again in 1966, sisal production on estates dependent upon the river for water came to an enforced halt for 2 months. The cost of ensuring alternative dry season supply for these enterprises from dams was placed at £260,000 while such construction would flood over 400 hectares of developed plantation land. Flood erosion and silting within Morogoro township were estimated to have done well over £24,000 of damage in 10 years, and the Morogoro river had been too low to be recorded in October 1958 and 1960, a serious problem in view of the fact that it provided the urban water supply.

In the late 1960s a new and ominous phenomena was recorded for the first time in the mountains namely catastrophic landslide damage. In Matombo in 1968 an unusually violent rainstorm triggered a large but unrecorded number of landslides. Several people were killed and several houses damaged. Landslides as an erosion danger had never been recorded before though they had undoubtedly occurred. On 23/24 March, 1969 a sudden storm devastated the area south of Kienzema and over 200 slides occurred in one night, but because the area was rather isolated, the catastrophe passed largely unnoticed. Then on 23 February, 1970 a further storm devastated the area around Mgeta, causing a loss of 6 lives, affecting almost 14 % of the households of the area, killing stock and damaging nearly 1600 *shambas* in the space of 3 hours. A detailed account of this event is presented below (Temple & Rapp 1972). Damage conservatively estimated at over Shs. 600,000 was sustained without evaluation of land damage and soil loss.

No earlier reports on soil erosion mention landslides as a menace, an indication either of their lack of thoroughness or that this was a new phenomenon. The latter hypothesis cannot be sustained though it is interesting to note that severe landsliding elsewhere has been interpreted as the terminal phase of man-induced accelerated erosion eg. by Sternberg (1949) and Tricart and Cailleux (1965).

## Future conservation policy

The purpose of the review presented above was to evaluate past experience in conservation policy and practice. That soil erosion of various types is actually a serious problem in the Ulugurus has already been indicated and will be demonstrated and quantified in detailed case studies presented below.

It remains, however, to make some comments on possible future policy. Because slope, rainfall, soil, cultivation methods and cropping varies from one locality to another, generalisation is difficult and much more technical data needs to be accumulated before definitive recommendations can be made.

Conservation measures to protect soil and water resources in such environments as the Ulugurus, to be acceptible, must bring (a) a demonstrable advantage to individual farmers in the short-run and (b) long-term advantages to the community. Past measures placed excessive emphasis on the latter point and were therefore rejected (Cliffe 1970, Temple 1971). Measures advocated must take account of what is feasible given technical and financial constraints and local opinion. The implementation of conservation measures will remain a more critical problem than their design. Excessive dependence on rules and regulations is no answer while the legacy of past policies and experience is a major barrier in the way of future ameleorative measures.

Certain recommendations can be advanced nonetheless. The existing *Forest Reserve* needs strict protection (Pereira 1969). As the current active encroachment in certain areas indicates, this is not the simple and routine task that Parry (1963) suggests. Forest cover, though a major user of water itself, ensures the maintenance of even stream flow of good quality during the dry season and a slower release of runoff during the wet season. Large-scale expansion of the Forest Reserve has been proposed on occasions in the past; it would have the following disadvantages: (a) by removing presently cultivated land from agricultural use, it would put further pressure on remaining cultivated areas, thereby reducing fallow periods and accelerating the depletion of the soil nutrient status; (b) it would antagonize the local people and thus be political unacceptable; (c) expansion of forest or woodland on a large scale would decrease the total volume of stream flow as EAAFRO's data from the Mbeya catchments (Pereira 1962, Pereira & Hosegood 1962) demonstrate; (d) it would disrupt the subsistence economy of the area.

Conservation measures on *cleared* or *cultivated land* should be adapted to local conditions of slope, soil and cultivation practice. There is still a very great need for detailed research and experimentation of the type begun at Mfumbwe before these can be recommended with confidence. There are however indications that landslides are the most serious erosional threat to cultivation on steep slopes in the Ulugurus. Landslides in this area are primarily caused by the build-up of pore water pressures within the regolith. The remedial or conservation measure normally recommended to remedy such sub-surface water pressure build-up from a geological viewpoint is drainage (ditches, tile drains or other conduits). Drainage increases the internal friction of the regolith by lowering its water content and prevents the entrance of excessive amounts of water into the ground. Drainage cannot however be recommended for this area because (a) it could not be justified economically as its cost would be vastly in excess of the value of the land so protected; (b) it is almost certainly financially impossible even if technically feasible; (c) it would accelerate channel erosion and downstream sedimentation by accelerating surface run-off. Haldemann's conclusions (1956) relating to an almost identical problem in the Rungwe mountains of southern Tanzania are thus confirmed.

Bench terracing is a most unsatisfactory remedial measure for this area. Its disadvantages have already been discussed. Bench terracing (a) holds water on the slopes thus accelerating the build-up of high pore water pressures which are the major cause of landsliding; (b) it involves vast labour inputs with no advantage because (c) it invariably exposes infertile subsoil. Where soils are thin this effect is unavoidable in the short-run; (d) it would certainly be rejected by the people.

The Mgeta landslides study (Temple and Rapp 1972 below) indicates a possible alternative to the measures rejected above, for it confirms the value of a tree cover and even isolated trees in curtailing landslide damage during severe water saturation of the soil. Reasons for this are well known and need not be recapitulated here. Most important is certainly the physical binding of soil and regolith to the underlying rock slope by deep-penetrating and sturdy roots. From the geomorphological data on slide locations and an evaluation of the costs of damage sustained, it is possible to identify specific sites where tree planting would be most beneficial:

1. On the upslope margins of main roads where the natural slope is steep (over 30°) or where road construction has created artificially-steepened cuts. The direct cost of clearing slide debris from roads and the

effects of the rupture of communications figure importantly in the storm damage evaluation around Mgeta.

2. In lines, along the contour some distance (approximately 30 m) *below* ridge crests as water pressure in this zone.
a counter measure to the build-up of pore
3. Upslope of villages and individual dwellings to protect dwellings and lives.
4. Along stream lines to restrict bank erosion by floods, excessive sediment transport, deterioration of water quality and downstream sedimentation on cultivated land, in culverts and in dams. Sedimentation downstream caused the major quantifiable damage in the Mgeta area in February 1960.

Further advantages of such a policy to those advanced above are: (a) it would ensure a supply of building timber and firewood at hand; (b) it would decrease the illegal depletion of the Forest Reserve; (c) it would generate local employment; (d) it is already recognised locally as an effective remedial measure against landslides; (e) it is cheap and feasible.

The introduction of new tree crops and the expansion of the area covered by tree crops would have the following advantages; (a) it would directly curtail erosion of all types; (b) it *could* be a means of introducing better husbandry methods if the provision of seedlings at low cost was made conditional upon eg. better control of burning or trash-barrier maintenance; (c) it would provide supplementary income and improved diet for the farmers—a tangible short-term incentive. Several types of fruit trees flourish in this area (eg. guava, apricot etc.) and a market (eg. Dar es Salaam, Morogoro) and marketing organization for vegetable export already exists, though it needs radical overhaul.

The proportion of land currently under tree crops in the Ulugurus is very low (5.7 %) and significantly lower than in the Usambara and Pare mountains (11.8 %) (Thomas *op. cit.)* and on Rungwe, Kilimanjaro and Meru. This probably results from clan ownership of land. Clan heads discourage tree planting because it restricts their right to reallocate land and takes arable land out of cultivation (Duff, personal communication).

Any encouragement of perennial crops to reduce the excessive dependence on annual crops like maize on the western slopes and hill-rice on the eastern slopes would also be advantageous as a means of improving soil structure and infiltration capacity. This would retard sheet wash. Though proposed in general terms on numerous occasions in the past, it has not been adopted. Local custom and traditional land ownship patterns appear to be the main constraints.

Conservation practices could be readily improved on land used for annual crops. Local farmers are prepared to adopt simple measures if these are *demonstrated* to provide better crop yields. The widespread employment of ladder terraces in the Mgeta area is an indication of this. The Mfumbwe data (Temple & Murray-Rust, 1972) confirms the value of this practice on steep slopes.

Few of these proposals are in themselves new. The criteria employed in identifying appropriate measures have been feasibility, low cost, the likelihood of local acceptance and technical considerations.

## Conclusions

Past conservation policies were often unsoundly based and unwisely implemented. Before 1945 efforts were piecemeal and uncoordinated. The major attempt at a comprehensive rehabilitation scheme foundered as a result of its own technical inadequacy and the resistance it provoked. The subsequent "laissez faire" policy has contributed little to the improvement of the situation.

Experience from this area indicates clearly that certain conservation measures are both desirable and necessary. The most practicable of these measures are briefly discussed.

## Acknowledgements

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made numerous most valuable criticisms of the text and provided the author with new insights into many of the events described in which both played key roles. Neither are responsible for the opinions expressed above (except where directly quoted).

*Professor P. H. Temple, Department of Geography, University of Dar es Salaam, P. O. Box 35049, Dar es Salaam, Tanzania.*

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# SOIL EROSION AND SEDIMENT TRANSPORT IN THE MOROGORO RIVER CATCHMENT, TANZANIA

BY ANDERS RAPP, VALTER AXELSSON, LEN BERRY, AND D. HAMMOND MURRAY-RUST

Department of Physical Geography, University of Uppsala
Graduate School of Geography, Clark University and
Department of Geology and Geography, City of London Polytechnic

ABSTRACT. The catchment covers an area of 19.1 km². It has a range of altitude from 550 m to 2138 m a.s.l. on the northern slopes of the Uluguru mountains. The uppermost 40 % of the catchment is covered by a rainforest reserve. On aerial photos from June 1970 cleared land with grass or bush fallow covered 44 %, and cultivation 10 % on slopes as steep as 26°—42°. The soils are sandy loams, derived from weathering of the Precambrian metamorphic bedrock. The annual rainfall is 2400 mm at 1450 m a.s.l., and 890 mm at 530 m a.s.l., where June—October are dry months with less than 50 mm rainfall.

Suspended sediments in the Morogoro river were sampled during three rainy seasons: March—May 1969, 1970 and 1971. The flow is flashy with very rapid rises and short-lasting peaks, which make manual sampling difficult. Highest concentration of suspended sediments measured was 10.6 g/lit. Mean annual sediment transport in 1966—1970 was calculated as 7500 tons based on streamflow data and sediment rating curve from the sampling period. It corresponds to about 390 tons or 260 m³ of annual sediment yield per km² of drainage area. The steep slopes and stream channels make it likely that the suspended material sampled in the river mainly consists of soil particles eroded and brought directly from the slopes by the same flood water.

Sheet wash from the cultivated 10 % of the catchment is thought to supply the main flow of sediments, occasionally increased by small landslides and mudflows. Rills occur only to a minor extent and steep-sided gullies not at all in these valleys. The absence of gullies is probably due to a high infiltration rate and thin soils. The main hazard of cultivating such steep slopes, beside the rapid exhaustion of the soils, is the danger of catastrophic erosion during extremely intensive rains with several years interval. See Temple & Rapp 1972 (this volume). A programme of chemical analyses of soils, runoff water and sediments was planned but could not be carried out. Continued research in this catchment should give high priority to analyses of the role played by solution losses.

The considerable losses of soil and water documented in our studies of the Morogoro river catchment can probably be reduced to acceptable proportions by simple conservation measures such as the following. Planting of tree belts on critical slope sections to reduce the danger of landsliding (cf. Temple & Rapp 1972). Extended use of grass barriers, trash bunds and mulching on bare fields to reduce splash and sheet wash (cf. Temple & Murray-Rust 1972). Manuring of fields to permit longer periods of cultivation and hence longer periods of grass and bush fallow on a larger proportion of the cleared slopes.

## Introduction

This report on the Morogoro river catchment is one of the DUSER project studies (Dar es Salaam/Uppsala Universities Soil Erosion Research). The study deals with the contemporary erosion by water in an instrumented, small catchment of the Uluguru mountains. This highland was the scene of the Uluguru Land Use Scheme which ended in riots in the 1950s (cf. Temple 1972, this volume).

The scope of this and the other DUSER studies in the Ulugurus was to obtain documentation on the types, extent and rate of contemporary soil erosion. Three different approaches were used in our investigations:

a) Measurements of the soil and runoff losses from a natural catchment basin, where sub-uniform conditions were expected to prevail. (The Morogoro river catchment.)
b) Studies of erosion and sedimentation from splash and rainwash in small experimental plots at Mfumbwe with different vegetation cover. (Temple & Murray-Rust 1972.)
c) Inventory and studies of the effects of an unusually heavy rainstorm in a catchment basin at Mgeta, western Ulugurus. (Temple & Rapp 1972.)

The paper deals with the first- mentioned type of study. The approach required a small-sized catchment basin in representative terrain and land use conditions, where background data on rainfall, streamflow and other parameters were available and where additional water sampling and inventories of catchment could be performed within the limited resources in time and personnel of the DUSER research

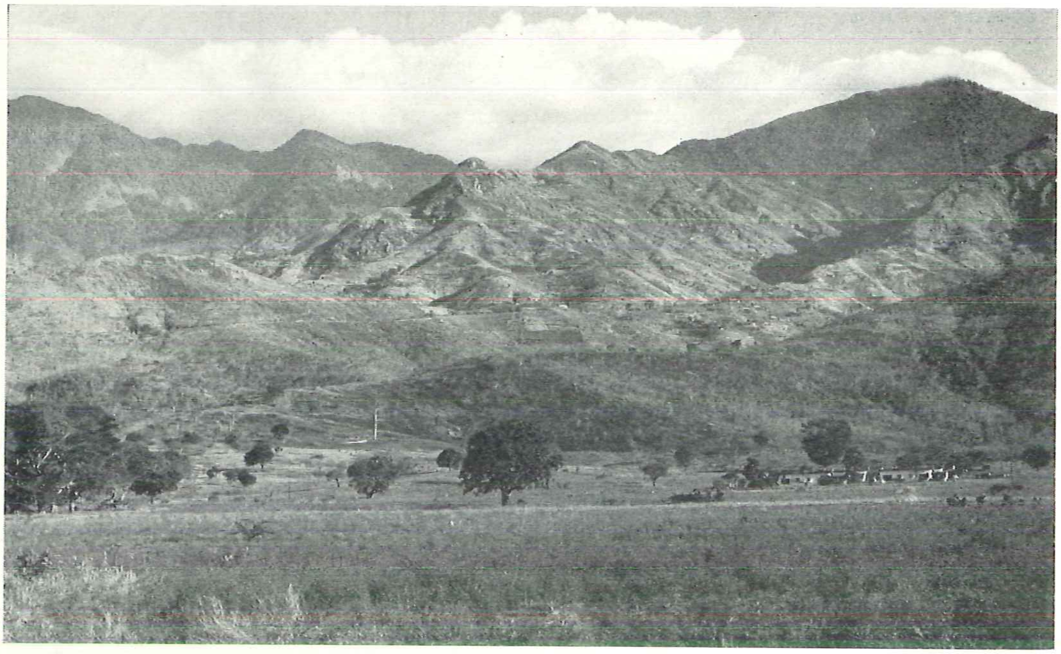

Fig. 1. View of the northern Uluguru mountain front and part of the Morogoro river catchment. Four altitudinal zones are visible. Montane rainforest covers the upper steep slopes of Bondwa (2120 m) at right and Kinazi ridge (2000 m) at left. Below the forest is a zone of steep cultivated slopes, e.g. the ridge of Kisamvili peak (1200 m) in the centre of the picture.

Below that zone are ridges with miombo woodland and black areas of newly burnt grass. In the foreground is a pediment slope with scattered trees. Photo AR 10/71 (= October 1971).

project. The upper catchment of the Morogoro river was selected in 1968 by A. Rapp and L. Berry. It drains an area of 19.1 km$^2$ on the northern slopes of the Uluguru mountains, above Morogoro town. This catchment was selected because it is representative of the Ulugurus in terms of terrain and land use and it is one of the few small mountain basins in Tanzania with regular recordings of precipitation and of stream flow.

A recording Dines rain-gauge with 24-hour graphs is operated by WD & ID above Morningside Farm in the upper part of the catchment at 1450 m a.s.l. (No. 96.37046, started in 1954, Jackson 1968, p. 31). A concrete Cipolletti weir and an Ott float water-level recorder are WD & ID:s stream gauging station no. 1 HA 8, established in 1954 (WD & ID 1967, p. 69). The stream gauge is located at the Morogoro river, 550 m a.s.l., and about 2 km upstream from Morogoro town (cf. Fig. 2). Good topographical and geological maps and air photo coverage, easy access to the catchment from the campus of the Agricultural Faculty at Morogoro and a mountain road trafficable by 4-wheel-drive vehicles in all seasons are other advantages, which this catchment offers as a study area.

The following research programme has been performed.

1. Sampling and analysis of suspended sediment load in the Morogoro river during three rainy seasons: 1969, 1970 and 1971. The sampling was done at the 1 HA 8 gauge by field assistants. Samples were taken in a one-litre water sampler of Uppsala type (cf. Nilsson 1969 and Fig. 16). The samples were later filtered and analysed for concentration of suspended load in the Laboratory of the Department of Agricultural Chemistry, Morogoro. The analysis was done by a laboratory assistant supervised by Dr. A. Kesseba (cf. Table 1).

   Sediment discharge rating curves for the three different periods of sampling have

Table 1. Numbers of samples and period of sampling suspended sediment in water of Morogoro river at Station I HA 8, Morogoro.

| Year | Period | Number of samples |
|---|---|---|
| 1969 | 20.3.69 – 19.5.69 | 320 |
| 1969 – 70 | 29.12.69 – 30.6.70 | 1500 |
| 1970 – 71 | 10.12.70 – 11.5.71 | 1500 |

been computed by V. Axelsson. He has also calculated the annual transportation of suspended sediment in the stream.

In addition to the analysis of suspended load it was also planned to do chemical analyses of soils, water and sediment in order to study the solution losses from the catchment. Such studies have been performed e.g. by Bormann, Likens & Eaton (1969) in the U.S. and by Douglas (1968) in Malaysia. During our sampling periods 4 water samples per week should have been analysed for pH, conductivity and total dissolved solids. In one water sample per month the main chemical constituents were supposed to be analysed, according to the planning. This part of the programme could not be carried out, due to circumstances beyond our control. In future studies of runoff and erosion in the Morogoro river catchment, high priority should be given to analyses of the role played by solution losses.

Further details of methods and their evaluation will be discussed below in the chapter on water and sediment load by V. Axelsson.

The rainy season of 1969 had many and high flow peaks, 1970 had rather few and 1971 was a dry year with only a few and low peaks. Manual sampling proved to be a difficult method to catch the high flow peaks, which are irregular, shortlasting and have a frequency maximum at night time in the Morogoro river. Due to these difficulties the number of flow peaks that have been sampled and analysed are not many, although sufficient to give the range of sediment concentration at various water stages. We tried in 1971 to use an automatic sediment sampler, type Hayim 7 but due to practical difficulties of manpower and mounting, the instrument could not be used at Morogoro. It was later installed in a catchment near Dodoma. (See Rapp, Murray-Rust et al. 1972, this volume.)

2. Catchment inventories by repeated transects on the ground. Land use and existing erosional features were noted such as areas eroded by sheet wash, rilling or landslide scars. Soil profile descriptions and soil sampling were performed in transects on slopes from ridges to valley bottoms. Colour, texture and structure of soils were noted (cf. Table 3). The samples were also analysed for grain size composition.
3. Detailed land use maps were made along two slope transects by Mr. Mbegu, a graduate student in geography, University of Dar es Salaam, supervised by Berry and Murray-Rust.

Old air photographs are available and have been used for comparisons. There is available a complete coverage of August 1955 (scale about 1 : 40,000) and another of Morogoro town and vicinity only, taken in July 1955 (approx. scale 1 : 5000). New air photographs were ordered by BRALUP and flown by Spartan Air Survey in June 1970 over the entire Morogoro catchment at a scale of 1 : 10,000. These air photographs will be of increasing value for future comparisons of the situation in the catchment as regards changes in erosion conditions, land use, number of farms or other factors (cf. Fig. 3). The land use map. Fig. 2, was based on the 1970 air photographs and ground checking.

The value of the data and documents of this catchment is partly the information they give about conditions until now, but particularly the basis they provide for comparisons in the future.

The little catchment of the Kikundi stream immediately W of the Morogoro river catchment (Fig. 2) offers very good opportunities for a parallel study in the future. It is smaller (area 4.2 km$^2$) than the Morogoro river catchment, it has no rainforest left and is thus more uniform in land use of mountain cultivation, it is very easily accessible from the Agriculture College Campus and is close to two raingauges with long records (Morningside Farm at 1450 m and Morogoro Agricultural Office at 530 m altitude). This catchment ought to be instrumented for studies of water balance and

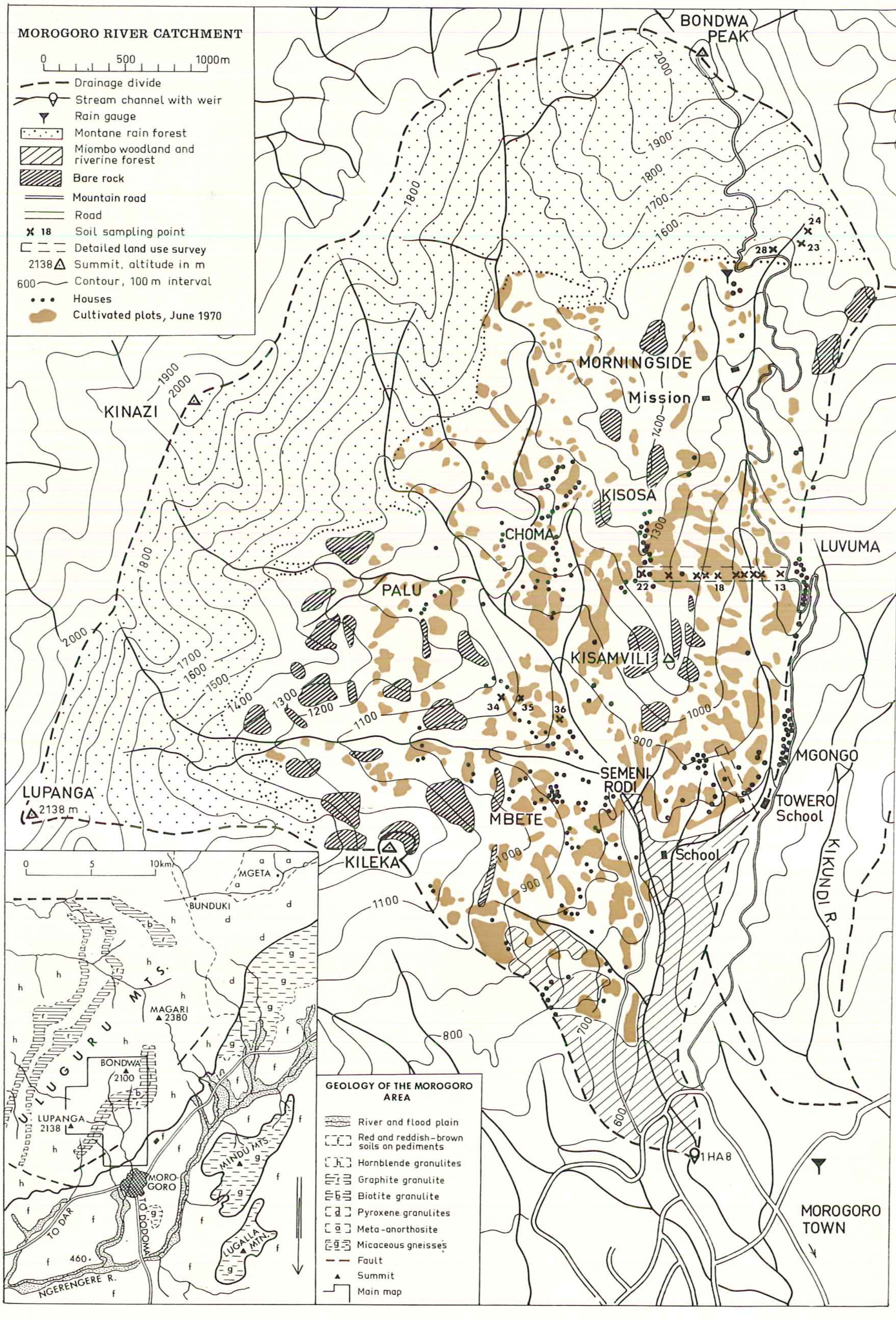
MOROGORO RIVER CATCHMENT
0
500
1000m
Drainage divide
Stream channel with weir
Rain gauge
Montane rain forest
Miombo woodland and riverine forest
Bare rock
Mountain road
Road
18
Soil sampling point
Detailed land use survey
2138
Summit, altitude in m
600
Contour, 100 m interval
Houses
Cultivated plots, June 1970
BONDWA PEAK
2000
1900
1800
1700
1600
24
23
28
MORNINGSIDE
Mission
1400
KINAZI
1900
2000
KISOSA
1300
CHOMA
LUVUMA
22
18
13
PALU
KISAMVILI
2000
1700
1600
1500
1400
1300
1200
1100
34
35
36
1000
900
MGONGO
SEMENI RODI
TOWERO School
LUPANGA
2138 m
MBETE
School
KILEKA
1000
900
1100
KIKUNDI R.
700
800
600
1HA8
MOROGORO TOWN
0
5
10km
MGETA
BUNDUKI
ULUGURU MTS.
MAGARI
2380
BONDWA
2100
LUPANGA
2138
MORO-GORO
MINDU MTS.
TO DAR
TO DODOMA
LUGALLA MTN.
460
NGERENGERE R.
GEOLOGY OF THE MOROGORO AREA
River and flood plain
Red and reddish-brown soils on pediments
Hornblende granulites
Graphite granulite
Biotite granulite
Pyroxene granulites
Meta-anorthosite
Micaceous gneisses
Fault
Summit
Main map


Fig. 3. Vertical air photograph of part of the Morogoro catchment. Mb, Ch, Mo and Ki = Mbete, Choma, Morningside and Kikundi streams. C, K, M and L = Choma, Kisosa, Mgongo and Luvuma villages. Photo Spartan Air, June 1970.

Fig. 2. Map of the Morogoro river catchment (opposite page).

Altitudes and contours from map sheet 183/3, Morogoro 1 : 50,000, 1970. Forest boundary, houses and cultivated plots from air photographs of June, 1970. Insert map of geology based on geological sheets 183 Morogoro and 64 N.E. Uluguru.

Fig. 4. Mbete valley, Morogoro river catchment. Lupanga ridge (2138 m) with montane rainforest on steep slopes in the background. The rocky, forest-free peak of Kileka (1360 m) to the left with steep cleared slopes and Mbete village in centre of picture. In foreground mainly slopes with grass fallows at 800 m altitude E of Towero School. Note grass barriers to combat slopewash in right foreground. Photo AR 10/71.

losses of soil and dissolved solids from the steep cultivated slopes. A minimum instrumentation for such studies should be a rain gauge within the catchment and a stream gauge with an automatic sediment sampler and combined manual sampling. The stream gauge should be built upstream of a stone quarry at the lower end of the valley, to avoid disturbances by sediment from the quarry.

## Relief, geology and soils

The catchment of the Morogoro river has approximately the form of a triangle (Fig. 2). One side is the mountain ridge where the drainage divide runs at about 2000 m elevation from the Lupanga peak (2138 m) in the east to Bondwa Peak (ca 2120 m) in the south. From there the drainage divide follows a N—S trending narrow ridge down to the stream weir 1 HA 8 at about 550 m altitude. There are two major tributary valleys in the catchment. One is the Morningside valley with the Morningside stream running S—N along the W side of the drainage divide. The other is the Mbete valley in the E part of the catchment, branching into several steep valley heads towards the Lupanga—Kinazi ridge. The two main tributary streams of the E part of the catchment are in this paper called the Mbete stream and the Choma stream (Fig. 3). The main mountain crests as well as the divides between the lower valleys are steep-sided bedrock ridges, such as the Kisamvili ridge between Morningside and the Mbete valley (Figs. 1 and 3).

The Uluguru mountains are a horst block of Precambrian rocks. "It is apparent that the Ulugurus have been uplifted as a block several times since the formation of the Karroo basins. Therefore the upper part of the scarp is probably a very old and deeply eroded fault-scarp" (Sampson & Wright, 1964, p. 9).

The small geological insert map of Fig. 2

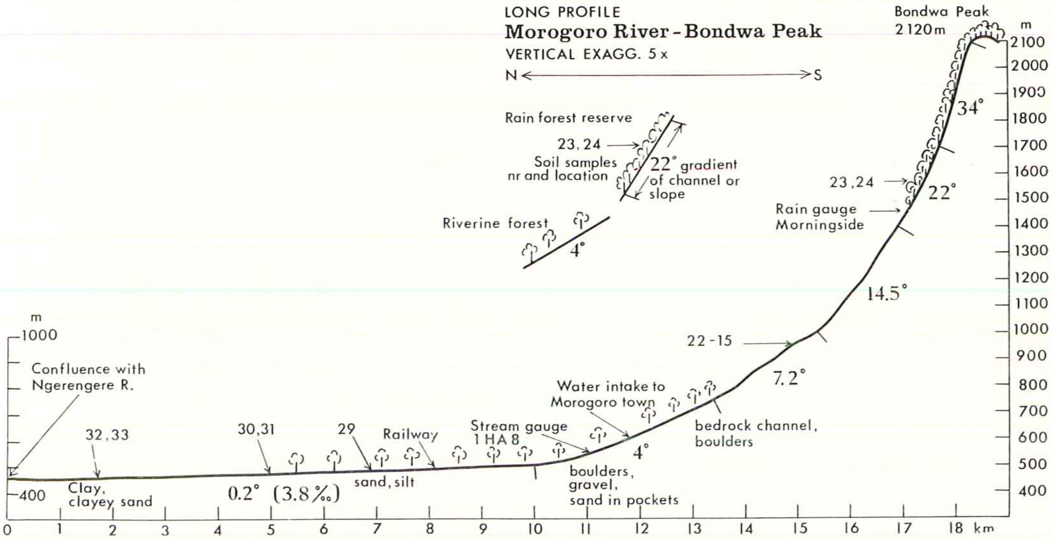


Fig. 5. Long profile from Bondwa Peak to Ngerengere river. Based on topographic sheet 183/3 Morogoro, 1970. For soil samples, cf. Table 3.

shows fault lines parallel to the mountain front on the lower slopes. Small faults have also been observed by us on the uppermost pediment slope near the Agricultural College, namely in two gullies, which have cut through thick colluvial sediments and exposed the faulted bedrock. These faults indicate repeated block uplift and heavy deposition of colluvium between the uplifts. (Fig. 24).

The main mass of the Uluguru mountains is made up of granulites. The term granulite is used for rocks of the granulite facies. It implies certain textural features of the rocks and certain mineral assemblages which are regarded as the result of metamorphism rather than origin or chemical composition (op.cit. p. 16).

The northern Ulugurus near Morogoro mainly consist of hornblende-pyroxene granulites. They are intensely folded and have in general northerly strikes, which is reflected in the N—S direction of many terrain ridges. "Along the northern face of the Uluguru mountains behind Morogoro, the granulites are extensively veined and injected with granitic material. In places, however, injection and migmatization have produced foliated gneisses and augen gneisses. Minor basic intrusions are also found in this area:" (op. cit. p. 48). Fig. 8 shows a roadside cut through soil and regolith with in situ foliation. The soil cover is only about 0.3 m thick and the weathered bedrock is penetrated by tree roots which follow the dip of the foliation.

Morogoro is the centre of the mica industry of Tanzania. The mica is mined in small quarries in veins all over the northern Ulugurus.

Fig. 5 is a long profile of channels and slopes from the Bondwa Peak at 2120 m a.s.l. to the confluence of the Morogoro river and the Ngerengere river at 460 m a.s.l. The profile is drawn from a map in scale 1 : 10,000 with a 20 m contour interval, a magnification of the 1 : 50,000 map. The uppermost part of the profile runs down slopes in the montane rainforest and shows an average gradient of 34° from 2100 to 1700 m. Locally slopes of up to 60° inclination occur in this zone, covered by forest and a thin, gravelly soil and regolith, anchored by tree roots. The colour of the soil is reddish brown.

The valleys are deep with average side gradients of 25°—35° from the foot of the rocky slopes above them, to the slightly incised stream channels at their base (Figs. 4 and 6).

The slopes of the catchment carry thin and eroded residual or colluvial soils. Character-

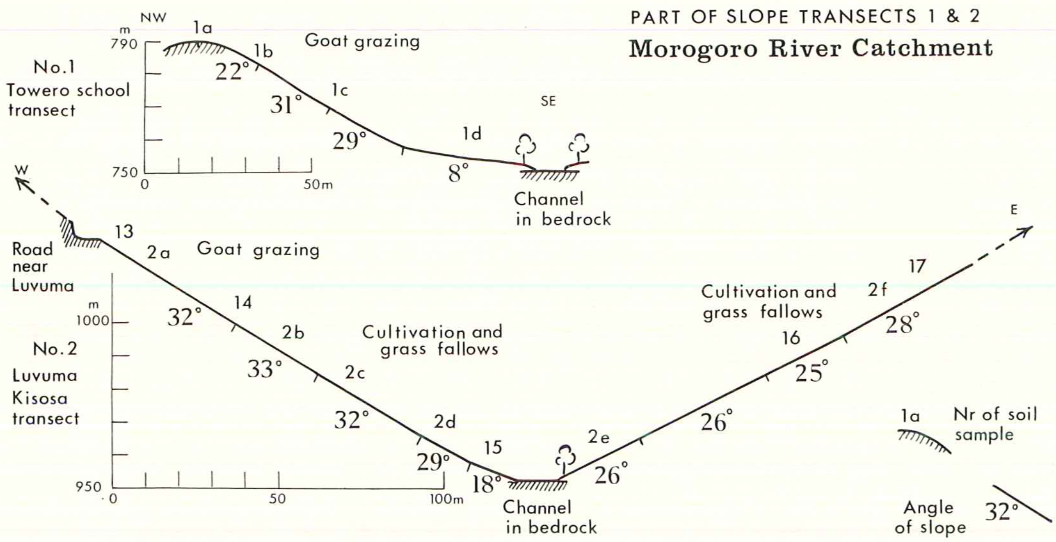


Fig. 6. Valley-side transects in the Morogoro river catchment. For location, see Fig. 2.

istic is a heavy washing out of fines on the upper, steep part of the slopes and some accumulation of clay and silt on less steep sections in valley bottoms (Table 2, sample 1d) or near grass barriers (sample 2e). The dark topsoil layer is generally only a few cm thick, or missing. Yellow-reddish sandy loams are the common soils on most of the slopes in the middle of the valley, all thin and eroded, resting upon a sandy regolith with pebbles and in situ veins of feldspar or quartz. Darker red coloured soils occur on the lower ridges below 800 m (e.g. samples la, 1b, Figs. 6 and 7) under the so-called miombo woodland there. Cf. Table 3.

Gravel material is not common in the regolith or topsoil, nor in the upper part of the alluvial fan below the 1 HA 8 weir at 550 m.

The streams have steep gradients and irregular long profiles with many thresholds of bare rock and bouldery courses between the rocky sections (Fig. 4). The gradient decreases

Table 2. Grain size composition of topsoil in the Morogoro river catchment. Grain sizes from sieving and hydrometer analyses by WD & ID soils lab, Ubungo. Sampling by A. R. and V. A. 1970.

| Sampl No. | Depth cm | Altitude m a.s.l. | Slope Angle | Vegetation or land use | Grain sizes in mm, weight % | | | | | Texture and colour |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | >2 | 2—0.2 | 0.2—0.02 | 0.02—0.002 | clay | |
| 4a | 0–20 | 1500 | 25° | Rain forest | 12 | 32 | 33 | 23 | — | Gravelly/sandy loam 10YR 5/6 |
| 3a | 0–25 | 1310 | 22° | Maize field | 8 | 24 | 38 | 14 | 16 | Sandy/silty loam 10 YR 4/3 |
| 2a | 0–25 | 1020 | 32° | Grazed fallow | 13 | 38 | 36 | 8 | 4 | Sandy loam 7.5 YR 4/4 |
| 2c | 0–25 | 980 | 32° | Former cassava field | 7 | 34 | 37 | 11 | 11 | Sandy loam 10 YR 3/2 |
| 2e | 0–25 | 960 | 26° | Elephant grass barrier | 2 | 24 | 33 | 7 | 34 | Sandy clay 7.5 YR 4/4 |
| 1c | 0–25 | 770 | 30° | Grazed grass & bushes | 2 | 27 | 43 | 5 | 23 | Sandy/clayey loam 5 YR 3/4 |
| 1d | 0–25 | 755 | 8° | Grazed grass & bushes | — | 17 | 45 | 8 | 30 | Sandy clay 5 YR 3/2 |

Table 3. Soil samples from the Morogoro river catchment above and below Morogoro town, Tanzania. Sampling in October 1971. Note predominance of thin sandy soils on slopes. For location of samples, cf. Figs. 2, 5, and 6.

| Sample | Location | Altitude m a. s. l. | Slope angle | Land use, vegetation | Depth cm | Colour | Texture | Comments |
|---|---|---|---|---|---|---|---|---|
| 24 | Ridge in forest | 1525 | $40^{o}$ | Rain forest | 0-10 | 5YR 3/4 | Silty loam | Much organic, stones on surface. |
| | | | | | 10-20 | 5YR 5/8 | Sandy loam | Weathered rock |
| | | | | | 20-40 | 5YR 5/8 | Silty sandy regolith | Weathered rock |
| 23 | Valley side slope in forest reserve | 1510 | $28^{o}$ | Rain forest | 0-10 | 5YR 3/3 | Silty loam | Organic, moist |
| | | | | | 10-20 | 5YR 4/6 | Silty sandy loam | |
| | | | | | 20-40 | 5YR 4/8 | Sandy loam | Many stones |
| 13 | Near Luvuma village | 1025 | $30^{o}$ | Goat grazing, guava trees | 0-10 | 7.5YR 4/3 | Sandy silty loam | Grass fallow with burnt patches. Weathered feldspar |
| | | | | | 10-30 | " | " | |
| 14 | Luvuma slope | 1000 | $32^{o}$ | " | 0-10 | 7.5YR 3/3 | Silty loam | Grass roots |
| | | | | | 10-30 | 5YR 3/3 | Silty loam | Weathered feldspar |
| 15 | Near valley bottom | 965 | $18^{o}$ | Cassava, weeds | 0-10 | 7.5YR 4/3 | Sandy silty loam | Moist below 10 cm |
| | | | | | 10-40 | 5YR 3/3 | Sandy silty loam, some stones | Pebbles below 50 cm |
| 16 | Kisosa slope | 990 | $25^{o}$ | Maize, grass | 0-5 | 7.5YR 4/3 | Silty-sandy loam | |
| | | | | | 5-20 | 7.5YR 4/6 | Clayey silt | Crack, 5-10 cm apart |
| | | | | | 20-40 | 7.5YR 5/8 | Clayey | Slight moisture, rock grains |
| 19 | Kisosa slope | 1105 | $28^{o}$ | Old Cassava | 0-5 | 7.5YR 3/3 | Silty loam | In soil deposit |
| | | | | | 5-20 | 7.5YR 2/3 | " | 1 m upslope of grass barrier |
| | | | | | 20-40 | " | Sandy loam | |
| 20 | Kisosa slope | 1185 | $28^{o}$ | Old Cassava | 0-10 | 5YR 2/2 | Silty loam | Slope of grass barrier 1 m down |
| | | | | | 10-20 | 5YR 4/6 | Sandy loam | Quartz grains, max. 7 mm |
| | | | | | 20-30 | " | " | |
| 21 | Kisosa slope | 1225 | $28^{o}$ | Maize shamba | 0-10 | 5YR 3/4 | Sandy silty loam | Much mica |
| | | | | | 10-20 | 5YR 3/3 | " | Much weathered mica |
| | | | | | 20-40 | 5YR 5/8 | Sandy | Weathered mica-rock |
| 22 | Village Kisosa 10 m wide ridge | 1260 | $5^{o}$ | Grazing | 0-10 | 7.5YR 5/4 | Sandy | - |
| | | | | | 10-30 | 7.5YR 7/8 | Sandy | Much mica |
| | | | | | 30-60 | 7.5YR 7/8 | " | " |
| 34 | Mbete valley | 1050 | $20^{o}$ | Cassava shamba | 0-10 | 5YR 4/8 | Clayey loam | Sand grains |
| | | | | | 10-50 | 5YR 5/8 | Clayey loam | Close to weathered bedrock + grains of quartz and feldspar |
| 35 | Mbete valley | 1000 | $30^{o}$ | Cassava and tomatoes | 0-5 | 5YR 4/4 | Crusted clayey loam with rock grains | On slope 20 m below steep rock cliff |
| | | | | | 5-20 | 5YR 3/4 | " | |
| | | | | | 20-40 | 25YR 3/6 | Clayey loam | + rock grains |
| 36 | Mbete valley | 875 | $17^{o}$ | Old maize shamba | 0-10 | 7.5YR 4/2 | Silty loam | Footslope near valley bottom |
| | | | | | 10-40 | 7.5YR 3/2 | Silty loam with rock grains | Below 40 cm is weathered bedrock |
| 29 | Morogoro river bank | 485 | Plain | Vegetables, sugar cane gardens | 0-10 | 5YR 4/4 | Silty sandy loam | On side of levée ridge |
| | | | | | 10-15 | 5YR 4/6 | Sand + mica flaces | |
| | | | | | 15-20 | 25YR 3/6 | Clayey loam | Crusted |
| | | | | | 20-50 | 5YR 6/8 | Sand | |
| | | | | | 145-170 | 25YR 3/6 | Clay - old weathered | Bedrock at water's edge, 270 cm below surface |
| 30 | Morogoro river flood plain | 480 | Plain | Sugar cane | 0-20 | 5YR 4/6 | Fine sand | |
| | | | | | 20-50 | 7.5YR 4/4 | Medium sand | |
| | | | | | 50-80 | 5YR 4/8 | Silty sand | River terrace |
| | | | | | 80-100 | 5YR 3/2 | Silty clayey loam | |
| 31 | Morogoro river flood plain 100 m from channel | 480 | Plain | Sugar cane | 0-25 | 7.5YR 5/4 | Silty loam | Floodplain 100 m from river |
| | | | | | 25-50 | 5YR 4/4 | " | |
| | | | | | 50-80 | 7.5YR 4/4 | Sandy loam | |
| 32 | Flood plain near Ngerengere | 470 | Plain | Rice field | 0-20 | 7.5YR 4/4 | Sandy clay | 100 m from W edge of floodplain |
| | | | | | 20-50 | 5YR 4/6 | Clayey sand | |
| 33 | Middle of flood plain | 470 | Plain | Rice field | 0-35 | 5YR 3/1 | Clay | Water level at 35 cm depth 250 m from edge of floodplain. |

to 4° above the weir at 550 m. Below that, the river enters a small fan above Morogoro town. The pediment slope is about 9 km wide and it has a gradient of 0.2° from the mountain foot at the weir to the Ngerengere river at 460 m altitude. The Ngerengere as well as the lower Morogoro river have distinct floodplains with clayey sediments in gently incised valleys between pediment slopes of about 2° gradient (Cf. Fig. 5 and Table 3).

Immediately below Morogoro town the alluvial deposits of the river are sandy levees only about 2 m thick, resting upon the weathered bedrock of the true pediment surface. In the middle of the floodplain close to the confluence with the Ngerengere river alluvial clays predominate, but sandy alluvium occurs along the marginal parts of the floodplain. (Table 3, samples 32, 33, cf. insert map of Fig. 2.)

The morphology and deposits of the Morogoro plains have been described by e.g. Louis (1964, note Fig. 2 and Plates 1 and 8). Louis interprets these plains as completed peneplains cut by incision of shallow "pure saucer-shaped valleys resulting from the cooperation of relatively strong sheet wash . . . with only slight down-cutting of the valley-bottom" (op. cit. p. 67).

## Climate and vegetation

The main weather station of the area is at the Morogoro Agricultural Office (Met. station no. 96.37000) located at lat. 6°51'S and long. 37°40'E, near the lower end of the Morogoro catchment (Fig. 2). The altitude is 530 m a.s.l. according to the new topographic sheet Morogoro 183/3. The station has recorded rainfall since 1905, but there are gaps of together 120 months in the older registrations (Jackson 1968, p. 30).

In the Morogoro river catchment is Morningside Farm, one of the few automatic recording stations in Tanzania (No. 96.37046). It is run by WD & ID and has been in operation since 1954 (op.cit. p. 31). It is located above Morningside at 1450 m a.s.l. on a ridge below the boundary of the forest reserve.

Data from the two stations are listed in Tables 4 and 6. Mean annual rainfall at Morogoro is 890 mm (1931—60). The dry season lasts from June to October. Rainfall data from Morningside in table 4 are limited to the period 1961—70 because of many gaps in the earlier records. Although the series of Morogoro is from a different period than the Morningside data their main trends can be compared. The rapid rise of rainfall with increasing altitude is evident: 160 mm/100 m. Morningside has an annual preciption of 2392 mm, a culmination of the "long rains" in April (525 mm) and another culmination of the "short rains" in November (250 mm). The driest month is August (96 mm). A comparison with the rainfall stations of the Mgeta area further to the SW in the Ulugurus shows great similarities between rainfall amounts at Morningside and at Bunduki (Temple & Rapp 1972, Table 3). These two mountain stations both have a significant season of "short rains" with a maximum in November and minimum in January, in contrast to their nearby valley-bottom stations which only have one rainy season, viz. that of the "long rains".

Rainfall, runoff and stream flow in the Mo-

Table 4. Climatic records, Morogoro, station no 96.37000 at 530 m a.s.l. and Morningside at 1450 m (only rainfall), Mean air temperature, potential evaporation ($E_0$) and amount of clouds for the period 1947—1960 from Woodhead 1968, p. 46. Rainfall data from E.A. Met. Dept. 1966 (Morogoro) and E.A. Met. Dept. archives (Morningside). Altitudes are corrected from contoured topographic sheet Morogoro 183/3 of 1970.

| Mean rainfall: | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 530 m a.s.l. (1931—60) | 94 | 102 | 158 | 206 | 105 | 24 | 9 | 11 | 14 | 24 | 59 | 84 | 890 |
| 1450 m a.s.l. (1961—70) | 132 | 175 | 274 | 525 | 245 | 115 | 104 | 96 | 123 | 170 | 250 | 182 | 2392 |
| Mean air temp. (° C) | 26.3 | 26.3 | 26.1 | 25.0 | 23.5 | 21.6 | 21.1 | 22.1 | 23.2 | 24.6 | 25.7 | 26.5 | 24.3 |
| $E_0$ (mm/month) | 173 | 159 | 167 | 126 | 111 | 106 | 112 | 126 | 146 | 179 | 176 | 179 | 1760 |
| Cloud (oktas) | 5.5 | 5.7 | 5.7 | 6.1 | 6.1 | 5.4 | 5.3 | 5.2 | 5.2 | 5.0 | 4.9 | 5.2 | — |

Table 5. Area percentages of different land use and vegetation cover in the Morogoro river catchment. Based on air photographs of June 1970.

| | Area, km² | Percent |
|---|---|---|
| Montane rainforest | 7.6 | 39.8 |
| Grass fallow, bush fallow | 8.4 | 44.0 |
| Cultivated plots | 2.0 | 10.5 |
| Bare, rocky slopes | 0.3 | 1.5 |
| Miombo woodland and riverine forest | 0.8 | 4.2 |
| Total | 19.1 | 100.0 |

rogoro catchment will be further discussed below under the headline "Rainfall".

The mean annual air temperature at Morogoro is 24.3° C. The coolest month is July (21.1°), the warmest is December (26.5°) which means a small seasonal variation of temperature. Also the potential evaporation and the cloudiness has only small seasonal variation (Table 4).

The montane rainforest area covers 39.8 % of the catchment in the zone of highest precipitation and steepest slopes. The lower forest limit runs at about 1500—1600 m a.s.l. above Morningside (Figs. 2 and 5), but lobes of forest reach down to 1250 m in the E part of the Mbete valley (Fig. 4). It is an artificial limit, caused by clearing, burning and cultivating up to the forest reserve boundary. It has been a forest reserve since the country was a German colony (cf. Temple 1972).

The slopes covered by the forest are very steep. Average inclinations of 22°—34° are shown in the profile Fig. 5 which runs in a straight line on the W side of the winding jeep track up to the Bondwa peak and radio tower at about 2120 m a.s.l. On the sides of this track forest-covered slopes of up to 60° occur. The slopes of the Lupanga ridge have still higher average gradients (Fig. 4). The montane forest is dominated by *Octea usambarensis, Strombosia Schlefferi, Albizia gummifera, Allanblackia stuhlmannii,* and other trees.

In the cleared and cultivated area between about 1500 m and 900 m the slopes are dominated by grass fallows and cultivation.

Below 900 m is a miombo woodland with *Brachystegia boehmii* and *B. bussei* as characteristic tree species and tussock grasses dominated by *Hyparrhenia rufa* and *Panicum maximum*.

## Population and land use

The people in the catchment are of the Luguru tribe. In 1970 the population was estimated to be around 800, to judge from figures of the 1967 census and a count of houses on the 1970 air photographs. This means a population density of 70 persons per km², in the catchment outside the uninhabited forest reserve. The distribution of settlements is shown on the map (Fig. 2). The settlements are concentrated in the lower valley bottoms (e.g. Semeni Rodi, Mbete, Choma, Palu) or on ridge crests (Kisosa, Luvuma, Mgongo). Few houses are built in midslope, probably from a fear of landslides.

The relationship between households and their fields is complicated. Most farmers have a number of small *shambas* in different parts of the catchment. This permits each household to have a wider range of both cash and food crops, as well as minimising the effects of a poor yield from one area. There is a growing shortage of land. This is causing out migration of young people who can get no land of their own.

Three main zones of land use can be distinguished in the Morogoro catchment:

a) the uninhabited montane rainforest reserve,
b) a middle altitude zone of mountain farming ranging approximately between 1500 m and 900 m a.s.l.,
c) a low altitude zone of foothill farming and *miombo* woodland, ranging from 900 m to the lower end of the catchment at 550 m a.s.l. In the lower zone is also included the riverine forest along the streams. The boundary between zones b and c is transitional and very vague, so it is not drawn on the land use map, Fig. 2.

The map was constructed from air photographs taken in June 1970, followed by field checking in stages throughout 1970 and 1971. Detailed land use mapping was carried out in two areas, called slope transect no. 1 and no. 2 (Fig. 6). Tables 5 and 9 summarize the land use percentages and land use zonation of the catchment.

As was mentioned above, the montane rainforest covers 39.8 % of the catchment. It is uninhabited.

The slopes in the zone of mountain farming are dominated by cleared land under fallow

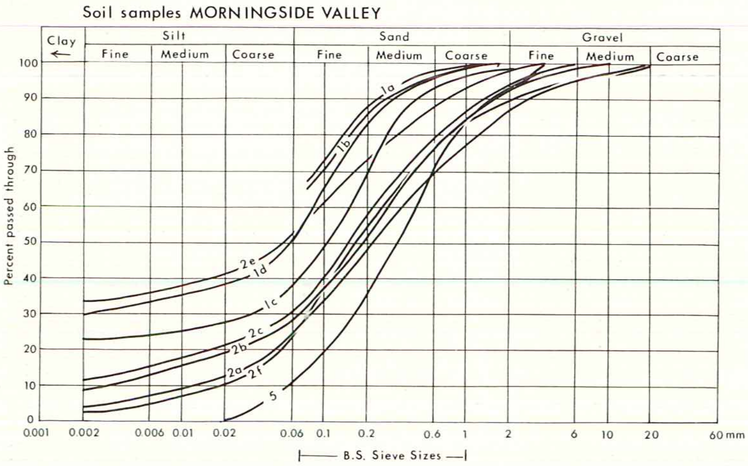


Fig. 7. Grain size composition of soil samples, Morningside valley. Sieve analysis by WD & ID, Ubungo. For location of samples, see Fig. 5. Sampling by A. R. and V. A.

(44.0 % of catchment in June 1970) and cultivated plots (10.5 %). Areas of bare rock are common near the ridge crests, particularly in the eastern part, and occupy 1.5 % of the catchment. The slopes of this zone from ridge-crest to valley-bottom channel in general have a straight or slightly convex-concave slope profile and an average inclination of 25°—35°. The soil is a thin cover of dark topsoil over sandy colluvium and regolith. (Cf. Tables 2 and 3 and Figs. 6 and 7.)

The land use is briefly described in the following summary from a report by C. Rombulow-Pearse to BRALUP, July 1969:

In the zone of mountain farming the farmers clear land in June and July and plant in August. There is enough moisture from occasional showers to make the crop grow. The main crop—maize or sweet potatoes—is ready for harvesting in January and February, after the short rains and before the long rains. The abundant growth of weeds, which flourish in the short rains protect the soil from severe splash erosion, where the weed cover is allowed to stay.

In the zone of foothill farming the land is cleared in September—October when the grass is dry and easy to burn. Maize is planted in January. It develops in the long rains when weeds cannot be tolerated and is harvested in April or May when the rains end. The soils seem to be more severely eroded at the lower levels and the local people say that many farmers have moved higher up in the valley or taken land in Mlali at an irrigation scheme in order to grow food more reliably (C.R.-P., op.cit.). For observations and discussion of soil erosion, see further below, Figs. 21—24 and accompanying text.

The miombo woodland is confined to the foothills, between the mountain slopes and the plains. The woodland covers some 4.2 % of the catchment (0.8 km$^2$). The area is used for goat grazing and it is burnt annually to promote new grass growth.

The cultivation is by hoeing. A common rotation is two or three years of maize and beans cultivation followed by cassava bush during one or two years and then grass fallow until the exhausted soil has regained some fertility. Manuring is not done. In some sections of the valley horizontal live barriers of elephant grass growing on low soil ridges remain as a conservation measure introduced in the 1950s during the Uluguru Land Use Scheme (cf. Figs. 3, 4, 21 and 23).

Throughout the catchment there are small areas in the valley bottoms that are irrigated, using bamboo or banana stems to distribute the water. In the high areas the crops are generally temperate vegetables, but in the lower parts there are more legumes, rice and sugar cane.

Most farmers keep a few goats, but not in such big numbers that they overgraze on the grass fallows. There are no cows kept in the valley.

During 1970 an inventory was made by Mr. Mbegu to measure the change in land use

Fig. 8. Section through soil and weathered granulite rock with in situ foliation. The soil cover is only about 0.3 m thick. The bedrock is penetrated by the roots of a mango tree. The roots follow the dip of the foliation and illustrate the typical anchoring effect of trees on steep slopes with thin soil and regolith. Roadcut at Towero School above Morogoro. Photo AR 10/71.

Fig. 9. Boundary of rainforest reserve near Morningside. To the left new cultivation on steep slope without any conservation measures. Photo AR 10/71.

during one year on two selected slope transects within the catchment. The method employed linear inventory of a 200 feet wide strip running downslope. At 100 feet intervals poles were placed down each line, and the various crop types, fallow areas, rock outcrops, terraces etc. sketched onto graph paper. Measurements of slope angle were taken at regular intervals. The first measurements were taken in September 1970, before the short rains. A second survey was carried out in December 1970, between the short and long rains. The



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results have been incorporated in this text. Copies of Mr. Mbegu's maps are kept in the files of BRALUP, Dar es Salaam.

## Rainfall

*The rainfall station*

A recording raingauge is located in the upper part of the drainage basin, just above Morningside Farm at 1450 m a.s.l. This means that about 40 % of the total catchment area is situated higher than the rain gauge. The records obtained at the rainfall station are therefore probably rather representative of the mean depth of rainfall on the catchment. The gauge is a Dines tropical model operating on a daily time scale of 0.5 inch per hour. The record produced by the gauge is in the form of a mass diagram and gives both the intensity and the total rainfall. Daily readings, that started in 1954, are taken at 9 a.m. and recorded for the preceding day.

According to Jackson (1970) very striking rainfall gradients occur over the Uluguru mountains. This is also the case over the Morogoro river catchment. The upper part of the catchment belongs to the wettest parts of Tanzania, but at Morogoro meteorological station, 530 m a.s.l. and 5.5 km north of Morningside (Fig. 2), the rainfall is considerably lower. The mean annual rainfall here is 890 mm (Table 4), that is less than 40 % of the rainfall at Morningside.

*Annual and seasonal variation*

Monthly and annual point-rainfall data for Morningside are given in Table 6. For the 10 yr period 1961—1970 the mean annual rainfall was as high as 2392 mm. The standard deviation was considerable, partly due to the short period of observation, and amounted to 540 mm or 23 %. With rainfall records covering only a 10-yr continuous period it is not possible to determine the true long-term mean. However, the deviation of the 10-yr mean from the true mean ought not to be too high. Binnie (1955), who studied the periodic variation in rainfall, found that a record 10-yr in length is probably within 8.2 % of the true mean and that records 30 or 40 yr in length in all probability give the true long-term mean rainfall with an average error of about 2 %.

The seasonal variation in rainfall is considerable but rather moderate in relation to most rainfall stations in Tanzania. The wettest 4-month period, February—May, has about half the annual rainfall, the dryest, June—September, less than 1/5. The wettest month, April,

Table 6. Monthly and annual rainfall in mm at Morningside. April 1954—July 1971. Data from E. A. Met. Dept. archives.

| Year | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1954 | — | — | — | 464 | 385 | 3 | 59 | 32 | 43 | 117 | 52 | — | — |
| 55 | 48 | 200 | 128 | 528 | 417 | 153 | 99 | 11 | 119 | 66 | 200 | 268 | 2237 |
| 56 | 209 | 179 | 266 | 601 | 271 | 80 | 8 | 3 | 59 | 54 | 79 | 181 | 1990 |
| 57 | 169 | 109 | 234 | 376 | 455 | 17 | 79 | 69 | 97 | — | 184 | — | — |
| 58 | 132 | — | 260 | 472 | 156 | 129 | 12 | 81 | — | 29 | — | — | — |
| 59 | 147 | — | 90 | 339 | — | — | 24 | — | 50 | 117 | 96 | — | — |
| 60 | 156 | 53 | 314 | 649 | 136 | 98 | 23 | 38 | — | — | 7 | 5 | — |
| 61 | 47 | 393 | 128 | 389 | 183 | 131 | 358 | 30 | 186 | 285 | 444 | 260 | 2834 |
| 62 | 193 | 109 | 93 | 357 | 72 | 3 | 65 | 118 | 40 | 64 | 42 | 138 | 1294 |
| 63 | 207 | 104 | 325 | 458 | 130 | 216 | 100 | 56 | 33 | 83 | 628 | 187 | 2527 |
| 64 | 102 | 137 | 466 | 494 | 180 | 63 | 33 | 64 | 36 | 175 | 0 | 153 | 1903 |
| 65 | 118 | 124 | 171 | 657 | 355 | 10 | 20 | 32 | 67 | 386 | 300 | 192 | 2432 |
| 66 | 168 | 240 | 273 | 495 | 264 | 172 | 9 | 57 | 91 | 242 | 127 | 64 | 2202 |
| 67 | 14 | 134 | 128 | 539 | 591 | 137 | 242 | 276 | 512 | 109 | 387 | 190 | 3259 |
| 68 | 118 | 77 | 532 | 709 | 303 | 219 | 53 | 42 | 46 | 49 | 323 | 179 | 2650 |
| 69 | 68 | 228 | 350 | 678 | 201 | 165 | 138 | 225 | 62 | 217 | 238 | 70 | 2640 |
| 70 | 287 | 208 | 275 | 472 | 170 | 32 | 26 | 61 | 163 | 85 | 12 | 385 | 2176 |
| 71 | 159 | 81 | 249 | 385 | 281 | 168 | 148 | — | — | — | — | — | — |
| Mean 1961—70 | 132 | 175 | 274 | 525 | 245 | 115 | 104 | 96 | 124 | 170 | 250 | 182 | 2392 |

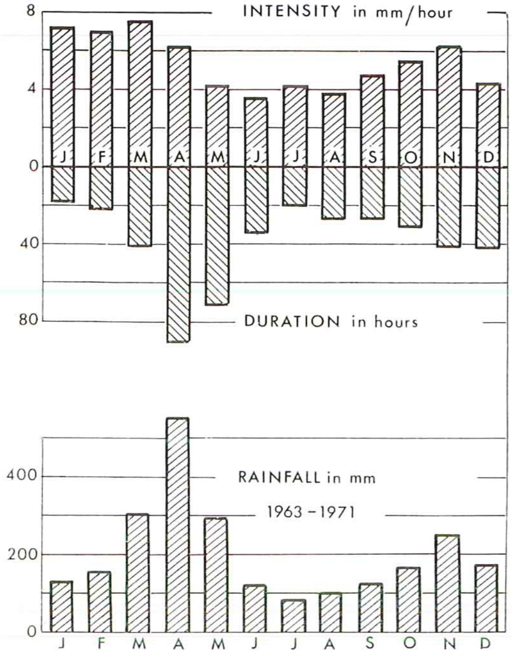


Fig. 10. Mean monthly amounts, intensities and durations of rainfall at Morningside, 1.8.1963—31.7.1971.

often has a rainfall of more than 500 mm. A secondary peak associated with the "short" rains often occurs in November at the mountain stations.

*Duration and intensity*

The duration and intensity of rainfall at Morningside was calculated for the 8-yr period August 1, 1963—July 31, 1971, and is illustrated in Figs. 10—12. During this period the mean annual rainfall was 2465 mm, that is 3 % higher than during the previously discussed 10-yr period.

During the 8-yr period the recorded mean monthly duration of rainfall was highest in April with in total 91 hours or 12.6 % of the time and lowest in January and July with in total 18 and 20 hours respectively, that is less than 3 % of the time (see Fig. 10). The mean annual duration of rainfall amounted to 465 hours, that is to 5.3 % of the time. The given values of rainfall duration are somewhat too low due to the difficulty in recording the duration of rainfall having very low intensity but are probably close to reality for periods with rainfall intensities higher than 0.1 mm per hour.

The monthly mean intensity of rainfall given by the ratio of total rainfall to duration (see Fig. 10) was highest in March (7.5 mm per hour) and lowest in June (3.5 mm per hour). The mean annual intensity was 5.3 mm per rainy hour. As shown by Fig. 11 the cumulated rainfall amount is log-normally distributed in relation to the mean intensity of individual storms. Storms having mean intensities higher than 50 mm per hour contribute only about 1 % of the total rainfall, while storms having mean intensities higher than 9 mm per hour contribute about half of the total rainfall.

Of greater hydrological significance than the mean storm intensity are the frequency and duration of high intensity fall. The intensity-duration curves in Fig. 12 are based on partial-duration series. The highest recorded half-hour intensity during the 8-yr period was 97 mm per hour. Half-hour intensities of 50 mm per hour were equaled or exceeded on the average 3 times a year. The highest recorded one-hour intensity was 65 mm.

The arithmetic mean value of the annual maximum series is 66 mm per hour for the half-hour intensity with a standard deviation of 14 mm, and 47 mm per hour for the one-hour intensity with a standard deviation of 8 mm. The probable two-year one-hour rainfall intensity amounts to 45 mm.

Most of the intense rainfalls occur in the first quarter of the year and in the late afternoon. During the studied 8-yr period about 90 % of all storms with half-hour intensities higher than 50 mm per hour occurred between the end of January and the middle of April, and about 60 % of these storms occurred between 3 and 8 p.m.

*Rainfall erosivity*

A suitable measure of the erosion potential or erosivity of a rainstorm is the product of the total kinetic energy of the storm and its maximum half-hour intensity. More specifically the energy-intensity value, $EI_{30}$, is the product of the kinetic energy of a storm expressed in foot-tons per acre and its maximum half-hour intensity in inches per hour. See further Wischmeier and Smith (1958), FAO (1965) and Hudson (1971).

The $EI_{30}$ values at Morningside are calculated for the previously mentioned 8-yr period. Only storms with half inch or more of rain are

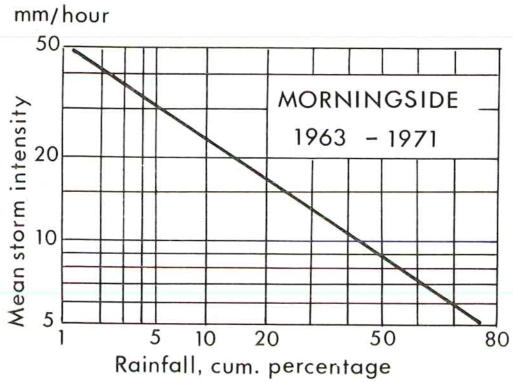


Fig. 11. Cumulative percentage of rainfall amount plotted against mean intensity of individual storms. Morningside 1.8.1963—31.7.1971.

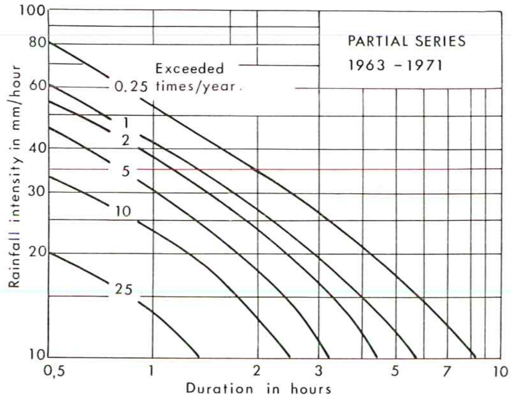


Fig. 12. Rainfall intensity-duration curves, based on records at Morningside 1.8.1963—31.7.1971.

considered. The storm energy (a function of the intensity) is based on values tabulated by Wischmeier and Smith (1958). The average total annual $EI_{30}$ value is very high and amounts to about 70,000 at Morningside. This value is of the same order as the highest reported from the United States by Smith and Wischmeier (1962). The erosivity of a single storm may be very high. One example of this is a storm on March 4, 1967. This storm had a duration of only 75 minues (15.30—16.45) but a maximum half-hour intensity of 97 mm (3.8 inches) per hour. The $EI_{30}$ value of the storm amounted to 11,000, that is to about 16 % of the total annual value.

According to Hudson (1971) erosion, especially splash erosion, is almost entirely caused by rain falling at intensities above 25 mm per hour. He therefore found the KE > 25 method, meaning the total kinetic energy of the rain falling at intensities of more than 25 mm per hour, to be more appropriate than the $EI_{30}$ method, when calculating the erosivity of tropical and sub-tropical rainfall.

At Morningside the average total annual KE > 25 value amounts to about 12,000 joules/$m^2$. This value is of the same order as the value Hudson (1971) used to exemplify the annual erosivity of tropical rain but much higher than the value he used for temperate rain. At Morningside the average monthly value is highest in April, higher than 3000, but lower than 100 in July and in August.

## Streamflow

*The gauging station*

The WD & ID:s stream gauging station no. 1 HA 8 was established in 1954. It is located at 550 m a.s.l. and 5.3 km downstream of the recording raingauge. The station (see the photo, Fig. 13) consists of a concrete Cipoletti weir, a standard vertical staff gauge and an automatic Ott float type water-level recorder. The recorder is geared to give a chart travel of 1 7/8 inch per day. It is set weekly when the chart is changed. The gauge pipe may sometimes be silted up, but the records are checked by twice daily staff gauge readings. The stage-discharge relation is poorly known for stages higher than 5 feet. However, the frequency of stages higher than 5 feet is less than once a year and the duration less than 0.01 % of the time (see Fig. 15).

Mean daily flows for the periods 26.3. 1954—31.10.1959 and 1.11.1959—31.10.1965 are tabulated in the two Hydrological Yearbooks, published in 1963 and 1967. The published discharge values are based on the two daily readings. The tabulated values are therefore of limited accuracy during the wet season, because the runoff is flashy.

*Streamflow variations*

The runoff is highly discontinuous with flash-flood peaks. They rise suddenly in less than one minute at the stream gauge, stay high as long

Fig. 13. Morogoro river gauging station 1 HA 8, from below. Photo AR 10/71.

as the rainfall in the valley is intense, and then gradually sink to baseflow level during some hours time (Figs. 14 and 17). On three observed occasions in March 1970, the time lag between the start of intense rains up the valley and the arrival of the flood wave at the gauge station was 65—90 minutes (see Fig. 17). The discharge can suddenly grow from below 1 $m^3$/sec. to more than 30 $m^3$/sec. The highest observed water stage, 5.46 feet on April 26, 1968, probably corresponds to more than 40 $m^3$/sec., that is more than 2000 litres per sec. and $km^2$.

During the 11 water years November 1, 1954—October 31, 1965, the mean annual water discharge varied between 0.30 and 0.81 $m^3$/sec. with an average value of 0.57 $m^3$/sec. This average value corresponds to an average runoff of 30 litres per sec. and $km^2$ or 940 mm per year. The mean monthly discharge was highest in April with 1.65 $m^3$/sec. (860 l/sec. and $km^2$) and lowest in September with 0.19 $m^3$/sec. (10 l/sec. and $km^2$). During the 5 water years November 1, 1960—October 31, 1965 the average annual water discharge was 0.60 $m^3$/sec., corresponding to 32 l/sec. and $km^2$ and to 1000 mm per year. The ratio of annual runoff at the gauging station to rainfall at Morningside varied between 0.40 and 0.65 with a mean value of 0.48. During this 5-yr period the mean annual rainfall was 2,102 mm, that is 12 % lower than during the 10-yr period 1961—1970. The above given figures are calculated from the previously published discharge values, that are based on the two daily gauge readings.

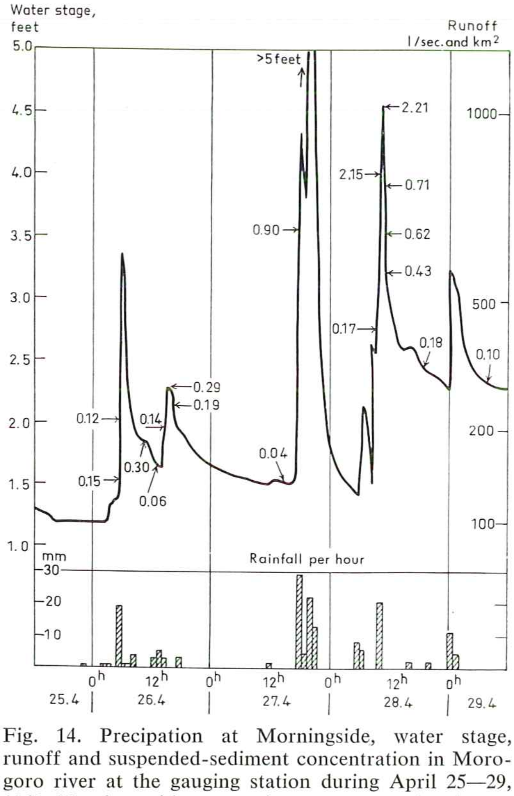


Fig. 14. Precipation at Morningside, water stage, runoff and suspended-sediment concentration in Morogoro river at the gauging station during April 25—29, 1969. Number with arrow shows concentration in g/l. Note the close relation between flash-flood peaks and rainfall.

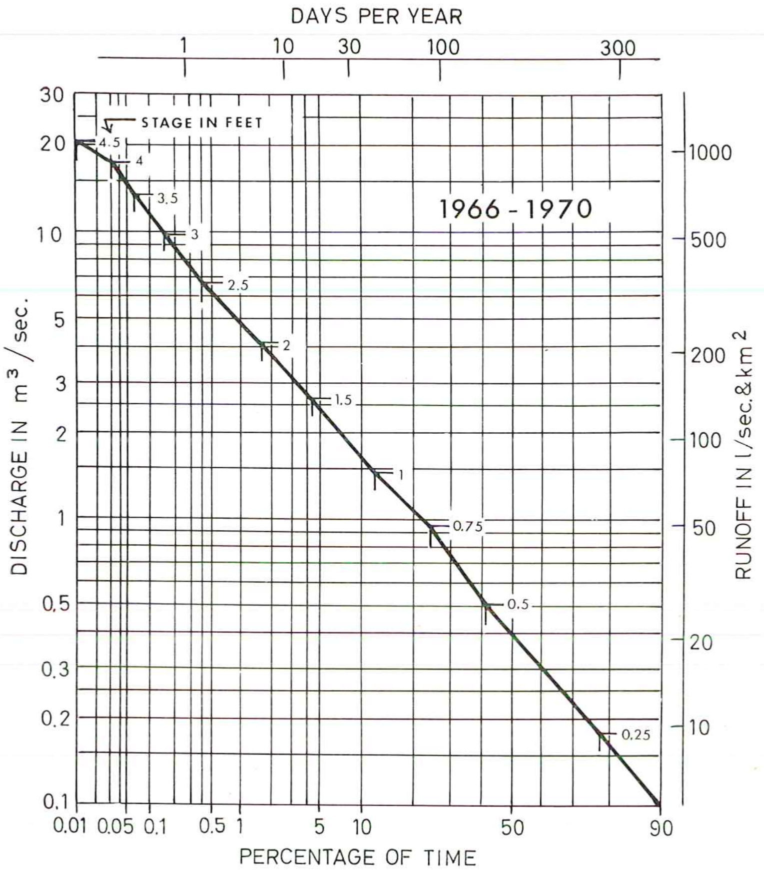


Fig. 15. Flow-duration curve for Morogoro river.

A calculation based on recorded values during the 5 calendar years 1966—1970 gives a mean value of 0.725 $m^3$/sec. corresponding to 38 l/sec. and $km^2$ or 1200 mm per year. The average ratio of annual runoff to rainfall amounted to 0.46. During this period the mean annual rainfall was 2585 mm, that is 8 % higher than during the 10-yr period 1961—1970.

The runoff-rainfall ratios vary considerably with rainfall intensity, infiltration capacity, drainage area, and other factors. Dagg and Blackie (1965) studied the water balance of cultivated and forested catchments with areas of approximately 20 hectares during 6 water years (1957—1963) at Mbeya in the Southern Highlands area of Tanzania. A calculation based on their published values gives an average ratio of runoff to rainfall of 0.25 for the forested catchment (mean annual rainfall 1598 mm) and an average ratio of 0.64 for the cultivated catchment (mean annual rainfall 1869 mm).

About 56 % of the Morogoro river catchment may be considered as more or less cultivated and about 44 % of the catchment as forested. If we assume the ratios of runoff to rainfall for the Mbeya catchments to be valid also for the cultivated and forested parts of the Morogoro river catchment we get an average ratio of 0.47, that is the same value as the average ratio of runoff at the Morogoro river gauging station to rainfall at Morningside for the 10-yr period 1961—1970. This may indicate that the long-term rainfall value at Morningside is rather representative for the average value of the catchment.

*Flow duration*

The flashy nature of the stream flow is illustrated by the steep flow-duration curve (Fig. 15), that is based on recorded flows during

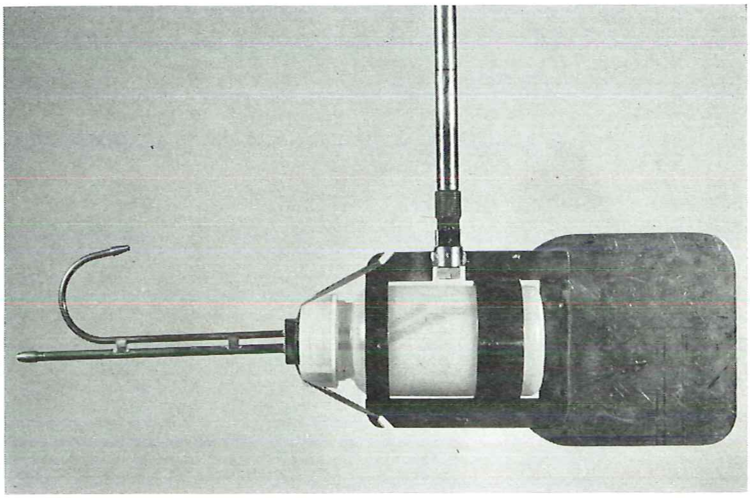

Fig. 16. Hand-operated suspended-sediment sampler with interchangeable nozzle tips. 1 litre plastic bottles are used as sample container. Cf. Nilsson 1969.

the 5-yr period 1966—1970. Flows higher than the mean flow for the period (0.725 $m^3$/sec.) had a total duration of about 30 % or about 110 days a year on average. The median flow as regards the duration (0.4 $m^3$/sec. or 20 l/sec. and $km^2$) was about half as high as the mean flow. The median flow as regards the total flow volume (1.3 $m^3$/sec.) was about twice as high as the mean flow, and flows higher than this median flow had a total duration of about 14 % (cf. Figs. 15 and 20).

The duration curve is based on a too short period of records to give an accurate indication of the long term yield of the stream. As previously mentioned the period 1966—1970 was somewhat wetter than the preceeding 5-yr period. However, the period was not extreme, and the duration curve therefore probably gives values of the proper order of magnitude.

## Transportation of sediment

*Methods*

The concentration and discharge of suspended sediment in Morogoro river was studied during the rainy seasons in 1969, 1970 and 1971. More than 3000 water samples were taken at the gauging station by field assistants. Most of the samples were taken with a point-integrating, hand-operated sampler (cf. Nilsson 1969 and Fig. 16). Since the flow peaks are short-lasting and often occur after sunset the number of samples taken at high flow peaks, however, was very limited.

The samples were analysed in the Laboratory of the Department of Agricultural Chemistry, Morogoro, by laboratory assistants, supervised by Dr. A. Kesseba. The water samples were filtered through Whatman filter paper no. 40. The amount of suspended sediment that passed through the filter paper was found to be negligible. After drying of the filter paper the concentration of suspended sediment was determined as the difference in filter-paper weight after and before filtration. Corrections were made due to varying moisture content of the filter paper. This method for determining the sediment concentration is rather inaccurate when the sediment concentration is low but acceptable when the concentration is high or moderate (higher than 0.1 g/l). It was, however, not possible to use more advanced methods for the routine analyses.

*Sediment concentration*

On some occasions water samples were taken also in the rainforest near Morningside. As exemplified by Table 7 the sediment concentration was considerably higher at the gauging station than near Morningside, indicating that most of the sediment load was supported by sheet wash from the steep cultivated fields. See further the discussion of soil erosion below.

Two complete series of water samples of flash flood peaks taken at 5 minutes interval were sampled in March 1970 by the senior author (Fig. 17, see also Fig. 14). Both series show the same sequence of events:

Table 7. Concentration of suspended sediment in runoff water during a rainfall in the Morogoro river catchment. Samples 437, 438 are from a small brook in rainforest 200 m W Morningside rain gauge. Samples 439–444 are from the Morogoro river at the gauge 1 HA 8. Rainfall on 10.2.1970 25 mm from 16.00–18.40, 30.3.1970 40 mm from 02.10–06.10. Sampling by A. R. and V. A.

| Date | Sample | Alt m | Time | Sedim mg/lit | Water level, feet | Comments |
|---|---|---|---|---|---|---|
| 10.2 1970 | 437a | 1450 | 1740 | 175 | — | In rainforest near Morningside |
| | 437b | 1450 | 1740 | 39 | — | In rainforest near Morningside |
| | 438 | 1450 | 1810 | 76 | — | In rainforest near Morningside |
| | 439a | 550 | 1850 | 491 | 1.5 | At weir 1 HA 8 |
| | 439b | 550 | 1850 | 354 | 1.5 | At weir 1 HA 8 |
| | 440 | 550 | 1915 | 320 | 1.3 | At weir 1 HA 8 |
| | 441 | 550 | 1930 | 534 | 1.2 | At weir 1 HA 8 |
| | 442 | 550 | 1950 | 316 | 1.1 | At weir 1 HA 8 |
| | 443 | 550 | 2005 | 281 | 1.0 | At weir 1 HA 8 |
| 11.2 1970 | 444 | 550 | 0930 | 46 | 0.4 | At weir 1 HA 8 |
| 10.3 1970 | 879 | 1450 | 1045 | 49 | — | In rainforest near Morningside |
| | 880 | 1450 | 1055 | 51 | — | In rainforest near Morningside |
| | 878 | 1200 | 1035 | 88 | — | Small brook below Morningside |
| | 877 | 550 | 0830 | 100 | — | At weir 1 HA 8 |

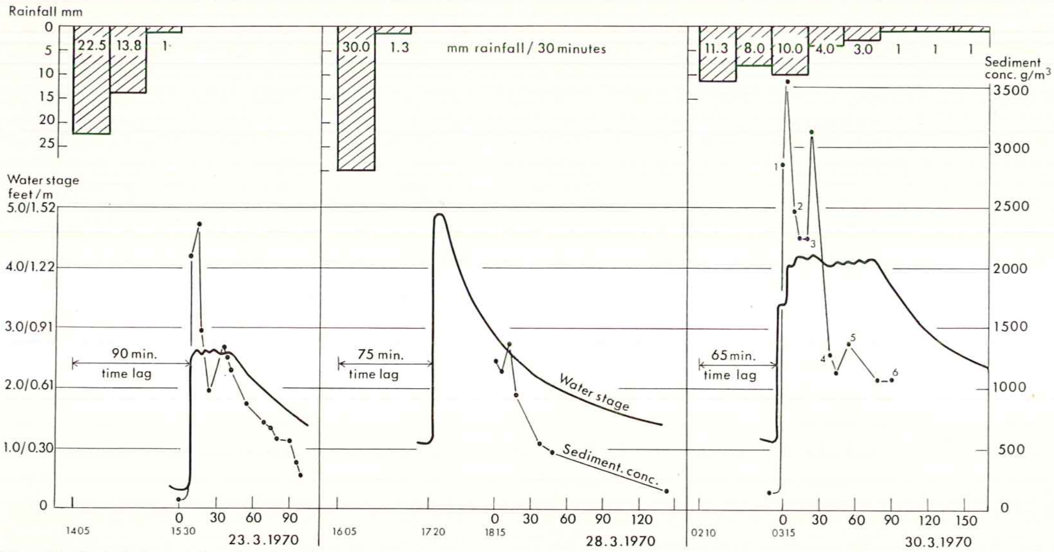


Fig. 17. Rainfall at Morningside (mm/30 minutes), water stage and suspended-sediment concentration in Morogoro river at the gauging station during three flash floods on March 23, 28 and 30, 1970. Numbers of samples 1–6 on 30.3 are the same as in Fig. 18. Water stage curve from automatic recorder and reading of staff gauge. Sampling by A.R.

a) Low baseflow with clear water and very low sediment concentration.
b) Rapid rise in 10—30 seconds to highest flood level in a number of surges from low to high level.
c) During the first minutes of high flood the samples showed high content of medium sand and low content of finer material (exemplified in Fig. 18 by sample no. 1). This water probably is a kinematic wave

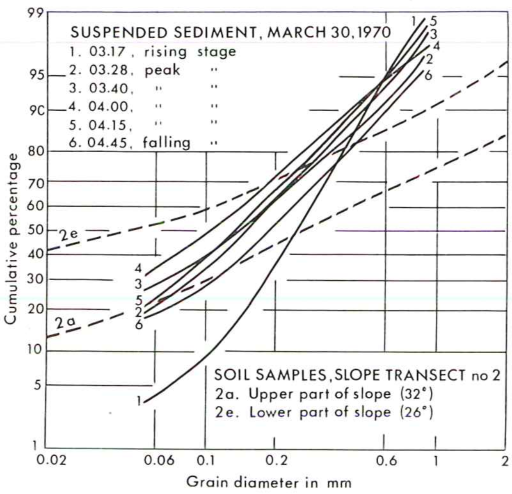


Fig. 18. Grain-size distribution of 6 suspended-sediment samples of a flash flood peak on March 30, 1970 and of 2 soil samples from the valley slopes. Cf. Fig. 17.

of channel water with eroded streambed material incorporated in suspension (cf. Kellerhals 1972, p. 136).

d) The samples from the main part of the flow and the falling stage (samples 2—6 in Fig. 18) show a gradual change to darker coloured, brownish suspension of more fine-grained load and brownish colloids, which most likely represent newly washed material from the slopes.

According to this interpretation two types of material are carried past the weir at the gauging station in each flow: channel material and slope material. However, also the channel material in steep catchments like these is probably carried beyond the weir in a few stormflows, so sampling during a whole wet season should give a record of actual erosion of the catchment slopes. This also means, that if an automatic sampler is used, it is important to sample both early and later parts of the flash floods to get a complete picture of type and amounts of material carried.

The grain-size distributions of the 6 sieved suspended-sediment samples of the flash flood peak on March 30, 1970 (numbered 1—6 in Fig. 17) are compared in Fig. 18 with the grain-size distribution of soil samples from the upper and lower part of slope transect no. 2 (for location of the soil samples, see Fig. 6). As shown by Fig. 18 the suspended sediment was better sorted than the topsoil and coarser than the soil from the lower part of the valley slope but less coarse than the soil from the upper part of the slope.

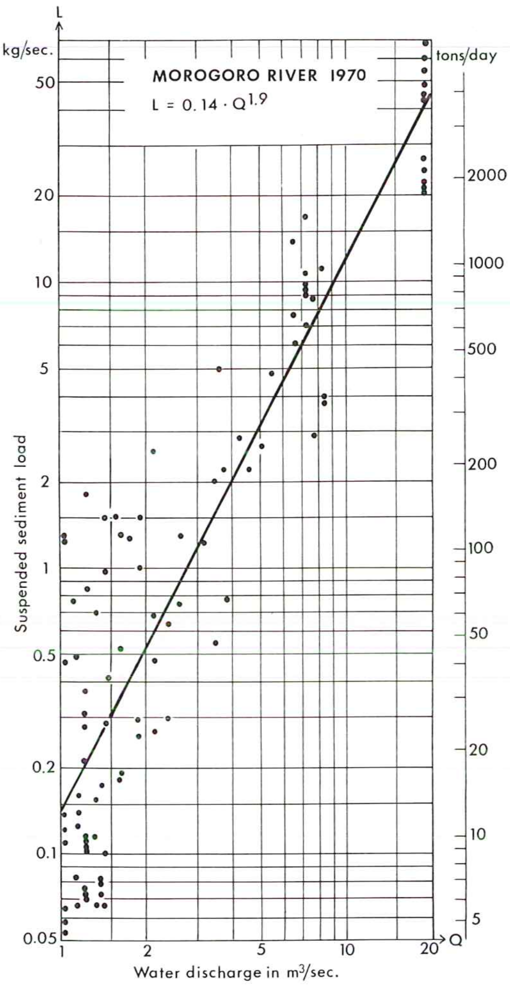


Fig. 19. Suspended-sediment discharge rating curve for Morogoro river, based on samples from flows higher than 1 $m^3$/sec. in 1970.

An increase in stream flow is usually accompanied by an increase in sediment concentration. The time-lag between the peak in sediment concentration and the peak in water discharge was very short and often the two peaks practically coincided. The calculated discharge-weighted mean suspended-sediment concentration is 0.3 g/l. Concentrations higher than this value have a calculated duration of only about 4 % of the time. The highest measured concentration amounts to 10.6 g/l.

*Sediment discharge*

The discharge of sediment was computed by multiplying the measured sediment concentration by the water discharge. The relationship of sediment discharge to water discharge was then calculated by the method of least squares. It was found that the sediment discharge during each of the three studied rainy seasons varied with about the square of the water discharge.

Suspended-sediment discharges measured in 1970 are in Fig. 19 plotted against water discharge for flows higher than 1 $m^3$/sec. The following relationship was obtained:

$$L = 0.14 \cdot Q^{1.9}$$

where L is the suspended-sediment discharge in kg/sec. and Q the water discharge in $m^3$/sec. Checks on the determination of sediment concentration showed the analyses in 1970 to be more accurate than the analyses in 1969 and 1971. The relationship of sediment discharge to water discharge was also found to be better in 1970 (correlation coefficient 0.91) than in 1969 and 1971. It was therefore considered justifiable to use the suspended-sediment discharge rating curve for the rainy season in 1970, as defined by the equation above, for calculation of the probable annual discharge of suspended sediment.

Calculations based on the rating curve in Fig. 19 and the flow-duration curve (Fig. 15) give a probable mean annual suspended-sediment discharge of about 7500 metric tons for the period 1966—1970. This value corresponds to about 390 tons of annual sediment yield per $km^2$ of drainage area. To this figure we have to add the bed load, that is trapped in the stilling pool at the weir. The amount of sediment deposited in the stilling pool is, however, not known, but is probably rather small in relation to the suspended-sediment discharge.

The discharge of suspended sediment varies considerably from year to year. In 1970, when the number of high flow peaks was rather small, the discharge of suspended sediment (3700 tons) was only half as large as the above calculated mean annual discharge.

The cumulative percentage of calculated suspended-sediment discharge and water discharge are in Fig. 20 plotted against cumulative percentage of time. As shown by Fig. 20, half of the calculated total annual discharge of suspended sediment takes place, on an average, during a total period of only about 11 days (3 % of the time). This period is about equal

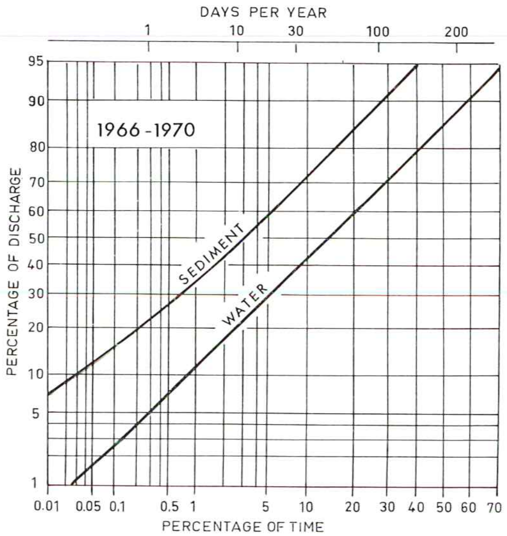


Fig. 20. Cumulative percentage of suspended-sediment discharge and water discharge in Morogoro river plotted against cumulative percentage of time.

Table 8 Chemical constituents in stream water sampled in the upper (1) and lower (2) part of the Morogoro river catchment during medium flow on 10 February 1970. 1 = sampling at Morningside, 1450 m a.s.l. at 17.40. 2 = sampling at 1 HA 8 gauge, 550 m a.s.l. at 18.50. Concentration in mval/l unless other information is given in the table. Analysis by Dept. of Limnology, Uppsala.

| | | |
|---|---|---|
| Sample | 1 | 2 |
| Date | 10.2.70 | 10.2.70 |
| Time | 17.40 | 18.50 |
| Alt | 1450 | 550 |
| Conductivity mmhos | 32.4 | 48.0 |
| Ca | 0.124 | 0.112 |
| Mg | 0.054 | 0.071 |
| Na | 0.146 | 0.227 |
| K | 0.030 | 0.025 |
| $A(HCO_3)$ | 0.214 | 0.217 |
| $SO_4$ | 0.152 | 0.194 |
| Cl | 0.082 | 0.080 |
| Si mg/l | 3.53 | 5.08 |
| Mn mg/l | 0.00 | 0.00 |
| pH | 6.7 | 6.48 |
| Susp. load mg/l | 39 | 354 |

to the total duration of flows equal to or higher than 3 $m^3$/sec. and that occur about 30 times a year on the average.

A programme of chemical analyses of runoff water was also planned in order to study the solution losses from the catchment. This programme could, however, not be carried out, and our knowledge of the chemical character of the runoff water is therefore very poor.

The ionic composition of two water samples from the Morogoro river is presented in Table 8. As shown by Table 8 the specific conductance of the river water is low as well as the concentration of the major ionic constituents. According to 6 determinations in February and October 1970 the specific conductance of the runoff water at the gauging station varied between 42 and 68 micromhos (at 20° C). If we assume the discharge-weighted mean value to be 50 micromhos, the salinity to be satisfactorily defined as the total concentration of the seven major ionic constituents (all bicarbonate being converted to carbonate), and the relationship of salinity to specific conductance calculated from sample 2 in Table 8 to be valid also for a longer period, we get a salt discharge of about 670 tons per year for the period 1966—1970.

The total discharge of dissolved solids is probably about one third higher. The above calculated salt discharge corresponds to an average gross yield of about 35 tons per $km^2$ and year. The major part of this roughly estimated gross yield is probably derived from the atmosphere through wet and dry deposition.

## Soil erosion and source areas of sediment in the catchment

The sampling and analyses of sediment in the Morogoro river at stream gauge 1 Ha 8 illustrate the quantity of eroded material transported out of the catchment by running water. But the samples do not reveal the source areas of the sediment. These have to be investigated on the slopes and in the channels of the catchment. In the following section we will analyse and discuss the possible source areas of erosion in the catchment: the stream channels, the zone of montane rainforest, the zone of mountain farming and the zone of foothill farming and miombo woodland (Table 9).

*Stream channels*

The form and gradient of the stream channels affect the mode and the rate of transportation of sediments from the slopes to the sampling point at 1 HA 8. Is the suspended sediment of the stormflows at the weir directly supplied from the catchment slopes, or does it come from the bed or banks of the stream channels?

The general steep gradients of the stream channels are illustrated on Fig. 5, the profile of which was described above.

The rivulets in the rainforest zone are weakly incised and run over bare bedrock. This is also typical of the zone from 1700 to 1400 m (Fig. 5). From about 1400 m altitude to the stream gauge at 550 m the average channel gradient decreases from 14.5° to 4° above the

Table 9. Altitudinal zones of rainfall, land use and soil erosion in the Morogoro river catchment.

| Land use zone | Altitude range, m | Annual rainfall mm | Slope gradients | Farming | Intensity of erosion (estimated) | Types of erosion |
|---|---|---|---|---|---|---|
| Montane forest reserve | 2100 \| 1500 | > 2400 | 60° \| 30° | No farming | Slight | Few landslides, some splash & sheet erosion. |
| Zone of mountain farming | 1500 \| 900 | 2400 \| 1500 | 42° \| 20° | Maize crop in Jan. Goat grazing | Severe | Episodic landslides. Sheet erosion. No gullying. |
| Zone of foothill farming | 900 \| 550 | 1500 \| 900 | 35° \| 5° | Maize crop in Apr/May Goat grazing | Severe | Episodic landslides. Sheet erosion. No gullying. |

weir. The channel is incised in bedrock in the bottom of V-shaped valleys. Sand-polished, rounded surfaces of bare bedrock dominate in the channels, alternating with sections of rounded boulders. Potholes are common in rock thresholds. As the gradient gets lower the bouldery sections increase in length. Above the weir at 550 m the channel is characterized by bouldery pools and riffles at irregular intervals. Pools of 5—10 m length alternate with riffles of 20—50 m length with (residual?) boulders of maximum 3—5 m size. Pebbles, coarse sand and even small amounts of silty material stay during low water in pockets of the bouldery or rocky pools. Nowhere along the channels are any sizeable sediment basins, fans or channel banks in fine-grained deposits.

At 600 m is the water intake of Morogoro town behind a concrete dam and a small stilling pool of some few metres length, which cannot trap and contain more than some $m^3$ of sediment, which means a negligible influence on the river transportation of suspended sediment.

Below the weir, at about 500 m altitude is the beginning of an alluvial fan with an incised stream course and a bed of large boulders. After passing through Morogoro town the stream builds up a floodplain with silty and sandy levées and clayey floodplain deposits in a 400 m wide belt to the confluence with the Ngerengere river.

In conclusion: several factors discussed above strongly support the opinion that the storm flow peaks at the weir 1 HA 8 are mainly carrying sediment directly supplied from the valleyside slopes. These facts are

a) the steep side-slopes in the valleys,
b) the steep gradients of the stream channels,
c) the scarcity of sand and finer material in the channels above the weir and the predominance of smooth, bare bedrock or coarse boulders.

*Montane rainforest zone*

The forested area, although covered by a dense canopy, green all the year, cannot *a priori* be regarded as an area of no erosion. Sediment production under tropical forest has been reported from many areas and three kinds of processes have to be considered:

a) landsliding and mudflows,
b) soil creep and
c) slope wash from splash and runoff water.

One *landslide* has been observed on the forested slopes of the catchment during the period 1968—1971. In May 1970 a debris slide, similar to those described at Mgeta in western Ulugurus (Temple & Rapp 1972) was triggered E of the jeep track at about 1800 m a.s.l. It created a wedge-shaped opening in the forest. The landslide scar was in dense forest and about 10 m wide, as estimated from observation in binocular from the Morningside road. This observation shows that landslides occur under rainforest and can be observed from a distance, but that they were negligible from a quantitative aspect during the three years of study.

*Soil creep* and so-called tropical solifluction is considered to be common in many environments of the humid tropics. Signs of such mass-movements have not been observed in any part of the Morogoro catchment. On the contrary, the vertical road cuts through soil and regolith seem to be remarkably stable along the whole mountain road from Morogoro to Bondwa peak (Fig. 2). Even on the 45—60° mountain slopes with forest cover on Mt. Bondwa the 2—3 m high vertical road-cuts do not show signs of deformation through slow flow or creep.

*Splash and sheet wash* under tropical rain forest has been convincingly documented by Rougerie (1960) from the lowland forest of the Ivory Coast and by Ruxton (1967) from lowland and montane rainforest in Papua, New Guinea. The observations made in the Uluguru rainforest agree with those made by Rougerie and Ruxton. The soil cover under the forest is very thin, 10—20 cm, and the tree roots penetrate into the regolith and rock, as in the section shown on Fig. 8. Under the dense forest cover the effects of raindrop erosion are seen in small splash pedestals under roots in such locations where leaf litter is sparse or absent. Rougerie and Ruxton both stress the fact that ground vegetation is very poor on the rainforest floor due to lack of light. "Waterdrop erosion is more important under rainforest than under temperate forest because of the higher upper storey, the greater rainfall, and the less abundant leaf litter. Small raindrops in light rainfall will re-form in the rainforest canopy into waterdrops which may be of large size." (Ruxton 1967, p. 90).

During heavy rainfall the small brooks from the forest area above Morningside contain muddy water, although the concentration of suspended sediment is much smaller than in the streams further down in the catchment. A series of measurements made on 10 February 1970 show an example of this (Table 7). The average concentration of suspended load in 3 samples from the rainforest was 80 mg/lit, as compared to 363 mg/lit average suspended load in 6 samples taken during the falling stage of the same flood at the main stream weir 1 HA 8.

For comparison it can be mentioned that Rougerie measured the slope wash from erosion plots of together 72 m$^2$ area on a 12—15 % slope under forest cover, underlain by Tertiary sandstone. He compared those with plots of 90 m$^2$ area, without any protection of vegetation, and 7—8 % slope (Rougerie 1960, p. 288). During the two wet seasons of a year (Ivory Coast), a denudation corresponding to 0.1 mm of rock (= ca 0.2 mm of soil) was measured on the plots under forest cover, but 50 times as much was denuded on the bare soil plots.

A study made by EAAFRO of the water and sediment budget in two small mountain catchments in the Mbeya highlands, gives a possibility to compare more closely with the Morogoro study, although soils are different. The Mbeya catchments are underlain by gneissic rocks with a cover of young volcanic ashes. Pereira & Hosegood (1962) report that due to difficulties in sampling storm flow, only the soil loss during steady flow was measured. During a complete water year, 1.12.1959—30.11.1960, the soil loss per km$^2$ was four times as high from a cultivated valley of 2 km$^2$ in size (A) as compared to a forested valley, 1.6 km$^2$ in area (C). If sampling had been successful also during stormflow the figures of soil loss should have become much larger particularly from the cultivated catchment, (cf. the sediment discharge curve for the Morogoro river in 1970, Fig. 19).

The concentration of suspended sediments in the Morogoro river at the gauge 1 HA 8 was 4—5 times higher (Table 7) than in a small brook from the steep slopes covered by montane rainforest above Morningside at two occasions in the rainy season of 1970, when comparative measurements were done both in the forest and at the weir. These occasions were during falling stage after stormflow, thus not peak flow. Another comparison made of concentration of suspended load in the small Kikundi stream, which drains a completely deforested catchment of 4.2 km$^2$ in size, W. of the Morogoro catchment, gave approximately five times as high a concentration during sinking flow, as compared to peak flow in the main Morogoro stream, during the same night.

The conclusion from the measurements and comparisons quoted above is that the rainforest area of the Morogoro river catchment only supplies a small part—probably less than 10 % —of the total annual flow of suspended load from the whole catchment.

Fig. 21. Cultivated steep slope below Kisosa village (on skyline). Evergreen trees at stream channel in foreground. Many grass barriers from the 1950's are visible in the centre of the picture. Slope transect 2 runs across the stream between the two trees and upslope to the ridge crest. Photo AR 10/71.

Fig. 22. Newly cleared shamba in secondary woodland near Morningside farm, Morogoro. The slope is 42°, planted with maize. Tree stumps and roots have been left (to stabilize the soil?). Stones and soil aggregates are falling down the slope occasionally and accumulate on the path. Photo AR 10/71.

*Zone of mountain farming*

Small debris slides similar to those described from the Mgeta area by Temple & Rapp (1972) seem to occur each year although generally in small numbers. Typical locations are below ridge crests, e.g. round the Kileka ridge, Mbete valley. Other typical sites are at the foot of slopes near stream channels, e.g. old scars on the Kisosa transect slope. Fig. 23 shows an example of a small sheet-slide in midslope position at Luvuma village, triggered in May 1970, probably by water blowout due to subsurface hydrostatic pressure in pipes and pores, as is discussed in the Mgeta cases (Temple & Rapp 1972). Slow earthflow and massive soil creep is not observed along the whole mountain road to Morningside, in spite of the high and vertical roadcuts through soil and regolith.

Figs 21, 22 and 23 are photographs showing details of the land use within the Morningside valley. Fig. 22 shows a nevly cleared shamba in earlier secondary woodland near Morningside. The slope of the field is 42°, the tree stumps and roots are left in the soil for stabilization (?) between the maize seedlings. Slope wash has not acted on the field, but soil aggregates and stones move downslope by rolling over the surface and are piling up at the lower end of the field. A small landslide has also occurred, cutting down to the regolith.

In spite of the steep slope angles, there are no distinct gullies at all in the valley within this zone. Distinct rills occur on the fields, but not commonly, nor even after the 40 mm rainfall of 30.3.1970 which was the most intensive storm that was experienced during our detailed inventory. On that occasion about 20 % of the Kisosa transect was occupied by maize shambas, 1/3 of them with bare soil between the maize, the other 2/3 with weed cover. Signs of erosion through splash, sheet wash and incipient rilling were obvious on bare fields after that storm.

During two weeks of the rainy season of 1970, when the senior author took part in the sampling at the Morogoro river, he also checked the amount of soil denudation by slopewash from a small plot on the pediment slope above the Agricultural College, Morogoro. On an area with cut grass and 90 % of bare soil a grid of simple erosion pins was arranged. The pins were wooden tooth-picks, stuck vertically into the ground with a free length of 30 mm above the surface. As the soil was slightly crusted from raindrop impact before the experiment was started the ground surface was well defined and measuring of pin heights was easy to do with high accuracy. The slope of the plot was 4.3° and the soil a reddish, sandy loam. The pins in one downslope transect were at 30 cm interval in a straight line. Of 20 pins in a transect, 19 remained upright after the period 22.3—5.4 and were showing an average erosion of 2.5 mm. Runoff occurred in a pattern of braiding, shallow rills of 2—5 cm width. Accumulation occurred in miniature traps above bare single grass roots or straws across the beds of the micro-channels.

A considerable net erosion over the whole surface was evident from the accumulation of

Fig. 23. Grass fallow with fresh debris slide. Luvuma village in the background. Note grass barriers for trapping slopewash. Newly cultivated fields with beans in foreground and right background. Photo AR 6/1970.

sandy sediments washed into a drainage ditch below the experiment plot.

The plot was not closed by frames of any kind, but was part of a pediment slope of an even gradient but with higher and more dense grass growth above the 10 m long plot of cut grass.

As Temple & Murray-Rust (1972) have concluded in their report of soil erosion plots at Mfumbwe, Ulugurus, these plots have too few measuring rods to give reliable average data. However, the trend is clear, e.g. for the so-called *"sesa"* cultivation (burning of trash after harvest, no protection of soil plot). The soil loss there was 28 mm per year (3 rods, 4 years), which decreased to 12 mm (2 rods, 10 years) under bush fallow. This indicates a reduction of soil loss of roughly 60 % during bush regeneration. The figures from the Mfumbwe plots show a similar decrease in soil loss when strip cropping is followed by bush fallow. The percentage figures are probably too low to be representative, but the trend is clear. Grass fallow is more efficient than bush fallow in reducing soil loss by slope wash.

Catastrophic rains causing landsliding, mudflows and heavy fluvial transport and sedimentation similar to the Mgeta events in February 1970 have not been directly described or reported from the catchments near Morogoro. However, an indirect description of a case, which most probably is of this type is included in a report by the Regional Water Engineer, Morogoro region, at a meeting on May 3rd 1963: "Following severe flash floods in February 1961 1100 tons of soil deposited by the flood water were dug out from the bed of Kikundi river in Morogoro at the cost of 1000 pounds." The Kikundi river drains a completely deforested steep catchment of 4.2 km$^2$ area, close to the Morogoro river catchment. It is likely that the 1100 tons dug out were

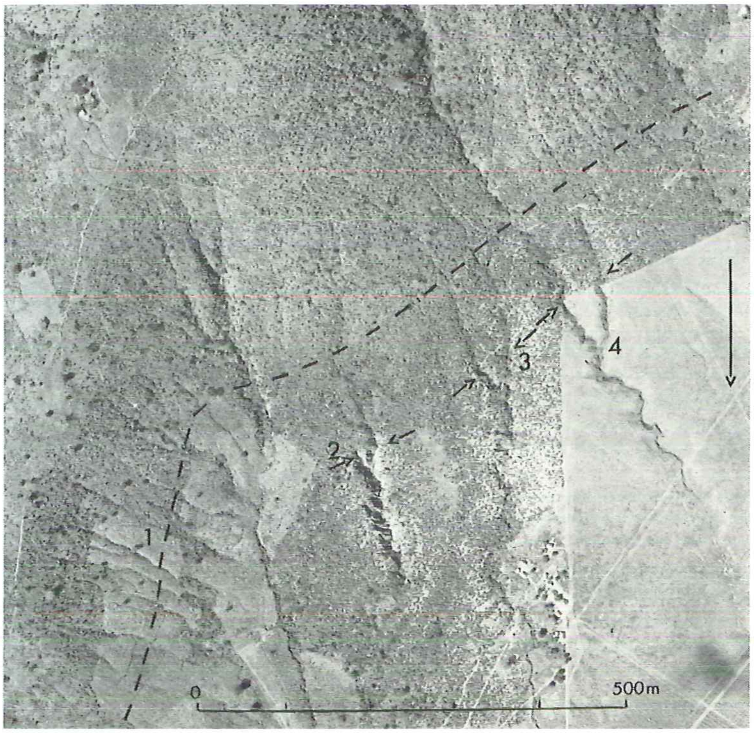


Fig. 24. Vertical air photograph of piedmont zone near the Agricultural College, Morogoro. Dashed line marks break of slope between hillslope and pediment. Figures 1—4 mark gullies. Note particularly abrupt and 6 m deep gully heads at 2, incised along fault line and into a local pocket of sandy fault-line colluvium. Fields of sisal to the right. Miombo woodland on the hillslopes. Air photo, July 1955, Survey Div. Tanzania.

sediments of direct damage to streets or houses in Morogoro town and thus only a fraction of the total deposits. The river passes pediment slopes of low gradient for about 1.5 km before entering the town. It is also noteworthy that the time of the flood was February, i.e. the onset of the long rains, as was also the case at Mgeta.

Other information of great interest in this respect from the same report is the following: "In 1961 and again in 1963 floods 2 feet deep occurred in the Mji Mpya area of Morogoro bordering on the Morogoro river. Though this may have occurred before, the writer despite enquiries has not yet heard of any previous occasion mentioned since the Kikundi river was diverted from its old course through Mji Mpya in 1930."

Young & Fosbrooke (1960) give other evidence for similar events in the northern and eastern Ulugurus further back in time: "There were memorable floods in the Uluguru mountains before 1884, the year selected by Mr. Savile for the entry of the Luguru into the hills. The explorer, Henry Stanley, records at considerable length a description of the damage inflicted by the great flood of 1871, when whole villages were washed away. In Tununguo, on the eastern side of the Uluguru massif, Mr. Fosbrooke has been shown stratified layers of mud from previous floods: some of these great floods were named and remembered in tribal tradition from periods long before the population pressure had reached its present density." (op.cit. p. 144)

Table 10. Amounts of soil erosion (−) and deposition (+) in mm at erosion pins on a slope of 4.3° with sparse grass cover and 90 % bare soil. Top of transect at upper left, end at lower right. Morogoro Agr. Coll. 22.3 to 5.4.1970. Most of the erosion was caused by a 30 mm rainfall on 30.3.1970.

| Upper end | | | |
|---|---|---|---|
| +3 | 0 | −2 | −2 |
| −9 | +1 | −16 | −3 |
| −2 | −4 | −3 | −5 |
| +5 | −1 | +2 | fallen |
| −2 | −2 | −2 | −6 |
| | | | Lower end |

### *Zone of foothill farming and miombo woodland*

The miombo woodland and the riverine forest occupy 4.2 % of the catchment (Table 5) below 900 m. As is shown on Fig. 2 there are also cultivated plots in this zone, both on the valley-side slopes and on the incipient valley-bottom pediments, which occur at this low level (Fig. 6, transect no. 1). The traces of sheet wash and rilling are more numerous and obvious in this zone than higher up.

The grass cover in the woodland is burnt each year at the end of the dry season. Slope transect no. 1 at Towero school was measured in February 1970 in the beginning of the rainy season and showed 20—50 % of bare soil on the grazed and burnt slopes, a surface desiccation crust of 5—10 mm thickness and thin, sandy soils over weathered granulite. The grain-size curves of Fig. 7 show 20—30 % of clay, 15—20 % silt and 50—60 % sand in the top 25 cm soil (Color 5 YR 3/2).

Gullying is not observed inside the catchment in this zone either, but a sequence of gullies appear at the lower hillslope/upper pediment along the mountain front immediately W of the Kikundi catchment near the Agriculture College campus at 600 m a.s.l. Fig. 24 shows the situation. Two 7 m deep and abruptly incised gullies with double heads are cut into pockets of sandy colluvium in front of a small, faultline which runs parallel to the mountain front 100—125 m in front of the piedmont junction. The isolated occurrences are faultline gullies of a similar type as those described by Rapp et. al. 1972, Fig. 27 and by Christiansson, 1972, Fig. 4. They indicate that gully incision is facilitated by thick deposits of colluvial sandy material. Thus one reason for the lack of gullies on the other slopes of the Uluguru catchments is probably the thin soil cover.

The gullies at the Agriculture College appear on air photographs of 1955 and have been widened and extended only to a little extent in the 16 years before our survey in 1971. These gullies are of considerable interest for the understanding of gully erosion, and how it is affected by lithology, soils, slope, runoff, vegetation and time, because all these parameters can conveniently be investigated and kept under observation so close to the Agricultural College.

## Conclusions and recommendations

The sediment sampling during the rainy seasons of 1969, 1970 and 1971 have together with inventories of erosion features on the slopes of the catchment shown a very high loss of soil from the cultivated fields, much smaller losses from grassland fallows, and negligible sediment supply from the rainforest area on the uppermost 40 % of the catchment. The calculated annual soil erosion in 1966—1970 was 0.26 mm as an average figure for the whole catchment, based on sampling of suspended sediments at the 1 HA 8 weir. Most of the soil loss occurred on the 10 % of the catchment area occupied by cultivated plots in 1970. The sediment yield in 1966—1970 was 390 tons/km$^2$ on an average, or probably 10 times as much from the cultivated areas.

The runoff coefficient is 0.46 taken over the five years 1966—1970. Highest concentration of suspended load during the three years 1969—1971 was 10.6 g/lit. measured on 25 April 1969. The peak floods above 5 feet level correspond to a runoff of about 2000 litres/second and km$^2$.

Rainsplash, sheet wash and incipient rilling are the most important forms of erosion, probably together with episodic landslides in connection with catastrophic rains of several years interval. Like in the Mgeta area, the landslide scars occur mainly in two zones: near the stream incisions and in an upper belt below the convex shoulders of the rounded ridge crests. Reafforestation is recommended in belts covering these two critical zones and on all other slopes above 30° gradient in order to counteract landsliding.

Slope wash can be considerably diminished by use of cover plants, trash bunds and mulching, extended use of grass barriers, cultivation of perennial crops as opposed to annual crops, and reduced burning. Manuring of cultivated fields would permit longer periods of cultivation and hence longer periods of grass and bush fallow on a larger proportion of the cleared slopes. Introduction of stall-feeding of cattle, as in the Kilimanjaro area, should help in reducing the destructive grass-burning.

These are less drastic measures than the evacuation of the total population and complete afforestation of the mountain catchments, suggested in two reports of 1963 by the Regional



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Water Engineer and the Regional Agricultural Officer, Morogoro.

Continued and extended studies of runoff and sediment budget from two catchment areas: the Morogoro river catchment and the Kikundi catchment are strongly recommended as a continuation of the catchment research reported in this paper. Such continued studies should also include the losses of dissolved matter from the soils of the catchment.

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*Dr. Anders Rapp and Dr. V. Axelsson, Department of Physical Geography, Box 554, University of Uppsala, Uppsala, Sweden. Prof. Len Berry, Department of Geography, Clark University, Worcester, Mass., USA. Mr. D. H. Murray-Rust, Department of Geology and Geography, City of London Polytechnic, London EC 3, England.*

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# LANDSLIDES IN THE MGETA AREA, WESTERN ULUGURU MOUNTAINS, TANZANIA

*Geomorphological effects of sudden heavy rainfall*

BY PAUL H. TEMPLE AND ANDERS RAPP

Department of Geography, University of Dar es Salaam and
Department of Physical Geography, University of Uppsala

ABSTRACT. Landsliding triggered by intense rainstorms is a major erosional process affecting steep, soil-covered slopes in a variety of climatic zones. This paper is a case study of the geomorphological and economic effects of one such intense rainstorm in a tropical mountain area, the western Uluguru mountains in Tanzania.

On February 23, 1970, more than 100 mm of rainfall were recorded in less than three hours in the Mgeta area. This storm caused slope failures and landslides in an area of approximately 75 km², and flooding, fluvial erosion and deposition over a greater area beyond. Minimum economic losses from the direct and indirect results of this storm are assessed as well over E.A. shs 600,000 (U.S. $90,000).

The storm initiated more than 1000 landslides, predominantly as small debris slides which quickly turned into mudflows and joined the stream at the base of the slope. Observations were made of locations, dimensions, slope positions, slope angle and forms of slide scars. 65 per cent of the scars were between 5 and 20 m wide and most averaged 1 to 1.5 m deep. 47 per cent originated in cultivated fields, 46 per cent in grassland but less than 1 per cent in woodland-covered areas. Characteristic landslide sub-types are identified on the basis of detailed field surveys.

A sample of 840 landslides displaced 270,000 m³ of debris over an area of 20 km² within the main area of damage. This approximates to a soil denudation rate of 14 mm.

The major mechanism of slide initiation probably was high pore water pressure, causing water blowouts. This hypothesis is examined in some detail.

## Introduction

The study reported here forms part of the Dar es Salaam/Uppsala Universities Soil Erosion Project (DUSER Project) and describes the geomorphological and economic consequences of one heavy rainstorm in the western Uluguru mountains. Together with the other papers on the Ulugurus in this volume, it attempts to provide basic data on the scale and seriousness of soil erosion of different types in a tropical mountain area presently largely cultivated.

Comparable heavy rainstorms are not unusual in this area; on the contrary they recur frequently and some cause severe and sudden erosional damage and economic loss. Thus a study of the magnitude and frequency of such events, the time required for the recovery of vegetation and soil and the renewal of cultivation is justified in both theoretical and practical terms.

The study complements information collected on "average-year" erosional effects in the Ulugurus derived from sediment sampling in the Morogoro river and erosion plot measurements at Mfumbwe reported elsewhere in this volume.

## Methods of study

Because of the importance of observing and recording the landslide scars and tracks while the forms were still fresh, reconnaissance work began in March and detailed work was completed between April and July 1970.

Detailed work comprised a survey of 34 representative landslides of different types and from different localities. Long profiles were measured by tape, slope angles by clinometer (Meridian). The direction of slide movement was measured by compass. The whole slope profile from ridge crest, through the slide scar and slide or mudflow track, down to the valley bottom was measured as well as cross profiles of slide scars and tracks. These measurements were used to construct a slide model from which volumes were computed. Soil samples were taken by auger at various places in the slope and samples of soil and regolith exposed in the scars and tracks of the landslides were later analysed by sieving and hydrometer for grain size composition. Notes were made on the detailed morphology of the slides, upon the vegetation and land use of the slope and upon the type and extent of slope damage. The more important features were photographed.

Reconnaissance studies were made both on the ground and from the air. Ground reconnaissance comprised the compilation by photography and field sketching of slides visible from high viewpoints. Tabulations of slide type, position, approximate dimensions and land use were made for over 200 landslides using binoculars and the surveyed slides in the area under examination for reference. Aerial reconnaissance and oblique air photography were used to delimit the area seriously affected by the landslides. Vertical air photography at the scale of 1 : 20,000 in black and white, normal colour and infra-red colour was ordered but not delivered due to shortage of aircraft and personnel and problems with weather conditions. If these data had been made available, a detailed distribution map of the landslides could have been prepared. Oblique air photographs, taken during the reconnaissance, were used to plot slide distribution in part of the survey area (see Fig. 6).

Analysis of the rainfall records of the three recording stations within the area and of the Mgeta river hydrograph records provided information on the intensity and distribution of the rainstorm which caused the landsliding. Field observations on the morphology of the slides and data from interviews with the local people indicated the probable mechanism of slide initiation. Work on soil redevelopment and vegetational recolonisation on the slide scars and tracks is in progress (see below).

## Relief, geology and soils

The upper Mgeta Valley is a catchment area of some 101 km$^2$, about 45 km SW of Morogoro town (6°51′ S; 37°41′ E). The area studied also includes a section of the upper Mbakana valley comprising about 32 km$^2$ around Kienzema village (Figs. 1 and 2).

The catchments studied are representative stream source areas in the western section of the Uluguru mountains. The local relief is high with an extreme altitudinal range from 2868 m a.s.l. on the Lukwangule plateau to 975 m a.s.l. at the Mgeta river gauge. The subdued relief of the Lukwangule plateau is bounded to the north and west by steep walls. To the west these drop abruptly to between 1780 and 1950 m in the Mizugu-Mbakana watershed, and to the north, over progressively decreasing gradients, to the Mgeta river. Relics of erosion surfaces have been identified on the Lukwangule plateau and on the Mizugu-Mbakana watershed, but generally the area is one of intricate, deep dissection, with narrow ridges and closely spaced minor valleys (Fig. 5 and 6). The Mgeta river has entrenched a curious circular course in the mountain mass, flowing NE and then N to Bunduki (Fig. 1), then W to Mgeta, then SW beyond the village. This anomalous, incised course captures the drainage of a large number of tributary streams flowing radially away from the central peaks and follows, below the junction with the Muhangera river, a shear zone in bedrock at the contact between the Uluguru meta-igneous rocks in the S and E, and peripheral, banded pyroxene granulites to the N and W (Sampson & Wright 1964). The granulites are typically banded into light and dark bands, the lighter bands being quartzo-feldspathic, the darker bands being quartz-plagioclase together with garnet, hornblende and biotite.

The meta-igneous rocks, which outcrop in the area of study S of the Mgeta river, are anorthositic, with gabbroic anorthosite as the most common type. The most important mineral is plagioclase (soda-lime feldspar) and petrochemical analysis shows characteristic high alumina and lime and low silica percentages (Sampson & Wright *op. cit.*, p. 35—38) (Table 1).

Table 1. Analysis (%) of two samples of gabbroic anorthosite from the Mgeta area (Sample numbers DNS. 875 and 303; generalised from Sampson & Wright, *op. cit.*, Table 11).

| | | |
|---|---|---|
| $SiO_2$ | 51.3 | 53.8 |
| $Al_2O_3$ | 26.2 | 24.2 |
| MgO | 2.6 | 1.3 |
| CaO | 10.7 | 8.8 |
| $Na_2O$ | 3.6 | 4.7 |
| $K_2O$ | 0.3 | 0.8 |
| $P_2O_5$ | trace | 0.7 |
| others | 5.3 | 5.7 |
| | 100 | 100 |

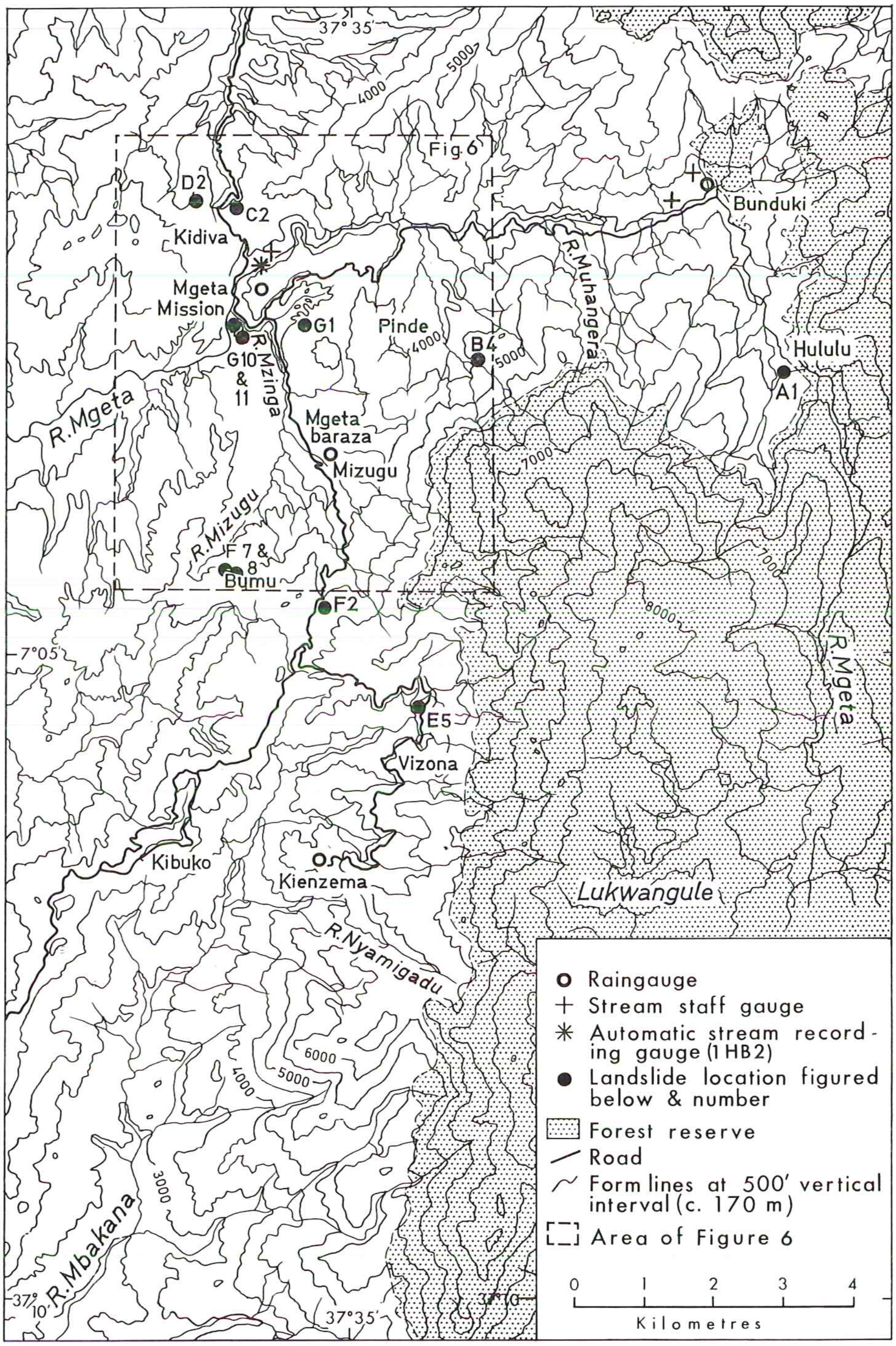


Fig. 1. The Mgeta area showing the major places and features described in the text. Area of detailed map (Fig. 6) indicated by a broken line.

Anorthite percentages in the plagioclase feldspar averaged over 50 % (Sampson & Wright, *op. cit.,* Table 10). These high values would presumably render the plagioclase highly susceptible to weathering and might thus explain, together with the preponderance of plagioclase itself, why these meta-igneous rocks break down so readily as is indicated e.g. by the rate of slide healing (see section "Recolonisation . . ." below).

The granulites which underlie the ridges N of the Mgeta River in the study area have a well-marked planar schistosity and the feldspars are also mainly plagioclase although there is also some potash feldspar. In both rock types deep weathered exposures have been examined along incised streams and in some slide scars. The maximum depth recorded was 10 m in the back scarp of slide scar A1 below Hululu falls (Figs. 1, 16) but the weathering front may well be locally deeper and is very irregular. Pockets of deep-weathered rock occur in some exposures in close contact with unweathered zones. In the meta-igneous rocks on the road to Kienzema near Bumu a characteristic weathering feature is core stones of spheroidal weathering, surrounded by completely rotten regolith. The longitudinal profile of the stream channels is highly irregular, with bedrock thresholds and waterfalls between more gently sloping sections. This is probably a reflection of the differences in depth of bedrock weathering.

The slopes of the highly dissected area are steep, with an upper convex part from a narrow crest, a long, straight middle section with a steep gradient of 36°—43° and a lower, slightly concave section ending in an incised stream channel (cf. Figs. 8, 9 and 13). The crests generally lack rock outcrops, except those near the main Uluguru mountain front (Fig. 13) where cliffs and rock knobs become more frequent. Otherwise the crests are narrow, smooth ridges with a thin cover of sandy soil on top of the bedrock.

The slide scars and other sections through the soil on the slopes show typically three different layers of soil and regolith. All three have similar grain size compositions: silty sand with about 1—7 % of clay (Table 2).

1. A black to greyish topsoil, 10—30 cm thick on the steep parts of the slopes. It is generally 30—50 cm thick on the lower slopes, (cf. Figs. 15, 17). The topsoil gets crusted and cracked when dry. The dark colour of the topsoil is probably due to high content of carbon from burnt grass and bush and from hoe-cultivation in small terraces (see further below).
2. Upper regolith. Below the topsoil is a light-coloured regolith, light grey to brown or reddish in some parts, 50—100 cm thick on steeper slopes, up to 2 m thick in places on gentler slopes. It is generally sandy with silt and some clay and with scattered pebbles. This layer is probably a short-transported colluvium to judge from the absence of weathered veins and other in situ structures, which are typical of the third layer.
3. Lower regolith. This is the regolith weathered in place. Most of the slide scars have cut down into the weathered rock in situ, which is exposed in the bottom of the slide scars. In nearly all cases of slide scars examined, the rock is thoroughly weathered and its grain size characteristics are similar to those in the upper regolith layer. Coarse and fine sand are predominant. The bulk density (dry) of the lower regolith is 1.08—1.67 (mean 1.45) in 11 samples analysed by Lundgren. For grain size compositions, see Tables 2a and b.

The predominant clay mineral is kaolinite (analyses by B. Lindqvist). Layers 2 and 3 correspond to zone I and zone II of Ruxton & Berry (1961, p. 18).

## Climate and vegetation

Rainfall decreases from E to W across the area; Bunduki, though lower in altitude, is significantly wetter than Kienzema (Table 3; Fig. 1). This is a reflection of the strong rain-shadow effect which differentiates the coastward-facing, wetter, eastern slopes of the mountains from the drier western slopes (WD & ID, Hydrological Yearbook 1963 & 1967). W and N of the Lukwangule plateau, annual totals are directly related to altitude. Cf. Kienzema, Mizugu and Mgeta Mission. Table 3 also indicates that the main rainy season is in March and April, beginning in late February and continuing into early May. Only at Bunduki is there a significant season of short rains during the period from late October into early December. This contrast was consistently de-

Table 2 a. Grain size composition and bulk density of regolith samples from 11 slide scars, Mgeta area. Samples were taken in metal cylinders, 10 cm long, pressed vertically into the slide scar surface. Values are averages of 3 samples at each site. L3 sampled in August 1970, others in February 1971. Grain sizes from sieving and hydrometer analysis. After L. Lundgren (unpublished data).

| Slide No. | Approximate altitude in m a.s.l. | Grain sizes in mm weight % | | | | | Bulk density (dry) |
|---|---|---|---|---|---|---|---|
| | | >2 | 2−0.2 | 0.2−0.02 | 0.02−0.002 | <0.002 | |
| L1 | 1600 | 3 | 25 | 28 | 24 | 20 | 1.21 |
| L2 = F1) | 1600 | 1 | 27 | 31 | 19 | 22 | 1.19 |
| L3 | 1800 | 5 | 48 | 30 | 7 | 10 | 1.35 |
| L4 (= F4) | 1500 | — | 3 | 17 | 41 | 39 | 1.08 |
| L5 | 1500 | — | 41 | 34 | 13 | 12 | 1.43 |
| L6 | 1200 | — | 58 | 27 | 7 | 8 | 1.66 |
| L7 | 1200 | — | 70 | 15 | 6 | 9 | 1.61 |
| L8 (= G1) | 1000 | — | 59 | 25 | 8 | 8 | 1.56 |
| L9 (= G2) | 1000 | — | 72 | 17 | 6 | 5 | 1.61 |
| L10 | 1100 | — | 61 | 27 | 6 | 6 | 1.56 |
| L11 | 1100 | 7 | 60 | 17 | 8 | 8 | 1.67 |

Table 2 b. Grain size composition of topsoil (T) and regolith (R) samples from slide scars, Mgeta area. Sampling in May 1970. Grain sizes from sieving and hydrometer analysis.

| Slide No. | Depth below surface, in cm | Grain sizes in mm weight % | | | | |
|---|---|---|---|---|---|---|
| | | >2 | 2−0.2 | 0.2−0.02 | 0.02−0.002 | <0.002 |
| F1 | 10 (T) | — | 46 | 42 | 8 | 4 |
| | 70 (R) | 1 | 51 | 38 | 6 | 4 |
| | 100 (R) | — | 53 | 37 | 6 | 4 |
| F4 | 10 (T) | — | 58 | 29 | 7 | 6 |
| | 30 (R) | — | 65 | 22 | 6 | 7 |
| | 150 (R) | — | 55 | 28 | 17 | — |
| G1 | 10 (T) | — | 67 | 29 | 3 | 1 |
| | 50 (R) | — | 61 | 31 | 5 | 3 |
| | 90 (R) | — | 56 | 35 | 5 | 4 |
| G9 | 10 (T) | 2 | 64 | 28 | 3 | 3 |
| | 50 (R) | 13 | 49 | 34 | 3 | 1 |
| | 100 (R) | 3 | 65 | 28 | 4 | — |
| G10 | 10 (T) | — | 58 | 34 | 4 | 4 |
| | 50 (R) | 1 | 62 | 31 | 5 | 1 |
| | 100 (R) | 1 | 65 | 30 | 4 | — |
| F2 | Regolith flow | — | 33 | 55 | 12 | |

monstrated by the available records (62 years) and found an extreme expression in October—November 1961 (See Table 7). Violent thunderstorms are a common introduction to the main rainy season.

Temperature and evaporation conditions are not recorded within the study area. Mean annual and mean monthly temperatures at Morogoro are presented in Table 4 (E. Afr. met. Dept. records). Lapse rates for East African highland climates calculated by Kenworthy (1966) permit the computation of the likely differences between temperatures in the study area from values cited for Morogoro, though the gradient in temperature with altitude in the Ulugurus may well be significantly steeper than average. The annual range of temperature (5.4° C) over the year is generally less than half the monthly temperature range. Seasonal temperature variations are clearly small and the diurnal range is certainly more significant (*Tageszeitenklima*) (Troll 1959). Mean monthly

Table 3. Mean monthly rainfall in mm at Kienzema (1675 m alt.; 23 yr. records), Bunduki (1280 m; 18 yr. records), Mizugu Mgeta (1100 m; 18 yr. records) and Mgeta Mission (1020 m; 21 yr records).

| Station | J | F | M | A | M | J | J | A | S | O | N | D | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kienzema (9737013) | 164 | 167 | 240 | 309 | 117 | 28 | 19 | 9 | 20 | 48 | 107 | 149 | 1377 |
| Bunduki (9737015) | 171 | 186 | 246 | 339 | 129 | 30 | 20 | 59 | 81 | 160 | 307 | 194 | 1922 |
| Mizugu Mgeta (9737016) | 120 | 143 | 170 | 240 | 72 | 10 | 7 | 7 | 20 | 48 | 109 | 112 | 1058 |
| Mgeta Mission (9737002) | 119 | 117 | 198 | 195 | 60 | 7 | 3 | 7 | 11 | 37 | 88 | 109 | 950 |

Table 4. Data on temperature and potential evaporation for Morogoro, 530 m alt. Mean monthly temperatures in °C and mean monthly evaporation ($E_0$) values in mm.

| Station: 9737000 | J | F | M | A | M | J | J | A | S | O | N | D | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean max | 31.5 | 31.7 | 31.5 | 29.6 | 28.2 | 27.3 | 27.2 | 28.3 | 29.8 | 31.2 | 31.8 | 32.0 | 30.0 |
| Mean min | 21.0 | 20.8 | 20.8 | 20.4 | 18.8 | 15.9 | 15.0 | 15.8 | 16.6 | 18.0 | 19.5 | 21.1 | 18.6 |
| Average | 26.3 | 26.3 | 26.1 | 25.0 | 23.5 | 21.6 | 21.1 | 22.1 | 23.2 | 24.6 | 25.7 | 26.5 | 24.3 |
| $E_0$ | 173 | 159 | 167 | 126 | 111 | 106 | 112 | 126 | 146 | 179 | 176 | 179 | 1760 |

values for evaporation are also presented in Table 4 (Woodhead 1968); values for the mountain area under consideration here would be at least 25 mm lower each month than the tabulated data indicate. Frosts are known to occur on the Lukwangule plateau and there are pronounced temperature inversions in the deep mountain valleys at night (Sampson & Wright *op. cit.*).

Before clearing began in about 1800 (Temple 1972) most of the study area was covered by montane forest or woodland. Only on the Lukwangule plateau at altitudes of above 2600 m a.s.l. did this vegetation give way on the thin peaty gravel soils to a grassy scrub climax dominated by the grass species *Andropogon spp, Exotheca abyssinica* and *Panicum lukwangulense* and *P. ecklonii* (Hill 1930). Below this level montane forest dominated by *Octea usambarensis, Parinari excelsa, Strombosia scheffleri, Albizia gummifera, Allanblackia stuhlmannii* and other trees formed a closed cover extending down to 1350 m on the wetter northern slopes, to 1200 m on the wettest eastern slopes but only to 1800 m above Kienzema. Below this, woodland covered the remaining area. In the Bunduki-Mgeta area this woodland was dominated by *Myrica salicifolia, Agauria salicifolia, Protea abyssinica* and *Erythrina abyssinica*. Sections of all these communities are preserved within the Forest Reserve area and the present woodland boundary is shown on Fig. 1. In the NE of the study area, where rainfall is lower, the woodland was of the eastern *miombo* type, dominated by *Brachystegia boehmii* and *B. bussei* (trees) with *Hyparrhenia rufa* and *Panicum maximum* (grasses). Stream courses in these woodland areas would be lined by riverine forest (Engler, 1895). The drier areas have been reduced by cultivation and fire to grassland and the wetter areas outside reserve areas are now mainly cultivated or fallow.

## Land use and population

The study area is within the Mgeta subdivision which is the most densely populated subdivision in the western Ulugurus. An analysis of population and land use in this area has been made by Thomas (1970) and the facts presented below are drawn from his report and from the 1967 population census (1969). The enumeration areas within the upper Mgeta catchment (Nos 3001—3018) show an average density of 125.3/km². If the forest reserve area is excluded (E.A. 3018), this value rises to 188.5/km². Detailed land use and household surveys were made by Thomas on 6 enumeration areas within the area; slope, soil, evidence of soil erosion and use and type of conservation methods were all recorded. Over these samples, the area covered by annual crops ranged between 38.9 and 59.6 % while the cropped land area ranged between 49.3 and 75.8 % of the total. Maize, millet and beans are the main crops, with vegetables and some coffee. Fallow and grazing land was 45.5 % in one area, where slopes of over 20° formed more than half the area but the average was 28 %. Densities in relation to currently cultivated land (arable together with fallow) calculated by Thomas, ranged from 171 to 507 persons/km².

Thus the overall population density and the cultivated area density are not high compared to other areas in Tanzania. These results indicate an extensive use of land, with a large proportion of the total area under cultivation but an extensive system of land use. Pressure of population has not apparently diminished the soil fertility or the proportion of fallow or shortened the fallow period unduly, despite the fact that the Mgeta area showed the largest intercensal population increase in the mountains (17 % between 1957 and 1967). This pressure has not resulted in more permanent cropping, as shown by the small ratio of tree crops to arable cultivation.

All the areas investigated by Thomas had more than 27 % of their area with slopes in excess of 20°. Over half these steep slopes are used for annual crops. The most common cultivation practice on the steep fields are small terraces, dug by hoe. They are called Mgeta terraces or ladder terraces, are about 1 m high and 1 m wide. There are only a few cows kept in the area and the number of goats is not large enough to create any overgrazing on the grass-covered slopes.

## Earlier studies and terminology

The qualitative importance of landslides in the modelling of slopes in mountainous humid tropical areas has been recognized since the work of Freise (1932) in Brazil and Sapper (1935). Birot (1960, p. 77) argues that landsliding plays a major role in slope denudation and is characteristic of the system of erosion found on slopes exceeding 40° in the humid tropics. These conclusions were based on the detailed work of Wentworth (1943) and White (1949) in Hawaii. There 80 % of the landslide scars had a slope between 42° and 48°, the upper limit being restricted by the absence on steeper slopes of a sufficient depth of soil. Wentworth (*op. cit.*) calculated that loss of material through landsliding represented an annual removal of 0.8 mm of soil from the area. This figure is of the same order of magnitude as that derived by Freise (*op. cit.*). Sternberg (1949) studied the effects of catastrophic rainfall in southern Minas Gerais, Brazil, and attributed the severity of flood and landslide damage to overexploitation of the land by man. Haldemann (1956) described the morphological effects of a fall of 425 mm of rainfall in 24 hours in the Rungwe mountains of southern Tanzania, and Doornkamp (unpublished) studied a series of debris avalanches resulting from heavy rainfall in the Buhweju mountains of western Uganda. Doornkamp found that they were restricted to slopes steeper than 26° but most common on slopes steeper than 32°; the debris avalanches were invariably in plots cultivated under annual crops or in fallow plots. Tricart and Cailleux (1965), from work in Salvador, considered that catastrophic landsliding was a paroxysmal stage in man-accelerated soil erosion. Simonett (1967) studied landslide distribution in the Bewani and Torricelli mountains of New Guinea. He found a clear relation to geology and topography with a lesser influence of vegetation and land use, and attributed most of the landslides to the effect of earthquakes. His discussion of possible effects of localized heavy rainfall (*op. cit.* p. 73) is inadequate, for landslides may be triggered by intense local rainstorms in many different climatic zones not the least of which is the humid tropics. Sudden heavy rainfall resulting in landsliding is in fact a major process affecting steep slopes covered with soil and debris in most humid climates (Table 5).

Any study of landslides involves decisions on terminology which depend upon a consideration of the processes of initiation of the slides and the manner of their subsequent movement. There are several different types of landslides

Table 5. Reports of landslides (L) and floods (F) triggered by heavy rainstorms in different climatic zones. [1] Rainfall record of more than 1 day.

| Location | Climatic zone | Recorded rainfall mm/24 hrs | Date | Geomorphological consequences | Author(s) |
|---|---|---|---|---|---|
| Rungwe, Tanzania | Tropical | 425 | 10/4/55 | L, F | Haldemann, 1956 |
| Shihmen, Taiwan | Sub-Tropical | 1356[1] | Sept/63 | L, F | Ling, Pan, Lin, 1969 |
| Hong Kong | Sub-Tropical | 401 | 11–12/6/66 | L, F | So, 1971 |
| East Hutt, New Zealand | Sub-Tropical | 110 | 25/4/66 | L | Jackson, 1966 |
| Darjeeling, India | Sub-Tropical | 465 | 4/10/68 | L, F | Starkel, 1970 |
| Nelson, Virginia | Temperate | 675 | 20/8/69 | L, F | Williams & Guy, 1971 |
| Little River, Virginia | Temperate | 229 | 18/6/49 | L, F | Hack & Goodlett, 1960 |
| Mayflower Gulch, Colorado | Temperate, Alpine | 245 | 18/8/61 | L | Curry, 1966 |
| Guil, France | Temperate, Alpine | 202 | 13/6/57 | L, F | Tricart, 1961 |
| Cairngorms, Scotland | Temperate, Alpine | 85 | 13/8/56 | L, F | Baird & Lewis, 1957 |
| Narvik/Abisko, N Scandinavia | Arctic, Alpine | 107 | 6/10/59 | L, F | Rapp, 1960 |

and similar rapid mass-movements which can occur on soil-covered slopes. The processes are often difficult to classify as they are transitional to each other. The general classifications (Sharpe 1938, Varnes 1958, Zaruba 1968) of landslides and related phenomena are based on a) the type of material involved and b) the type of movement. In the classifications two types of landslide material are generally distinguished, namely "rock" and "debris". *Rockslides* consist predominently of coarse bedrock material of boulder size detached from bedrock in situ. *Debris slides* consist mainly of material from the soil cover or weathered mantle (regolith) or other loose deposits on a slope. The slope failures in the Mgeta area in February 1970 involved the soil cover and the upper thoroughly-weathered regolith i.e. debris.

In the classifications, three types of rapid slope failure movements are distinguished: fall, slide or flow. *Fall* is the free falling through the air down a cliff, or the bouncing of individual blocks of rock or soil down a steep slope. *Slide* is a rapid movement of a mass of rock or debris, gliding on one or several slide planes on the substratum and creating considerable friction and erosion along the slide scar. *Debris flow* is movement by plastic flow or by shear along many planes in masses of soil or debris.

Using Varnes' terminology four types of mass-movement would be recorded in the Mgeta area, namely "debris slides", "debris avalanches", "debris flows" and "mudflows". These types would form a gradational series from drier to wetter masses and from sliding to flowing movement, but the distinctions between the first two types are rather vague. "With increase in water content or with increasing velocity, debris slides grade into the flowing movement of debris avalanches" (Varnes *op. cit.* p. 29).

The many fresh scars on the slopes at Mgeta, created by the rainstorm of 1970, indicate that the majority of slope failures started as slides. But the features of the mass-movement tracks below the slide scars show that many of the slides were rapidly transformed into flowing movements of wet porridge-like debris, and passed downslope into the valley-bottom streams without causing any erosion of their flow tracks (see below). Thus most of the transfer of material appears to have taken place as the result of debris flows. As these were fine-grained we call them "mudflows" in accordance with the terminology used by Varnes (*op. cit.* p. 37): "... the term is reserved for material with at least 50 % sand, silt and claysize particles". Tables 2a and b show that all the analyzed samples of soil and regolith from the Mgeta area contained more than 80 % of sand and finer particles.

In summary, most of the landslides around Mgeta started as debris slides and of these the majority continued as mudflows, using these terms as has been defined above. The term "debris avalanche", though possibly convenient for labelling a landslide which starts as a slide but becomes transformed into a flow, is not employed here, because it lacks precise definition and is confusing in relation to movement. The terms debris slide and mudflow, as defined in the previous paragraphs will therefore be employed.

For convenience of discussion, debris slides are subdivided below according to the morphology of the slide scars into sheet slides (long and short) and bottle slides. In one example the debris from the slide fell down a rock cliff and was deposited as a debris cone.

## Rainstorm of 23 February 1970

An example of the heavy rainstorms discussed above was experienced in the study area on February 23, 1970, when 100.7 mm of rain fell in one 24 hour period at Mizugu Mgeta.

Evidence from interviews indicates that this rainfall was concentrated in a three hour period between 1400 and 1700 hours. 185 mm of rain were recorded in a 72 hour period centred upon this day. Equivalent falls for Bunduki were 58.4 mm in 24 hours and 97.7 mm in 72 hours and at Kienzema 76.6 mm and 160.9 mm. This period represented the onset of the 1970 main rains and was by far the heaviest and most intense occurrence within that period.

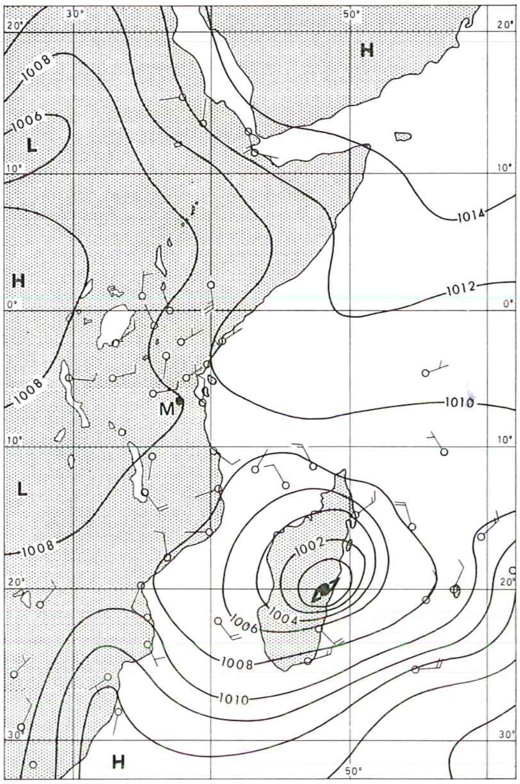


Fig. 2. Synoptic chart of eastern Africa for February 23, 1970, at 0900 hours. M = Morogoro and Mgeta.

The synoptic charts indicate that the rains had occurred in combination with generally low pressure, overcast conditions and light easterly winds over mainland Tanzania together with the extra-tropical movement south of cyclone "Jane" to the E of Madagascar (Fig. 2). Examination of the daily rainfall figures indicates a rapid onset of rain after a long dry spell and such a break is locally characteristic of weather patterns associated with the southerly movement of tropical disturbances offshore. The occurrence of such cyclones offshore is not uncommon for they recur in a similar form every two or three years (Mörth, personal communication), but only rarely do they cross the coast (Sansom 1953a, Neave 1967).

The rainstorm affected only the north-western Ulugurus and showed a maximum intensity over 3 hours in the afternoon suggesting that it resulted from moist upper air conditions in conjunction with local convection favourable to thunderstorm activity, rather than from oro-

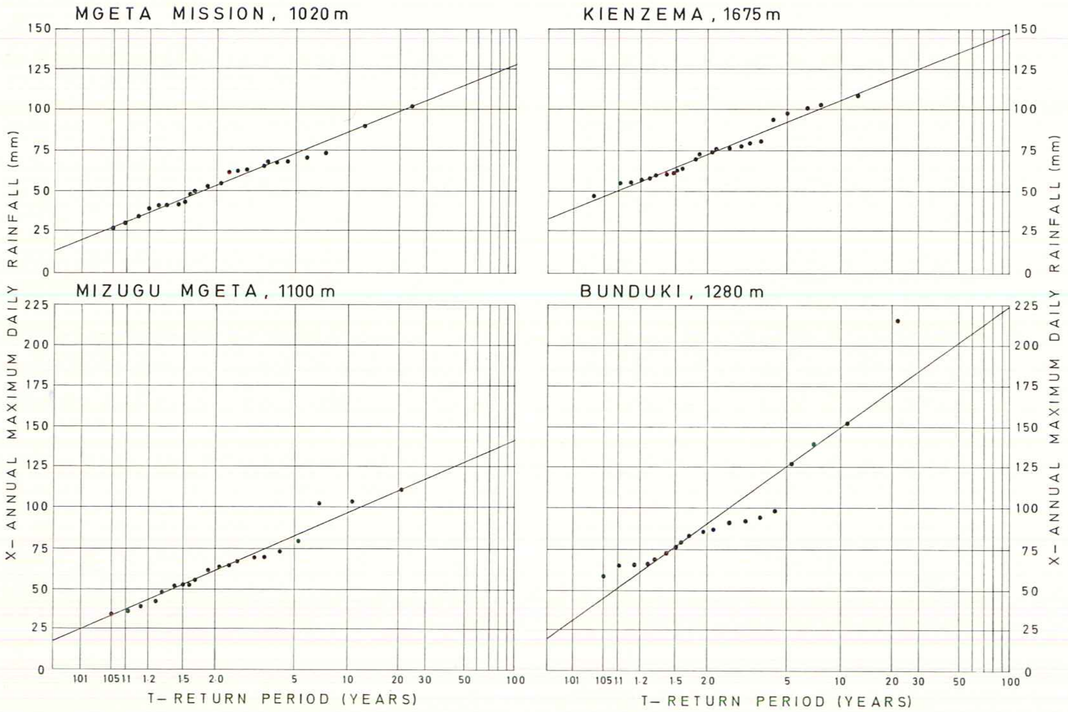


Fig. 3. Return periods in years (T) of annual maximum daily rainfalls (X) for Mgeta Mission, Mizugu Mgeta, Kienzema and Bunduki. (Cf. Table 3).

graphic influences. Sansom (1953, p. 6) characterizes a mature thunderstorm as consisting of a number of cells or centres of activity, individual cells having a life less than that of the storm as a whole which is generally between 1 and 3 hours. The average mature stage of individual cells, producing the heaviest rain is usually only 15—30 minutes, and their size is rarely more than 8 km diameter. He describes the storm mechanism in the following terms: "The most efficient rain producing mechanism is a convergent convective cell, in which a deep layer of moist air flows radially inward and is lifted to great height before undergoing radial outflow. The amount of moisture which can be precipitated depends upon the depth of the inflow column, the height to which the column is lifted, and the difference in moisture content between the inflowing and the outflowing air" (Sansom *op. cit.*, p. 6). Sansom constructed a model for the structure and vertical extent of the cell, noting that in the tropics, convection reaches much greater heights (c. 15,000 m) than in other latitudes. It is this model which is used below to determine the maximum probable precipitation for the Mgeta catchment stations.

The frequency of such rainstorms is a vital factor in assessing their morphological consequences over time. Thus the return period (or frequency or recurrence interval) of extreme rainfall occurrences was determined statistically using a graphical frequency analysis. Annual maximum daily rainfalls (one daily maximum value per year) form a true distribution series and are therefore susceptible to such analysis. The four station records of the area were examined separately, the return period being defined as the average time interval within which a certain value will be equalled or exceeded once. After ranking by order of magnitude, the data were processed according to procedures described by Gumbel (1958) and Wiesner (1970) and values for the return period (T) plotted against the relevant maximum value (X) on extremal probability

Table 6. Frequency of daily rainfall values in excess of 25 mm at Kienzema, Bunduki, Mizugu Mgeta and Mgeta Mission over the recorded period.

| mm range | 200–224.9 | 175–199.9 | 150–174.9 | 125–149.9 | 100–124.9 | 75–99.9 | 50–74.9 | 25–49.9 | |
|---|---|---|---|---|---|---|---|---|---|
| Kienzema: 23 yr. 9 m (June 1946–March 1970) | 0 | 0 | 0 | 1 | 3 | 8 | 50 | 280 | 342 |
| Bunduki: 18 yr. 12 m (April 1951–March 1970) | 1 | 2 | 2 | 3 | 4 | 24 | 65 | 342 | 443 |
| Mizugu Mgeta: 18 yr. 7 m (September 1951–March 1970) | 0 | 0 | 0 | 0 | 3 | 1 | 26 | 135 | 166 |
| Mgeta Mission: 21 yr. 12 m (Aug. 1934–July 1956) | 0 | 0 | 0 | 0 | 1 | 1 | 21 | 161 | 184 |
| Totals | 1 | 2 | 2 | 4 | 11 | 33 | 163 | 918 | 1135 |

paper. Straight lines for each set of data were then plotted by eye-fit (Chow 1964, 8—30) (Fig. 3). At Mgeta Mission daily maximum values of 75 mm (a minimum amount causing severe damage in 1970, as at Kienzema) have a mean return period of less than 6 years, at Mizugu Mgeta of 4 years, at Kienzema of over 2 years and at Bunduki of 1.5 years. This frequency refers to 24 hour time periods. However as most of the extreme rainfalls of the area are from thunderstorm cells, it seems likely that there would be a close relationship between return periods for 24 hour time intervals and shorter intervals.

This is born out by an examination of Table 6 which shows the frequency of different daily extreme values. Daily falls in excess of 75 mm appear from these values to recur once every 0.5 years at Bunduki, once every 2 years at Kienzema, once every 4.7 years at Mizugu Mgeta and once every 11 years at Mgeta Mission. The mean recurrence value is thus 4.6 years. The accordance between the two methods is good; the frequency ranking is the same, and the values for the return periods for Kienzema and Mizugu Mgeta are very close.

Table 7 tabulates daily falls over 75 mm and their dates of occurrence. It is clear that such downpours occur predominently during the rainy months (see above) but are clearly not restricted to them and only the period June through August has been devoid of such occurrences. Furthermore heavier falls than that experienced on February 23 at Mizugu Mgeta have been experienced at all stations except the lowest (Mgeta Mission), and have in fact been experienced twice at Mizugu Mgeta over the recorded period.

From the standpoint of morphological effects, economic repercussions and conservation policy, it is valuable to consider the maximum probable precipitation for the catchment. A method for making such an assessment has been established by Sansom (*op. cit.*). He calculated the maximum rainfall delivery for areas up to 10 km$^2$ for durations of 3 hours using a thunderstorm model appropriate to East African conditions, where a duration of rain of 3 hours was assumed with a probability of maximum rainfall intensity occurring over a more limited time interval (40 minutes), often in the middle of the storm. This model matches the Mgeta occurrence. Sansom's analysis was extended to cover 24 hour periods by McCallum (1969) and elaborated and checked against recent data by Lumb (1970).

As the volume of effective precipitable water varies inversely with ground elevation, it is a simple matter to apply the results of these analyses to the stations under review. The value of maximum precipitable water (We) for the Mgeta stations was derived from graphical plotting using Sansom's calculations (*op. cit.*, p. 9) for We against elevation. We for Mizugu Mgeta was 41.5 mm, for Bunduki 38 mm and for Kienzema 35 mm. Lumb (*op. cit.*) has pointed out that such point values generally overestimate area values by 10—15 %; accordingly these values were reduced by 10 % to derive approximate area values giving 37.3 for Mizugu, 34.2 for Bunduki and 31.5 for Kienzema. Those values were then multiplied by six (Sansom, *op. cit.*) to derive values for probable maximum falls over a 3 hour period. In the Mizugu area these could reach 223.8 mm, around Bunduki 205.2 mm and around Kienzema 189.0 mm. Comparing these values with those recorded in the 3 hour storm of February 23, 1970, it will be seen that the Mizugu area then received 45 %, Bunduki 28.5 % and Kienzema 40.5 % of their probable maximum precipitation. It is apparent that all areas might receive in future considerably greater rainfalls than that which damaged the Kienzema-Mgeta area so severely in 1970.

Analysis of the hydrological records both unpublished and published (WD & ID, *op. cit.*) supplements the meteorological data already discussed. Records consist of twice-daily staff gauge readings maintained since November 1959 and an Ott float-type automatic recorder trace since June 1967.

Prior to 1970 the highest recorded discharge, measured by staff gauge in November 1959 was 108.5 m³/sec. But twice-daily staff readings will frequently miss flash floods of 2—3 hour durations generated by high intensity rainfalls in small catchments. Furthermore gauge readings have only been maintained for 12 years and high floods have washed away the staff gauge four times in that period (in February 1961, January 1962, December 1962 and January 1963). It is certain therefore that at least four very intense floods over this period were not recorded at all. Flood waters on February 23, 1970 overtopped the automatic recorder, filling the lower pipe inlet with sand and interfering with the recording arm. The flood peak was thus not directly recorded. However the height reached by the water at the site was pegged on the following day and soon after the cross-profile of the valley and the peg-height were surveyed by officers of the Water Development and Irrigation Division. Fig. 4 shows a reconstruction of the water stage graph using all available data (gauge readings, automatic trace, ground survey and extrapolations for missing periods). This checks against the 24 hour rainfall records. The flood peak recorded was the highest ever (13.5 ft or 4.11 m) and the associated discharge was calculated by WD & ID, as 230.5 m³/sec. (over double the previous record). As the control is permanent this figure is probably accurate and corresponds to a peak runoff of 2280 lit/sec km². The catchment area above the gauge is

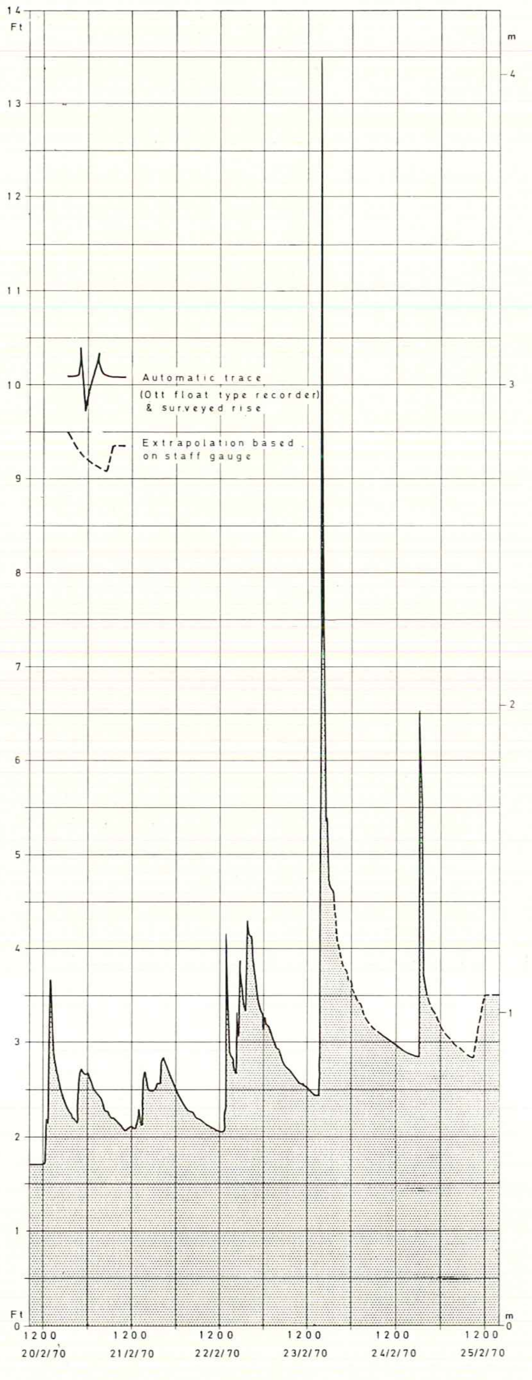


Fig. 4. Water stage graph of the Mgeta river at the automatic gauge (1 HB2, see Fig. 1), February 20—25, 1970.


Fig. 5. Aerial oblique of landslide-scarred slopes in the Mizugu headwaters. The Mzinga valley (1), the Lukwangule plateau edge (2), Kienzema (3) and Bumu Mission (4) are shown. Slides F1—F4 and F7 and F8 (Fig. 14) are identifiable. Photo AR: 6/70.



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Table 7. Amount and occurrence of extreme daily rainfalls (over 75 mm/day) for stations in the western Ulugurus over the recorded period. Note: Only two records of this magnitude for Mgeta Mission between 8/34 and 7/56 namely 88.9 mm on 21/1/48 and 100.1 mm on 13/12/40.

| Month | Kienzema | | Bunduki | | Mizugu Mgeta | |
|---|---|---|---|---|---|---|
| | mm | date | mm | date | mm | date |
| Jan | 108.7 | 21/48 | 86.4 | 18/60 | 102.9 | 18/60 |
| | 94.2 | 15/63 | 76.2 | 27/66 | | |
| | 79.2 | 4/50 | | | | |
| Feb. | 97.0 | 26/68 | 110.2 | 4/61 | 100.7 | 23/70 |
| | 76.6 | 23/70 | 90.2 | 17/52 | 78.0 | 10/63 |
| | | | 87.6 | 1/66 | | |
| | | | 81.8 | 1/69 | | |
| Mar. | 135.0 | 24/69 | 162.6 | 25/61 | — | |
| | 102.4 | 17/58 | 151.4 | 26/57 | | |
| | 76.0 | 29/64 | | | | |
| | 75.0 | 7/67 | | | | |
| Apr. | 77.2 | 24/52 | 127.5 | 18/61 | | |
| | | | 97.5 | 7/59 | | |
| | | | 90.2 | 21/58 | | |
| | | | 83.8 | 15/57 | | |
| | | | 83.8 | 9/53 | | |
| | | | 76.2 | 7/69 | | |
| | | | 76.2 | 27/69 | | |
| May | 80.0 | 2/66 | 96.5 | 3/57 | — | |
| Sept. | 101.6 | 25/57 | 78.2 | 10/65 | 110.0 | 23/57 |
| Oct. | — | | 195.1 | 30/61 | — | |
| | | | 91.4 | 4/69 | | |
| | | | 76.7 | 24/51 | | |
| Nov. | — | | 216.2 | 6/61 | — | |
| | | | 193.0 | 27/61 | | |
| | | | 160.0 | 28/61 | | |
| | | | 138.9 | 16/55 | | |
| | | | 119.6 | 25/61 | | |
| | | | 113.8 | 3/56 | | |
| | | | 94.2 | 21/51 | | |
| | | | 88.9 | 13/69 | | |
| | | | 87.6 | 15/61 | | |
| | | | 86.4 | 15/51 | | |
| | | | 86.4 | 23/61 | | |
| | | | 85.3 | 26/62 | | |
| | | | 80.3 | 26/61 | | |
| | | | 76.5 | 4/59 | | |
| | | | 76.2 | 9/65 | | |
| Dec | — | | 126.2 | 25/56 | — | |

101 km² (WD & ID 1967). The peak runoff in the area of maximum recorded rainfall and slide damage in the Mzinga-Mizugu catchment was possibly 40 % greater than that in the Mgeta catchment to judge from the differences in rainfall recorded at Mizugu (100.7 mm) and that recorded at Bunduki (58.4 mm). Furthermore, as Fig. 1 shows, the upper catchment of the Mgeta is under woodland and forest, while that of the Mzinga-Mizugu is largely deforested. Fig. 4 shows that the flood was extremely flashy, the river stage level rising 3.4 m in an hour to a peak, delayed only 1 hour after the commencement of the rainfall. 2 hours after the peak, the river stage had fallen 2.9 m, and the flood lasted only 3 hours. Fig. 1 shows that both the staff gauge and the automatic recorder are situated on the Mgeta river upstream of its confluence with the river Mzinga. Thus discharge from the catchment with maximum rainfall was not recorded at all; discharge below the confluence less than 1 km from the gauges would almost certainly have been greatly in excess of the recorded amount.

## Types of erosion observed in the area

The rainfall values for individual stations within the study area indicate that the heaviest and most intense rain was centred upon an area around Mizugu Mgeta (Fig. 1). Field work and aerial reconnaissance confirm this but indicate that the areas of maximum damage lay on the steeper cultivated hill slopes to the south in the upper Mzinga and Mizugu catchments between Bumu and Tengero. Most of the damage around the storm centre took the form of landslides; other damage resulted from flash flooding, stream bank erosion and silting and damage of this type extended far beyond the storm centre.

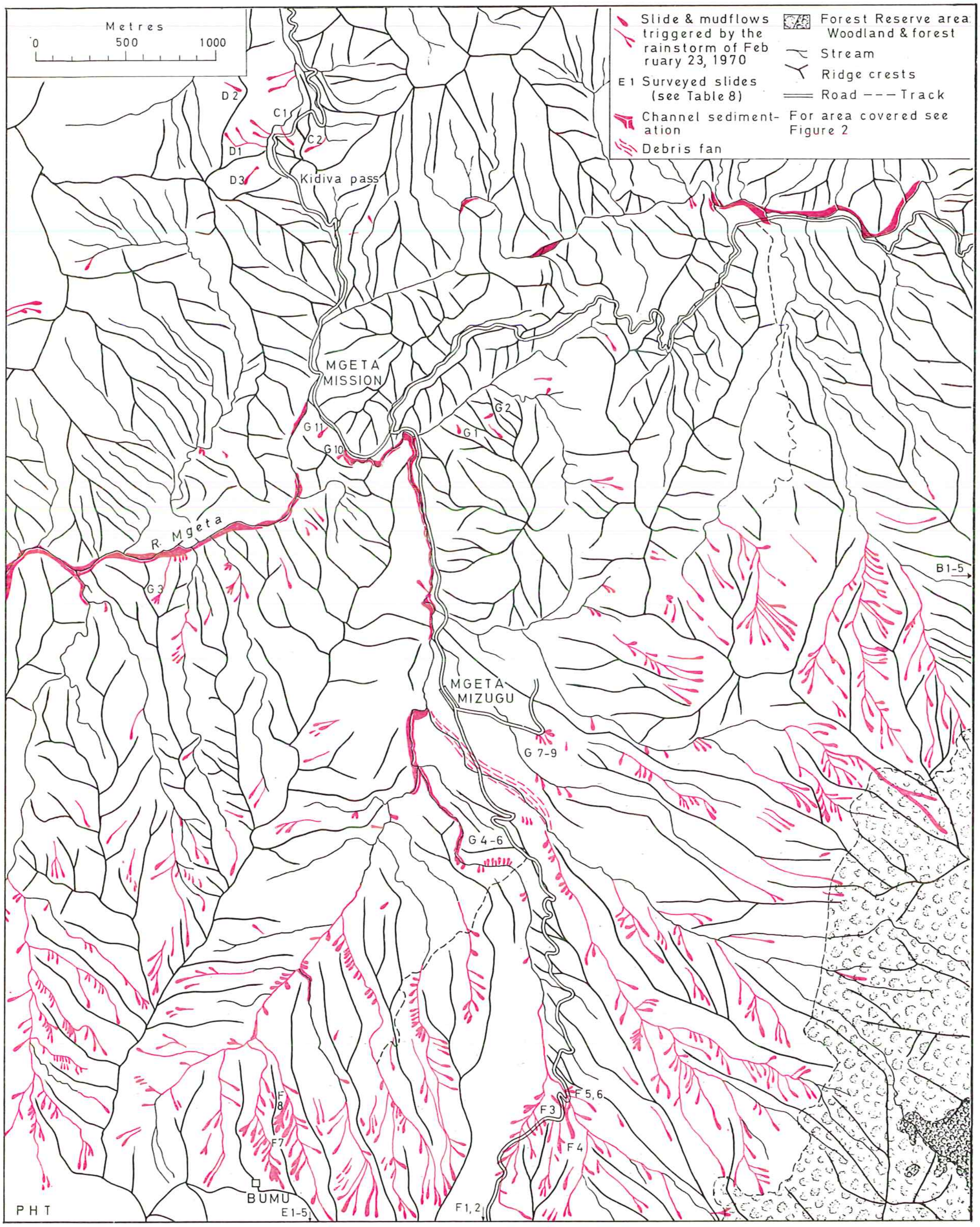
More than 1000 fresh slide scars were counted after the February 1970 rainstorm in the Mgeta area. Fig. 5 shows one of the most heavily damaged areas on the slopes of Kingino hill. This figure should be compared with Fig. 6. The latter one plots the distribution and form of slides in the most severely affected part of the area. The slides are separated into types for discussion (see above).

*Sheetslides*

(ss, sl, slm and dc in Table 8)

The slide scars of this type were typically 5—

Fig. 6. Landslide and mudflow distribution in the Mzinga-Mizugu catchments, plotted from aerial obliques. For the area covered see Fig. 1. North is upwards.


Metres
0
500
1000
Slide & mudflows triggered by the rainstorm of February 23, 1970
E 1 Surveyed slides (see Table 8)
Channel sedimentation
Debris fan
Forest Reserve area Woodland & forest
Stream
Ridge crests
Road --- Track
For area covered see Figure 2
D 2
C 1
C 2
D 1
D 3
Kidiva pass
MGETA MISSION
G 11
G 10
G 1
G 2
R. Mgeta
G 3
B 1-5
MGETA MIZUGU
G 7-9
G 4-6
F 5, 6
F 3
F 4
F 8
F 7
BUMU
E 1-5
F 1, 2
P H T

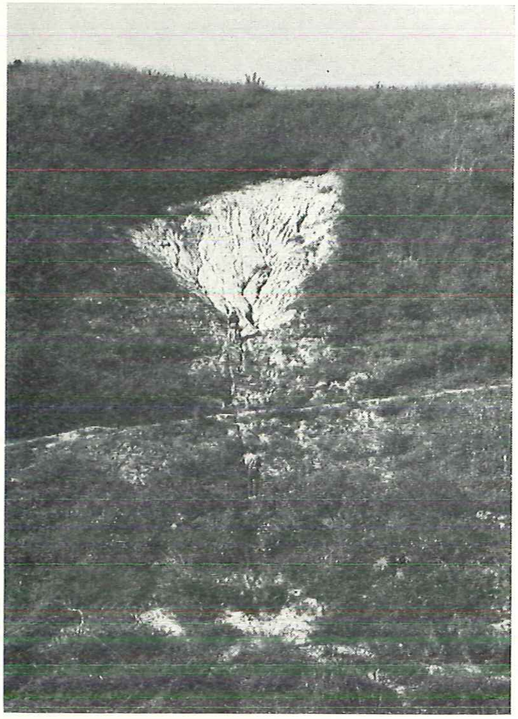


Fig. 7. Small landslide and mudflow at Mgeta (Gl: see Fig. 8). Slope under fallow with older scars above the scar on the left. The mudflow crossed the valley in the foreground and flowed 16 m up the reverse slope of 18°. Photo AR: 5/70.

20 m wide, 10—50 m long, up to 2 m deep, wide near the upper end, narrowing in a wedge-like fashion downslope. Basically they are debris slides, which due to their small thickness are here called "sheet-slides". Slope profiles were measured of several slide scars and the flow tracks below them. A selection of the profiles is shown in Fig. 8.

A typical example of such a slide, though small and short, is C2 near Kidiva pass (cf. also Figs. 8, 9 and 10). The slide scar was 9 m wide and 10,5 m long from the upper to the lower end. It had a slightly concave slide plane, cut into gneissic regolith showing in situ structures. The maximum depth of the scar was 1.5 m in the central upper portion. The upper limit of the scar was semicircular and cut through dark topsoil, with an overhanging root mat of grass, into the light-colored regolith below. The average slope of the scar bottom was 42,5°. Its upper end was 22 m downslope from the convex ridge crest, covered by grass fallow *(Hyparrhenia rufa)*. Former cultivation of the slope was revealed by an overgrown pattern of terraces about 1 m high, the so-called ladder terraces, made by hoeing (cf. Fig. 9). Most of the other slide scars of this type had an elongate form (Table 8). Some occurred in groups, converging towards a single flow track (Fig. 14). Data presented in Table 8, where scar widths are tabulated in size classes, show that 45 % of the recorded slides were between 5 and 10 m wide, 24 % between 1 and 5 m wide and 20 % between 10 and 20 m wide. The length of slide scars ranged between 8 and 90 m, but most were 2—4 times longer than they were wide and narrowed downslope. Most scars were continued downslope as mudflow tracks or lobes. Typical examples of sheet slides studied are presented in Figures 7, 8, 9, 11, 12 and 13 and in Plates 2A and 2B.

All of the sheet slides had occurred on steep slopes and affected soil and regolith. Slopes affected ranged between 28° and 44° and scars were located 5—95 m downslope from the ridge crest. The angle of slide scar given in Table 8 refers to the gradient of the bottom of the scar, measured below the upper scarp. This angle is generally a little lower than the slope of the ground surface beside the scar. Most slide scar angles measured were within the interval 33,5°—44°, which indicates critical slope angles for triggering of sheetslides. Slides with a scar angle below 30° were either transitional or clear bottle slides (see below). Case A 1 is a clear example of a bottle slide and the other slides with an angle of scar below 30° in Table 8 also had evidence of long-lasting regolith flowage (F3, F7 and G9). Data presented in Table 10, where scar positions are tabulated, show that almost 60 % of the recorded slides had occurred on straight valley sides well below ridge crests; only 12 % had occurred on the upper parts of slopes. Many slides (12 % in our sample, but this is certainly an underestimate, see above) were close to stream sides, on the lower steepening of slopes resulting from stream incision. None of the examples studied had resulted from flood erosion however. 9 % were located in steep tributary valley-heads where drainage was probably concentrated. Most commonly affected soil profiles showed 10—30 cm of dark,

Table 8. Types, dimensions, angles of scars, positions and land use of areas affected and orientations of surveyed landslides in the Mgeta area. Dimensions in metres. Orientations describe slide track direction. Angle of slide scar refers to the slope angle of the slide scar bottom. Slide A1 was excluded from calculations of averages and total volume, as it is older than the other slides of Table 8, and of different type.
Key to slide types: bs = bottle slide; ss = sheet slide—short; sl = sheet slide—long; slm = sheet slide (long) + mudflow; dc = debris cone.
Key to land use; m = maize *shamba;* b = beans *shamba;* ca = cassava *shamba;* cp = cow pea *shamba;* v = vegetable *shamba;* c = coffee *shamba;* sp = sweet potatoe *shamba;* g = grass; f = fallow; t = ladder terraces. Combinations indicate intercropping or scar affecting two different land uses.

| Slide No. | Slide type | Scar dimensions Max. width | Max. depth | Length | Angle of slide | Volume in m3 | Distance from ridge crest | Land use | Orientation (°) |
|---|---|---|---|---|---|---|---|---|---|
| A1 | bs | 60.7 | 8.9 | 64.4 | 21 | 6 484 | ? | m | 313 |
| B1 | ss | 27.2 | 2.0 | 70.0 | 38 | 1 135 | 23.3 | m+b+t | 54 |
| B2 | slm | 8.2 | 1.0 | 32.8 | 40.5 | 83 | 30.8 | b+t | 34 |
| B3 | ss | 16.1 | 1.6 | 42.0 | 38 | 322 | 18.4 | g | 60 |
| B4 | dc | 19.7 | 1.0 | 65.6 | 42.5 | 418 | - | m | 345 |
| B5 | sl | 16.7 | 1.3 | 65.3 | 36.5 | 401 | 21.3 | g | 248 |
| C1 | slm | 13.8 | 1.6 | 29.5 | 35 | 185 | 43.3 | m+t | 327 |
| C2 | slm | 8.9 | 1.5 | 10.5 | 42.5 | 49 | 24.9 | g+f+t | 37 |
| D1 | slm | 14.4 | 1.0 | 25.9 | 34 | 103 | 35.4 | g | 20 |
| D2 | slm | 14.1 | 2.3 | 12.1 | 36.5 | 125 | 18.7 | cp | 270 ? |
| D3 | ss | 7.2 | 1.3 | 18.7 | 35 | 49 | 69.0 | m | 0 |
| E1 | ss | 9.8 | 1.0 | 18.4 | 35 | 52 | 5.6 | f | 256 |
| E2 | slm | 17.1 | 2.3 | 36.1 | 38 | 428 | 28.2 | m | 312 |
| E3 | sl | 5.9 | 2.0 | 40.4 | 41 | 146 | 94.8 | v | 318 |
| E4 | sl | 10.5 | 1.5 | 38.7 | 42 | 194 | 66.9 | g+m | 332 |
| F1 | slm | 29.5 | 2.1 | 90.2 | 39 | 1 687 | 37.4 | f+t | 353 |
| F2 | slm | 23.6 | 1.0 | 57.1 | 42.5 | 442 | 24.9 | f+t | 0 |
| F3 | sl | 15.1 | 2.3 | 22.0 | 29 | 187 | 38.7 | m+c+t | 320 |
| F4 | slm | 9.5 | 2.3 | 28.9 | 36 | 178 | 6.2 | m+c+t | 6 |
| F5 | slm | 6.2 | 2.3 | 35.4 | 35 | 138 | 37.0 | g | 250 |
| F6 | slm | 8.2 | 2.0 | 29.2 | 38.5 | 142 | 53.2 | c+m+t | 250 |
| F7 | slm | 13.1 | 5.0 | 61.4 | 24 | 773 | 75.1 | c+m+t | 8 |
| F8 | slm | 27.1 | 2.0 | 85.1 | 39 | 1 391 | 12.7 | c+m+t | 1 |
| G1 | slm | 16.4 | 2.6 | 29.5 | 34 | 348 | 27.9 | f+t | 0 |
| G2 | ss | 8.2 | 1.0 | 22.3 | 37 | 53 | 10.2 | g | 214 |
| G3 | slm | 23.0 | 1.6 | 37.1 | 44 | 487 | 14.4 | f+t | 30 |
| G4 | ss | 7.6 | 1.0 | 9.5 | 41 | 24 | 4.0 | g | 164 |
| G5 | ss | 26.2 | 1.5 | 9.2 | 36 | 137 | 6.6 | g | 167 |
| G6 | ss | 16.4 | 3.0 | 23.3 | 36 | 340 | 8.5 | f+t | 175 |
| G7 | slm | 7.2 | 0.8 | 7.9 | 35 | 14 | 56.4 | f+t | 340 |
| G8 | ss | 15.7 | 1.6 | 35.1 | 33.5 | 238 | 30.5 | sp+t | 336 |
| G9 | slm | 9.8 | 1.3 | 14.1 | 26.5 | 40 | 54.8 | m | 225 ? |
| G10 | slm | 18.4 | 1.6 | 20.7 | 33.5 | 174 | 15.1 | g | 79 |
| G11 | slm | 3.6 | 1.3 | 23.6 | 41.5 | 34 | 68.6 | m | 36 |
| Mean values B1-G11 | | 14.4 | 1.8 | 34.8 | 36.8 | 318.7 | 33.2 | - | - |

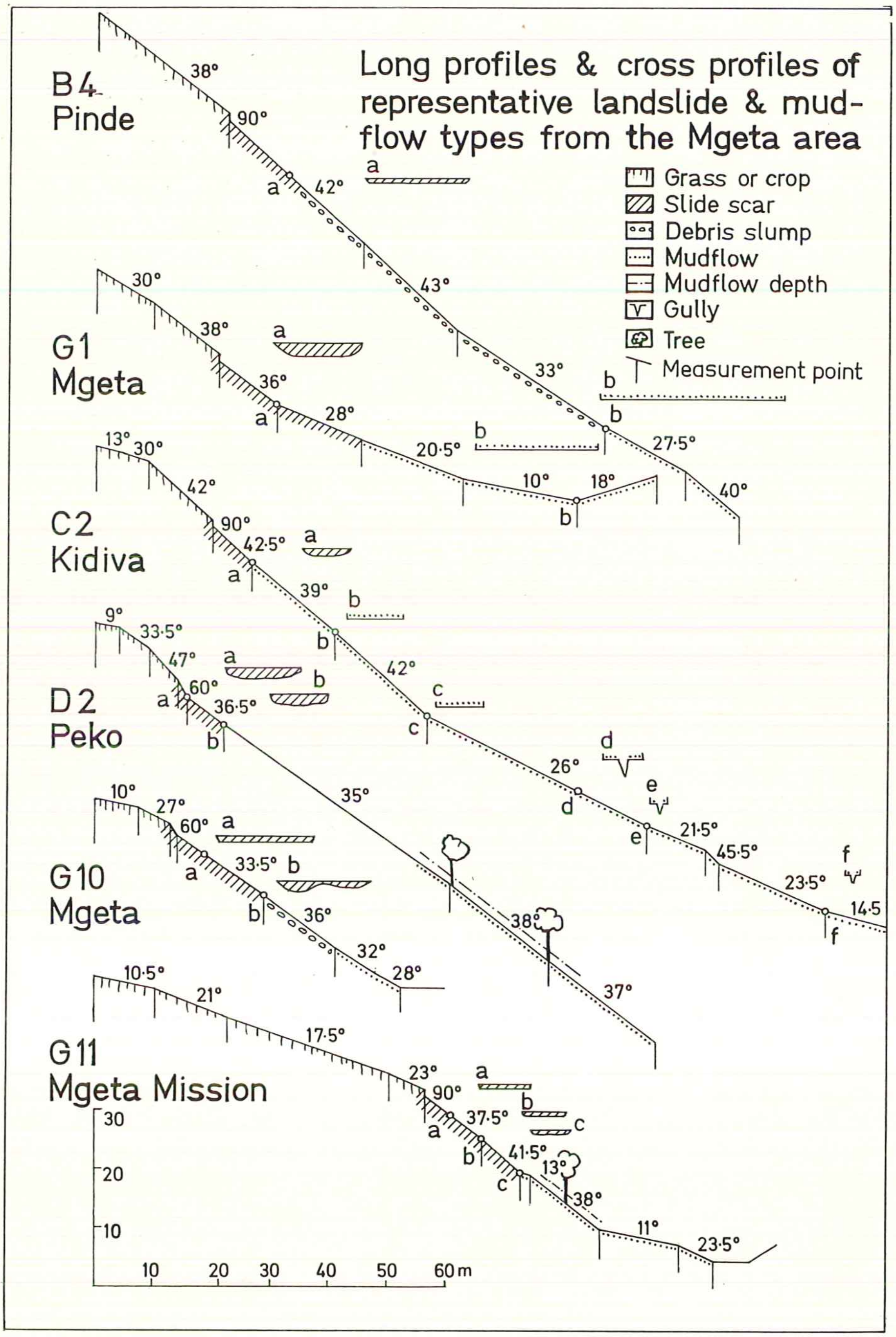



Fig. 8. Surveyed long profiles and cross profiles of representative landslide and mudflow types from the Mgeta area (B4, G1, C2, D2, G10 & G11; see Table 8).

Table 9. Width of slides examined.

| Locality | over 30 m wide | 20–30 m wide | 10–20 m wide | 5–10 m wide | less than 5 m wide | Totals |
|---|---|---|---|---|---|---|
| Reconnaissance observations | 3 | 17 | 38 | 105 | 61 | 224 |
| Surveyed slides | 1 | 6 | 14 | 12 | 1 | 34 |
| Percentages | 1.6 | 8.9 | 20.2 | 45.3 | 24.0 | 258/100 |

Table 10. Position of slides examined (see text).

| Locality | Ridge crest | Valley head | Valley side | Stream side | Others: eg. rock spur etc. | Totals |
|---|---|---|---|---|---|---|
| Reconnaissance observations | 30 | 21 | 128 | 29 | 16 | 224 |
| Surveyed slides | 2 | 3 | 26 | 3 | 0 | 34 |
| Percentages | 12.4 | 9.3 | 59.7 | 12.4 | 6.2 | 100 |

crusted topsoil overlying thin sandy colluvium on a variable thickness of weathered bedrock (regolith) in situ.

Of particular interest from a conservation viewpoint is the data presented in Table 11, where the slide sample is analysed with regard to the land use of the locality affected. 47 % of the slide scars affected cultivated *shambas* (cultivated plots), most of these being planted with maize. A further 47 % affected grass-covered slopes, a high proportion of these being formerly cultivated land then under fallow. Less than 1 % of the sample affected woodland and forested slopes, though these were generally even steeper than the cultivated slopes, a very clear indication of the stabilizing effect of tree roots and tree cover in steep soil-covered slopes (Selby 1967). On the other hand the few slides that occurred under tree cover at Mgeta show that trees are not an absolute protection against debris slides. Slides under dense forest cover have been reported from other areas (Hack & Goodlett 1960, Jackson 1966, Starkel 1970, G. M. Clark, personal information). Even beyond the woodland margins, the stabilizing effect of individual trees was clearly discernible. In several surveyed slide scars, tree roots had retained large protrusions of undisturbed soil profile on the slide margin and made it irregular in form (eg. scar B5). Elsewhere (eg. scars G10, Fig. 12 and F7, Fig. 14) individual trees had restricted the lateral damage on a slide affected slope. Of the hundreds of small slides from road cuts only one was seen which had displaced bush cover. All others had occurred on cleared slopes.

*Mudflows*
(slm in Table 8)

Mudflows were intimately related to sheetslides and the majority of sheetslides developed into mudflows downslope. Of the scars surveyed (Table 8), 20 out of 34 showed evidence of mudflow development at their lower ends. The majority of the remainder were short and had discharged their material more or less directly into stream courses. For example, a *mudflow track* continued downslope from the lower end of the C2 sheetslide, running 160 m down a concave slope, 39°—42° steep in the upper part, flattening to 15° at the lower end—the confluence with the stream channel. The width of the flow track was the same as that of the slide scar in the upper part of the track. The track ran over undamaged soil terraces (Fig. 9) where some fresh regolith had been dropped on the terrace

Fig. 9. Small landslide scar and mudflow track at Kidiva (C2: see Fig. 8). Slope under fallow with ladder terrace system prominent. Note also old slide scar to the left of the figure. Photo PHT: 4/70.

Fig. 10. Part of the mudflow lobe at the bottom of C2 (Cross section f, Fig. 8). Photo PHT: 4/70.

steps. Lower down the mudlow track narrowed to 6—8 m and ran through dense grass, which had been pressed down to the ground and "combed" in the direction of flow. The lower part of the track was on both sides of a gully, 2—2.5 m wide and 0.5—3 m deep. Thin mudflow lobes, 12—15 cm thick, had been left in patches on plastered grass on both sides of the gully (Fig. 10) near the confluence with the main channel.

The evidence of mudflows was of different types. Complete *mudflow lobes* were found below landslide scars above roads, for in such situations the flowing mass spread out in a wide fan-shaped deposit over the flat road surface below. Concentric flow ridges and an

Fig. 11. Landslide and mudflow at Peko (D2: see Fig. 8). Slide started immediately below fallow grass in a *shamba* of cow peas. The mudflow carried away part of a maize crop below (clear track) and left debris and marks on the trees in its path, indicating that the flow there was 1.5 m thick. Photo PHT: 5/70.

Table 11. Land use of localities affected by landslides.

| Locality | Cultivated mostly maize | Grass often with old terraces | Forest or bush | Other rock etc. | Totals |
|---|---|---|---|---|---|
| Reconn. observations | 103 | 104 | 2 | 15 | 224 |
| Surveyed slides | 18 | 16 | 0 | 0 | 34 |
| Percentages | 46.9 | 46.5 | 0.8 | 5.8 | 258/100 |

even, flat, crusted surface of fine-grained material, mixed with vegetation debris and stones formed diagnostic features. For example, the mudflow track associated with slide E2 was 12 m wide on the slope above the road but expanded into an 18 m wide lobe on the road surface. Slides F5 and F6 converged into one complex flow lobe in a comparable position. In these last examples the distance from the lower part of the slide scar to the distal end of the mudflow lobe was only 15 m, indicating a very rapid transformation from sliding to flowing movement after slope failure. Partial remains of mudflow lobes or *levees* were found plastering flow tracks on sections of low gradient eg. slide C2 (Figs. 8 & 10). *Mudflow tracks* were clearly distinguishable on slopes covered with high grass. The grass had been combed and plastered down to the ground in the direction of flow (Fig. 9). In two of the cases studied (slides G1, Fig. 8 & D1), the mudflow had moved across the valley bottom beneath the release scar and up the opposite slope. Flow D1 had moved 16 m upslope, this corresponding to a 4 m vertical rise.

Mudflows which had crossed cultivated fields or fallow grassland had caused almost no erosion of soil. Their movement was probably facilitated by the presence of very wet grass or soil below the slide scars. Small ladder terraces remained intact in the flow track but growing crops (eg. maize in slides C1, C2, D2, Fig. 11) and small coffee bushes below slide F 4) had been completely removed. Large trees located in the mudflow tracks had had their trunks evenly plastered with mud on the upslope side, to heights of 1.2—1.5 m above the ground, and showed evidence of bark damage over the same height range (e.g. slides D2, G11, Figs. 8 & 11). This mudplastering and bark damage was used to gauge the thickness of the mudflow at that point.

The rapid transformation of displaced slide material into mudflow, which was general, indicates that the water content of the source material was in most cases high.

*Bottle slides*
(bs in Table 8)
The other type of landslide scar which occurs in the Mgeta area is called here a "bottle-slide". This is a descriptive term, which emphasizes that the typical form of the landslide scar is deep and wide in the upper part, narrowing downslope to an outlet like a bottle-neck with steep side-walls with a slowly flowing, wet and viscous mass of debris moving

Fig. 12. Stream side slide and mudflow at Mgeta (G10: see Fig. 8). Note how trees have controlled the form of the slope failure on both sides. Scoured bedrock and coarse boulders in the Mzinga river channel and sandy flood deposits on the flood plain in the foreground are evident. Photo PHT: 9/70.

Fig. 13. Large landslide from natural woodland in the upper left center of the photograph. This slide was one of the largest observed, but was not surveyed in detail. Note the contrast between the two lone slides in woodland and the numerous smaller slides affecting cultivated land. Compare colour Plate no. 2A. Photo AR: 5/70.

down the outlet channel. The flowing mass in this case consists of thoroughly weathered and water-saturated gneiss or granite. Similar cases have been described by Haldemann from the Rungwe area, Tanzania and by Magnusson and others (1963, p. 501) in the clayey Post-glacial deposits along the Göta river in Sweden where they were termed bottle slides.

The cases described below from the Mgeta area are probably similar to the so-called *lavakas* of the pear-shaped type, described by Tricart (1972, p. 239) and others.

The largest of the bottle slides surveyed (A1, Figs. 15 & 16) had a near vertical back-wall nearly 9 m high, excavated in deep-weathered granulite. Quartz gravel from scattered veins was the only unaltered mineral visible. The slide affected a slope of only 21° and had developed initially in 1963. In 1970 its dimensions were 60 m width and 65 m length (Figs. 15 & 16). This form had probably developed over the 8 year period since its initiation by retrogressive slumping of back-wall and sidewalls and by episodic accelerations of debris flow transfer. From recently deposed debris on rocks in the river bed below the slide it was clear that a major acceleration of flow had been occasioned by the rainstorm of February 1970.

The form of this flowing debris was lobate, convex in cross profile and 40 m wide. The long profile of the flow was also convex with an inclination of 16° in the middle section (lower than that of the affected slope) increasing to 25.5° at the distal end where it reached the stream course. The margins of the lobe were marked by shearing cracks, and the frontal part was very wet and muddy and seamed at the surface by gullies about 1 m deep. Material in the flow lobe was largely silty-clayey regolith but contained residual boulders up to 2 m across. Continuous flow was evidenced by remains of a series of down-slope-deflected footpaths crossing the lobe.

Observations made on the two surveyed examples suggest that such forms are restricted to localities where there had been a deep-reaching and thorough chemical weathering

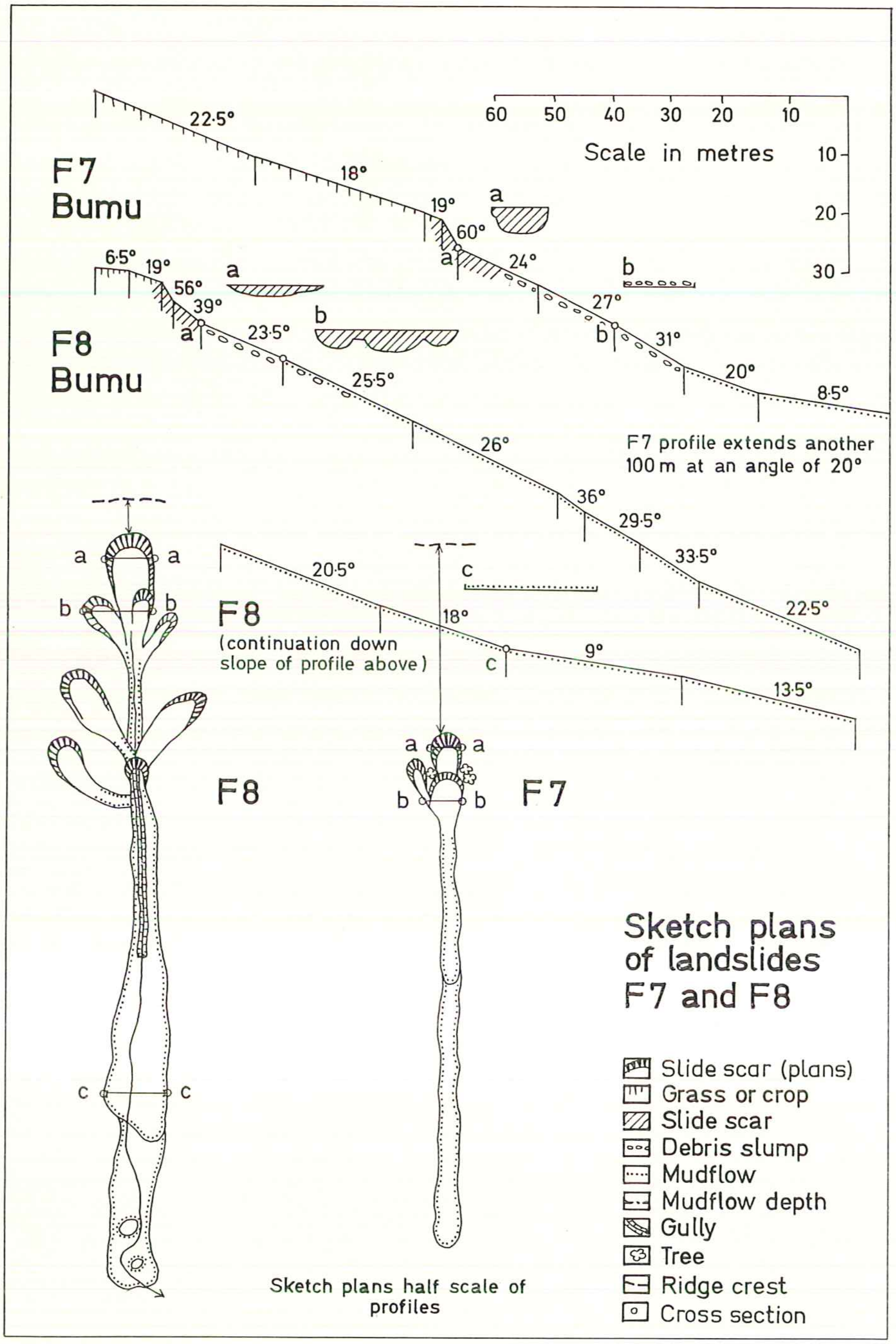



Fig. 14. Surveyed long profiles and cross profiles of complex landslide—mudflow types in the Bumu area (F7 & 8).

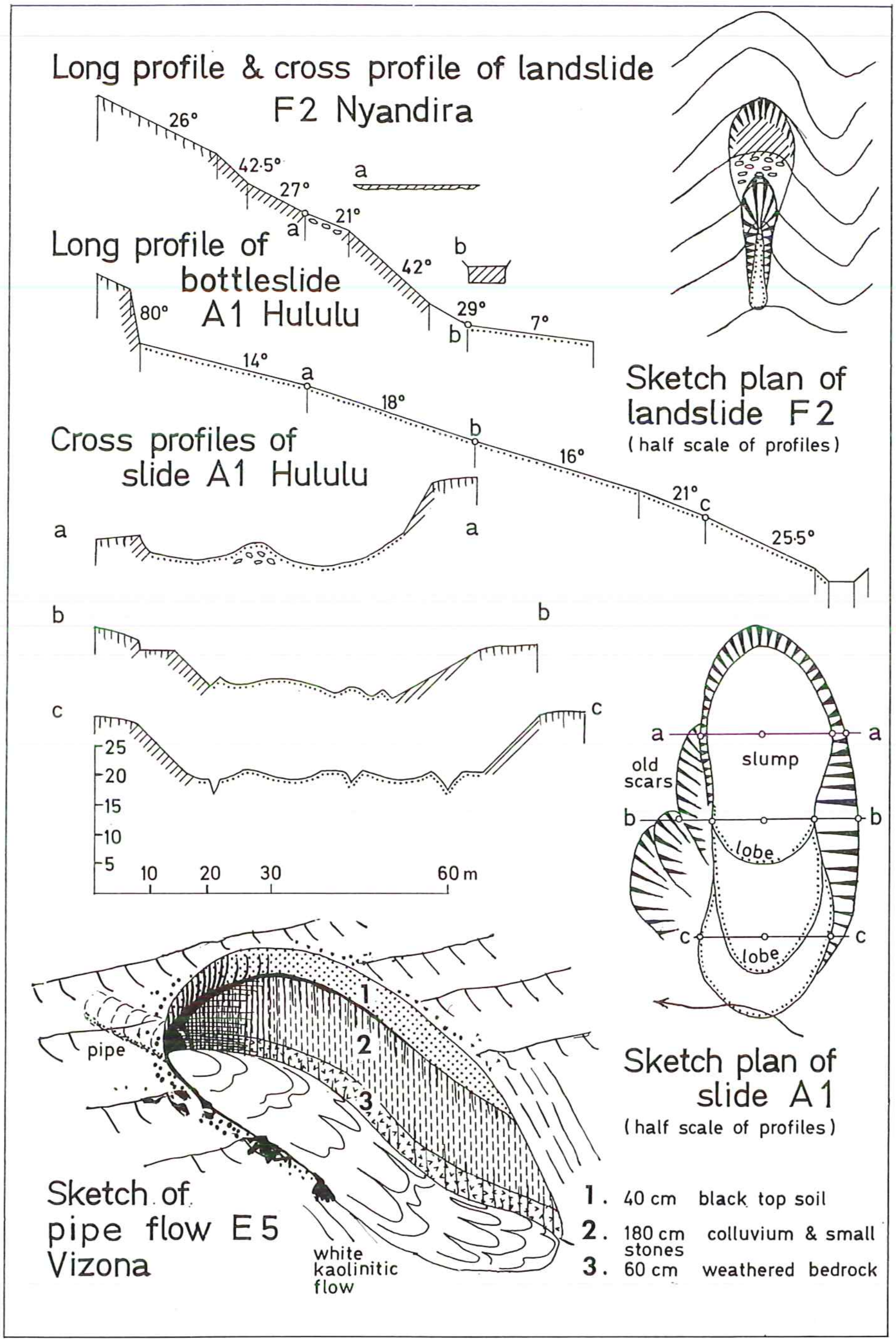



Fig. 15. Surveyed long profiles and cross profiles of bottle slides (F2 & A1) and sketch of pipe flow (E5). Key to shading as in Fig. 14.

Fig. 16. Large bottleslide at Hululu (A1: see Fig. 15). Photo: PHT: 12/69.

Fig. 17. Pipe flow near Vizona (E5: see Fig. 15). Photo: PHT: 5/70.

of the bedrock, combined with high infiltration and considerable subsurface flow of water. Bottle slides probably develop from large subsurface pipes formed by throughflow of water and regolith (Ward, 1966). Their initial form is probably similar to the pipe flow E5 shown in Figs. 15 and 17. From this stage, a combination of slumping and flow enlarges the form into a feature analogous to slide F2 (Fig. 15). Once a large hollow has been excavated, the process of growth may well continue naturally until most of the regolith is removed. Numerous inactive bottle slide forms are evident on air photographs of the area, particularly near Bunduki.

*Gullying, rilling and slope wash*

There were few gullies deeper than one m. They were best developed in the lower sections of some of the mudflow tracks. The gullies appeared to pre-date the mudflows although little mudflow material was found in them. These gullies were cut in bedrock and regolith and exhibited longitudinal profiles of great irregularity, formed of a series of potholes and steps.

The only fresh gullying certainly associated with the February rainstorm was that which affected sections of the Mgeta-Kienzema road

Fig. 18. Flood deposition of February 23, 1970 in the Mgeta valley, looking downstream below the Mission. Photo: PHT: 5/70.

in the neighbourhood of Nyandira. These gullies resulted from the diversion of subsidiary streams along the dirt road surface due to landslide blocking. One of these gullies had spectacular dimensions (Fig. 18).

Rilling and sheet erosion were prominent on the bare surface of the landslides scars (eg. see Fig. 7). Rills up to 50 cm deep were cut into the exposed regolith of many of the slide planes; these rills converged towards the base of the scar in conformity with the geometry of the slide scar and often fed into a deeper rill or gully below. It is thought that most of this rilling developed shortly after the release of the slide when the regolith was still saturated and abundant water was still being supplied by pipes and pores to the shear plane. Slope wash and rain splash effects (stone capped or root-capped regolith pillars up to 5 cm high) had subsequently begun to modify the scars and thus to inhibit vegetational recolonisation.

Slope wash on many cultivated plots in areas unaffected by slides was evident from the exposure of roots of growing grain, the residual mounds around plant roots, the sandy or stony surface of the soil and by shoestring wash lines. This process had been previously identified as the major denudation mechanism in this area but no substantiation of this hypothesis had been offered (Savile 1945—46) (see below).

*Stream flooding: erosion and deposition*

The flood hydrograph of the Mgeta river has already been examined above; maximum discharge recorded there was 230.5 $m^3$/sec. (8140 cusecs). Both the meteorological and the hydrological data indicate that severe flash flooding occured. This was particularly severe in the Mzinga-Mizugu catchment to judge from the geomorphological evidence and rainfall data. This element of the Mgeta flood went unrecorded as the gauge is upstream of the confluence of this tributary (Fig. 1).

Flood erosion effects in the Mzinga catchment were spectacular. All the small tributaries draining the slopes of the mountain showed

Fig. 19. Gully development on Mgeta-Kienzema road at Nyandira. Gully cut in one afternoon and over 5 m deep. Photo: PHT: 6/70.

deep white scars, for much of the stream load and sections of channel bank had been flushed away. Even the minor tributary stream from Mgeta Baraza had moved boulders up to 2 tons many tens of metres. Most of the bridges and causeways had been destroyed, including the main road into Mgeta. Supplementing the load scoured by streams from their own channels was the vast mass of debris supplied to them by landslides.

After the flood the Mzinga channel was partially choked with deposits; in the lower course, these deposits were very mixed in grade with many very coarse, irregular blocks. Some of this material was accumulated in a debris train 40 m wide (Fig. 6) of irregular surface form and comprising materials ranging from gravel size to boulders 1.5 m across and 3.4 $m^3$ in volume. Only one such fan was observed in the study area. Lower downstream in the Mgeta valley deep thicknesses of sand and gravel had been deposited on the flood plain (Figs. 6 & 19) while finer grade material had been moved much further on to the plains surrounding the mountains at Kisaki (Fig. 1). Comparable deposits were examined at Mlali.

No detailed studies were made on the extent or nature of stream flooding effects.

## Calculation of slide volumes and denudation rates

Details of slide types, dimensions, scar angles, volumes, positions, land use and orientation are presented for a selection of slides in Table 8, the localities of many of these slides being shown on Fig. 6. The volumes of sheet slide scars were calculated using a model comprising a combination of a cylindrical and spherical section, representing the slide head ($V_1$) and a conical section representing the middle and lower section of the scar (Fig. 20). $V_1$ was calculated from the formula:

$$V_1 \approx \frac{\pi}{8} a^2 \frac{b}{2} \sin \Theta + \frac{\pi}{16} a^2 \frac{b}{2} \sin \Theta$$

where "$a$" is the maximum width and "$b$" the maximum depth, measured vertically. The dimension "a" is considerably larger than "b". $V_2$ the conical part, was calculated from the formula:

$$V_2 = \frac{1}{2} \cdot \frac{7}{8} \cdot \frac{1}{3} \cdot \pi \cdot \frac{a}{2} \cdot b \cdot 2l \cdot \sin \Theta$$

where "$l$" is the length of the conical section and $\Theta$ is the angle between the slope and the vertical. Slide volumes were obtained by summing $V_1$ and $V_2$:

$$V = V_1 + V_2 \approx \pi ab \sin \Theta \, (0.021a + 0.146\, L)$$

where L is the total measured length of the slide scar, e.g. L = l+a/2. Using this model,

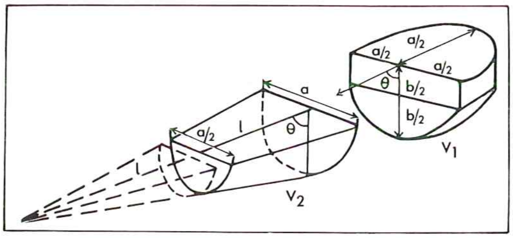



Fig. 20. Model used for the calculation of slide volumes (see text).

it will be seen that the 33 sheet slides described in Table 8 displaced a total volume of 10,500 $m^3$.

If it is assumed that these 33 slide scars form a representative sample of the total, it becomes possible to calculate approximately the denudation caused by slides in the most severely eroded area in $m^3/km^2$. Here it is necessary to refer back to Fig. 6.

Fig. 6 shows the distribution and form of slides in the most severely damaged area. This figure was compiled from aerial obliques (eg. Fig. 5) and the landslide outlines were then transferred to enlarged prior vertical aerial photography. Plotting on to the base map (Fig. 6) could not be adjusted as the print formed the edge of the photo coverage. It therefore contains scale errors though positions of slides will be approximately correct along radial lines from the figure centre. Plotted scar sizes were checked against the ground survey; slide representation is approximately true to scale. Reported values of mudflow lengths and widths are approximate. However correctness of size representation is not significant for the purpose of the present argument.

Because of the absence of vertical prints (see above) it is believed that this plot represents a 20 % underestimate of the slide numbers in the area. All major slides have been plotted but numerous small stream-side slides are not shown as they could not always be seen on the obliques. Slides from roadcuts which numbered 100 between Mizugu Mgeta and Kienzema and about 120 over the map area as a whole have been excluded both from the figure and from the total count as many of them were small and simply slumped onto the road, travelling only short distances. Even then Fig. 6 shows 697 slides as well as the routing of triggered debris into the drainage network. It also shows the major sedimentation zones of the area, though most of the debris supplied to the streams was transported beyond the limits of the area mapped.

The main area of sliding covers an area of approximately 20 $km^2$ (5×4 km S of the Mgeta river to the southern limit of the map and from Bumu to the edge of the Forest Reserve). Within this 20 $km^2$ area, 670 slides are shown. If this represents a 20 % underestimate of numbers (see above), the total slide numbers would be nearer to 840. From the slide model described above, the average volumetric displacement of a representative slide was 320 $m^3$. Thus 840 slides probably displaced 270,000 $m^3$ within an area of 20 $km^3$ or 13,500 $m^3/km^2$; this corresponds to a soil denudation rate of 13.5 or 14 mm in round figures over the area of maximum damage.

A comparison can now be made with data collected in the Morogoro river reported by Rapp and others above. Within that catchment of approximately 19 $km^2$, sediment transport in suspension and largely derived from sheet wash totalled 7500 tons in annual average 1966—1970. If the average density of soil and regolith is 1.5 (Table 2a), this tonnage corresponds to 5000 $m^3$. This represents a minimum value as it takes no account of bed load transport or of material deposited by wash or mass movements on the lower parts of the catchment slopes. These two amounts might double the total soil erosion loss figures for the Morogoro catchment. Thus per year the Morogoro catchment probably showed a soil loss of between 5000 $m^3$ (measured minimum) and 10,000 $m^3$ (estimated maximum), while an approximately equal catchment area near Mgeta lost approximately 270,000 $m^3$ in less than 3 hours on February 23, 1970.

This would suggest that it takes some 25—50 years of "normal" denudation to bring about the same volume of denudation as can be accomplished in such environments by one very severe storm in a matter of hours.

## Mechanism of slope failure

Two divergent explanations are commonly invoked to explain the simultaneous triggering of many debris slides on steep slopes. Conclusions of many studies have correctly attributed catastrophic landsliding to the effect of earthquake shocks. Other studies have shown that heavy rainfall can and does cause catastrophic landslide damage (Table 5) due to sudden rises in pore water pressure (Terzaghi 1950, p. 119).

The possibility that the landslides under investigation around Mgeta had been triggered by an earthquake shock was examined with the assistance of the IRSAC seismological station at Lwiro, Bukavu. The station reported that a shock of force 4.7—5.0 (Richter scale) had occurred on February 21, 1970, some 54 hours before the period of landsliding at Mgeta. No



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after-shocks had been recorded. The earthquake epicentre was located some 115 km NE of Mgeta at 6°9′ N, 38°3′ E. The distance of the epicentre from the landslide damaged area, the fact that it was located in a different structural zone, the facts that the two events were not contemporaneous and no aftershocks were recorded suggest strongly that tectonic activity was not a casual factor in the landsliding at Mgeta even though the Uluguru mountains are a strongly seismic area. Such a conclusion is supported by the meteorological, hydrological and oral evidence which provides an entirely satisfactory alternative explanation, fully compatible with the geomorphological evidence. This alternative can now be examined.

Sudden rises in pore water pressure resulting from heavy rainfall cause a reduction in *shear strength*. Shear strength here refers to the ability of debris and soil to resist sliding along internal surfaces within the mass and thus to maintain stability on a hillslope. But water movement below the soil surface creates a seepage force which acts in the direction of flow and is proportional to the hydraulic gradient. On slopes this is laterally applied as shear stress and if this stress is large, as it may be with considerable unit weights of water, large hydraulic gradients and if the area cross section of the soil is limited, then a considerable upward force is applied to soil and debris masses below ridge crest lines. The unit weights of water will of course vary with rainfall, infiltration and throughflow rates while both the hydraulic gradient and the area cross section of the soil will be in part related to slope. This shear stress is frequently unequally applied and mostly affects the friction material (regolith) in the profile: Thus *shear failure* occurs along this horizon, despite the downward stabilizing pressure of the saturated upper soil layer (cohesive material).

Geomorphological evidence from the landslides examined indicates that shear strength had been reduced below the force of the applied shearing stress and caused a shear failure. "Such a failure occurs very suddenly and the whole mass appears to flow laterally as if it were a liquid" (Spangler 1961, p. 312).

Significant geomorphological data which support this conclusion are as follows:

1. Slide scars were invariably located some distance below ridge crests suggesting that a critical hydraulic pressure was necessary to trigger shear failure. This pressure would be built up in subsurface pore spaces and pipes. The variable distance of slides below ridge crests is explainable by differences in slope geometry, throughflow rates, soil profiles and vegetation cover.
2. The common occurrence of inclined subsoil pipes, particularly at the junction between soil/colluvium and regolith or at the base of the regolith (Selby 1967 p. 13). The pipes were generally 2—10 cm wide and evidenced much subsurface flow along these junctions.
3. The occurrence of vertical holes up to 0.5 m deep and up to 20 cm wide in hollows leading into a number of the large slide scars eg. slide F2, evidencing rapid infiltration of water into the profile.

All these observations suggest that strong seepage and hydraulic pressures affected the slide scar localities.

4. Clear and general evidence of the very rapid conversion of sliding masses into a mudflow below the lower lip of the slide scar. In many cases the soil and vegetation cover below the scars had not been destroyed and fragile hoe-made terraces were ofter well preserved (Fig. 9). Thus the moving material had clearly been very liquid. In two surveyed examples (slides D2 and G1) the high water content of the mudflow was indicated by the fact that the flow had moved like a wave upslope on the opposite valley side, combing and plastering down the grass cover like a sheet flow of mud. In several cases the thickness of the moving mudflow surges could be estimated from mud plastering and vegetation debris plastered onto the upslope side of tree trunks (slide C2 and G11, cf. Figs. 8 & 11) or boulders in the mudflow track (slide F4). Thicknesses of mudflow lobes of 1.2—1.8 m were thus recorded. These data indicate a generally very high water oversaturation of the moving debris, which probably had a thin porridge-like consistency.

Eye-witness accounts provide valuable supplementary information on the mechanism of slide release. Numerous local people were interviewed who had witnessed the release of these landslides or *miporomoko*. While there were some discrepancies in the accounts provided, salient facts were corroborated by witness after witness. These can be summarised as follows:

1. All the slides were associated with a very rapid movement of material or a very sudden slope failure.
2. The moment of slide occurrence was accompanied by a considerable noise like thunder.
3. The air smelt as if quarry blasting had occurred for some time after slides moved (the local people are familiar with explosives as Mgeta is one of the most important collecting-centres for mica from tiny mines scattered all over the Mgeta area).
4. Individual slides and displacements were accompanied by a cloud of discoloured, usually brown coloured gas or dust.
5. When the slides occurred it was raining with extreme intensity.
6. Almost all the movements and slope failures occurred within a very limited period of time (1 hour). Around Mgeta the slides mostly moved around 1500 hours; around Bumu the major slide occurrence was somewhat later while at Kienzema it occurred at 1600 hours as the rain storm passed SW across the face of the mountains.

Observations 1—3 confirm the geomorphological field data and the laboratory findings that sudden shear failure had occurred. A thunderous noise would result from movement along shear planes. A smell of dust and heat would also result from friction of regolith over bedrock. Observations 4—6 are completely consistent with this conclusion. It is interesting to speculate whether the puffs of brown gas were dust, condensing steam, spray or a combination of these. Close questioning of eyewitnesses failed to clarify this. Dust could have resulted from friction if sufficient heat was generated along the shear surface to release it. Steam seems more likely as an excess of water at the shear surface was the release mechanism for the material. Spray could have been formed by the sudden release of pore water pressure at the moment of shear failure. It seems likely that all of these were involved.

Hack and Goodlett (1960, p. 45) describe the erosion scars created by outburst of subsurface water on slopes as follows: "Another common feature of the slopes produced by the 1949 flood are holes in the debris mantle averaging about 80 feet in diameter ... the term "water blowout" is used here. These features typically are semicircular in plan. The upslope side is a crescent-shaped scarp generally exposing the bedrock at its base. The downslope side is a pile of debris that has slumped or been thrown out of the cut or break. Water blowouts show no evidence of erosion or break in the ground cover either above or below. Eisenlohr believes that they form as a result of hydrostatic pressure at geologically favourable horizons where water in the ground is concentrated at one point by intersecting fractures. He noted in Pennsylvania that they occur in rows along the bedding planes", and he noted that people had seen blowouts "burst forth". "The field evidence indicates that ... the water blowouts were accompanied by the flow of a large volume of water. The transfer of debris downslope was either explosive or sufficiently fluid so that the soil mantle was not destroyed."

There seems little doubt that both the nature of the slide forms and the release mechanism involved in the Mgeta catastrophy were closely comparable to those described above. The similarity between Fig. 6 above and Hack and Goodlett's Plate 1 supports this contention.

On the basis of the evidence presented above, it is concluded that the mechanism of slide release was high pore water pressure, which suddenly reduced shearing strength below shearing resistance and resulted in most cases in water blowouts. These were the major mechanism for debris transfer downslope into, in most cases, the river channels.

## Recolonisation of slide scars

Recolonisation of slide scars by vegetation and the development of soil on their surfaces will occur at variable rates, depending upon a wide range of factors including altitude, depth of the slide scar in relation to soil and/or regolith and the availability of soil moisture and of colonising species. Studies of vegetation and soil development are currently being undertaken by Mrs. L. Lundgren. Eleven scars were selected for study at different altitudes and affecting slopes with different land use covers. Table 12 summarises the data collected so far, but the scars will be observed until a complete

Table 12. Percentage vegetation cover and soil carbon on plots in 10 slide scars of differing characteristics. Numbering and analysis after Mrs. L. Lundgren (unpublished data). Authors surveyed slide numbers in brackets. Key to land use as in Table 8.

| Slide No. | Scar length | Scar width | Angle of slide scar | Altitude | Land use | % Vegetation cover on plots | | % Total carbon in soil | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Aug. 1970 | Feb. 1971 | Aug. 1970 | Feb. 1971 |
| L1 | 20 | 20 | 40 | 1600 | f + m | 0.1 | 3.3 | 0.147 | 0.434 |
| L2 (= F1) | 90 | 30 | 39 | 1600 | f + g | 0.0 | 0.1 | 0.326 | 0.271 |
| L4 (= F4) | 29 | 10 | 36 | 1500 | f | 0.0 | 0.0 | 0.322 | 0.480 |
| L5 | ? | ? | ? | 1500 | f | 0.4 | 3.3 | 0.129 | 0.164 |
| L6 | 10 | 20 | 35–40 | 1200 | f + g | 0.1 | 5.0 | ? | 0.067 |
| L7 | 10 | 10 | 35–40 | 1200 | f + g | 0.8 | 4.6 | ? | 0.138 |
| L8 (= G1) | 30 | 15–20 | 34 | 1000 | f | 1.4 | 4.8 | 0.135 | 0.149 |
| L9 (= G2) | 22 | 10 | 37 | 1000 | f + g | <0.1 | 4.0 | ? | 0.079 |
| L10 | 20 | 10 | 40–50 | 1100 | f + g | <0.1 | 9.0 | ? | 0.143 |
| L11 | 15 | 10 | 35 | 1100 | f + g + m + c | 0.3 | 5.0 | 0.147 | 0.07 |

vegetative cover has been established over a period of years.

Surveys of the vegetation on each of the selected slides and their surroundings were made in August 1970 and February 1971. A sample plot, measuring four m$^2$ was laid out on each scar as near its centre as possible. Within this plot, every plant was recorded together with its height and diameter. The species were identified and an estimation made of the percentage cover. Slabs of top soil and vegetation which had collapsed onto the slide scar and the slide margins were carefully examined to determine the possible vegetation spread from them. Soil samples were also taken in order to analyse the development of a new soil cover, while bench marks were established on each slide in order to document changes taking place by photographic means. At the time of writing, only the initial period of recolonisation and soil re-development has been observed and is recorded in Table 12. First recordings of vegetation and soil characteristics were made 6 months after slide movement and the second recording 5 months later.

The centres of the slide scars, where excavation had been deepest were mostly being colonised by weeds derived from the surroundings ground. *Conyza floribunda* and *Pentas zanzibarica* were most common though other species were frequently recorded such as *Rubia cordifolia* and *Helichrysum kirkii*. From slide edges and slumped grass sods left on the scar surface at the time of slide release, other species, particularly readily branching grasses like *Hyparrhenia rufa,* and climbing plants like *Rubia cordifolia* and *Commelina benghalensis* colonise neighbouring areas on the slides. Table 12 gives some preliminary indications of the pace of this initial colonisation and the rate of soil change (after Mrs. L. Lundgren). These data are inconclusive at present, but local farmers believed that many of the slide scars would take only 2—3 years to recover and develop a reddish or brownish soil cover, this being an indication of a cultivable soil.

## Economic consequences

Damage resulting from the sudden heavy rainfall was severe to (a) cultivated land and growing crops and to (b) roads, bridges and culverts, causing consequent disruptions of communications. 6 people were killed, 9 houses destroyed and 20 goats killed (Table 13 and Fig. 21). Damage was also sustained by neighbouring engineering works (Temple 1972 a).

Some 1570 fields (*shambas* averaging 0.3 hectares area) or approximately 500 hectares of cultivated cropland were partially destroyed. 13.6 % of the households of the area were affected by loss of soil and crops. The storm occurred just before the harvest of the main staple crop, maize. It was estimated that in financial terms this harvest loss amounted to over Shs. 40,000. The landslides also destroyed

Table 13. Partial record of the damage caused by the storm of February 23, 1970.[1] For other damage see text.

| Village location/ area | Men killed | Households affected | Shambas destroyed | Houses destroyed | Goats lost |
|---|---|---|---|---|---|
| Gole-Mkanuzi | 0 | 138 | 314 | 1 | 2 |
| Bunduki-Kibigiri | 0 | 38 | 61 | 0 | 7 |
| Visada and Nyandira | 0 | 71 | 174 | 3 | 0 |
| Langali-Mgeta | 2 | 61 | 93 | 2 | 9 |
| Lusungi and Mwarazi[2] | 0 | 44 | 139 | 1 | 0 |
| Pinde | 0 | 54 | 401 | 1 | 1 |
| Tengero | 0 | 44 | 106 | 1 | 1 |
| Kienzema | 1 | 93 | 115 | 0 | 0 |
| Bumu | 0 | — | 168 | 0 | 0 |
| Location unrecorded | 3 | — | — | — | — |
| Total | 6 | 543 | 1571 | 9 | 20 |

[1] See Figure 21 for approximate areas of these village locations.

[2] In some versions of this report, shambas destroyed in Mwarazi are listed as 138 and in Lusungi as 139; These areas are adjacent and under the same headman and this seems like a case of double recording. The areas and figures are combined here.

and removed a significant proportion of the best and deepest soils in the area, leaving behind barren scars which will take a period of years to recover. Damage to roads prevented vehicular access to Mgeta for 6 weeks and to Kienzema for over 9 weeks. Much of this damage was caused by flood waters which destroyed bridges and embankments but a large amount was caused by the release of landslides from oversteep, man-made roadcuts. Repairs to roads (many of them very temporary) in the western Ulugurus resulting from this single storm cost Shs. 507,500. The disruption of vehicular communications over the period after the storm necessitated the transport of all gods into and out of the area as head loads. This area normally exports considerable quantities of fresh vegetables to the urban markets of Morogoro and Dar es Salaam; during March and April 1970, 40,000 kilos of vegetables, conservatively valued at Shs. 13,000 rotted for lack of transport. The reduced quantities carried out by headload cost consumers an extra Shs. 42,000 above normal prices and cost producers untold expenditure of effort. Flood waters generated by this storm damaged a water intake and the engineering works of an irrigation scheme on the mountain fringe, for which repair costs are estimated at Shs. 10,000.

An approximate addition of some of the direct costs of this single event can thus be placed at over Shs. 620,000 ($90,000). This figure is over half the total sum allocated in colonial times for a 10 year comprehensive rehabilitation scheme for the whole Ulugurus (Temple *op. cit.*).

The storm of 1970 is not an isolated event. Damage of comparable magnitude was probably experienced on March 23/24 1969 when 135 mm of rain fell during the night at Kienzema and 170 mm fell at Kikeo, 11 km to the south (Fig. 1) triggering over 200 landslides, carrying away bridges and houses and killing

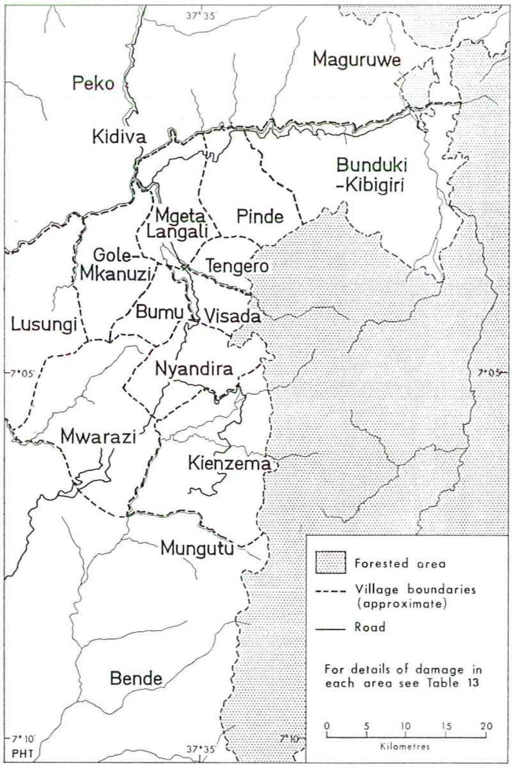


Fig. 21. Village areas (approximate). These areas correspond to the reporting of damage detailed in Table 13.

one man (W. Graat, personal communication). In 1968 a comparable event was experienced in the Matombo area in the eastern Ulugurus (Fig. 1).

## Conclusions

*Geomorphological conclusions*

The rainstorm of February 23 triggered over 1000 landslides and mudflows within a 75 km$^2$ area in 3 hours. It generated a peak runoff of 2280 lit/sec km$^2$ in the gauged section of the area and probably significantly greater runoffs in the most severely affected part of the catchment. A sample of 840 landslides displaced 270,000 m$^3$ of debris in 20 km$^2$ of the main area of damage. This corresponds to a soil denudation rate of 14 mm.

The return periods of such storms were reconstructed using standard methods. The return period of 75 mm storms (a first approximation to the critical value for severe slide damage in this area) varied over the study area from 6—18 months for Bunduki to 6—11 years at Mgeta Mission. The return periods of such storms in the western, drier part of the study catchment was averaged from two analyses as 4.8 years and as 1 year by similar means in the eastern, wetter section. These values should be treated with caution as they give little indication of rainfall intensities for periods shorter than 3—24 hours. It is probable that extreme rainfall intensities over periods of 30 minutes to 1 hour are the critical parameters for the build-up of porewater pressure and for shear failure. Furthermore, extreme short-period intensities will have a return period significantly longer than either 75 mm falls in 3 or 24 hours. Geomorphological evidence and interview data supports a considerably longer return period for storms which cause heavy landslide damage in this area.

The period of time required for the partial recovery of slide scars by soil development and vegetational recolonisation in this area may be as short as two to five years. Examination in October 1971 of slide scars produced in February 1970 lends some support to this conclusion. Thus in the western part of the study area, most storms reaching the necessary critical intensity will trigger extensive sliding. With the shorter return periods of such storms that is characteristic of the Bunduki area, many such storms will not trigger slides because of the absence of a sufficent depth of weathered material susceptible to transfer.

From the data collected and presented above it is clear that landslides and mudflows form a dominant process affecting steep slopes and first-order catchments in the western Ulugurus. They probably occur in small numbers every rainy season and in large numbers with a return period of approximately a decade in any one locality. These frequent events are thus only catastrophic in terms of economic effects and are a normal process affecting these slopes from a morphological viewpoint. The frequency of their recurrence together with the amount of work achieved by one event supports the above conclusion (Wolman & Miller 1960).

To judge from the landforms of the area, sheetslides and mudflows are the main processes involved in the widening of tributary valleys and the creation of fine textured, fluted upper slopes. Mudflow transfer of debris is responsible for the maintenance of steep angle slopes as it does not favour the accumulation of debris fans but can transfer debris on low gradients and even upslope for short distances, into stream channels in a fluid state. Bottle slides, associated with piping and showing headward recurrent slumping and episodic slow mudflow, create tributary valleys of low gradient and open basin form. Vertical cutting along main stream courses is favoured by high precipitation and favourable lithology.

Morphological activity of the types described is active under forest and woodland but is greatly accelerated after deforestation as the data show.

The present topography of this area can be understood in terms of observable processes active today and in the recent past as the close relationship between slope forms and present processes indicates.

*Conservation conclusions*

There is no feasible and economic means as yet of controlling rainfall. Slope angles may be changed by bench terracing; this was tried and proved unacceptable in the Uluguru and Usambara mountains. Furthermore it is technically unsound in such areas. The only feasible means of restricting landslide damage is by the modification of current land use practices to curtail rather than prevent damage, for the areas presently experiencing severest hazard are agriculturally valuable and often densely settled. Haldemann (*op. cit.*) concluded from his studies in Rungwe that remedial measures normally recommended from a geological viewpoint (mainly drainage) would be economically unjustifiable as the costs would be out of all proportion to the value of the land so protected. Furthermore he concluded that reforestation, which would effectively control soil erosion, was only possible to a limited extent without disrupting the agricultural economy of such areas. These conclusions appear to have a general validity for conservation measures to be acceptible must bring (a) a demonstrable advantage to individual farmers in the short-run and (b) long-term advantages to the whole community. Past measures considered only the latter point and were rightly rejected (Cliffe 1970, Temple *op. cit.*). Measures should be soundly researched before implementation, otherwise they are counterproductive in effect, actually accelerating the wastage of land resources (Temple *op. cit.*). The most feasible measures would be to (a) encourage tree planting in lines below ridge crests, along road cuts and stream sides (b) encourage a change towards perennial tree crops and away from annual cropping.

Because events of the magnitude described are not exceptional, the data presented above have a practical engineering relevance for the design of road cuts, embankments, bridges and culverts. Critical external angles in cuts and embankments should be avoided and trees used to protect steep man-made slopes. Ridge crest alignments are favourable for roads and settlements to avoid slide damage, as the local people appears to know. Bridges and culverts should be designed to accomodate the extremely flashy rises of local streams while earth embankment crossing over minor channels should be avoided where possible. Water intake and irrigation project design should allow for the excessive sediment transport associated with some of the flash floods of the area.

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*Professor P. H. Temple, Department of Geography, University of Dar es Salaam, P. O. Box 35049, Dar es Salaam, Tanzania.*
*Dr. A. Rapp, Department of Physical Geography, Box 554, University of Uppsala, S-751 22 Uppsala, Sweden.*

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## Abbreviations

BRALUP = Bureau of Resource Assessment and Land Use Planning, University of Dar es Salaam.

EAAFRO = East African Agriculture and Forestry Research Organization, Nairobi.

WD & ID = Water Development and Irrigation Division, Tanzania.

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# SHEET WASH MEASUREMENTS ON EROSION PLOTS AT MFUMBWE, EASTERN ULUGURU MOUNTAINS, TANZANIA

BY PAUL H. TEMPLE AND D. H. MURRAY-RUST

Department of Geography, University of Dar es Salaam and Department of Geology and Geography, City of London Polytechnic

ABSTRACT. Seven erosion plots with an adjacent control were established at Mfumbwe in the eastern Uluguru mountains in December 1956. The plots were designed to measure the rate of erosion by splash and sheet wash on slopes planted with hill-rice. On each of the plots a different method of soil conservation was used consistently over a period of approximately 3 1/2 years. Sheet wash was measured by reference to previously marked rods driven vertically into the ground to a fixed depth in lines down each plot. 5 sets of measurements were made, the last 4 being spaced at annual intervals. After July 1960, the experiment was abandoned and the plots allowed to revert to bush. In February 1969 and August 1970, those rods which could be relocated were remeasured.

The paper presents the data and comments on their significance.

## Introduction

The study reported below provides some quantitative data on the rate of sheet wash on hillslopes in the eastern Uluguru mountains in Tanzania. While the experimental design contained several flaws, it was considered worthwhile to report briefly on the results as they span a considerable period of time and provide quantative indications of the efficacy of (a) different agricultural conservation techniques and (b) of bush regeneration on soil stability in this locality. Furthermore they are the only available means of ascertaining the previously-held views (Savile 1945) that sheet wash is the major soil erosion mechanism in this area Temple 1972 a).

Splash and sheet wash detaches, transports and redistributes top soil downslope. It generally operates selectively carrying away first the finer mineral particles and lighter organic matter most valuable to plants. The soil is thus impoverished and thinned on the upper segments of the slope while concomitant accumulation or soil burial generally occurs on lower slope segments particularly where sheet wash does not carry material into channels. The results are that the soils on the upper slope segments show reduced infiltration and water-holding capacity. This causes a loss of water to the soil, often as severe in its effects on plant or crop growth as the actual loss of soil. If the process is rapid, or in excess of the rate of soil regeneration, reduced soil moisture storage becomes increasingly critical in dry years and soil losses increasingly severe in wet years. This may not at first adversely affect the lowermost slope segments but may do so eventually if the process is unchecked.

Accurate measurements of the rate of sheet wash on natural slopes are difficult to obtain. A comparison of measurements on undisturbed slopes with those from similar slopes under cultivation, under a single crop but employing a range of different conservation techniques should permit both an assessment of the significance of sheet wash on all plots and resultant indications of the most effective means of controlling soil loss.

The method of measurement used Mfumbwe was graduated metal rods placed vertically in the ground (Temple 1972 b).

## The Mfumbwe experimental plots

The experimental plots are located at Mfumbwe (6° 53′ S, 37° 49′ E), a small scattered settlement some 7 km N of Mkuyuni and lying W of the Morogoro—Matombo road at an elevation of 700 m. They occupy part of a former German estate made available to the Department of Agriculture under the Uluguru Land Usage Scheme (ULUS) for experimental work. The land now belongs to Mr. O. Gonza, formerly an ULUS agricultural instructor.

Mfumbwe has an average annual rainfall of 169 cm, 43 % of which falls during the main

Fig. 1. The Mfumbwe experimental site. Erosion plots and rods were located in the spur slope in the middle distance. House in the right foreground is the former German estate farm, now occupied by Mr. O. Gonza. Photo PHT: 6/70.

rains of February, March and April and 24 % during the short rains of November and December. All months, even the driest, August, receive appreciable rain (over 5 cm). The original vegetation was a semi-dry, mesophylitic, closed, semi-evergreen forest dominated by *Chlorophora excelsa, Moraceae, Afzelia quanzensis, Caesalpiniaceae* and *Albizzia* spp. (T. Pocs, personal communication.)

The plots were established for two major reasons: (a) as demonstrations to show the advantages or disadvantages of various soil conservation measures which might be practiced in the area (ULUS, 5, 1959); (b) "to devise a system of soil conservation in the shallow red soil—rice areas of the eastern Ulugurus which would be acceptable to a peasant family" (Duff 1960). The erosion plot studies formed one part of a broader programme of experimentation, involving a range of different conservation-orientated agricultural innovations set up after the failure of ULUS. Initially the experiments included assessments of crop yields and labour inputs but these records were not kept up.

The original intention was to conduct the experiment over an area of two hectares "to give a rough cross section of the type of land and soil of the area" (ULUS, 2, 1957). Later an area of 4000 $m^2$, orientated NE and varying in slope between 19 and 30° was selected (Fig. 1). This slope had been under fallow for two years previous to its clearing in December 1956 and was said to possess a "fairly good depth of soil . . . somewhat typical of surrounding rice lands and containing a fair amount of humus" (ULUS, 1, 1957). Samples taken from a mid slope position on Plot VI and can thus be described as dark red silty loams. When wet these soils are friable; they contain a variable percentage of organic matter (0.8—6.8 %) and are acid (pH 4.85—6.05).

After clearing, the slope was divided into plots 10 m wide, separated one from the other by furrows. The plots extended from a variable distance below the uncleared ridge top down-

Table 1. Erosion plot data, Mfumbwe. n.a. = not available; C = control plot in neighbouring bush.

| Plot or strip number | Strip area m² | Average slope in degrees | No. of rods | Original conservation method | Identification method 1969—1971 |
|---|---|---|---|---|---|
| I | 979 | 19 | 4 | 54 cored ridges (*matuta ya kiamwezi*) | broad terraces |
| II | 1008 | 23 | 5 | 9 live barrier hedges, 2 m apart of *Lucina glauca* and *Vetiveria zizanioides* | live barriers in place |
| III | 1250 | 23.5 | 4 | Strip cropping with 3 strips of cow peas, later replaced by bananas | bananas growing |
| IV | 1052 | 25 | 5 | Strip cropping with 5 strips of pumpkins, later replaced by cow peas. | verbal information only |
| V | 1052 | 25 | 4 | None: trash burnt (*sesa*) | verbal information only |
| VI | 1420 | 28 | 5 | 16 trash barriers at 6—7 m intervals strengthened by stakes | ridges visible |
| VII | 1008 | 30 | 5 | 73 closely-spaced ladder terraces (*matuta ya ngazi*) | ridges visible |
| C | n.a. | n.a. | 3 | None: bush left uncleared | not found |

slope to a flat, streamless valley bottom. Metal rods (angle irons c. 90 cm long, 3 cm wide and graduated in inches) were sunk to half their length in lines down the centre of each plot. The spacing of the rods was not exactly uniform and not all distances were recorded. Between 3 and 5 rods were emplaced in each plot, greater numbers being fixed in the longer plots. Rice was planted on all plots except the control plot, which had been left under bush, in January 1957, but on each plot a different conservation method was applied. Details of the strip areas, average slopes, original conservation methods and number of rods emplaced are given in Table 1.

## Measurements from Mfumbwe erosion plots

Measurements on the rods began in March 1957 and were continued at annual intervals from July 1957 to July 1960. The results of these measurements are presented in Table 2 (ULUS, 6, 1960). The plots were then abandoned and reverted over a period of 9 years to dense secondary bush cover some 4—5 m high. The plots were relocated by A. Rapp, J. R. Watson and D. H. Murray-Rust, with the assistance of Mr. Omari Gonza in November 1968 and the lines of rods were partially

Fig. 2. Measuring surface level changes against fixed rods in June 1970. Rods installed in December 1956. Note dense secondary bush and the litter cover. Photo PHT: 6/70.

cleared to provide access. In February 1969, those rods which could be located were measured by Murray-Rust and Watson. A further set of measurements was made in August 1970 by the authors together (Fig. 2). Table 3 presents these results.

## Discussion

Before considering the significance of the data presented in Tables 2 and 3, it is important to comment on the overall design and organization of the experiments. Several defects should be noted: (a) the site chosen was small, and its representativeness is open to question; (b) the plots varied both in slope (between 19 and 30°) and length (at least between 47 and 60 m), the steeper slopes being also the longest (cf. Zingg 1940); (c) no detailed slope profiles were surveyed along each line of pegs to establish the initial form or full length of the slope; (d) the measuring rods were not accurately positioned at uniform distances or painted or numbered so that the re-identification of rods after 9—10 years of bush regeneration was difficult. Much reliance had thus to be placed on identification of plots and rods by Mr. Gonza, the person in local charge of the experiments when cultivation was in progress. Mr. Gonza's iden-

Table 2. Measurements on fixed rods at Mfumbwe, December 1956—July 1960 during the period of active experimentation and plot cultivation. C = control plot in neighbouring bush. Rods numbered from plot base upward. Change is marked + for accumulation, — for erosion.

| Plot & rod numbers | | Readings on rods in cm. | | | | | | Absolute change over 44 months, mm | Rod spacing in m. | Rate of change mm/yr. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dec. 1956 | Mar. 1957 | 31.7.57 | 31.7.58 | 31.7.59 | 31.7.60 | | | |
| I | 1 | 45.7 | 45.7 | 45.7 | 45.7 | 47.0 | 38.1 | + 76 | ? | +21 |
| | 2 | 45.7 | 45.7 | 43.2 | 40.6 | 36.8 | 38.1 | + 76 | ? | +21 |
| | 3 | 45.7 | 45.7 | 47.0 | 50.8 | 53.2 | 58.4 | −127 | ? | −35 |
| | 4 | 45.7 | 45.7 | 44.5 | 36.8 | 39.4 | 40.0 | + 57 | ? | +16 |
| II | 1 | 45.7 | 40.6 | 36.8 | 31.8 | 25.4 | 22.9 | +228 | 0 | +62 |
| | 2 | 45.7 | 43.2 | 41.9 | 30.5 | 30.5 | 25.4 | +203 | 2.9 | +55 |
| | 3 | 45.7 | 45.7 | 47.0 | 47.0 | 50.8 | 53.3 | − 76 | 11.8 | −21 |
| | 4 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 50.8 | − 51 | 33.5 | −14 |
| | 5 | 45.7 | 45.7 | 43.2 | 33.0 | 27.9 | 22.2 | +235 | ? | +64 |
| III | 1 | 45.7 | 41.9 | 40.6 | 40.6 | 38.1 | 34.3 | +114 | 0 | +31 |
| | 2 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 43.2 | + 25 | ? | + 7 |
| | 3 | 45.7 | 45.7 | 44.5 | 44.5 | 44.5 | 48.3 | − 26 | 39.7 | − 7 |
| | 4 | 45.7 | 45.7 | 44.5 | 45.7 | 44.5 | 45.7 | 0 | 51.2 | 0 |
| IV | 1 | 45.7 | 45.7 | 45.7 | 33.0 | 20.3 | 15.2 | +305 | 0 | +83 |
| | 2 | 45.7 | 45.7 | 45.7 | 43.2 | 43.2 | 48.3 | − 26 | 6.6 | − 7 |
| | 3 | 45.7 | 45.7 | 43.2 | 45.7 | 48.3 | 48.3 | − 26 | 13.1 | − 7 |
| | 4 | 45.7 | 45.7 | 45.7 | 43.2 | 43.2 | 48.3 | − 26 | 26.2 | − 7 |
| | 5 | 45.7 | 45.7 | 43.2 | 45.7 | 45.7 | 48.3 | − 26 | ? | − 7 |
| V | 1 | 45.7 | 45.7 | 45.7 | 50.8 | 38.1 | 35.6 | +101 | 0 | +28 |
| | 2 | 45.7 | 45.7 | 47.0 | 48.3 | 53.3 | 55.9 | −102 | 15.8 | −28 |
| | 3 | 45.7 | 45.7 | 47.0 | 48.3 | 50.8 | 50.8 | −101 | 20.0 | −28 |
| | 4 | 45.7 | 45.7 | 45.7 | 49.5 | 53.3 | 55.9 | −102 | 47.2 | −28 |
| VI | 1 | 45.7 | 41.9 | 39.4 | 41.9 | 41.9 | 36.8 | + 89 | 0 | +24 |
| | 2 | 45.7 | 45.7 | 45.7 | 44.5 | 38.1 | 35.6 | +101 | 7.9 | +28 |
| | 3 | 45.7 | 45.7 | 45.7 | 44.5 | 45.7 | 45.7 | 0 | 26.9 | 0 |
| | 4 | 45.7 | 43.2 | 43.2 | 43.2 | 43.2 | 43.2 | + 25 | 36.4 | + 7 |
| | 5 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 0 | 59.7 | 0 |
| VII | 1 | 45.7 | 45.7 | 43.2 | 40.6 | 33.0 | 35.6 | +101 | 0 | +28 |
| | 2 | 45.7 | 45.7 | 43.2 | 41.9 | 43.2 | 38.1 | + 76 | ? | +21 |
| | 3 | 45.7 | 45.7 | 45.7 | 43.2 | 40.6 | 47.0 | − 13 | 25.6 | − 3 |
| | 4 | 45.7 | 45.7 | 45.7 | 41.9 | 40.6 | 39.4 | + 63 | 39.4 | +17 |
| | 5 | 45.7 | 45.7 | 44.5 | 38.1 | 38.1 | 41.9 | + 38 | ? | +10 |
| C | 1 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 48.3 | − 26 | ? | − 7 |
| | 2 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 0 | ? | 0 |
| | 3 | 45.7 | 45.7 | 45.7 | 45.7 | 45.7 | 47.0 | − 13 | ? | − 3 |

Table 3. Measurements on fixed rods at Mfumbwe, July 1960 – August 1970 spanning the period of vegetation regeneration to 4–5 m bush cover. M = missed or missing; f = rod fallen out; *change over 103 months only.

| Plot & rod numbers | | Readings on rods in cm. | | | Absolute change over 121 months mm | Rate of change mm/yr |
|---|---|---|---|---|---|---|
| | | 31.7.60 | 2.69 | 24.8.70 | | |
| II | 1 | 22.9 | 25.4 | 26.7 | − 38 | − 4 |
| | 2 | 25.4 | 33.0 | 31.8 | − 64 | − 6 |
| | 3 | 53.3 | 55.9 | 55.9 | − 26 | − 3 |
| | 4 | 50.8 | 52.7 | 53.3 | − 25 | − 3 |
| | 5 | 22.2 | M | M | ? | ? |
| III | 1 | 34.3 | 29.2 | 33.0 | + 13 | + 1 |
| | 2 | 43.2 | M | 43.2 | 0 | 0 |
| | 3 | 48.3 | 51.4 | M | − 31* | − 4 |
| | 4 | 45.7 | 77.5 | M | −318* | −37 |
| IV | 1 | 15.2 | 8.3 | 7.6 | + 76 | + 8 |
| | 2 | 48.3 | 44.5 | 51.4 | − 31 | − 3 |
| | 3 | 48.3 | 52.1 | M | − 38* | − 5 |
| | 4 | 48.3 | 49.5 | M | − 12* | − 1 |
| | 5 | 48.3 | M | M | ? | ? |
| V | 1 | 35.6 | 14.0 | M | +216* | +25 |
| | 2 | 55.9 | f | f | ? | ? |
| | 3 | 50.8 | 55.9 | M | − 51* | − 6 |
| | 4 | 55.9 | 70.5 | M | −146* | −17 |
| VI | 1 | 36.8 | 33.0 | 33.0 | + 38 | + 4 |
| | 2 | 35.6 | 38.7 | 38.1 | − 25 | − 3 |
| | 3 | 45.7 | 49.5 | 50.2 | − 45 | − 5 |
| | 4 | 43.2 | 45.7 | 45.1 | − 19 | − 2 |
| | 5 | 45.7 | 46.4 | 47.0 | − 13 | − 1 |
| VII | 1 | 35.6 | 26.1 | 24.1 | +115 | +12 |
| | 2 | 38.1 | M | M | ? | ? |
| | 3 | 47.0 | 51.4 | 55.9 | − 89 | − 9 |
| | 4 | 39.4 | 46.4 | 45.7 | − 63 | − 6 |
| | 5 | 41.9 | M | 41.9 | 0 | 0 |

tifications were cross-checked against field evidence (Table 1) and file descriptions and appeared to be accurate. Some residual uncertainties must remain, however, due to the washing out or burial of rods and their irregular and sometimes unrecorded original spacing. The rods themselves tended to obstruct soil movement; (e) the measurements taken on the rods during the progress of the trials were approximate as no standardised method appears to have been adopted (Schumm 1967). It is impossible to ascertain whether they were taken on the upslope, downslope or side of the rods or whether they relate to general ground level established by template (the correct method); (f) the process of cultivation and particularly the construction of cored ridges artificially displaced the soil around the rods and, for a number of the plots, rendered the collected measurements meaningless; (g) an element of bias was (? intentionally) introduced into the experiment through the employment of the conservation techniques traditionally used by the Luguru themselves (Sesa, trash barriers and ladder terraces: Temple 1972) on the steepest (all over 25°) and longest plots, presumably in the hope that they would show most soil loss and compare unfavourably with 'improved' and imported measures; (h) lack of expert supervision during cultivation and conservation practices; in some years, some plots were planted weeks before others and disturbance of soil against measuring rods was not checked during cultivation (ULUS, 4, 1958); (i) seed for some plots was differently treated than seed on others (? another attempt to prejudice the results).

For these reasons, only a selection of the data presented in Table 2 and 3 is considered worthy of discussion.

## Sheet wash during cultivation of hill rice

Cultivation of all plots but the control occurred between December 1956 and July 1960 (44 months), rice being planted annually in early January. All rods were in place and regularly measured (Table 2); the conservation measures adopted for each plot are indicated in Table 1.

Data from plot I is here ignored as the results are of no significance due to the excessive artificial disturbance of the soil around the rods resulting from the annual construction of cored ridges (ULUS, 4, 1958). Data from plot VII, where step or ladder terracing (*matuta ya ngazi*) was employed is also suspect due to artificial soil displacement. "When cultivating, vegetation and crop residues are spread on the top of the terraces and covered with soil cut from the face of the terrace above. This is also done when weeding and so there is a slow mechanical movement of soil downwards. But these terraces give better yields as little subsoil is dug out and organic matter is incorporated regularly" (Grant 1956). Furthermore soils cultivated in this way acquired an open and free-draining structure. "Only rarely does a terrace system of this nature break down under heavy rain and cause gully formation" (Page-Jones & Soper 1955, p. 4). The preponderance of accumulation of soil on this plot, besides indicating that soil was being washed onto the plot from above, indicates the efficacy of these small, easily-made hoe terraces in retarding water and soil loss through sheet wash in wet years. The closely-spaced terracettes also conserve water in dry seasons, due to their form and humus content (ULUS, 5, 1959). The latter results from the regular incorporation of organic matter in the process of terrace construction (Temple 1972 a).

Data from plots II through VI and from the control are more valuable as indications of the rate of sheet wash. All cultivated plots showed heavy accumulation at the base of the slope over the cultivation period, varying between 24 and 83 mm/year : most plots, except III and VI showed a loss of soil from the upper part of the plot, the major loss (28 mm/year) in this slope section being experienced on the plot (V) where no conservation measures had been practiced. Most of the middle sections of the plots showed a loss. The one major discrepancy is the gain of soil at the top of plot II which must have derived from material transported from upslope. The control plot, in uncleared bush, showed remarkable stability over a 3 year period from the start of the experiment.

## Sheet wash under regenerating bush

After July 1960, cultivation of the plots was abandoned, and the experimental plots gradually reverted over a 9—10 year period to a bush cover, composed of a dense tangle of saplings and stinging creepers, almost impossible to penetrate except along cut lines. This secondary bush is mostly evergreen and represents a successional stage in the reversion to forest. Species of the original forest, itself well-represented in patches with a few hundred metres of the plots (see above), are intersperced with *Leucaena glauca* and *Mimosaceae* (T. Pocs, personal communication). No cultivation took place on any of the plots during this period (Mr. O. Gonza, personal communication). In February 1969 and August 1970, those rods not washed away or buried that could be found were remeasured (Table 3).

Unfortunately the control plot rods could not be relocated. All the rods in plot I had become displaced; thus no data was obtained from either plot. Under a regenerating bush cover, all the plots except plot II showed an accumulation of soil at the slope base ranging between 1 and 25 mm/year i.e. a much slower rate of accumulation than during cultivation.

All showed soil removal from the upper parts of the slope ranging between 1 and 17 mm/year, again a much lower rate of loss than during cultivation. The plot showing maximum instability during regeneration was plot V though even here the rate of loss was only 60 % of what it had been during cultivation.

It is clear from the data that bush regeneration induced greater soil stability. This protective influence would almost certainly be progressive, low at first before the open slopes were effectively colonized by weeds and woody plants but increasing as a full cover, with associated litter and root binding developed. Bush regeneration probably also affects soil structure by improving infiltration and humus content, thus improving water-holding capacity and both directly and indirectly reducing splash and wash effects.

But the measurements indicate that sheet wash is still continuing under the bush cover; under this cover there is little herbaceous or grass ground cover due to the smothering effect of dense saplings. Leaf litter covered only approximately 50 % of the soil surface and the rest was bare. Physical indications of sheet wash were seen in the piling up of soil upslope of roots and under-cutting downslope together with root exposure on the slopes (Ruxton 1967). Wash patterns could also be discerned from close examination of the bare soil areas and litter patterns.

It remains to discuss the severity of sheet erosion. There is no data on the rate of soil formation in this area. In the drier western Ulugurus around Mgeta, soil development appears to be rapid (Temple and Rapp 1972) but the parent material there is readily weathered. The parent material around Mfumbwe is a more resistant hornblende pyroxene granulite. With slower weathering and higher average rainfall, sheet wash appears to be a greater erosional hazard than in the west. The measurements give some indication of this.

Of the conservation methods tested during the cultivation of the plots, trash barriers and ladder or step terraces appeared to show the best results. Both are methods employed by the local people in other parts of the Ulugurus. Plot V, on which trash was burnt and no protective measures taken, the local method of cultivation in the eastern Ulugurus, showed maximum instability both over the total cultivation period and during regeneration. But it gave the best yields of rice and the minimum loss of soil in the *first* year of cultivation (ULUS, 3, 1957). The combination of destroying organic residue and absence of any physical protection clearly represents a most destructive and wasteful way to use land over a period in excess of one year. It is surprising to note however that this plot remained very stable over a period of two years, presumably reflecting the beneficial effect on soil structure of two previous years under fallow. To judge from this information, if plots are to be cultivated in this manner, they should not be cropped for more than 1—2 years.

## Conclusions

The Mfumbwe erosion plot data are deficient in many respects. They are however the only quantitative data on erosion plots in the Ulugurus from which the severity of sheet wash and the efficacy of various counter measures can be judged. They indicate that the normal cultivation practices of this area are destructive of the soil (i.e. *sesa* or cultivation on the original slope without protective measures after the burning of trash). They also indicate that conservation measures used elsewhere in the Ulugurus (eg. trash bunds as on the northern slopes or ladder terraces as in the west) would offer considerable protection to the soil on such slopes under cultivation. As might be anticipated the most effective defence against sheet wash would be to allow woodland regeneration. This measure is probably impractible on a large scale even on steep slopes as it would remove too much land from cultivation, thus disrupting the economy of the area.

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*Professor P. H. Temple, Dept. of Geography, University of Dar es Salaam, P.O. Box 35049, Dar es Salaam, Tanzania. Mr. D. H. Murray-Rust, Dept. of Geology and Geography, City of London Polytechnic, 680 Commercial Road, London.*

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# MEASUREMENTS OF RUNOFF AND SOIL EROSION AT AN EROSION PLOT SCALE WITH PARTICULAR REFERENCE TO TANZANIA

BY PAUL H. TEMPLE

Department of Geography, University of Dar es Salaam

ABSTRACT. The principal results of a series of experiments designed to measure runoff and soil losses at an erosion plot scale in tropical and sub-tropical African environments are tabulated and discussed. Most of these results are not widely known, even in Tanzania.

Methodology as well as data are commented upon. Erosion plot data are particularly significant as a guide to local land use practice at the farm plot or field scale and as indicators of the magnitude and processes involved in runoff and soil erosion. The problems of extrapolating the results to larger scales and different areas are discussed.

In zones such as semi-arid central Tanzania where soil moisture availability is the chief limitng factor on crop yields and where soils are readily eroded under careless cultivation or through overgrazing, quantitative data on runoff and soil erosion are of particular value. In zones like the mountain footslopes of Kilimanjaro and Meru, where rainfall is higher, moisture deficiency is still a problem at the end of the dry season and soil erosion can be serious when steep land is cleared for cultivation.

## Introduction

The basic data discussed in this paper are drawn from reports of agricultural and veterinary research stations in Tanzania and neighbouring areas. These data were generally obscurely published and many of the results are now lost. The available data merit wider circulation and further analysis as they provide quantitative information of considerable scientific interest on the magnitude and process of soil erosion and water losses by runoff at the small farm plot (*shamba*) or field scale. The results are thus also of practical value to local farmers. This review of data collected from erosion plots is aimed at complementing data collected at different scales (eg. small catchments and large river basins) reported elsewhere in this volume.

Measurements on the erosion plot scale aim to provide quantitative data on water and soil loss from hillslope segments under differing but carefully monitored conditions. Erosion plot data have been widely employed as a means of determining the relative merits of:

a) different crop covers,
b) different conservation measures under the same crop

They have also been employed as a means of comparing such losses from otherwise uniform plots when one parameter (eg. slope, soil etc) is varied. Erosion plot data have provided very significant practical information on cultivation and conservation methods as well as on slope and soil evaluation.

The design and scale of such plots renders them most suitable for studies of raindrop impact and sheet wash effects on limited slope segments. They are unsuited to the measurement of other erosional processes eg. gullying or soil creep for which other techniques are used (cf. Seginer 1966; Young 1972).

Furthermore considerable caution must be exercised in the extrapolation of results obtained from such studies to different localities or to different scales. Processes operating on limited slope segments are not the same either in nature or magnitude to those operating over whole slopes or in river basins. (Carson & Kirkby 1972).

In order to facilitate comparison with other results set out in this volume, all original data were transformed into metric equivalents. Conversion of tons to $m^3$ was made by division by 1.5. Presentation of data on soil loss in $m^3$/ha should not be assumed to apply uniformly to larger areas: the scale of the plots where the data were obtained should be noted. Thus quantities tabulated have a greater relative than absolute value, as is reflected by comments on them below.

## Methodology

Accurate measurements of runoff and soil loss through splash effects and sheetwash on natural hill slopes are difficult to obtain and frequently difficult to interpret because of the complex controls operating. In order to isolate particular controls for detailed examination, erosion plots have been set up to monitor both processes and rates of water and soil loss during different types or runoff. Water and soil are most commonly collected in tanks, or pans: this sediment and water loss can then be measured and results obtained for both parameters and related to the size of the plot. The detailed techniques of such experiments are described by Gerlach (1967), Leopold and Emmett (1967) and Schick (1967). Data obtained by comparable methods are available for a number of localities in Tanzania.

Other methods have been employed in an attempt to obtain a more comprehensive picture of changes over whole slopes. Slopes may be periodically resurveyed between fixed points and the resultant profiles compared (Menne 1959, King & Hadley 1967). To be meaningful, surveys must be done with very considerable accuracy. In addition, changes of ground surface level caused by erosion and deposition can be measured at points identified by fixed and graduated rods placed vertically in the ground (Evans 1967, Schumm 1967). This method is the easiest of the three to operate but measurements may often be difficult to interpret even if they are carefully made and the rod placing well-designed.

## Some results obtained from plot measurements of runoff and soil erosion

*Rhodesia*

Experiments designed to measure runoff and erosion, the mechanics of erosion and methods for its prevention in Rhodesia are of relevance to proper land use practices in the drier parts of Tanzania. The design, instrumentation and operation of these experiments are described by Hudson (1957a), and some of the principal results are set out by Hudson (1957b & 1959) and Hudson and Jackson (1959). Besides presenting unexpected data on the relation between maize yield and soil loss in terms of maize yield per unit soil loss, Hudson and Jackson present data on soil loss in relation to slope (Table 1). These data document a clear relationship between slope angle and soil loss even over low gradients; a plot of 3.5° lost more than double the soil lost from a plot of 1.5°. The authors comment "that the effects of many factors controlling erosion are, in comparison with American results (eg. Zingg, 1940), exaggerated by the greater erosivity of tropical rainfall".

Table 1. Soil erosion from three clay soil plots with different slopes under identical treatment (continuous maize); soil loss in $m^3$/ha (modified after Hudson & Jackson 1959).

| Season | Slope in degrees | | |
|---|---|---|---|
| | 3.5 | 2.5 | 1.5 |
| 1953/54 | 6.6 | 4.1 | 4.6 |
| 1954/55 | 2.8 | 1.0 | 1.8 |
| 1955/56 | 6.9 | 2.5 | 1.7 |
| 1956/57 | 11.0 | 7.1 | 3.6 |
| 1957/58 | 1.2 | 0.5 | 3.3 |
| 1958/59 | 11.5 | 6.9 | 3.5 |
| Average | 6.7 | 3.7 | 3.1 |

Data on processes are also presented, concerning the relative importance of raindrop splash and surface flow in a sub-tropical savanna environment (100 cm average annual rainfall). Two identical plots were kept free of weeds so that there should be no impedance of surface flow: over one plot a fine wire gauze was suspended which broke the force of the raindrops and allowed rain to fall through as fine spray: the other plot was left without such a cover. The results are presented in Table 2: the uncovered plot lost over 100 times more soil than the gauze-covered plot over a period of 6 years. Hudson and Jackson comment that "in conditions of subtropical thunderstorms with high intensities and large drop sizes very severe erosion occurs when there is no protective cover, and this can be completely controlled by complete cover". A further interesting result was that on a comparable plot with a dense grass sward, giving both full cover *and* impedance to surface flow, soil loss was not significantly less than that from the gauzed plot. They therefore concluded that "the well known ability of grass to reduce erosion is thus almost entirely due to its cover effect, since no (significant) additional benefit is obtained from the surface impedance effect . . . erosion should be influenced more by cover

Table 2. Soil erosion from two plots, one bare, one with a gauze cover; soil loss in $m^3/ha$ (modified after Hudson & Jackson 1959).

| Season | Bare | Gauzed |
|---|---|---|
| 1953/54 | 101.3 | 0.0 |
| 1954/55 | 372.0 | 1.5 |
| 1955/56 | 99.7 | 3.3 |
| 1956/57 | 90.6 | 0.2 |
| 1957/58 | 36.4 | 0.2 |
| 1958/59 | 147.8 | 1.8 |
| Average | 141.3 | 1.2 |

than soil factors, eg. slope and infiltration rate, which (thus only) affect quantity and rate of runoff" (Ibid, p. 580). The authors present other data substantiating this view, particularly significant being the data presented in Table 3, which tabulates soil loss and runoff from various crops, arranged horizontally in order of increasing cover and vertically in terms of land class. The table indicates that there is a decrease in soil loss and runoff on each soil type as cover increases and also that, over progressively poorer land classes, soil loss and runoff increase, except over the coarser sandy soils with high infiltration capacities, when runoff is reduced compared to that from finer sands. Even over coarse sands, runoff is inversely related to cover and soil loss is greater than from finer sands.

*Uganda*

Experimental data are available from Uganda (Namulonge, 0°30′N, 32°37′E: 1300 m a.s.l.) on the high intensities of tropical rainstorms. The significance of rainfall intensity in determining runoff and the amount of soil lost by erosion was recognised and measured (Hutchinson, Manning, & Farbrother 1958) using special instrumentation over a period of 6 years.

The data demonstrate important characteristic relationships between intensity, duration and amount of rainfall in tropical storms. It was not however found possible to predict peak rate from amount for any specific storm due to the great variations. The collected data demonstrate a straight line log relationship between log duration and intensity for individual storms and between log amount and rate.

Small erosion plots of circular shape, smooth surface and low slope (1°) and $3m^2$ area were given different treatments (Table 4) and runoff and percolation rates recorded. The authors argue that while "it is usual in studies of the effects of cropping practices and soil treatments to measure susceptibility to erosion in terms of runoff . . . in view of the dependence of runoff on rainfall intensity, the use of percolation rate is to be preferred as an index of a surface treatment" (Ibid, p. 258). Percolation rates showed greater consistency than runoff variations and may thus be a better and more significant index of moisture conservation (though not necessarily of the susceptibility of the soil to erosion).

Furthermore such rates are not a function of plot scale as is runoff.

Table 4 indicates that at Namulonge, ten times more runoff occurred from bare plots than from grass-covered plots, and that a grass-mulch cover was twice as effective as a stone mulch in terms of runoff control. Infiltration of water into the soil was most rapid under grass cover being three times as rapid as on a bare plot thus showing that a grass cover

Table 3. Runoff and soil erosion from various crops, soils and slopes; runoff (a) as percentage of seasonal total; soil loss (b) in $m^3/ha$ (modified after Hudson & Jackson, 1959).

| Land class and soil type | Late planted green manure crop | | Maize (ordinary) | | Maize (good) | | Grass row cropped | | Grass uniform cover | |
|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | a | b | a | b | a | b | a | b |
| Class II Clay | 10 | 2.3 | 6 | 1.8 | 4 | 1.2 | 1 | 0.3 | — | — |
| Class III Clay: 1.5° | 19 | 4.6 | 19 | 2.6 | — | — | 1 | 0.3 | — | — |
| Class III Clay: 2.5° | 19 | 6.8 | 20 | 3.6 | 3 | 1.3 | 2 | 0.7 | — | — |
| Class III Clay: 3.5° | 21 | 17.5 | 23 | 6.8 | 7 | 2.0 | 3 | 0.8 | 3 | 0 |
| Class III Sand | — | — | 23 | 8.2 | 17 | 6.1 | — | — | 6 | 0.5 |
| Class IV Sand | — | — | 15 | 21.9 | 12 | 10.6 | — | — | 3 | 1.0 |

Table 4: Runoff in mm (a) and overall percolation rates in mm/hour (c) for small plots under various treatments at Namulonge (modified after Hutchinson, Manning & Farbrother 1958).

| Year | Rain mm (1) | Rain-storms > 6 mm | Bare soil | | Stone mulch | | Grass mulch | | Grass (Cynodon) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | a | c | a | c | a | c | a | c |
| 1951 | 1840 | 1148 | 666 | 23 | 158 | 53 | 94 | 64 | 165[1] | 53[1] |
| 1952 | 1180 | 633 | 264 | 33 | 51 | 58 | 41 | 66 | 20 | 76 |
| 1953 | 1220 | 805 | 493 | 18 | 201 | 43 | 61 | 79 | 69 | 74 |
| Average | 1410 | 862 | 474 | 25 | 137 | 51 | 65 | 70 | 45[2] | 75[2] |

[1] Before full turf cover established:
[2] Average of two years.
(1) annual rainfall totals after E.A. Met. Dept., 1966.

not only retains water at the surface but also allows it to penetrate more rapidly into the soil than all the other treatments considered. A grass mulch was however almost as effective in encouraging infiltration and percolation.

*Tanzania*

A considerable volume of valuable data exists for certain sites in Tanzania, data which have not been previously assembled or properly discussed. A full analysis of the early Mpwapwa data was never published (Staples 1939). Data exist in various detail for the following sites:

(a) Mpwapwa; (b) Lyamungu; (c) Tengeru; (d) Shingyanga; (e) Mfumbwe (Temple & Murray-Rust 1972).

(a) *Mpwapwa* (6°20′S, 36°30′E: c. 1128 m a.s.l.)

Experiments designed to obtain quantitative data on runoff and erosion in a semi-arid area of Tanzania were initiated at Mpwapwa in 1933 (Staples 1934).

Comparative data for erosion plots differing with regard to plant cover and cultivation treatment were obtained under controlled conditions for at least 7 years (up to at least 1939): unfortunately only 2 years results are now available. Data collection from the erosion plots was resumed in 1946 under different treatments and a further 8 years results published in summary form (van Rensburg 1955).

Six plots were established on a uniform pediment or fan slope of 3.5° at the foot of the Kiboriani mountains. The slope was underlain by a coarse, red sandy, friable loam (clay percentage 33, silica—sesquioxide ratio 1 : 92). The soil dried to at least 2 m by the end of the dry season and had a highly porous structure but showed no cracking or fissuring (Milne 1932). Staples observed that this soil appeared to be the least erodible of the three principal soil types of the area. Two further plots under deciduous thicket cover on the same site but having a slope of 4.5° were added in February 1935. Plots 1 to 5 measured 27.7 m downslope by 1.8 m wide (area 50 m²). Plot 6 had the same width as the others but only half their length. Plots 7 and 8 had the same length as plots 1—5 but had double the width of all other plots.

The plots were enclosed by low walls and runoff and soil collected in tanks built flush with the soil surface at the bottom of each plot. Runoff was measured after each storm by reference to the water level in the covered tanks and soil loss by weighing dry collected sediment after each rainy season.

Plot treatments were as follows:

Plot 1: Bare: no cultivation: all weeds carefully removed until 1938 when the plot was allowed to regenerate naturally to thicket in order to assess the speed of this process.

Plot 2: Bare: flat cultivation to between 7—15 cm depth: no cropping: kept weed free until 1938, then allowed to regenerate like plot 1.

Plot 3: Bulrush millet (*Pennisetum typhoides*): ridge cultivated down slope after initial flat cultivation; weeded.

Plot 4: Sorghum (*Sorghum vulgare*): after initial experimentation, ridge cultivated downslope until 1938: then flat cultivated.

Plot 5: Grass (*Cenchrus ciliaris*) after flat cultivation, grass seeded giving 50 % surface cover at 8 cm above surface by year two: cut subsequently for hay and burnt at the end of each dry season: the grass has an erect and tufted habit of growth and grows up to 1 m high.

Plot 6: Treatment identical to plot 2 but the plot was half the length of the rest.

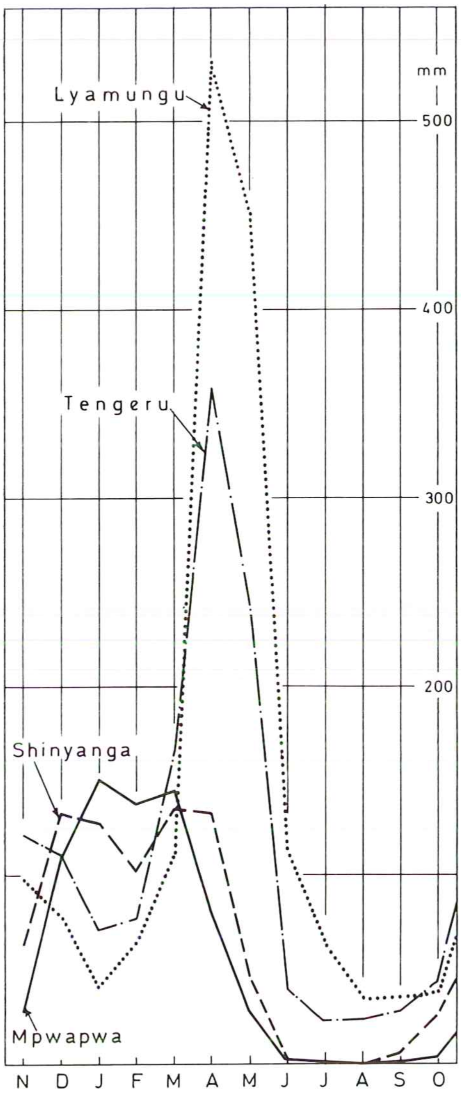


Figure 1. Mean monthly rainfalls at Mpwapwa, Lyamungu, Tengeru and Shinyanga (1931—60) (after E. Afr.Met.Dept., 1966).

Plot 7: Deciduous thicket: a closed formation of well-developed secondary growth: under African cultivation some 30 years before: dominant tree species *Grewia platyclada, Commiphora pilosa, Commiphora* sp. nr. *lindensis* with a few specimens of *Acacia tortilis* ssp. *spirocarpa, A. senegal, Albizzia petersiana* and *Hippocratea buchananii:* trees from 6 to 7.5 m high, below which a dense shrubby stratum up to 3 m high of *Grewia bicolor, Vitex* sp., *Allophylus rubifolius* and *Gnidia* sp. (= *Lasiosiphon emini*). Plots 7 and 8 were twice the width of previous plots to obtain a representative area of vegetation: no grazing: added to the experiment in January 1935 as was Plot 8.

Plot 8: Deciduous thicket as above but browsed by goats.

Slight inconsistencies should be noted between the various reports on the treatment of some plots at particular times. These treatments were designed to simulate the major land use variations of the area. Plot 1 was designed to resemble the bare slopes and hard compacted soil common in the more densely populated areas of central Tanzania. Plot 2 represented a variant of the above with surface compaction broken by cultivation. Plots 3 and 4 were cropped in rough accordance with local Gogo practice. Plot 5 was designed to test grass cover effects in a region where stock are of great importance. Plots 7 and 8 were representative of the vegetation covering large areas of dry central Tanzania (Staples 1935).

Mpwapwa has an average annual rainfall of 690 mm, 91 % of which falls on average over 65 days in the period December through April (Fig. 1). Rainfalls are very erratic even during this period: downpours of over 75 mm in an hour have been recorded.

During the 1933/34 rains 31 storms generated runoff, the smallest totalling 3 mm, the largest 72 mm (Fig. 2). During the 1934/35 rains, 28 storms generated runoff, the smallest totalling 1 mm, the largest 57 mm (Fig. 2).

Data from plot 1 (bare ground) are presented in Fig. 2. This demonstrates a clear relationship between rainstorm amount and runoff, particularly significant being the very rapid multiplication of runoff amounts in association with the larger storms. The majority of these are convectional, presumably showing a very strong correlation between storm amount and rainfall intensity (Hutchinson & others, see above).

The scatter of points may be explained partly by differences in rainfall intensity and partly by soil water conditions. For example, comparing storms A1 and A31, the first and last runoff generating rains of the 1933/34 season, the last storm generated nearly 8 times more runoff from the plots than did the first storm though it was only 5 % heavier. This indicates that soil moisture storage was inhibiting infiltration at the end of the rains and favouring greater runoff, precipitation being normally just sufficient during the rains to

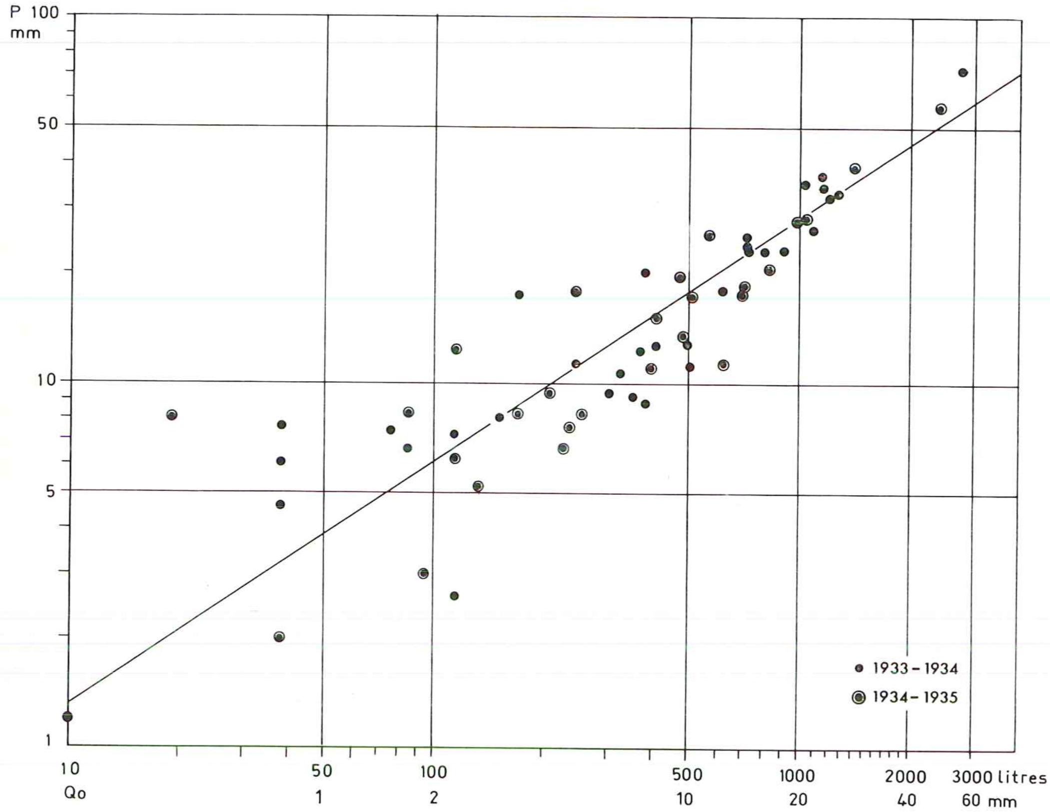


Figure 2. Runoff (Qo) in litres and mm for all storms causing runoff over two rainy seasons against precipitation (P) in mm on bare ground at Mpwapwa (data from Staples 1934, 1936). Size of plots are 50 m².

saturate the soil (Fig. 3).

Runoff from bare crusted soil occurred 59 times in 2 seasons compared to 7 times from a grass cover (mostly before the grass cover was fully developed) and an average of 13 times from the cultivated plots. There was no runoff from plot 4 while it was cultivated (for half a rainy season) with contour ridging; these ridges obstructed the wash flow downslope and afforded a larger soil surface for moisture infiltration than flat cultivation. The results show that grass cover assists infiltration (see above) while cultivation, by opening up the surface functions in the same way, but less effectively.

Extremely severe water losses from bare ground and cultivated plots were recorded. For example Storm B 20, the heaviest of the 1934/35 rains (57 mm) caused a percentage loss of 83.7 from plot 1, 70.9 from plot 2, 48.0 from plot 3 but only 9.2 from the grass plot. If soil wash losses had been measured for each storm rather than for each season, there is no doubt that excessive soil loss would also have been demonstrated to be related to the heaviest storm (Temple & Rapp 1972). One such heavy storm of 51 mm in 30 minutes caused a loss of nearly 3500 m³ from a 10 hectare Kenya coffee field with a slope of 8°; this approximates to a soil loss of 35 mm (Brook 1955).

Table 5a shows the percentage of the annual total precipitation lost by each plot. Over two season's recordings, runoff from bare uncultivated soil was over half of the total season's precipitation and showed more than 53 times the loss recorded from an established grass cover, which lost less than 1 % of the seasonal rainfall supply to runoff (see Hudson & Jackson 1959, Table 3 above). Runoff loss from the sorghum plot was 29 times the loss from established grass. The deciduous ungrazed thicket plots lost only half the amount

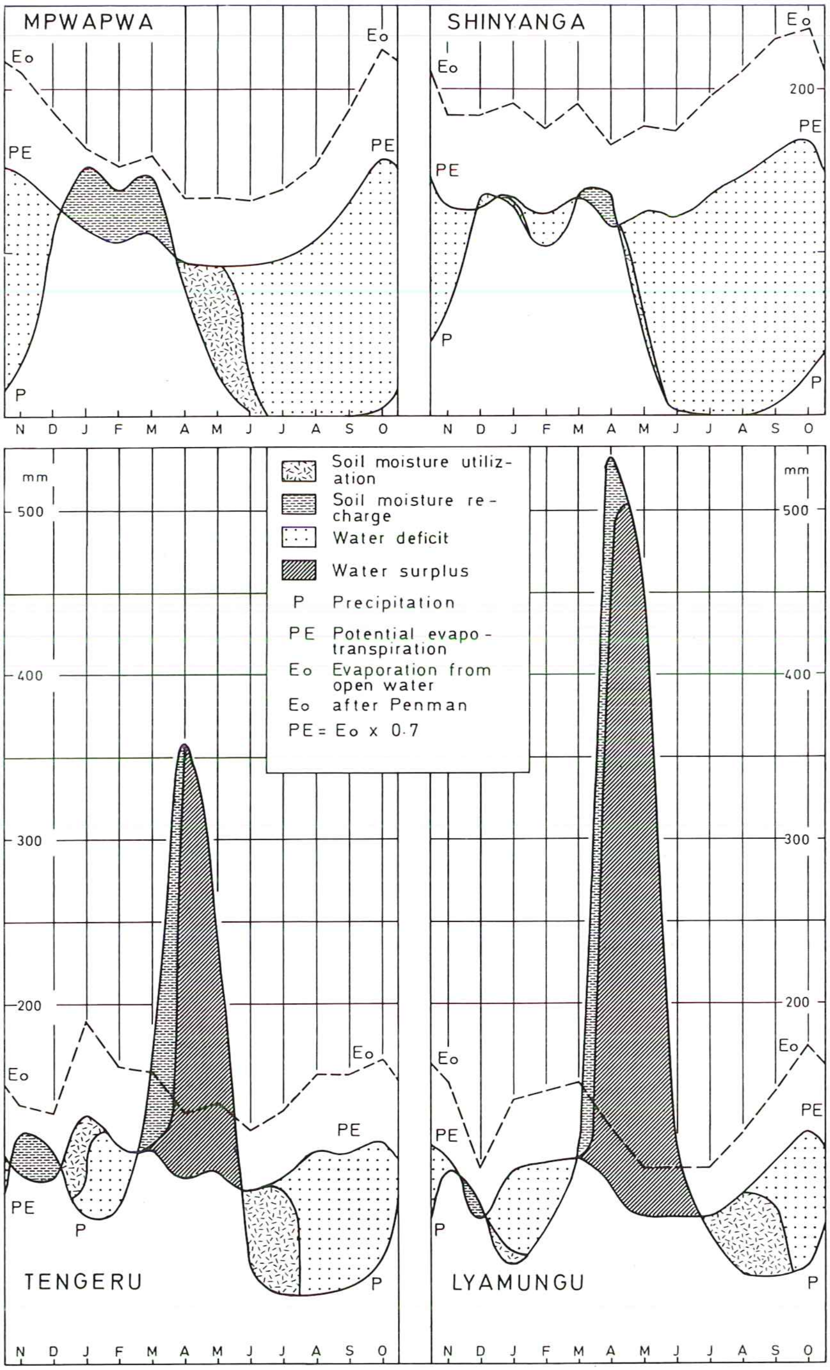


Figure 3. Water balance diagrams for Mpwapwa, Lyamungu, Tengeru and Shinyanga. For $E_0$ conversion to PE see Penman (1963).

Table 5. Runoff, soil erosion and sediment concentration, Mpwapwa erosion plots (modified after Staples 1936).
a) Percentage runoff of total precipitation: rainfall 1933/34, 675 mm; 1934/35, 564 mm.
b) Soil erosion in m³/ha. Quantity relates to less than half the 1933/34 rainy season, before which, ridges on contour and no soil loss.
c) Sediment concentration total in runoff in mg/l.

| Season | Plot 1 Bare: uncult. | Plot 2 Bare: flat cult. | Plot 3 Bare: ridge cult. | Plot 4 Bulrush millet or sorghum | Plot 5 Grass | Plot 6 Bare: flat cult. | Plot 7 Decid. ungr. | Plot 8 Thicket |
|---|---|---|---|---|---|---|---|---|
| a. | | | | | | | | |
| 1933/34 | 52.9 | 34.8 | 25.2 | 29.1 | 2.8 | 33.3 | ? | ? |
| 1934/35 | 47.8 | 28.2 | 20.8 | 22.9 | 0.9 | 27.1 | 0.5 | 0.4 |
| Average | 50.4 | 31.5 | 23.0 | 26.0 | 1.9 | 30.2 | 0.5 | 0.4 |
| b. | | | | | | | | |
| 1933/34 | 97.0 | 80.4 | 20.9* | 66.5 | 0 | 37.5 | ? | ? |
| 1934/35 | 98.7 | 90.0 | 44.7 | 37.5 | 0 | 25.0 | 0 | 0 |
| Average | 97.8 | 85.2 | 43.3+ | 52.0 | 0 | 31.3 | 0 | 0 |
| c. | | | | | | | | |
| 1933/34 | 42,205 | 53,180 | 53,280 | 37,515 | — | 25,745 | — | — |
| 1934/35 | 56,275 | 86,805 | 73,935 | 52,285 | — | 30,235 | — | — |
| Average | 49,240 | 69,993 | 63,608 | 44,900 | — | 27,990 | — | — |

Average determined by doubling 1933/34 value and probably an underestimation.

of water through runoff that was lost from the grass plot and less than 1 % of the water lost from bare uncultivated ground. This indicates that complete clearing of thicket by fire and felling on even small slope segments may be expected to increase runoff loss by two orders of magnitude.

Soil loss was, for technical reasons, determined only on a seasonal basis and not for individual storms. Table 5b presents the data. Despite a lower seasonal rainfall (15 % below average) and lower rainfall intensities in 1934/35 compared to 1933/34 and lower runoff, soil losses were greater in the second year of the trial than in the first. This anomaly may be explained by the progressive reduction in soil organic matter (primarily grass roots) causing a greater erodibility of the soil (decreased infiltration and moistureholding capacity and decreased binding effect) in 1934/35. Soil loss was negligible from the thicket and grass plots despite some runoff from both plots. (Cf. Rapp, Murray-Rust et al., 1972, Fig. 5).

The effect of slope length on soil loss is clearly demonstrated by reference to plots 2 and 6 which had identical treatments. Plot 6, half the length of plot 2, lost only 30 % of the soil lost from plot 2. The effect of length of slope on soil loss has been established by Zingg (1940).

Table 5c shows the relationship of total runoff and total soil loss for both seasons in the form of sediment concentration values for each plot. The wide contrast in values between the two seasons data is evident, the rise in concentration on all plots showing measurable loss being a function of the lower runoff and great soil loss experienced in the second year of the trials. Concentration values are greatest for plot 2, indicative of the fact that more water percolated into the soil on this plot than into the compact soil of plot 1, causing 60 % lower runoff (Table 5a) but that the lower runoff was able to transport almost as much soil, as a result of the surface soil being loose due to cultivation.

In late 1946 recording of soil and runoff losses were recommenced on Plots 1 to 6, under modified treatments. The results are reported by van Rensburg (1955).

Plot 1 was cultivated and planted with sorghum without any conservation method. Plot 2 was left under grass cover (mainly *Cynodon plectostachyus*, a robust creeping grass growing up to 1 m tall. Plot 3 was divided into two; the top half under sorghum as on plot 1, the bottom half under grass as on plot 2. Plot 4 was treated in the same way as plot 1. Plot 5 was under grass cover (mainly *Cenchrus ciliaris;* see above). The shorter plot 6 was

Table 6. Runoff and soil erosion from various crops on identical plots at Mpwapwa; runoff (a) as percentage of annual total; soil loss (b) in m³/ha (modified after van Rensburg 1955).

| Year | Rainfall mm | Cultivated plot | | Cultivated plot + narrow grass belts across slope | | Plot 50 % cultivated 50 % grass | | Grass plot | |
|---|---|---|---|---|---|---|---|---|---|
| | | a | b | a | b | a | b | a | b |
| 1946/47 | 780 | 9.0 | 18.5 | — | — | 3.9 | 3.8 | 1.2 | 0.6 |
| 1947/48 | 530 | 16.4 | 14.3 | — | — | 10.4 | 2.1 | 3.4 | 0.3 |
| 1948/49 | 650 | 21.8 | 44.1 | — | — | 19.2 | 1.8 | 7.3 | 0.5 |
| 1949/50 | 580 | 12.8 | 8.3 | — | — | 13.1 | 0.6 | 4.7 | 0.2 |
| 1950/51 | 670 | 26.7 | 65.3 | 19.1 | 7.7 | 15.4 | 2.2 | 5.3 | 0.9 |
| 1951/52 | 860 | 28.9 | 86.4 | 10.0 | 30.3 | 9.0 | 1.8 | 6.5 | 0.7 |
| 1952/53 | 410 | 13.3 | 6.2 | 11.8 | 3.0 | 6.9 | 0.9 | 3.9 | 0.3 |
| 1953/54 | 520 | 25.5 | 48.8 | 21.2 | 37.2 | 14.3 | 3.4 | 7.2 | 0.4 |
| Average | 690 | 19.3 | 36.5 | 15.5 | 19.6 | 11.6 | 2.1 | 4.9 | 0.5 |
| Average[1] | | — | 36.9 | — | 20.2 | — | 2.2 | — | 0.5 |

[1] Including soil washed to the bottom of the plot but prevented by the tank lip from entering the tank: for grass plot none.

divided into two; the top half treated as Plot 1, the bottom half as plot 5. At the beginning of the 1950/51 rainy season the treatment of plot 5 was modified; previously under grass for 4 years, it was cultivated but two 2 m wide grass belts were left a third and two-thirds of the distance down the plot.

By the time of this later series of measurements soil transfer *on the cultivated plots only* had caused vertical erosion at the plot tops of over 30 cm and accumulation at the base of the plots which affected the functioning of the experiments. This accumulation of debris had to be removed in order to prevent runoff flowing over the containing side walls at the lower ends of these plots and thus not entering the collecting tanks. At the end of the experiments this accumulation was measured and is added to the material collected in the tanks to give a more realistic average for soil loss over the 8 year period of data collection.

Percentage runoff for these plots over 8 seasons is presented in Table 6. Van Rensburg unfortunately does not tabulate the data for individual plots but aggregates them. Runoff losses from the cultivated sorghum plots without conservation averaged four times those from grass plots, while the plot half cultivated and half grass lost double the runoff that the grass plot showed. The extent to which runoff loss was reduced by introducing narrow grass strips into cultivated plots was very significant.

Soil erosion data over the same period are also presented in Table 6. Taking first the values measured in the collecting tanks, the cultivated plots lost 76 times the amount of soil that was lost from the grass plots. Narrow grass strips incorporated in the cultivated plots reduced soil loss by 53 % compared to unprotected cultivation. The plot with half cultivation, half grass showed only 4 times the soil loss of the grass plot and one twentieth of the loss from the wholly cultivated plots. If the soil which accumulated at the base of the slope is included in the calculations, these contrasts become even more striking eg. the cultivated plots then lost nearly 120 times the soil lost by the grass plots.

Van Rensburg emphasises that the data provided by these measurements may not be relevant for large slope segments. He also recorded the progressive decline in crop yields from the cultivated plots, indicative of the agricultural effects of the heavy water and soil loss recorded.

(b) *Lyamungu* (3°15′S, 37°15′E: 1300 m a.s.l.)

Experimental plots designed to measure soil erosion and runoff under young coffee using various conservation treatments were established at Lyamungu near Moshi in 1934. Results were reported in the Annual Reports and Quarterly Notes of the Coffee Research and Experimental station (1937, 1938 & 1939)

Table 7. Runoff soil erosion from coffee plots established in 1934 at Lyamungu; runoff (a) as percentage of annual total: soil loss (b) in m³/ha (modified after Mitchell 1965 & Annual Reports of Lyamungu 1937 1938)

| Plot No. | Plot treatment: Coffee[1] | 1935 | | 1936 | | 1937 | | 1938 | 1939 |
|---|---|---|---|---|---|---|---|---|---|
| | | a | b | a | b | a | b | b | b |
| 1 | Clean weeding | 2 9 | 18 0 | 8 1 | 53.4 | 26.2[1] | 55.4 | 4.8[2] | 1.2[2] |
| 2 | 3 contour ridges 10m apart on which were hedges (*Crotalaria* sp.) lowest ridge 0.6m from tank | 1.9 | 1.4 | 4.4 | 8.9 | 7.8[3] | 0[3] | 3.0[3] | 1.4[3] |
| 3 | Clean weeding | 3.0[4] | 13.8[4] | 5.3[4] | 35.6[4] | 26.0[4] | 33.6[4] | 2.6[5] | 0.3[5] |
| 4 | As plot 2 + procumbent cover of *Dolichos hosei* | 0.5 | 0.1 | 1.8 | 0.7 | 7.3 | 0 | 2.4 | 0.5 |
| 5 | Clean weeding | 2.7 | 23.2 | 11.1 | 47.5 | 7.0[6] | 0[6] | 1.7[6] | 0.4[6] |
| 6 | Procumbent cover of *Dolichos hosei* | 1.1 | 0.3 | 2.0 | 0.5 | 7.7 | 0 | 1.6 | 0.3 |
| 7 | Mixed erect cover of *Crostalaria* sp. & *Canavalia ensiformis* | 1.7 | 0.3 | 3.3 | 9.9[6] | 10.9 | 0 | 6.1 | 2.1 |
| 8 | Clean weeding | 2.8 | 30.6 | 7.3[4] | 26.7[4] | 25.6[4] | 33.6[4] | 2.6[4] | 0.3[4] |

[1] Estimate as tank overflowed at least once.
[2] Excessive weed growth (*Commelina* sp.) uncontrolled.
[3] Contour ridge spacing reduced by half & hedges dug up as ridges had silted and hedges were breached.
[4] Weeds placed in lines across slope.
[5] Procumbent cover crop established.
[6] Mulched with banana trash; only 60% surface cover due to poor reseeding. In 1935 and 1936 all coffee trees and plots 4, 6 & 7 envelope forked: plots 1, 2, 3, 5 & 8 *jembe* forked: from 1937 onwards routine weeding only.

and are summarised by Mitchell (1965). Similar data from Kenya are available (Gethin-Jones 1936; Maher 1950).

Eight adjacent plots were located on a uniform slope of 9.5°, cleared from thick bush in March 1934. The soil was a deep, free-draining, partially laterised volcanic red earth of clay-loam texture and well-aggregated structure, possessing a fairly high moisture-retaining capacity. The subsoil was a deep, freely-draining, friable chocolate-red clay. The plots measured 30.5 m long downslope by 4.5 m wide (area 137.25 m²). The individual plots were walled round and tanks at their foot constructed to collect eroded soil and runoff. Coffee was planted on all plots at 3 m×3 m spacing in April 1934 and treatments begun. Measurements began in February 1935 when the treatments were deemed effective. Unfortunately treatment of plots was not consistent over the full period of the trials. (Table 7 & notes).

Lyamungu has an average annual rainfall of 1660 mm, 73 % of which falls on average in March, April and May (Fig. 1). Heavy rainstorms are common during this period, many totalling well over 100 mm in 24 hours with intensities of up to 76 mm/hour (Table 8).

Runoff associated with each runoff—generating storm over the 3-year period is shown in Table 8 for each plot. During many of the heavier storms, the water-collecting tanks overflowed and runoff had to be estimated. In several of these instances, calculations show that these estimates are too high (i.e. in excess of the total rainfall on the plot according to the station raingauge some distance away).

The results require careful analysis due to changes in plot treatment (see Table 7). The clean weeded plots (1, 3, 5 & 8) lost most water, plots 3 and 8 despite the lines of weeds placed across the slope. This measure was thus shown to have little value in the prevention of runoff. The results confirm the value of heavy vegetative mulching indicated by the Namulonge data (above) and the Tengeru results (below).

Of the cover crops, the mixed erect cover gave poorest control, next came contour ridges and hedges, then procumbent (growing along the ground) cover. The best protection against runoff loss was a combination of procumbent

Table 8. Percentage runoff at Lyamungu associated with individual storms.

| No. | Date | Rain mm | Int. mm/hr | Plots 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 35.04.13 | 104 | 76 | 9.0 | 9.0 | 14.1 | 8.3 | 15.0 | 10.0 | 11.7 | 16.9 |
| 2 | 35.05.07 | 143 | ? | 26.1 | 14.3 | 23.1 | 0 | 19.1 | 5.5 | 10.5 | 19.3 |
| 3 | 36.04.10 | 50 | 20 | 11.5 | 11.0 | 15.8 | 8.6 | 38.7 | 10.0 | 12.9 | 17.2 |
| 4 | 36.04.18 | 125 | 50 | 75.7 | 54.5 | 53.3 | 20.1 | 78.0 | 21.8 | 38.7 | 75.7 |
| 5 | 36.05.19 | 43 | 20 | 80.0 | 20.0 | 63.4 | 9.2 | 100+ | 7.5 | 18.4 | 48.4 |
| 6 | 36.06.13 | 47 | 12 | 48.1 | 5.3 | 3.8 | 5.3 | 30.5 | 6.1 | 3.1 | 37.4 |
| 7 | 37.04.07 | 108 | 40 | 85.0 | 25.6 | 79.0 | 23.6 | 20.6 | 20.9 | 23.9 | 80.3 |
| 8 | 37.04.14 | 91 | 48 | 100+ | 34.7 | 100+ | 29.2 | 26.8 | 28.0 | 50.4 | 100+ |
| 9 | 37.04.20 | 120 | 50 | 75.0 | 31.0 | 68.4 | 27.8 | 36.4 | 47.5 | 55.3 | 58.6 |
| 10 | 37.04.28 | 82 | 60 | 100+ | 21.9 | 100+ | 24.5 | 19.2 | 21.9 | 41.5 | 100+ |
| 11 | 37.05.04 | 99 | 25 | 95.6 | 19.9 | 97.0 | 21.4 | 15.9 | 16.3 | 25.3 | 97.0 |
| 12 | 37.05.11 | 182 | ? | 52.0 | 21.7 | 52.8 | 18.9 | 17.7 | 17.3 | 24.0 | 52.8 |

cover and contour ridges (plot 4); this plot showed only 28 % of the losses experienced by the clean weeded plots.

The influence of soil moisture is demonstrated in Table 8. The storm of maximum intensity (No. 1) early in the 1935 rains caused only a limited surface runoff averaging less than 14 % on the clean weeded plots, yet a storm (No. 5) of only 43 % the size and 26 % of the intensity, coming the day after a very heavy downpour the previous day, generated an average of 73 % run off from the clean weeded plots. The three seasons show both a progressive increase in rainfall (161 cm in 1935; 195 cm in 1936 and 221 cm in 1937) and an increasing number of storms generating runoff (2 : 4 : 6). This in itself may explain the runoff increase over the period: it may also be due to soil deterioration after initial clearance in 1934 (see Mpwapwa results above).

As at Mpwapwa, soil loss was not measured in relation to individual storms but over the whole rainy season. Table 7 presents the results. The clean weeded plot (1) lost most soil, averaging 38 $m^3$/ha and year. Even during the first year of the experiments, the clean weeded plots (1 & 8) showed rill development and the bare plot with ridges (2) showed a silting up of the banks and a consequent breaching of some of the hedges. Weed lines across such plots, although they did little to reduce runoff, apparently cut down soil loss to an average of 24 $m^3$/ha (i.e. by 27 %). Banana mulch on clean weeded coffee reduced soil loss to negligible quantities (i.e. 1 $m^3$/ha and yr).

Of the conservation measures, all proved valuable in reducing soil loss but to varying degrees. Widely spaced ridges & hedges (plot 2) were less successful than all other treatments emphasising the validity of the Rhodesian results on the value of cover. Nonetheless the plot protected in this way lost only 5 $m^3$/ha and yr over 2 years—an 86 % reduction in soil loss over the clean weeded plot 1. Closer spacing of the ridges after 1937 cut soil loss to very small amounts ($< 2$ $m^3$/ha and yr), emphasising that it is not the technique itself but its proper application that is important.

Erect cover was the least effective of the various cover treatments, approximating to ridges in its control over soil loss (Table 7). Soil loss from beneath an erect cover averaged 6 $m^3$/ha and yr. But during 1936 poor reseeding gave only 60 per cent cover, probably causing excessive soil loss. A properly maintained erect cover is probably more effective a conservor of soil than widely-spaced ridges but less effective in this role than closely-spaced ridges. Most effective of all in terms of soil conservation was a procumbent cover crop: the addition of ridges showed no advantage. In fact plot 4 lost slightly more soil on average than plot 6.

But it was noted that in contrast to soil moisture conditions recorded at 38 cm depth at the end of the rains, when no difference was observed between the plots, 4 months later the clean weeded plots showed a significantly higher soil moisture retention than all other treatments, and coffee on these plots maintained more than double the leafage of all other plots. The coffee on the bare plots flowered earlier in response to rain (by 5 days) and was in better condition at the end of the dry season. Thus, although heavy soil erosion and runoff losses occurred from the clean weeded plots indicating that conservation measures were necessary during the wet season, these had to be designed to conserve soil moisture during the long dry season. It was noted that soil moisture conditions in nearby terraced plots were no better after 4 months drought than those of clean weeded flat plots. Closely spaced contour ridges without hedges were consequently selected as the best and cheapest conservation practice, costing less than a tenth the price to establish on such slopes and the same price to maintain as bench terraces (Ann. Rept. for 1937, 1938, p. 30), and causing vastly less disturbance of the soil and no exposure of subsoil (Temple 1972).

(c) *Tengeru* (3°22′S, 36°48′E: 1463 m a.s.l.)

Experimental plots designed to measure runoff and soil erosion under different crops and different conservation methods were established at Tengeru near Arusha in 1954. Results were reported by Anderson (1962) and Mitchell (1965). Though full data on the experiments are not now available, a summary table (Table 9) lists the main findings for a three year period. Plots were of uniform size (not available) and slope (18°) and underlain by deep red volcanic soil.

Tengeru has an average annual rainfall of 1300 mm, 59 % of which falls on average over 47 days in March, April and May (Fig. 1). Rain days (> 0.25 mm) average 100 annually.

Table 9, which presents the plot treatments in inverse ranked order of control over soil and water loss, reveals striking contrasts between the different crops and treatments. Both crops (coffee, maize, bananas and grass) and conservation methods were representative of local land use practices.

Soil and water losses were least on the grass plots. The banana plot lost 15 times more soil than the grass plot and 30 % more water. But bananas showed a much better control over soil erosion and water loss than all other food crops tested, even over the short period reported. It is no accident that bananas are the principal subsistence crop on most steep high rainfall mountain slopes in East Africa (e.g. Mt. Meru, Kilimanjaro, Tukuyu, Mt. Kenya, Mt. Elgon and Kigezi) and support locally very high rural population densities. As bananas are a perennial crop, the soil is mantled by a permanent cover and, due to the build-up of soil fertility with the normal heavy mulching, may be expected to show progressively improving results over time relative to other treatments.

Table 9. Runoff and soil erosion from various crops on identical plots at Tengeru for the three years, 1958–1960; runoff (a) as percentage of annual total; soil loss (b) in $m^3$/ha (modified after Mitchell, 1965). Average annual rainfall 1958–1960: 1070 mm.

| Plot treatment | a | b |
|---|---|---|
| Coffee: pruned; 3×3 m spacing; clean weeded continuously; no shade | 5.0 | 22.4 |
| Maize: stover removed; no conservation measures | 3.4 | 12.0 |
| Maize: stover & dead grass removed; grass bunds of *Pennisetum purpureum* at 3 m VI | 2.3 | 7.2 |
| Maize: stover & dead grass removed; grass bunds of *Pennisetum purpureum* at 2.1 m VI | 2.2 | 5.0 |
| Maize: stover and trash bunds at 3 m VI | 2.1 | 3.9 |
| Maize: stover & trash bunds at 2.1 m VI | 2.0 | 1.0 |
| Bananas: banana trash mulch | 1.8 | 0.5 |
| Grass (*Chloris gayana*): cut for hay: average of 8 plots | 1.4 | 0.0 |

Annual food crops showed a poorer degree of control over soil erosion and runoff. A maize plot lost over twice the amount of soil and 10 % more water, even under the most effective conservation practice tested, compared to the banana plot. Table 9 indicates most strikingly the value of proper but simple and inexpensive conservation techniques. Trash bunds were clearly more effective than grass bunds in preventing losses. The maize plot protected by grass bunds at 2.1 m vertical interval with dead grass and stover removed, lost 5 times as much soil and 10 % more water than the maize plot protected by trash stover bunds of the same spacing. The contrast between maize with closely spaced trash bunds and maize grown without any conservation method is even more striking. The unprotected plot lost 12 times more soil and 70 % more water than the well-conserved plot. These data are of great importance for proper agricultural extension advice on comparable slopes and soils

Table 10. Loss of fertility under various crops at Tengeru 1954—1961 (after Anderson 1962).

| Plot treatment | pH ($CaCl_2$) | Organic carbon % | Available P (ppm)[1] | Total P (ppm) | Organic P (ppm) | % Organic in total |
|---|---|---|---|---|---|---|
| Coffee (clean weeded) | 5.86 | 2.76 | 428 | 3208 | 450 | 13.6 |
| Maize (no conservation) | 5.85 | 3.44 | 514 | 4688 | 782 | 17.0 |
| Maize + 3m VI grass bunds | 5.97 | 3.20 | 382 | 4584 | 524 | 11.4 |
| Maize + 2.lm VI grass bfnds | 5.95 | 3.22 | 451 | 4188 | 396 | 9.9 |
| Maize + 3m VI trash bunds | 5.99 | 3.00 | 366 | 4084 | 925 | 23.0 |
| Maize + 2.lm VI trash bunds | 6.07 | 3.22 | 412 | 4063 | 912 | 22.1 |
| Bananas | 6.06 | 2.90 | 402 | 5813 | 2111 | 31.9 |
| Grass | 5.99 | 3.54 | 454 | 5229 | 2454 | 46.5 |

[1] Extractable in 0.3 N HCl.

on the slopes of Mt. Meru and probably also on Kilimanjaro.

A further striking point shown by the table is that the cleanweeded coffee plot showed by far the greatest losses of soil and water. These losses were far above those recorded from the maize grown without conservation measures. Coffee lost nearly double the soil and almost 50 % more water than unprotected maize. These data call in question the commonlyheld assumption that a perennial bush crop is invariably better conservation practice than an annual crop grown using traditional farming methods. The coffee plot lost well over 700 times as much soil and nearly 4 times as much water as an equivalent plot under grass.

Anderson (1962) analysed the effect of these treatments on soil fertility by taking three composite samples of soil from 0—15 cm depth from each plot, one at the top, a second in the middle and a third at the bottom of each of the eight plots. He measured pH, the percentage of organic carbon, available, organic and total potassium and the percentage of organic potassium in the sample. The major results are shown in Table 10.

Anderson summarises his results as follows . . .

"Maize without soil conservation and clean-weeded coffee plots have the lowest mean pH which is in accord with their higher soil and water losses. Organic carbon is highest under Rhodes grass (*Chloris gayana*) with the control which has received the greatest return of maize stover coming second, despite the soil loss. The coffee soil on the other hand is the lowest in organic matter, showing that continuous clean-weeding under this crop can bring about a marked loss of organic matter in a few years. Total phosphorus in these soils is highest under the bananas and grass and it is surprising that over a third of the total phosphorus has been lost from the coffee plot in 7 years. The much greater content of organic phosphorus under the bananas and grass than on the other plots indicates how efficient these crops are in preventing losses. Taking the grass and bananas as a rough standard of the original status of the soil about three quarters of the organic phosphorus has been lost from the coffee and elephant grass (*Pennisetum*) bund plots and over half of it from the other maize plots. Phosphorus extractable in 0.3 N HCl bears little or no relationship to the total organic or inorganic phosporus in these soils and is highest in the control plot where the greatest opportunity for mineralisation of the phosphorus in the maize stover exists. The percentage organic phosphorus in the total phosphorus like the total and organic phosphorus is highest on the banana and grass plots and lowest on the elephant grass bund plots. (Thus) Rhodes grass and bananas are not only better in soil conservation than maize or coffee but much better in maintaining the fertility of the soil" (Anderson 1962, p. 2).

These data, in conjunction with economic analysis should be of value in planning more intensive land use in the area.

(d) *Shinyanga* (3°35′S, 33°25′E: 1200 m a.s.l.)

Erosion plots were established in Shinyanga (Rounce, King & Thornton 1942, p. 15), but the data obtained were apparently neither published nor analysed. Shinyanga has an average annual rainfall of 780 mm, 81 % of which falls on average in the period December through April (Fig. 1). The only known result is that erosion plot data had demonstrated a 60 % reduction of soil erosion as the result of contour hedge planting by *Euphorbia tirucalli*. Closely planted *Euphoribia* reduced wash from the time of its planting. As this plant has a caustic and semi-poisonous latex it is never grazed, hence part of its value. By contrast sisal hedges across the contour, favoured in this area, only become effective as a control on soil loss when the plants are large enough to protect the grass and weeds beneath them from grazing. In other words, their effect was indirect. It may be noted here that sisal hedges are employed to conserve the soil in the Kondoa area. This area has some of the most severely-eroded slopes in East Africa. On the evidence of the Shinyanga erosion plots, *Euphorbia* should have been employed.

## Discussion

### *Runoff and soil erosion*

The data from Mpwapwa, Lyamungu and Tengeru are not exactly comparable as plot sizes, plot slopes, soil types and treatments varied. Thus no quantitative comparisons are possible. However, some generalisations can be usefully made. Indications of the climatic differences between the various localities are given in Figs. 1 and 3.

The Mpwapwa and Lyamungu plots were approximately the same lengths (27.7 and 30.5 m); unfortunately the dimensions of the Tengeru plots are not mentioned in the published report. The Lyamungu plots were twice as wide as most of the Mpwapwa plots. This difference may well have affected the soil erosion measurements but not the percentage runoff. The Lyamungu and Tengeru plots had similar soils but were steeper (9.5 and 18°) than the Mpwapwa plots (3.5—4.5°).

Despite this gentler slope, a sandy soil and the low rainfall at Mpwapwa, runoff from grass was nearly 3 times as great and soil loss averaged 8 times as much as at Tengeru. The runoff percentage from cultivated plots of bulrush millet at Mpwapwa averaged 10 times that from maize plots at either Lyamungu or Tengeru. Differences in ground cover were not measured and may have been contributory factors. More important causes were probably the differing infiltration capacities of the soils and the contrasts in the frequency of runoff-generating rainstorms. It would appear from the limited data presented above that in semi-arid central Tanzania runoff-generating storms are much more frequent than they are on the better-watered mountain footslopes in the north. This may be a function of different types and intensities of rainfall received in the two areas but must also be a function of soil differences. More comparative data are necessary to verify these suggestions.

Clean weeded coffee plots lost approximately double the water and soil at Lyamungu as at Tengeru. This difference is largely explained by the greater cover provided by the more mature Tengeru coffee (4 years old at the start of the measurements reported). A further influence may be the greater water balance surplus at Lyamungu as compared to Tengeru.

Other results of the data are treated below.

### *Land use and conservation*

The principal value of the experimental results set out above is in providing quantitative data at the *shamba* (small cultivated plot) scale of the effects of various cropping and conservation practices in particular localities. As both crops and conservation measures employed were selected to match or improve local agricultural practices, the results are of practical agricultural relevance. The localities chosen for the expertments were representative of the two contrasted environments identified earlier as critical, namely semi-arid interior plains and deforested mountain slopes. But much more work on the geomorphology, soils and land use practices of both areas would be necessary to establish how representative of local conditions the plots actually were.

Nonetheless some further comments on cropping and conservation strategies for both environments seem justified. The assembled data indicate the seriousness of soil and water losses associated with improper land use in both central Tanzania and on the northern mountain footslopes.

It seems probable that the Mpwapwa data are relevant to cultivation practices over considerable areas of central Tanzania, particularly to those areas known as the "cultivation steppe", where the natural vegetation has been largely destroyed. Cultivation steppe was estimated to cover 30,000 km$^2$ in 1929 (Phillips 1929) but there are no later estimates. The Lyamungu and Tengeru results are likewise relevant to cultivation practices on the northern mountain footslopes.

The Mpwapwa data demonstrate extremely severe losses of soil and water associated with clearance, cultivation and overgrazing. Thicket and good grass, both ecologically well-adapted to the local environment, show low runoff and little soil loss even on steep gradients or when they are lightly grazed or burnt annually. But under thicket water is lost by other means. Staples (1934, p. 101) calculated that 30 % of the rainfall was lost by evaporation from interception storage and a further 65 % lost by transpiration leaving only 5 % to feed springs and water courses. Thus under such a cover the bulk of the water supplied by precipitation is used for the physiological requirements of the thicket. Thicket has only a limited value as a source of firewood, timber, wax, honey, game and poor grazing.

Presumably grass, being shallower rooted than thicket would loose less water by transpiration. As grass appears almost as effective as thicket in inducing infiltration, such a cover would conserve water much more effectively, releasing greater amounts to springs and water courses. Grazing by stock should be so managed as to maintain a good grass cover: this would ensure more and better fodder as well as retarding soil and water loss. Proper management would be assisted by the planting of sisal hedges around fields. But proper grazing management is difficult in such an area where people are sedentary and where cattle are kept for prestige and bride-price. Artificially high stock numbers together with rather limited mobility of herds encourages overgrazing of both grass and thicket. As Staples' data showed, this is rapidly reflected in increased soil and water losses, which become extreme if cover is completely destroyed (Table 5). Bare uncultivated land should be encouraged to regenerate naturally by control of fire and grazing. Staples' data showed that such regeneration may reduce runoff by half and soil loss to one thirtieth in a single year, at least in some sites.

The data indicate clearly the importance of some form of cover, as bare plots, whether cultivated or uncultivated lost extremely high amounts of soil and water (Table 5). Losses were much reduced under a grain crop (bulrush millet or sorghum). Bulrush millet is very drought resistant, gives reasonable yields on light, infertile, sandy soil unsuitable for other cereals, matures quickly (3—4 months) and is thus also drought-evading. Its initial growth is rapid and it tillers freely, thus causing a suppression of weeds and an increase in cover (Acland, 1971, 27—28). But it is lower yielding than maize, more prone to bird damage and less easy to thrash and winnow. Sorghum is also very drought resistant, yields reasonably well on infertile soils and has a very efficient well-branched root system. Sorghum is second only to bulrush millet in its ability to withstand drought and to give satisfactory yields on poor or exhausted soils. It matures in 3 to 6 months. Like bulrush millet, it is heavily attacked by birds and is more difficult to harvest, thresh and clean than maize (Acland, op.cit.).

On the Mpwapwa erosion plots these grains were planted as clear stands, presumably sown broadcast as is the local custom. But according to Rigby (1969, p. 27—28) clear cropping is not the local custom of the Gogo people. Sweet potatoes, pigeon peas, grams, marrows and gourds are often interplanted with grain on Gogo fields, while many uncultivated plants grow up with the crops and are left standing during cultivation. All of these crops except groundnuts are drought resistant, and all except sweet potatoes give good yields on infertile sandy soils. Many are procumbent eg. sweet potatoes and marrows and thus give excellent soil cover: others are leguminous eg. cowpeas and pigeon peas and enrich as well as protect the soil. Cassava is very drought resistant and can give good yields on poor soils. As it removes very few nutrients from the soil, it is equivalent to fallowing even if clear weeded (Acland, op.cit., pp. 33—38).

Thus the soil and water losses (Table 5) recorded from the bulrush millet/sorghum erosion plot are likely to be higher than experienced under traditional cultivation practice with interplanting and lesser weeding. Maize according to Rigby (op.cit., p. 26) is spreading in this area; this could have adverse effects as maize requires good soil and adequate rainfall and will have a greater tendency to failure in



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Ugogo. Its cultivation encourages ox-ploughing, row cultivation and clean weeding, all of which would favour increased losses of soil and water except on the flattest slopes.

Keeping fields small conserves the soil but has limited effects on runoff. The introduction of grass strips even across small plots has beneficial effects for both soil and water conservation. Staples noted that such a measure may have only short-term advantages as farmers are tempted to dig up the strips once they become fertile through silt deposition. Also cattle damage them unless an unpalatable and densely-tufted grass like *khus-khus (Vetiveria zizanoides)* is employed. Hoe-built contour ridges at suitable spacing (1—2 m) and well-graded provide an excellent form of control, inadequately employed in this area.

Data from Sukumaland indicate that if such ridges are cross tied every 2.5 m "this is a complete answer to soil erosion and increases the effectiveness of rainfall and the yield of crops" (Peat & Brown 1960, p. 103). The authors quote mean yield increases resulting from tied-ridging as compared to normal contour ridging as follows: bulrush millet 128 %; sorghum 57—87 % according to soil type; groundnuts 59 %; cotton 39 % and maize 15 %. Tied ridging gives up to three times the yield from non-tied ridging in drought years as it reduces runoff and increases infiltration and soil moisture (le Mare 1954, Brown 1963). This method should be used in this drought-plagued area. Ridges retain their utility when the land is returned to fallow.

The Lyamungu and Tengeru results can be discussed together, as environmental conditions and cultivation practices are similar. Both areas have soils of high fertility, a strongly aggregated structure, high permeability and water-holding capacity developed from volcanic parent material. Both areas appear to have large seasonal water surpluses (Fig. 3) and soil erosion may be serious in the absence of proper conservation techniques. Soil water deficiency at the end of the marked dry season may be a problem for perennial croups such as coffee.

Erosion was high under clean weeded coffee and water lost by runoff during the rains is unavailable to sustain treees during the critical fruiting period. Both water and soil losses are greatest when the trees are young and fall off as they mature. Proper conservation measures are therefore essential during the first 3—4 years after planting. As no cover crop has been found in East Africa which does not compete severely with coffee (Acland 1971, p. 72), control of erosion, runoff and weeds is best achieved by mulching. Grass mulch induces almost as great infiltration as grass (Hutchinson & others, above) but requires both land and labour. One hectare of grass is needed to supply adequate mulch for one hectare of young coffee (Acland, op.cit.). Banana mulch is better and it does not rot so quickly. Contour strip mulching of young coffee was found adequate for slopes between 1.5 and 5.5°. Contour ridging at 0.6 m vertical interval was found necessary for slopes between 5.5 and 11°. On slopes steeper than 11° coffee growing was not recommended, but either grass or bananas provided good safeguards against water and soil loss. While the interplanting of coffee and bananas reduce coffee yields, on steep slopes this disadvantage is far outweighed by much reduced soil and water losses and the reduced dependence on a single crop (Mitchell, 1965), a clear justification of the normal Chagga and Meru farming methods.

The data from Tengeru demonstrate most clearly the beneficial effects of bananas compared to an annual crop such as maize as a control over runoff and erosion and in terms of soil fertility.

## Conclusions

Quantitative experimental data on runoff and soil losses relevant to Tanzania conditions are presented in Tables 1—4. The Rhodesian data show the critical influence of vegetative cover in controlling soil and water loss and indicate the progressive problems of cultivating land of increasing slope. The Uganda data establish the relationships between duration, amount and intensity of rainfall in tropical rainstorms and relate these to soil and water losses. Data from the Mpwapwa experiments are presented in Tables 5—6. They provide quantitative indications of the seriousness of water and soil losses in the semi-arid central area of Tanzania. This area is characterized by soils of low fertility and a low and erratic rainfall. As soil moisture is the major limiting factor on crop yields, there is a need to limit surface runoff losses on cultivated land, to increase infiltration and reduce soil erosion. Losses of water and soil, which are quantified for selected periods and treatments, can be drastically reduced if simple conservation practices are employed. These practices are described in the text. The data also show that an undisturbed vegetative cover of thicket or grass induces rapid infiltration and reduces soil loss. If this cover is damaged by overgrazing, water and soil losses rise rapidly.

Runoff and soil erosion losses are apparently much less serious on the mountain footslopes of the northern volcanic areas (Tables 7—9), than they are in semi-arid central Tanzania. On these footslopes soils are deep and fertile and possess a good structure. Rainfall is higher and much less erratic. Even in these areas however soil moisture conditions may become critical for perennial crop yields at the end of the dry season. There is thus a need to conserve water and prevent heavy runoff. During the heavy rainfalls of the wet season, losses of soil are heavy under some existing types of cropping (eg. young coffee and maize). Again such losses of water and soil can be drastically reduced by sensible farming practices; these practices are examined.

As such losses will increase with increasing slope, and as a large proportion of the cultivated land of the area is steeper than that of the experimental sites (eg. the intermediate slopes of Kilimanjaro and Meru) the need for effective conservation measures is reinforced.

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*Professor P. H. Temple, Department of Geography, University of Dar es Salaam, P. O. Box 35049, Dar es Salaam, Tanzania.*

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# CONSERVATION PROBLEMS, POLICIES AND THE ORIGINS OF THE MLALO BASIN REHABILITATION SCHEME, USAMBARA MOUNTAINS, TANZANIA

BY JOHN R. WATSON

Ministry of Rural Development, Lusaka, Zambia

ABSTRACT. Between 1946 and 1949 a pilot scheme in the Usambara mountains in Tanzania was responsible for the development of a viable conservation-based farming system. The methods tested and adopted by the scheme, as well as the orientation of the survey, were drawn from existing policies and problem perception. The commitment to research reflected the uncertainty apparent in the early decision making.

## Introduction

One of the characteristics of the closing decades of British administration in Africa was the increasing importance attached to the economic and social development of colonial territories (Goldsworthy 1971, p. 45). One means of development was the planned agricultural project, and those implemented had a variety of objectives including increased production, agricultural mechanisation and soil conservation. Among the most comprehensive of projects were the regional development schemes, efforts at "rural reconstruction" (Liversage 1944) that attempted to combat soil erosion whilst laying the basis for an improved agriculture and a rising standard of living.

Over the period 1946—58, the Usambara mountains in NE Tanzania were the focus of one of these attempts at development. Two projects were involved: the Mlalo basin rehabilitation scheme and the larger, and later, Usambara development scheme. The Mlalo basin, a valley of some 130 km$^2$ in the W of the range (Fig. 1), was considered typical of conditions that prevailed in the Usambaras as a whole; as a result, two programmes were undertaken there between 1946 and 1949 with the dual purpose of developing an agricultural system for the rehabilitation of an eroded area, and generating information and experience for later use. It is with the origin of these programmes that this paper is concerned.

The first programme, carried out in an experimental area of 250 hectares, encompassed the closure to cultivation of steep slopes ($> 25°$), contour ridging, the protection of stream banks, the planting of grass leys for fodder and the stall-feeding of stock. The aim of the Mlalo programme was to assemble these components into a viable system. The extent to which this was achieved is exemplified in the changing land use of the experimental area; over the three year period, the staple bearing acreage increased by a third, largely through the virtual elimination of grazing (Lushoto District File; LDF, 62/9J). The second programme took the form of a comprehensive socio-economic survey of the population and settlements of the basin.

The Mlalo basin scheme constituted a commitment to a particular course of action and it became a programme of research in its own right. It determined the methods and approach of its successor, the Usambara development scheme, as well as acting as a major influence upon the design of projects elsewhere in the country.

Mlalo represented a problem whose dimensions were apparently well understood. It employed methods that were entirely orthodox by the standards of the technical departments involved. Nevertheless, the same departments chose, before implementing those methods, to test and develop them at length, and to augment them by an intensive survey programme. This may have reflected commendable caution or it may have resulted from a fundamental uncertainty about the appropriateness of the solutions proposed.

## The dimensions of the problem

The existence of a problem at all in the Usambaras turns upon the evidence for soil erosion on the steep slopes of the range. The annual reports of the Department of Agricul-

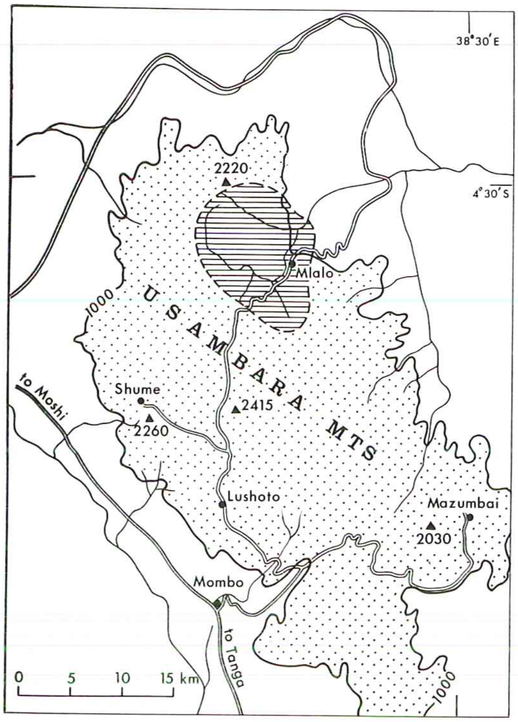


Fig. 1. Location map of the Usambara mountains (light shading, above 1000 m altitude) and the Mlalo basin (dark shading). Altitudes in metres a.s.l.

ture stressed this issue with increasing urgency from 1930 onwards:

"each succeeding long rains brings home more and more painfully the undeniable fact that on the mountain slopes of the Usambaras, of Kilimanjaro and Meru through erosion the native is losing his heritage" (Dept. Agr. Annu. Rep. 1931) and:

"the steeply sloping sides of many of the valleys are deeply gulleyed and the subsoil and rock is exposed over large areas where forest grew a few decades ago. The reduction of the forest continues with cutting for domestic fuel supplies and by burning to produce early grazing" (Ibid, 1932).

The conviction that burning, clearing, bad agricultural practices and overstocking were cumulatively the processes responsible for the damage became widely accepted in the 1930's, though not without dispute. This brought into being a series of campaigns to counteract the destructive processes involved. The reforestation campaign of the Forest Department aimed at ameliorating the position in Mlalo, "a very denuded and eroded neighbourhood" and elsewhere in the Usambaras. Parallel campaigns of the Agricultural Department attempted, in the first instance, the introduction of level bench terraces though this was soon abandoned in view of the labour and subsoil disturbance involved (LDF 3/14 Vol. II 107A). Live contour hedges replaced them.

Such separate remedies were soon subsumed however into a comprehensive structure of anti-erosion measures embodied in legislation. The impetus for this step stemmed partly from the determined efforts of individuals within the territory and partly from the increasing tempo of international concern with soil erosion and environmental deterioration. The Native Authority Ordinance of 1926 granted to Native Authorities powers to control burning and water use. In theory this placed the initiative with the traditional authority. In practice, the colonial administration employed the necessary combination of advice and persuasion to ensure that its concerns were legislated for. The 1930's saw the promulgation of sets of anti-erosion rules for most of the seriously threatened districts of the territory, generally containing provision for the protection of cultivated slopes and watercourses, for the control of burning, for the introduction of cover crops and the closure of steep slopes to cultivation.

These rules were not always enforced, though the number of prosecutions under the Act increased steadily, year by year (Annu. Rep., Prov. Comm., 1930 onwards). However, in the minds of many in the administrative and technical departments, they remained a sufficient solution, if properly enforced, for the problems of environmental deterioration.

A second dimension of the problem, identified at this time, was the assertion that traditional systems of cultivation and herding were breaking down under novel and increasing stresses: soil or pasture damage was a symptom rather than the disease itself.

This assertion had its origins in the assumption that traditional African societies had existed in some kind of equilibrium with their environment. Malthusian forces such as warfare, disease, drought, tsetse had preserved the overall balance. Steep slopes had remained unused and the fertility of cultivated lands had been maintained by long fallows. However, with the introduction of health and veterinary facilities, an end to internecine warfare and the growth of wage employment, it seemed that the old controls had lessened in their impact. Population and stock numbers, and hence the demand for land, had increased enormously. The resulting pressure was responsible for environmental deterioration.

The evidence for this assertion was in part the visible damage to the soil. There was also some evidence, though by no means conclusive, that the population in general was growing (Census, Native Population 1931, p. 3), that stock numbers were multiplying (VAR 1930, pp. 51—2) and the proportion of cultivated land under fallow was falling (Dobson 1940). And there was an assumption that the fertility of the soil—and its capacity to bear crops—was in decline (Harrison 1938, p. 217). Admittedly, substantive evidence for this last proposition must have been limited; published African crop yields for instance (Blue Books, 1926—30) by no means bear it out. But, or so the argument ran, systems of agriculture which, for the most part, did not practice manuring or any other form of fertilising, and which depended upon the fallow as a means of restoring fertility, were *ipso facto* vulnerable to population pressure. As R. D. Linton, then the agricultural officer responsible for the Usambaras, put it:

> "the greatly increased population of humans and cattle has given rise to overcultivation and overgrazing with the result that the reserves of moisture retaining humus and natural fertility have become so depleted that crop yields are no longer sufficient to feed that people. The land gets no rest and the cultivated areas are constantly trampled upon by livestock and this has accelerated the process of soil erosion" (LDF 3/14 Vol. II. 106)

One virtue of this definition of the problem is that, to some extent, it specified its solution. Cattle herding and cultivation had perforce to be integrated into a 'mixed rotational farming' system where manure was used to fertilise the soil. The concept of mixed farming as a basis for an improved agriculture became common currency in Tanganyika.

Another, and allied, dimension for the problem arose directly from changing British and international attitudes to the welfare of colonial peoples. One feature of traditional agricultural system was their seeming inability to provide anything but the minimum of subsistence; and the increasing concern of the Colonial Office and others for the nutrition of their charges (Nutrition Policy in the Colonial Empire, 1936) emphasised the need for a better, as well as an improved system of agriculture (Stockdale 1938). A better system was defined as one which would generate the necessary surplus for an improved standard of living while ensuring the protection of the soil.

## Reports and memoranda, 1942—45

It is tempting to read into the preamble of the 'Staples Report' (LDF 3/25.161, 1942), the first substantial proposal for a conservation project in the Usambaras, a measure of concern for each of the identified dimensions of the problem. The report dealt with the following issues

> "an increasing human and cattle population is bringing about a serious state of affairs on many of the steep slopes of this mountain block . . . it would not be advisable to prohibit the grazing of cattle as it seems that the future welfare of the people lies in the development of mixed farming . . . but the conservation measures need to be unusually and thoroughly well planned" (Ibid)

The recommendations of the report however, centred upon existing remedies, combined in a comprehensive system. A selected area of "at least some 2000 acres in size" would demonstrate and test the measures with a view to later extension throughout the range. The components of the system were the closure and afforestation of badly denuded areas, the construction of terrace banks and enforced manuring. These were augmented however by a proposal for an enforced extension of the area under fallow, but neither the manpower resources, nor the official will were adequate to ensure the implementation of this scheme at the time.

Between December 1944 and September 1945, F. J. Nutman submitted a series of memoranda to Government. The first of these (SMP 33049. vol. I. folio 9) outlined his proposals for the agricultural and industrial development of a large portion of the western Usambaras. The memorandum had been prompted by the realisation that an old timber ropeway, then unused, could be employed to link commercial production in the mountains with the railway that lay at their foot. Nutman envisaged a scheme which would "reconcile in a native area the conflicting claims of forestry, agriculture, industry and economics". The measures he suggested were numerous: the claims of agriculture, for instance, would be met by improved subsistence production and the growing of fruit and vegetables for export to the coast, portable mills and native pitsawers would exploit the forest, industry's scope would include ceramics, brick making, fibre board and carton manufacture, organised on a village basis. The area as a whole would become a "planned community" with a high and increasing standard of living.

The memorandum was not well received by Government. Many of those invited to comment on it felt that the scheme was impractical. The local reaction of administrative and technical officers in the Usambaras was that Nutman was unfamiliar with the area and therefore with its problems. The District Commissioner wrote:

> "apparently he is unaware that the Usambaras are overstocked with cattle and that . . . there are . . . large and increasing eroded areas which are a definite danger to agriculture and animal husbandry" (LDF 62/9.12)

Before preparing subsequent memoranda, Nutman discussed his proposals with R. D. Linton, meetings in which the accepted dimensions of the problem, as far as the Agricultural Department was concerned, were put to him. He later wrote:

> "the desirability of including the districts of Mlalo . . . in the scheme has been thrashed out. These areas are overpopulated, overstocked and are deteriorating with some rapidity . . . I feel bound to record the formidable extent . . . and the marked increase of erosion in the last few months" (SMP 33049. vol. I. 51)

The area, he felt, "has now reached the stage when sudden and complete collapse can shortly be expected" (Ibid. 59).

The argument of these latest proposals was that the basin contained a large and increasing population confined to a limited area where agriculture was the sole source of income. The high standard of living that prevailed had been brought by increasing pressure on the land; this had led to:

> "deforestation; abandonment in part of the sound native practice of shifting agriculture; extension of cultivation; decline of fertility; diminishing yields; and soil erosion"

This thesis was in part backed up by the results of a series of interviews with inhabitants of the basin.

Remedial measures proposed had to increase cash incomes while reducing the quantity of foodstuffs exported. Above all, the pressure on the land had to be reduced. The programmes envisaged included wattle planting, as an agent of erosion control on steep slopes and as a source of bark for an extractive industry, grass leys and the development of market gardening; de-stocking was suggested, as well as population movement from the basin.

Nutman's progressive emphasis upon environmental deterioration and the urgency of rehabilitation was sympathetically received; there was by then an awareness within the administration that:

> "a bold experiment on land reclamation and development, scientifically carried out, will have to be done in this Territory sooner or later" (33049. vol. I. 63)

## The provincial committee, and the decision to undertake the scheme

An important element in the administration's initial reaction to Nutman's proposals resulted from their imprecision and the absence of any evidence to support their argument or conclusions. The lack of substantive material in the initial memorandum had been responsible for the suggestion that a locally assembled team of administrative and technical experts be appointed to scrutinise the proposals (LDF 62/9. 12). This was later implemented with the establishment of a Provincial Committee. Most of the time of the committee was taken up with a close textual examination of Nutman's memoranda.

It was clear that the experience and opinions of the committee were at variance with a wide range of Nutman's assumptions. This was the case also over factual points and the members found it difficult to accept that Mlalo had even been a particularly fertile area (Minutes . . . of the Committee, Korogwe District File; KDF: 269/7 para. 7). They queried the assumption that cattle had been responsible for the initiation of soil erosion; "in their opinion, bad agriculture on steep slopes had begun what the grazing and trampling of cattle . . . are now finishing" (Ibid. para. 14). Other weaknesses were identified.

From this critique, the committee turned to Nutman's proposals, and in particular, to the suggestion that a wattle industry be established. Nutman argued strongly that diversification of the rural economy of the basin was essential; he suggested that erosion was certain to occur in an overcrowded community where the economy is based upon agriculture. The committee, by contrast, felt that there was no guarantee of the success of the wattle proposals for, if they failed, they would have absorbed arable land and, if they succeeded, there was the danger of a population influx to the basin. In any case, there were uninhabited areas elsewhere in the Usambaras which were intrinsically more suited to the project (Ibid. paras. 26, 32 and 55).

The committee agreed that "there was no soil erosion problem in the Mlalo Basin that a knowledgeable man could not solve with our present knowledge" (Ibid. para. 25) but recommended that "anti-soil-erosion measures should be enforced with the maximum diligence in the Mlalo area". But these measures could, and should, be complemented by steps to improve the basis of the economy of the area. Wattle growing was one possibility; grass leys for fodder another; a de-stocking programme another. But, before any of these alternatives could be implemented, it was necessary to know the actual carrying—capacity of the basin, for population and stock.

The point was that, for a balanced agriculture, either more grazing or substitute foodstuffs would have to be found, or the acreage of arable reduced. De-stocking, *per se,* was no answer; a manure shortage would result (Ibid. para. 40). The optimal balance under existing methods of agriculture was 10 acres per family for cultivation and 15 for grazing, if sufficient crops were to be produced without damage to the land (Ibid. para. 14). But, the present estimate of 4.48 acres per family was entirely insufficient. Therefore, either more land must be found (and the estimate checked) through an agricultural and village survey (Ibid. para. 61). Or, implicitly, an improved agricultural system must be designed.

The final decision of the meeting was that the village survey should be implemented. This should be followed by the demonstration and testing of a system of conservation methods in a experimental basin with the proposed methods "enforced" throughout.

## Conclusions

The "Staples Report" proposed existing remedies for the identified issue together with appropriate legislation and was hindered only by the inadequacy of available resources. Nutman, on the other hand, employed unfamiliar concepts in an individual interpretation of the Usambara problem that encountered considerable criticism in Government circles, resulting from its material defects, wrong focus, and bypassing of the real—and the increasingly urgent—evidence for environmental deterioration throughout the mountain range.

Increasing financial and manpower resources and colonial commitment to post-war development ensured that a modified version of the proposals came before a provincial committee where, however, the concern for rural industrialisation on the one hand and that for the prevention of soil erosion and reclaiming the land on the other were felt to be in opposition. A fundamental difficulty was the prevailing uncertainty about the condition of the basin.

This explicit uncertainty might not have been significant if the definition of the problem had been confined to effective soil conservation. But the conservation legislation which the Staples proposals embodied had not been designed with modifications to suit local conditions. Furthermore the decision-takers were concerned for the introduction of a 'balanced' farming system to the basin. In the light of this ambivalence, the need for further information about existing human and resource constraints upon agriculture, and the kind of agricultural system that would serve their purpose of change was evident. The commitment to village survey reflected the first need; the 'Staples' scheme, in actual implementation became the latter.

*Mr. John R. Watson, Ministry of Rural Development, P.O. Box RW 291, Lusaka, Zambia.*

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# COMPARISON OF SOME SOIL PROPERTIES IN ONE FOREST AND TWO GRASSLAND ECOSYSTEMS ON MOUNT MERU, TANZANIA

BY BJÖRN LUNDGREN AND LILL LUNDGREN

Department of Forestry, Makerere University, Kampala and Department of Physical Geography, University of Stockholm

ABSTRACT. In the Forest Belt on the eastern slopes of Mt. Meru, patches of open grassland exist within the forest. Previously, these grasslands were kept open by fire and grazing, but, since this part of the mountain was included in the Arusha National Park, it is probably mainly grazing by buffaloes that prevents the forest from invading parts of the open plots.

In this investigation a number of chemical and physical soil properties were studied under three vegetation types—one heavily grazed area, where the grass *Cynodon dactylon* dominates, one area which is dominated by tall, non-grazed tussock grasses, *Eleusine jaegeri* and *Setaria trinervia*, and finally an adjacent forest area.

The soil properties under the three vegetation regimes are compared. The age and origin of the grassland areas are discussed in light of the edaphic factors and findings of pieces of clay pottery and charcoal in the soil.

## Introduction

The present investigation was carried out on the E slopes of Mt. Meru, within the Arusha National Park, in August 1970 and February 1971.

Mt. Meru is situated in northern Tanzania, ca 80 km WSW of Mt. Kilimanjaro. The top of the mountain stands on latitude 3°14′ S and longitude 36°45′ E, the altitude being 4562 m (14966′) (Atlas of Tanzania, 1967). It rises steeply from the surrounding plains which lie at an altitude of ca 1500 m.

### *Geology and geomorphology*

Mt. Meru, like Kilimanjaro, is a young volcano of Pleistocene to Recent origin (Logachev 1969, pp. 11—12). The two volcanoes are, together with some other volcanic formations, located on a transverse branch of the southern Gregory Rift. The genesis of the mountain has recently been described by Krasnov (1968, pp. 42—46 and 1969 pp. 18—20), who distinguishes a number of different development stages. He describes the first stage as explosive, creating a mass of yellow tuffs. This was followed by an alternation of multiple eruptions that formed the main body of the mountain to a height considerably above the present, with snow and ice on the top.

The next stage included a collapse of the summit and the upper E side of the mountain. The rock masses lubricated with water, flowed out over the plains between Mt. Meru and Mt. Kilimanjaro, creating the present lahar (volcanic mudflow) topography in that area. This area is characterized by a complex of mounds and ridges, the depressions between them often being occupied by lakes or swamps. A paleolimnological study of some of these alkaline lakes dates the bottom sediments to only 6000 years, indicating this recent age of the lahar formation and collapse of the mountain (Hecky 1971, pp. 1—208). After the collapse a number of lava outflows have occurred, the latest in the second half of the nineteenth century (Guest and Leedal 1953, p. 44). At present the mountain seems to be in a stadium of weak fumarolic activity (Krasnov 1968, p. 46).

The surface lavas comprise a phonolitic series marked by the presence of nepheline and trachytes. Nepheline and other rock forming minerals are mainly alkaline in composition, having a low to medium silica content (Mauritz 1908, pp. 324—326, Oates 1934, p. 27, Guest and Leedal 1953, p. 41; Krasnov 1969, p. 20).

Only generalized descriptions on the soils of Mt. Meru are available. On the S and SW slopes, the lavas are covered by deep, homogenous ash deposits, the soils being immature, with little structural development.

On the E, collapsed side of the mountain, where the study area is situated, the soils are formed in the recent mudflow deposits and are normally shallow.

*Climate*

The SE, S and SW slopes receive more rain than the rest of the mountain. At Narok Forest Station on the S slopes (1830 m, lat. 3°20′ S, long 36°40′ E) the annual rainfall is 1811 mm, falling mainly during March—June and November—December (E. Afr. Met. Dept. records). No meteorological records exist from corresponding altitudes on the N and E slopes, although climatological measurements were commenced recently in some places in the Arusha National Park.

*Vegetation*

The S slopes of the mountain have a well developed Montane Forest Belt merging upwards into Ericaceous and finally Alpine Vegetation Belts (Hedberg 1951, pp. 177—180). The lower edge of the forest has been pushed upwards by intensive cultivation and the present forest line follows the Forest Reserve boundary. On the W and N slopes, the Forest Belt is narrower due to drier climate and repeated fires that have swept up the mountain, in one place leaving a continuous deforested strip from the Savanna to the Ericaceous Belt.

On the E collapsed slope the forest differs markedly from the rest of the mountain. Between appr. 1800 m and 2200 m a Lower Montane Forest, dominated by *Olea hochstetteri* and *Nuxia congesta,* is developed. The trees are strikingly low and much-branched and heavily covered with epiphytes (mosses, ferns etc.), features not normally associated with Lower Montane Forest with these species and on similar gentle slopes.

Above 2200 m and up to appr. 2600 m the forest changes into a Higher Montane Forest dominated by *Juniperus procera* and *Podocarpus gracilior,* the trees here being more typically tall and straight. Numerous glades and patches of open grassland of various sizes are found within the Forest Belt (see Fig. 1).

*History and landuse*

The early history of the area is not known. When the first Europeans arrived in the late nineteenth century the area just below the mountain was fought over by Masai groups. Early in this century the forests were set aside as Protection Forest Reserves and later they were also declared Game Reserves (Procter 1968, p. 66). During the 1940s and 1950s parts of the E slopes were cultivated for short periods by European pyrethrum growers and Kikuyu refugees. In 1967 the whole E side of the mountain was included in Arusha National Park.

*Reason for study*

The present study is one in a series of investigations carried out by the authors in mountain environments in Tanzania aiming at elucidating the influence of various land use and ecosystems on erosion, soil recovery and soil conditions. Studies of an early phase of soil recovery are being undertaken by the present authors on newly slide-exposed regolith surfaces at Mgeta in the Uluguru Mts. (see Temple and Rapp 1972) while the present study deals

Fig. 1. A full view of the E, collapsed side of Mt. Meru. In the foreground are lahar mounds. In the centre below the peak of the mountain, is the mosaic of grassland areas in the Forest Belt, where the study area is situated.

with a late phase of recovery of soils and vegetation.

The study was first initiated by Mr. Vesey-FitzGerald of Tanzania National Parks, who for a number of years has studied the impact of buffalo grazing in the forest glades in the Arusha National Park. The origin of the large grassland areas in the Forest Belt is not clear, though it is quite evident that they have been burnt and grazed by buffaloes and elephants for an unknown time. These factors, though they say nothing about the origin, are enough to explain why no forest has invaded the glades recently.

One of the aims of the study is to investigate any significant differences in the soil conditions between the grassland and the forest that could elucidate age and origin of the grasslands. Another aim will be to reconstruct at least some trends in the history of soil erosion and soil recovery on the E side of Mt. Meru. This report deals mainly with the first aim.

## The study areas

Three typical sample areas were subjectively chosen: one in forest, one on heavily grazed grassland and one on nongrazed grassland. The two grassland areas were situated adjacent to each other on almost level ground (see Fig. 2) and at an altitude of 1980 m. In order to find a typical forest area on equally level ground it was necessary to choose it about 1 km further up the slope at an altitude of 2070 m.

On the heavily grazed area (from now on called Gl-A) *Cynodon dactylon,* a stoloniferous perennial grass, forms a dense sward of about 10—15 cm height. Occasional herbs occur, e.g. *Caucalis incognita, Centella asiatica, Geranium arabicum, Oxalis corniculata* and *Stephania abyssinica.* No shrubs or tree seedlings are present.

The vegetation on the non-grazed grassland (from now on called Gl-B) consists of tall (about 50 cm), non-grazed tussocks of *Eleusine jaegeri* and *Setaria trinervia,* the tussocks cover-

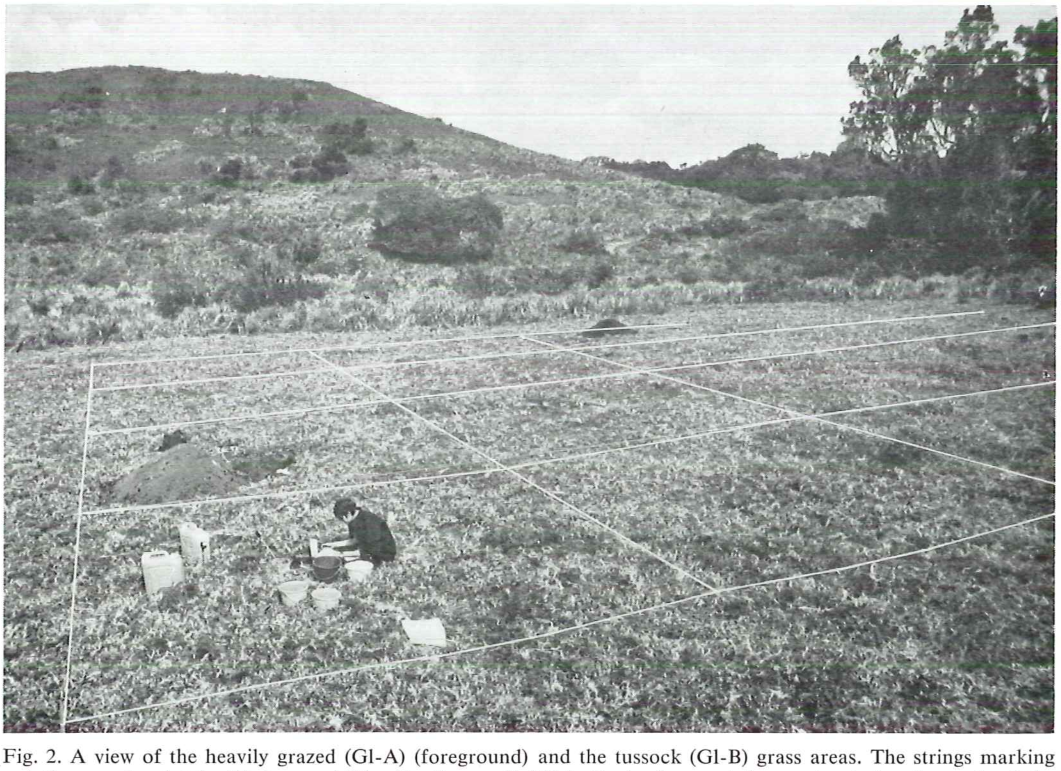

Fig. 2. A view of the heavily grazed (Gl-A) (foreground) and the tussock (Gl-B) grass areas. The strings marking out the sample plot in Gl-A are visible. On the small hill in the background the grazing-induced mosaic of the short *Cynodon dactylon* and the tall *Eleusine jaegeri*/*Setaria trinervia* is well developed. Young, woody regeneration is coming up in the tussock grass areas. To the right is a small group of old trees entirely surrounded by grassland.

ing 75—90 % of the surface area. Some climbing herbs are growing on the tussocks e.g. *Geranium arabicum, Stephania abyssinica* and *Rubia cordifolia*. On the spaces between the large tussocks *Centella asiatica* is dominant together with *Eleusine jaegeri, Geranium arabicum, Setaria trinervia, Stephania abyssinica* and *Viola abyssinica*. Some shrubs and typical forest colonizing species like *Bersama abyssinica* and *Clutia abyssinica* are also found here.

In the forest (from now on called Fo) the trees are rather widely spaced although in most places they form a closed canopy due to their much-branched growth. Common tree species are *Olea hochstetteri* (dominant) and *Croton megalocarpus, Ekebergia rueppiliana, Fagaropsis angolensis, Ficus thonningii, Nuxia congesta, Olea africana* and *Teclea simplicifolia*. The forest floor is dominated by *Drougetia debilis, Selaginella kraussiana* and an *Acanthaceae sp. indet.*

## Methods

In each of the three areas one sample plot, measuring 20 × 20 m, was marked out with strings. The sample plots were further divided into sixteen 5 × 5 m subplots, which were also marked out with strings (see Fig. 2). On three randomly chosen subplots, within each plot, soil samples were taken for chemical analyses from the depths 0—10, 10—20, 20—30, 30—40 and 40—50 cm. These samples were all collected with steel-cylinders, measuring 10.0 cm in height and 32.5 $cm^2$ in crossection. In addition, undisturbed soil cores were taken in the same way from one of the sixteen subplots for physical analyses. The profiles were described and some special samples were collected from structurally distinguishable horizons. Litter samples (1 $dm^2$) were collected from all sixteen subplots in each of the three sample plots. Water infiltration capacity of the soils was measured with a double-ring, constant head infiltrometer (inner ring 20 cm in diameter) in the Gl-A and Fo plots. The thick and hard grassroot layer in Gl-B prevented the measurements of infiltration there.

## Analyses

*Physical analyses*

The cylinder samples taken for analyses of physical soil properties were immediately sealed after collection and weighed the same day to be able to calculate current water content. In the laboratory, these samples were used to determine the water content at field capacity (1/3 atm.) and wilting point (15 atm.) with the membrane method. Bulk density, specific gravity and pore volume were determined as well as analyses of the texture.

*Chemical analyses*

Air drying of the samples was carried out in the field.

Total contents of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) were determined in both the soil and the litter samples. Available P and K were determined for the soil samples only. Furthermore, the following analyses were determined for the soil samples only: organic carbon (C) content, electrical conductivity (EC), cation exchange capacity (CEC), total exchangeable bases and silica/sesquioxide ratio ($SiO_2/R_2O_3$). Loss on ignition and pH (in $H_2O$ and KCl) were determined for both soil and litter samples.

## Results

*Description of the profiles*

Since the soil sampling procedure for chemical and physical analyses was carried out for quantitative ecological studies rather than for qualitative pedological descriptions, the results of the analyses are in some cases only (when a 10 cm sample falls wholly within a distinguished genetical horizon) directly applicable to the horizons described. The horizons have been distinguished on the basis of their visible features such as colour, structure, amounts of roots and texture as decided roughly in the field.

Little, if any, pedological work has been carried out on Mt. Meru. According to the Atlas of Tanzania (1967, p. 3A) in which D'Hoore's soil classification has been adopted (D'Hoore 1964, pp. 92—93), the soil type on the slopes of Mt. Meru is an "eutrophic brown soil on volcanic ash, lava or pumice" (mapping unit Ha) and the soil type on the lahar is classified as a "lithosol on basic parent materials (lavas)" (mapping unit Ba).

According to the FAO classification (1968, p. 12) the present profiles should be classified as *Vitric Andosols* (mapping unit Tv) and according to the American 7th Approximation

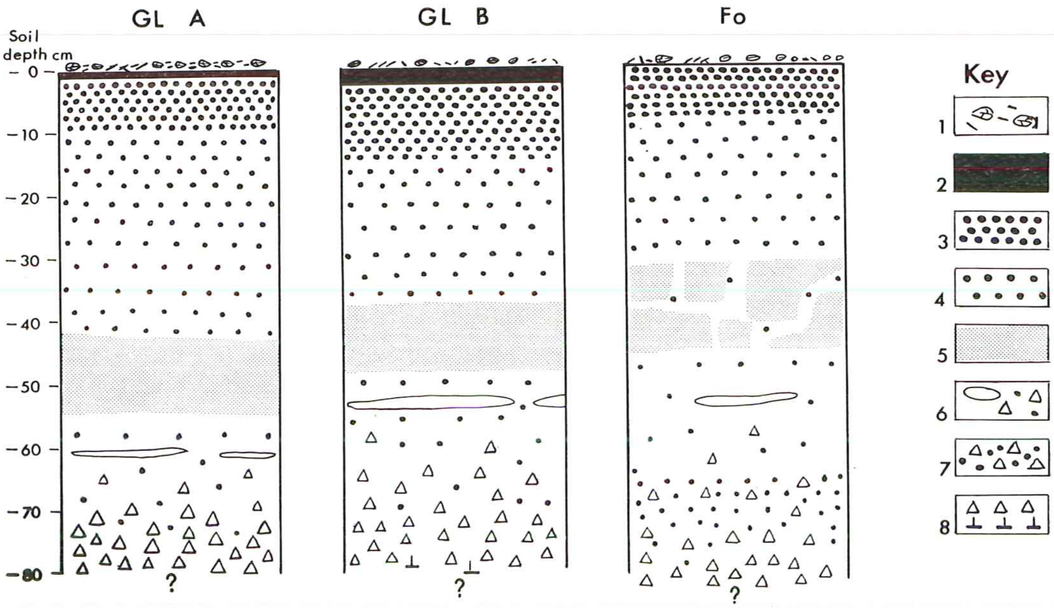


Fig. 3. Symbols:
1 = *Litter*, undecomposed.
2 = *Decomposing humus*, dense development of fine roots, some mineral particles present.
3 = *Topsoil*, loose, fine to medium, granular structure, high humus content, loss on ignition appr. 30 %, dark reddish brown (5YR 2/2), low bulk density 0.6—0.7 g/cm³ (air dry), many roots.
4 = *Transition horizon*, no or very weakly developed granular structure, loss on ignition: 12—22 %, dark brown (7.5 YR 3/2), bulk density: 0.7—0.9 g/cm³ (air dry), fairly many, evenly spread roots (tree roots in Fo).
5 = *Duripan* ("padas"), very hard, loss on ignition: 3—7 %, dark grey brown (2.5 Y 4/2), high bulk density: 1.2—1.4 g/cm³ (air dry), $SiO_2$ content higher (appr. 40 %) than in the horizon above (appr. 35 %), in Gl-A and Gl-B the hardpan is unbroken and seems to prevent root penetration, in Fo it is more irregular allowing a few roots to penetrate.
6 = *Subsoil*, varying horizon, grey, greyish brown to light brown in colour, increasing percentage of pebbles and stones with depth, very few roots, in some of the pits lenses of sand.
7 = *Buried humic horizon* (in Fo only), loss on ignition: 10 %, dark brown (7.5 YR 3/2), bulk density: 0.9 g/cm³ (air dry), roots that have penetrated the duripan have spread out in this horizon.
8 = *Stones and gravel* in the bottom, in at least two pits the rock was reached.

(U.S.D.A. 1960, pp. 139—141 and 1967, pp. 89—91) they are *Durandepts.*

The Gl-A and Gl-B profiles are very similar to each other with only some minor, though significant, differences (see Fig 3). In the forest, the profile shows some marked dissimilarities although the general picture is the same. The duripan is irregularly developed here whereas in the Gl plots it is a continuous, unbroken pan running parallel to the surface. This type of duripan, "padas", is a common feature in coarse textured young volcanic soils (Buringh 1970, pp. 88—93). Furthermore, a buried horizon, at appr. 60—70 cm depth was reached in two of the forest pits (see Fig. 3). No such horizon was found in the grassland area.

The texture of the soils is coarse with increasing percentage of sand with depth. Clay content is less than 10 % throughout all the three profiles. All the studied areas seem to have shallow soils. In none of the pits was it possible to dig further down than 80—90 cm due to the high frequency of stones. At least in two of the pits, the underlying rock was reached. The shallow soil, possibly in combination with the duripan, is most likely the reason for the low, much-branched growth of the trees in the area.

Pieces of charcoal were found in many of the pits, both above and below the duripan. A sample taken *below the duripan* in the forest was dated by $C^{14}$-method to 765±100 years BP

(= 1950) and one sample *above the duripan* in Gl-A was dated to 970±205 years BP.

In some of the pits in both Gl-A and Gl-B pieces of clay pottery were found at about 30 cm depth or just above the duripan. This will be discussed below.

Since this part of the work did not aim at studying the pedological features no attempt shall be made here to conclude about the genesis of the soil types. In a later phase of the work, however, the soil profiles and their stratigraphy will be used to analyse the history of soil erosion in the area.

*Litter*

Litter samples were collected and analysed for the quantity and quality of the undecomposed plant and animal debris, factors that normally have a profound influence on the properties of the topsoil. The results are summarized in Table 1. In Gl-A and Gl-B the litter is mainly made up of dead grass while in the forest, leaves, twigs, bark etc. from the trees form the bulk of the litter. The larger amount of litter accumulated in Gl-B, relative to Gl-A, is probably not so much due to a slower rate of decomposition as to the fact that much living biomass is removed from Gl-A through grazing. There is a markedly higher content of N, P and K in the grass litter compared to the forest litter whereas this contains a significantly higher amount of Ca. The Mg level seems to be similar in all litter samples. Comparing the two grassland types it is clear that the nutrient content is higher in the litter under the grazed *Cynodon dactylon* sward than under the *Eleusine jaegeri* and *Setaria trinervia* tussocks, except for K, which is higher in the latter type. Since the three mentioned grass species constitute the bulk of the biomass in their respective ecosystems it can quite certainly be concluded that the quality of the litter is a reflection of the nutrient contents and, hence, requirements (since they are growing under almost identical environmental conditions) of the species. The pattern of the distribution of the available forms of the analysed nutrients in the profile can thus be used as an indication of the relative time the area has been under the different vegetation types.

*Physical properties*

The soil of the investigated areas possess some of the typical physical features associated with young volcanic soils.

The results of the physical analyses are summarized in Table 2 (particle size distribution), Table 3 (bulk density), Fig. 4 (porosity and water content at field capacity and wilting point) and Fig. 5 (infiltration capacity).

Unlike the silty ash deposits on the S side of Mt. Meru, the soils in the study area are coarse-textured. In view of the fact that the particle size analyses have been carried out on one set of samples only, from each of the three ecosystems, there is a striking similarity in the results which suggest a similar genesis of the soils. The higher content of material coarser than 2 mm in the 40—50 cm sample in Gl-A is merely because the gravelly and stony subsoil was reached in the specific pit where the sample was taken. There is a slight tendency in all sample sets for increasingly finer texture in upper samples, indicating a low and uniform degree of weathering.

The bulk density values are comparatively low, except in the duripan, the location of which is obvious in Gl-A and Gl-B at 40—50 cm depth. In the Fo there is only a slight increase in bulk density at the 30—40 cm depth due to the previously mentioned irregular development of the duripan there.

*Table 1* Quantity and quality of the litter in the three ecosystems.

| Area | Amount of litter kg/ha (air dry) | pH (in $H_2O$) | $N_{tot}$ | | $P_{tot}$ | | $K_{tot}$ | | $Ca_{tot}$ | | $Mg_{tot}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | % | kg/ha | % | kg/ha | % | kg/ha | % | kg/ha | % | kg/ha |
| Gl-A | 4200 | 6,1 | 2.48 | 104 | 0.29 | 12 | 0.34 | 14 | 1.56 | 65 | 0.22 | 9 |
| Gl-B | 7800 | 5.8 | 2.04 | 159 | 0.22 | 17 | 0.45 | 35 | 0.93 | 73 | 0.16 | 12 |
| Fo | 5600 | 6.1 | 1.84 | 103 | 0.18 | 10 | 0.26 | 15 | 1.93 | 108 | 0.23 | 12 |

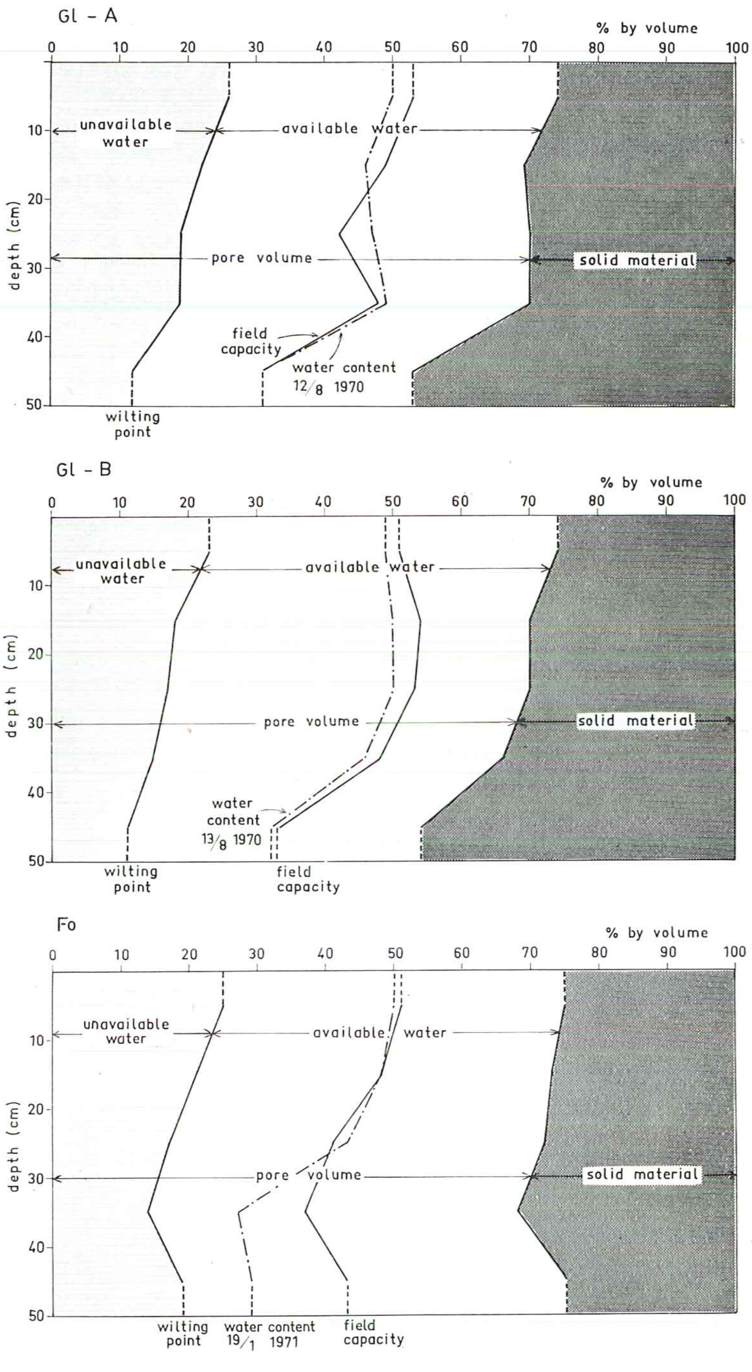


Fig. 4. The distribution of solid material and pore volume in one 0—50 cm profile from the heavily grazed (Gl-A), the tussock (Gl-B) and the forest (Fo) areas. Soil moisture content at field capacity and wilting point, determined as the moisture retained at 1/3 atm. and 15 atm. respectively, are shown. As an example, the soil moisture contents on the days of sampling have been drawn.

Considering the 0—30 cm depths, there is a striking similarity between all three profiles in per cent of solid material, pore volume, moisture content at wilting point (unavailable water) and field capacity. In the Gl-A and Gl-B profiles, where the duripan is regularly developed and is situated at the same depth (40—50 cm), the similarity continues down to 50 cm. In the Fo, the duripan is irregularly developed at 30—40 cm depth, which is clearly visible in the Fig.

The general distribution of solid material and pores in the three profiles is the same, except for the irregular duripan development in Fo and its position closer to the surface, which is clearly visible (see Fig. 4). Pore volume is high and, consequently, the solid material percentage low as compared to most other mineral soils. The percentage of water retained at 15





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*Table 2* Analyses of the particle size distribution from the three areas. Fraction in % by weight. Grain sizes: gravel (>2 mm), coarse sand (2–0.2), fine sand (0.2–0.02), silt (0.02–0.002), clay (<0.002 mm).

| Area | Particle class | Depth (cm) 0–10 | 10–20 | 20–30 | 30–40 | 40–50 |
|---|---|---|---|---|---|---|
| Gl-A | gravel | 1 | 3 | 1 | 2 | 12 |
| | coarse sand | 20 | 15 | 18 | 24 | 29 |
| | fine sand | 31 | 38 | 40 | 41 | 35 |
| | silt | 39 | 35 | 34 | 28 | 20 |
| | clay | 9 | 9 | 7 | 5 | 4 |
| Gl-B | gravel | 2 | 3 | — | — | 1 |
| | coarse sand | 17 | 18 | 18 | 24 | 31 |
| | fine sand | 38 | 37 | 34 | 39 | 40 |
| | silt | 37 | 34 | 38 | 34 | 24 |
| | clay | 6 | 8 | 10 | 3 | 4 |
| Fo | gravel | — | 7 | 1 | 1 | 1 |
| | coarse sand | 19 | 19 | 24 | 23 | 27 |
| | fine sand | 42 | 39 | 41 | 43 | 44 |
| | silt | 32 | 29 | 29 | 29 | 24 |
| | clay | 7 | 6 | 5 | 4 | 4 |

atm. suction (permanent wilting point) is surprisingly high in view of the coarse texture. This is probably due to the presence of allophane (amorphic hydrated aluminium silicates) in the clay fraction and the relatively high amount of organic matter. Here also the irregularities caused by the duripan are reflected. The amounts of water available to plants in the 0—50 cm layer at field capacity (1/3 atm. suction) are 125 mm, 155 mm and 124 mm respectively in Gl-A, Gl-B and Fo. For comparison the amounts available at the respective dates of sampling have been marked out. The corresponding values in mm are 125, 143 and 101.

The eye-fit curves in Fig. 5 have been drawn from the infiltration capacity measurements in Gl-A and Fo. In Gl-A the infiltration comes to an equilibrium at 25 mm/h and in Fo at 38 mm/h. Most likely the difference is due to the unbroken duripan in Gl-A which prevents faster infiltration. In Fo the irregular duripan allows deep percolation of the water. Other factors affecting the infiltration capacity, e.g. pore volume, texture, organic matter and initial moisture content are very similar.

### *Chemical properties*

The results of the chemical soil analyses are summarized in Table 4. To allow an easier direct comparison, six important chemical pro-

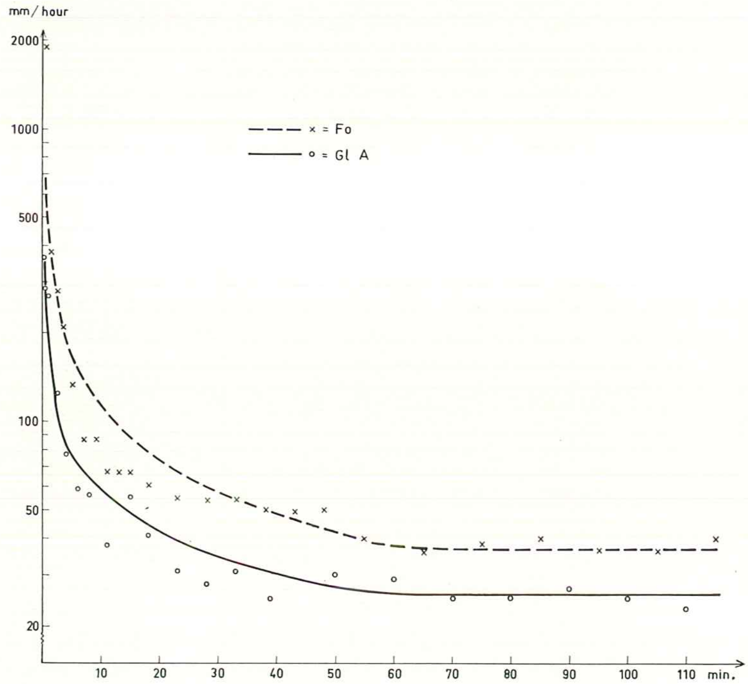


Fig. 5. Infiltration capacity graphs for the heavily grazed grassland (Gl-A) and the forest (Fo). The measurements were conducted with a double ring infiltrometer.

*Table 3* Bulk density in g/cm³ of oven-dry (105° C) samples.

| Area | Depth (cm) | | | | |
|---|---|---|---|---|---|
| | 0–10 | 10–20 | 20–30 | 30–40 | 40–50 |
| Gl-A | 0.54 | 0.72 | 0.69 | 0.76 | 1.29 |
| Gl-B | 0.54 | 0.71 | 0.72 | 0.84 | 1.29 |
| Fo | 0.56 | 0.67 | 0.71 | 0.84 | 0.66 |

perties have been presented in graph form in Fig. 6.

It should be noted that all the present chemical results are averages of three samples, as described above in Methods. For some properties, where the variation is small between the samples, this gives a fairly good value, whereas others are less accurate. It must also be borne in mind that the results of many chemical analyses on soil samples from andosols are difficult to use for comparison with other soil types due, among other factors, to the special water and exchange properties of the allophane. The analyses are however useful for the present purpose of comparing soil data from the three ecosystems on the same soil type.

The pH-trends (Table 3 and Fig. 6) differ markedly between the Gl-A and Gl-B on one side and Fo on the other. In both the grassland soils the pH increases with depth, while in the forest soil it decreases. At the 40—50 cm depth the values are the same. There seems to be an obvious correlation of the pH values to the total Ca levels, these being appreciably higher in the Fo topsoil than in Gl-A and Gl-B while here also the values converge towards the same levels in the 30—50 cm layers.

Loss on ignition, C and N amounts are all closely related to the organic matter fraction of the soil. All these values are slightly higher in the Gl-A than in the other two ecosystems. In Fo the influence of the buried humic horizon is visible in the 40—50 cm layer in that the organic matter and related properties show a slight increase.

The C/N ratios indicate fairly well decomposed humus in all the soils without any significant difference between the three.

Analyses of the total amounts of various elements in the soil are mostly interesting from a mineralogical point of view, since they mainly reflect the plant-unavailable mineral-bound fractions of the element. Uniformity in the amounts of some elements between different areas can be used as an indication of similar mineralogical origin. The total amounts of some of the major elements can however be used to study various aspects, e.g., in the case of some plant nutrients, the magnitude of plant uptake from deeper soil layers and redistribution to the topsoil by the litter decomposition. Also from a pedological viewpoint analyses of total amounts of minerals might yield interesting results regarding leaching and concentration of the elements in various horizons.

Though P is a major plant nutrient there is a marked similarity both in magnitude and distribution within the profile between the three ecosystems. A slightly lower level might be distinguished just below the topsoil in Gl-B. There are two interesting features in the distribution of K. One is the obvious concentration in the duripan (40—50 cm in Gl-A and Gl-B, 30—40 cm in Fo), the other the generally higher level in the forest compared to the grassland areas. In the case of Ca there is an even more pronounced difference between the forest and the grassland values in that the topsoil values are considerably higher in the forest than in the grassland. Gl-B in turn has lower values than Gl-A. These results correspond well to the litter analyses. In Gl-A and Gl-B the Ca levels are slightly higher in the duripan. Mg levels and distribution are very similar in the three plots, probably due to the small, though vital, amounts required by plants.

The exchangeable amounts of P and K are more direct indices of the relative fertility of the soil, although the present values should not be compared with other soils without great caution. The much higher P values in the 0—10 cm layers in all three ecosystems is a natural property because of the release of exchangeable P at litter decomposition. There are however two noteworthy features in the exchangeable P distribution. It is difficult to explain the apparent minimum levels reached at the 10—30 cm depths in all three areas. The higher values obtained at all soil depths under Gl-A compared to both Gl-B and Fo are also difficult to explain. There is hardly any support for the belief that it could be caused by some specific plant requirements here. Although the percent content of P in the litter layer in Gl-A

*Table 4* Summary of all chemical analyses. All values quoted are averages of three different samples from the same level in each of the ecosystems.

| Area | Depth (cm) | pH in $H_2O$ | pH in KCl | Loss on ignition % | EC (20° C) μmho/cm | C % | $N_{tot}$ % | C/N | Total amount P % | Total amount K % | Total amount Ca % | Total amount Mg % | Exchangeable P mg/100 g | Exchangeable K mg/100 g | CEC me/100 g | V % | $SiO_2$ % | $SiO_2/R_2O_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gl-A | 0–10 | 5.5 | 5.2 | 35.6 | 932 | 15.9 | 1.68 | 10.4 | 0.55 | 0.37 | 1.59 | 0.26 | 16.1 | 145 | 74 | 62 | | |
| | 10–20 | 6.0 | 5.4 | 21.0 | 233 | 8.9 | 0.96 | 10.0 | 0.58 | 0.49 | 1.51 | 0.33 | 5.4 | 145 | 45 | 56 | 34.6 | 1.5 |
| | 20–30 | 6.0 | 5.3 | 16.9 | 137 | 6.7 | 0.73 | 9.8 | 0.55 | 0.52 | 1.47 | 0.33 | 4.5 | 178 | 36 | 50 | | |
| | 30–40 | 6.0 | 5.2 | 12.8 | 116 | 4.7 | 0.53 | 9.3 | 0.52 | 0.62 | 1.46 | 0.37 | 6.9 | 246 | 25 | 52 | | |
| | 40–50 | 6.3 | 5.3 | 6.2 | 75 | 1.8 | 0.20 | 9.0 | 0.46 | 0.75 | 1.63 | 0.45 | 8.8 | 275 | 10 | 70 | 39.7 | 1.6 |
| Gl-B | 0–10 | 5.3 | 4.9 | 33.5 | 638 | 14.6 | 1.40 | 11.4 | 0.58 | 0.35 | 1.42 | 0.25 | 15.2 | 188 | 70 | 49 | | |
| | 10–20 | 5.5 | 4.9 | 21.5 | 194 | 8.3 | 0.89 | 10.1 | 0.50 | 0.43 | 1.21 | 0.29 | 2.7 | 114 | 36 | 33 | 34.7 | 1.7 |
| | 20–30 | 5.7 | 5.0 | 16.2 | 123 | 6.4 | 0.70 | 9.7 | 0.49 | 0.46 | 1.19 | 0.32 | 1.4 | 128 | 27 | 41 | | |
| | 30–40 | 5.8 | 5.0 | 10.0 | 68 | 3.1 | 0.37 | 8.7 | 0.44 | 0.61 | 1.51 | 0.41 | 2.2 | 167 | 15 | 27 | | |
| | 40–50 | 6.1 | 4.9 | 7.0 | 52 | 2.0 | 0.22 | 9.4 | 0.42 | 0.74 | 1.62 | 0.41 | 4.1 | 228 | 11 | 45 | 39.5 | 1.5 |
| Fo | 0–10 | 6.6 | 5.9 | 31.2 | 543 | 13.3 | 1.52 | 9.6 | 0.55 | 0.47 | 2.15 | 0.28 | 9.5 | 149 | 65 | 63 | | |
| | 10–20 | 6.3 | 5.6 | 18.3 | 263 | 7.3 | 0.87 | 9.0 | 0.59 | 0.61 | 1.76 | 0.35 | 1.2 | 175 | 46 | 37 | 36.1 | 1.5 |
| | 20–30 | 6.1 | 5.3 | 13.1 | 159 | 4.9 | 0.58 | 8.9 | 0.54 | 0.69 | 1.66 | 0.39 | 1.3 | 206 | 33 | 45 | | |
| | 30–40 | 6.2 | 5.3 | 9.1 | 94 | 2.8 | 0.32 | 9.1 | 0.48 | 0.76 | 1.62 | 0.41 | 2,4 | 232 | 27 | 33 | | |
| | 40–50 | 6.2 | 5.1 | 8.9 | 107 | 3.3 | 0.39 | 8.7 | 0.45 | 0.64 | 1.46 | 0.33 | 3,1 | 209 | 29 | 28 | 43.2 | 1.7 |

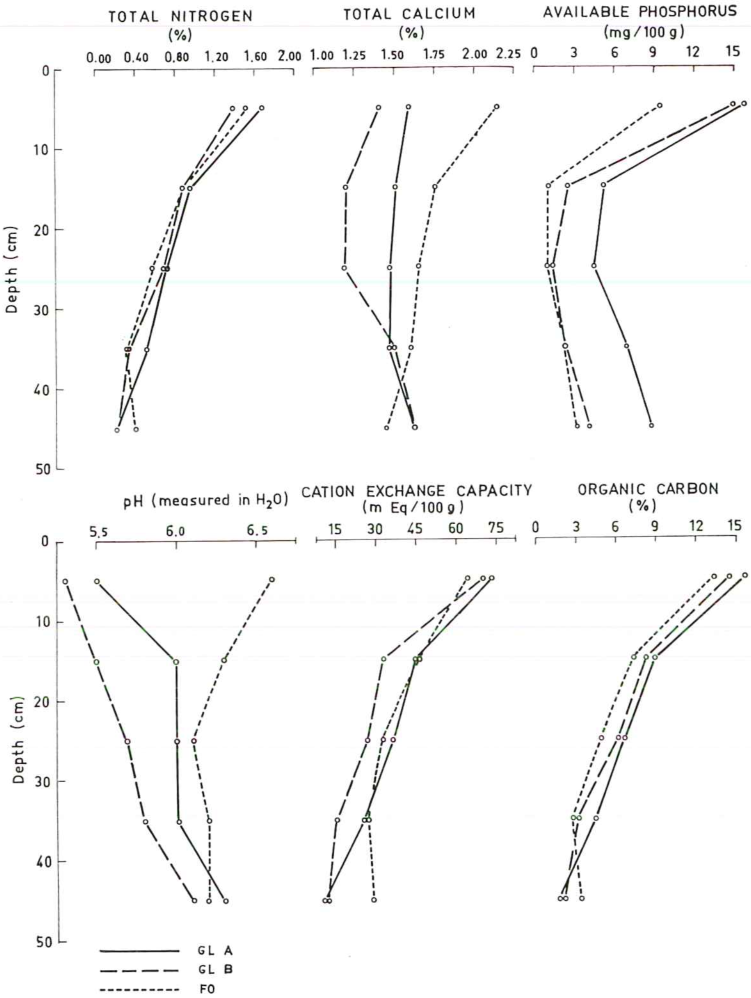


Fig. 6. The variation of six chemical soil properties in the 0—50 cm soil layers in the three investigated ecosystems. Organic carbon and total nitrogen contents are very similar in the three soils. The slight increase in the 40—50 cm layer in the forest (Fo) is caused by the fact that two of the three samples at this depth partly reached the buried humic horizon. Cation exchange capacity determinations are quite uncertain, but the magnitudes seem to be of the same order in the three ecosystems. pH and total calcium figures are significantly higher in the Fo topsoil. They are converging towards the same levels at the 30—50 cm depths. The exchangeable or available phosphorus graphs all follow the same shape with an apparent minimum level at 10—30 cm depths. The absolute level is much higher in the heavily grazed grassland (Gl-A) subsoil than in the two others.

Note that figures for organic carbon refers to per cent by air dry weight while total nitrogen and calcium refers to per cent by oven dry (105° C) weight.

is higher, the amount expressed as kg/ha is not (see Table 1). The only plausible explanation is the higher degree of fertilization by animal droppings in this heavily grazed area compared to the others.

The figures of exchangeable K also show two notable features. One is the higher levels in the duripan layer which directly correspond to the total K figures. The other is the higher level in the 0—10 cm layer and lower values in the 10—30 cm layers under Gl-B compared to the other two ecosystems. This supports the idea that the main grass species at Gl-B have a high requirement of K, which is reflected in the redistribution of the element from the up-taking zone to the upper parts of the topsoil where the decomposition of the K-rich litter gives higher values.

Since the cation exchange capacity (CEC) and base saturation (V) figures are fairly inaccurate due to difficulties in the analyses, no comments will be made upon these features, except that the general levels are high to very high in all three areas.

The $SiO_2$ and $SiO_2/R_2O_3$ (sesquioxides) ratio are normally used as a measure of the degree of weathering of the mineral soil and are mainly interesting for mineralogical and soil classification purposes. They are presented here only to lend support to the theory that "padas", duripans, in coarse textured andosolic soils, are silica-cemented.

## Discussion

No conclusive facts have been brought forward by this investigation to indicate that the glades are caused by some edaphic factor preventing forest from establishing itself. Most of the investigated physical and chemical soil factors rather underline the great similarity in initial soil conditions. The differences that do exist, e.g. the Ca content and pH values, are much more likely to be the result of the differences in vegetation than vice versa. In the case of Ca this is supported by the litter analyses.

It seems most likely that the more irregular development of the duripan in the forest than in the two grassland plots is a result of the penetrating force of the larger tree roots and the disturbances in the soil by windfalls. However, the influence of the duripan on the vegetation needs a more detailed investigation before it can be concluded that this difference is not decisive to the regeneration of trees. Groups of trees of the same species and sizes as in the surrounding forest occur in the glades indicating a former lager extent of the forest. As has been mentioned earlier, fires and grazing are most likely the agents that have prevented forest regeneration. This is supported by the presence of young trees of typical colonizing species, such as *Bersama abyssinica* and *Clutia abyssinica,* in the areas of high tussock grasses (Fig. 2). These must have been established during the last ten years, when it is known that no fires have effected the glades (Vesey-FitzGerald, personal communication). Also the forest edge shows typical signs of recent expansion onto the glades (Fig. 7). The distribution of the tussock grass and the short, grazed sward is a typical example of a grazing mosaic as described by Vesey-FitzGerald (1965, pp. 42—44 and 1969 pp. 134—138). The relative areas of the different grass types are an indication of the grazing pressure. There is a slight tendency for a higher content of organic matter and definitely a higher level of available P in the soil under the short grass compared to the tussock. This might be an indication that the vegetation in the two plots has been different for a relatively long time, since the vegetation and probably the fertilization by buffalo droppings have caused measureable differences in the chemical soil properties. The evident redistribution of exchangeable K from the zone of nutrient uptake to the topsoil via the tus-

Fig. 7. A representative picture of the forest-grassland mosaic, showing the three investigated ecosystems. On the forest edges, young shrubs and trees indicate the expansion of the forest onto the glades, a result of absence of fires for the last ten years. The short, much-branched growth of the trees (see text) is also visible.

sock-grass also supports this hypothesis.

The pieces of clay pottery at 30—40 cm depth in three of the six grassland pits are an interesting indication of early human influences on the glades. However scanty these findings might be as evidence for the origin of the glades, they become much more valuable when seen in relation to a similar study, carried out in the West Kilimanjaro area in 1958—60 by Wood (1965, pp. 108—111). Here also, large open glades within the Forest Belt have been studied with the object of finding out their origin. Altitude and climate are similar to the present study area. The soils are also volcanic, but are older, deeper and more weathered. It must also be remembered that the areas are situated only 70 km apart, so there is reason to suspect a similar cultural history.

Wood discusses the influence of different biotic and abiotic factors on the origin, maintenance and fluctuations of the glades. Numerous findings of obsidian tools and arrowheads in the soil in combination with certain vegetational evidences of cultivation lead him to the hypothesis that the glades were originally clearings for cultivation taken up during early, dry periods. After these early cultivations the glades have been kept open and even expanded by fire, grazing by wild animals and by Masai cattle. The latter are known to have used the West Kilimanjaro glades for dry season grazing for a very long time.

In the present investigation, $C^{14}$-analyses of charcoal samples collected from the same soil depths as the pieces of clay pottery gave a value of $970 \pm 205$ years appr. corresponding to 800—1200 A.D. Dale (1954, p. 28) believes that the dry conditions that prevailed in East Africa during the fourth, fifth and eighth centuries lead to the smallest area of high forest, excluding mountain forests, in the Christian era around 1000 A.D. Thus it is probable that people moved up in the relatively wetter Montane Forest Belts to take up cultivations during this time. The $C^{14}$-dated pieces of charcoal, found at 30—40 cm depth, give an indication of the speed of recent soil deposition in the study area.

## Conclusion

No edaphic factors are likely to have caused the present distribution of open grasslands in the Forest Belts on the E slopes of Mt Meru. Certain indications, such as the finding of pieces of pottery and $C^{14}$-dated charcoal as well as agreement with some of the cited theories of Wood (1965, p. 110) and Dale (1954, p. 28), rather suggest that human clearings in the Forest Belt during early, drier periods gave rise to the openings. These have then been kept open until now by fires and grazing.

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*Mr. Björn Lundgren, Department of Forestry, Makerere University, P.O. Box 7062, Kampala, Uganda. Mrs. Lill Lundgren, Department of Physical Geography, University of Stockholm, Box 6801, S-113 86 Stockholm.*

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# SOIL CONSERVATION POLICIES IN THE SEMI-ARID REGIONS OF TANZANIA, A HISTORICAL PERSPECTIVE

BY LEN BERRY AND JANET TOWNSHEND

Both formerly of BRALUP, University of Dar es Salaam

ABSTRACT. The semi-arid regions of Tanzania have been plagued by problems of soil erosion, at least since 1900. This paper outlines the various approaches to these problems in the dry areas of the country in the period 1900—1970.

The causes of erosion given by the colonial administration are presented together with an examination of the agents of conservation.

Some of the more important conservation schemes and techniques are reviewed and the reasons for their comparative success or failure are discussed.

## Introduction

Measurement of rates of erosion generally show the occurrence of much higher rates in steeply sloping areas. For example, Corbel (1964) shows mountain areas to have, on average, rates 10—20 times higher than the lowlands and figures presented by Fournier (1960), although disagreeing in many other points, show similar differences of erosion rates with relief. Perhaps in response to this, perhaps because of the more defined nature of the problem, or because of the attractiveness of the landscape, much more attention has generally been given in Tanzania to the problem of soil erosion in the mountains.

However, the semi-arid plateau areas of Tanzania have equally pressing problems. Erosion rates are high and replacement rates of soil are a good deal lower than in the upland areas. The effect of soil erosion on land and people is thus considerable. Solutions of the physical problems are more difficult in these areas because the use of land and the resultant erosion and deposition are intrinsically bound up with the cultural and social systems. Cattle and more cattle are an important part of social wealth and prestige to the farmer. For example as Rigby's recent work clearly shows, a considerable mobility in the face of drought or other land problems is a normal preservation device for the Wagogo (Rigby 1970). That is to say, if land is scarce or useless, the solution is to move and not to improve existing land. This is in strong contrast to the mountain areas where land is scarce and is a vital possession. Thus in the mountains an individual farmer is more likely to handle his land carefully.

Increasing population, both human and animal, serve to steadily intensify the problem of a diminishing resource base in the plains. Solutions demand a major reappraisal of the physical and human use of the area. While overgrazing is the predominant problem in some areas such as Arusha, Mbulu and parts of Singida, erosion on cultivated land is equally menacing.

The main areas considered in this review are Sukumaland, the old Central Province of Tanganyika, Masailand and Mbulu District (Fig. 1). The historical analysis is meant to serve as a background to the following three contemporary studies of erosion in these areas. It is meant also as an indication that few easy solutions can be expected.

## Historical background

Soil erosion has been a problem to be faced in parts of Tanzania, at least since the beginning of this century. By 1930, soil erosion was a menace in a number of areas. Gillman writes:

"It (erosion) is, thus, most concentrated in the more densely settled regions of the semi-arid country in the tilt-block topography of the Great Rift with its comparatively loose and shallow and dominatingly granitic soils: Ugogo, Irangi, Unyaturu, Isanzu and S. E. Usukuma are the typical representatives of far advanced erosion. Surrounding this "core-land", marginal lands often extending from the severer climate expressed by thornbush into the slightly moister type indicated by *Brachystegia* dry savannah forest, carry areas of soil erosion, and these areas seem to grow in extent in proportion to the density of population, i.e., in proportion to the extent of artificially created "culture steppe". Northern Usukuma, Songea, parts of Ufipa and Uha are typical examples. Purely nomadic grazing, on the other hand, as e.g., in much of the Masai and Mangati country, where the scarcity of

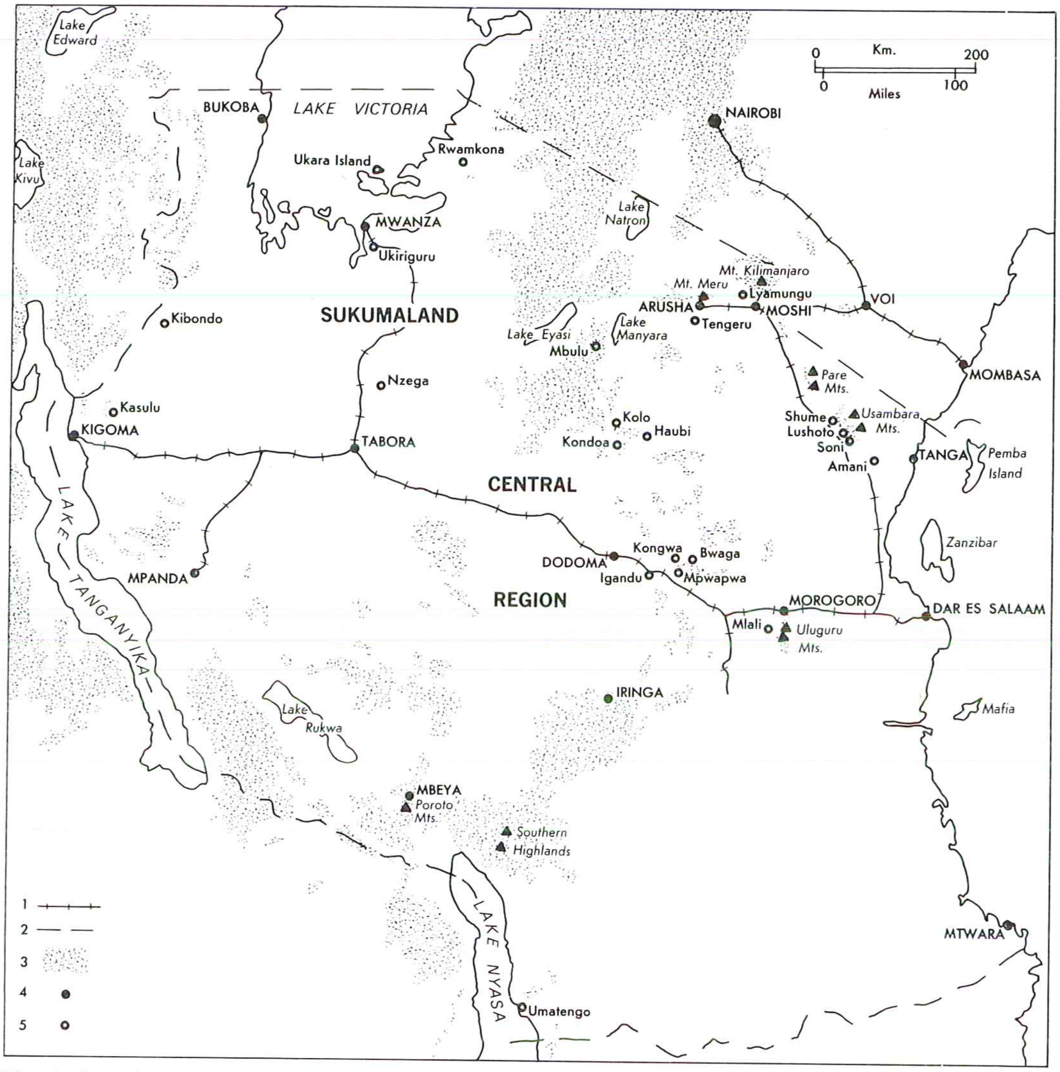


Fig. 1. Location map. Key: 1 = Railway. 2 = National boundary. 3 = Highland. 4 = Important town. 5 = Other place mentioned in text.

natural water supplies is the best safeguard against overstocking, is decidedly free from soil erosion, except in the vicinity of water holes where periodic concentration of cattle takes place." (Gillman 1930, p. 5).

Conservation methods were built into some local agricultural systems and must have been practiced over many generations but before 1930 there was little government concern with the problem (Hartley 1938, Stenhouse 1944, Thornton and Rounce 1936). In 1929, the situation changed when E. H. Harrison was appointed Director of Agriculture. One of his major interests was in soil erosion, which was then gaining prominence in international scientific circles and he was prepared to make soil conservation a priority of the Department. Further impetus was given by the severe and widespread droughts of 1929 which were followed by a season of exceptionally heavy rain in 1930.

A conference on soil erosion was held at Dodoma in 1929 and the meeting led to the establishment of an advisory committee on soil erosion. This committee met for the first time at Amani in 1931 and found it easy to quote many examples in presenting the problem to the central administration (TNA 1). Two main problem areas were seen to exist; the "overcrowded" mountain areas (Temple 1971) and the "overstocked" pastoral areas in the plains. The need for conservation work was agreed on and a sub-committee was formed which was to advise different technical departments on the introduction of demonstration plots, the planting of improved browse plants in pastoral areas and the alienation of land for forest reserves. The committee saw the great problem of the plains as overstocking, but it saw serious difficulties in trying to reduce stock numbers. It was more practical to introduce water supplies and improved pasture, but this again would lead to larger herds, posing an even greater problem. In 1932 the committee emphasized the menace erosion was presenting to the new railway extension in Central Province and the excessive erosion being caused by burning in Northern Mbulu and overgrazing by the Masai in Ngorongoro.

During the 1930s a number of demonstration plots were set up in the mountain areas of Kilimanjaro, the Usambaras, the Pares and Mt. Meru. Harrison and other researchers wrote on the methods of conservation which could be used in these areas (Harrison 1935). The demonstration plots were used by the administrators to convince the "Native Authorities" that soil conservation was necessary to give better yields on steeper slopes and maintain the fertility of the soil. The Native Authority was a local government, usually comprising the chief of a tribe and his council. The Assistant District Commissioner would liase with this local government and through them impose the will of the Central Colonial Administration. The Native Authority was empowered to enact orders using their own ordinances.

Experiments were carried out at Agricultural Research stations throughout the country, to measure soil and water loss from land with different types of vegetation cover (Staples 1933, 1935, 1938), to measure yields of coffee and cotton on different types of land management (Annual Reports of the Research stations at Ukiriguru and Lyamungu) and to discover which pasture plants combined soil conservation properties with adequate nutrients for use in Central Province (French 1943). These experiments went on right into the mid 1950s—the major work being performed at Mpwapwa (van Rensburg 1955, 1958).

At a conference of technical officers at Mpwapwa in 1936, Staples said that "erosion in Central Province is rampant in its most acute form over large areas" (TNA 2). He believed that this was mainly due to wrong methods of cultivation and overstocking as stock rates were now over the carrying capacity in many areas.

By 1939 there were reports that the measures introduced by the Native Authorities of eight Districts (Moshi, Korogwe, Pare, Arusha, Mbulu, Iringa, Rungwe and Mbeya) covering all cultivation were being successful in conserving the soil. The measures were therefore being extended to other areas notably the Ulugurus (Harrison 1938*a*, 1938*b*, 1939 and TNA 3). The only disappointing areas were the pastoral lands such as Central Province and Sukumaland where no progress could be made until the Native Authorities appreciated the need for integrated pasture care, using rotation and a good distribution of watering places.

In the early 1940s there was a continued expansion of soil conservation, notably in Central Province where thousands of miles of contour banks were being constructed by local people under supervision of the Department of Agriculture Extension staff (TNA 4, TMA 1). A number of areas in Dodoma, Singida and Shinyanga Regions had been set aside for controlled grazing experiments and plans were in hand to combine this with depopulation, reduction of stock and resettlement schemes.

Despite all these efforts, progress was hampered for two reasons. Firstly there was a great shortage of trained technical staff, so that the efforts of the Department of Agriculture were necessarily concentrated in accessible areas. There were only about 50 fully trained Agricultural Officers and Assistants (Fuggles-Couchman 1964). Secondly the climate of the territory consistently hampered conservation because if the weather was dry there was no obvious advantage of soil conservation measures and if the rains were heavy the conservation works were often destroyed. The concentration then had to be on repairs rather than construction and people became discouraged. To try to deal with the first problem the colonial government established a soil conservation service at Tengeru in 1948 which was to train extension staff who would then go to all Districts to advise on the execution of schemes (ARA 1948). But the second problem was ever present and could not be dealt with until some conservation works had existed for many years and there was visible proof of improving yields and increased soil fertility.

Up to the early 1940s soil conservation had been a piecemeal affair (i.e., there was not organized policy for the whole country). There were very few areas where the majority of farmers were now soil conscious. The central administration saw that there was a need for integrated large-scale schemes in the worst effected parts of the country with central government funds to supplement the grants of the Native Treasuries and with more trained manpower to ensure smooth running. In 1944, when a favorable outcome of World War II appeared certain a comprehensive post-war development plan was drawn up to cover the period 1947—56. One and one-quarter million pounds out of a projected budget of 19 million was allocated to 8 agricultural schemes, covering 68,500 sq. miles and affecting two million people. (Fuggles-Couchman 1964). This was the period of the ground nut scheme, a disasterous attempt to utilize the semi-arid plateau which failed in part through a lack of understanding of climatic and soil conditions in the area (Wood 1950).

In Sukumaland and at Kolo in Kondoa, pilot areas were set aside for rotational grazing and resettlement schemes. These were the small beginnings of the two most important conservation schemes in the semi-arid area—the Sukumaland Development Scheme, 1946 (TNA 6) and the Kolo Rehabilitation Scheme, 1948 (ARA 1948). Two other major schemes were planned for the Ulugurus and the Usambaras and with seven smaller schemes soil conservation was thus extended to all parts of the country (TNA 7). All the big schemes had impressive lists of rules attached to them, governing such things as place of cultivation, extent of grazing and prohibitation of burning. People were convicted and fined if they contravened the rules.

This increase of effort did not continue. For many reasons, the people began to be discouraged and often became directly opposed to the conservation measures which had been introduced. Conservation became a political issue in the vicinity of major schemes and by 1954 many of the schemes were being forced to disband after civil disturbances had stopped any active conservation effort. The government were forced to stop enforcement of the conservation rules and by 1958 most of the schemes had fizzled out and people were busy pulling down many of the terraces and banks which had been so painstakingly constructed.

The colonial administration did not give up entirely. In one area they began rather belated plot experiments to discover plant behavior under different land management (Temple 1972) and detailed soil and water conservation and land use schemes were being worked out at Tengeru, Ukiriguru and Iringa (ARA 1950). In areas peripheral to the main schemes there was often an initial interest in organized conservation for example, Ukara Island Native Authority published its first conservation orders in 1958 (TNA 8). But in general, the colonial administrators were cautious and concentrated more on improving individual holdings and on more general catchment experiments (Temple 1971).

For some time after independence there was very little direct mention of soil conservation in the Ministry of Agriculture files. In fact, agricultural schemes incorporated conservation but not usually as the central theme. For example, the Ufipa Wheat Scheme, the Kitulo Sheep Scheme and the Turkish Tobacco Scheme in the Southern Highlands (TMA 2) and the Gulu and Rwamkona assisted settlement schemes of Sukumaland (TMA 3) have all combined soil conservation with the other aims of the projects. Although the extension staff of the Land Planning Units in the Ministry of Agriculture do offer assistance to people who desire to conserve their land, there has only been one big scheme incorporating land planning, conservation and settlement which was begun at Shume in the Usambaras in 1963 (TMA 4).

In general, soil erosion has not been seen as a problem to the development of Tanzanian agriculture in the 1960s although the senior soil scientist at the Ministry did point out the dangers of clearing land in Tanzania without planning conservation (Baker 1969). Early party policy was to denounce conservation measures as being part of bad colonial rule and the extension staff thus find it difficult to preach soil conservation to people who have in their lifetime built conservation works and then destroyed them under different orders (TMA 5). As part of the second five year plan 1969—74, soil conservation measures once more appeared in government proposals. But the Ministry now mainly concentrates on introduction of new crops, new varieties and experiments concerning yields of crops using fertilizer, etc.

## Earlier opinions on the causes of erosion

A wide variety of soils and an even wider range of types of agricultural practices are found in Tanzania. Causes of accelerated erosion in any one locale are often complex and while general comments on causes are common in the literature all too rarely have they been backed up by detailed study and analysis.

On the plains and plateau areas, accelerated sheetwash occurred where there was degeneration of pasture due to concentration of grazing in one particular area for long periods as in Ugogo area of Central Province or where there had been very heavy rain on unprotected arable land, for example, in the cotton growing area of Sukumaland (Van Rensburg 1942, ARA 1935). In the Kondoa area a combination of deeply weathered friable gneissic rock, and a sparse vegetation cover, in an area subject to periodic drought and intense rainstorms, was disasterous. The area which seemed untouched by accelerated erosion in the 1890s, became devastated over the next 30 years (Gillman 1930). Gullies developed, often along cattle tracks, but rapidly extended in the weathered gneiss and affected even areas which retained dense deciduous thicket vegetation. By the 1930s the area was considered irretrevable (TNA 4, TMA 1; Van Rensburg, 1958). Wind erosion occurred on arable land, where light sandy soils dried out quickly after rain, for example, in Singida District. Wind erosion was also a problem where mechanised large scale arable farming was introduced without the protection of windbreaks or strip cropping.

Staples (1933*b*) estimated that the cattle population of Tanganyika had increased from 1,650,000 in 1913 to 5,170,000 in 1930 though this latter figure at least seems highly overestimated. More recent estimates of cattle numbers are: 1950—6 million, 1960—8 million, 1965—10 million (Jensen 1968, p. 25). The increasing population density meant that people began to cultivate submarginal land and pasture became scarce. This necessitated long journeys to find food and water in the dry season and resulted in the trampling of vegetation and the use of marginal land as pasture. The result was exposure and subsequent erosion and depletion of soils which already had inherently low reserves of fertility. In the highland areas of the Porotos, the nature of the soils was such that "natural" erosion was claimed to be active everywhere in 1954 (TNA 9). The soils of the plains areas are light and easily worked but sheetwash was considerable in some areas.

R. A. Baker wrote, that "most Tanzanian soils are extremely erodible once the surface cover is removed." (Baker 1969, p. 42). The volcanic soils on the plains below Mt. Meru and Mt. Kilimanjaro are unstable and under permanent cultivation they became puffy and dry (Smith memeo undated).

Apart from these indigenous causes of erosion, government policies and efforts to control erosion often aggravated the situation when unsuitable conservation methods were used. In some cases, erosion was instigated where there had been none previously!

## The agents of conservation and the conservation techniques adopted

Conyers in a recent study (1971) has identified over 200 significant agricultural systems in Tanzania. There are at least as many different agricultural environments in the country. Assuming some degree of interaction, one with another, there still remain a bewildering variety of man-land relationships, especially if we take into account the dynamic pattern of change in the agricultural systems over the last 50 years.

Many, if not all, indigenous agricultural systems were evolved in a precise relationship with the environmental, social and technological conditions of a particular time and a particular place. Most systems that have been studied in detail tend to conserve land, labor and other resources. Population growth, rapid increases in the livestock population, introduction of new crops and expansion of some agricultural systems to new areas have all contributed to imbalance and in some areas to erosional problems. Sometimes readjustments

Table 1. Mechanical measures used in Tanzania to counteract soil erosion
Symbols: + measures accepted by the peasants, S measures said to be successful by the colonial administration, — very unpopular measures.

| Measures | | Description |
|---|---|---|
| Contour hedging. | + | The planting of trees, thicket bush or tall grass along the contour to stop soil movement downslope. |
| Contour ridging. (Tuta cultivation). | S | The building up of topsoil into ridges along the contour-crops being planted on the ridges, which stop water movement downslope providing the plants on the ridges with adequate moisture. |
| Tied ridging[1]. | S | The tying of contour ridges by building other ridges at right angles to the main ridges, producing a 'lattice-effect'. The crops were again planted on the ridge and water collected in the pits. |
| Matengo Pit System[2]. | + | A similar idea to the above. Cut grass was laid in a grid of 7—10 foot squares. The centre of the squares were dug out and the grass lines covered with soil on which crops were then planted. Water collected in the pits and any soil washed off the ridges. After harvest the pits were filled in and the process repeated. |
| Trash bunding. | + | Lines of trash were laid along the contour and plants were grown above on the hillside. Soil wash was collected in these lines of trash. |
| Contour banks. | S | When enough soil had been deposited on trash bunds either by soil wash or by the farmer moving it—a bank was formed on which crops could be planted. |
| Narrow based terraces[3]. | S+ | In steep areas if more soil was washed downslope and caught by contour banks, the banks grew in size and eventually small terraces were formed. Some tribes were already using these before the government interfered. |
| Broad based terraces.<br>Bench terraces. | —<br>— | The significant difference between these two types of terrace and the narrow based was that they were larger and were constructed by actually digging soil out of the hillside. In doing so, the soil profile was disturbed and in most cases all the topsoil was used to construct the terrace. This led to their failure because in many cases after a few years all topsoil was washed away. |
| Boxed terraces. | — | The same principle as tied ridging, where smaller ridges were built at right angles to existing terraces to form boxes, where moisture collected. These involved a considerable amount of difficult construction work. |
| Gully stopping.<br>Check dams. | | This process took many forms from the laying of brushwood across the floor of gullies to building actual concrete dams across the gully to check rapid water flow. The most successful were found to be where brushwood and stones were pushed right down into the floor and sides of the gully forming a barrier which trapped water and sediment in heavy storms. Afterwards water gradually seeped away leaving rich alluvial sediment which could be used to grow grass. |
| Diversion ditches.<br>Stormwater drains. | | The construction of ditches on slopes which were contour banked or terraced, or alongside roads and gullies to ensure constant flows of water during storms and avoid water building up which would then burst banks or terraces. |

[1] A description of tie-ridging, contour banks and ridges (also called bunds and tuta cultivation), closing hilltops, contour hedging, grass stripping, mulching, windbreaks and the control of gullies appears in M. Lunan, 'Soil Erosion' in Rounce 1949.

[2] The Matengo Pit System is a system of laying out grass in the form of a grid of about 10 ft. squares. The centre of the squares are dug out to form a basin shaped pit and the grass lines are covered with the soil. Planting is on the ridges and the water collects in the pits. At the end of the season the pits are filled in with crop residues and the system repeated (Stenhouse, 1944).

[3] For a description of terracing in all its forms see 'Conservation of Soil Fertility on Coffee Estates' G. H. Gethin-Jones *E. A. A. J. Vol. 1.* and for box terracing R. B. Alnutt 'Rice Growing in Dry Areas' *E. A. A. J.* Vol. 8, p. 103.

Table 2. Methods of improved land management also used to control erosion

| | |
|---|---|
| In the mountain areas. | 1) Reafforestation and non-felling of trees.<br>2) Non-grazing of stubble and stall feeding.<br>3) Non-burning of vegetation.<br>4) Closing hilltops and steep or eroded slopes to cultivation and planting perennial crops e.g. bananas and coffee.<br>5) Stopping shifting cultivation |
| In the plains. | 1) Destocking and culling to obtain a good stock distribution and an adequate land carrying capacity.<br>2) Rotational grazing-establishment of grazing reserves.<br>3) Poisoning thornbush to promote grass growth.<br>4) Introduction of improved pasture plants e.g. legumes.<br>5) Building windbreaks. |
| General measures. | 1) Depopulation moving people from overcrowded areas to areas of lower densities.<br>2) Grass stripping—leaving areas of grass between plots<br>3) Contour ploughing.<br>4) Manuring.<br>5) Non cultivation or grazing near roads, gullies or streams.<br>6) Grading, closure and/or realignment of paths, roads and cattle tracks. |

of cultivation practices have locally redressed the balance, but this has proved more difficult in areas with animal husbandry.

## Spontaneous responses to soil conservation needs

Increased population has in some parts of Tanzania resulted in marked changes in the use of land. The Wakara of Ukerewe Island in Lake Victoria have for many years suffered population pressure due to increasing population densities within the fixed limits of their island. The soils are sandy and to allow increasingly intensive cultivation the Wakara have adopted a number of anti-erosion methods such as tie-ridging and terracing, fencing of gullies and banking of streams (Thornton and Rounce 1936). For a description of these and other measures see Tables 1 and 2. The Wamatengo of Southern Tanzania and the Erok of Mbulu have both had to adapt their agricultural systems to different terrain, after being forced to live in steep mountain areas by the aggression of other tribes. The Wamatengo developed a system of pit cultivation, which is now commonly known as the Matengo Pit System and the Erok have developed a system of reinforced terracing (Hartley 1938). Some peoples have used agricultural techniques which, perhaps without their explicitly realizing it, have conserved soil. For example, in Musoma hedging was originally used to keep cattle off crops but it was recognized as a way of keeping the soil stable and fertile (Harrison 1938*b*). The Wafipa have a method of mound cultivation which also protects their soil from deterioration and therefore erosion (Lunan 1950). In 1930, the District Officer Morogoro commented that the idea of terracing was not foreign to the Waluguru, who had used terraces to cultivate steep slopes in the past (TNA 12).

From 1930 onwards the government at local and national level played a large part as an agent of soil conservation. But this did not mean that there was no new spontaneous soil conservation (ARA 1932). In general these local activities were on a small-scale, for example, trash bunding, building small banks/ridges and grass stripping. In the early days of organized conservation the peasant farmers were recorded as being most enthusiastic and receptive to new ideas (ARA 1934).

There is apparently no record of large estate-owners taking special steps to conserve their soil until 1937 (ARA 1937). But by the 1940s most sales of Rights of Occupancy were subject to the buyer promising to use anti-erosion measures on his land (ARA 1943). By 1954, in Kilimanjaro Region the main impetus for conservation came from the estate-owners (ARA 1954). This is explained in part by the greater amount of money available to them for the purchase of equipment to help conservation, whereas the ordinary peasant farmer had to perform the often arduous, but not immediately productive, work manually.

## Government activity

There were two levels of government soil conservation; that financed by the local government (the Native Authority) from their own treasuries and that which was financed from the Central Government offices. Most soil conservation measures in the 1930s and the early 1940s were locally administered and brought about by Native Authority orders. Central Government did not bring in any legislation for soil conservation until the late 1940s, when using the Natural Resources Ordinances, they introduced rules to allow the development of large-scale schemes.

## Native Authority conservation

In the 1930s the Native Authorities were advised by the Department of Agriculture to adopt soil conservation measures in their areas. In practice this meant that the adoption of conservation measures was dependent on the initiative and powers of persuasion of the District Officer and the responsiveness of the chief and his council on the Native Authority. There is, of course, virtually no documentary evidence of the methods of persuasion used and in some cases it is probable that advice and persuasion on the part of the District Officer was accompanied by coercion. There are records in the government files of favorable and unfavorable receptions of the extension staff by the local people. At Mgeta in 1945, vigorous action by the subchief in posting extra instructors resulted in intensive conservation work (TNA 10). But only a few miles away at Morogoro the headmen were less willing to adopt conservation methods (TNA 3). When the chief at Kongwa saw the improvements made at Bwaga Dam, he requested the same treatment for his own area (ARA 1941).

The first areas to have conservation orders were usually those which were accessible to the Extension Staff, who were few in numbers. Thus it is probably not an accident that the first serious conservation took place in the Usambara Mountains, Mt. Kilimanjaro and Mt. Meru, and Bukoba, which are climatically the most pleasant areas of the country for Europeans.

In the 1940s, the main measures introduced in the plains were controlled grazing, by rotation and destocking of pasture land, depopulation and tie-ridging (box tuta) cultivation on arable land. Bush was poisoned at Msomalo to promote grass growth and "gully stopping" was introduced in other parts of Central Province (TMA 1). In the Dodoma and the Msomalo/Igandu Reclamation areas, the main efforts were concentrated on contour banking and ridging. Later, broad based terraces were introduced.

In 1951, a conference was held at Arusha on Land Development Schemes (TNA 7). It recommended: "In highland areas, erosion caused by overstocking should be controlled by stallfeeding and erosion caused by bad cultivation controlled by reafforestation. In lowland areas, there is a need first to determine the land carrying capacity of an area and then measures can be introduced to achieve a balance between population and stock."

By the early 1950s, the main focus was on the big new development schemes of the Central Government, but by this date most areas of the country had Native Authority orders governing conservation measures and although there was little mention of the fact, there was continued conservation work in areas not covered by the schemes. For example, in some areas of Sukumaland, not protected by the scheme there, hilltops were closed to cultivation and grazing, windbreaks and contour hedges were planted on arable land, which was already protected by tied contour ridges. Check dams were built in gullies and elephant grass was planted to give extra protection (ARA 1955). Native Authorities continued to introduce conservation orders until 1958 (TNA 8), three years before Independence.

## Central Government conservation

As described earlier, in 1944 the government put forward a development plan for the Territory 1 1/4 million pounds being allocated to eight agricultural schemes, later increased to eleven. Three of the eight schemes were for land management in the plains, the most notable being the Masai Development Scheme and the Sukumaland Development Scheme. The other five schemes were for rehabilitation and protection of mountain areas, the main ones being the Ulugurus Land Usage Scheme, the Usambaras Scheme and the Kolo Rehabilitation Scheme.

The main aim of the schemes in the plains was to control population and stock densities in order to ensure that cattle numbers were kept below the land carrying capacity. The main object of the Masai Development Scheme was to supply water in such a way as to obtain a better distribution of the stock population, which in turn prevented trampling around watering points in the dry season leading to soil erosion in the wet season (Fuggles-Couchman 1964). This scheme was badly organized and poorly manned. The government went head first into building new water sources without forward planning. The Sukumaland Development Scheme involved more planning, having pilot areas to begin with, where land was divided into Land Usage Areas (L.U.A.'s) and detailed mapping and gazetteers were carried out for each L.U.A. Later population and stock were moved from densely settled areas and spread out over the greater part of Sukumaland. Complicated sets of rules were attached to cultivation, grazing and eventually most facets of agricultural life. There were rules on tie-ridging, manuring and burning. People were forbidden to cultivate near water, cut trees or move cattle without permission (Rounce 1949). By 1953 the Sukuma peasant thought he was being regimented, (Maguire 1969). He had to plant and harvest at a given time, he was told what to plant, he had to sell off his cattle and have the rest dipped and on top of this he was taxed and levied to pay for it (Maguire 1969). In areas like Nzega where there was no room for stock movement into different areas, culling was thought to be the only answer for conserving the soil (TNA 7).

After the failure of the large schemes, there were only limited attempts at conservation by the colonial administration. In 1957 there were two schemes begun at Kasulu and Kibondo (TMA 5), to conserve soil moisture and fertility but these were more carefully controlled than previous schemes.

After 1961, although most agricultural and settlement schemes have incorporated some soil conservation there has been little specific emphasis on conservation schemes. In the Southern Highlands the Huhuri Land Use Scheme, linked the provision of rural water supply with soil conservation (ARA 1966) and the Ufipa Wheat Scheme, the Turkish Tobacco Scheme and the Kitulo Sheep Scheme all had some contouring and terracing (TMA 2). Also in Lake Province the settlement schemes at Galu and Rwamkona incorporated ridging (TMA 3).

The Land Planning Units of the Ministry of Agriculture have made efforts to introduce soil conservation measures in areas of known erosion. For example, when ujamaa villages were established in Arusha Region the Land Planning Unit gave advice on wind erosion problems and the adoption of stubble mulch (ARA 1969). They were more successful than the Land Planning Unit in the Usambaras who have had little response to advice on conservation apart from some contouring, even though political rallies have included lectures on conservation (TMA 6).

## The successes and failures of the conservation measures and schemes

In the previous section the measures used by the colonial administration to diminish soil erosion in the semi-arid areas have been outlined.

The success or failure of the various measures adopted can be gauged in two ways: firstly by the actual success achieved by the colonial administration in physically stopping soil erosion in practical application and experiment, and secondly by the extent to which measures were accepted or rejected by the local people.

The colonial administrators viewed the success of conservation measures entirely from the amount of agricultural improvement achieved. For example, Fuggles-Couchman (1964) writes, that "in general the Sukumaland Development Scheme was (regarded as) a qualified success: its main achievements were the orderly settlement of large undeveloped areas accompanied by a greatly increased output of cotton and an increase in watering points".

However, the main problem of overstocking still remained. There were rapid improvements in pasture quality and bush regeneration when rotational grazing was introduced into the Msomalo area of Dodoma in the 1940s and two thirds of the population were moved to conform with grazing and cultivation rules (TNA 2). But when rotational grazing was



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introduced without the construction of many new water sources, thousands of cattle converged on one spot for water in the dry season, trampling the soil and making it susceptible to extensive erosion in the wet season.

Much experimental work was done on the effectiveness of conservation techniques, in relation to crop production and soil conservation. At Ukiriguru, South of Mwanza, in the 1950s recorded yields of cotton and finger millet were found to be much higher on tied-ridges than ordinary ridges. On the sandy soils of Mwanza Region the runoff during storms was rapid and tied-ridges proved to be the only successful conservation measure (ARA 1950). At Tengeru, trials were held for hill cultivation and the best yields were obtained from crops planted on tied-ridges or using the Matengo Pit System. In fact, in the Ulugurus, at Tengeru and Ukiriguru the Matengo Pit System had the acknowledged best yields but where rainfall was high tie-ridging was superior (ARA 1950). The Provincial Agricultural Officer, Dodoma, found check-dams with a core wall and bush pushed into the bottom of gullies the most successful technique for water storage in gullies because for months after the rains, water gradually seeped through and perennial grass grew below the dams (TMA 1).

Some measures obviously failed because they gave no improvements in crop yields, land fertility and soil stability. At Tengeru, trials proved too late that bench terraces led to disturbance of soil and drainage and the practice of planting elephant grass on the terraces reduced yields. Wider terraces took more man-days to build only to give worse yields. They also discovered that narrow-based contour banks led to considerable interbank erosion on slopes (ARA 1950). Gully stopping was found to be impractical if bush and trash were merely laid across the gully floor in lines, because the first storms swept it away, causing more erosion than was prevented.

The peasants actually accepted some of the proposed measures, but this was usually because the technique was familiar to them or because the measure was clearly going directly to benefit them. Contour ridging was said to be the most effective measure in Central Province, because the people agreed on the rationale behind it, making it relatively easy to implement (TNA 4). In the Usambaras, in the 1950s the rule against grazing of stubble was said to be popular with the women because it was their labor which was wasted when crops were trampled by cattle (TNA 5). Also in Northern Province and the Southern Highlands, the distribution of free seedlings was a success, because the people were getting financial improvement for no additional outlay on their part and reafforestation was one of the physically easier conservation tasks. This is probably also why live contour hedges are quoted as being the only mechanical method of conservation not regarded with disfavor in the Usambaras (TNA 5).

We have already seen that most conservation schemes failed in Tanganyika. However, the reasons for their failure cannot be found simply in an examination of the physical factors of the soil and environment. With some notable exceptions such as the use of terracing in the Ulugurus, most of the measures involved could have been successful in physically preventing soil erosion. However, the colonial administrators were wrong in their particular approach to the problem and it is here and in the reaction of the Africans to the colonial attitudes that we can find the reasons for failure.

Many of the measures actually adopted in conservation programs were unpopular with the people, because they cut across accepted agricultural practices. The peasants often had practical reasons for disliking measures. Wide grass strips and contour hedges were rejected because they used up too much land. In Mbeya, contour banks were unpopular because they led to infestation by rats (ARA 1948). People cleared their land because otherwise they had problems from tickborne diseases. Most peasants believed that burning improved their land, they were against the given alternative—manure because they thought it attracted weeds (Harrison 1938*b*). Cliffe (1964) maintains that the rules often challenged the peasant's economic security and his culture. In particular, the herding people were unwilling to part with their cattle, because they represented their wealth and security. Destocking was merely seen as a measure to benefit the underutilized factories of Tanganyika Packers in Arusha and Dar es Salaam (Cliffe 1964). Arable farmers were equally conscious of their land rights and depopulation measures meant that people had to give up their inheritance.

Despite the large investment involved, there was a lack of planning for the large schemes. Technical officers rarely agreed on technical answers to the problems, so some had no enthusiasm for their work and if particular methods proved totally impractical changes in policy had to be made after a few years (TNA 7). Underestimation of staff needs led to half finished conservation works, lack of maintenance and little or even no supervision if staff were diverted to other activities such as famine relief. But for the administration, the most serious consequence of lack of staff was the lax enforcement of rules (TNA 3). The colonial administration could have partially improved matters by paying local people but they were unwilling to do this (TNA 4). Most officers reported resistance from the people because the work was usually too laborious (TNA 4).

Not only was there a lack of planning on the part of the administration, but they also failed to appreciate the culture and social organization of the various tribes of the country. Van Rensburg advocated that improvements should have been fitted into the tribal and social structure but this point seems to have been passed over by the administrators for they continued to press for depopulation of mountain areas and culling of cattle in pastoral areas (Van Rensburg 1942). Also the administration had not appreciated that many groups had adapted their agricultural system to their environment and could control soil erosion. Although scientific papers were written about indigenous conservation methods, there were few suggestions to use these in other areas. There was no attempt to adapt conservation methods to existing agricultural systems. For example, wide contour hedges failed where narrow ones would have been accepted by the people. Blanket measures were suggested for areas covering hundreds of square kilometers and these were enforced immediately without considering tribal and environmental variation at all.

All these factors combined to produce a strong element of mistrust among the African farmers for soil conservation. Soil conservation orders or rules applied only to the indigenous people, so the small farmer felt he was being discriminated against (TNA 7). Campaigns for extra production and soil conservation were often misconstrued by the local people to mean the Europeans wanted to exploit them and their soil (Cliffe 1964). Also rumors often spread when no one knew exactly what measures would be adopted.

Much has been written about the failure of the large development schemes in Tanganyika and authors are unanimous in their condemnation of the colonial government for their bad management (Cliffe 1964, Fuggles-Couchman 1964, Temple 1971, Young and Fosbrooke 1960). Comments on three of the schemes may illustrate the range of issues involved.

Fuggles-Couchman (1964) concluded that the Masailand and Mbulu Development Schemes failed because there was insufficient control of stock movements to and from the development areas. In particular, no provision was made for the control of livestock in the dry season and areas around watering points in Masailand were devastated. In Mbulu, operations had to be discontinued in 1953, when the development fund came to an end and the Native Authority could not take over the finance of a scheme of that scale.

Maguire (1969) states that the main reason for failure of the Sukumaland Development Scheme was the complexity and number of restrictions involved. There were rules attached to every facet of agricultural existence, many of which cut right across the accepted way of life. The administration, in particular, the Provincial Commissioner, did not show any understanding and were not interested in an idealistic program which was adapted to the people's needs (Maguire 1969). It was unfortunate for the administration that Sukumaland was the most politically conscious area of the country (Cliffe 1964) and failures were used to stir up the people against the colonial government. In 1958 there were many outbreaks of civil disobediance and the entire regimen of restrictive legislation was abolished in November of that year (Maguire 1969).

It is clear that many factors must be considered, before any soil conservation schemes are planned in the semi-arid areas of present-day Tanzania. The first obvious point is that detailed planning should be carried out before any scheme is started, to determine soil type and suitable conservation methods for the particular environment. A number of measures are quoted above as being acceptable to the people and these should be used as far as possible. However, not only the physical environment needs to be considered. The great mistake made by the colonial administration was their virtual total disregard of tribal, social and cultural differences between the peoples of the country. In future, conservation schemes should be preceeded by intensive adult literacy campaigns if the aim is to change the views of the people. For example, the Pares Community Development Scheme was partially a success because there was a literacy campaign before conservation was introduced (Fuggles-Couchman 1964). If this is not done, measures should be adapted to the existing system, as the people need to appreciate that operations are practical. They should be small-scale so that finance is not a constraint and if possible measures should be introduced which have immediate apparent benefits. The great overall need, however, is for integrated planning to ensure that schemes run smoothly and changes in policy do not have to be made after a few years.

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*Professor Len Berry, Dept. of Geography, Clark University, Worcester, Mass. U.S.A.*
*Mrs. Janet Townshend, Dept. of Geography, University of Reading, Reading, England.*

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TMA — Tanzania Ministry Agriculture File

TMA 1. P/SCH/CP — Land Use Schemes — Central Province.
TMA 2. P/SCH/SHP — Land Use Schemes — Southern Highlands Province.
TMA 3. P/SCH/LP — Land Use Schemes — Lake Province.
TMA 4. P/SCH/SHU/LD — Land Use Schemes — Shume.
TMA 5. P/SCH/NP — Land Use Schemes — Northern Province.
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# SOIL EROSION AND SEDIMENTATION IN FOUR CATCHMENTS NEAR DODOMA, TANZANIA

By ANDERS RAPP, D. HAMMOND MURRAY-RUST, CARL CHRISTIANSSON AND LEN BERRY

Formerly BRALUP and Department of Geography, Dar es Salaam
Present affiliations, see end of paper.

ABSTRACT. The catchments studied are located in semi-arid central Tanzania. The mean annual rainfall at Dodoma is 567 mm and the dry season is 7—8 months long. All four catchments are underlain by granitic rocks of Precambrian age. Pediment slopes and rocky inselbergs are the predominant landforms. The land use is a combination of cattle grazing and cultivation.

The rate of sedimentation in four reservoirs was measured by periodic re-levelling of known cross-profiles on the floors. Inventories of the erosion features in the catchment areas were made through air photo interpretation and field checking.

Rainsplash and sheet wash are probably the most important types of erosion. Gullies appear in distinct zones on the upper pediment slopes near the foot of the inselbergs, but gullying is probably of less quantitative importance in these areas as compared to splash and wash.

The reservoirs have high rates of sedimentation and two of them (Ikowa and Matumbulu) have very short expected total life-lengths of 30 years and still shorter economic life-lengths. The annual sediment yield corresponding to the sedimentation in the four reservoirs is 195, 406, 601 and 729 m³/km² (mean values for longest period of available data). In addition large volumes of sediment have been deposited upstream of the reservoirs as thin sandy sheets on lower pediments, as sand fans along stream channels and silty-clayey mbuga floodplains, the latter particularly in the Ikowa catchment. The reservoir sedimentation corresponds to a soil denudation rate of 0.2—0.73 mm per year.

Erosion control and increased life-length of the reservoirs is mainly a question of better management of grass cover in the catchments and protection of cultivated fields against splash erosion. Reduction of stock numbers, of overgrazing and of excessive burning of grass and mulch is necessary in order to combat erosion and increase the life-lengths of the reservoirs. Three of these have considerable potential as future groundwater storages as they are being filled mainly with sandy sediments. This potential should be further investigated.

## Introduction

This paper is a report on studies of contemporary soil erosion and sedimentation in the four catchment basins of Ikowa, Msalatu, Imagi and Matumbulu in the semi-arid savanna landscape of the Dodoma region in Tanzania (Figs. 1, 2, Table 1). As explained in the introductory paper of this volume, the main purpose of the DUSER project was to obtain basic information on the types, extent and rates of soil erosion and sedimentation in two types of areas in Tanzania, viz. deforested mountains and semi-arid interior plains.

The four catchment basins were in 1968 selected as study areas by A. Rapp, L. Berry and P. H. Temple after checking of available background material and reconnaissances in the field. The criteria for selecting areas are presented below. Field work was performed in the dry seasons (October and November) of 1969, 1970 and 1971 and in the wet season of 1970 (February) and in 1971—72 (December—January). The field work teams have been supervised by H. Murray-Rust (Ikowa, Matumbulu, Msalatu 1969 and Ikowa 1970), C. Christiansson (Matumbulu, Msalatu and Imagi in 1970 and later) and A. Rapp (Ikowa 1971).

## General approach of study and selection of areas

The semi-arid inselberg plains of the Dodoma region are known as areas of erratic rainfall, droughts, overgrazing and repeated famines (Brooke 1967, Skerman 1968, p. 41). Streams are ephemeral and there are no long term gauging records of small catchment streams available. Consequently our investigation of water erosion and sedimentation could not be based on sediment sampling in streams as in the Morogoro study but had to focus on: (a) reservoir sedimentation surveys combined with (b) catchment erosion surveys.

### *Reservoir sedimentation surveys*

Man-made lakes act as sediment traps and store part of the sediment eroded from the catch-

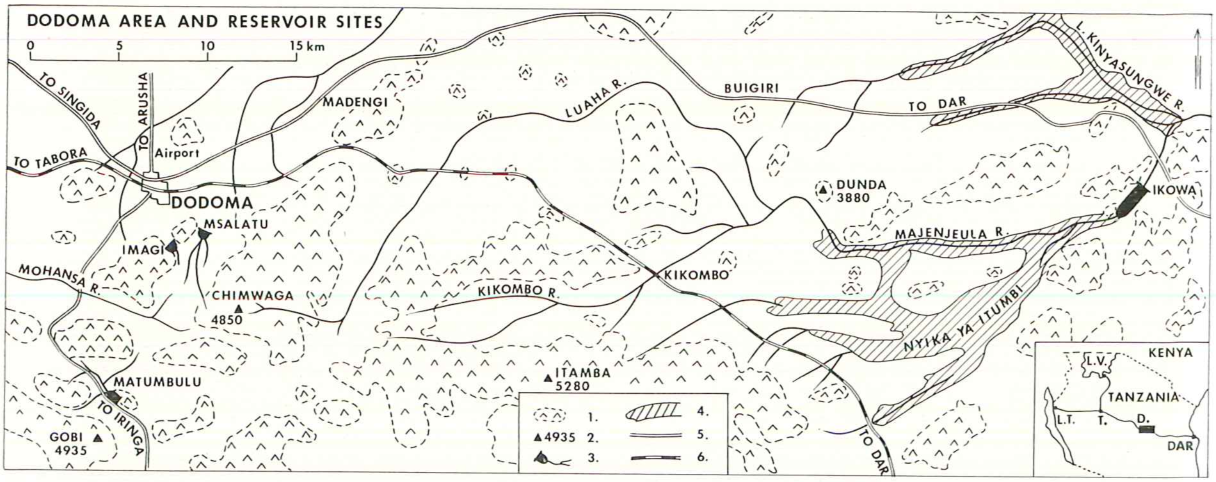



Fig. 1. Location map of reservoir sites, Dodoma area. Key: 1. Bedrock hills of granite or migmatic granite. 2. Summit with altitude in feet. 3. Reservoir investigated in the DUSER project. 4. Mbuga floodplain. 5. Road. 6. Railway.

On insert map L. V. = Lake Victoria, T. = Tabora, D. = Dodoma, L. T. = Lake Tanganyika, Dar = Dar es Salaam. Black square marks site of main map.

ment (Figs. 3, 4). The volume of sediments deposited on the bottom of the four reservoirs was calculated from surveyed transects across the reservoir during the dry season. The transects were made by manual soundings from a rubber boat and by levelling on the dry parts of the bottom. The volume of sediment deposition in the reservoir was calculated on the basis of a comparison between these surveys, and earlier maps or transects.

Levellings were also done of sedimentation surfaces upstream of the reservoir, e.g. of the sandy channel beds at Msalatu and Matumbulu, as a basis for measuring the aggradation of sediments above the reservoir's Full Supply Level (cf. Figs. 19A, 31A and 45A).

The reservoir transects were run parallel to each other at regular intervals, e.g. in the Ikowa survey 500 feet between the transects and 100 feet between the points of sounding in each transect (cf. Figs. 18 and 43). A sufficient number of bottom elevations were thus determined and a contour map of the bottom was drawn. The area enclosed by each contour was determined

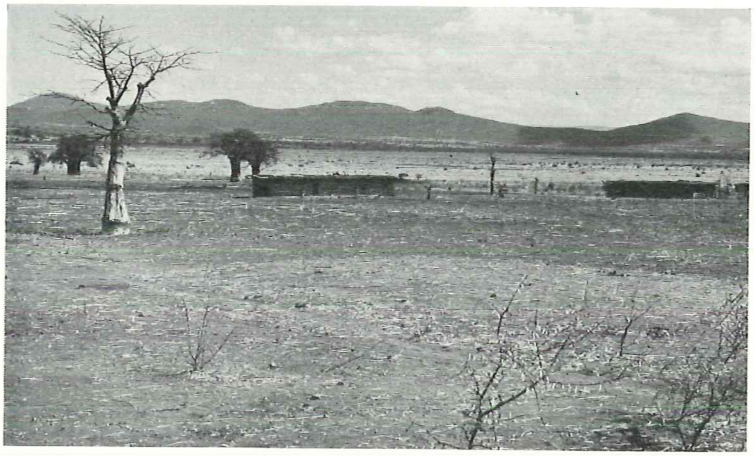


Fig. 2. View across the mbuga of Nyika ya Itumbi (center) towards Madowda hills in the south, Ikowa catchment. In foreground gently sloping cultivated fields, bare after harvest, two Gogo homesteads and baobab trees. Photo AR 10/71.

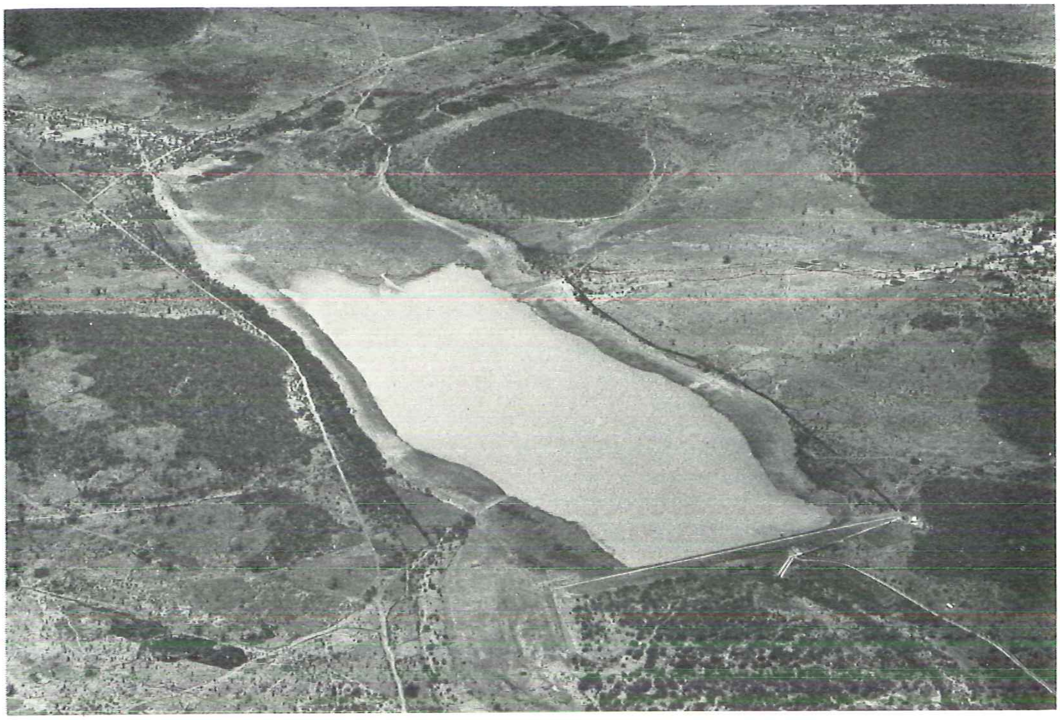


Fig. 3. Oblique air photo of Ikowa dam and reservoir. Dark, delta-like surface at the upper end of the reservoir is exposed bottom with clayey sediments. Mtwango inselberg with dark miombo woodland in center of picture. Level of reservoir is 126.6 ft., = 2.26 m below FSL. Photo AR 25/9/71.

by planimeter and the volume between two consecutive contours computed, using the formula

$$V = h/2\ (A+B) \text{ where}$$

$V$ = volume in $m^3$
$h$ = contour interval in m
$A$ = area of upper contour in $m^2$
$B$ = area of lower contour in $m^2$

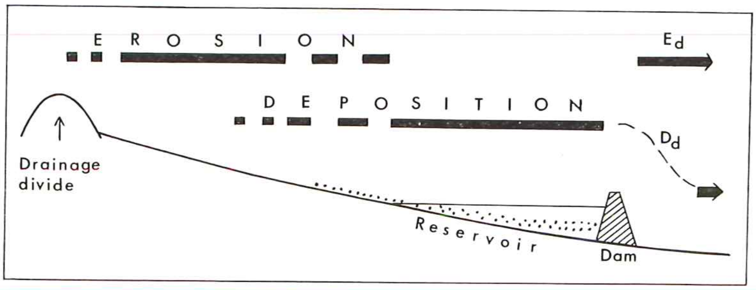
The volume below the lowest contour was calculated by multiplying the area of the lowest contour by mean depth from that contour to bottom. The summation of volumes for the different contour intervals plus the volume below the lowest contour gives the total volume of the reservoir.

As a preparation for future data processing by computer in Tanzania, Mr. Bo Wingård, WD & ID, wrote a programme for volume-computation of reservoir volumes. The programme was checked against our data on reservoir volumes from manual planimetering. The difference between computed and planimeter-based data was less than $\pm 5\ \%$. The following summary is quoted from B. Wingård's programme description:

"The lake is divided in a number of rectangles. From the surveys, the depth in each square corner is computed, supposing that the line between 2 surveyed points is a straight line. The volume is then computed as the sum of a number of columns, the bottom area of each is the area of a rectangle, the height is the mean depth from Full Supply Level to the rectangle.

The programme is compiled and stored on magnetic tape at the computer project of the Ministry of Finance in Dar es Salaam. The original card-deck is stored at WD & ID, Ubungo."

The data on annual sediment accumulation also provides an index of the rate of water erosion in the catchment. However, as is illustrated in Fig. 4, deposition of sediments from erosion in the catchment does not only occur in the reservoir, but also upstream and downstream of it. Consequently the reservoir sediment is only




Erosion in catchment = Deposition in catchment ($D_u$)
of slopes ($E_s$) + in reservoir ($D_r$)
gullies ($E_g$) + beyond dam ($D_d$)
river channels ($E_c$)

$$E_s + E_g + E_c = D_u + D_r + D_d$$

Fig. 4. Diagram of erosion and deposition zones in the Dodoma catchments. Heavy continuous lines above profile mark zones of supposed highest intensity of erosion and deposition respectively. Dashed lines = zones of less intense erosion and deposition. Note overlap of zones. Ed = Erosion of channel beyond dam. Other symbols explained in the drawing.

a part of the material eroded and transported within the catchment.

Langbein and Schumm (1958) made a study of sediment yield in relation to mean annual precipitation in a number of drainage basins in the United States. They selected about 160 reservoirs "below small drainage areas, which on that account were presumed to be more indicative of sediment yield nearer the source" (op.cit.). Reservoirs having catchment areas between 10 and 50 square miles (26—130 km$^2$) and with a high trap efficiency were used in their study. Langbein and Schumm also state that sediment yields decrease with increased catchment area, reflecting the flatter gradients of the drainage basin. Their curve of sediment yield as determined from reservoir surveys shows a maximum of about 1500 tons sediment yield/square mile per year. This corresponds to 385 m$^3$ sediment/km$^2$ per year if a bulk density of 1.5 g/cc is assumed (Table 11) or to a soil denudation rate of 0.385 mm per year (cf. also Kirkby, 1969, p. 236). The maximum sediment yield obtained in the study by Langbein and Schumm is in dry grassland conditions with poor vegetation cover and an "effective annual precipitation" of 250—300 mm.

In Fig. 6 a comparison is made between the Langbein/Schumm curves and the sediment yield data obtained in the DUSER studies in Tanzania. The data from semi-arid America and Tanzania appear to be of the same magnitude according to this comparison. It should however be emphasized that the scatter of the individual points behind the American curve in reality is very large and is influenced by

Table 1. Morphometric data on reservoirs and catchment basins near Dodoma (1—4) and Arusha (5) in Tanzania. Matumbulu dam was in use from 1960 but broke and was rebuilt in 1962. Max. depth of Msalatu reservoir is given after raising of spillway level with 0.6 m in 1950. Relief is measured from spillway level to highest summit on water divide in cases 1 and 5, to average of the two highest summits in cases 2, 3 and 4.

| Place | Location | Original Reservoir | | | Catchment | | |
|---|---|---|---|---|---|---|---|
| | | Volume thousands m$^3$ | Max depth m | In use from | Area km$^2$ | Relief ratio h/l m/km | m/m |
| 1. Ikowa | 6°10'S., 36°10'E. | 3800 | 6 | 1957 | 640 | 730/50 | 0.015 |
| 2. Matumbulu | 6°17'S., 35°45'E. | 364 | 8 | 1960 | 18.1 | 257/4.4 | 0.058 |
| 3. Msalatu | 6°12'S., 35°45'E. | 388 | 9.4 | 1944 | 8.7 | 183/4.1 | 0.045 |
| 4. Imagi | 6°12'S., 35°45'E. | 174 | 8.5 | 1930 | 1.5 | 122/1.6 | 0.076 |
| 5. Kisongo | 3°20'S., 36°35'E. | 121 | 5 | 1960 | 9.3 | 225/5.7 | 0.040 |

many environmental factors, of which annual precipitation is probably one of the less significant.

Relief, soils, rainfall intensity, vegetation, land use and other parameters which all come into the picture are probably more significant factors affecting the rate of soil erosion. The large influence of land use and vegetation is here exemplified by Fig. 5 in an erosion plot scale. Comparisons between different areas are probably more relevant if they are based on factors which are related to runoff and erosion in a closer way than annual precipitation. Two examples of such closer comparisons are represented by Figs. 47 and 48, based on American data from Schumm and Hadley 1961.

*Catchment erosion surveys*

The surveys of reservoir sedimentation have to be combined with inventories of features of erosion and sedimentation in the catchment if the pattern of erosion and its intensity is to be understood. The inventories in this study were made by air photo interpretation and by field checking, mainly as slope traverses from valley bottom to hilltop (cf. Fig. 14). The slope traverses include observations of slope angles, vegetation cover, soils, land use and forms of

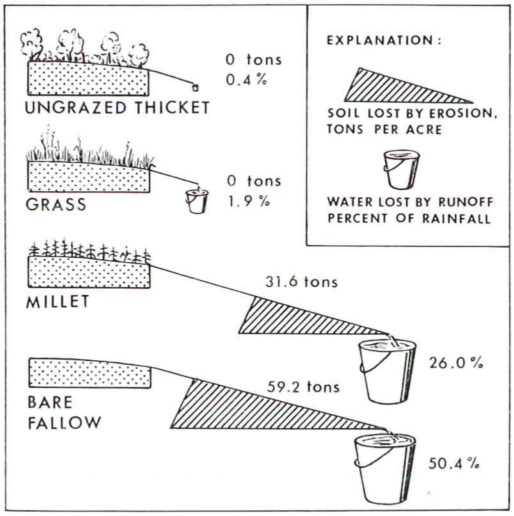



Fig. 5. Results of soil erosion tests on ground with different vegetation covers at Mpwapwa, Tanzania. Annual average of two years records in erosion plots of 50 m² area of red sandy loam soil on a pediment slope of 3.5° gradient. Data from Staples 1938. Design of diagram after Gilluly et al. 1960. The grass cover effectively prevents loss of soil and water.

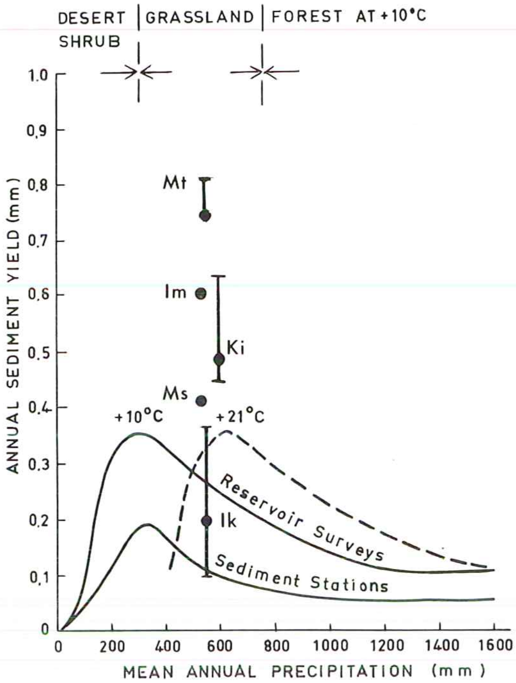



Fig. 6. Comparison of sediment yield data from catchments in USA (full curves) and Tanzania (bars and dots). The curves are from Langbein and Schumm (1958). Highest rates of erosion and sediment yield are in dry grassland and desert, where vegetation cover is sparse and runoff still can be heavy. The dashed curve shows the shift towards higher annual precipitation in tropical areas with higher mean annual temperature and higher evaporation losses.

The Tanzanian values are of similar magnitude as the peak of the American curve of reservoir surveys. However it should be emphasized that the scatter of points behind the curve peak is very large and is influenced by many environmental factors, of which annual precipitation is probably less significant than such factors as land use, size of catchment and others. Cf. Figs. 47, 48. Average size of American catchments in reservoir surveys was 80 km². Ik = Ikowa, Ms = Msalatu, Ki = Kisongo, Im = Imagi, Mt = Matumbulu, Dot = mean annual sediment yield from longest available time period. End of vertical bar = mean of shorter time period. Cf. Table 20.

erosion and sedimentation. Maps of land use and zones of erosion and sedimentation were made over all catchments by interpretation of available air photos from 1960. Catchment areas and percentages of different types of land were measured on these maps (Plate 1A, Figs. 28 and 40) and tabulated (Tables 5 and 15). Due to its considerably larger size, the Ikowa catchment could not be mapped in as much detail as the smaller catchments.

The purpose of the erosion survey is to locate areas of erosion and deposition, distinguish their type and, if possible, intensity. The relative importance of different types of erosion is fundamental to know as a basis for the strategy of conservation measures. This is stressed e.g. by N. Hudson in his textbook on soil conservation, based partly on his thirteen years of experience with conservation research in Rhodesia (Hudson 1971).

The effects of rainsplash on bare ground are summarized as follows by Young (1972, p. 65): "detachment of soil particles by impact; downslope transport of particles thrown above the surface; sealing of the soil surface through dispersion of fine particles and clogging of pores, hence increasing runoff; deterioration of soil structure; and removal of fine particles with relative accumulation of sand." To these effects may be added the probably increased sheet erosion caused by turbulence from raindrop splashing in thin sheets of runoff water (oral information by R. Bryan). Many of the splash effects mentioned above are working in such close connection with sheet wash, that the two processes of splash and wash cannot easily be separated.

We had hoped to be able to measure the splash and wash by using erosion pins and similar methods described by Leopold, Emmett & Myrick (1966) in their studies of catchments in New Mexico. But thefts of nails or other markers left in the terrain made this difficult in the Tanzanian catchments. Inventory and interpretation of micro-relief of erosion and sedimentation forms in relation to vegetation and land use on the undissected pediments had to be used. Splash pedestals and so-called tree mounds (Figs. 15—16), were the most informative features in this respect. As concerns the process of gullying, comparisons of measured transects and large-scale air photographs of different age (Figs. 29 A and B) will probably make quantitative analyses of gully growth possible (cf. Murray-Rust 1972, Table 4).

The reasons for selecting catchment basins in the Dodoma region for a closer study are as follows:

1. The Dodoma region is typical of large areas of interior Tanzania in terms of physical environment. The topography is dominated by inselbergs and pediment plains underlain by Precambrian basement rocks. The dry season is long and pronounced and the area is noted for droughts, famines, overgrazing and erosion.
2. The four reservoirs and catchments selected for study in this area of severe environmental conditions had background data such as reservoir maps and records of water levels. A. P. Fawley (1956 b) has published a report on the Msalatu reservoir and catchment. His study provides very valuable information on the earlier history and sedimentation problems of that catchment.
3. The catchments also had a suitable size for an investigation of this kind as they form a series from medium-size (Ikowa, 640 km$^2$) to smaller and steeper catchments (Matumbulu, Msalatu, Imagi), which offered opportunities for analysing the influence of catchment size and slope gradient on the erosion and sedimentation. Studies of erosion plots were not included in our programme for the Dodoma catchments, because of our limited funds and manpower. Furthermore, fundamental information on the importance of sheet erosion and surface runoff from unprotected plots in the environment of central Tanzania is already available. Pioneering work on erosion plot studies was performed by Staples in 1934—35 and van Rensburg in 1946—54 at the Veterinary Research Station at Mpwapwa, 33 km SE of Ikowa dam (Staples 1938, van Rensburg 1955a). Cf. Fig. 5 and Temple 1972.
4. The four catchments are all reasonably accessible by road from Dodoma and have a good coverage of topographical maps and aerial photographs.

## BRIEF DESCRIPTION OF THE AREAS INVESTIGATED

Table 1 gives some morphometric data on the four Dodoma reservoirs and catchments (1—4). The table contains corresponding data for the Kisongo catchment near Arusha, which was studied by H. Murray-Rust and is described by him in a separate paper of this volume (Murray-Rust 1972).

### Relief and geology

The maps Fig. 1 and Plate 1A and B show the location and main relief features of the four

Figs. 7A and B. Two photographs of sheet flood on pediment plain about 4 km E of Dodoma. The flood was caused by a local thunderstorm on 19/12/1970. Both photos by P. H. Temple.

Fig. 7A (above). Note the wide sheets of water flowing between low islands of mounds under bushes. Flow direction is towards the camera. Chimwaga hill in background at left side.
Fig. 7B (below). View westwards on N side of road. Flood-water fills 5 m wide road ditch. Note sheet flood under *Acacia* bush at right.

catchments. The Ikowa reservoir is situated at 900 m a.s.l. The other three reservoirs studied are close to 1190 m a.s.l. (3900 feet). All catchments have inselbergs and pediment slopes as predominant landforms. The bedrock is Precambrian basement rocks of the Dodoman system, mainly a massive biotite granite and a gneissose granite (Wade & Oates 1938, Temperley 1938, King 1953). In all catchments a rather strong fault-line control is evident, e.g. in the Madengi scarp, which forms the western boundary of the Ikowa catchment and is marked as two major and several small faults along the zone from Madengi to Iymbi Hills on the new geological sheet under production at the Geological Division in Dodoma. The southern boundary of the Ikowa catchment is formed by a series of bedrock ridges, culminat-

Table 2. Climatic records, Dodoma met. station (no. 96.3501) at lat. 6°10'S., long. 35°46'E., alt. 1120 m a.s.l. Mean rainfall in mm for 30 (1931–60) resp 42 (1929–1970) years. Mean air temp., wind speed, cloud amount and evaporation (Eo) for 10 years (1955–1964). Sources of data: E.A. Met. Dept., 1966, E.A. Met. records, and Woodhead, 1968, p. 40.

| | Jan. | Feb. | Mar. | Apr. | May | June |
|---|---|---|---|---|---|---|
| Mean rainfall, 30 yrs | 146 | 116 | 121 | 51 | 6 | 1 |
| Mean rainfall, 42 yrs | 142 | 115 | 119 | 52 | 5 | 1 |
| Ave. no. of rain days (30 yrs) | 12 | 10 | 11 | 7 | 2 | 0 |
| Mean air temp. (°C) | 23.8 | 23.7 | 23.5 | 23.1 | 22.1 | 20.5 |
| Wind (km/day) | 124 | 90 | 64 | 72 | 64 | 62 |
| $E_0$ (mm/month) | 167 | 153 | 160 | 149 | 160 | 150 |
| Cloud (oktas) | 5.7 | 5.5 | 5.7 | 5.9 | 5.1 | 3.9 |

| | July | Aug. | Sept. | Oct. | Nov. | Dec. | Annual |
|---|---|---|---|---|---|---|---|
| Mean rainfall, 30 yrs | 0 | 0 | 0 | 5 | 22 | 105 | 573 |
| Mean rainfall, 42 yrs | 0 | 0 | 1 | 4 | 20 | 108 | 567 |
| Ave. no. of rain days (30 yrs) | 0 | 0 | 0 | 1 | 2 | 9 | 54 |
| Mean air temp. (°C) | 19.8 | 20.5 | 22.1 | 23.5 | 24.8 | 24.6 | 22.7 |
| Wind (km/day) | 64 | 62 | 51 | 61 | 69 | 85 | — |
| $E_0$ (mm/month) | 160 | 188 | 210 | 229 | 208 | 188 | 2123 |
| Cloud (oktas) | 3.5 | 3.4 | 3.1 | 4.0 | 4.6 | 5.3 | — |

ing in the highest point of the area, Itamba at 1610 m (5280 feet). Tectonic movements, probably in connection with the Rift Valley tectonics, caused a rejuvenation of the relief, with mountain blocks and basins. These are now modified by the pedimentation processes.

The Chimwaga hill on the drainage divide between Ikowa and Msalatu catchments is also the divide between three of the main drainage systems in Tanzania: the Kinyasungwe-Wami river basin to the E, the Ruaha river basin to the S and the Bahi basin with internal drainage to the W of Chimwaga.

The valley floors of the area are characterized by "sandy rivers", dry river beds of sandy alluvium, and "mbugas", which are grass-covered floodplains on dark, clayey sediments, generally flooded in the rainy season (Fig. 2).

Coster (1959, p. 17f) gives the following general description of mbugas. "Mbuga is a name used by the African population . . . to describe an open or sparsely tree covered flat stretch of country . . . The soils of the mbuga are commonly found to be of the black, clayey variety, often misnamed black cotton soil. The mbugas are in general, but not always, situated within drainage lines, and during the rains large quantities of water move on the surface of these mbugas . . . The clayey soils at the end of the dry season contain a network of often large and deep cracks which close up during the first showers of rain. The black clays are often as much as 20 to 25 ft. thick. Geologically mbuga deposits can conveniently be divided into clay mbugas and limestone mbugas, although all gradations are found between the two. The main formations occuring are clays, often gray and sandy, marls, limestones and often layers of concretionary, more or less solid limestone. Impure limestone with sand or precipitated silica and diatomite beds also occur. Sandy beds are rare. Mbuga deposits may reach a thickness of 400 ft. or more.

Many of the mbugas in central Tanzania are connected with blockfaulting and the clays and limestones have filled the greater part of the hollows created by the faulting. Others are to be found in areas of old, sluggish drainage systems connected with widespread peneplanation."

Table 3. Annual rainfall in mm at Dodoma met. station 1931—1971. Source: Unpubl. records 1961—1971 E.A. Met. Dept. 1966. See also Table 2.

| Year | mm | Year | mm | Year | mm | Year | mm |
|---|---|---|---|---|---|---|---|
| 1931 | 534 | 1941 | 742 | 1951 | 668 | 1961 | 647 |
| 1932 | 403 | 1942 | 711 | 1952 | 449 | 1962 | 576 |
| 1933 | 596 | 1943 | 394 | 1953 | 411 | 1963 | 434 |
| 1934 | 617 | 1944 | 934 | 1954 | 363 | 1964 | 619 |
| 1935 | 481 | 1945 | 577 | 1955 | 522 | 1965 | 609 |
| 1936 | 674 | 1946 | 308 | 1956 | 532 | 1966 | 350 |
| 1937 | 511 | 1947 | 1083 | 1957 | 539 | 1967 | 671 |
| 1938 | 578 | 1948 | 362 | 1958 | 773 | 1968 | 638 |
| 1939 | 499 | 1949 | 500 | 1959 | 645 | 1969 | 283 |
| 1940 | 620 | 1950 | 480 | 1960 | 632 | 1970 | 546 |
| | | | | | | 1971 | 609 |
| 10-year means | 553 | | 611 | | 554 | | |
| 30-year normal ........................ | | | | | 573 | | |

## Rainfall and runoff

Monthly data on rainfall, raindays, air temperature, wind, cloud amount and evaporation are given in Table 2. They are from Dodoma meteorological station, which has the longest record of the weather stations in the area. It is situated at Dodoma airport, N of the town (Plate 1B). The distance to Ikowa dam is some 50 km, to Imagi dam 3 km, to Msalatu dam 4 km and to Matumbulu dam 12 km. Rainfall stations also exist at the damsites and some comparisons will be made with these.

Mean annual rainfall for the period 1929—70 is 567 mm. The large variation in annual rainfall is evident from the data in Table 3. A period of 7 months, May—November has less than 50 mm monthly precipitation. Most of these months are completely dry. December to April is the rainy season, with a maximum mean monthly rainfall of 146 mm in January. Violent convectional rainstorms of some kilometers diameter are typical in the rainy season of the Dodoma area, as in other semi-arid savanna plains in East Africa. Figs. 7A and 7B show the surface runoff from such a storm on December 19, 1970 near the Morogoro road, 4 km E of Dodoma. The storm cell covered an area of 5 km width along the road, but outside this zone only small amounts of rain fell (P. H. Temple, personal information). At the Dodoma meteorological station only 7.2 mm of rain was recorded on that day. Another example of high intensity rainfall of local range is a storm which poured 64 mm of rain over Dodoma on 13 December 1969 after more than 8 months of continuous drought. However, periods of more general heavy rain can also occur and are important in generating high flows in the larger catchments.

A method of comparing the frequency and intensity of high rainfall is provided by graphs of recurrence or return period of maximum daily rainfall. Fig. 8 is such a graph for Dodoma, period 1937—1970. The maximum daily rainfall is only an approximate expression for rainfall intensity, as most storms last only for a

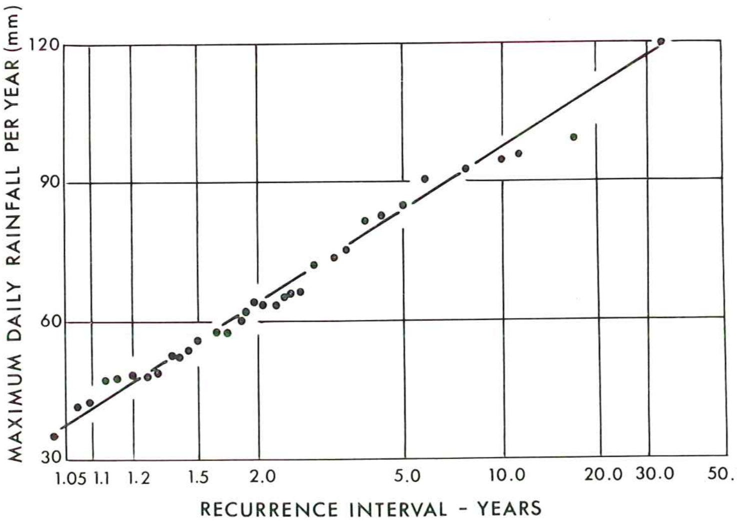



Fig. 8. Graph showing return periods of maximum daily rainfall per year, for Dodoma Met. Station, 1937—1970. Regression line is drawn by eye-fit.

few hours or less. But as most stations only record 24-hour precipitation it is the only available data for comparison. The 75 mm daily rainfall occurs with a return period of 3.5 years in Dodoma, which indicates more frequent storms of high intensity there than at Mgeta Mission and Mizugu Mgeta in the Ulugurus which both have an annual average precipitation of more than 950 mm, but longer return periods of daily rainfall in the 50—100 mm range. The 30-year maximum daily rainfall is 120 mm at Dodoma, about the same at Mizugu Mgeta and about 105 mm at Mgeta Mission (cf. Temple & Rapp 1972, Fig. 3). The two stations Bunduki and Kienzema in the Ulugurus are situated at higher elevations and have both higher daily intensities and higher mean annual precipitation than the other three stations.

A detailed study of rainfall and runoff in semi-arid ranchland in northern Uganda is of interest for comparisons with conditions in the Dodoma area. The Uganda study was started by EAAFRO in 1958 (Pereira, 1962, p. 42) in the Atumatak catchment, an area of 8 km$^2$ on a severely overgrazed "scrub-covered undulating basement-complex peneplain" (op. cit. p. 43). The catchment is similar to those studied by the DUSER project near Dodoma in geology, soils, gradient, vegetation and size. It has higher precipitation, 750 mm average annual rainfall 1958—61. Pratt (1962, p. 75) describes the results of three years detailed studies of relationships of rainfall to runoff at Atumatak and makes the following conclusions: "Stormflow, which constituted the whole of the streamflow, was directly proportional to the amount of effective rainfall, i.e. rainfall in excess of the amount needed to satisfy the storage capacities of the catchments. The runoff averaged 40 per cent of the effective rainfall. However, the first rains of the wet season appear to go to fill the reservoir in the coarse sand of the river-beds since they yield little streamflow in spite of previous wetting of the soil surface."

These conclusions from a well instrumented and intensively studied catchment agree with the approximate data published by A. P. Fawley (1956b) on the Msalatu reservoir and catchment, Dodoma. That reservoir generally starts to fill up in November or December and begins to overflow in January in most years. As no readings are taken for water that overflows, the data on runoff calculated from increase of storage in the reservoir during December are probably relevant: they are taken after the first flows which are largely absorbed by heavy infiltration into sandy rivers etc. and before the overflowing of the dam. Fawley has calculated the runoff from the catchment in percentage of rainfall for the years 1945—1953. For five years out of nine the runoff percentage in December is above 20, and two years are above 26 %. These percentages only give orders of magnitude as the rainfall is extrapolated from only one rain gauge, furthermore they only cover an early phase of the rainy season when infiltration of water into the ground is still considerable. For individual storms the single rain-gauge at the reservoir will seldom give a figure equal to the average rainfall over the entire catchment area, and may be in error by 50 per cent. However, it is probable that the average of a year is normally within 20 per cent of the correct figure (Fawley 1956b, p. 74).

From Pratt's and Fawley's data it can be concluded that runoff from semi-arid pediment areas in East Africa with a poor vegetation cover can reach 30—40 % of the rainy season's precipitation for catchment areas a few km$^2$ in size.

Surface runoff from small control areas like erosion plots can be still higher and varies very much with the type of vegetation cover and land use. Staples (1938) and van Rensburg (1955a) have recorded surface runoff and soil losses from erosion plots at the Veterinary Research Station at Mpwapwa, central Tanzania, in an environment which is similar to that of Dodoma. Six erosion plots were laid out on a red sandy loam soil, typical of the area, on a pediment slope of 3.5° gradient. The plots were 50 m$^2$ in size (1.8×27.7 m). They are further discussed by Temple 1972 (this volume). Individual rainstorms gave as high runoff as

Table 4. Percentage surface runoff from erosion plots, Mpwapwa. Size of plots 50 m$^2$, slope 3.5°. Average data from eight years of recordings, 1946—1954. A is cultivated plots with millet. B is half cultivated and half grass-covered. C is entirely grass-covered. From van Rensburg 1955a.

| A | B | C |
|---|---|---|
| 19.31 % | 11.55 % | 4.94 % |

81.3 % from a bare non-cultivated plot, compared with 70.1 % from a plot planted to bulrush millet and 25.2 % from a grass-covered plot and that before the grass was firmly established (van Rensburg, op. cit. p. 228). For eight years recordings under vegetation-covered plots the average percentage runoff varied from 20 % to 5 % as is shown in Table 4. Cf. Temple 1972, Fig. 2.

In larger catchments like Ikowa (640 km²)

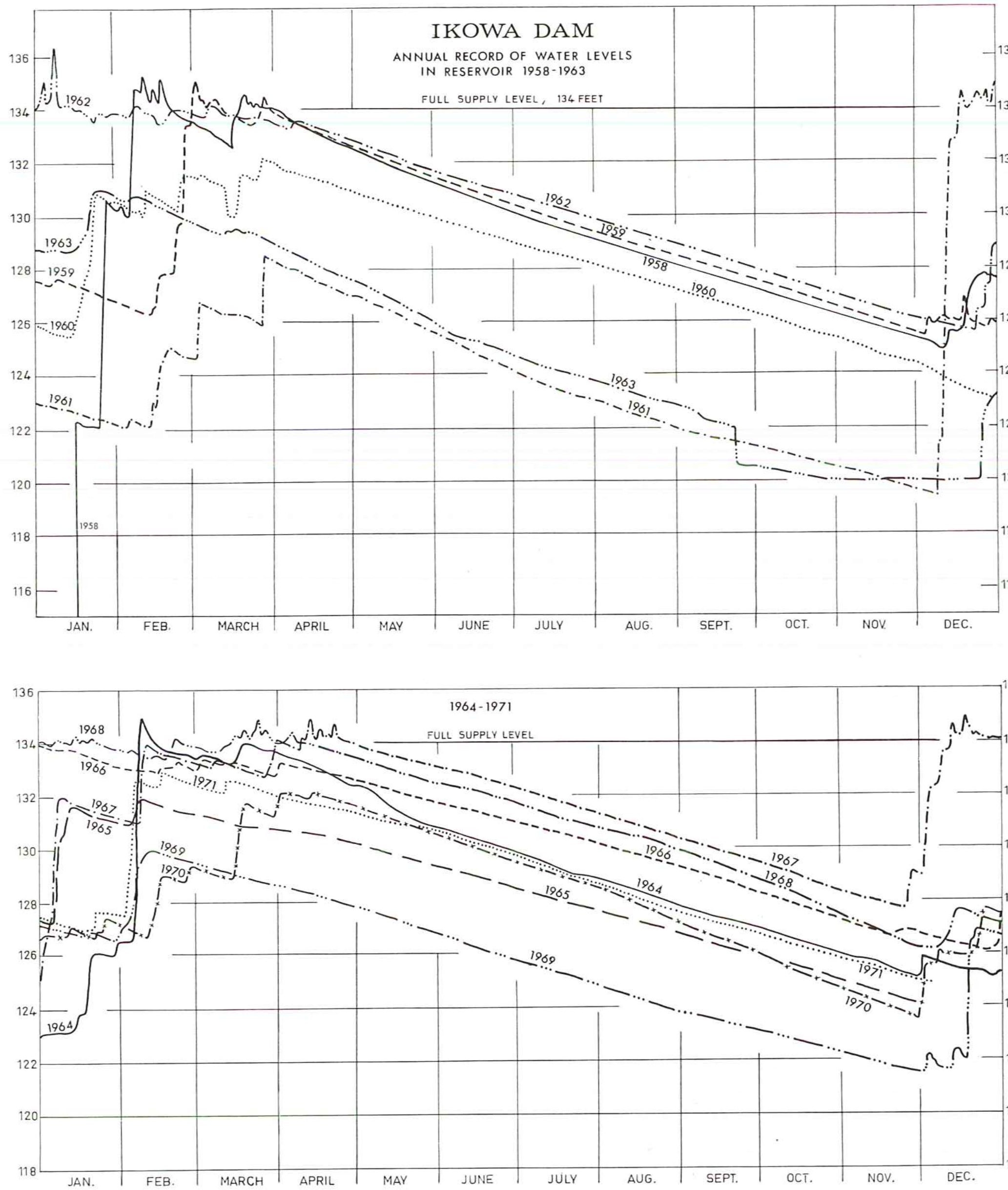



Fig. 9. Records of water levels in Ikowa reservoir 1958—1963 and 1964—1971. Depths in feet below Full Supply Level (FSL). Abrupt rises of level in the rainy season (e.g. 1958) and steadily sinking level in the dry season May—November is evident. Irregular sinking is due to irrigation flow. 1961, 1963 and 1969 were particularly dry years. FSL was not reached in 1969—1971. Levels are read on staff gauge once a day. Data from WD & ID.



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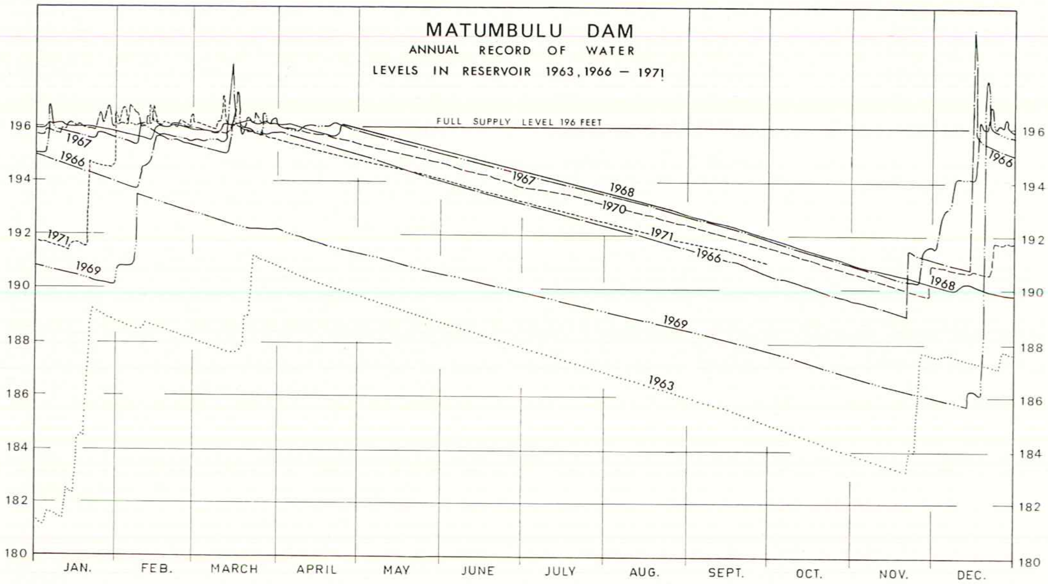


Fig. 10. Records of water levels in Matumbulu reservoir 1963 and 1966—Sept. 1971. The dam was repaired in 1962. Level is read three times daily. Cf. Figs. 9 and 41. Data from WD & ID.

proportionally more of the precipitation is infiltrated into the large areas of sandy rivers, sand fans and mbugas. From there it is partly lost by evaporation during the dry season, which reduces the percentage of runoff that reaches the reservoir. For example, in the year of 1960 the Ikowa reservoir received 1.7 mill. $m^3$ water which corresponds to only 2.65 mm of runoff from its entire catchment. Coster (1959) quotes an annual runoff figure of 1.35 % for the Ikowa catchment in the first year the reservoir was used.

Streamflow in the area is short-lasting and flashy, connected with intermittent runoff from rainstorms. During the whole dry season April—November the riverbeds are dry "sandy rivers". The slowly sinking groundwater level, enables people and animals to obtain drinking water from holes dug in the riverbeds. Under these hydrological circumstances it is understandable that stream gauging is very difficult. Horst concluded in his report on the entire Kinyasungwe-Mkondoa river basin, of which the Ikowa catchment is one of the tributaries: "As a result no reliable data for riverflow have been arrived at" (Horst, 1964, p. 4).

An illustration of the flashy flow of the streams is provided by the diagrams Figs. 9 and 10 of the water levels in the Ikowa and the Matumbulu reservoirs. The Ikowa diagrams show distinctly the period of rapid rises of the water level at phases of flashy riverflow from December through March. In the wet year of 1967 the overflow through the spillway continued until late in April. The dry season is marked by a steadily sinking water level during 7—9 months. At Ikowa the sinking is due to evaporation, irrigation, cattle watering, household use and seepage. These together caused a drop of ca. 220 cm in 8 months at Ikowa 1969 (27.5 cm/month) and 180 cm in 8 months at Matumbulu 1969 (=22.5 cm/month). The more rapid sinking levels at Ikowa are due to the irrigation outlet of water there.

Data on monthly potential evaporation for Dodoma are presented in Table 2, from Woodhead 1968. They are based on calculations according to the Penman formula. October is the month of highest potential evaporation, 229 mm.

## Soils and vegetation

The soils of the area occur in catena sequence; thin gravelly and stony soils on the inselbergs, red- or grey-coloured sandy soils on pediment slopes and black, clayey soils on the mbuga floodplains. The Dodoma geological sheet shows the soils on the pediment slopes as two groups: grey sandy soils and reddish brown soils, the latter being more fine-grained and of higher fertility. The soils are often crusted, cemented by calcium (calcrete), silicium (silcrete), iron (ferricrete) or with a clay hardpan (claycrete), as described by e.g. Fawley (1956b). See Table 9 for grain size analyses.

The following brief description of soils and vegetation is mainly based on an FAO/UNDP Livestock Mission report by Skerman (1968).

The main parent rocks are two: granites which give rise to greyish sandy soils around Dodoma and gneisses from which are produced reddish or pink sandy loams. Both are poor in plant nutrients.

1. *The granitic sands* of the Dodoma area are largely taken up by existing and abandoned cultivations and natural grazing is relatively scarce. Secondary bush species include some *Acacias, Grewia* and *Dichlorstachys.* "The ground flora consists mainly of shortlived annual grasses which are able to grow and set seed within the short growing period, and some legumes and weeds . . . The legume *Stylosanthes fruticosa* is the most important grazing plant for 20 miles around Dodoma on the sandy granite soils". (Skerman p. 2).

2. *The red sandy loams* vary from pink to red in colour and are wide spread on the pediment slopes throughout the Dodoma and Mpwapwa districts. They carry the extensive belts of (a) deciduous thicket, (b) secondary thicket reverting back after cultivation and (c) existing cultivation.

The deciduous thicket consists of a number of low-growing trees forming a dense canopy during the rains. It includes *Combretum, Acacia tortilis, Adansonia digitata* (the baobab tree) and many other species. Except for a few evergreens, the scrub loses its leaves early in the dry season and produces a rapid flush of young leaves at the beginning of the rains. "The thicket does perform an important function in holding the soil against erosion". (Skerman p. 4). This effect is clear from the erosion tests by Staples at Mpwapwa (cf. Fig. 5).

Secondary thicket after cultivation is dominated by one tree, *Acacia tortilis subsp. spirocarpa,* four scrubs, perennial or annual weeds and eleven annual grasses, according to investigations at Mpwapwa. In former thicket areas reversion to bush is extremely rapid once cultivation has ceased. The pasture has little time to reach a climax as when a certain degree of fertility has been restored the land is again required for cultivation (Skerman, p. 7).

3. *The mbuga floodplains* vary from areas only slightly inundated in the rainy season to those which are permanently wet. The mbugas of the Ikowa catchment have dark clayey soils. As in other areas they are the lowest unit in the catena sequence.

"The chief value of the mbugas is as dry season grazing in conjunction with pasturage on higher ground used during the rains. Water can usually be found at shallow depth by boring and the clay is sufficiently impervious to allow for surface storage in dams. The wetness of the soil during the rains protects them from grazing and their topography prevents erosion. Generally the soils are of higher fertility than the upland soils and cattle grow well in this environment" (Skerman, p. 8).

The clayey mud flats of the bare reservoir bottom at Ikowa are colonised by scattered bushy stands of *Polygonum senegalense* (Fig. 22). They form a very dense thicket, about 1 m high on the shores of the Matumbulu reservoir, but are restricted by grazing at Msalatu. The *Polygonum* has increased much on the Ikowa mudflats since 1968, possibly because the delta was not flooded up to FSL in 1969—1971 (See Fig. 9). The floating plant *Achyranthes aquatica* has also spread at Ikowa (D. Johansson, personal information).

4. *Termite mound areas* are numerous around Dodoma and in the western part of the Ikowa catchment. Skerman describes these as the "sodium hardpan complex" and leaves it open if they are of termite origin or are remains of earlier human habitation . . . They are circular patches of grey bare claycrete, slightly domed and 10—25 m wide. The patches occur at regular intervals and are very striking when seen from the air or on aerial photographs (cf. Plate 1A and Fig. 12). Grove (1971, p. 35) and E. G. Hallsworth (personal information) interpret similary spaced patterns as old termite mounds and the present writers found evidence for termite structure on the surface of many of these patches in the Ikowa catchment. This was particularly obvious in sloping areas where denuded termitaria were observed on the upslope edge of the bare patches which were elongated downslope. It is likely that the genesis of these patches is as

follows. The termites bring up particles from the subsoil to build their pillars. When abandoned by the termites the mound is eroded by rainsplash, and the clay crust extends downslope due to a combination of wash and splash. The crust prevents vegetation from recolonizing the sites. According to Skerman (p. 8) the bare patches are exposed clay, often with the domed columns characteristic of solonetzic structure due to the presence of sodium in the clay. "The areas are bare of vegetation and the intervening soils with a sandy surface carry a vegetation consisting mainly of low trees of *Grewia* species and with low quality *Giligochloa indurata* grass as the dominant ground flora. This soil complex has either never been cultivated or been abandoned because of the salt . . ." (Skerman, p. 9).

5. Sandy skeletal soils of the "miombo" woodland occur on the inselbergs of the area. The trees belong mainly to the *Brachystegia—Isoberlinia* association and the grass flora is dominated by *Hyparrhenia* ssp. with *Eragrostis, Aristida* and *Setaria* ssp. These grasses are burnt annually. It is believed that the miombo is a fire climax community. The soils are usually poor and shallow (Skerman, p. 9).

## Population

Most of the inhabitants of the Dodoma area are Gogo. The population of the Ikowa catchment is estimated at 22,500 (1967 census data), a density of 35 persons per km$^2$. This is higher than the average density for Dodoma District and is probably a reflection of relatively numerous water supplies. The number of households in the catchment in 1967 is estimated at 2400, thus averaging 9.4 persons per household. An indication of the distribution of settlements can be obtained from the 1 : 50,000 topographic maps (based on 1960 air photography) although only 1700 houses are indicated. The discrepancy is probably due to new settlements through population growth and to imprecise mapping.

There were 87 homesteads in the Matumbulu catchment in 1960 (See Table 15). Msalatu catchment had 4 homesteads and Imagi none. The northwestern part of Ikowa is sparsely inhabited, the only settlements being near Ihumwa, where the water table is locally close to the surface of the sandy river even at the end of the dry season. In the central part of the catchment population densities are high, particularly along the water courses and the dry season roads. The two nucleated villages, Kikombo and Buigiri are located in this area.

East of Kikombo the number of settlements increases around the mbuga basins, because of better grazing and ground water supplies. Around Ikowa reservoir population densities are low. This situation was changed in 1971 when an ujamaa village of about 4000 people was established 2 km N of the Ikowa dam.

## Land use

The Gogo have been termed "cultivating pastoralists" (Rigby 1969, p. 26) emphasising the conflict between cultivation, with its subsistance reward, and the maintenance of large stock holdings for social status and wealth. Erosion may have developed as a result of this dichotomy, for although the main interest of the Gogo is in cattle, settlement location and mobility are determined by water and agricultural constraints, not availability of grazing.

Grazing, like water, is freely available to all herders, with no individual having the right to reserve grazing for himself. All parts of the catchment are consequently grazed, but a general grazing cycle can be seen. During the wet season, when milk yields are highest, cattle are usually grazed near homesteads. Milk forms an important part of the diet during the rainy season, but yields drop to very low levels during the annual drought. As grass and water supplies become scarcer, cattle are walked to more distant grazing areas on the upper pediment and then onto the inselbergs. The only exception to this pattern comes in areas with substantial dry season grazing on mbuga clays. These cannot be grazed in the wet season.

Stock numbers are kept as high as possible for a number of reasons. Cattle holdings are regarded as a measure of status and of wealth. They are used as insurance against bad harvests, for as grain can only be stored for short periods, surplus yields are sold to enable stock purchases.

There are no accurate stock counts for the catchment since the Gogo do not willingly divulge information concerning their cattle. One estimate of stock holdings (Rigby, *op. cit.*, p. 51) is 1.5 stock units per person, the equivalent of some 34,000 stock units in the catchment. This gives density of 1.9 hectares/stock unit.

The carrying capacity clearly varies throughout the catchment due to the variation in vegetation. The UNDP/SF livestock project in Dodoma uses an average of 2.5 hectares/stock unit as a minimum safe density (D. Thornton, personal communication). Ikowa catchment is by this measure consequently overstocked.

Apart from supplying milk and occasional meat, cattle provide manure for fields near the homesteads. These fields, situated on the lower pediments or in valley bottoms, are cultivated every year and it is only through constant manuring that yields are maintained (Rigby, *op. cit.,* p. 29). In many areas population densities do not permit a fallow period, and fallow periods are short as after two years the land is free for cultivation by any farmer.

The fields on the upper pediment slopes are less intensively used. Yields drop rapidly as no manure is available, and they are generally abandoned within three years. In addition they are cleared communally, which involves extra expense for the owner. It is a sign of increasing pressure on available land that there are more fields visible on the upper slopes, on the 1960 than on the 1949 photographs. The numbers have probably increased still more in the last decade. The mbuga areas are not cultivated as they are too wet during the rains, and dry out quickly on the surface during the dry season.

It is difficult to define the area under cultivation at any one time, due to the complex of cleared and abandoned fields. The 1960 air photographs have been used as a basis for calculating cultivated areas (Table 5) although continued population growth will probably have entailed an increase in the cultivated acreage since then. The cultivated areas have not been indicated on Plate 1A for reasons of scale and clarity, but the distribution of settlements reflects the pattern of cultivation.

## IKOWA CATCHMENT AND RESERVOIR

### Introduction

Ikowa dam was completed in 1957 by WD & ID. It was built for the purpose of flood control and irrigation (Horst 1964, p. 6). The dam stores the water of the Majenjeula river, which is one of the upper tributaires of the Kinyasungwe-Mkondoa river basin (cf. Fig. 1 and Table 1). Two other larger dams are included in the flood control system, Hombolo dam and Dabalo dam, both of them north of Ikowa catchment. They store the water from two other tributary rivers. The former dam has a catchment of 1500 km$^2$ and the latter 3000 km$^2$ (Horst, op. cit.). Both of them were too large and inaccessible for study within the limited resources of the DUSER project.

Already in the 1964 report by Horst, (*op. cit.* p. 8) the following critical conclusion is drawn concerning the irrigation project at Ikowa: "This has been a failure due to a combination of the fact that the farmers were not irrigation minded; lack of guidance and discipline; siltation of the reservoir and the occurrence of a dry year combined with water misuse (waste)." An analysis of the Ikowa irrigation scheme is found in Berry & Kates (1970).

Table 5. Areal inventory of main landform units and extent of cultivation in the Ikowa catchment. The analysis is based on the map Plate 1A in its original scale of 1 : 50 000 and on interpretation of aerial photographs of 1960. Ground checks in 1968–71.

| Landform units | Area, km$^2$ | % of catchment | Cultivated area km$^2$ | % |
|---|---|---|---|---|
| a) Inselbergs and other bedrock hills | 65 | 10.1 | 1 | 0.5 |
| b) Upper pediment slopes | 114 | 18.1 | 19 | 10.0 |
| c) Lower pediment slopes except d+sand fans | 281 | 43.6 | 150 | 77.0 |
| d) Termite-mound areas | 138 | 21.6 | 23 | 12.0 |
| e) Mbugas | 42 | 6.6 | 1 | 0.5 |
| Total | 640 | 100.0 | 194 | 100.0 |

Table 6. Chemical analyses of water from Ikowa, Msalatu and Matumbulu reservoirs. Ikowa 1, Msalatu 1 and Matumbulu 1 were taken in February 1970 (rainy season). The other samples were taken in October 1971 (dry season). Matumbulu 2G is groundwater from 3 m depth in the sandy delta, 3R is from the reservoir.

| Reservoir | pH | $\varkappa_{20} \cdot 10^6$ | Ca | Mg | Na | K | $A(HCO_3)$ | $SO_4$ | Cl | Si mg | Mn mg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ikowa 1 | 8.03 | 186.0 | 0.751 | 0.355 | 0.832 | 0.134 | 0.431 | 0.478 | 0.166 | 4.83 | 0.00 |
| Ikowa 2 | 7.95 | 440 | | | | | | | | | |
| Msalatu 1 | 7.37 | 53.8 | 0.244 | 0.119 | 0.134 | 0.072 | 0.428 | 0.123 | 0.043 | 4.31 | 0.00 |
| Matumbulu 1 | 7.18 | 46.4 | 0.134 | 0.084 | 0.187 | 0.071 | 0.375 | 0.069 | 0.047 | 4.10 | 0.00 |
| Matumbulu 2G | 7.30 | 138 | | | | | | | | | |
| Matumbulu 3R | 7.41 | 81 | | | | | | | | | |

As concerns the conditions of the catchment the following views were expressed by Horst: "Through the years the steadily increasing number of cattle has exceeded the grazing potential of the land. This, combined to a lesser extent with agricultural practices not in accordance with soil conservation, has led to serious overgrazing and consequently denudation of large parts of the area. The semi-arid climate ... urged the construction of watering points for cattle. This resulted in an increased cattle population and more soil destruction in the vicinity of the watering points. The increasing cattle population on the one hand and the decreasing grazing potential on the other will lead to a rapidly increasing rate of soil destruction, erosion and siltation."

## Methods of catchment erosion surveys

The results of the catchment erosion survey are illustrated by the catchment map (Plate 1A). The map was drawn at an original scale of 1 : 50,000 on the basis of the topographical map, 1 : 50,000 air photo mosaics and 1 : 40,000 air photographs taken in 1960. These were compared with the actual situation by aerial survey and oblique photographs from a small aircraft in October 1969, March 1970 and October 1971. Plates 2D and E are two colour photographs showing some of the advantages of aerial inspection and colour photography in this open terrain.

Systems of wide gullies, areas of intense overgrazing with large cattle tracks, groups of naked termitaria (termite mounds), dry stream beds (so-called sandy rivers) and their fan-like accumulation areas, all appear clearly on aerial photographs at 1 : 40,000. Examples of these features in the Ikowa catchment are shown on Fig. 12. Small gullies do not appear in 1 : 40,000, but come out clearly in 1 : 15,000 (cf. Figs. 29A, B).

The slope transects of the Ikowa catchment (cf. Fig. 14 and Plate 1A) were measured from the valley floor to the foot of the inselberg, at right angles to the contours and along a straight line. At 50 m interval readings of slope gradient were taken by Meridian inclinometer, which has an accuracy of $\pm 0.25°$. Percentage of grass cover on the ground was taken by linear inventory along each 50-m length of the measuring tape. Soil samples were taken in pits which were dug to 30—50 cm depth. Notes on bedrock, soils, erosion and sedimentation features, land use and vegetation were taken along the transects. Average gradient of inselberg slope was read on the Meridian at the upper end of each transect. Height of the hilltop in the transect was taken from the topographic map. See also Table 8.

The erosion and sedimentation forms of the main stream channels were checked at ca 30 points throughout the catchment during dry season conditions in October 1971. (Table 10).

## Description of erosion and sedimentation features in Ikowa catchment

Plate 1A, Fig. 14 and Tables 5 and 7 summarize the main features of the basin.

*Inselbergs and other hillslopes*

The slopes of inselbergs and other bedrock hills in the area probably have only a very small importance as sources of sediment, to judge from the following facts:

They have a small total area, 10 % of the catchment, consist to a large extent of bare rock and big boulders without visible weathering rinds and have a fairly dense vegetation cover made up of trees, bush and grass cover.

Table 7. Tabulated description of Ikowa catchment concerning relief, soils, erosion features, vegetation and land use.

| | Inselbergs and other hillslopes | Pediments | | Termitaria Areas | Mbugas |
|---|---|---|---|---|---|
| | | Upper | Lower | | |
| RELIEF | 50-500 m irregular slopes 15-30°. Many rock outcrops and detached boulders ½-5 m dia. Precambrian shield with NE trending fault structures. | 3-10° slope generally cut by many gullies, ½-3 m deep. Sharp break with hillslope. | 1-3° slope, straight or concave, grading into upper pediment and with indistinct boundary with valley floor. Locally with scattered termitaria. Some gullies. | Circular, bare patches of 10-25 m diameter and 40-60 m intervals, slightly domed microrelief in some cases with denuded termite stack remaining. | Flat to 1° slope with shallow drainage channels. |
| SOILS | Skeletal, thin, gray/light brown sands, very stony with many boulders. Well drained. Derived from massive biotite granites or gneissose granites. | Thin bright reddish brown sandy loams less 50 cm deep. Increases in depth downslope with loams overlying light brown sandy clays. Well drained. | Pallid soils with concretionary layers - sandier than upper pediment. Well drained. | Termitaria are bare areas with clay crust and sodium in the clay (Skerman). | Deep black cracking clays with mottling and calcic nodule. Uniform profile. Poorly drained. |
| EROSION FEATURES | Shallow rill channels between boulders and some sheet wash. | Shallow rill channels and pronounced gullying common. Tree mounds indicate heavy erosion from splash and wash outside tree cover. | Splash and sheet wash dominant with shallow rill channels. | Probably very strong splash and wash. | Impeded drainage. Shallow channel flow on margins. Main channels locally incised 1-3 m into mbuga clays with 1-2 m sandy channel beds over mbuga clay. |
| VEGETATION | Dense deciduous thicket - av. 8 m high with poor grass cover. Commonly <u>Acacia</u>, <u>Combretum</u>, <u>Commifora</u>, <u>Dichrostachys</u>, <u>Euphorbia</u> and <u>Adansonia digitata</u> (Baobab). | Modified by cultivation and grazing. Commonly <u>Acacia tortilis</u> with some <u>Combretum</u>, <u>Dichrostachys</u>, <u>Cassia</u> and <u>Adansonia</u>. Grasses include <u>Digitaria</u>, <u>Eragrostis</u>, <u>Chloris</u> and <u>Dactyloctenium</u>. | Greatly modified by cultivation and grazing. Many shrubs including <u>Solanum</u>, <u>Justica</u> and <u>Vernonia</u>. | Dense thicket average 5 m mainly <u>Acacia</u> and <u>Grevia</u> between bare areas on termitaria. | Grasslands including <u>Panicum</u>, <u>Pennisetum</u>, <u>Cynodon</u> and <u>Themeda</u>. <u>Polygonum senegalense</u> and <u>Achyranthes aquatica</u> on reservoir mudflats |
| LAND USE | Dry season grazing. Very scattered cultivation plots usually abandoned after one or two years cropping. | Wet and early dry season grazing, three year rotation on cultivated plots. | Dry season grazing. Semi-permanent cultivation with manuring. | Some grazing - little cultivation. | Dry season grazing. No cultivation. |

At some places in the catchments of Msalatu and Matumbulu with a wide and gradual transition zone from inselberg to pediment (piedmont zone acc. to Young 1972, p. 204), the vegetation on inselberg slopes has been cleared in shifting cultivation. This has resulted in severe but local erosion.

*Upper pediment slopes*

Slope transects and air photos show an upper pediment zone marked by a dense network of converging gullies, generally 2—4 m wide and maximum 3 m deep. There are many signs of severe splash and sheet wash (splash pedestals under roots and stones, tree mounds, rilling). The grass cover is very sparse or entirely missing, both in the dry season and in the wet season due to overgrazing (cf. Figs. 11, 12, 15—16 and colour plates 2D and E). The upper pediments extend from an angle of about 10° at the piedmont zone down to lower gradients of 2—3° where they gradually merge into the lower pediment slopes.

Nearly all upper pediments are marked by dense gullying on 1949 and 1960 air photographs. Comparisons in 1971 in the Ikowa catchment showed that gullied zones appear to the same extent. There was no clear evidence of gully spreading into earlier ungullied areas. Recent examples of slight wall collapse due to undermining by seepage or stream water have been observed. (See also evidence of gully growth from Msalatu and Matumbulu catchments.)

Table 8. Example of description of slope transect, Ikowa transect No 4. Starting on mbuga upstream of Ikowa reservoir, heading north into cleared part of inselberg (cf. Plate 1A and Fig. 14). Gradient in degrees.

| Points | Slope gradient | Distance m | % grass cover | Remarks |
|---|---|---|---|---|
| A–B | 0.5 | 50 | 80 | Mbuga clays, red on top, black below. Short grass cover, some shrubs. Burnt. |
| B–C | 0.5 | 50 | 50 | Similar, but slightly less grass. Soil darker. |
| C–D | 0.5 | 50 | 50 | As B—C |
| D–E | 1 | 50 | 40 | As B—C |
| E–F | 1 | 50 | 35 | Soil browner, less grass, more shrubs. Soil still very clayey with deep cracks. |
| F–G | 1 | 50 | 25 | Mbuga soils end at 25 m where all cracks disappear. Little grass although shrubs remain. Then onto brown soil with surface sand and silt. Slight tree mounds. Heavily grazed. Some termite activity. |
| G–H | 1.5 | 50 | 20 | As F—G |
| H–I | 1.5 | 50 | 20 | Sand deposition in hollows. Some cattle tracks near H. Some small rills near I plus tree mounds. |
| I–J | 2.5 | 50 | 20 | Slightly less channelling. *Solanum incanum* suggests old shamba. Thicket denser nearer J. |
| J–K | 2.5 | 50 | 15 | Mostly an old shamba, very bare after 20 m. |
| K–L | 2.5 | 50 | 35 | Open thicket, with gully/rill channels, sand accumulation. Channels 2 m × 1 m in reddish brown soil. Very marked tree mounds. |
| L–M | 3 | 50 | 5 | Very open cleared area. Severe sheetwash, but channels similar. |
| M–N | 3 | 50 | 10 | Similar. Channels with much sand in base. |
| N–O | 3 | 50 | 10 | Mainly in old shamba of bulrush millet. |
| O–P | 2.5 | 50 | 5 | Severe grazing. Only minor channels, sand infill. |
| P–Q | 3.5 | 50 | 0 | In shamba above cattle track. Large channel 20 m to west. |
| Q–R | 3.5 | 50 | 0 | Shamba ends at 25 m, then severely grazed area. Occasional shrubs. Soil sandy with tree mounds. Large channel 25 m to west. |
| R–S | 3 | 50 | 10 | Change at 15 m to lag gravel on surface. Many tree mounds, much crusting. No deep channels except large channel 24 m west. |
| S–T | 3.5 | 50 | 10 | As R—S |
| T–U | 4 | 50 | 5 | As R—S |
| U–V | 2 | 50 | 10 | Deposition of fine material on surface as slope decreases. Channel to west now smaller. Soil colour changing to more grey than brown. |
| V–W | 3 (across) | 50 | 5 | Coarse material up to 20 cm on soil surface. Many small channels with sand in bottom. |
| W–X | 3 (across) | 50 | 5 | As V—W |
| X–Y | 5.5 | 50 | 10 | Pale grey/brown soil, many rocks on surface. |
| Y–Z | 11 | 50 | 15 | Onto true inselberg soon after passing Y. |
| Soil samples: | IT4Aa, Ab at Y<br>IT4Ba, Bb at T<br>IT4C at H<br>IT4Da at A | | | Junction with pediment not so clear as on other transects. Slope to skyline 22°. Much bedrock exposed, some poor grass cover, but extensive clearing of vegetation for shamba. Above clearing, thicket increases in density with many baobab trees. |

The main impression is however that no large-scale gully erosion has occurred since 1949. The relative resistance of gullies to widening is probably due to soil crusts near the upper edge of the side walls. Most gullies have such crusts in claycrete or ferricrete, tending to stabilize them from rapid widening or further branching. In general gullies seem to be deeper and more dense in the western part of the catchment. Msalatu and Matumbulu catchments are in this respect as in others similar to the western Ikowa catchment.

Gully erosion under similar conditions in the nearby Mpwapwa area is described by van

Table 9. Grain size composition of soil samples from the Ikowa catchment. Grain sizes from sieving and hydrometer analysis in Uppsala.

| Sample | Depth below | Grain sizes in mm, Weight % | | | | |
|---|---|---|---|---|---|---|
| No. | surface in cm | >2 | 2–0.2 | 0.2–0.02 | 0.02–0.002 | <0.002 |
| IT1Aa | 0–15 | 7.8 | 39.2 | 36.6 | 5.6 | 10.8 |
| IT1Ab | 15–40 | 10.2 | 44.8 | 15.6 | 12.5 | 16.9 |
| IT1Ba | 0–30 | 0.6 | 48.4 | 30.9 | 4.2 | 15.9 |
| IT1Bb | 30–60 | 0.4 | 43.6 | 41.9 | 5.5 | 8.6 |
| IT1Ca | 0–15 | 2.3 | 56.2 | 27.6 | 5.3 | 8.6 |
| IT1Cb | 15–50 | 3.5 | 46.0 | 34.0 | 4.8 | 11.7 |
| IT1Da | Weath, bedrock | 5.5 | 43.0 | 49.9 | 0.9 | 0.7 |
| IT3Aa | 0–20 | 6.7 | 55.8 | 28.7 | 5.6 | 3.2 |
| IT3Ab | 20–50 | 16.4 | 49.1 | 26.2 | 6.7 | 1.6 |
| IT3Ba | 0–30 | 0.4 | 61.6 | 28.6 | 1.5 | 7.9 |
| IT3Bb | 30–80 | 0.5 | 63.5 | 28.4 | 1.3 | 6.3 |
| IT3Ca | Upper sand | 0.0 | 71.0 | 25.1 | 3.9 | 0.0 |
| IT3Cb | Lower sand | 0.0 | 61.0 | 36.2 | 2.8 | 0.0 |
| IT4Aa | 0–10 | 6.0 | 64.0 | 24.0 | 3.8 | 2.2 |
| IT4Ab | 10–30 | 12.6 | 68.8 | 15.8 | 2.8 | 0.0 |
| IT4Ba | 0–10 | 6.0 | 68.0 | 20.5 | 5.5 | 0.0 |
| IT4Bb | 10–30 | 3.3 | 74.2 | 17.0 | 5.5 | 0.0 |
| IT4C | 0–10 (sand) | 0.4 | 84.0 | 15.6 | 0.0 | 0.0 |
| IT4Da | 0–10 (mbuga) | 0.0 | 0.0 | 14.0 | 85.0 | 1.0 |
| IT4Db | 10–20 | 0.0 | 0.0 | 37.8 | 61.5 | 0.7 |
| Kikombo bank | Mbuga+sand | 0.2 | 24.3 | 33.3 | 13.8 | 24.4 |

Rensburg (1958, p. 190): "Active gully erosion continues to take place under cover of indigenous deciduous thicket that has been given complete protection for many years, particularly along foothill areas on steep fan slopes. Although the roots of this vegetation type must inevitably afford considerable protection, erosion continues at a very marked rate. The deciduous thicket does not provide satisfactory arrest against the ravages of heavy downpours,

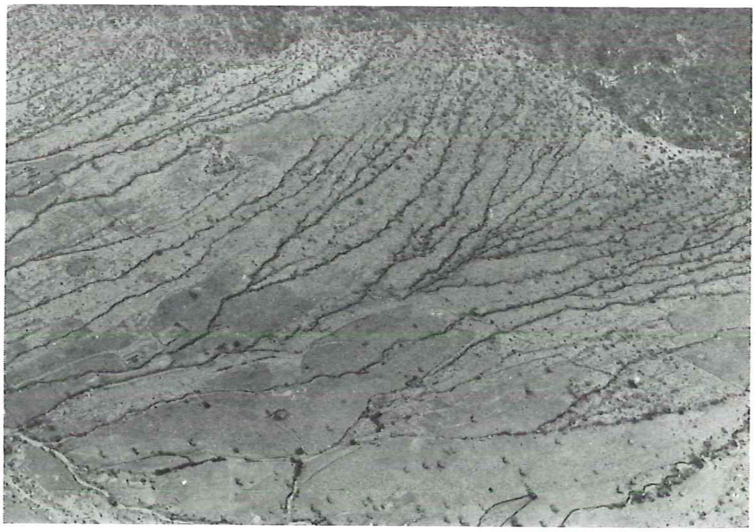

Fig. 11. Oblique aerial photo of gullied pediment slope, SE of Kikombo station, Ikowa catchment. Ngolo inselberg with miombo woodland above upper pediment slope with dense network of converging gullies. Lower pediment slope with parallel gullies, cultivated fields in fallow and homesteads. Photo PHT 25/9/71.

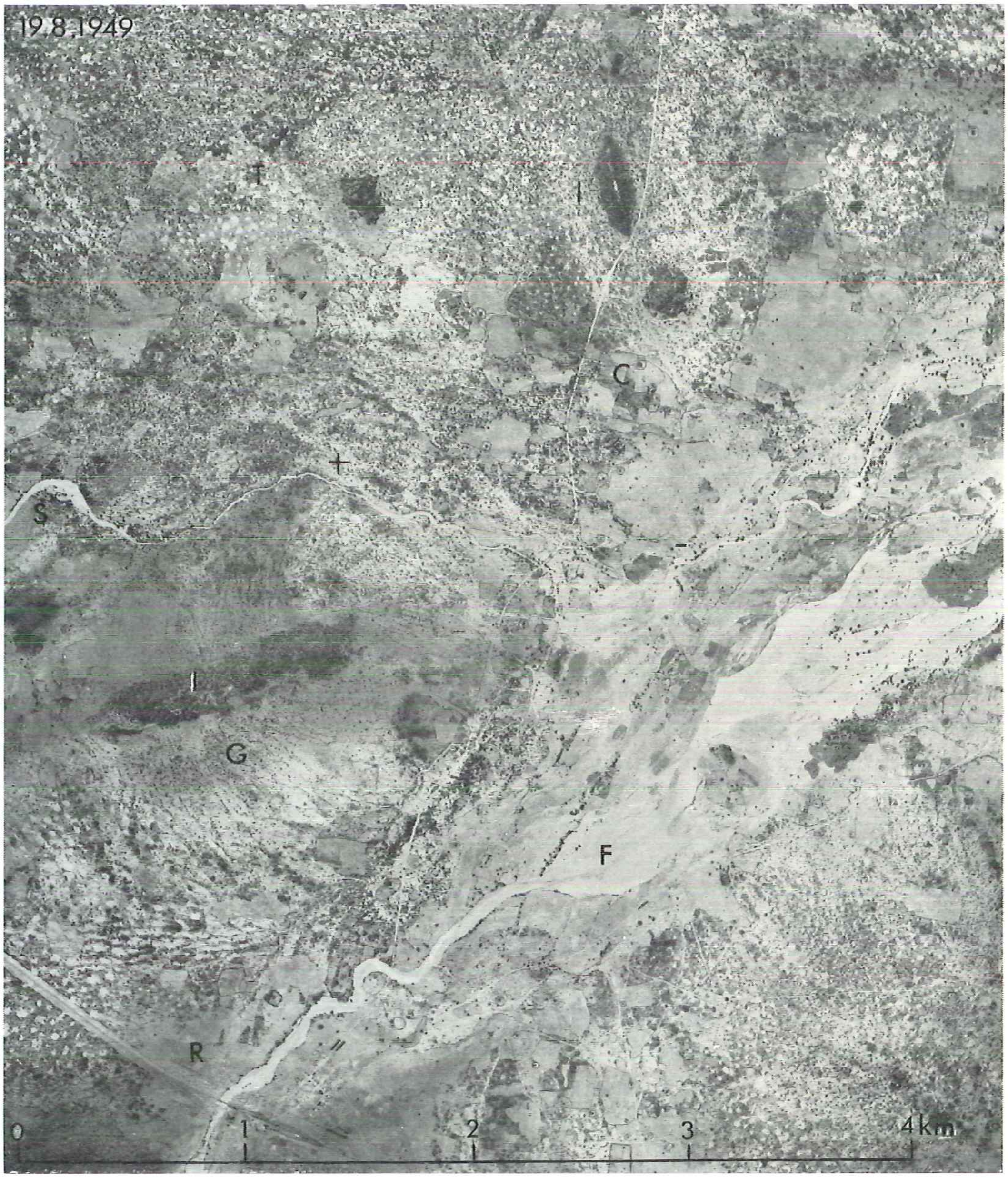


Fig. 12. Vertical aerial photo showing part of Ikowa catchment for comparison with the map (Plate 1A). The following features have been marked with letters on the picture. Kikombo railway bridge (R) over the sandy channel of Kikombo river and its wide sand fan (F). A small inselberg at (I) with dense network of gullies (G). White patches (T) are eroded termite mounds. Cultivated fields with homesteads at (C). Road to Buigiri and two small inselbergs above C. From aerial photo 82A/276/TAN taken 19/8/1949.

Table 10. Notes on stream channels, Ikowa catchment, October 1971. Depth and width of channels, type of material in banks and bed and depth to ground water in water holes are tabulated.

| Site | Location | Altitude in feet | River banks | | Channel | | Water holes |
|---|---|---|---|---|---|---|---|
| | | | height | material | width | material | |
| 1 | Transect 4 | 2970 | 0.5 m | Dark clay | 20 m | Clay | — |
| 2 | Makoja mbuga | 3000 | 2 | Clayey loam | 15–25 m | Sand over clay | 1.1 m, dry |
| 3 | Kibede tributary | 3040 | 1.5 | Dark clay | 20 m | Sand | — |
| 4 | Transect 3 | 3210 | 1.5 | Gneiss bedrock | 15 m | Sand, gravel | — |
| 5 | Kikombo village | 3300 | 0–1 | Clay+sand layers | 50 m | 0.5 m sand over clay | 4.5 m, dry |
| 6 | Kikombo road cross | 3400 | 2–3 | Clayey loam, dark clay | 40 m | sand | 0.5 m to water |
| 7 | Magungo tributary | 3350 | 2–3 | ″ | 50 m | Sand, gravel, pebbles | 3 m to water |
| 8 | Luaha river, Ihumva village | 3580 | 3 | Sandy/clayey loam | 75 m | Sand | 0.2 m to water |

especially during the early part of the rainy season when there is no foliage to break the force of the rain".

This quotation contains the most precise literature information we have found about active gully erosion in the Dodoma/Mpwapwa area. Yet it is not precise enough to tell how fast and how often the gullies grow. Such information is needed for different environments.

Quantitative documentation of the rate of gully erosion as compared to inter-gully splash, sheet wash and rilling should have a high priority in continued soil erosion surveys in semi-arid Tanzania.

The inter-gully slopes of the upper pediment zone in the Ikowa catchment show many signs of severe and active soil erosion. One of the most informative detailed forms in this respect is a type of dome-shaped mound that appears under trees. This form is here called a tree mound.

The tree mounds (Fig. 15) are best developed in the upper gullied pediments on the inter-gully slopes. The margin of a tree mound corresponds to the periphery of the crown of the tree; the mounds are dome-shaped, slightly crusted and reach 15 to 40 cm above the surrounding ground. The detailed forms of pedestal erosion (Hudson 1971, p. 38) below roots etc. indicate that the tree mounds are not accumulation forms of trapped and dropped sediment of slopewash or eolian dust, but that they are erosion remnants formed

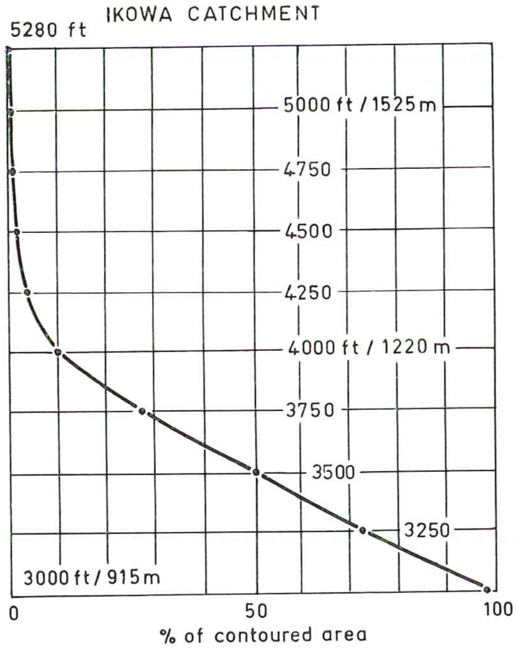


Fig. 13. Hypsographic curve, Ikowa catchment. The areal dominance of pediment slopes is expressed in the gently sloping lower limb of the curve.

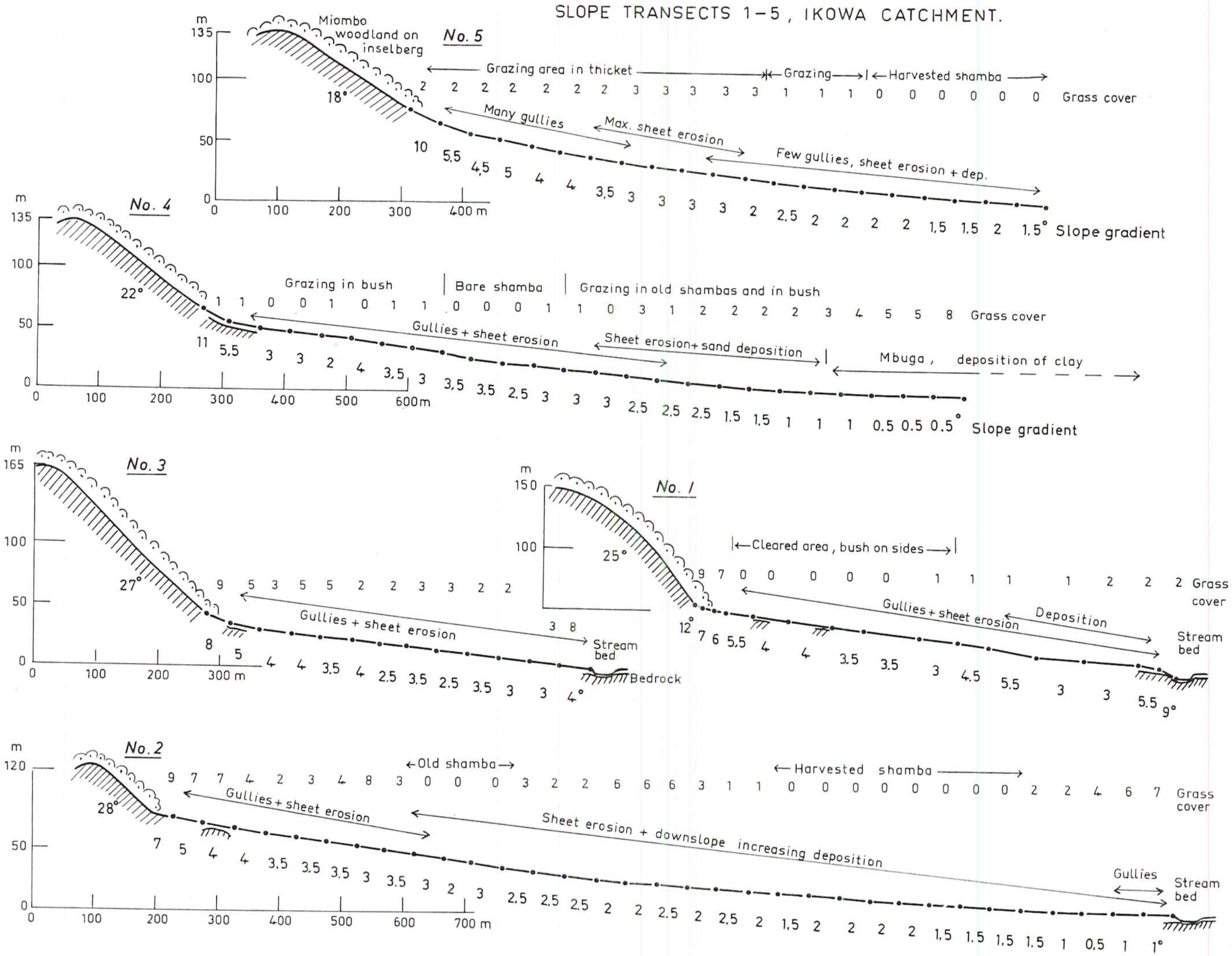


Fig. 14. Slope transects, no 1—5, Ikowa catchment. For location see Plate 1A. Slope gradients in degrees. Grass cover is expressed in tens of percent (0—9 % = 0, 10—19 % = 1 etc.). Note how close to the surface the bed-rock occurs in transects 1—3.

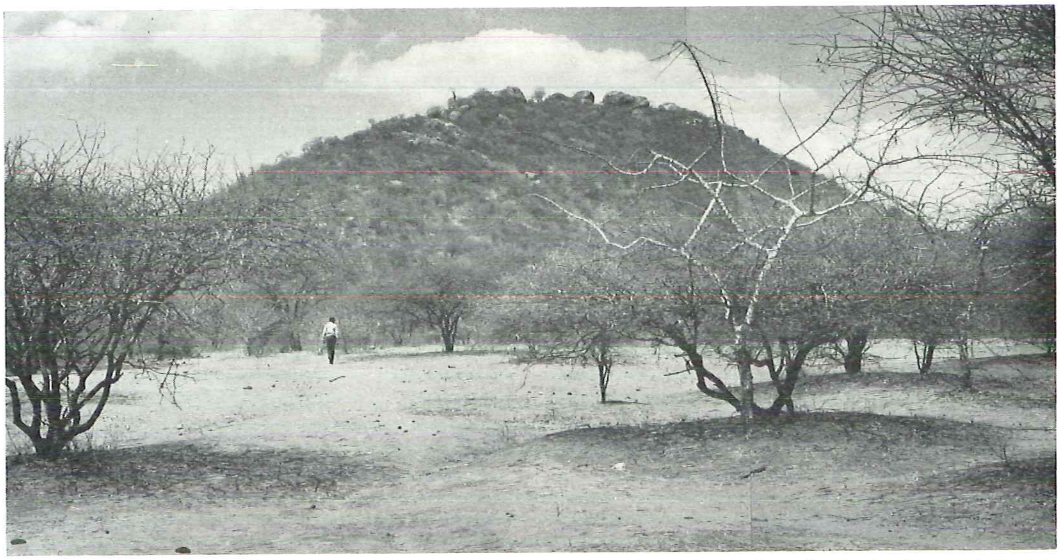

Fig. 15. Upper pediment slope in transect no. 3, Ikowa catchment. Dunda inselberg in the background. Acacia bush on overgrazed, almost bare ground. Note tree mounds under trees protecting from heaviest rain splash. Photo AR 10/71.

during the lifetime of the tree (cf. Fig. 16). Some tree-ring counts at Ikowa indicate that the trees on 30—40 cm high tree-mounds have an age of 20—30 years. Hence such trees and mounds show a general lowering of the surrounding ground by about 1 cm per year on the most intensely eroded parts of the upper pediments.

Splash erosion also acts on the mounds, lowering their surface so their relative height gives a minimum measure of the rate of erosion. A denudation rate of 1 cm/year corresponds to a sediment yield of 10,000 $m^3/km^2$ per year. That order of magnitude has been measured in erosion plots of bare soil at Mpwapwa (see Table 20: 8) by Staples, so it is probably a reasonable figure also for bare pediment surfaces in the Dodoma area. See further below under "Discussion of erosion . . ."

*Lower pediment slopes*

The upper pediments grade into the lower at a slope gradient of about 2° to 3°. In this belt gullies tend to gradually decrease in depth and be filled with sand deposits until they disappear and merge into thin sheets of sand.

The lower pediments are intensely cultivated. This zone is probably also one of severe splash and sheet wash as no vegetation cover is left at the end of the dry season. Dry stalks from maize, millet or other crops (Fig. 25) are burnt after harvest. No estimate of the amount of sheet wash could be made due to lack of reference marks of any kind. However, erosion and wash is evident from the occurrence of shallow rills over the cultivated fields. These end in minor fans of sandy/silty material interfingering with the black clays at the edge of the mbuga deposits.

A different area of lower pediments dissected by long parallel gullies, 2—3 m deep and 4—6 m wide is found on the low slopes SE of Kikombo station near slope transect nr 5. See Figs. 11 and 14: 5. The gradient there is below 1.5° and yet the slope is gullied. This may be due to rather abundant supply of runoff water from some of the highest and most extensive hillslopes in the whole area.

*Termite-mound areas*

See also description above under "Vegetation and soils".

The termite-mound areas are probably zones of high surface runoff and marked splash erosion. No detailed evidence to support this view can be mentioned, but the numerous patches of bare, claypan ground are very likely exposed to heavy splash and high runoff. They are bare

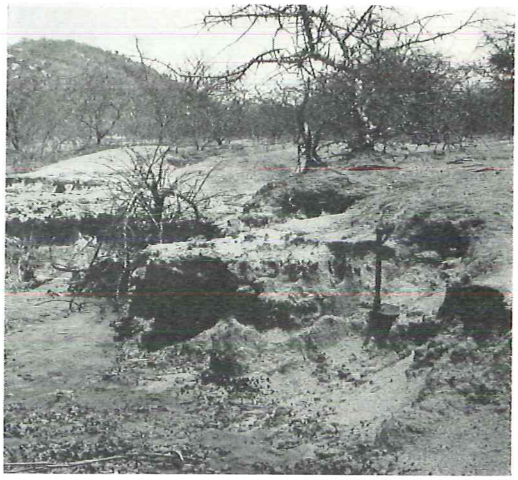

Fig. 16A. Erosion from splash, leaving pedestals under tree roots. Slope transect no 3, Ikowa. Photo AR 10/71.

Fig. 16C. Rill erosion with typical regrowth of grass in rill bottoms with better supply of moisture. Msalatu catchment. Photo AR 10/71.

Fig. 16B. Gully erosion in crusted soil on upper overgrazed pediment. Slope transect no 2, Ikowa catchment. Scale: spade handle 0.7 m long. Photo AR 10/71.

Fig. 16D. Grass fallow on abandoned shamba in thicket near upper end of pediment, transect no 2, Ikowa catchment. Kidonyasi inselberg in background. Photo AR 10/71.

also during the rainy season, to judge from aerial inspection of the Dodoma region in March 1970.

Earth brought to the surface by termites is common all over the pediment surfaces, also on overgrazed and crusted soils. The termite or ant material, generally in the form of small, sandy cones a few cm high, is particularly susceptible to sheet wash (cf. Young 1972, p. 67).

*Stream channels, sand fans and mbugas*

Two main streams drain the western part of the Ikowa catchment: the Luaha river and the Kikombo river (Plate 1A). They both run in a northeasterly direction in parts of their upper courses, probably reflecting fault-line influence. Their confluence is near the northern drainage divide at Dunda inselberg. From there the river is called the Majenjeula. Its course runs through mbuga floodplains into Ikowa reservoir. The long profile of the Kikombo and the Majenjeula rivers is shown on Plate 1C. Its lowest gradient above the confluence is 5.5 m/km (0.0055) and below the confluence 2.6 m/km (0.0026), in the mbuga area above the reservoir.

The stream channels are dry "sandy rivers" during the whole dry season and carry water during a short period in the wet season. Aggradations of sand into sand fans (Plate 1A) occur both in tributaries of small size and in the main streams. The most extensive are the twin sand fans downstream of Kikombo station (Fig. 12). The fans are not only remarkable as sites of sand accumulation but also as zones of heavy water infiltration. Their location is probably controlled by a decrease in channel gradient or by loss of water, or by both factors in combination. Similar conditions are described by Schumm & Hadley (1961, p. 12) from semi-arid areas of Western United States: "The reason for the aggradation is probably the loss of water by infiltration into the channel bed, which results in an increased sediment concentration in the remaining flow. Therefore, aggradation may occur in those reaches of the channel where little water is added to the existing flow." The sand fans can have a slightly convex surface, both in cross profile and in long profile.

The map of the Matumbulu catchment (Fig. 40) shows three sand fans in typical position where a tributary channel joins a channel of higher order. There are several examples of this type also in the upper part of the Ikowa catchment. But many of the sand fans are along single stream courses, e.g. the three lower fans of the Luaha river (Plate 1A). The one near Buigiri is so close to the drainage divide that sometimes the channel shifts over the fan to the north spilling water over the normal divide and into the Buigiri reservoir.

Table 10 summarizes some observations made on channel dimensions, type of material and depth to ground water table at the end of the dry season in October 1971.

The stream courses above and below the sand fans are generally incised and have 1—3 m high vertical banks even in the mbuga areas. The channel bed sands generally rest upon clay. This observation is in agreement with Coster's general statement (1959, p. 45): "In the arid and semiarid parts of the territory a great number of sandy and dry river-beds occur where water can be found near the surface all through the dry season. The movement of water in the river-bed sands presents a complicated pattern. In the Central Province there is frequently a clay layer below the sands which are seldom more than 20 ft. in thickness ... For a short period after the rains, water in the sands is still being replenished by effluent seepage. Eventually, the river-bed will be divided into sections; where the sands are deeper it will still contain water, other sections, possibly divided by rock bars, will be dry."

As some of the observations listed in Table 10 show, channels are incised also into the clayey mbuga sediments in many places and channel beds of sand are resting upon mbuga clays. This incision is probably a consequence of higher and more rapid runoff from the denuded pediment slopes of recent times.

See further "Discussion on erosion and sedimentation ..." below.

### Ikowa reservoir

The main embankment of the Ikowa dam is 570 m long and maximum 12.5 m high. The spillway is 150 m wide. At completion the capacity of the reservoir was 3,807,000 m³. The maximum depth of water was 6.0 m beside the stream channel, which was 2—3 m deep (Fig. 18).

Fig. 17. Bank of Kikombo river near Kikombo station. 3 m high, vertical bluff through clayey—silty floodplain deposits. Note clay blocks on riverbed sand. Photo AR 10/71.

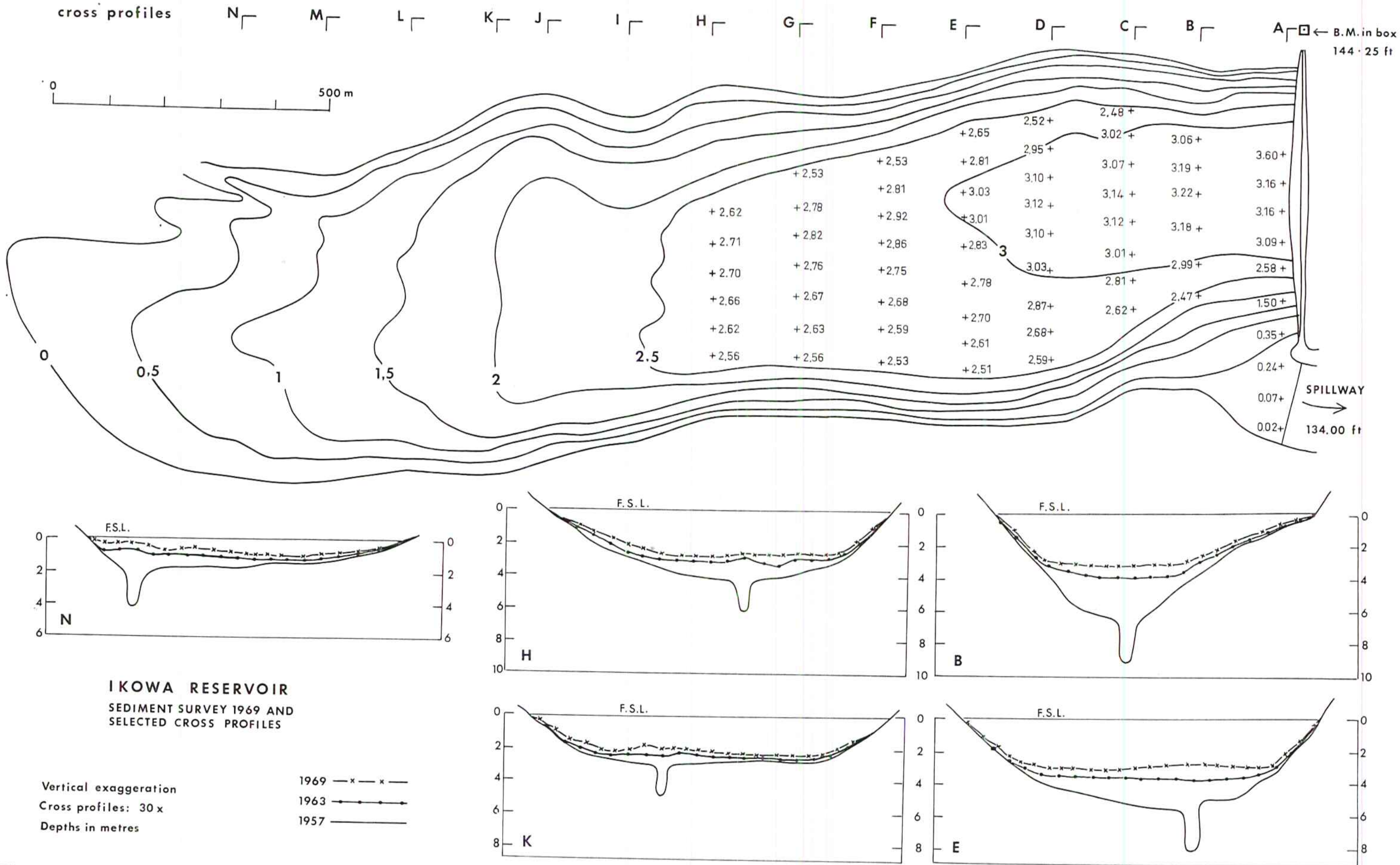


Fig. 18. Contour map of Ikowa reservoir bottom in October 1969 and selected cross profiles. Surveys in 1969 by H. M. R. Transects were measured from points A—N and parallel to dam. Distance: Dam crest—A = 100 ft, A—B = 500 ft, B—C = 400 ft, C—D and on = 500 ft. except J—K which is 280 ft. Distances between levelled points on transects = 100 ft. Only every second sounding marked on map below contour 2.5.

Table 11. Sediment characteristics, Ikowa reservoir, 1969. Analyses by G. Hellström, WD & ID. Pit 2 is at 0.30 m below FSL, pits 3 and 3A at 2.4 m below FSL in northern part of transect B.

| Pit No. | 3 | 3 | 3A | 2 | 2 |
|---|---|---|---|---|---|
| Depth (m) | 0.5 | 1.0 | 0.5 | 0.5 | 1.0 |
| Bulk density, dry (g/cc) | 1.66 | 1.63 | 1.54 | 1.65 | 1.63 |
| Moisture content (%) | 44.8 | 59.1 | 47.5 | 30.7 | 45.3 |
| Clay and silt (%) | — | 97.0 | 98.0 | — | 90.0 |
| Fine sand | — | 3.0 | 2.0 | — | 2.0 |
| Medium sand | — | 0.0 | 0.0 | — | 4.0 |
| Coarse sand | — | 0.0 | 0.0 | — | 3.0 |
| Liquid limit (%) | 87.0 | 82.1 | 82.5 | 73.6 | 84.9 |
| Plastic limit (%) | 31.1 | 30.0 | 32.4 | 30.4 | 31.9 |
| Plasticity index (%) | 55.4 | 52.1 | 50.1 | 43.2 | 53.0 |

## Methods of reservoir surveys

Sediment surveys were made by WD & ID in 1960, 1961 and 1963. Further surveying was carried out by DUSER teams in 1969 with some additions in 1970 and 1971. Eventually the 1961 survey was discarded when it was found that the map was not accurate enough for comparisons.

General methods of transect surveying and calculation of volumes have been described above. The 1969 survey was carried out in October when the reservoir was completely dry. The bench mark 120 ft. W of the first marker stone on the dam crest was used as a starting point. The bench mark has a reduced level of 144.25 ft. compared with a full supply level of 134.00 ft. of the reservoir. Although the survey was made using feet and inches, all DUSER reservoir data have been standardized to read in m below full supply level (Fig. 18).

In 1971 only transects A and B of the reservoir near the embankment were sounded. Some discrepancies between the 1969 and 1971 surveys were found, indicating a loss of sediment between the two measurements. This could have been due to disturbance by fishermen who drag their nets over the bottom each day and can create sediment removal through the irrigation intake or could be due to errors in the survey for part of the bottom. A resurvey to check this was planned for November 1971, but could not be carried out due to circumstances beyond our control. Therefore the 1969 survey data have been used.

In 1969 a number of pits were dug in the dry part of the reservoir bed to enable examination of sediment characteristics and to check the depth of annual accumulation.

A sampling trough developed in Uppsala was used in October 1970 to take sections of the sediment in pits. The metal troughs, 1 m × 5 cm × 2.5 cm were hammered into a vertical pit face and then cut free with a wire loop. This was found to be the method that disturbed the sediments least. The troughs were covered with metal lids, lined with rubber to prevent damage in transport, and sealed with paraffin wax to prevent moisture losses. Cf. Fig. 23.

Coring or digging pits through the reservoir sediments to check their total and annual thickness and other characteristics should be given high priority in a future study to follow up the DUSER reservoir investigations.

## Morphology of deposits and types of sediments

Tables 11, 12 and 13 give information on the sedimentation of the Ikowa reservoir. In the period 1957—69 the loss of reservoir capacity was 39.2 % of the original volume, corresponding to a loss of 3.27 % per year or 30 years expected life. The total accumulation of sediments below Full Supply Level during 12 years was 1,492,000 $m^3$, corresponding to a sediment yield of 195 $m^3/km^2$ per year. In this is not included the unknown amounts of suspended

Table 12. Volumes of Ikowa reservoir, 1957–69. 1957, 1960 and 1963 data from WD & ID reservoir maps, 1969 data from H. Murray-Rust.

| | Volume ($m^3$) | % of original volume |
|---|---|---|
| 1957 | 3,807,000 | 100.0 |
| 1960 | 3,111.000 | 81.6 |
| 1963 | 2,740,000 | 71.9 |
| 1969 | 2,315,000 | 60.8 |





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Table 13. Sedimentation rates and corresponding sediment yields, Ikowa catchment 1957—1969.

| | 1957—60 | 1960—63 | 1963—69 | 1957—69 |
|---|---|---|---|---|
| Sediment accumulated ($m^3$) | 696,000 | 371,000 | 425,000 | 1,492,000 |
| % of original capacity | 18.4 % | 9.7 % | 11.1 % | 39.2% |
| Number of years | 3 | 3 | 6 | 12 |
| % loss of original capacity p.a. | 6.13 % | 3.23 % | 1.85 % | 3.27 % |
| Sediment yield rate ($m^3/km^2$ per yr.) | 362 | 193 | 111 | 195 |
| Soil denudation rate (mm/yr.) | 0.362 | 0.193 | 0.111 | 0.195 |

sediments which have left the reservoir in irrigation or spill flow. The dry bulk density of the sediments is ca 1.6 g/cc (Table 11). If the bulk density of the soil also is assumed to be the same—a conservative estimate, as it probably is lower—the average soil denudation rate of the catchment is 0.195 mm/year.

Hydrometer analyses of samples from three pits in transect B show 90—98 % of clay + silt and 2—10 % sand (Table 11). The latter is in thin layers, washed out from the nearest shore. The bulk of the sediments is clay and fine silt, supplied by the Majenjeula river during its short episodes of flow (Fig. 9).

The contour map of the Ikowa reservoir (Fig. 18) and the photograph Fig. 3 show the smooth delta surface at the inflow end of the reservoir. It has a slightly incised channel of the main Majenjeula inflow, but is otherwise an even mud-flat with a gently slope of 2.2 m/km from the 0 to the 2.5 contour on the map. This gradient is almost the same as that of the buried channel under the reservoir sediments (Fig. 19A). Below the 2.5 m contour of the 1969 map the floor flattens out to an almost horizontal bottom. The smooth surface of sedimentation without any breaks in profile indicating a delta front, is in contrast to the clearly visible break in slope of the sandy deltas of Msalatu and Matumbulu reservoirs (Figs. 30, 31A, 43 and 45A). The smooth surface forms of the sediment flats at Ikowa are due to the predominance of sedimentation of suspended load and is further accentuated by the fluctuations in water levels (Fig. 9).

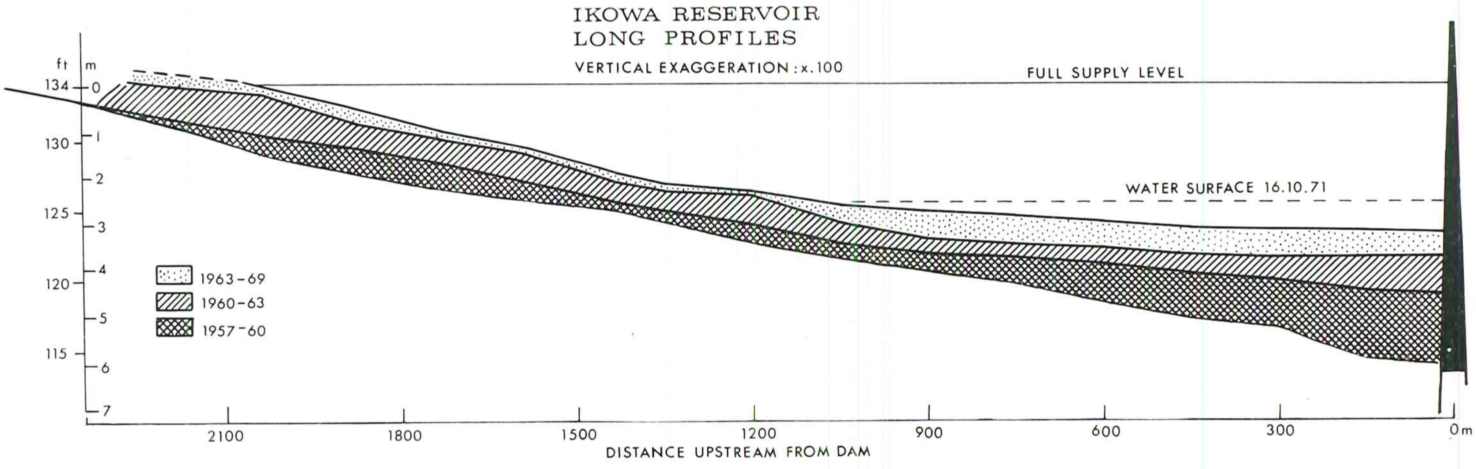
The total sedimentation is thickest in the deeper part of the reservoir, where a flat bottom surface has been formed. The thickest deposits on top of the 1957 surface at the side of the old stream channel is 3.3 m, which means 27.5 cm average deposition per year, (Fig. 18, transect B). As is shown in the cross profiles of Fig. 18 and the long profiles of Fig. 19 the sedimentation in 1963—69 has been small in the proximal parts of the delta mudflat. According to direct observations in 1969 and 1971 the annual deposition was 2—3 cm thick on the surfaces near the middle of transects J—M.

The sediments are stratified into varves with one varve being formed from each major inflow of storm water. It was hoped to measure various layers and try to assess annual accumulation as a check on the other reservoir surveys, but this was difficult due to disturbed layering from desiccation cracking and cattle trampling. In the dry season the exposed clays crack into polygonal columns at first 10—30 cm high and between 20 and 40 cm wide. The surface of each polygon is further broken up into smaller aggregates, and surface spalling is common. Stock movement on the sediment causes further disturbances.

During the dry phases the sediments are compacted. In 1961, 1963 and 1969 the bottom was all dry at the end of the dry season (Fig. 20), which probably means that compaction occurs through the whole beds of reservoir sediments.

Near the water's edge sediments are less cracked and the stratification is easier to observe. As the pits rapidly filled with water it was difficult to get deep sections for study. It was found at Ikowa that pits between 50 and 100 m from the water's edge were the most suitable for study of the stratigraphy.

The best preserved storm layers in the reservoirs studied by the DUSER teams were



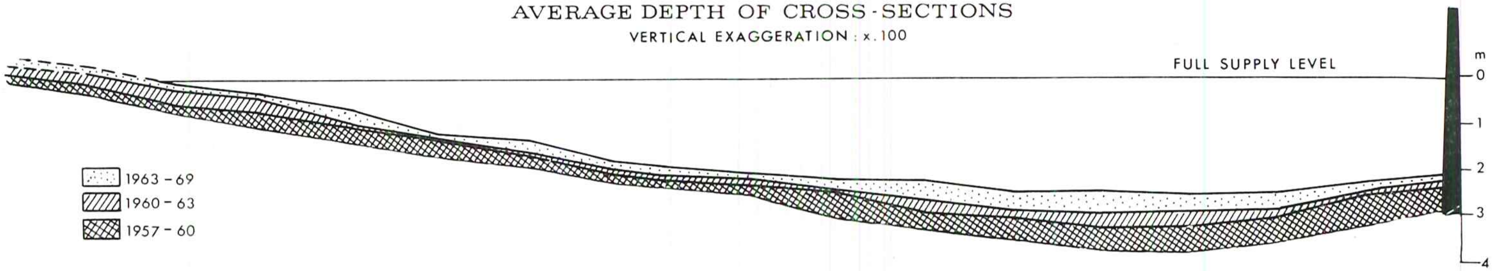




Fig. 19A. Ikowa reservoir. Long profiles of 1957, 1960, 1963 and 1969. Earlier surveys by WD & ID, 1969 survey by H. M. R. Thickest deposit is in the deepest part of the reservoir. Cf. Fig. 19B and cross profiles of Fig. 18.

Fig. 19B. Ikowa reservoir. Average depth of cross sections A—N. For each cross section the percentage of sediment fill is proportional to the thickness of the layers drawn on the figure.

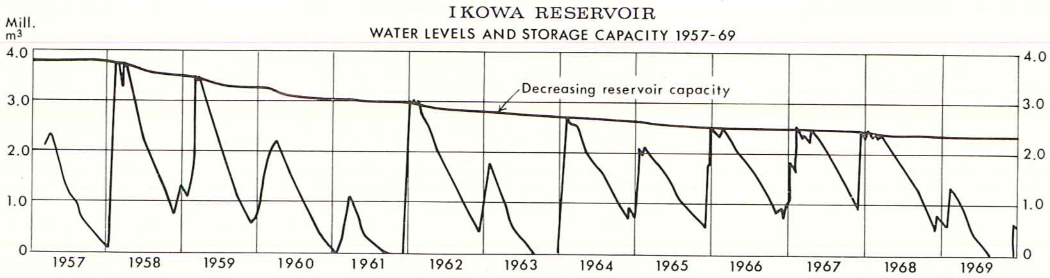



Fig. 20. Ikowa reservoir. Water storage in million m³ (peaked curve) and decreasing storage capacity 1957 to 1969. The reservoir had by 1969 lost 39.2 % of its original capacity due to sedimentation. It dried out completely in 1961, 1963 and 1969.

in the Kisongo reservoir, where no trampling of cattle had disturbed them (cf. Murray-Rust 1972, Figs. 16 and 17).

Examination of the troughs (Fig. 23) shows that there are a number of recognizable layers. Each inflow is marked by deposition of a silty layer grading upwards into finer clayey sediments. Sedimentation in the dry season will result in accumulation of a rather thick layer of fine material including redeposition of wave-washed material from the shore-line belt. The thickness of this layer will probably depend on the depth of water at the end of the rainy season and the intensity of wave-wash.

Near the inflow the sediments are dominated by micro-layers, and there are few fine bands. The relative proportion of micro-layers decreases as the dam wall is approached, and may not be visible in the sediments furthest from the inflow.

This pattern is disturbed by inflow of coarse material derived from the slopes draining directly into the reservoir. Aerial observations indicated that these sediments take the form of small fans associated with stock routes leading to the reservoir. This form of sedimentation was noted in the 1950's and a hedge of *Euphorbia tirucalli* was planted around the reservoir to deny cattle direct access. The fence has subsequently been neglected, but the volume of sediment entering the reservoir is small in comparison to that derived from the main inflow.

It was hoped to study the sediments in more detail during the dry season of 1971 by sampling progressively as the water level receded, but this programme could unfortunately not be carried out. Samples taken suggest that identification of annual sedimentation is possible, allowing annual sediment accumulation to be calculated as a check on the results obtained by repeated soundings of the reservoir bottom.

## History of sedimentation

Annual sediment yields will vary considerably between successive years, due to fluctuations in erosion and runoff. Although direct measurement of annual sediment accumulation was not possible, some indication of the relative importance of various sedimentation processes between each survey can be obtained.

The normal long profiles (Fig. 19A) are constructed from direct readings from the various surveys. In order to diminish effects of local sedimentation e.g. in the old stream channel, which may be misleading, an "average" long profile has been constructed from average depths of cross sections (Fig. 19B).

It should be emphasized that only the average depth of sediments and water can be read from that profile, and that volumes in different parts of the profile are not comparable.

In the period 1957—1960, most sediments were deposited in the deepest parts of the reservoir and in the former stream channel. There was no significant deltaic formation. Only three storms greater than 50 mm were recorded at Ikowa during this period, suggesting that only moderate amounts of coarse material would have been transported.

Between 1960 and 1963, there were significant fluctuations in the discharges entering the reservoir. The rainy season started late in 1960/61, so that the reservoir was dry for a short period before the rains came. The rains were, however, very poor, and only 1.10 million m³ of water entered the reservoir (Figs. 9 and 20). Consequently it dried up before the 1961/

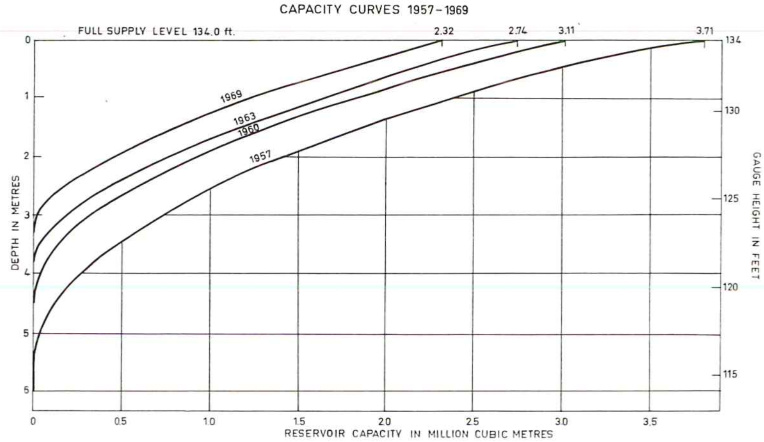



Fig. 21. Capacity curves of Ikowa reservoir 1957—1969.

62 rainy season. This rainy season was one of the wettest on record. The reservoir filled up in eight days in mid-December, the result of six storms above 50 mm in 17 days. The highest water level recorded at Ikowa was on January 6, 1962 when the height of water over the spillway was 0.68 m. This period of high discharge is most likely the cause of the large deltaic accumulation indicated on Fig. 19A, for the inflow in the years 1962/63 was poor, the reservoir failing to fill by 0.9 metres, and drying out before the next rains. The paucity of sediments in the deeper areas are probably the result of the low water levels in 1961 and 1963, with corresponding decreases in the deposition of suspended material.

## Discussion of erosion and sedimentation in Ikowa catchment

Splash erosion and sheet wash are very severe on the over-grazed upper pediment slopes, where areas of bare ground seem to be eroded at a rate of about 1 cm/year, to judge from indirect evidence of tree mounds. A similar intensity of erosion of bare, cultivated fields on the upper or lower pediment slopes is likely to occur. Dense networks of small gullies are common on the upper pediments, but gully growth seems to have been of less importance as a source of sediments to the streams and reservoir than the splash and sheet wash from inter-gully flats. Rapid gully cutting probably occurs at long time intervals as catastrophic events, but the gullies are also harmful to the land use in the intervening time as they act as channels for rapid transport of water and sediments from the inter-gully areas and thus speed up the overall erosion and desiccation of the pediment slopes.

Soil and water conservation should consequently concentrate firstly on reclamation against splash and sheet wash and secondly against gully erosion in these areas. The major line of conservation measures should be protection against splash erosion by improved grass management or suitable cover crops or mulching. This is a recommendation that is valid also for erosion control in gullies, where particularly seeding of Star grass (*Cynodon plectostachyum*) on gully floors is efficient in holding moisture and trapping soil particles (van Rensburg 1958, p. 190) as has been investigated and demonstrated at the research station in Mpwapwa.

The inventory of the stream channels showed that there are two zones of sediment deposition along the stream courses: sand deposits in many sand fans in the upper and middle sections of stream channels, silt and clay deposits in the mbuga floodplains of low gradient.

The zoning of erosion and sedimentation is illustrated in the simplified diagram, Fig. 4.

The upper pediment slopes occupy 18.1 % of the total area of the Ikowa catchment (Table 5). To judge from vertical and oblique air photographs, the tree crowns cover less than half of the ground in those areas, so 10 % is a reasonable estimate for the area of completely bare and heavily eroded upper pediments as percentage of the total Ikowa catchment. An

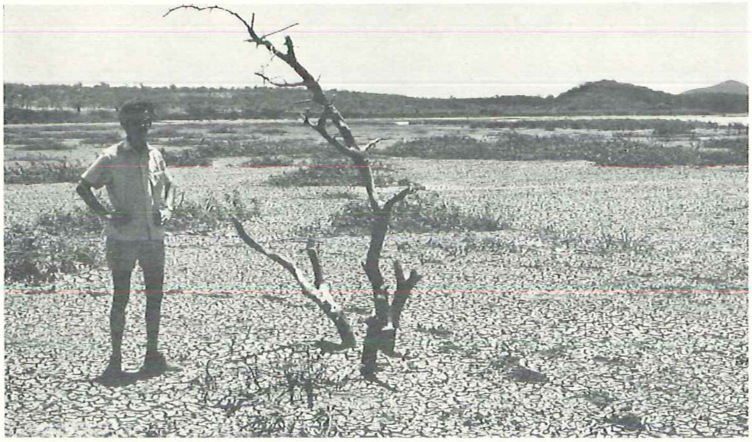


Fig. 22. Dry bottom of Ikowa reservoir with half-buried tree in clayey sediments with cracking surface. Tussocks of *Polygonum senegalense* grow on the mudflat. Location: Cross section K, SE part. Photo AR 9/1971.

annual denudation of 10 mm within this zone corresponds to an average denudation rate over the whole catchment of 1 mm/year. To this should be added erosion in other areas, e.g. on cultivated lower pediment slopes. The average annual sedimentation in the Ikowa reservoir 1957—69 corresponds to a general rate of soil denudation of 0.2 mm. From the discussion above it is likely that less than half the amount of soil eroded from the upper pediments per year is deposited in the reservoir. Most of it is deposited on lower pediments, in sand fans and in mbugas.

## Prognosis of reservoir sedimentation

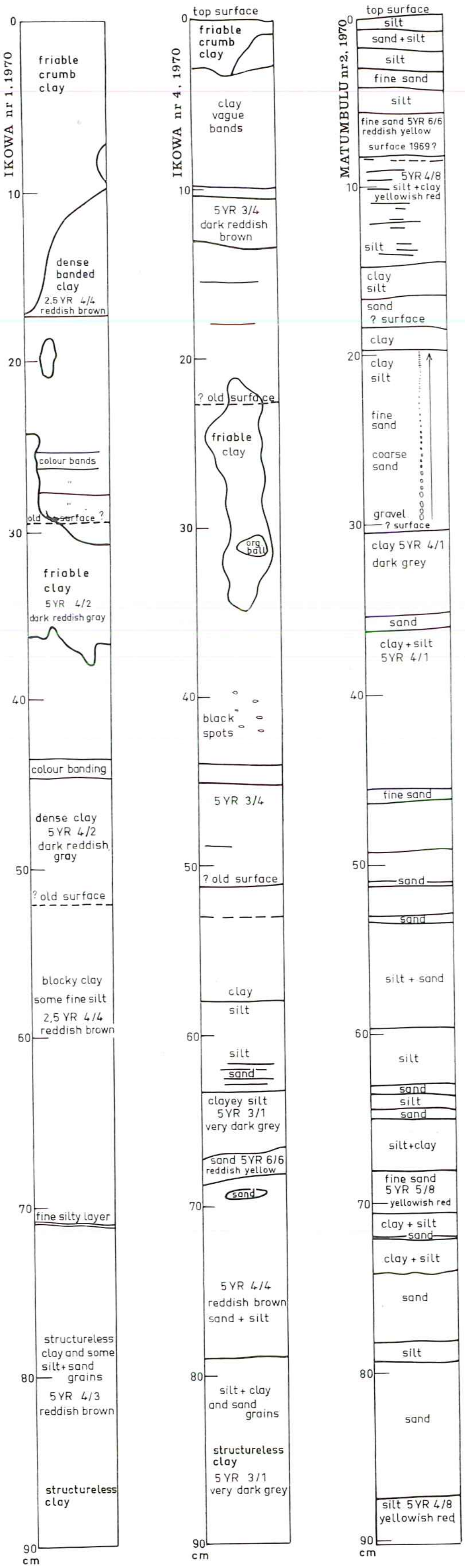
The 1969 survey shows that there has been rather high sedimentation in the deeper areas since 1963, but little deltaic accumulation. This is probably due to lack of a period of heavy rainfall as experienced in 1961/62, but may also be the result of a decrease in channel slope due to earlier deltaic growth and subsequent upstream sedimentation. Fresh flood deposits of mainly clay and silt in thin layers on the mbuga indicate its effect as a trap for fine-grained sediment upstream of the reservoir.

The lower values of sediment yield in 1963—69 as compared to the earlier periods listed in Table 12 may be explained by

a) few high floods during the period,
b) a high proportion of deposition of suspended load on mbugas and delta areas upstream of the reservoir,
c) reduced trap efficiency of the reservoir as concerns suspended load, because of the gradually reduced volume and depth of water due to the cumulative sedimentation.

The trend towards lower rate of sedimentation per year in the Ikowa reservoir during the periods 1957—60 (6.1 % annual loss of capacity), 1960—63 (3.2 % annual loss) and 1963—69 (1.9 % annual loss) is evident. The land use in the catchment shows no sign of improvement during these years—rather the opposite with more of bare cultivation and more overgrazing—so the reason for the decrease in sedimentation is probably not due to decreased erosion. For a prognosis of the future rate of sedimentation in the Ikowa reservoir, the average data on sedimentation during the whole period 1957—69 are probably more useful as a basis for extrapolation than the most recent period 1963—69. This is because the longer time series will give a better representation of the variations in size and frequency of the floods, factors which are crucial importance in this case. Therefore the extrapolation is based on the longest available period and the mean value of 3.3 % annual loss of reservoir capacity. This means a total expected life

Fig. 23. Sediment cores from Ikowa and Matumbulu reservoirs. Drawings and photographs of 0.9 m long cores in metal troughs. Colour symbols according to Munsell soil colour chart. See text for closer description. Core Ikowa no 1 is from transect I at 1.75 m below FSL, W side. Ikowa no 4 is from transect L at 0.80 m below FSL, near inflow. Matumbulu no 2 is from center of delta, 1.5 m below FSL.


IKOWA nr 1, 1970
0
friable crumb clay
10
dense banded clay
2,5 YR 4/4 reddish brown
20
colour bands
old surface ?
30
friable clay
5 YR 4/2
dark reddish gray
40
colour banding
dense clay
5 YR 4/2
dark reddish gray
50
? old surface
blocky clay
some fine silt
2,5 YR 4/4
reddish brown
60
70
fine silty layer
structureless clay and some silt+sand grains
5 YR 4/3
reddish brown
80
structureless clay
90
cm
IKOWA nr 4, 1970
top surface
0
friable crumb clay
clay vague bands
10
5 YR 3/4
dark reddish brown
20
? old surface
friable clay
org ball
30
40
black spots
5 YR 3/4
50
? old surface
clay
silt
60
silt
sand
clayey silt
5 YR 3/1
very dark grey
sand 5YR 6/6
reddish yellow
sand
70
5 YR 4/4
reddish brown
sand + silt
80
silt + clay and sand grains
structureless clay
5 YR 3/1
very dark grey
90
cm
MATUMBULU nr2, 1970
top surface
0
silt
sand + silt
silt
fine sand
silt
fine sand 5YR 6/6
reddish yellow
surface 1969?
5YR 4/8
silt + clay
yellowish red
10
silt
clay
silt
sand
? surface
clay
20
clay
silt
fine sand
coarse sand
gravel
30
? surface
clay 5YR 4/1
dark grey
sand
clay + silt
5YR 4/1
40
fine sand
50
sand
sand
silt + sand
60
silt
sand
silt
sand
silt+clay
fine sand
5 YR 5/8
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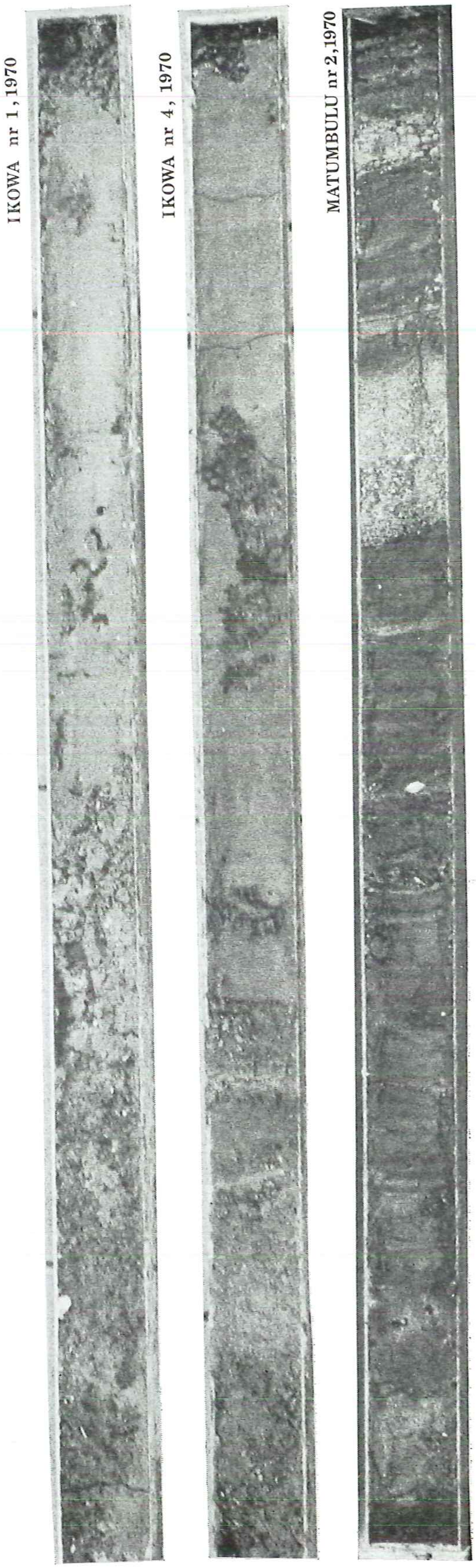

IKOWA nr 1, 1970
IKOWA nr 4, 1970
MATUMBULU nr 2,1970

Table 14. Comparison of annual rainfall in mm at 5 stations in Dodoma town and surrounding. All stations are situated within 3.5 km distance from the town centre. 1947 was a "wet" year, 1952 a dry. After Fawley 1956.

| Station | 1947 | 1952 |
|---|---|---|
| Dodoma Geol. Office | 932 | 430 |
| Dodoma Alliance Sec. School | 935 | 460 |
| Imagi reservoir | 883 | 433 |
| Msalatu reservoir | 848 | 412 |
| Dodoma 2nd order station | 1082 | 449 |

length of 30 years, or complete filling up of the reservoir with sediment in 1987. The economic life of the reservoir is considerably shorter.

Systematic measures of soil and water conservation in the catchment such as a better grass management in the areas of erosion as well as on the mbuga areas of siltation immediately upstream of the reservoir, may considerably prolong the useful life of the reservoir.

## MSALATU AND IMAGI CATCHMENTS AND RESERVOIRS

### Introduction

In 1926 it was decided to build a dam below Imagi Hill approximately 2 km S of Dodoma town. No records of evaporation and runoff existed. However runoff from the catchment was estimated at 62 %. After the dam construction in 1929—30 the actual runoff varied from 3 to 17 %. Water losses due to evaporation and leakage turned out to be far higher than expected. In some years such losses consumed 70 % of the water that entered the reservoir.

In years with adequate rainfall Imagi reservoir supplied a sufficient volume of water to Dodoma town although the reservoir seldom fills, because of the catchment being too small. In dry years water from wells and boreholes had to be used as a supplement.

In 1943 the Imagi reservoir dried up and the town suffered from shortage of water. It was then decided to build a second town dam.

A site was selected 3.5 km SE of Dodoma at Msalatu river. The Msalatu is a rather small stream draining the slopes of Chimwaga Hill. The embankment across the stream was built in 1944 and in September 1945 the new dam was brought into operation.

Later droughts and growth of population have raised discussion on the addition of one or two more surface dams. In the beginning of the fifties a possible site at Mkonze 6 km SW of Dodoma was investigated (Plate 1 B). The proposed reservoir was planned to be bigger than the other two. However the plans were never realized (James 1950; Fawley 1954). Today Dodoma gets most of its water from bore-

Fig. 24. Oblique aerial photograph of Msalatu reservoir and part of catchment. Sand bed of channel A in foreground. Channel B to the right. Cultivated plots within dark lines of thorn-bush fences. Cattle tracks mark areas of overgrazing and lack of grass cover. Cf. Figs 28, 29. Photo AR 25/9/1971.

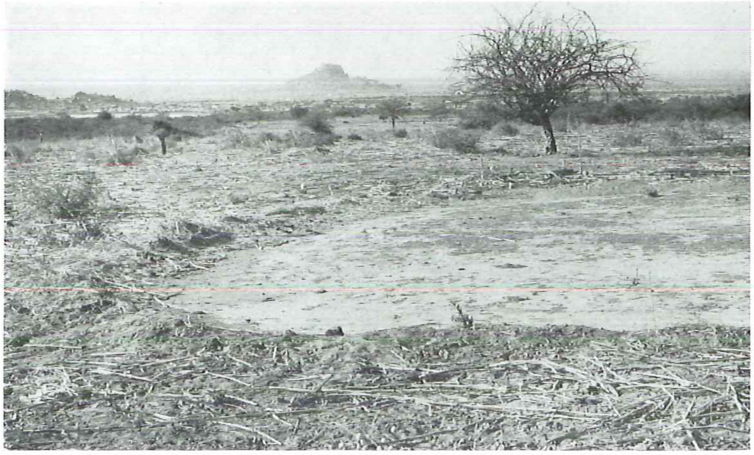


Fig. 25. Harvested field of bulrush millet, Msalatu reservoir near channel B. (Fig. 29B at B—C). Treshing-patch on old termite claycrete pan in the foreground. Msalatu reservoir in the left background, Lion's Rock (Mlimwa) inselberg at Dodoma in the center. Photo AR 10/71.

holes in the Makutapora depression 24 km N of the town. The two dams still serve as a supplementary supply.

## Description of Msalatu catchment

The physical environment of the Msalatu and Imagi catchments has been described in broad terms above. See also Tables 14—20 and Figs. 24—26. The percentages given below refer to 1960, the year of the aerial photography used for this analysis of the area.

Inselbergs occupy 19.4 % of the Msalatu catchment. On the Chimwaga hill in the S the drainage divide reaches its highest point 1475 m a.s.l. Also the N divide is well marked by lower inselbergs (Iseni hills, 1250 m). The inselbergs consist of Precambrian biotite granites or granite migmatites. The slopes of Chimwaga have gradients of 25—30° from the top of the inselberg to the pediment at 1300 m. The pediment slope that takes up the rest of the catchment is slightly concave, the gradients ranging between 0.5° and 5° along a measured transect near the E limit of the catchment. The concave shape of the slope is also indicated by the long profiles of the stream channels,

Table 15. Areal inventory of landforms, land use and soil erosion in the catchments of Matumbulu, Msalatu and Imagi reservoirs. The analysis is based on interpretation of aerial photographs of 1960. Cf. maps figs. 28 and 40.

| | Matumbulu | Msalatu | Imagi |
|---|---|---|---|
| Total area | 18.12 km² | 8.67 km² | 1.49 km² |
| Number of homesteads | 87 | 4 | 0 |
| Areal percentage | | | |
| Inselberg | 27.2 | 19.4 | 51.0 |
| Cultivations | 22.3 | 5.9 | 1.3 |
| Gully erosion | 16.8 | 22.3 | 4.6 |
| Sheet erosion | 8.4 | 12.8 | 14.6 |
| Sheet erosion + marked gullies | 1.5 | 5.9 | 4.6 |
| Sandy rivers | 0.5 | 0.2 | — |
| Sand fans | 1.0 | — | — |
| Reservoir | 0.5 | 1.4 | 3.3 |
| Pediment slopes with slight erosion | 21.8 | 32.1 | 20.6 |
| Total percentage | 100.0 | 100.0 | 100.0 |
| Gullying on inselberg area in percent | 5.4 | 2.9 | 2.4 |

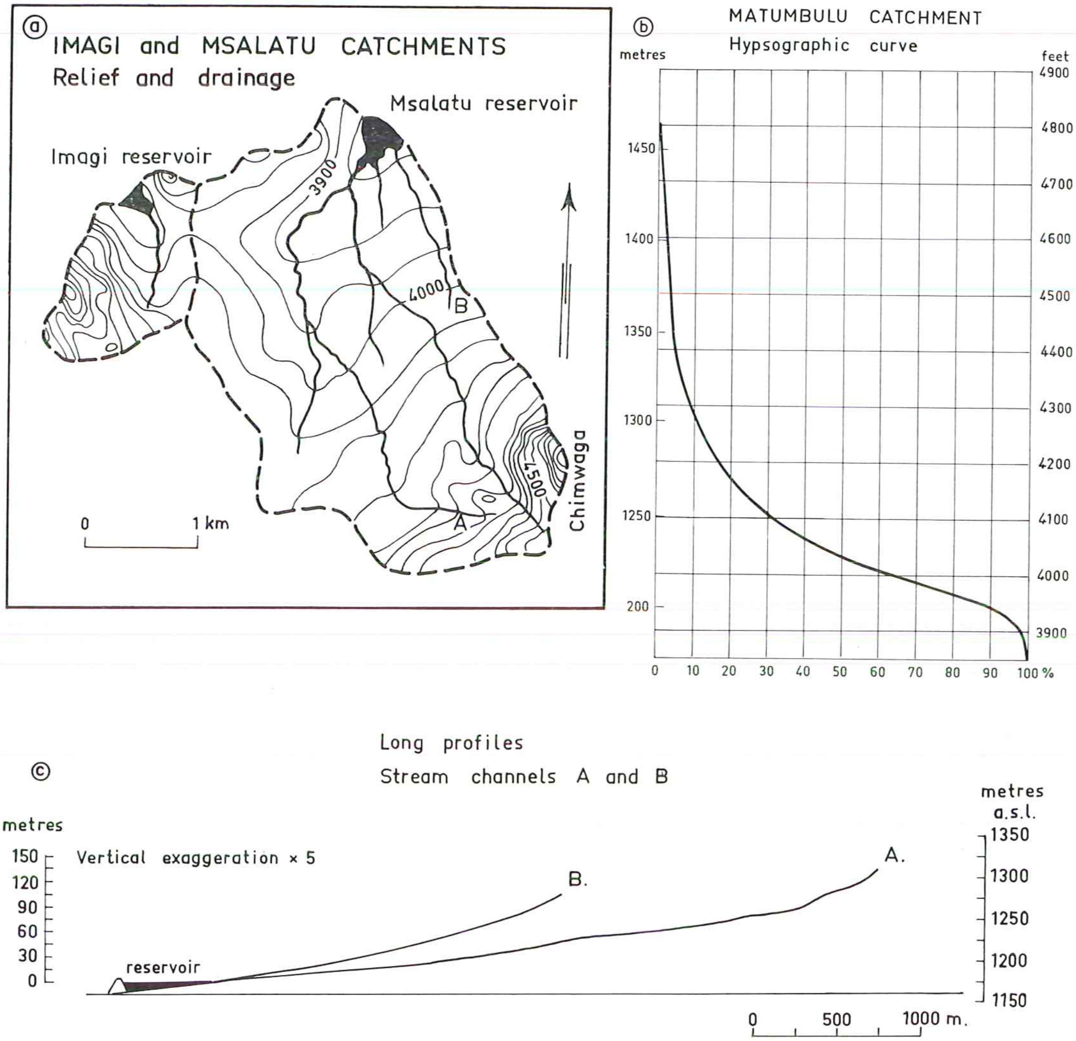



Fig. 26A. Relief and drainage map, Imagi and Msalatu catchments. Contour interval is 50 ft. Stream channels A and B are marked on the map.
Fig. 26B. Hypsographic curve, Msalatu catchment.
Fig. 26C. Long profiles of stream channels A and B, Msalatu catchment.

(Fig. 26). Particularly channel B is a good example of this.

At least one fault line traverses the catchment from NE to SW close to the contour 4100 ft on Fig. 26 A. The line can be traced on air photos. The only points where the fault features are clearly visible in the field are where gullies or stream channels cross the faults and suddenly drop 1—5 m and become both wider and deeper (Fig. 27). The fault can be one of the southern extents of the bigger Madengi-Iyumbu fault system, which forms the eastern escarpment of the E branch of the Great Rift system. The Msalatu fault can be followed towards the SW beyond the catchment.

These structures in combination with the way in which loose deposits appear indicate at least three different phases in the late development of the present landscape around Dodoma:

1. An earlier denudation surface has been broken up by extensive fault movements.

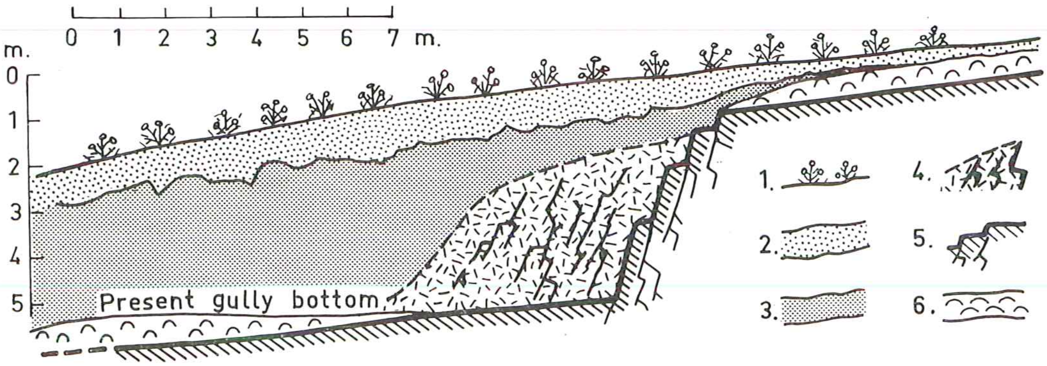



Fig. 27 Section of a discontinuous gully crossing a fault line. Fault lines covered by pediment deposits are revealed by some gullies incised and widened into fault zone bedrock and colluvium. Symbols: 1. Ground surface. 2. Dark red loose sandy-silty loam. 3. Yellowish red sandy material. 4. Heavily weathered bedrock with fault structures. 5. Exposed bedrock in gully bottom. 6. Cemented calcrete and silcrete in gully bottom.

2. Rapid deposition of large amounts of colluvium has taken place in the fault basins and soils have developed on the colluvial cover.
3. Changed climatic conditions or/and the impact of man has initiated a new phase resulting in gullying of the residual soils and the colluvial deposits. Redeposition of sediments is now taking place at lower levels. Areas of deposition are now sandy rivers and sand fans, mbugas, lakes and man-made reservoirs.

Most of the catchment area is covered with a few feet of loose sandy soil which overlies calcrete or silcrete. In some areas the sandy soil has been completely removed by erosion and the "cemented" layers are exposed at the surface. In some of the gullies bedrock is exposed indicating that the deposits covering the pediment are thin.

Fig. 27 shows the two types of soil and regolith that predominate in the catchment: a red sandy soil resting on yellowish red or grey gravelly-sandy colluvium (cf. Tables 16 and 9).

The runoff is canalized into gullies with partly hard surfaced bottoms of silcrete or similar material. There are no flat mbugas or big sand fans above the reservoir to cause sedimentation and water loss as in the Ikowa catchment. Some channels have sections with sand beds, however, and there both infiltration and sedimentation occurs.

Precipitation and water data are given above (Tables 2, 3, 6). A comparison between rainfall stations in the Dodoma area shows that recorded annual rainfall varies considerably over short distances (Table 14).

Only a small percentage of the catchment was occupied by cultivation in 1960 (5.9 %). As the system of shifting cultivation is practised this area varies from year to year (cf. Fig. 29 B). Most of the fields are "bush fields". (There are two types of fields for grain crops: 1. Fields near the homestead which are usually

Table 16. Grain size composition of weathered bedrock, probably in situ (no. 1–3) and of colluvium (no. 4–7) from boreholes in the Mkonze valley, 5 km SW of Imagi dam and 5 km N of Matumbulu dam. Data from Fawley 1954.

| Material | Depth below surface | Gravel >2 mm | C. sand 1–0.42 | Fine sand 0.42–0.05 | Silt 0.05–0.005 | Clay <0.005 |
|---|---|---|---|---|---|---|
| 1. Granite | 11.9 m | 6.0 | 52.5 | 33.6 | 6.0 | 1.9 |
| 2. " | 14.9 m | 0.0 | 31.0 | 47.6 | 17.5 | 3.9 |
| 3. Gneiss | 9.5 m | 65.0 | 17.3 | 15.3 | 1.7 | 0.7 |
| 4. Colluvium | 12.8 m | 35.6 | 21.2 | 30.7 | 10.2 | 2.3 |
| 5. " | 13.4 m | 29.1 | 26.5 | 31.4 | 10.1 | 3.0 |
| 6. " | 7.9 m | 3.6 | 26.6 | 52.9 | 12.7 | 4.8 |
| 7. " | 7.3 m | 60.2 | 26.4 | 18.2 | 3.9 | 1.3 |

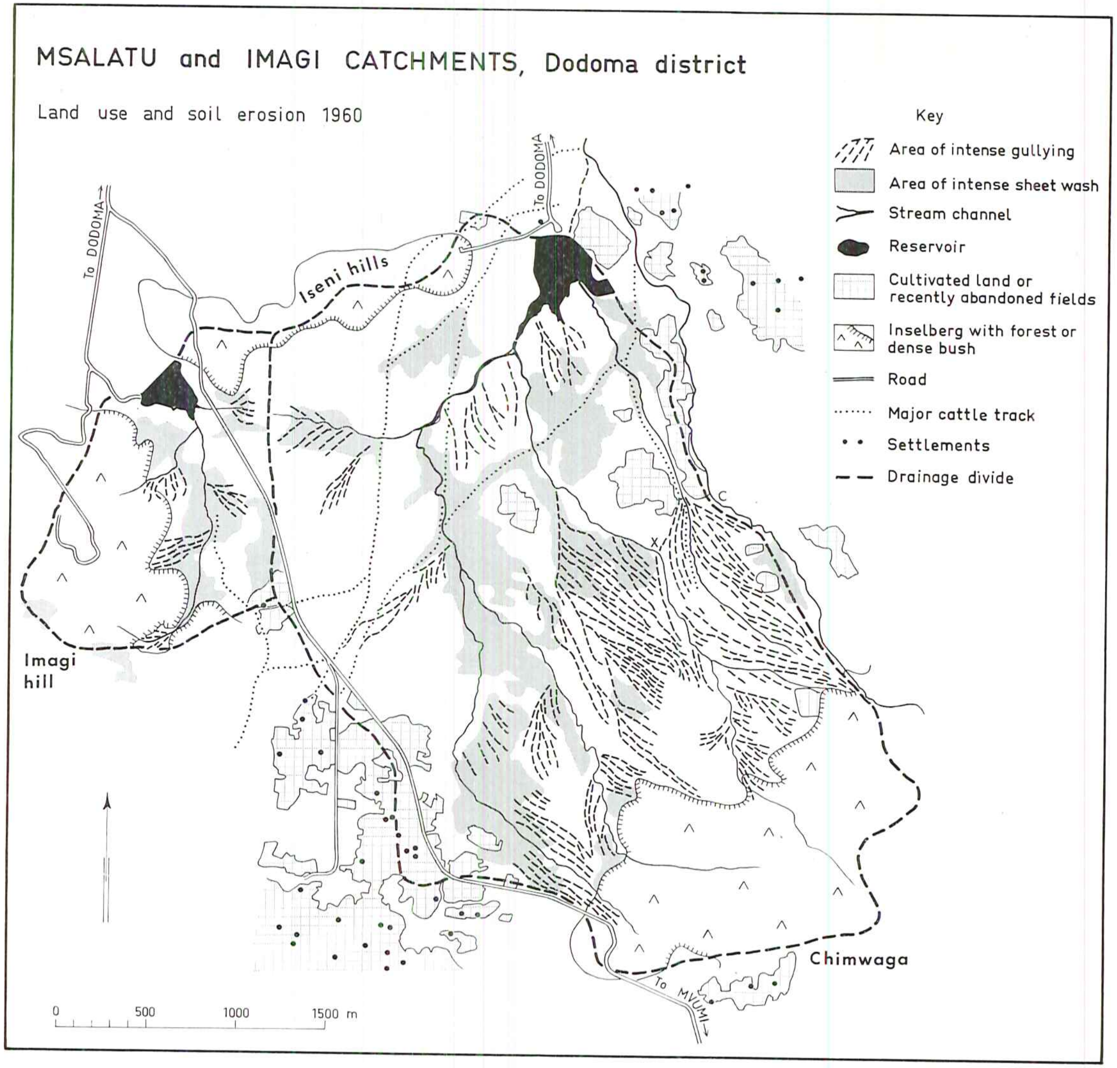



Fig. 28. Msalatu and Imagi catchments. Map of land use and zones of soil erosion. Based on aerial photographs of 1960 and field checking. Points X and C are for identification on Figs. 29A and B.

Figs. 29A and B. Vertical air photographs of gullied area in Msalatu catchment. A in June 1953, B in June 1970. Note extensive new cultivation in 1970. Cf. Fig. 28. Points X, B and C are identical in both photographs. The gully pattern (dark, parallel lines) is similar in 1953 and 1970. Fig. 25 is a photo taken of cultivation near letter B (= channel B) of 1970 aerial photo. Photos A. S. D. Tang 1080/71/1953 and Can:8/Roll No 106, 1970.


1970
C
X


1953
C
B
X
0
0.5
1 km

manured and used more or less permanentely and 2. Bush fields which are used for a few years and then left fallow. They are often situated far away from the homesteads.) There are 4 homesteads inside the catchment limit near the water divide in SW. In this corner there are also some permanent fields. There are many settlements just outside the catchment in the SW and some in the N and several herds of cattle graze within the catchment every day. Two major stock routes run through the area from N to SW.

Cutting of wood and charcoal burning is common in the catchment. New areas were cleared and cultivated in 1970, e.g. in the catchments of channel B and channel A (Fig. 29B).

## Erosion in the catchment

Fig. 28 and Table 15 summarize the occurrences of erosion features. A dense thorn thicket occupies the inselberg slopes. In these areas erosion is insignificant. The weathered bedrock is everywhere near the surface. Towards the top bedrock is exposed in some places. There is only little material to be transported.

Where the forest vegetation is disturbed by grazing animals and wood cutting for charcoal burning, the soils are being eroded. This is specially the case near the foot of the inselberg and on the upper pediment. In Msalatu catchment gullying has proceeded up the inselberg slope in two places where the vegetation has been partly removed. About 3 % of the inselberg slopes have in this way been subject to gully erosion.

The most prominent feature of the upper parts of the pediment is the dense gully pattern and the bare surfaces with hardly any vegetation at all. The gullies are generally 1—5 m deep, with vertical, crusted side walls.

Of the whole catchment 22.3 % is badly dissected by gully erosion, 12.8 % suffer from intensive sheet wash. Within 5.9 % of the catchment there is a combination of severe sheet wash and gully erosion.—In all areas of gullying, sheet erosion is also active.

A documentation of erosion and sedimentation in the area before the Msalatu dam was constructed is the following report, which most likely deals with the downstream reach of the Msalatu stream, where it crosses the railway (Fig. 1). "East of Dodoma, the railway has repeatedly been threatened with obliteration by the shifting sands of another drainage channel from the hills to the south. It is reported that in 1916, before these hill slopes were so extensively cultivated, the bridge conveying the railway over this watercourse was ten feet above the sandy bed. At the present time the accumulated sands have reached the lower edges of the steel joists of the bridge, and already the railway engineers have been forced to add additional spans to it to maintain communications". (Wade & Oates 1938, p. 56.)

In Msalatu three zones of erosion can be distinguished (Fig. 28, 29A and B). Gullying dominates within a wide zone of the upper pediments below Chimwaga hill. Within this zone there is a sparse thorn vegetation but the original grass cover is nearly completely removed by grazing cattle. Hence the rate of sheet wash is probably also high in this area. The slope gradient is 4—5°. Bedrock is encountered 0.5—1.0 m below the surface. The fallow shambas in this zone are now dissected by shallow gullies and rills.

In Msalatu and Matumbulu catchments, which were checked on the ground in 1969 and 1971, some cases have been observed where gullies have eaten backwards a few metres during two years time or been locally widened a few decimetres due to undermining and collapse of side walls.

Below the gullied area in the direction of the reservoir is a zone where sheet wash dominates or where gullying is less evident than further up. These are the main grazing areas within the catchment. In the dry season there is very little grass in this zone except underneath the thorn-bushes where it is out of reach of the cattle. The sandy topsoil is washed away and the infertile hard cemented layers are exposed. These bare surfaces are particularly conspicuous along the cattle tracks. Below this zone the gradient steepens again and another set of gullies have developed on the slopes towards the lower course of the Msalatu stream.

There are no sand fans upstream from the reservoir probably because of the fairly steep and even gradient. Some of the eroded material is temporarily deposited in the stream-channels, before it is transported to the reservoir, which is the main area of sedimentation in the catchment.

On cultivated fields without vegetation, sheet wash and rilling is obvious. Rills are often obliterated by the cultivation, but when the cultivation ceases new rills develop across the fields. Sometimes the stalks are left on the fields after the harvest. This prevents splash erosion and sheet wash to some extent. It is more common practice to rake the stalks together and burn them and to use the ash as fertilizer (Fig. 25).

No significant conservation measures have been undertaken in the catchment. In 1953 some of the gullies were filled with brushwood in order to trap some silt. However, the method was not successful. In some cases the water cut new channels around the brush, in others the brush itself was carried into the reservoir (Fawley 1956).

## The Msalatu reservoir. Description and map comparisons

Msalatu reservoir is also called Town Dam no. 2. It was completed in October 1944. The dam filled in the wet season of 1944—45 and it was brought into use as water supply in September 1945. The dam crest has a length of 366 m. The maximum height at the time of construction was 12.8 m. The embankment has a clay core partly taken from the stream bed below the dam. The outer parts of the embankment consist of surface debris taken from the area next to the dam site. The reservoir had a total volume of 388,000 $m^3$ in 1944, which by 1971 had been reduced to 300,000 $m^3$.

Background data such as information about construction details and some maps and drawings exist. Unfortunately the old reservoir maps are inaccurate in several respects. It was not possible to find original sets of drawings and the few copies that still exist are not in a good condition. Records of reservoir volumes, depths, runoff, rates of erosion and sedimentation are contradictory in many respects. The existing data are kept in several departments in Dar es Salaam and Dodoma.

Fawley has published a very valuable account of Msalatu dam (Fawley 1956b). He points out that no completion drawings were available so he could only refer to approximate outlines of the details. The accompanying map showing the embankment has serious errors. The spillway is in a wrong position and the embankment is too short. Estimations of the catchment size made by James (1950) gave a figure that is slightly smaller than the actual size. The error is probably due to less accurate topographical maps of the area in the late 1940s and a limited possibility to use air photographs.

In order to compute the volume of the sediments in the reservoir the difference between the original storage capacity and the present capacity of the dam was calculated. As no accurate map of the original topography of the reservoir bottom was available, photo copies in slightly different scales of a dye-line copy of an original drawing were used. The old map is based on a limited number of levelled points. This map had to be corrected on some points as it contained errors. This was revealed after checks on air photos, new maps and field surveys.

Reservoir mapping was carried out in October and December 1971 (Figs. 30 and 31). The corrected original map has been used for construction of long profiles and average long profiles of the reservoir bottom. For calculation of sediment yield and rate of erosion the figures from the 1971 survey have been compared with data supplied by Comworks and WD & ID in Dodoma. These figures show the estimated capacity and sedimentation during the first few years. Estimations of capacities in 1944 and 1950 have been compared with the 1971 figures from the DUSER surveys. Curves showing the decreasing capacity have been constructed (Fig. 32). For the calculations of the reservoir volumes we have used a method of photoelectric planimetering of areas (Ekman & Wastenson 1971).

In 1953 Fawley estimated the reduction of the capacity of the reservoir as 2 mill. gallons per year (9000 $m^3$/year). However the recent sediment survey shows that the rate is lower if not considerable amounts of sediment have been removed from the reservoir. Nothing seems to indicate that this should be the case. According to Fawley's estimations the capacity of the reservoir at the end of 1953 was 70 mill. gals (317,000 $m^3$). But as in 1971 the volume was 300,000 $m^3$, Fawley's figure is too low.

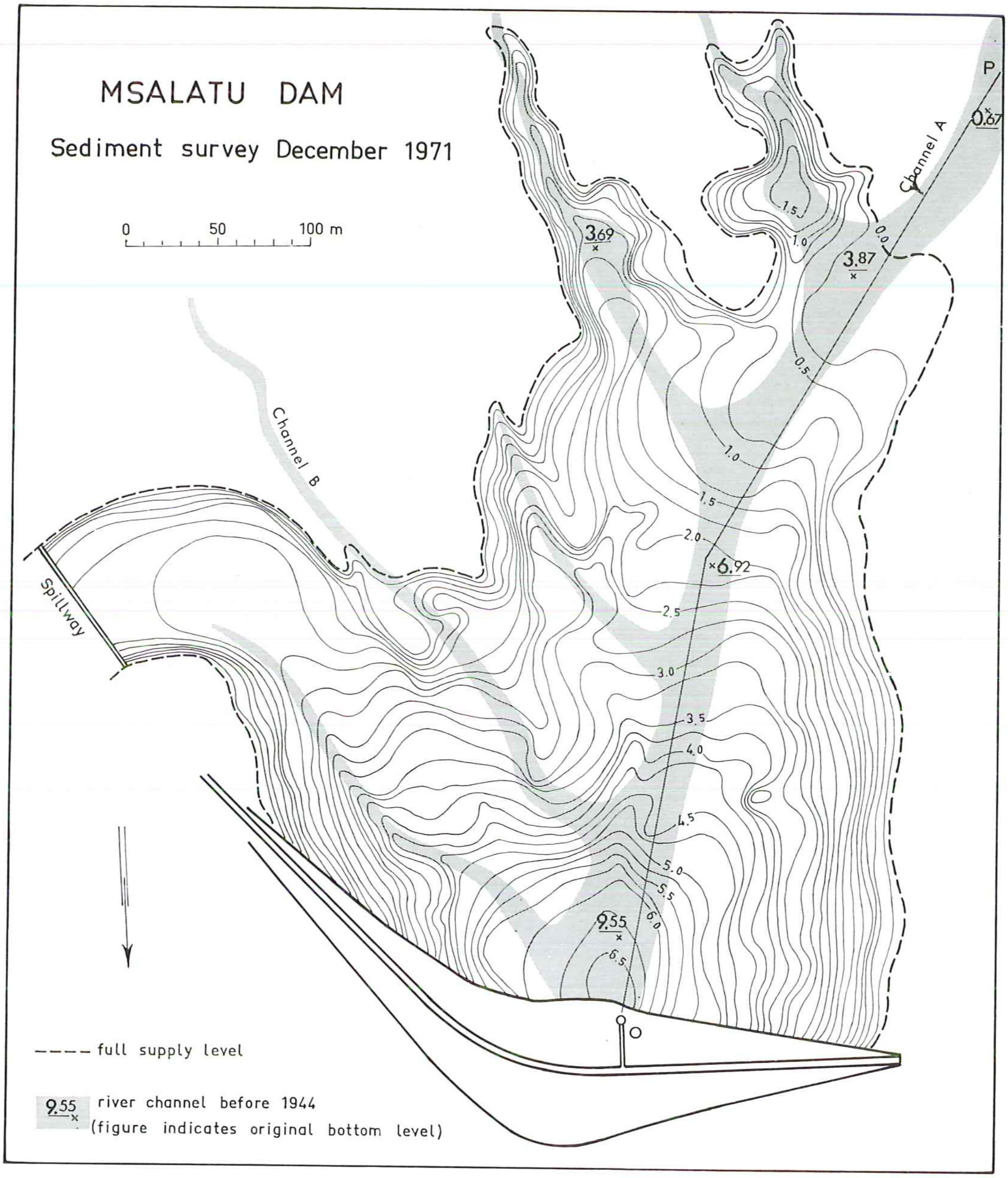
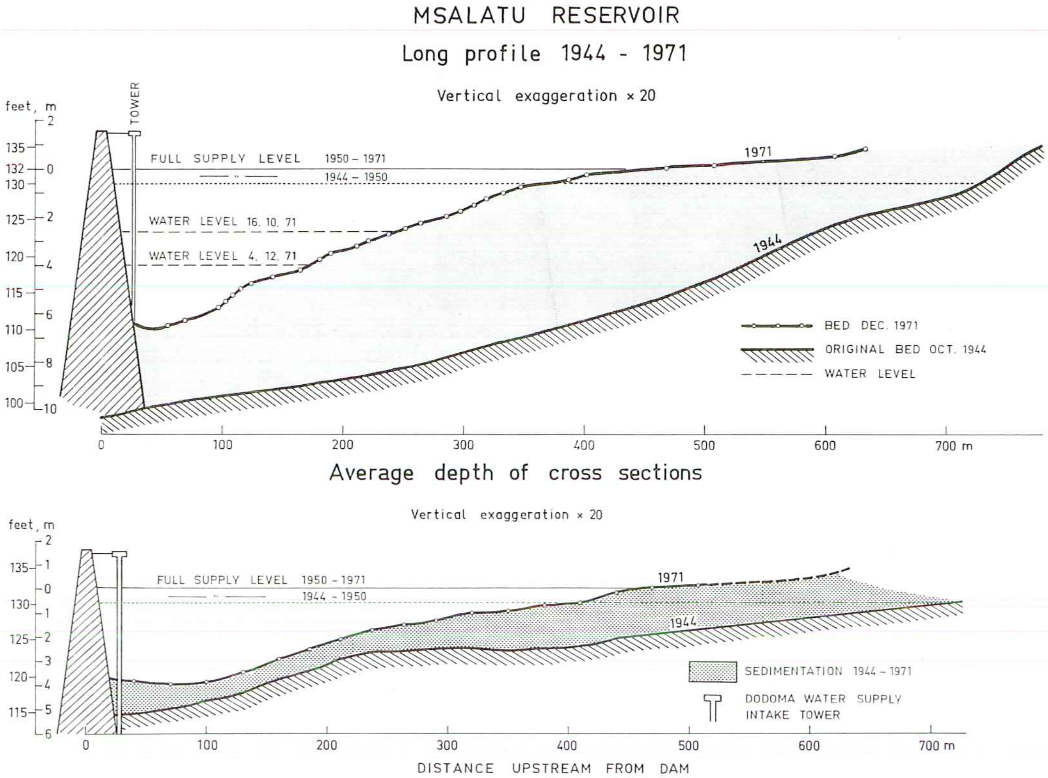



Fig. 30. Sediment survey of Msalatu reservoir, December 1971. Stream channels before dam construction in 1944 are marked in half tone. The line O—P marks long profile of Figs. 31A and B. Survey by C. C.

Surveying and mapping of the sediments in the reservoir during 1971 was fairly easy and the accuracy of the map is regarded as high. Soundings from a rubber boat were made in October 1971. In December 1971 the rest of the survey was done. The correspondance between the two maps of 1971 is very good.

For construction of the final reservoir map




Figs. 31A and B. Long profiles of Msalatu reservoir 1944—1971. The long profiles (above) are along the line O—P of Fig. 30. The profile below shows average depth of sections across the whole reservoir. Note the delta fronts at FSL of fig. 31A. 1971 surveys by C. C.

blow-ups of air photos have been used. Photos with the reservoir full or nearly full have been used to determine the full supply shore line. Photos where the reservoir is nearly empty have been used to define the extent of delta lobes and local channels in the reservoir bottom.

The figures of sediment accumulation, sediment yield, corresponding rate of soil denudation and expected life-length of reservoirs are listed in Table 20 and commented upon in the section "Prognosis" below.

## Morphology of deposits and types of sediments

In front of the inflows of channels A and B into the Msalatu reservoir distinct sandy deltas have been formed. Signs of an older delta surface with a break in slope corresponding to the earlier 2 feet lower FSL can be distinguished (Fig. 31 A). Near the main inflow the delta (A) has cut off a right-side tributary channel, which now forms a shallow pond or delta lagoon (Figs. 24, 30). The same process is seen on the second tributary to the right, showing the predominance of bedload sediment supply from channel A as compared to its two neighbours. Fig. 31 A shows that 6 m of sediments have been deposited in 27 years in the middle of the delta. Fig. 31 B gives the average depth of sediments along a number of cross sections.

The gradient of the sandy channel surface from FSL and 200 m upstream is 0.004 m/m measured along the profile O—P (Figs. 30, 31 A). Near the end of this upstream reach the channel bed has been raised about 3 m due to upstream sedimentation. Below FSL the delta slope gradient increases to 0.020 m/m. The old channel gradient was 0.013 m/m. All three of these gradients are slightly steeper than the corresponding values of the Matumbulu reservoir delta (Figs. 43, 45). This is to be expected



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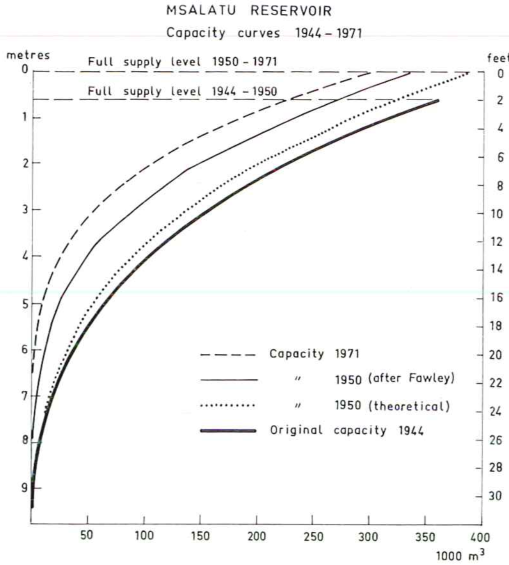



Fig. 32. Capacity curves, Msalatu 1944—1971. The dam was raised by two feet in 1950.

to judge from the larger catchment and probably higher peak discharges at Matumbulu.

The sediments of the Msalatu delta A are well stratified sand and silt layers in the upper parts of the beds below FSL. The sediments form individual storm layers. Coarse material at the bottom of each stormflow varve grades upwards into sand, silt and even thin clay layers. In October 1970 some cores of 35 cm depth were taken on the delta front, 1 m belows FSL. They contained in round figures: silt 30, sand 65 and gravel 5 % (maximum size of grains 6 mm).

Most of the sand is reddish yellow or reddish brown in colour. The fine silt and clay layers are black, dark grey or reddish.

Suspended material is deposited in higher proportion towards the middle of the reservoir or passes through the spillway in times of floods. When the sediments dry up due to sinking water levels, they are compacted, and later broken by desiccation, trampling cattle and growing grass-roots. Thin crusts of cracking clays were observed on the dry reservoir bottom in October 1971, e.g. at the 1.5 m contour in the spillway section (Fig. 30).

## Automatic sediment sampler

In order to check the concentrations and grain sizes of suspended sediment in flood water an automatic sediment sampler was installed in stream-channel B, approximately 150 m from the inflow into the reservoir. The installation was made in November 1971 with the help of Dr. H. Kuschel, WD & ID, Dodoma, who also checked the instrument after floods.

The sampler is of the type Hayim 7 and was designed by A. Schick and his collaborators in Jerusalem. Similar samplers (types Hayim 4 to 6) are described by Schick (1967, p. 181). Hayim 7 is primarily for desert streams where floods are violent and shortlived. It is a modification of the standard automatic single stage sediment sampler used in the United States. The water intake pipe is of 7 mm inner diameter and 9 mm outer diameter. The filling time of the Hayim 7 is about one minute per sample (Schick, personal information). It abstracts one-litre samples during the rising stage of a flood at 5 cm water level intervals. The instrument has 12 plastic one-litre bottles mounted inside a housing of 2 mm sheet metal. On top of the housing there is an exhaust pipe through which air from the bottles is diverted via plastic tubes (Fig. 33). The lowest intake (no 1) in channel B, Msalatu is 15 cm above the stream bed, the highest (no 12) is 70 cm above the bed (Table 17).

The sampler was installed on the sandy bed of channel B in a narrow gully section with steep, crusted side walls (Fig. 33 A). The first rains of 1971/72 rainy season caused very little flow in the channel. When the first heavy rain came in January (85 mm in one day) the gauge reader was sick and before he recovered another heavy rainfall occurred (24th February, 60 mm, personal information from H. Kuschel). When the sampler was finally checked the whole housing was filled with sediment. The bottles contained sediment, ranging from 15 to 75 g/l. (Tables 17, 18 and Fig. 33.) Similar sediment concentrations ranging from 10 to 131 g/l were reported from flash floods in the Negev desert, according to data from another Hayim automatic sampler (Schick 1971, p. 126). The concentration of sediment in the samples at Msalatu, Dodoma, are of the same range as the concentrations measured in runoff water from erosion plots at Mpwapwa by Staples. There, the average annual concentrations during two years of recordings ranged from 25 to 87 g/l (Temple 1972, Table 5). This includes sus-

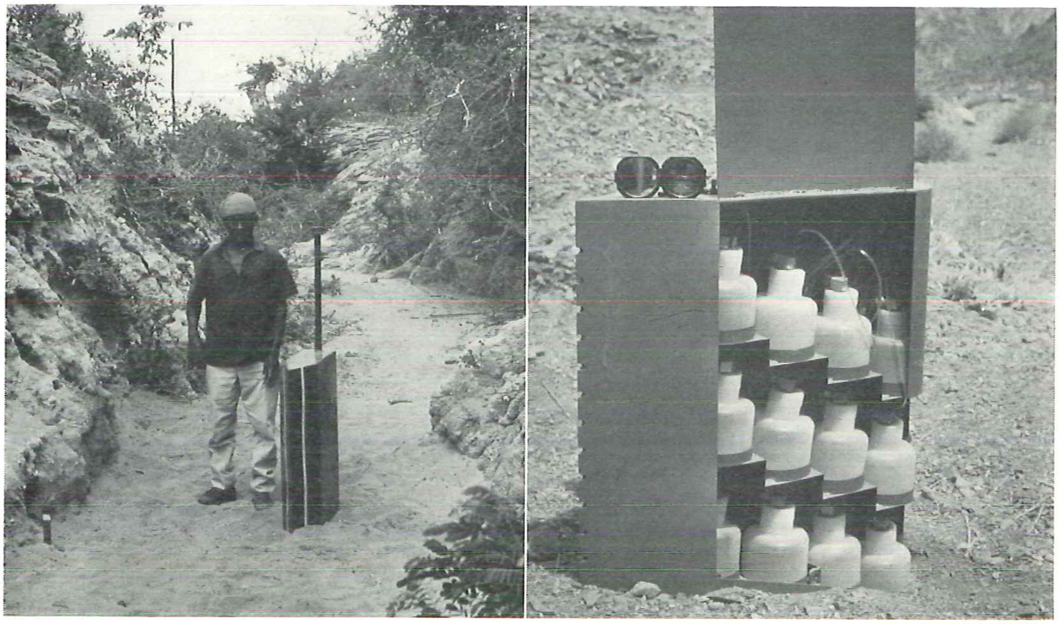


Fig. 33A and B. (Left) Automatic sediment sampler Hayim 7 mounted in gully channel B, Msalatu catchment. Photo C. C. 10/71. Note steep, crusted gully sides and sandy bed. (Right) Sampler Hayim 7 opened. Photo AR 1968.

pended load and bed-load in slope wash from erosion plots af 50 m$^2$ in size.

The grain sizes of the floods in channel B, Msalatu, indicate rather unsorted transportation including clay, (25—40 %), silt (30—50 %) and sand (15—50 %) (Fig. 34).

Table 17. Concentrations of suspended sediment in flood water of stream "B", Msalatu reservoir. On 11 January 1972. 85 mm of rain fell in one day. Later on a rainfall of approximately 60 mm was recorded on 24.2.1972. Sampling in an automatic sediment sampler, type Hayim 7. Cf. Table 18 and Fig. 34.

| Sample no. | Level above channel bed, cm | Sediment g/lit |
|---|---|---|
| 12 | 70 | 30.78 |
| 11 | 65 | 57.65 |
| 10 | 60 | 74.72 |
| 9 | 55 | 18.62 |
| 8 | 50 | 18.85 |
| 7 | 45 | 27.26 |
| 6 | 40 | 27.14 |
| 5 | 35 | 57.22 |
| 4 | 30 | 22.39 |
| 3 | 25 | 19.82 |
| 2 | 20 | 14.98 |
| 1 | 15 | 15.95 |

The high proportions of clay and silt indicate that most of the suspended sediments do not come from the sandy channel bed, but from the inter-gully areas or the gully walls. Which of the possible sources is the most important will be checked by continued recordings.

## Description of Imagi catchment

Area percentages are listed in Table 15. Cf. also Fig. 28.

Imagi catchment has a similar geology but steeper inselberg slopes than Msalatu (Figs. 36A and C). On the upper parts of Imagi hill are extensive areas of bare rock. The sides of the hill are covered by dense vegetation. The pediment slopes have a rather dense growth of thicket but in between the bushes and underneath the thorn trees are bare patches or a very sparse growth of grass. The slope along the slightly concave long profile of the stream channel ranges between 0.5 and 7°.

There are hardly any cultivated fields within the catchment (1.3 % in 1960). Except for one homestead on the water divide there are no settlements.

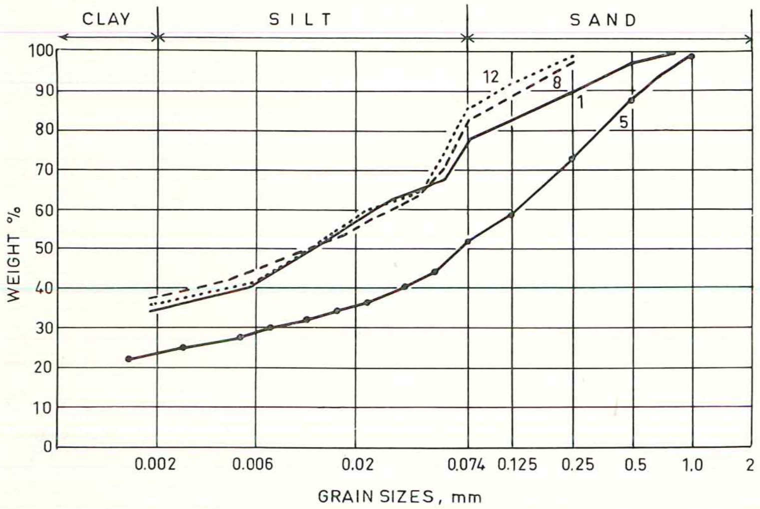



Fig. 34. Grain size composition of 4 sediment samples from flash flood in channel B, Msalatu, February 1971. Note high percentage of clay and silt. Sampling in Hayim 7. Cf. Tables 16 and 17.

Inselberg with vegetation or bare rock surfaces occupy 51 % of the catchment. In a small area in the woodland the vegetation has been removed with the consequence that sheet erosion has been initiated. This occupied 2.5 % of the inselberg area in 1960.

Pediment slopes form approximately 45 % of the catchment. Sheet wash dominates and 14.6 % of the catchment is subject to severe sheet erosion. 4.6 % are suffering from gully erosion and another 4.6 % has severe sheet erosion combined with gullying.

In order to increase the size of the catchment furrows have been dug along the N and NW slopes of Imagi Hill and along the ridge E of the reservoir. But as the furrows have been intact only occasionally, and not working at all during many years (Guest 1949) this temporary artificial increase of the catchment has not been considered in this paper. As there is only a small accumulation of sand in front of the outlet of the furrow it has obviously never brought much sediment into the reservoir. A "record of improvements to Kikuyu Furrow, April 1941" is filed in Comwork's office in Dodoma.

The furrow on the E side of the catchment has since long ceased to operate.

Table 18. Grain size composition of suspended matter in flood water of stream "B", Msalatu, February 1972. Sample numbers as in Table 17. The high percentage of silt and clay indicates that most of the material comes from inter-gully splash and sheet wash in catchment.

| Sample no. | Weight % of size classes | | | |
|---|---|---|---|---|
| | 2–0.2 | 0.2–0.02 | 0.02 –0.002 | < 0.002 |
| 1 | 13 | 30 | 22 | 35 |
| 5 | 33 | 32 | 12 | 23 |
| 8 | 6 | 39 | 17 | 38 |
| 12 | 3 | 40 | 21 | 36 |

## Imagi reservoir

Imagi reservoir is also called "Town Dam No 1". It now serves only as a supplementary source of water for Dodoma Town.

The dam crest has a length of 275 m. The maximum height of the embankment at the time of construction in 1929—30 was 12.75 m. There are no adequate maps or construction drawings available. All information about the construction has been taken from a map of unknown age (possibly 1926) showing a preliminary outline of the dam site. There are a few levelled points on this map. Of interest is also that the spillway was finally built in another angle than is shown on the map. Drawings of some details are available in Comwork's office in Dodoma.

According to computations made from the 1926 (?) map the maximum capacity was 174,000 m$^3$ In 1953 Fawley made an estimation and found that the capacity had decreased

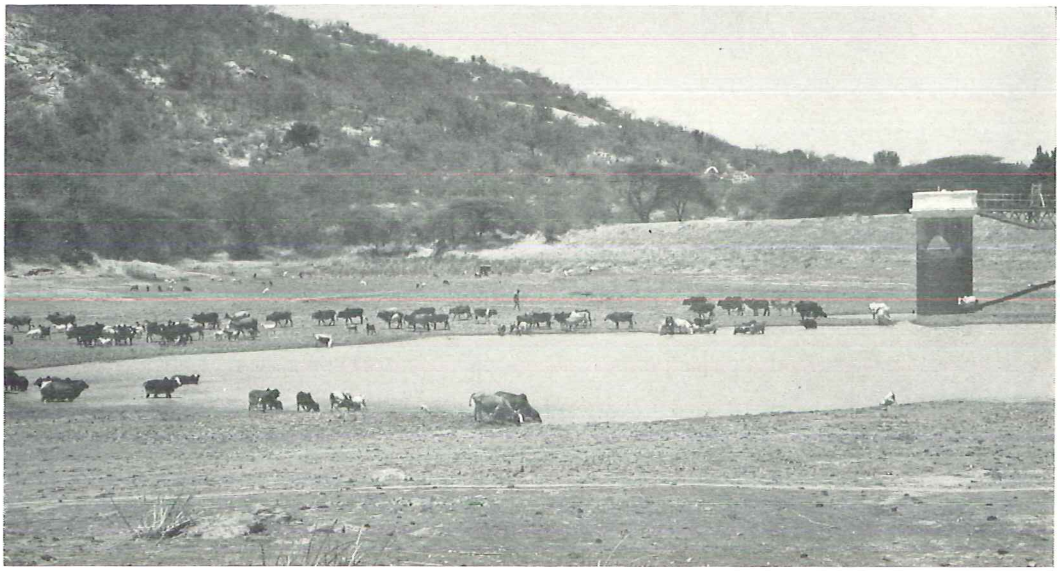


Fig. 35. Imagi reservoir at low water stage. Photo AR 10/1971.

considerably. According to Fawley's data the dam could hold not more than 154,360 m$^3$ in 1953. The capacity in December 1971 was 136,000 m$^3$.

Originally it was intended that the dam should supply 136,000 m$^3$ of water to Dodoma town every year but up to 1953 it had supplied an average of only 36,000 m$^3$ per year. The reason for this low return was primarily that the runoff from the comparatively small catchment varied between 3 and 17 % instead of 62 % which had been expected. Moreover the reservoir was rarely filled with water due to the catchment being too small. This is indicated by the deltas and wave marks on the embankment below FSL (Fig. 37). The sediment yield is 601 m$^3$/km$^2$ (Table 19).

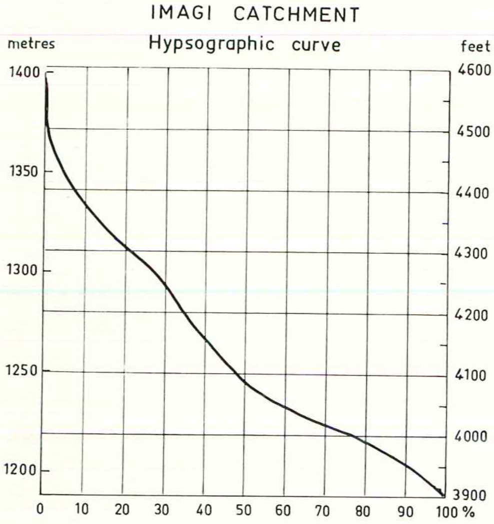
Some conservation measures have been undertaken in the catchment. In the little stream leading into the reservoir sediment traps have been constructed. They are now filled up and hold at least hundreds of m$^3$ of sediments. All this should otherwise have been transported into the reservoir.

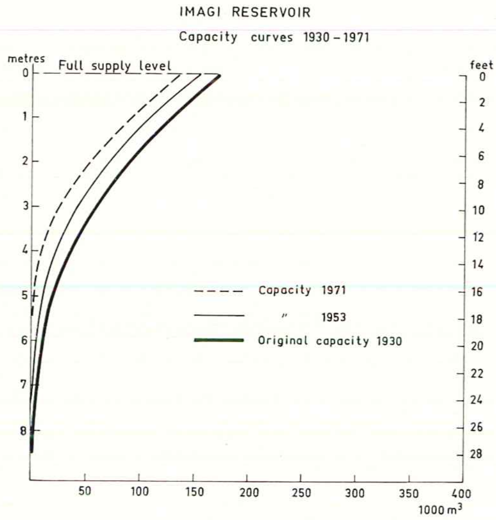
### Prognosis of sedimentation in Msalatu and Imagi reservoirs

The following report on Msalatu reservoir is a direct quotation from Fawley (1956b, p. 72) with addition now of measures converted into the metric system given within brackets. "The original capacity of the reservoir was 79 million gallons (359,000 m$^3$). This was theoretically increased to 85 million gallons (387,000 m$^3$) by raising the spillway height by 2 feet in 1950. However, considerable silt enters the reservoir and the actual capacity is thereby reduced by about 2 million gallons per year (9100 m$^3$). In 1953, a total of 10,500 cubic yards of silt was excavated from the reservoir, equivalent to about 1.75 million gallons (8000 m$^3$)."

To judge from this description Fawley reconstructed the original capacity in 1944 to 387,000 m$^3$ by adding an extrapolated value from the 2 feet raise in the spillway height in 1950. The capacity of the Msalatu reservoir in December 1971 was 300,000 m$^3$ as calculated from detailed surveys by the DUSER team. This means a total accumulation of 95,000 m$^3$ of sediments in the period 1944—1971 if 8000 m$^3$ excavated in 1953 are added. The annual sediment yield based on these data is 406 m$^3$/km$^2$, which corresponds to a soil denduation rate of 0.40 mm/year, if we assume the same bulk density (dry) for sediments as for soils in the catchment.

The total expected life-length of the Msalatu reservoir calculated as a linear extrapolation of



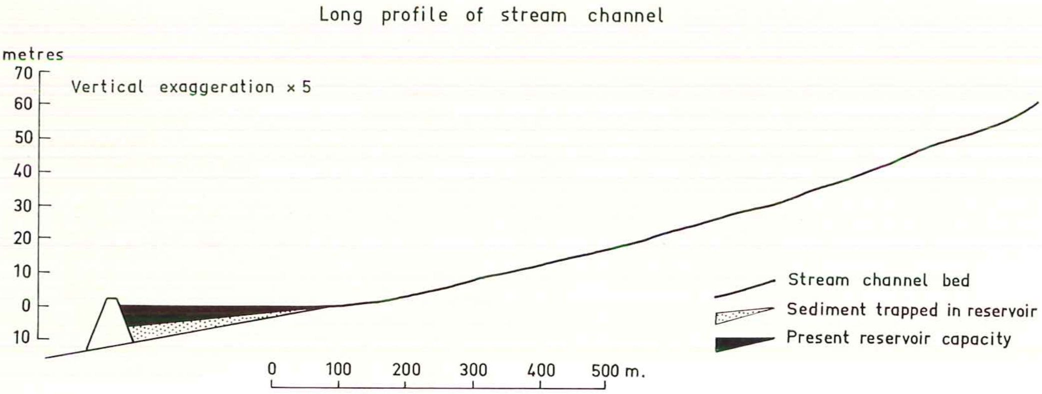




Fig. 36A. Hypsographic curve, Imagi catchment.
Fig. 36B. Capacity curves 1930—1971. Imagi reservoir.
Fig. 36C. Long profile of stream channel, Imagi catchment.

the 1944—1971 sediment accumulation is 110 years. This value should be regarded with caution for two reasons. Firstly, the basic map of the reservoir in 1944 and Fawley's reconstructions in 1953 are approximate. Secondly, the economic life of a reservoir is much shorter than the total expected life. The DUSER reservoir map of 1971 (Fig. 30) is a good basis for more exact future control of the contemporary rate of sedimentation in the Msalatu reservoir.

Similar comments can be added to the data on sedimentation in the Imagi reservoir. The original approximate map shows a capacity of 174,000 $m^3$ in 1930. The DUSER team map of December 1971 gives a capacity of 136,000 $m^3$, which means a sedimentation of 38,000 $m^3$ in 41 years (927 $m^3$ per year) or a sediment yield of 600 $m^3/km^2$ per year. The expected total life-length of the reservoir is 190 years.

The sediment yield is 50 % higher than in the Msalatu catchment. However, as the Imagi catchment is small and steep and the reservoir has a higher trap efficiency, the sediment yield is in fact of the same order of magnitude as that in Msalatu.

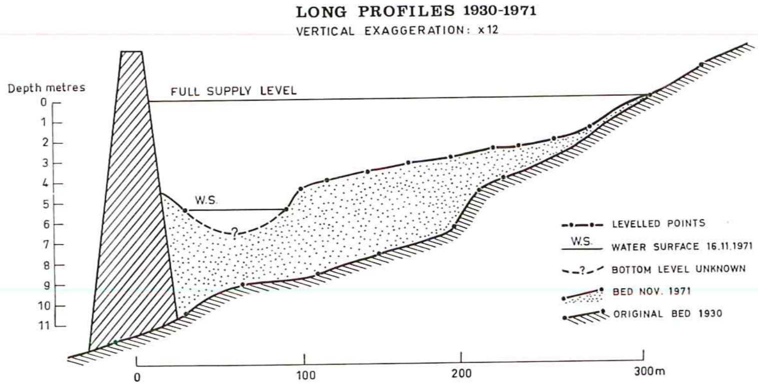



Fig. 37. Imagi reservoir. Long profiles 1930—1971, along line A—B in Fig. 38. The sandy delta surface is below FSL, as the reservoir rarely is filled to the spillway level. 1971 surveys by C. C. Levelled points in surveys of 1930 and 1971 are marked by dots.

## MATUMBULU CATCHMENT AND RESERVOIR

### Introduction

Matumbulu dam is situated near the Dodoma-Iringa road, 12 km S of Dodoma (Fig. 1. Plate 1 B).

The dam was completed in 1960. In 1961 the embankment broke and had to be repaired at a cost of 380,000 T. Shs (54,000 $ U.S.). This seems to have taken nearly 2 years because of heavy floods in 1961—62. The reservoir was in use again in 1963. The purpose for building the dam was a proposed irrigation project at Matumbulu village downstream from the dam and also flood control. Unfortunately the soils were unsuitable for irrigation. In March 1971 the plans for an irrigation project were finally cancelled partly because of the rapid sedimentation of the reservoir.

### Description of the Matumbulu catchment

The Matumbulu catchment covers an area of 18.12 km². It has a rhomboidal outline with drainage divides trending NE—SW and E—W. This probably reflects fault lines, one of which is assumed to run in the valleys along streams D and A (Fig. 39 A), as a continuation of the Madengi-Msalatu scarp, described above (cf. Plate 1 B). Gobi inselberg W of Matumbulu reservoir reaches 1500 m (4935 ft.) a.s.l., Njenje and Nyankali in the NW both reach above 1350 m (4400 ft.). According to James (1950) the inselbergs consist of granite. Other rock types, eg. gneiss with pegmatite veins and amphibolite in dikes occur in the valleys. They are usually covered by loose deposits.

The loose deposits and soils on the pediment surfaces are similar to those in the Msalatu catchment. Drillings through regolith and bedrock at Mkonze, about 5 km N of Matumbulu have given information of relevance also to Matumbulu and Msalatu. According to the data from Mkonze the following is a typical section.

The surface is covered by red or grey sandy soil. In some places a layer of sandy clay is found below the soil. A typical sample from the sandy clay layer at 60 cm below the surface

Table 19. Rates of sedimentation, sediment yields and soil denudation at Imagi, Msalatu and Matumbulu reservoirs, Dodoma. No corrections were made for differences in bulk density between sediments and soils.

| Period | Imagi 1930–71 | Msalatu 1944–71 | Matumbulu 1962–71 |
|---|---|---|---|
| Catchment area, km² | 1.5 | 8.67 | 18.12 |
| Sediment accumulated, m³ | 37,706 | 95,036 | 118,686 |
| % of original capacity | 21.7 | 24.4 | 31 |
| Number of years | 41 | 27 | 9 |
| % loss of original capacity/yr | 0.52 | 0.9 | 3.4 |
| Annual sediment yield, m³/km² | 601.5 | 406 | 729 |
| Soil denudation rate per year | 0.60 | 0.40 | 0.73 |

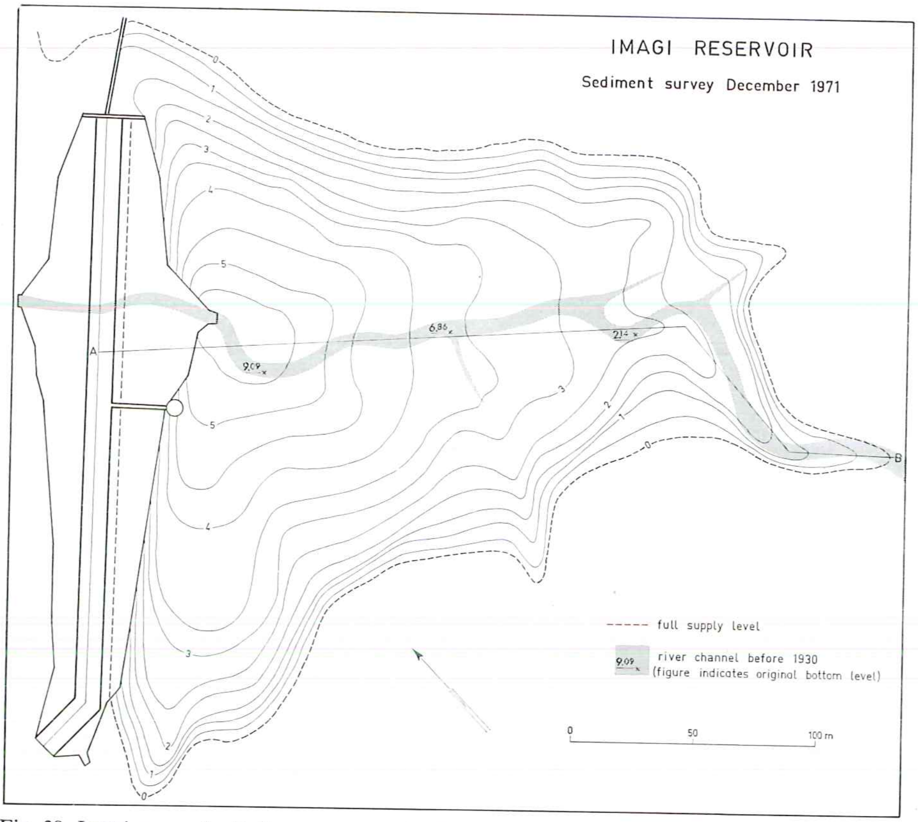



Fig. 38. Imagi reservoir. Sediment survey of 1971 by C. C. Contours at 0.5 m intervals below FSL.

contained about 40 % of clay, 20 % silt and 40 % of fine sand (Fawley 1954). The clays in the valley bottom at the proposed dam site at Mkonze ranged in colour from almost black to light yellowish brown. Typically they are dark grey at the top and become lighter in colour towards their base. They rest on an underlying calcrete-silcrete crust layer. The contact may be abrupt or gradational (Table 16).

Below the crust is a continuous layer of semi-consolidated gravel, ranging from 0.5 to 9 m in thickness. The gravel layer is a roughly sorted colluvium of clay, silt, sand and gravel. It also contains some pebbles and a few boulders. It seems to have been deposited by slope wash and rests on weathered igneous and metamorphic rocks. The weathering extends to depths of 10—40 m. The weathering front is very irregular due to the banded rocks of steep dip. The gneiss bands are deeper weathered than the granites. Both rocks form a sandy regolith.

Soil samples have been collected in transects of the catchment. They are either red or grey sandy soils of similar grain size composition as those described above from the Ikowa and Msalatu catchments.

In general the area is covered with Acacia thorn scrub which in some places is relatively open. In the valleys the scrub has since long been cleared. These areas are now cultivated. The slopes are used as grazing areas for cattle although grass is usually extremely sparse. On the inselberg slopes above the pediments thorn vegetation is almost impenetrable. Baobab and *Euphorbia* trees are typical to the area.

At the N end of the D valley is a small mbuga. Parts of the sediments derived from the slopes are deposited in this area. Moreover,

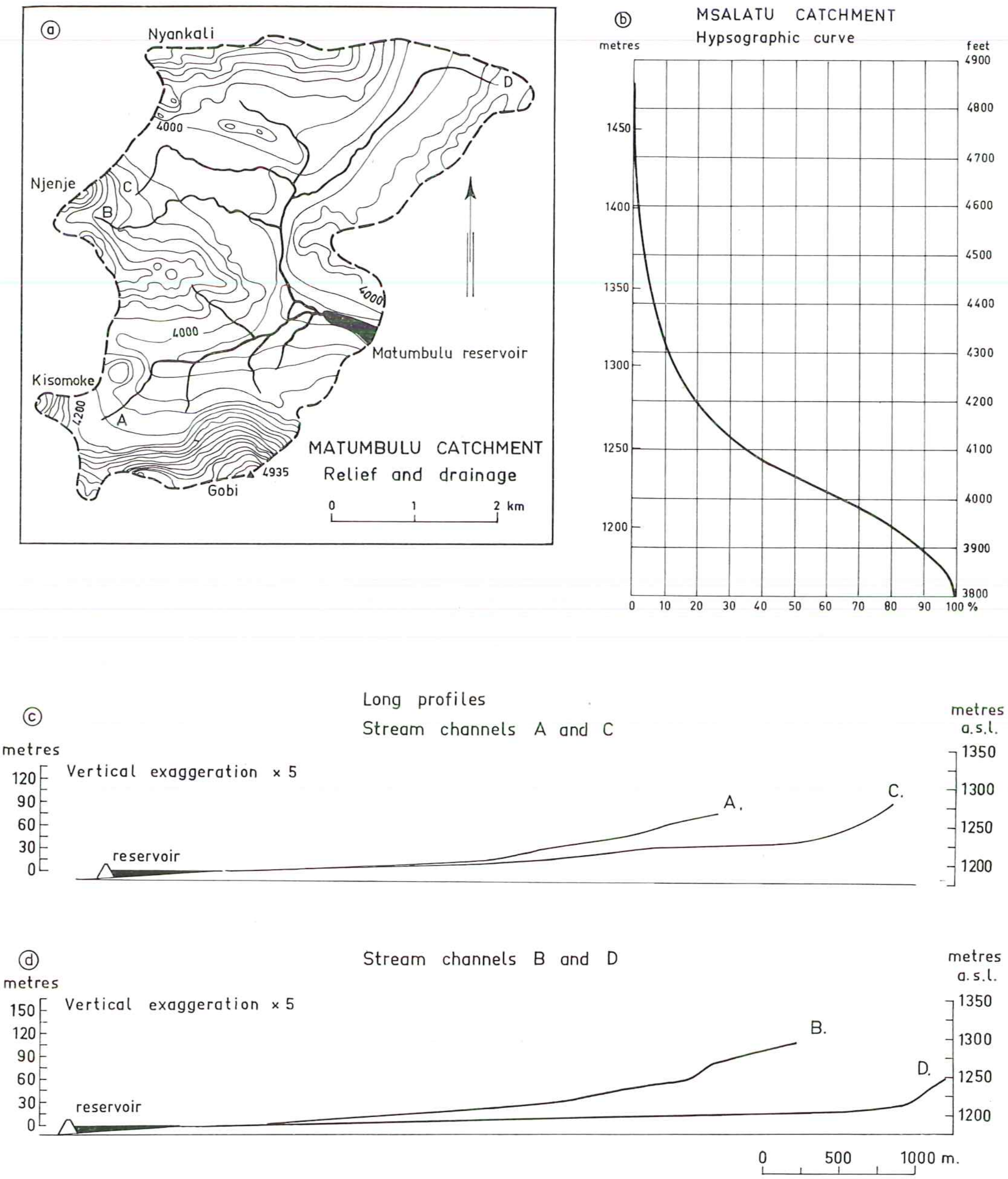



Fig. 39A. Relief and drainage map, Matumbulu catchment. Contour interval is 50 feet. Stream channel A, B, C and D are marked on the map.
Fig. 39B. Hypsographic curve, Matumbulu catchment.
Fig. 39C. Long profiles of stream channels A, B, C and D, Matumbulu catchment.

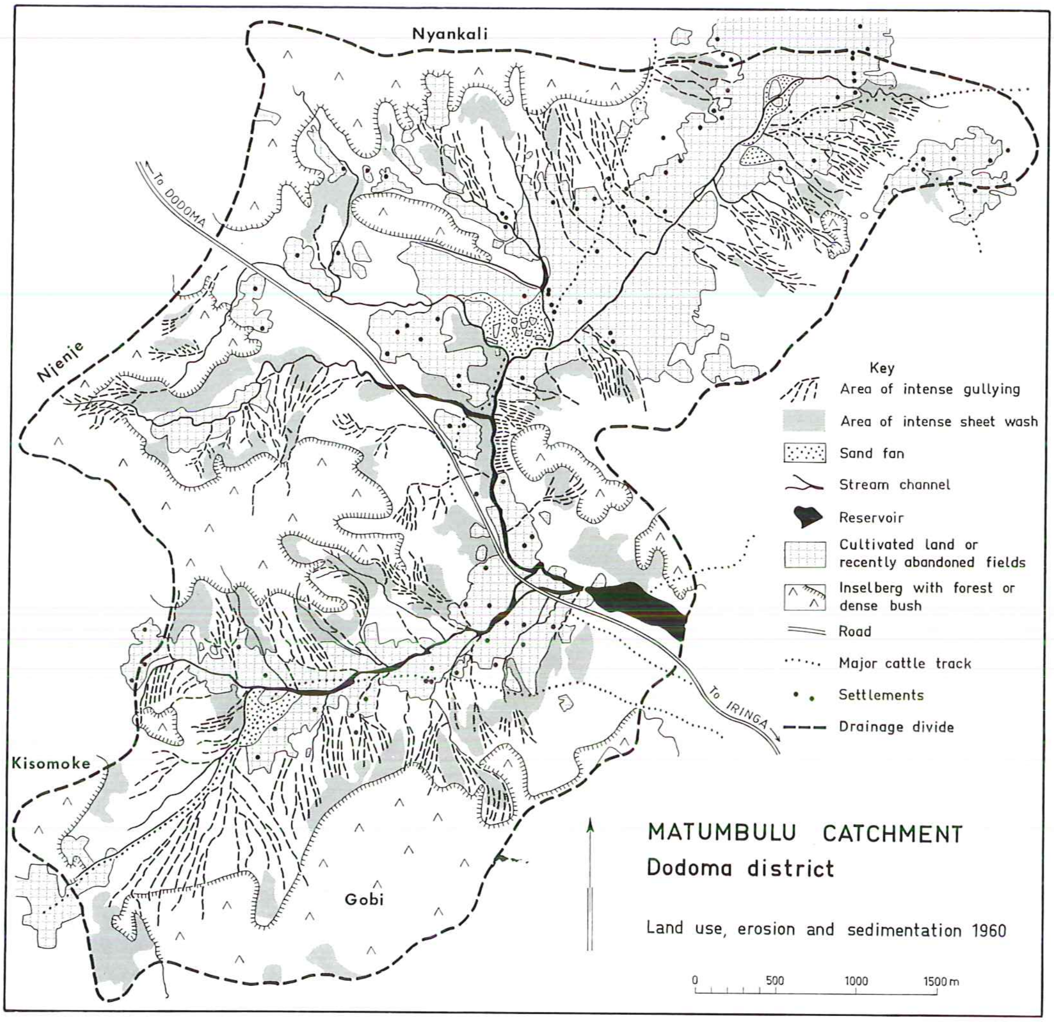



Fig. 40. Map of land use, erosion and sedimentation, Matumbulu catchment. Based on air photographs of 1960 and field checking. Note the zones of erosion and deposition: gullied upper pediments with intense sheet wash, cultivated lower pediments, stream channels with three sand fans, reservoir with heavy sedimentation.

nowadays there is a small earth dam across the N tributary. This construction is new as there are no signs of an embankment in this area on air photos of the catchment from 1960. Field checks in 1970—71 show that sediments are trapped here.

Domestic water is collected from wells in the dry river bottom upstream from Matumbulu dam. These wells supply water throughout the dry season. In the middle of December 1971, right at the end of the dry season, water was found at a depth of 2.5 m below the river bed in a place approximately 100 m upstream from the 1971 FSL. Further up in the catchment the ground water surface is much nearer the dry river bed and most wells are between 1—1.5 m deep. Here "cemented" sediments or clay is found at the bottoms of the wells.

## Population and land use

In 1960 there were 87 homesteads in the Matumbulu catchment, corresponding to approximately 800 persons if there are 9.4 persons per household. This indicates a population density

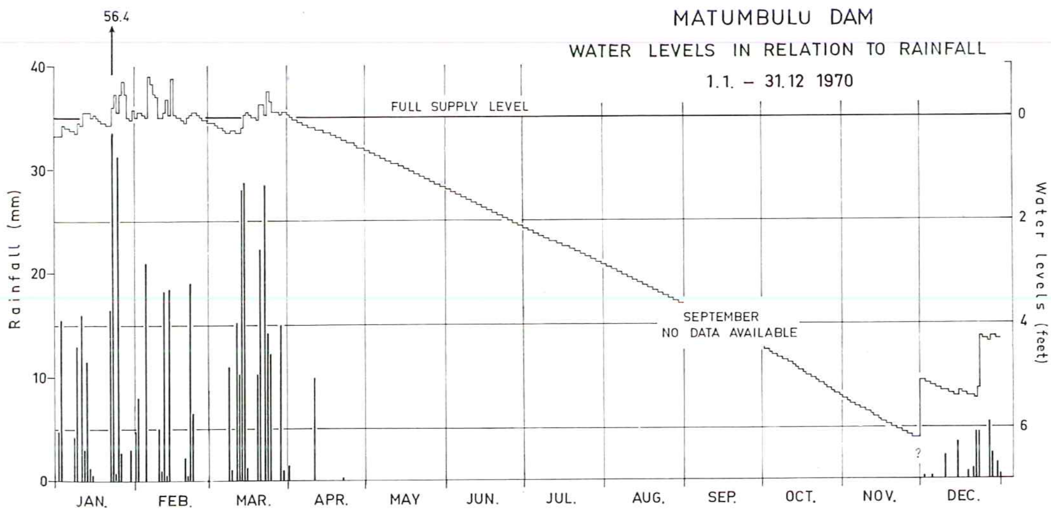



Fig. 41. Water levels in relation to rainfall, Matumbulu reservoir, 1970. Water losses mainly from evaporation. Rainfall data from raingauge at the reservoir. Data from WD & ID.

of 45 per km². (See Table 15.) This is slightly above the mean population density in the areas S and SW of Dodoma Town (Berry 1971).

From these figures stock density can be estimated. Rigby has from tax figures and own studies estimated the numbers of cattle and small stock (sheep and goats) in homestead herds in two areas. The average number of stock units (1 stock unit equals 1 head of cattle or 5 small stock) "owned" per capita was found to be 1.50. If this figure is true for Matumbulu, the people living within the catchment own 1200—1300 stock units. If these are all grazed within the catchment it means less than 1.5 ha/stock unit including all land in the catchment.

The UNDP/FAO Livestock Mission Dodoma (Skerman 1968, p. 39) estimated for grazing scheme purposes the carrying capacity of several areas in similar environment. The mission reckoned that 4—6 ha/head of cattle is required, if the area should not be overstocked. According to this estimate the number of cattle in the Matumbulu catchment is at least 2—3 times too high.

In 1960 22.3 % of the catchment was covered by cultivation. As the Gogo practice shifting cultivation the figure for areas of cultivated land varies from year to year. Only few of the fields in the Matumbulu catchment are "bush fields". Most cultivated land is in the valley bottoms.

## Erosion and sedimentation in the catchment

The sequence of erosion and sedimentation is similar to that described above from the Ikowa catchment: upper gullied pediment slopes, lower ungullied pediments with cultivation, sandy stream channels, sand fans and one incipient mbuga, the reservoir with rapid sedimentation. The features appear on the map, Fig. 40.

The upper parts of the pediments suffer from both sheet and gully erosion. The gully systems are most obvious in the SW and E parts of the catchment. It is also in these parts that sheet wash is most widespread. This distribution could be due to steeper slopes in these parts of the catchment but also to the main valley being narrower here leaving less flat land for cultivation and grazing. There are also some very badly eroded areas in the northernmost part. Here some of the deepest gullies in the catchment occur (3—4 meters). However, these areas contribute only to a minor extent to the supply of sediment into the reservoir as some is trapped in the mbuga and some in the small man-made pond.

The dense gully network in the central part of the catchment on the E side of the road has developed right across an abandoned system of contour ridges. The gully network and sheet eroded area on the opposite side of the road has also been formed on ground which has been subject to conservation measures some decades ago.

The percentage of badly gullied areas in the catchment is 16.8. Another 1.5 % has developed into virtual badlands through a combination of sheet wash and gullying.

Sheet erosion is dominant within two different zones, which together occupy 8.4 % of the catchment.

1. The uppermost part of the pediment slope near the inselberg break with a sparse cover of thorn vegetation.
2. The central parts of the catchment with low gradients. These are severely overgrazed with vast surfaces completely bare.

Sedimentation takes place in four well defined areas: three sand fans, one small mbuga, sandy rivers and the reservoir. In three places covering together 0.2 km² (1.0 %) sand fans have developed. In valley "D" is a small mbuga area S of the northernmost sand fan. There is no defined stream channel through this area. Since the small earth dam was built across the channel SW of the mbuga even this acts as a sediment trap. Another area of sedimentation is the reservoir. Here heavy sedimentation takes place and during 9 years 119,000 m³ have been deposited, an average of 13,000 m³/year. Much of the material deposited in the reservoir probably originates from eroded areas in the southwestern part of the catchment.

## Morphology of deposits and types of sediments

The sedimentation in the Matumbulu reservoir has formed a distinct sandy delta with one main lobe advancing into the basin (Figs. 42, 43, 45). The slope of the sandy channel surface above FSL is 0.003 m/m. Below the convex break of slope at the FSL the delta surface has a slope of 0.015 m/m. Both figures refer to the survey of October 1971. The gradient of the buried old channel was 0.008 m/m. All these gradients are slightly gentler than the corresponding slopes at the Msalatu reservoir delta.

The long profiles A—B (Fig. 45 A) from the DUSER surveys of 1969, 1970 and 1971 show a close correlation. The total thickness

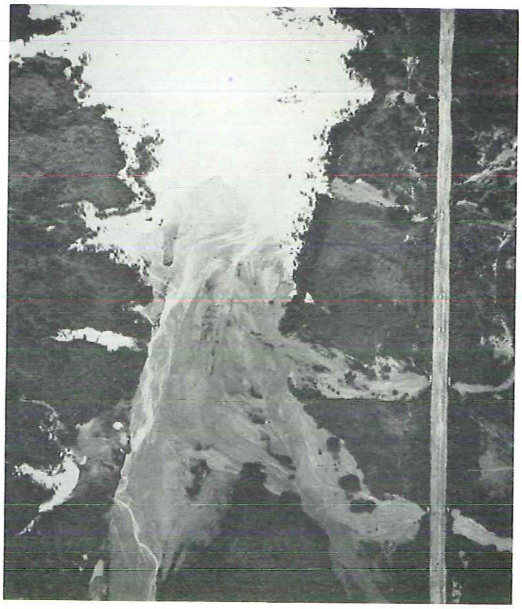


Fig. 42. Aerial photograph of sand delta in Matumbulu reservoir at Full Supply Level. Photo AR 15/3/1970: Road to Iringa at right side. Distinct lobe of sandy delta fed by converging sandy channels with aggrading beds. Note choking of road culverts to the right and damming of tributary pools to the left side. Cf. Plate 2C.

of deposits 1960—71 is 3 m at the FSL line 550 m upstream of the embankment. It is thinning out to 1.6 m on the reservoir bottom 200 m from the dam wall and it is 2 m at the upper end of the long profile, 800 m from the embankment (Cf. also Figs. 43, 44).

The aerial photo Fig. 42 shows the central delta lobe at a stage when the reservoir is full (March 1970). The deposition of sand upstream of the reservoir has resulted in cutoff pools at the mouths of small tributaries from the E and blocking of road culverts on the opposite side.

Fig. 23 shows a 90 cm long core taken vertically from the delta surface 1.5 m below FSL in October 1970. It contains well stratified sediments in stormflow varves, grading from fine gravel to sand and silt and dark clay at the top. The silt and clay layers reflect the deposition of suspended load after the stormflow. The sand and silt is generally yellowish red, the clay is either red or dark grey. In round figures the percentage of different grain sizes in this core is: gravel 5, sand 40, silt 40 and clay 15 %.

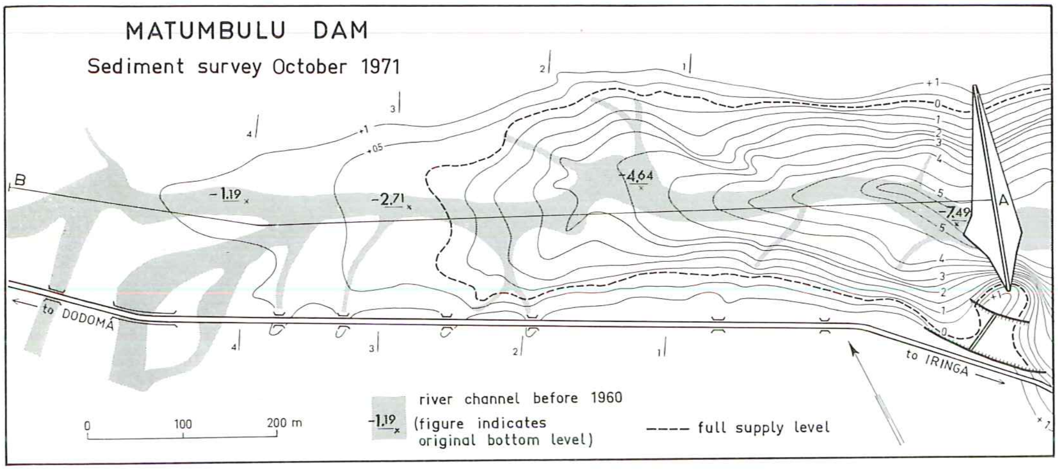



Fig. 43. Matumbulu reservoir. Sediment survey of October 1971. Contour interval is 0.5 m. Cross profiles of Fig. 44 and long profile of Fig. 45 are indicated. Surveys by C. C.

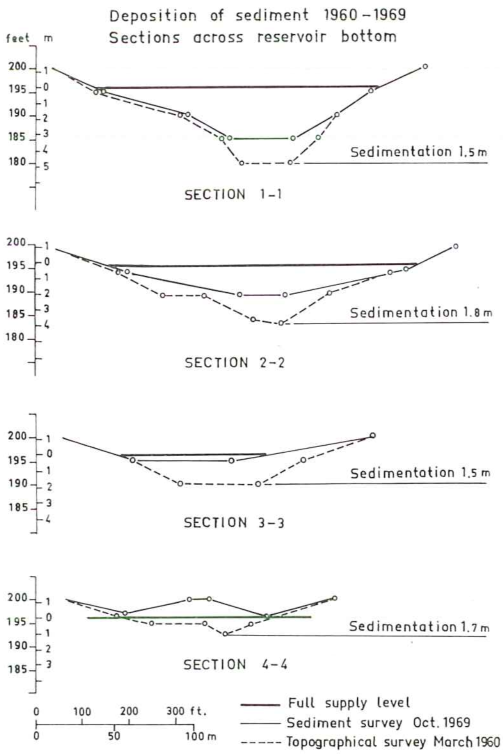



Fig. 44. Cross sections of Matumbulu reservoir floor, 1960—69. Cf. Fig. 43 for location of cross sections.

The deepest part of the reservoir contains a higher percentage of clay and silt to judge from sediment samples scooped up with a shovel on a rod.

The Matumbulu sediments have a high percentage of sand and even gravelly layers. This means a high permeability and good possibilities to extract ground water from the reservoir when it has been filled with sediments. The ground water capacity can be estimated at 30—40 % of the total capacity, or the same as the total pore volume of the sediments. The sand layers will yield a clean and cool water and prevent evaporation losses during the dry season, provided that the floor is kept free from deep-rooted and water-consuming weeds.

## Prognosis of sedimentation in Matumbulu reservoir

When the original topographic survey map of the damsite is compared with air photos from the same year, it is evident that the embankment is in a wrong position on the drawing. Nor are the bridges across the little streams along the Great North Road in right positions on the map. Later surveys by the author have been necessary to correct the errors in the basic material. The errors in the base map are con-

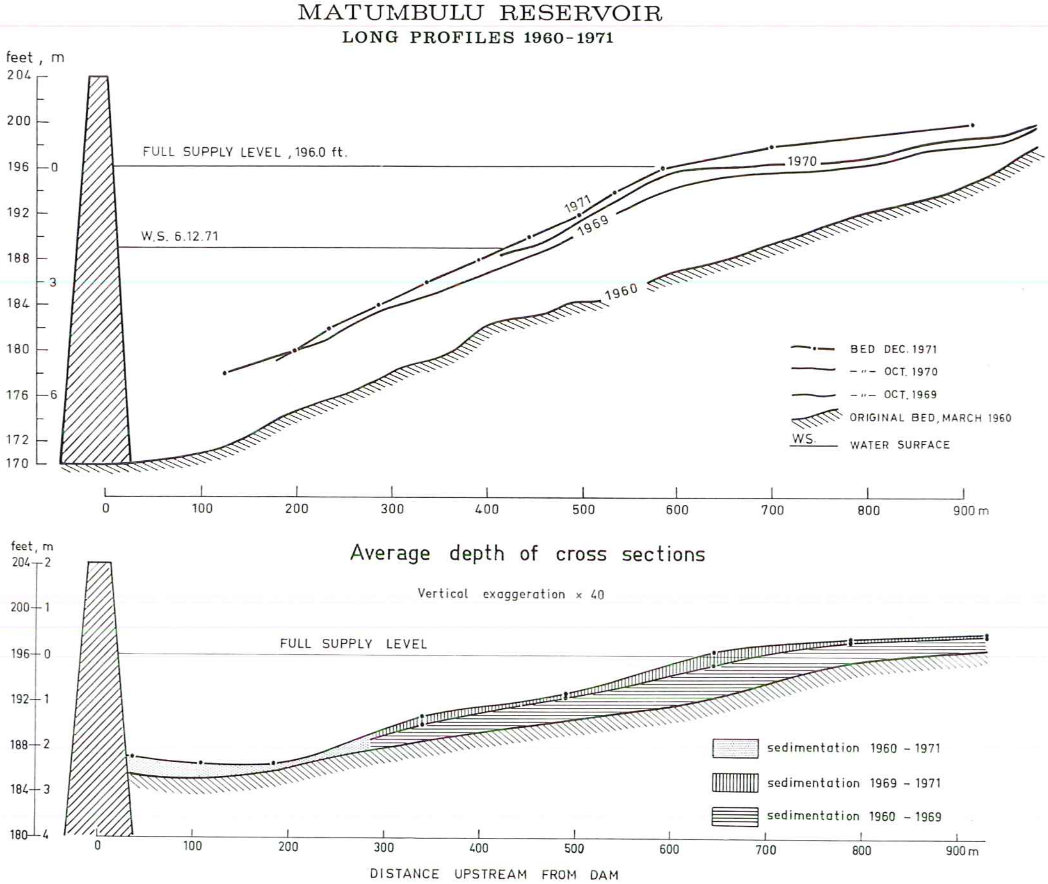



Fig. 45A. Matumbulu reservoir. Long profiles of 1960, 1969, 1970 and 1971. Surveys in 1960 by WD & ID, other years by DUSER teams. Note the break in slope of delta at FSL.
Fig. 45B. Matumbulu reservoir. Average depth of cross sections in 1960, 1969 and 1971.

sidered as less than ± 10 % of contour areas after corrections.

The analysis of sediment accumulation in the reservoir is made for the period 1962—1971, that is, from the completion of the embankment reconstruction in 1962 to the DUSER reservoir survey in October 1971. In this period 119,000 $m^3$ of sediment was accumulated in the reservoir below FSL, or an average of 13,200 $m^3$ per year. The annual sediment yield is 729 $m^3/km^2$ and as in the other catchments a large amount of sediments is deposited upstream of the reservoir. This is particularly obvious at Matumbulu reservoir where the beds of the feeding streams have been raised considerably. They are now blocking the culverts under the road (Cf. Fig. 42).

The expected total life-length of the Matumbulu reservoir is 30 years. In comparison with Msalatu and Imagi catchments Matumbulu has a higher sediment yield and a higher rate of soil denudation. In all three reservoirs the bulk of the sediments are bed-load sands, hence the trap efficiency of the reservoirs should not make much difference. Matumbulu catchment is cultivated to a much higher extent than the other two catchments (22.3 % as compared to 5.9 and 1.3 in Msalatu and Imagi respectively in 1960), and this together with higher population density and probably higher grazing intensity may explain the high rate of erosion and sedimentation in this catchment. The 5.4 % of gullying on inselberg areas in Matumbulu catchment in 1960 also indicates a higher pressure

Table 20. Soil denudation rates in 7 catchment basins in Tanzania compared with data from soil erosion plots (8). Nos 1—5 are catchments with reservoirs. Data on denudation rates are based on reservoir sedimentation (nos 1—5), sampling of suspended load in streams (no 6) resp. total volume of landslide scars resulting from one rainstorm of 2 hours duration (7). No. 7 is the only case based on volumes of erosion features. Hence it is not directly comparable to the other cases, which are based on measurements of sediment deposits or sediment load in streams. Average bulk density (dry) of sediments and soils is estimated at 1.5. Relief ratio is maximum relief of catchment (see text) divided by length. Expected life of reservoir until 100 % sedimentary fill. Economic life is shorter than this.

| Place | Catchment area km² | Relief ratio h/l m/km | Relief ratio h/l m/m | Sediment yield m³/km² year | Soil denudation rate mm/year | Period | Expected life of reservoir |
|---|---|---|---|---|---|---|---|
| 1. Ikowa | 640 | 730/50 | 0.015 | 195 | 0.20 | 1957—69 | 30 yrs |
| ″ | 640 | 730/50 | 0.015 | 362 | 0.36 | 1957—60 | — |
| ″ | 640 | 730/50 | 0.015 | 193 | 0.19 | 1960—63 | — |
| ″ | 640 | 730/50 | 0.015 | 111 | 0.11 | 1963—69 | — |
| 2. Matumbulu | 18.1 | 257/4.4 | 0.058 | 729 | 0.73 | 1962—71 | 30 yrs |
| 3. Msalatu | 8.7 | 183/4.1 | 0.045 | 406 | 0.41 | 1944—71 | 110 yrs |
| 4. Imagi | 1.5 | 122/1.6 | 0.076 | 601 | 0.60 | 1930—71 | 190 yrs |
| 5. Kisongo | 9.3 | 225/5.7 | 0.040 | 481 | 0.48 | 1960—71 | 25 yrs |
| ″ | 9.3 | 225/5.7 | 0.040 | 446 | 0.45 | 1960—69 | — |
| ″ | 9.3 | 225/5.7 | 0.040 | 640 | 0.64 | 1969—71 | — |
| 6. Morogoro | 19 | 1598/6.8 | 0.235 | 260 | 0.26 | 1966—70 | No res. |
| 7. Mgeta-Mzinga | 20[a] | 1325/6.2 | 0.214 | 13,500 | 14 | 23.2.1970 | No res. |
| 8. Mpwapwa | 50 m² bare plot | | 0.066 | 9,800 | 9.8 | 1933—35 | No res. |
| ″ | 50 m² cultiv. plot | | 0.066 | 5,200 | 5.2 | ″ | ″ |
| ″ | 50 m² grass-cov. plot | | 0.066 | 0 | 0 | ″ | ″ |

[a] Approximate area and relief ratio due to less accurate topographic map than for catchments 1—6.

on land than in the other two catchments (Table 15).

As the Matumbulu reservoir is being filled mainly by sandy sediments, it can be useful as a ground water reservoir after filling up completely. This also applies to the Msalatu and Imagi reservoirs.

## DISCUSSION AND COMPARISON WITH OTHER AREAS

In the introduction to this paper we defined the purpose of the study as a documentation of the types, extent and rates of soil erosion and sedimentation in the areas investigated. The following section is a discussion of the results from the catchment studies in the Dodoma area as compared to other areas.

### Rates of processes

The rates of the processes measured are summarized in Table 20 and compared with data from other areas in Tanzania. The four catchments in the Dodoma area and Kisongo catchment (Murray-Rust 1972) rank in the following order as regards mean value of sediment yield: Matumbulu (729 m³/km²), Imagi (601), Kisongo (481), Msalatu (406) and Ikowa (195). The sediment yield as calculated from reservoir deposition is only an indirect index of the rate of erosion in the catchment, because much of the eroded material is deposited upstream of the reservoir and some passes through in times of flood. Comparisons with other areas and other methods to measure sediment yield and erosion are included in the table as nos. 6—8. The two mountain catchments nos. 6 and 7 are Morogoro and Mgeta-Mzinga in the Ulugurus (Rapp et al. 1972, Temple and Rapp 1972) which both have similar size and similar gradients. The rather low value of sediment yield for Morogoro river—a steep mountain stream as compared to the low gradients of the Dodoma catchments—indicates moderate losses of soil during years with average or low flood peaks, catastrophically increased at extreme occasions of high intensity rainstorms by landslides and mudflows, as exemplified by the case no. 7. It should also be stressed that the method of calculating sediment yield in the latter case is gross erosion of slide scar volumes, of which a considerable part is probably temporarily deposited in the catchment.

Finally Table 20 also contains data from Staples (1938) measurements of soil loss in erosion plots at Mpwapwa, which stress the protecting action of vegetation cover against splash and sheet wash.

Sediment yield in $m^3/km^2$ has been transformed into values of soil denudation rate under the assumption that the dry bulk density of sediments and of soils are both 1.5 g/cc. This is a conservative estimate, as the soils generally have a lower bulk density than the compacted sediments (Table 11). In his world-wide comparisons of rates of soil erosion, Fournier (1960, p. 189) uses an average bulk density of 1.4. His average figure for soil loss in Africa is 510 $m^3/km^2$ and year.

The expected total life length of the reservoirs has been calculated by extrapolation from a value of annual deposition expressed as the mean of the longest available recorded period. Ikowa reservoir in this respect shows a trend towards decreasing rate of sedimentation, Kisongo one of increasing rate through the time. The economic useful life-time of a reservoir is shorter than the total life. The trend towards decreasing rate of sedimentation when a reservoir is becoming shallower can also change in the last phase of filling, due to colonisation of water vegetation and more effective trapping of sediments in that vegetation.

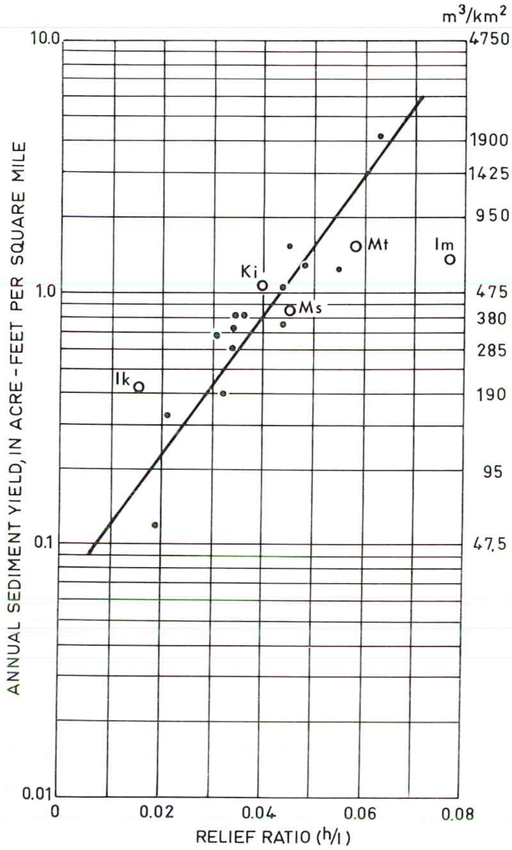



Fig. 47. Relation of mean annual sediment yield to relief ratio for 5 catchment basins in Tanzania (open circles) and 14 small basins (dots) underlain by the Fort Union sandstone and shale formation in eastern Wyoming. The amount of sediment yield is similar in the two groups and the increase of sediment yield with increasing relief ratio is evident. Cf. Fig. 48. Wyoming cases, regression line and diagram from Schumm & Hadley 1961.

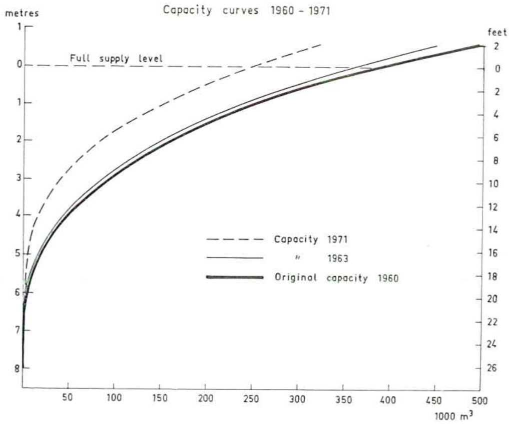



Fig. 46. Matumbulu reservoir. Capacity curves 1960, 1963 and 1971.

The problem of sedimentation in the catchment has been commented upon earlier in this paper, e.g. by reference to Schumm and Hadley (1961). They state in their study of catchments in the semiarid western United States, that the decrease in sediment yield with increased drainage area is explained as due to: a) decrease in stream gradients and slope angles, b) water losses in sandy ephemeral stream channels and c) the formation of bot-

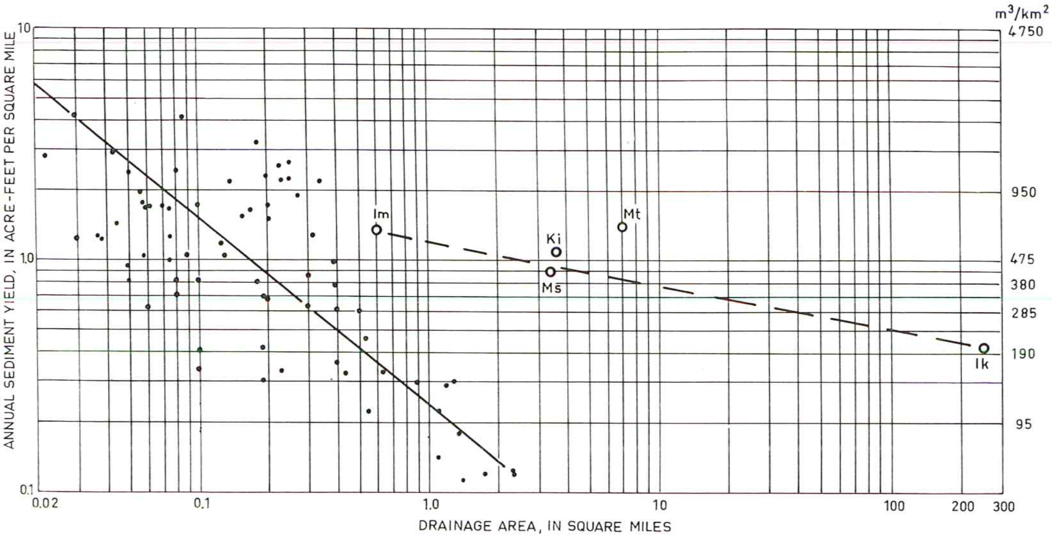



Fig. 48. Relation of mean annual sediment yield to drainage area for 5 catchment basins in Tanzania (open circles) and 73 basins (dots) in eastern Wyoming. The latter after Schumm & Hadley 1961. The basin data of Ik, Ms and Im have longest records and most similar environment characteristics of the Tanzanian cases. They are connected by a dashed line. Decrease of sediment yield with increasing drainage area is evident in both groups but is less marked in the Tanzanian cases. 1 acre-foot = 1233.5 $m^3$. 1 square mile = 2.6 $km^2$.

tomlands or flood plains bordering the stream channels. In an analysis of 76 small drainage basins in the Cheyenne River basin they found that "bottomland begins to form in drainage basins larger than 0.1 square mile" *op. cit.* p. 7).

In Fig. 48 the relation between sediment yield and size of drainage area is shown for 73 small catchments in E Wyoming and 5 catchments in Tanzania. The former data are from Schumm and Hadley 1961, the latter from this paper and from Murray-Rust 1972. The decrease of sediment yield with increase in drainage area is evident in both the American and the Tanzanian groups. It is however less marked in the Tanzanian cases. In the diagram Matumbulu stands out as a catchment with particularly high sediment yield in relation to its size. All the Tanzanian catchments have high sediment yields, which are of similar intensities as the considerably smaller American catchments of 0.3—1.5 $km^2$ in size.

In Fig. 47 the relation between sediment yield and catchment gradient is shown. Again it is a comparison based on Schumm and Hadley 1961, Fig. 2. The increase in sediment yield with increasing relief ratio seems to be similar in the two groups although the increase is less steep in the Tanzanian cases. The height factor in the relief ratio is calculated as difference in elevation between spillway level and highest summit in a catchment, or if there is one particularly high summit, as the average height of the two highest peaks. The latter is the case in Matumbulu, Msalatu and Imagi catchments.

Leopold, Emmett and Myrick (1966) report on their detailed studies of sediment budget in small catchments in semiarid areas in New Mexico as follows: "The finding of Hadley and Schumm that sediment accumulation per unit area of basin decreases rapidly with increasing drainage area is in keeping with our results that sheet erosion basin-wide estimated from erosion pins gives a value of sediment production about 4.5 times larger than can be accounted for in channel aggradation and reservoir accumulation. This feature is probably related in part to the same cause postulated by those authors: absorption of water in the dry channel beds below areas affected by local storms. But the fact remains that even in our detailed study of deposition, sediment spread thinly over colluvial areas does not show up in measurement data."

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forms in the catchments near Dodoma have very clearly shown similar kinds of catchment deposition as suggested by the American authors quoted above. We particularly refer to the maps of the Ikowa catchments (Plate 1 A) and the Matumbulu catchment (Fig. 40) as well as to our conclusion concerning the Ikowa catchment: "It is likely that less than half of the amount of soil eroded from the upper pediments per year is deposited in the reservoir. Most of it is deposited as thin sandy sheets on lower pediments, in sand fans of the channels and as clayey/silty material in the mbugas."

## Types of processes—relative importance of gullying, splash and sheet wash

The most spectacular form of soil erosion is gullying, but it does not follow that gullying also is the quantitatively predominating process of sediment production.

It is interesting to notice the opinions expressed in this respect by Hudson (1971, p. 42) who from a soil conservationist's standpoint has strongly and rightly stressed the importance of splash erosion in Africa. Hudson regards splash and rill erosion to be the most important on arable lands and as a threat to the production of food crops, but not so in the case of reservoir sedimentation. "The most important source of this silt will probably be gully erosion or streambank erosion. This is because the soil by these forms goes immediately and wholly into the stream, where it is possible for soil to be lost in large quantities from arable lands but trapped in vegetation or deposited in ditches before it reaches the stream." (Hudson 1971, p. 44). For several of the reservoirs studied within the DUSER project (Kisongo, Ikowa, Msalatu) we have found that the bulk of the sediments probably comes from splash and wash on the inter-gully flats and not from gully or streambank erosion.

This opinion is in agreement with the results obtained in more detailed studies of sediment budget in small catchment basins in semiarid areas in New Mexico by Leopold, Emmet and Myrick (1966). They measured splash and sheet erosion by using erosion pins and washers and they also measured gully erosion, aggradation of channels and deposition in dams. They concluded: "By far the largest contribution of sediment is by sheet erosion. Channel deposition is only about half of the total sediment trapped, the latter being only about one-quarter of that produced . . . It is our opinion that the sediment moved as sheet erosion does not all get into the channel, but is temporarily stored in thin deposits widely dispersed over the colluvial area . . ." (op. cit. p. 239).

In other areas gullying may be more important and as an example we quote the following opinion based on a detailed study of gully development and sediment yield in small catchments with thin loess covers: "Physically, all gully systems investigated are far from being stable, and they probably contribute a major part of the sediments trapped in reservoirs in the southern part of Israel." (Seginer 1966, p. 251).

It is a task for continued research to establish an improved documentation of the relative importance of gully as compared to inter-gully erosion in different areas.

## Geomorphological conclusions

The rates of soil erosion are very high in the four catchment investigated. They correspond to sediment yields of 195 to 729 $m^3/km^2$ per year as average for the longest periods of available records. These sediment yields are of the same order of magnitude or higher than in rapidly eroding drainage areas of similar size and slope gradients in the arid parts of western USA.

The erosion of the Dodoma catchments results in a rapid sedimentation of sandy material on gently sloping parts of pediments and channels, and of silty/clayey sediments on flood-plains (mbugas) and in the reservoirs. Two of the reservoirs thus have an expected life-length of only 30 years. The other two reservoirs have an expected life-length of 110 years and 195 years, the latter with less intense grazing and cultivation in the catchment.

The most important process of erosion is splash and sheet wash from overgrazed and cultivated parts of the pediment slopes of 2—6° gradient. An average figure for the amount of splash and sheet erosion on bare, umprotected soils of sandy loam on the pediment slopes of the area is about 10 mm of soil denudation per year. This conclusion is based on geomorphic evidence from splash pillars and tree mounds in the Dodoma catchments and on available records of erosion plot investigations at Mpwapwa.

Gullying occurs mainly on the upper pediments where gradients exceed 2—3°. Here gullies of 1—3 m depth and crusted sides are cut into the shallow soil and upper regolith on the gneiss or granite bedrock. Field inventories in 1969—71 compared with studies of aerial photographs from 1949 and 1960 show that the dense network of small gullies of the upper pediment zones and the larger, more widely spaced gullies of the lower pediment zones have the same distribution pattern in 1949 as in 1971. No drastic increase in the gully zones can thus be traced after the first aerial photographs of 1949. The gully systems are larger in the W parts of the area studied. This may reflect more intense land use, steeper slopes and thicker deposits of erodible slope sediments, either separately or in combination. Single examples of gully extension or widening has been observed during the survey period of 1969—71.

It is concluded that erosion by splash and sheet wash are quantitatively more important than gully erosion in the area. On the other hand, the gullies may have a discontinuous growth in connection with maximum rainstorms of long return periods. The gullies are also very important transportation channels for runoff of water and soil from the intergully slopes.

The methods employed and tested in this investigation have provided valuable quantitative data. Sediment surveys in reservoirs, catchment erosion surveys of slope transects and air photo interpretation are consequently recommended for continued and extended use in Tanzania and elsewhere. The main local difficulties have been inaccurate original reservoir maps and basic data, difficulties of transportation and lack of laboratory facilities for analysis of water, sediments and soils. Gaps in reservoir mapping have made necessary new surveying and mapping by our teams. The material presented in this paper will hopefully serve as basic material for future comparisons in the catchments investigated by us and in other catchments.

## Conservation conclusions

Our studies in the field and compilation of evidence collected in Tanzania during the last decades by other workers show obvious exemples of very high rates of soil erosion and rapid loss of reservoir capacity. The need for soil and water conservation measures in semi-arid Tanzania is vast and urgent. The following measures are recommended.

Improved soil and water management in catchments by reduction of stock numbers, controlled (fenced) grazing and controlled burning. Furthermore, reseeding of grass to cover eroded land. Also gully bottoms should be planted with grass and herbs as recommended particularly by van Rensburg (1955 a and b, 1958).

Soil erosion and water loss on cultivated areas can be reduced by the use of mulch cover on cultivated fields, particularly during the early part of the rainy season. The moisture absorption in the soil can further be improved through the use of ridging, tie-ridging and inter-row cultivation (van Rensburg 1958, p. 192).

An improved vegetation cover on grazing lands and cultivated areas will reduce the flow into the reservoir of sediment and runoff water. The former effect is obviously positive as it keeps more soil on the fields and increases the life length of the reservoir. The latter effect may in some reservoirs or in some years reduce the water storage to below full supply level. The disadvantage of less water yield in the reservoir ought to be compensated for in most cases by the increased production of grass and crops plus increased ground water storage in the catchment, as a result of the higher infiltration of water on the slopes and in the gullies. We realise that many of these measures will need new outlooks on farming and land management in the area.

Construction of new dams and reservoirs should continue. Even a short-lived reservoir may be economically justified in areas where the need for water is so pressing as in central Tanzania. But the construction plan should include a carefully made prognosis of the expected rate of sedimentation and life length of the reservoir. It should further include a plan for control of stock numbers and for other methods of soil and water conservation measures in the catchment.

Both water and sediment budget should be recorded continuously in the existing reservoirs.

The type of sediment which fills the reservoir is of great importance for its continued use after silting up. A reservoir which is filled with sandy or coarser sediments can be used as a ground-water supply in the future. Depending on the pore-volume of the sediments the reservoir will hold ca 30—40 % of its original water capacity. The water losses through evaporation in the dry season will be negligible in contrast to that from an open water surface, and it will yield a clean water of relatively low salinity. Reservoirs filled with clayey or silty sediments will also hold much groundwater, however less useful for human needs due to low permeability of the sediments which makes the water more difficult to pump or extract by gravity flow, and also less clean than in a sandy reservoir.

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*Dr. Anders Rapp, Dept. of Physical Geography, Box 554, University of Uppsala, Uppsala, Sweden. Mr. D. Hammond Murray-Rust, Dept. of Geology and Geography, City of London Polytechnic, London EC 3, England. Mr. Carl Christiansson, Dept. of Physical Geography, University of Stockholm, Stockholm, Sweden. Prof. Len Berry, Dept. of Geography, Clark University, Worcester, Mass., USA.*

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## Maps and air photographs

*Topographical maps*

1 : 50,000,
- Dodoma W. 162/1
- Dodoma E. 162/2
- Luatu 162/3
- Mvumi 162/4
- Chilonwa 163/1
- Handali 163/3

1 : 2,500, Dodoma Town
- Sheet 14
- Sheet 15
- Sheet 16

*Geological maps*

1 : 250,000
- Degree sheet 52 Dodoma Geol. Surv. Tanganyika, 1936.

1 : 125,000
- Quarter degree sheet Mpwapwa south B37/M1. Geol. Surv. Tanganyika, 1953.

*Air photographs*

Imagi, Matumbulu, Ikowa, Msalatu
- 1 : 33,000/ August 1949, 82A/276/TAN

Msalatu and Imagi
- 1 : 40,000, June 1960, 49TN6 No. 126—128
- 1 : 10,000, Aug 1953, 1080 No. 67—71, 71—81, 88—91
- 1 : 12,500, Nov 1960, 1546 No. 133—138
- 1 : 10,000, June 1970, CAN: 8, 106 No. 135—138, 164—169, 192—193

Matumbulu
- 1 : 40,000, June 1960, 49TN6 No. 151—155

Ikowa
- 1 : 40,000, June 1960, 49TN6

Ikowa reservoir
- 1 : 14,000, August 1957, 1387/40—45

## Abbreviations

BRALUP = Bureau of Resource Assessment and Land Use Planning, University of Dar es Salaam.

DUSER = Dar es Salaam/Uppsala Universities Soil Erosion Research.

EAAFRO = East African Agriculture and Forestry Research Organization, Nairobi.

WD & ID = Water Development and Irrigation Division, Tanzania, now Ministry of Water and Power.

# NOTES ON MORPHOLOGY AND SOIL EROSION IN KONDOA AND SINGIDA DISTRICTS, CENTRAL TANZANIA

BY CARL CHRISTIANSSON

Departement of Physical Geography, University of Stockholm and BRALUP, University of Dar es Salaam

ABSTRACT. A preliminary note on studies of soil erosion within two areas in central Tanzania is presented. Selected problems and experiences are discussed. The studies, initiated in 1971, are concentrated on collection of quantitative data. Methods include field surveys as well as air photo interpretation.

## Introduction

Within the scope of the DUSER project, soil erosion, its distribution, scale and rate are being studied in selected areas in Kondoa and Singida Districts, Central Tanzania. Related processess such as transport of eroded material and sedimentation are also considered. The areas selected are representative of those parts of the central plateau that suffer from soil erosion and its consequences.

As morphology together with several other parameters is of great importance for the genesis and acceleration of soil erosion, various features in the landscape have been examined in relation to the intensity of erosion. It is hoped that the areas under study may serve as type areas for continued studies of soil erosion and the development of soil and water conservation methods in East Africa. As field data and samples from the present studies are not yet analysed the following report should be considered as preliminary.

## Kondoa

The investigations are concentrated on the highland area of central Kondoa District between the western fringe of the Masai Steppe and the upper course of the Bubu River. The road from Kolo eastwards past Pahi forms the northern boundary and in the south, the Kelema River marks the limit. The area (1300 km$^2$) is covered by topographical and geological maps (Fozzard 1960, Selby & Mudd 1965, Walker 1969) as well as air photos in the scale 1 : 40,000.

The air photos have been invaluable for the studies as considerable parts of the area are so badly dissected by deep gullies that it is extremely time-consuming to carry out surveying in the field. Over a small area near the township of Kondoa a sequence of large scale air photos (1 : 10,000) are available. They have made possible a detailed study of some slopes with well-developed gully systems and a local sedimentation basin.

The area under study is underlain by Precambrian crystalline rocks with a dominance of felspathic gneisses. (Leedal 1954, Fozzard 1960, 1963). The topography is partly determined by fault lines associated with the Central Rift Zone (the southward extension of

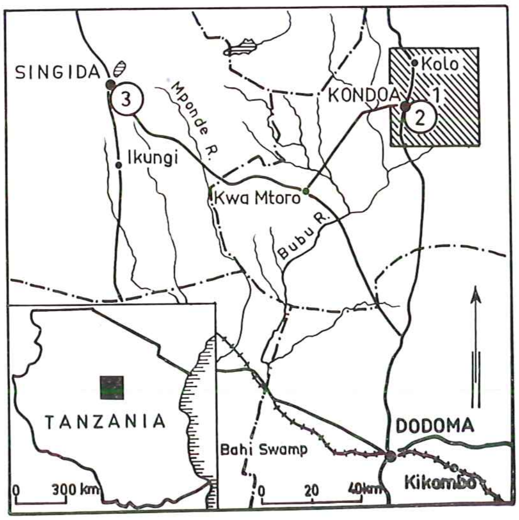


Fig. 1. Location of research areas in Kondoa and Singida Districts: 1. Kondoa Highlands. 2. Bicha catchments. 3. Magipandwa and Maheta catchments.

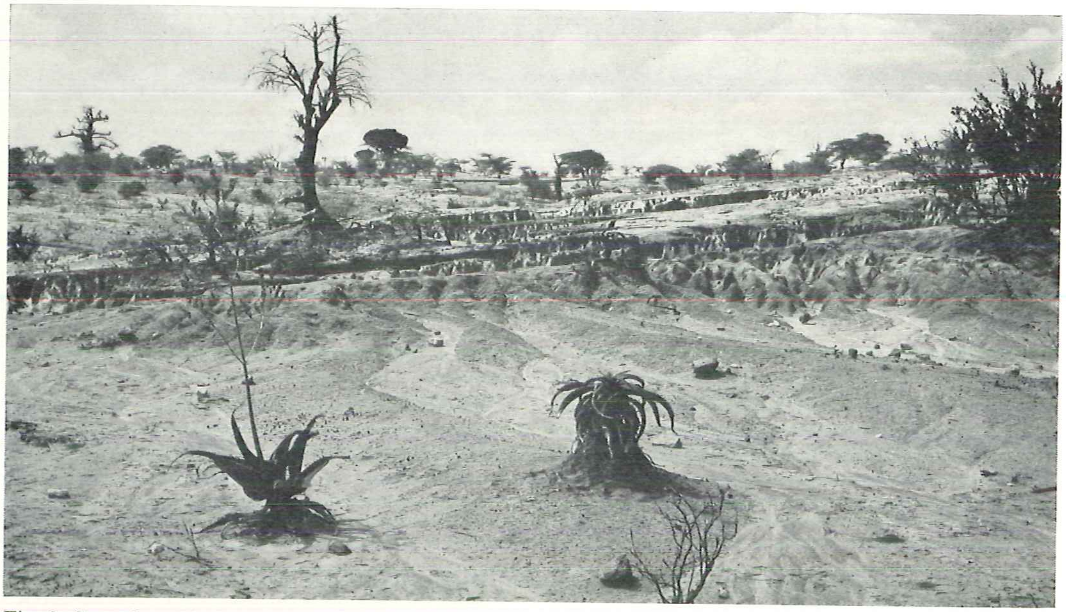

Fig. 2. Severely eroded area near Mela Road Camp, 6 km S of Kondoa town. Splash and sheet erosion in foreground, gullying of crusted soils in centre of picture. Photo AR 9/71.

Kenya's Eastern Rift). (Aitken 1950 p. 2). Seismic activity within the area indicates that movement is still continuing (Selby & Mudd 1965). Apart from the fault topography the dominating features in the landscape are steep rocky hills with broad river valleys in between. The hills usually rise to about 200 m above the valley bottoms. The average altitude of the Kondoa Highlands is about 1500 m a.s.l. The very dissected land surface is of greatest importance for the development of the slopes and for the pattern of erosion by water.

The climate is semi-arid. Mean annual rainfall at Kondoa township is 625 mm (1931—60). Because of the low rainfall soil development is poor. Consequently soils are thin and the vegetation on the hillslopes is restricted to scattered thornbushes.

The Kondoa area is largely drained by SW and S flowing rivers. It forms part of the 10,000 km$^2$ Bubu River Catchment. Within the area are several internal drainage basins. The largest is Lake Haubi in the NE. Others are Lake Bicha, Seese Swamp and the basin at the S end of the Chivi River.

The climatic conditions with an annual, short but concentrated rainy season in conjunction with sparse vegetation, steep slopes and thin soils make the area susceptible to erosion (Lambert 1956). The rather steep sloping hill-sides have been cleared of natural vegetation by man, intensely cultivated and overgrazed. This has resulted in extensive sheet and gully erosion (Fig. 2). Alluvial fans and pediment slopes are dissected by gullies, up to 15 m deep. The ultimate effect of the erosion is in many cases a barren pebble-strewn surface. Often a ferruginous crust or lateritic layer is present. Earth pillars, capped by quartz boulders or crusts are a common feature in many of the gullies, and buried horizons of laterite and quartz pebbles are evidence of earlier erosion surfaces possibly resulting from fault movement with intervening periods of relative stability.

Within the group of small catchments near Lake Bicha where detailed studies have been initiated, vegetation cover, slope gradients and soils have been checked along transects from the hilltops down to the bottom of the valleys. These factors have been related to the intensity of soil erosion.

Grass cover is almost non-existent on the lower slopes of the hills. Further up where thorn scrub vegetation increases, the grass cover also increases as grazing cattle can not reach all the grass. Percentage figures for the bush cover have not been calculated but the use of a scale from 0 (no bush vegetation) to 4 (dense thicket) reveals that along one transect (1600 m) across a centrally situated hill, denser bush vegetation than 2 was nowhere encountered. Grass cover ranges from 0 to 20 %, with the densest cover on the upper parts of the hills and along some stream channels. The slope gradients range from 1 to 5° on the pediments. Further up towards the hilltops gradients increase to 16—17°.

Reddish grey sandy soils dominate on the lower slopes. Where the gradient is lower than 2° splash and sheet wash are the dominating types of erosion. Further up near the junction between inselberg and pediment gullying starts. The gradient is here 5—6°. The soil is very thin and weathering bedrock is encountered 10—40 cm below the surface. The ground surface is stony and strewn with quartz pebbles.

The gullies which often develop right down to the bedrock are shallow in their upper parts but deepen quickly. Only 50 m down the slope some of the bigger gullies are several metres deep indicating a considerable volume of loose deposits below the foot of some of the inselbergs. Where gullies are shallow as in the little catchment NW of Bicha, bedrock is encountered near the surface even in the bottom of the central valley.

The slope gradients of six of the gully bottoms on each side of the central valley were measured. Five turned out to have gradients of 4° and one had a gradient of 2,5°. The latter was the only one where bedrock was not exposed in the bottom.

No drastic change in the gully pattern in the Bicha catchments can been traced during the period 1954—1971. There are sets of air photos covering parts of the catchments from 1954, 1960 and 1964. The assessment of the 1971 situation is based on field surveys. The surveys show that most of the gullies have approximately the same length and the same shape as they had in 1954 and 1964, others however show an upslope increase in length of 10—20 m. The most common type of development seems to be seepage of rainwater near the gully bottom with consequent undermining and slumping of material down into the gully. This material is then washed away and a steep gully head is formed. Where soil is coarse-grained and where bedrock is near the surface there is usually a gradual beginning of the upper end of the gullies.

For conservation purposes sisal hedges were planted during the colonial time. These were effective only to a certain extent. In many cases the gullies have developed backwards right through some of the hedges. Today when no conservation measures are taken even the old hedges are being destroyed. The local population burn the hedges for fear of snakes and the long stalks are used as firewood which is otherwise extremely scarce.

The material eroded from the major part of the small catchments E of Kondoa, is transported to Lake Bicha where it is deposited. Lake Bicha covering an area of approximately 0,5 km$^2$ is situated at the bottom of a dischargeless basin. As it is gradually filling up with sediments the present depth is only a few metres. With an annual evaporation rate at Kondoa of 225 cm (WD & ID, 1968) the lake is only semi-permanent, drying up in some years.

The material that is not brought to Lake Bicha is deposited in the Mkuku, a huge ephemeral river, and one of its tributaries. The Mkuku on its turn is a tributary of the Bubu River.

The volumes deposited in Lake Bicha can be estimated with some accuracy. The bottom topography of the basin, before the acute and accelerated erosion processes started, is not known, but the annual sedimentation during the last few decades can probably be computed from the thickness of the varved sediments in the central parts of the lake. The deposition of material is estimated at a few cm per year. As it is mainly the suspended fine grained material that reaches the central part of the basin the sedimentation is rather slow here. The major part of the sediments is deposited as large sand lobes or deltas at the inflows of the streams and on the river beds upstream from the lake.

Still more spectacular are the conditions in and around Lake Haubi, another dischargeless basin 25 km NE of Kondoa. Lake Haubi is a permanent lake although the water level sinks considerably towards the end of the dry season. Because of the size of the catchment and the great relative relief the transport of sediment into the lake is very striking.


Fig. 3. Detail of vertical air photograph, Magipandwa catchment, 6 km SE of Singida town. Cf. Fig. 4, which shows the profile A—B, parallel to the road. Dark patches are termite mounds on the pediment and on the plateau. Recent sand fans in valley bottom contrast with dark zones of vegetation due to groundwater seepage. Air photograph 49TN15, 169, Aug. 1960.

## Singida

Soil erosion is being studied within two catchments east of Singida in the semi-arid part of central Tanzania. The catchments under study cover approximately 34 km$^2$ (Fig. 1).

The northern limit of the catchments runs close to the Singida-Babati road. The SE boundary follows a line of granite tors on a low ridge on top of the Turu Fault Block. The southern water divide is not clearly distinguished as it runs in part across flat country. The water divide between the two catchments follows the higher hills near the W scarp of the Turu Fault Block (Figs. 3, 4).

The two river systems draining the catchments, the Magipandwa in the NW and the Maheta in the SE occupy broad valleys with gently undulating, partly grass-covered slopes. The main topographical feature in the area is the prominent fault line which runs from NE to SW dividing the Magipandwa catchment into two parts; an upper part where erosion is excessive and a lower part, in the valley, where the eroded material is deposited. Altitudes in the two catchments range from 1525—1760 m.

The area is covered by recent topographical maps. The latest air photography was in 1960. The geological map is from 1938 (Eades & Reeve 1938).

The catchments are inhabited by people of the Turu tribe. The Turu are mainly agriculturalists but they often posses large herds of cattle. The population is fairly evenly spread over the catchments, with concentration on the upper parts of the low ridges that traverses the area from NE to SW. Even the lower slopes along the escarpment are densely populated. The valley floors are uninhabited as they are liable to flooding in the wet season. Altogether there are some 200 homesteads within the catchments indicating a total population of well over 1000 people and possibly over 1500. This means a population density around 50/km$^2$.

Singida District lies at the SW extremity of the Eastern Rift system. Raised blocks and fault scarps form significant morphological features. The depressions between the uplifted blocks often show dischargeless basins. The superficial deposits range in age from Miocene to Recent. Youngest are alluvial fans and talus slopes now in process of formation. Clay

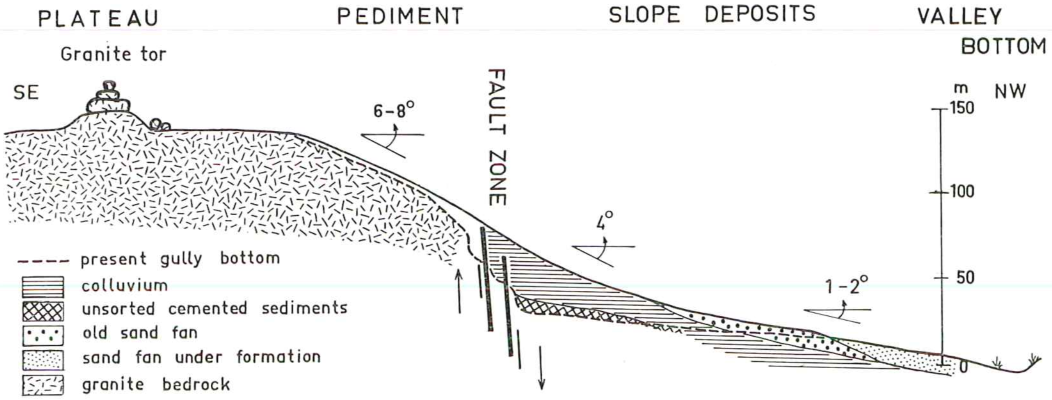


Fig. 4. Profile of the W slope of Turu Fault Block, Magipandwa catchment, Singida. The block has been raised 150 m in relation to the valley below. Magipandwa valley is covered with fairly thin "mbuga"-sediments. Bedrock is exposed in a few places in the bottom of the stream channel. Cf. Fig. 3, where the gully A—B marks the position of the lower part of the profile. "A" is halfway up the pediment slope.

deposits of some "mbuga" areas clearly antedate the latest block faulting. They are now being cut into, by the streams that drain them, because of the change in base level (Eades & Reeve 1938, p. 42).

At present most of the slopes around the granite inselbergs show an almost complete lack of natural vegetation. They are used for cultivation and grazing. The soil here forms a complex of red earths passing through yellow and grey sands on the higher ground to black calcareous clays in the depressions.

Over large areas soil erosion has become a serious problem. Large tracts of country still consist of open grasslands though the term "grasslands" is partly a misnomer as a result of the extensive overgrazing by cattle.

Sheet erosion is the dominating type where the landscape is gently undulating but where gradients are steeper as along fault lines and on the pediment slopes below the inselbergs, gullies have developed. As strong winds persist throughout the dry season, wind erosion plays an important role in exposed positions.

The present research on soil erosion and its effects on the landscape has included mapping of erosion features, surface drainage pattern and studies of channel morphology. As seepage steps (erosion steps caused by underground water) are common in this area the occurence of groundwater and waterlogged areas have been taken into consideration (Fig. 3). In this context permanence of surface water and its significance for the distribution of water-holes and stock-routes has also been examined.

The detailed studies have so far been concentrated on eroded areas along the escarpment, on the pediment and in the valley bottom. Wind erosion which is important in these partly treeless areas has also been included in the studies.

The slopes along the faultline suffer badly from both gullying, splash and sheet wash. Sheet wash dominates on the newly weathered, coarse material. Bedrock is here often only 10—40 cm below the surface. Where rills and gullies occur these have cut down into the soft bedrock. Further down the slope where the gradients steepen the gullies become wider and deeper, but as bedrock is near the surface even here the water has eroded into the regolith. Just where the pediment slope reaches the fault line the gullies suddenly become wider and deeper, cutting into the loosely consolidated masses of colluvial deposits which are found below the fault line. The material is poorly sorted but layers indicating water transport at some stage can be traced. The material which is grey to yellowish is fairly uniform down to a depth of many metres. A hard light grey cemented layer occurs immedeately on top of the weathering bedrock. This layer is seldom more than 2 m thick. Below the escarpment the running water has cut into this material exposing bedrock at several places along the fault.

In some places the uppermost 1 or 2 m have a different appearance from the underlying thick unsorted greyish sediments. This layer is brown and sandy with clear evidence of water transport. It is interpreted as sand fans developed during an early stage of gully erosion on the edge of the Turu Fault Block.

During later stages of erosion new sand fans have developed on the lower slopes. Some of the bigger fans, now cover large parts of the alluvial soils in the valley bottom. In some cases these fans have been cut into and new lobes have formed in front the old ones.

This creates a serious practical problem as the best cultivation and grazing areas in the valley bottoms are gradually covered by infertile sandy sediments. As the gradient from the innermost parts of the valley towards Lake Kindai, the final sedimentation basin, is very low and as there is no defined stream channel for long stretches, most of the coarser material remains where it is deposited in the valley.

Throughout the dry season strong winds blow. This means that the sand fans that have no vegetation cover are subject to wind erosion. Many of the low tree-less ridges also show signs of wind drift. In the most exposed positions virtual dune landscapes are under formation. In several cases drifting sand has invaded cultivated fields, making future cultivation impossible.

Already in this early stage of the studies it can be stated that both wind and water erosion is a serious problem in parts of Singida District, particularly around the township, where the population pressure is high. Immediate measures have to be taken if large areas are not going to be converted into local deserts. However, reseeding of the denuded areas, planting of trees and the introduction of controlled grazing can certainly stop the present unfortunate deterioration.

*Mr. Carl Christiansson, Department of Physical Geography, Box 6801, University of Stockholm, S-113 86 Stockholm, Sweden.*

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## Maps and air photographs

*Topographical maps*

1 : 250,000, Y503
- Singida SB-36-4
- Manyoni SB-36-8
- Naberera SB-37-1

1 : 50,000, Y742
- Singida W. 102/3
- Singida E. 102/4
- Masange 104/2
- Serya 104/3
- Kondoa 104/4
- Busi 105/3
- Kelema 124/2

*Geological maps*

1 : 250,000, Degree Sheet
- No 29 Singida

1 : 125,000, Quarter Degree Sheet
- No 104 Kondoa
- No 105 Busi
- No 124 Kelema

*Air photographs*

Kondoa, 1 : 10,000, Sept. 1954
- 1146 No 83—99

Kondoa, 1 : 40,000, July 1960
- 49TN11 No 123—135; 139—156
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# SOIL EROSION AND RESERVOIR SEDIMENTATION IN A GRAZING AREA WEST OF ARUSHA, NORTHERN TANZANIA

BY D. HAMMOND MURRAY-RUST

Department of Geology and Geography, City of London Polytechnic
formerly Department of Geography and BRALUP, University of Dar es Salaam

ABSTRACT. The paper describes the causes of soil erosion within a semi-arid catchment, and provides detailed descriptions of the various processes involved. Overgrazing is shown to be the main cause of sheet erosion development, which affects 14 % of the catchment, while gully erosion is found both in overgrazed areas and along stock routes. Measurement of sediment volumes in a reservoir provides calculations of overall erosion rates within the catchment. The original capacity of the reservoir in 1960 was 121,000 m$^3$, but this had been reduced to 83,600 m$^3$ by 1969 and to 71,700 m$^3$ in 1971. With a catchment area of 9.3 km$^2$ the overall sediment yield is estimated to be 446 m$^3$/km$^2$ year during the period 1960—1969 and 640 m$^3$/km$^2$ year during the subsequent two years. The economic life length of the reservoir is estimated at 15 years. The dangers of soil erosion developing as a result of unplanned water supply in semi-arid areas are stressed.

## Introduction

This paper provides a case study of soil erosion in one part of the rangeland of northern Tanzania; in Arusha Region alone there are some 74,000 km$^2$ of semi-arid grazing land. Population pressure on the neighbouring Mt. Meru has led to an expansion of the sedentary Arusha tribe into the fringes of the Masai rangeland. The results presented here are based on field work carried out between 1968 and 1971 at Kisongo, 23 km W of Arusha, where soil erosion has developed as a result of changed land use.

Kisongo was chosen as one of the study catchments with the DUSER project for a number of reasons, the most important being the presence of a small reservoir constructed in 1960. This reservoir acts as a sediment trap, allowing calculations of overall erosion rates which can be directly compared with those obtained from other reservoir catchments in other parts of Tanzania (Rapp *et al.* 1972). Other important considerations were wet season accessibility and good quality air photo coverage permitting analysis of erosion development since the completion of the reservoir.

Field work was carried out in the wet seasons of 1969 and 1970, and in the dry seasons of 1969 and 1971. The wet season field work concentrated largely on examination of erosion processes and development of erosional landforms, while the dry seasons were used for measurement of volumes of reservoir sediments. The methods employed are described in detail in this paper, while only summary descriptions of the physical environment are presented as they are fully documented elsewhere (Murray-Rust 1970).

## The physical environment

The catchment has an area of 9.3 km$^2$ and lies on the southern footslopes of Monduli mountain (2660 m), an extinct volcanic cone of (?) Neogene age. Underlying the whole catchment is a series of olivine basalts derived from Monduli mountain, but these are seldom exposed due to an overlying ash and tuff layer, from 1.5 to 15 m thick, originating from numerous small volcanic cones on the southern and eastern slopes of Monduli mountain (Dawson 1964).

Kisongo dam (Fig. 1) lies at an altitude of 1330 m, and the catchment slopes gently up to a maximum elevation of 1590 m (Figs. 2, 3 & 4). Relative relief is moderate, generally less than 50 m, and only exceeding 100 m in the northern section. Ungullied interfluve slopes are gentle, between 3° and 5° in the southern and central sections, but occasionally exceeding 10° in the northern section.

Rainfall in the area is strongly seasonal, falling in two main periods: the "long rains" from March to May, and the "short rains" of October and November. There are considerable fluctuations in monthly totals (Table 1). Rec-

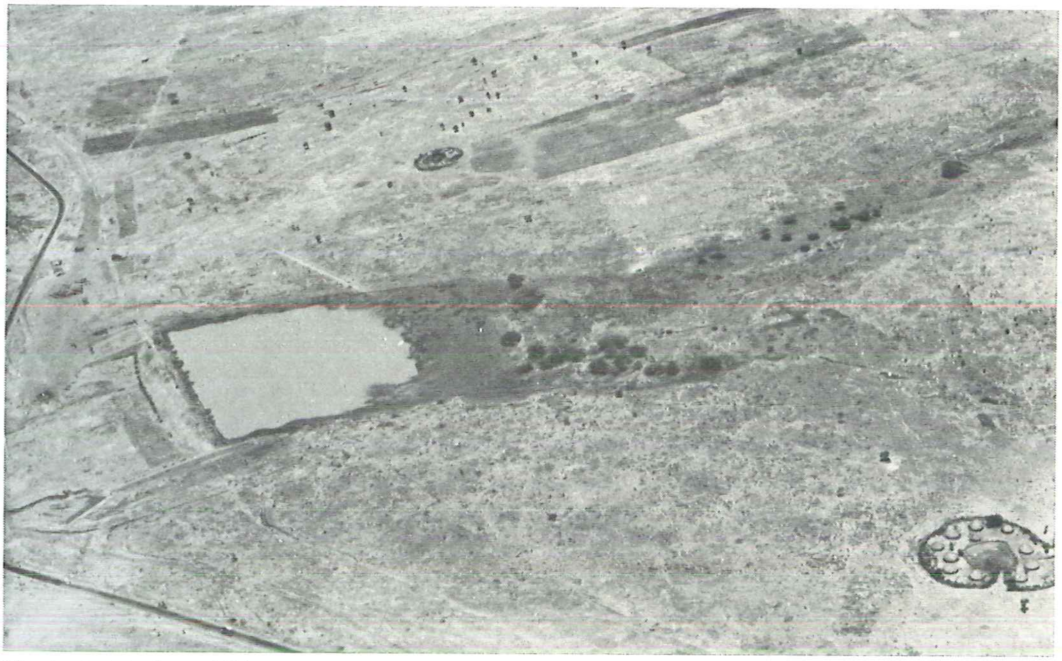

Fig. 1. Aerial view of Kisongo reservoir, 24 October 1971. Water level 1.4 m below spillway crest. Conspicuous are Arusha-Dodoma road, settlements and exposed reservoir sediments. (Photo: P. H. Temple)

ords from Monduli, 15 km NW of Kisongo show that rainfall during April has varied from 0.0 to 259.4 mm in the past 12 years. There are also large local variations in rainfall. In April 1970 151.3 mm were recorded at Monduli, while personal observation at Kisongo showed that no rain fell at Kisongo during the same period. The annual rainfall at Kisongo is estimated at 750 mm, but in view of the wide annual fluctuations this figure is of limited meaning.

The alternating wet and dry seasons have considerable importance with regard to erosion development. The long dry season from May to October allows the soil to dry out thoroughly, with the formation of deep cracks. In addition the vegetation cover dies off, so that bare soil is exposed to the next rains. Soil exposure is intensified by overgrazing and clearing of fields for cultivation.

Evaporation pan records from Arusha airport, 15 km E of Kisongo, show an annual loss of some 1700 mm; it is likely that such values would also apply at Kisongo. Temperatures range between 16° and 22° C. Wind speeds are moderate for most of the year, ranging between 130 and 170 km/day, but increasing to 250 km/day at the end of the dry season (Woodhead 1968).

Table 1. Mean monthly rainfall in mm at Arusha airport and Monduli, 1960–69. The monthly figures for 1969 from Arusha airport are given to show the failure of the main rains, leading to drought conditions later in the year. (Source: EAMD. records, Dar es Salaam.)

| | Arusha airport Mean | | Monduli Mean 1960–69 |
|---|---|---|---|
| | 1960–69 | 1969 | |
| J | 61.1 | 99.8 | 67.3 |
| F | 84.1 | 135.4 | 92.9 |
| M | 142.7 | 95.1 | 150.2 |
| A | 259.5 | 39.1 | 219.5 |
| M | 65.6 | 38.0 | 95.8 |
| J | 19.3 | 8.5 | 10.7 |
| J | 12.1 | 2.6 | 2.7 |
| A | 7.2 | 14.7 | 3.9 |
| S | 10.4 | 1.7 | 5.0 |
| O | 27.0 | 18.2 | 21.7 |
| N | 151.2 | 113.3 | 91.6 |
| D | 98.7 | 50.8 | 106.8 |
| Total | 938.9 | 617.2 | 868.1 |

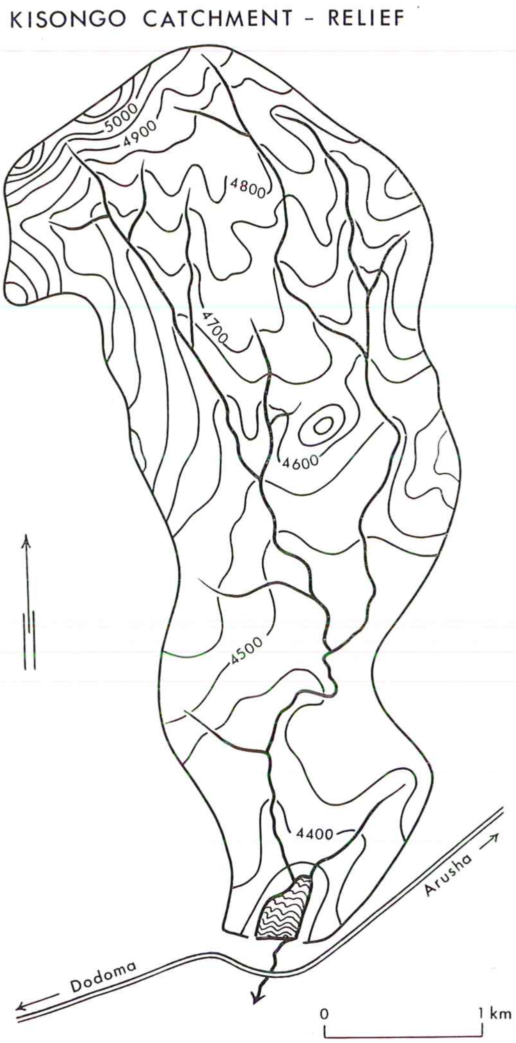


Fig. 2. Contour map of Kisongo catchment. Contour interval 50 feet (15.3 m). Based on Tanzania 1 : 50,000 series 1-DOS, Sheet 55/3 Arusha.

The soils of the catchment are characterised by uniform profiles, the formation of deep cracks during the dry season and the presence of calcium carbonate concretions throughout the profile. These features, together with the high clay content (> 60 %) suggest they should be classified as vertisols (Buringh 1968, p. 99). Although dark coloured, their organic carbon content is low, and this combined with the seasonal variation from hard blocky to extremely plastic texture reduces their agricultural potential. An analysis of a typical profile is presented in Table 2.

Table 2. Mechanical and chemical analysis of a typical soil profile, Kisongo, April 1969.

| | Depth of sample (cm) | | | |
|---|---|---|---|---|
| | 0–20 | 20–60 | 60–90 | >90 |
| % Sand | 20.2 | 18.2 | 13.9 | 28.6 |
| % Silt | 25.5 | 21.5 | 21.7 | 27.4 |
| % Clay | 54.3 | 60.3 | 64.4 | 44.0 |
| pH | 7.3 | 8.0 | 8.2 | 8.6 |
| % Org. C | 1.2 | 0.8 | 0.4 | 0.2 |
| Ca | 16.2 | 22.0 | 31.7 | 28.0 |
| Mg | 6.0 | 7.2 | 15.1 | 13.2 |
| Base Saturation | 91.0 | 94.0 | 100.0 | 100.0 |

The most important soil features from an erosion point of view are the deep cracks and the calcium carbonate concretions. The deep cracking in the dry season allows rapid infiltration of water at the start of the wet season. This enables throughflow to commence, an important process in gully development. The concretions in the soil are significant insofar as they are generally too large to be removed by throughflow and sheet flow, and consequently form a residual surface layer inhibiting further stripping through sheet flow.

The natural vegetation of the catchment has been considerably modified by human activity, but as in most savanna areas, it is difficult to

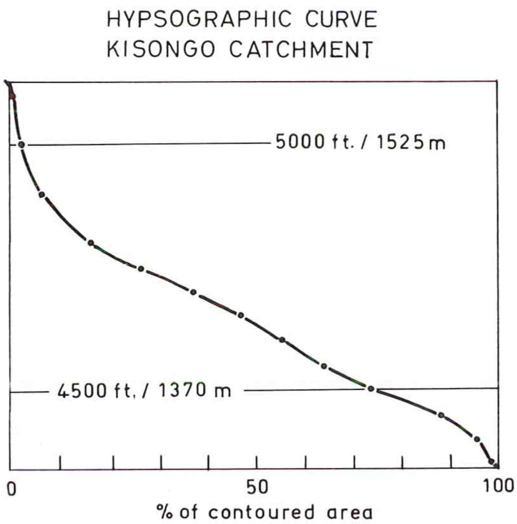


Fig. 3. Hypsographic curve, Kisongo catchment.

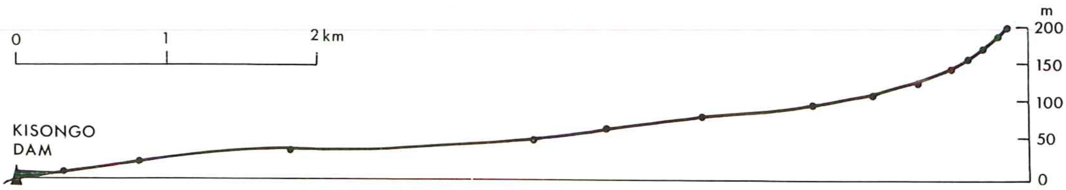


Fig. 4. Longitudinal profile of main stream channel. Vertical exaggeration: × 5.

assess the importance of grazing, felling and burning. Tree cover is most extensive in the northern section, as there has been little felling on the steeper slopes. The dominant species is *Acacia drepanolobium,* while *Ballanites aegyptiaca* and *Commiphora* spp. are common. The central and southern areas are dominated by grassland. There is little variation in species, which include *Themeda triandra* and *Pennisetum massaicum,* both of which are perrenial clump species (Napper 1960).

*Solanum incanum,* (the Sodom Apple), a woody shrub resistant to grazing and with harmful effects on cattle, is common. It is possible that this species is favoured in areas of overgrazing. The deltaic sediments of Kisongo reservoir have been colonised by *Cyperus alopecuroides* and *Polygonum senegalense.*

## Human influences

The development of soil erosion in the Kisongo area can be largely attributed to the migration of the Arusha tribe into the area (Gulliver 1960). In nearby areas at present unpopulated there are only isolated erosion features. Mbuyuni reservoir catchment, 40 km W of Kisongo, only has a few gullied patches, and sheet erosion is very limited.

Until 1945 the Kisongo area belonged to the Masai, pastoralists whose cattle represent wealth, status and security. Stock numbers under the Masai system are maintained by seasonal transhumant movements to areas of better grass and water supply. Because of these movements overgrazing is reduced, and some of the Masai area is attractive to neighbouring tribes. The Arusha are one such tribe, and there has been a long history of land conflict between the Masai and the Arusha. For a closer analysis of ecology under the Masai system, see Talbot 1971.

Although the two tribes have similar attitudes towards cattle, with slaughter or selling of stock only in times of severe drought, the Arusha are also cultivators. Their traditional crops are bananas, coffee and maize. The stock owned by each household is of importance primarily as symbols of wealth and status, but of secondary importance agriculturally.

Before 1914 the Arusha were confined by the Masai to the western slopes of Mount Meru (4560 m), an area of fertile deep red soils and abundant, reliable rainfall (about 2000 mm/year). Between 1914 and 1945 population growth and increasing land shortages in the traditional Arusha tribal areas led to a period of expansion, and conflict with the Masai ensued. The colonial authorities were too weak to intervene effectively, so that the Arusha were able to drive the Masai out from their territories north and west of Arusha town. Although this area is drier and less fertile than the mountain slopes the traditional crops can still be grown. Yields, however, are lower, so that the plains area supports a population of lower density.

By 1945 this area was fully occupied, and a second period of expansion began. Partly through force, and partly through assistance by the colonial government the area around Kisongo and north to the Meru—Monduli divide became Arusha territory. The poor soils and unreliable rainfall do not permit the traditional Arusha crops to be grown here, and there has thus been an emphasis on maize and small holder wheat production. Stock holdings are far larger than on the mountain slopes due to the greater availability of grazing land, but the same social attitudes to cattle have been maintained.

Soil erosion began to develop soon after the Kisongo area became permanently settled in the 1950s, and appears to have resulted directly from the inability of the Arusha to adapt to their new environment (Gulliver *op. cit.*, p. 13). Family holdings have to be larger than in the upland areas to counterbalance lower yields and crop failures through drought. Consequently the area available for grazing has decreased, although the stock numbers have been maintained or even increased. By the late 1950s overstocking was resulting in stock losses through hunger and drought.

Kisongo dam was completed in 1960 in order to alleviate the critical water situation. Although no precise figures are available on stock numbers, as the Arusha are reluctant to divulge such information, it appears that stock numbers rose as a result of the provision of a new water supply. There was, of course, no corresponding increase in neighbouring grass supplies, so that pressure on grazing was further increased. Soil erosion was already established by 1960, and has intensified with the continued depletion of the vegetation cover.

The situation at Kisongo is still flexible, and will change radically once again when the reservoir ceases to be a permanent water supply (see below). The carrying capacity of the surrounding area will fall again as soon as water shortages are experienced, for drought will again become an important factor in the control of stock numbers. The continuing depletion of grazing areas during the intervening 15 years will mean that the carrying capacity of the Kisongo area will drop to a *lower* level than prior to the dam construction. Stock deaths will be inevitable so that any beneficial effects of the new water supply will soon be lost.

## Animal husbandry and the development of soil erosion

Overstocking within the catchment has led to the development of two distinct erosion landscapes. One set of landforms is directly related to overgrazing, and is typified by dispersed areas of gullies with dendritic patterns, which have formed on areas suffering from severe sheet erosion. The other is related to stock movement, characterised by linear patterns of gully channels developed on stock routes, those leading to Kisongo reservoir being the most affected. The distribution of these erosion types is shown in Fig. 5, which was constructed from air photo interpretation and subsequent field checking.

The air photographs of 1961 (Fig. 6) are clear enough to identify the eroded areas, although detailed measurements are not possible. Some gullied areas can be seen in the northwestern corner. The areas of severe sheet erosion appear as paler areas on the photographs due to the exposure of calcium carbonate concretions at the surface (Fig. 7) and reduction in vegetation cover.

*Development of dendritic gully patterns*

Dendritic gully patterns are invariably associated with severe overgrazing and do not generally develop in areas where the vegetation cover is still partially preserved. Overgrazing results from overstocking, an excess of stock relative to the carrying capacity of an area. It is difficult, however, to quantify the carrying capacity of a particular area as it is a function of several variables, the most important being grass supply, water availability, and food requirements of stock. Clearly all these will vary in a single year, and generally carrying capacities should be calculated for drought years, when overgrazing is most likely to occur.

Estimates of carrying capacity in Arusha Region vary between 2 and 10 hectares/stock unit, depending on water supply (Moris, personal communication). The Masailand Range Commission has allowed 5 hect./stock unit on their Kolomonik ranch, 10 km W of Kisongo (P. R. Olekuney, pers. comm.). An estimate of the stock population within the catchment was made in 1971 by counting numbers in herds approaching the reservoir from the catchment, and deducting those herds apparently coming from areas beyond the divide. Although probably only accurate to 20 %, the estimate was of 500 cows and 700 sheep and goats, the equivalent of 700 stock units. With a catchment area of 9.3 km$^2$ this gives a density of 1.3 hect./stock unit. Approximately 20 % of the catchment is cultivated (Fig. 8) and although some areas are left fallow they are not always grazed. The stock density is thus increased to about 1.0 hect./stock unit, suggesting that the local carrying capacity may be exceeded by between 2 and 5 times.

The result of this overstocking is a general depletion of the vegetation cover, exposing the soil to erosion from sheetwash and rainsplash.



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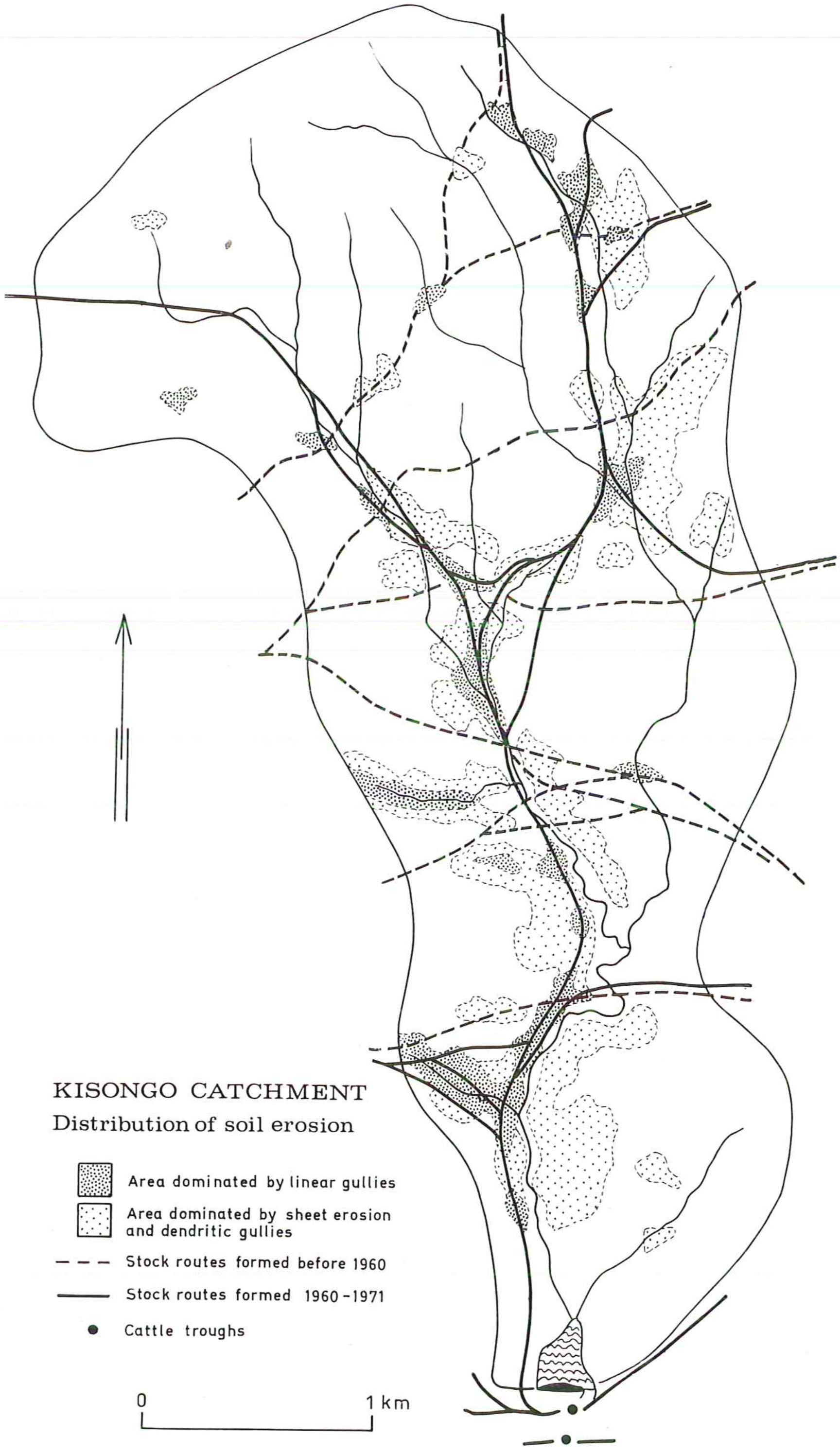


Fig. 5. Distribution of erosion and relationship to stock routes. The areas of dendritic gullies bear little relation to stock routes, while linear gullies are generally close to the north-south stock routes.

Fig. 6. Aerial photograph showing Kisongo reservoir. Note low water level of reservoir due to drought. North at top of photograph; scale approximately 1 : 30,000. (Enlarged from aerial photograph ASD, TANG. 467, 160/3, August 1961)

The high clay content of the soil (cf. Tables 2 & 6) causes it to swell on wetting, reducing severely its infiltration capacity. Infiltration is further reduced by stock trampling and rainsplash, so that much of the rainfall is converted rapidly into surface runoff. The depleted vegetation cover also reduces the surface roughness coefficient and the effects of root stabilisation, so that higher velocities of runoff can be attained, and greater volumes of soil transported (Webster and Wilson 1968).

Sheetwash can generally only remove fine particles, leaving behind a residue of coarser material on the soil surface (Epstein *et al.* 1966). Unless transported by other processes these residual coarser particles accumulate until a continuous surface layer forms. In Kisongo catchment the coarse fraction is largely composed of calcium carbonate concretions, so that the end stage of the sheet erosion process is the formation of a fairly continuous white gravel layer on the surface (Fig. 7).

On steeper slopes surface runoff is often sufficient to stimulate rill formation. Breaching of the surface carpet follows. The rills often act as the foci for gully development, especially where they drain into larger stream channels, for the break in slope provides sufficient relative relief for gully head formation. The gully heads then migrate up the rill channels.

The drainage pattern of the gully systems formed in this way is dendritic, as there are no surface constraints on the development of tributary gullies, and because the pre-existing rill pattern acts as a guide for migrating gully heads. The width and depth of the gullies increases downslope in response to the increasing discharge as tributary gullies feed the main channels. Gully deepening may result from recession of breaks in slope in the gully floor caused by the increase in discharge at a gully confluence. Recession of such breaks in slope proceeds either from hydraulic action or from collapse due to undermining by throughflow.

The cross-profiles of the dendritic gullies show a generally rectangular cross-section near the bottom of the gully, with convex interfluves above. This convexity is maintained through rainsplash and creep; the sharp contact between walls and floors results from lateral undermining during each successive flow. Dimensions of the channels of dendritic gullies vary considerably. Channel lengths are generally short, seldom exceeding 50 m, although some clearly predate the construction of Kisongo dam; widths reach a maximum of 3 m, while the maximum depth recorded was 3.5 m.

*Erosion along stock routes*

The more spectacular erosion forms in the catchment are associated with stock routes. The movement of stock along these routes leads to the destruction of the vegetation cover through grazing and trampling. In their initial

Fig. 7. Calcium carbonate concretions forming a surface layer after removal of fine material by sheetwash and rainsplash. Concretions are being exposed in a residual soil mound protected by grass. Height of soil face about 15 cm. (Photo: HMR 4/70)

stages these routes are only narrow paths between grass clumps, but gradually the intermediate vegetation is destroyed and the paths coalesce to form bare strips up to 10 m wide. Where routes traverse the slope, erosion development is limited, but when they run downslope the rate of gully development is normally rapid.

Where stock routes run downslope gully development starts during the earliest stages of stock route formation, as runoff is channelled down the bare strips, with grass clumps remaining as interfluves (Fig. 9). Although the channels are often damaged considerably by trampling in the dry season, they reform quickly at the start of the following rainy season.

The drainage pattern of gullies formed on stock routes is linear, for the migrating gully heads follow the channels initially formed by stock movement. There are few tributaries as lateral movement of water is limited by the grassed interfluves and channels may run parallel for long distances. Channel shape also differs from gullies found in overgrazed areas, as walls are often vertical, separated by flatter and narrower interfluves. The channels maintain constant widths for long distances, as there is little change in discharge downslope. Most gully deepening is initiated at the downslope end of the channel, the necessary relative relief being provided by continuing deepening of the tributary streams in response to higher discharges resulting from vegetation denudation.

Two distinct orientations of stock routes can be recognised. The older routes run approximately east-west across the catchment leading to Kisongo cattle market, 8 km E of the reservoir. This market meets weekly, but as stock is sold only when absolutely necessary, the trampling on the routes is slight; some erosion has developed, but the area affected is small.

The newer routes run N—S to the two drinking troughs immediately below Kisongo reservoir. The area surrounding these troughs is severely overgrazed by waiting herds. Watering of stock directly from the reservoir is strictly prohibited to prevent contamination of human water supplies. During the wet season stock can generally obtain sufficient water from pools in the stream channels, and they are taken to the drinking troughs only about once a week. In the dry season, when the reservoir is the only source of water, stock is watered every one or two days, so that the volume of movement is great on the newer routes.

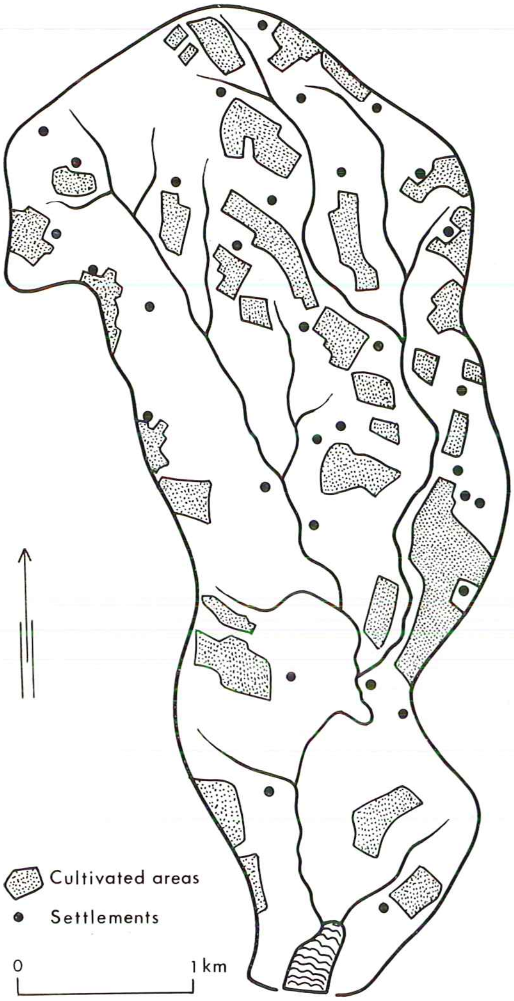


Fig. 8. Cultivated areas and settlements, 1970. (Based on 1961 aerial photos, with field checking)

Two factors have favoured gully development on the newer routes. The greater volume of movement leads to rapid vegetation depletion through grazing and trampling, increasing rates of runoff. Secondly, the slopes traversed are generally steeper than those of the older E—W routes. Where the new routes cross tributaries of the main stream channels, slopes often exceed 10°, whereas they seldom exceed 5° on the older routes. It is on these steep sections that gully development is most rapid. In addition the banks of the tributary stream channels often have sufficient relative relief to stimulate gully head formation, which then migrate upslope either through hydraulic action on the lip or by throughflow (cf. Hadley and Rolfe 1955).

The dimensions of linear gullies contrast with those having dendritic drainage patterns. Although widths and depths are smaller, seldom exceeding 2 m, their lengths are far greater. The maximum recorded length was over 200 m, and many examples over 100 m can be seen. Although the air photos of 1961 are of too small scale to permit accurate measurement of gully dimensions, it appears that the majority of linear gullies have developed since the completion of Kisongo dam. This indicates average rates of gully extension in the order of 10 to 25 m/year, which are probably far in excess of recession rates in areas of dendritic gullies. Field measurement of gully recession proved unsatisfactory (see below). In some places the

Fig. 9. Gullying developed on a stock route. The channels are essentially linear, forming along former stock paths. Vegetation cover is only partially removed. Ash cones on horizon beyond Kisongo reservoir. (Photo: HMR 4/70)

stock routes have become so gullied that alternatives have to be used, extending gully damage into adjacent grazing areas.

*Other erosion types*
Three other erosion processes have been identified within the catchment. It is unlikely, however, that they are significant sources of sediment in comparison with gully and sheet erosion.

*Seepage steps* are present in many areas suffering from sheet erosion. These steps form when throughflow emerges at a breach in the soil surface, weakening the exposed subsoil. Throughflow is encouraged by differential infiltration rates within the soil, and at Kisongo it appears that seepage steps are linked with clay layers within the soil. Runoff during the early stages of a rainy season flows down deep cracks leading to an excess of water in the subsoil. Swelling of the topsoil reduces evaporation losses so that throughflow is encouraged. The step retreats by undermining of the topsoil, followed by collapse either by gravity or by trampling. Overgrazing will lead to a reduction in root stabilisation of the vertical slope, and reduced evapotranspiration. Although individual steps may be small, between 10 and 100 cm high and up to 5 m wide they are of importance in that they leave bare patches as they retreat (Hadley and Rolfe *op. cit.*), which will subsequently be affected by sheet erosion.

*Wind erosion* is important within the catchment towards the end of the dry season, when vegetation cover is at its lowest and wind speeds are greatest (Woodhead *op. cit.*). Some soil is transported by "dust devils" but most wind erosion is associated with stock movement (FAO. 1960). Small gorges may form where stock routes cross ridge crests, and the overall level of the stock route will be lowered through kicking of soil into the air. This is emphasized at Kisongo for the dry clay soils are particularly susceptible to wind erosion.

*Stream channel erosion* might be expected in such an area as Kisongo where there have been hydrological changes consequent on erosion development. The small scale of the 1961 air photos do not permit measurement of stream channel dimensions so that it is not possible to measure the expected changes in channel width and depth (Leopold *et al.* 1964, p. 451); it is unlikely, however, that sediment yields would be very important.

## Reservoir sedimentation and rates of erosion

The original site survey for Kisongo reservoir, prepared by WD & ID. in 1959 (Fig. 10), was used as a basis for determining subsequent sediment accumulations. Although the dam was originally designed to retain 120 acre-feet (146,000 $m^3$) modifications of the design led to the reduction of the original capacity to 121,000 $m^3$.

The first silt survey was carried out in October 1969. The spillway level was assumed to be 30.00 ft, as indicated on the plan, as no permanent bench mark could be found. Subsequently a bench mark, reduced level 37.10 ft, was set up at the top of the steps leading from the spillway to the embankment. A baseline perpendicular to the embankment was set up, with sections surveyed parallel to the embankment at 50 foot intervals.

At the time of this survey some 7000 $m^2$ of the reservoir were covered by water. Soundings taken from a boat were used to determine water depths, although some errors resulted from imprecise location of the boat at the time of measurement.

A similar method was used in a second survey carried out in October 1971 (Fig. 10). The position of the boat was more accurately located at this time by mooring it with a long nylon line.

For methods of calculating reservoir volumes from the contour maps, see Rapp *et al.* 1972.

## Sedimentation rates and the life length of Kisongo reservoir

The original capacity of Kisongo reservoir in 1960 was 121,000 $m^3$. The results of the two silt surveys indicate a reduction in capacity to 83,600 $m^3$ by 1969 (69.1 % of the original capacity) and to 71,700 $m^3$ by 1971 (59.6 % of the original capacity).

The average annual loss of initial storage capacity during the period 1960—1969 was 3.34 %, but this increased to 4.75 % in the two subsequent years. If this faster rate of sedimentation is maintained, the reservoir will be filled with sediment in a further 12.5 years, although a longer period could be expected as

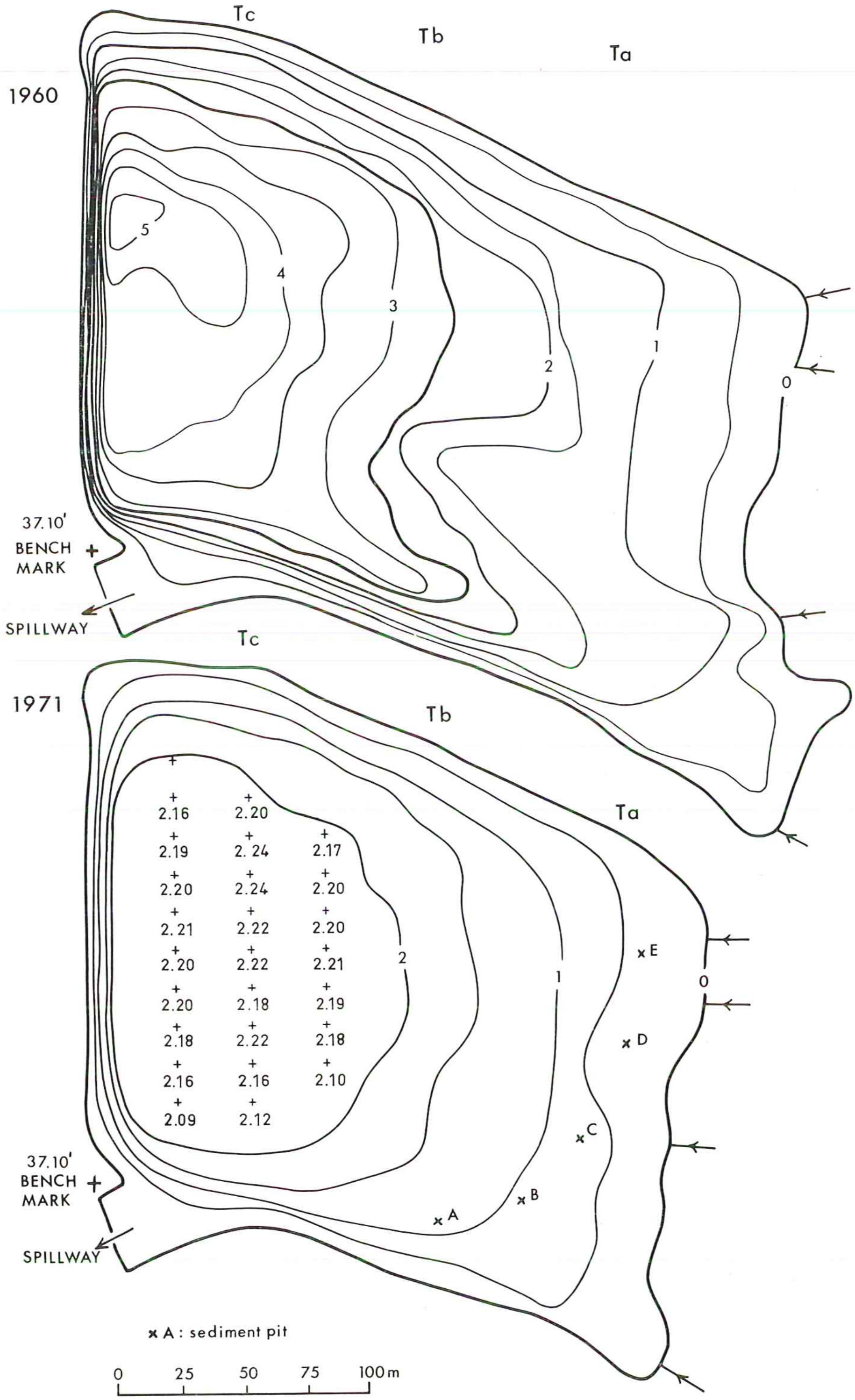


Fig. 10. Bottom surfaces of Kisongo reservoir. Contour interval 0.5 m.
a) Original surface, based on WD & ID plan AR/4865, Kisongo dam, 1959
b) Bottom surface, October 1971. Letters indicate sampling points (see Fig. 17). The topographical irregularities of the original bottom have been smoothed out, with the formation of a flat area in the deepest part.

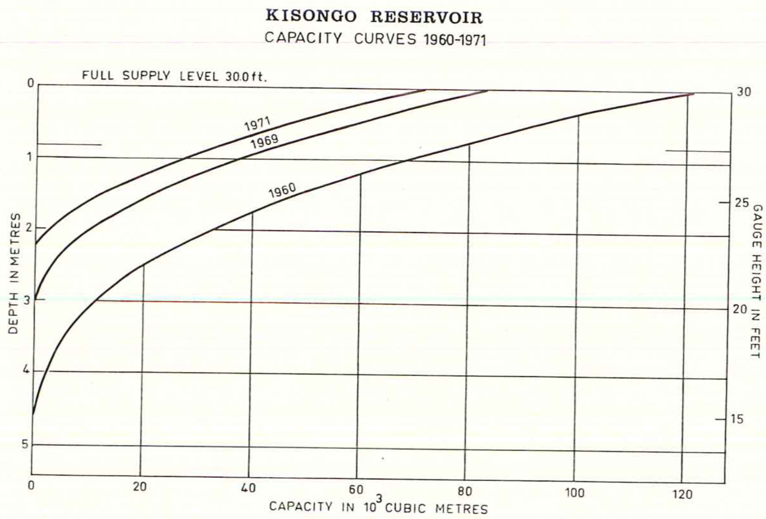


Fig. 11. Capacity curves for Kisongo reservoir, 1960—1971. The line indicating a level 0.8 m below full supply level represents the estimated loss by evaporation during a normal dry season.

decreased capacity may lead to decreased sedimentation (Lewis 1936). There are indications, however, that the sediment supply is increasing, which would be consistent with a gradual reduction in available grazing areas without corresponding reductions in stock numbers.

The economic life (Eakin 1936) of Kisongo reservoir can only be estimated, as there are no records of water use. Some indication of the impending water crisis at Kisongo can be obtained from examination of the capacity-area curves (Fig. 11). With evaporation losses estimated at 0.8 m during a normal 5 month long dry season the available water in 1971 would have been only 34,500 m³ (48 % of the total capacity), and it is clear that the percentage loss of storage to evaporation will increase as sedimentation progresses.

If it is assumed that both sedimentation and water consumption remain constant, then the economic life length of Kisongo is only another 3 or 4 years (Table 3). It is, however, probable that both factors fluctuate annually as a result of rainfall variations and grass supply, and consequently the data in Table 3 can only be regarded as indicative of the overall trend.

The figure for domestic and stock water consumption is based on the WD & ID planning estimates for Arusha Region (Moris, personal communication) which allow 60 m³/day for cattle and 20 m³/day for domestic purposes in a grazing area of 7 km radius. In an average dry season of 150 days the total

Table 3. Reservoir capacities, evaporation losses, water consumption and surplus storage, Kisongo Reservoir, 1960—1975. All figures in m³. Capacities are given at full supply level (F.S.L.). Evaporation losses are calculated for a 5 month dry season. Water use is the volume required for stock and human consumption.

| Year | Capacity at F.S.L. | Evaporation losses | Water use | Total vol. required | Surplus storage |
|---|---|---|---|---|---|
| 1960 | 121,000 | 43,000 | 12,000 | 55,000 | 66,000 |
| 1969 | 83,600 | 37,600 | 12,000 | 49,600 | 34,000 |
| 1971 | 71,700 | 37,200 | 12,000 | 49,200 | 22,500 |
| 1975 | 47,900[1] | 35,900 | 12,000 | 47,900 | nil |

[1] This figure has been estimated on the assumption that sedimentation will continue at the rate calculated for the period 1969—1971. If the rate for the period 1960—1971 is used the surplus storage will not be reduced to zero until 1976.

water consumption will be approximately 12,000 $m^3$.

## Erosion rates in Kisongo catchment

It was hoped that direct measurement of rates of erosion within the catchment could be made in order to compare the relative importance of each erosion process, and to compare these with the rates of reservoir sedimentation. Unfortunately numerous problems were encountered which prevented any useful results from being obtained.

The greatest handicap was the lack of major storms during the latter part of the wet seasons of 1969 and 1970, when little erosion occurred. Problems of instrumentation were also present. Erosion pins were disturbed by stock trampling or stolen by the local people; wooden reference markers were used for firewood. Uncontrollable circumstances prevented any fieldwork in the wet season of 1971, so that numerous storms were missed which might have been recorded. It is clear, however, that precise instrumentation will be a major problem in such a heavily grazed and densely populated environment.

As no actual erosion rates were obtained, no figures are available to qualify the overall sediment yields obtained from the two sediment surveys of Kisongo reservoir carried out in 1969 and 1971. The figures obtained are minimum estimates as no account has been taken of solution load and suspended material lost over the spillway in times of flood, or of the sediments deposited upstream of the full supply level of the reservoir. It is unlikely that losses over the spillway are of significance, but the upstream deposits may total some 10,000 $m^3$. It has not, however, been possible to check this figure as the boundary between the sediments deposited before and after the completion of the reservoir cannot be distinguished.

The total volume of sediment accumulated in the reservoir during the period 1960—1971 is 49,300 $m^3$. With a catchment area of 9.3 $km^2$ this gives a sediment yield of 481 $m^3/km^2$-year, or an overall soil loss in the catchment of 0.481 mm/year. During the period 1969—1971 the sediment yield rose to 640 $m^3/km^2$-year, a soil loss of 0.640 mm/year, assuming that the bulk density of the catchment soils is the same as the reservoir sediments.

The most likely reason for this increased erosion rate is that the extended drought of 1969 (see Table 1) led to favourable conditions for erosion in the following rainy season. The stock routes were more intensely used than in other years, and by October 1969 a layer of unconsolidated material up to 10 cm thick had accumulated on the tracks. This was quickly removed at the start of the rainy season the following month. In addition the severely depleted vegetation cover permitted sheet erosion over an abnormally wide area. The dry conditions probably led to deeper soil cracking, a favourable condition for the development of throughflow.

Although the dry season of 1969 was prolonged, similar conditions can be observed at the end of every dry season. It is probable that the maximum sediment yield will be experienced during the relatively short period between the onset of the rainy season and protection of the soil through vegetation regrowth.

By April 1970 it was clear that no useful results were going to be obtained from direct measurement of different erosion processes, due to theft of markers etc. It was decided therefore to assess the relative importance of each process by other methods.

The first method involved calculations of gully volumes within the catchment, and comparison of the total recorded with the volume of sediment within Kisongo reservoir. Some 300 gullies were measured, about 50 % of all gullies in the catchment, selected randomly throughout the area. The volume was obtained by multiplying length of channel with an average of three cross-sectional areas. The results, presented in Table 4, indicate that gully

Table 4. Estimated gully volumes in Kisongo catchment, April 1970. Lin. = linear gullies, Dendr. = dendritic gullies. The rate of gully erosion is the average for 1960—1970 in $m^3/km^2$ and year.

| Catchment Section | Area ($km^2$) | Gully volumes ($m^3$) | | | Erosion rate |
|---|---|---|---|---|---|
| | | Lin. | Dendr. | Tot. | |
| Northern | 5.76 | 1185 | 665 | 1850 | 32 |
| Central | 1.91 | 1460 | 1395 | 2855 | 149 |
| Southern | 1.63 | 1525 | 930 | 2455 | 151 |
| Total | 9.30 | 4170 | 2990 | 7160 | 77 |

volumes total about 7160 $m^3$, compared with a sediment accumulation by October 1969 of 37,400 $m^3$. Consequently a maximum of 19 % of the accumulated reservoir sediments can be attributed to gully erosion. In reality this percentage should be lower as some gullies measured were in existence before the reservoir was completed. During field measurement the linear and dendritic gullies were distinguished so that the relative importance of stock movement as a cause of erosion could be determined. It can be seen from Table 4 that linear gullies account for a larger proportion of gully volumes than dendritic gullies, although it is likely that there were more dendritic gullies prior to the reservoir construction. It is interesting to note that the volume of the linear gullies increases as the reservoir is approached, supporting the idea that increasing stock movement is likely to lead to increased erosion.

The second approach was to measure the area affected by severe sheet erosion. Stone-capped pillars, grass clumps and exposed roots were used as field evidence of sheet erosion. About one seventh of the catchment is affected severely (Table 5), and this proportion rises to nearly one quarter in the area adjacent to the reservoir.

The third approach was a comparison of grain sizes of samples of top soil and reservoir sediments. The top soil samples were taken from a slope near the reservoir, with determinations of grain size at 0.5 and 10 cm depths, allowing topsoil changes downslope to be differentiated from overall soil changes (Table 6a). The general trend is one of fine material moving downslope with the formation of a coarse residual layer. This is in agreement with field evidence from other parts of the catchment (see above, also Fig. 7). The material reaching the slope foot will be finer than the average soil texture.

The analyses of the reservoir sediments, obtained by hydrometer analysis, are presented in Table 6b. These sediments are finer than most of the soils analysed, but it should be noted that much of the coarse material is deposited upstream of the reservoir. These coarse sediments, estimated at 10,000 $m^3$ are still insufficient to account for the overall deficit of coarse material in the reservoir sediments.

Each of the three approaches lead to the same conclusion. Gully volumes can account for only about 15 % of the reservoir sediments; the remaining 85 % must derive from the other processes described above, as no other alternative sources of sediment are apparent. Neither step erosion, wind erosion nor channel bank erosion are sufficiently serious to merit further attention, implying that sheet erosion is the most important process.

Table 5. Areas suffering from severe sheet erosion, Kisongo catchment, April 1970.

| Section | Area ($km^2$) | Sheet erosion ($km^2$) | Sheet erosion % |
|---|---|---|---|
| Northern | 5.76 | 0.60 | 10.4 |
| Central | 1.91 | 0.36 | 18.8 |
| Southern | 1.63 | 0.40 | 24.4 |
| Total | 9.30 | 1.36 | 14.6 |

Table 6 a. Grain sizes of soil samples from slope near Kisongo Reservoir, April 1970. Analyses by sieve and hydrometer by G. Hellström, WD & ID.

| Site | Depth (cm) | Sand % | Silt % | Clay % | Slope |
|---|---|---|---|---|---|
| Slope | 0,5 | 36 | 24 | 40 | |
| crest | 10 | 23 | 28 | 49 | 1° |
| Upper | 0,5 | 34 | 30 | 36 | |
| slope | 10 | 20 | 26 | 54 | 3° |
| Mid | 0,5 | 15 | 19 | 66 | |
| slope | 10 | 18 | 27 | 55 | 6° |
| Lower | 0,5 | 20 | 16 | 64 | |
| slope | 10 | 26 | 17 | 57 | 4° |
| Slope | 0,5 | 12 | 12 | 76 | |
| foot | 10 | 21 | 16 | 63 | 2° |

Table 6 b. Sediment samples from Kisongo Reservoir, October 1969. Analyses by sieve and hydrometer by G. Hellström, WD & ID.

| Site | Sand % | Silt % | Clay % |
|---|---|---|---|
| Delta Area | 8 | 50 | 42 |
| Mid Reservoir | 1 | 40 | 59 |
| Deepest Sediments | 1 | 29 | 70 |

## Sedimentation processes

The lack of coarse material in the reservoir is reflected by the long profiles of the various surveys. The initial long profile (Fig. 12) has been constructed from the final plans, but is misleading insofar as minor irregularities in the bottom topography may appear as major sedimentary features. Consequently a second long profile was constructed using the average depth of each cross-section (Fig. 13). This gives a more reliable indication of the various sedimentary environments. Both the long profiles and the selected cross-sections (Fig. 14) indicate that sediment depth is closely related to water depth, and further analysis of the 1969—1971 sediments indicate that this relation is well defined when water depths exceed 2.40 m (Fig. 15).

In order to study further the various sedimentary processes a series of sediment pits was dug. These pits revealed a series of sedimentary layers similar to glacial varves (Fig. 16). Each successive discharge into the reservoir transports a certain amount of coarse material, deposited on the surface of the existing sediments. Between inflows fine grained material in suspension settles out in thin graded beds separating the coarse layers. The suspended material will continue to settle out in the dry season, resulting in a thicker layer of fine material; the thickness of this layer depends on the length of dry season submergence and the intensity of reworking of sediment by

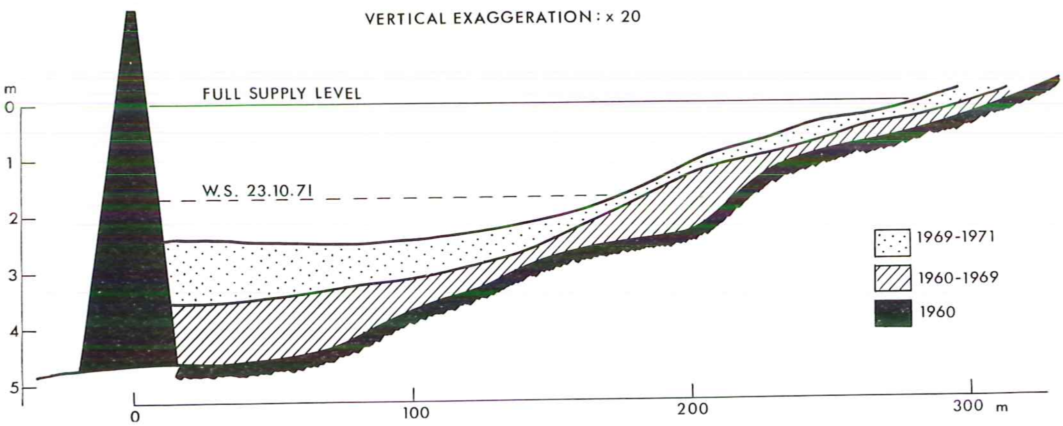


Fig. 12. Long profiles of Kisongo reservoir, 1960—1971. The lack of deltaic growth is noteworthy.

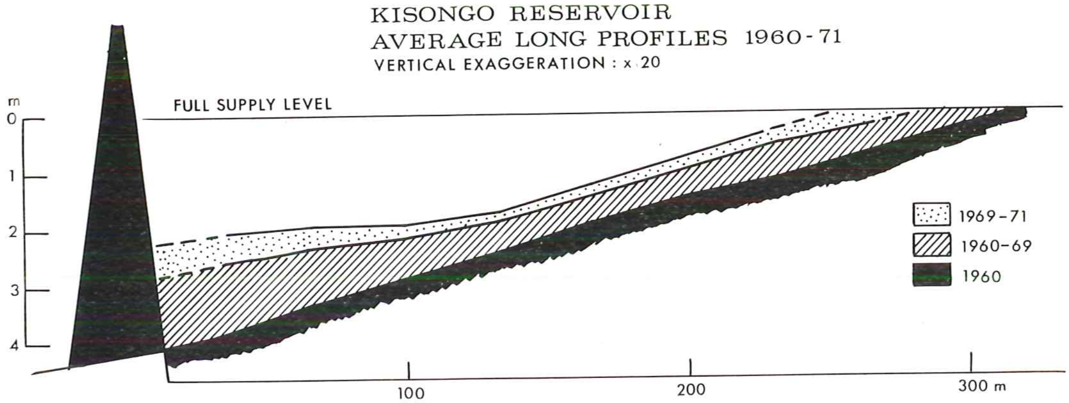


Fig. 13. Average long profiles, 1960—1971. The average depth of water in each surveyed cross-section reduces the effects of local sedimentation in old channels (see Fig. 12), giving a clearer view of the various sedimentary zones.

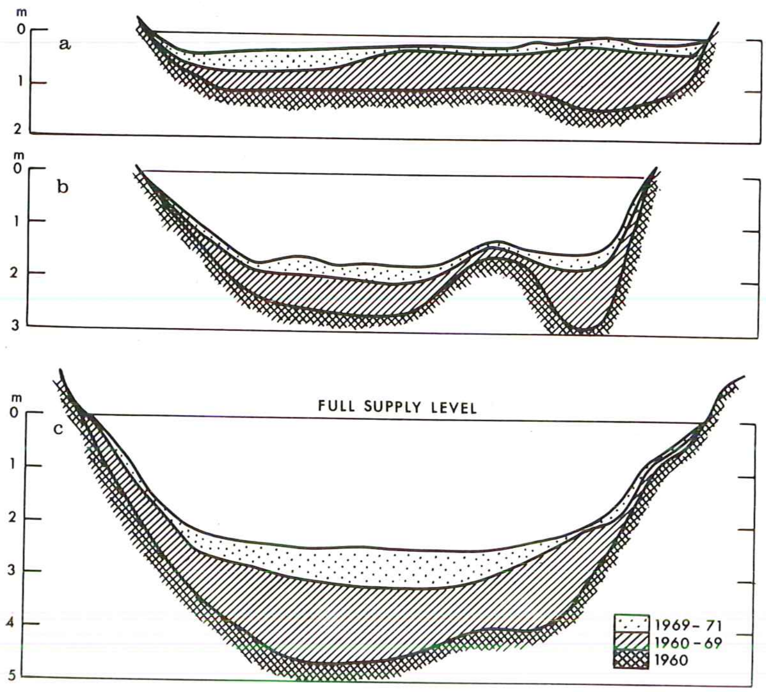


Fig. 14. Selected cross-sections, 1960—1971.
a) 225 m,
b) 150 m,
c) 75 m upstream of the dam.

wave action.

It was hoped that a stratigraphical history of the reservoir sediments could be built up by studying various sediment sections (Fig. 17), but there was no opportunity available to carry out a systematic sampling procedure at various times throughout the dry season so that the sediments could be preserved before cracking through exposure at the surface.

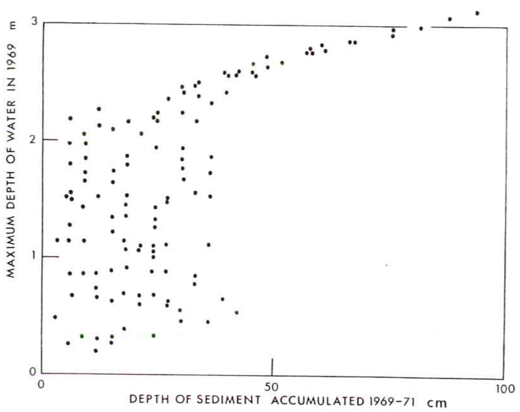


Fig. 15. Relationship between water depth and sedimentation, 1969—1971. The relationship above 2.40 m is obscured by slight deltaic accumulation and re-working of sediments by wave action during the dry season.

## Geomorphological conclusions

Kisongo catchment affords a clear example of soil erosion developing as a result of anthropogenic causes, with the formation of two separate erosion systems. The more spectacular is associated with stock movement, when constant trampling and grazing cause the formation of bare strips. These strips act as the foci for *linear gully development,* with the drainage pattern largely predetermined by the surviving vegetation. The growth of linear gullies is rapid, up to 25 m/year, but cross-sectional areas seldom exceed 4 $m^2$.

*Dendritic gully patterns* develop on over-grazed areas. Gullies of this type develop more slowly, and are generally shorter, than the linear gullies, although their cross-sections may exceed 10 $m^2$. Overgrazing followed by severe *sheet erosion* is a prerequisite of most dendritic gully patterns.

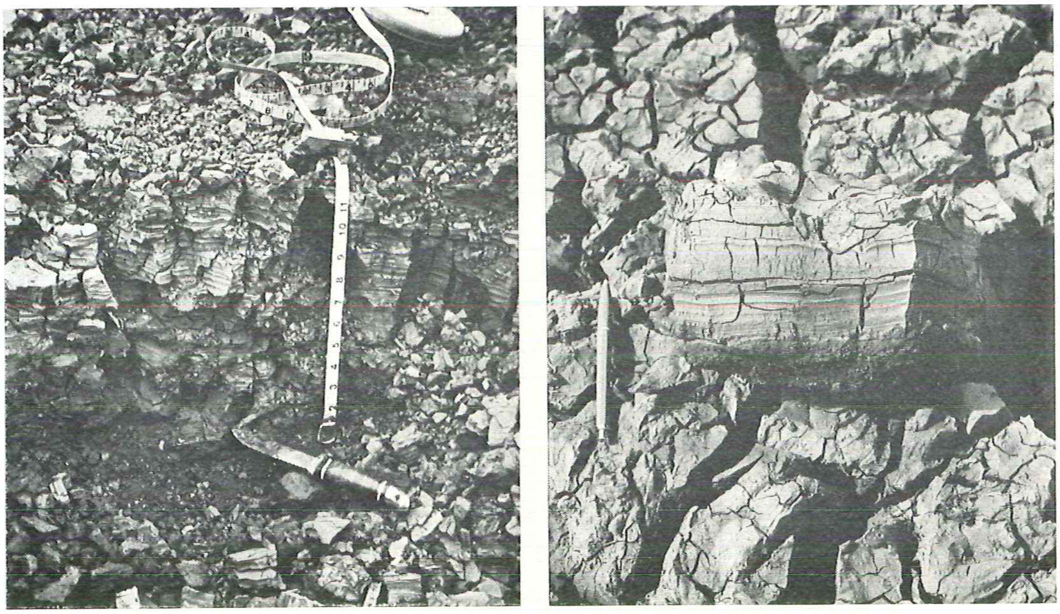

Fig. 16. Layered, clayey sediments, Kisongo reservoir. Photo a, left. The dry upper sediments are heavily cracked, but show clearly the micro-layers representing individual flows. The wetter sediments beneath do not exhibit these layers so clearly. (Photo HMR 10/69).

Photo b, right. To the right of the pen is a block of 1971 sediment, from pit E (Fig. 17). The pen is resting on cracked surface of dry reservoir bottom. Note on the clayey block the dark, crumbly layer of 1970 dry season's cracking and above that 7—8 storm layers of the 1971 sediments. (Photo AR 10/71).

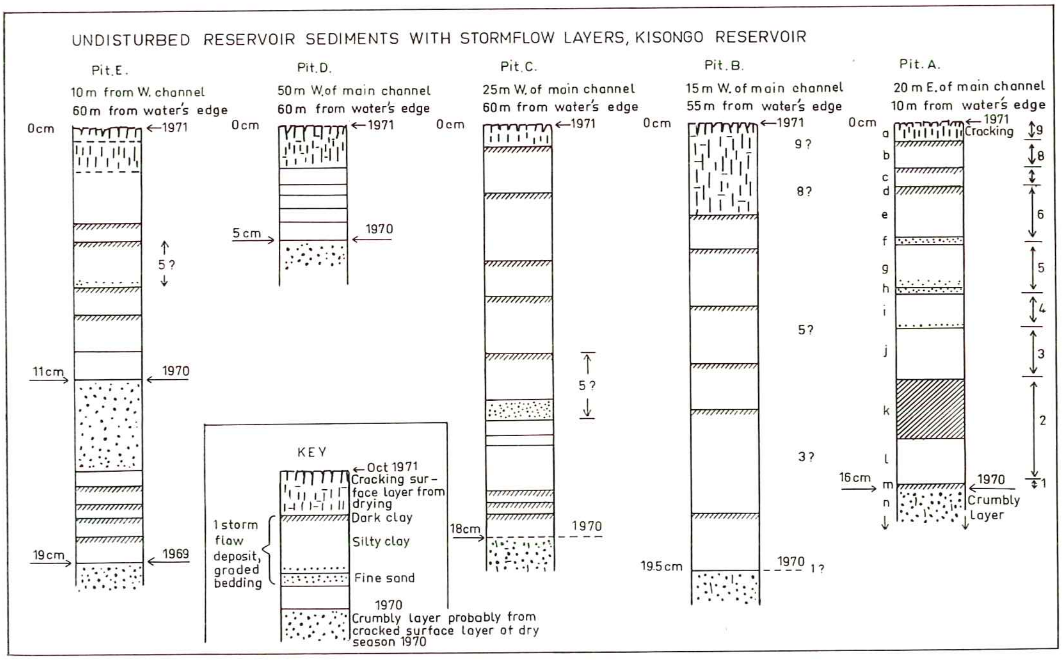


Fig. 17. Vertical sections of sediments from Kisongo, October 1971. Sampling points are located on Fig. 10. Surface of 1970 dry season identified as top of crumbly layer. The accumulation of 1971 in pits A to E is 5—19.5 cm thick. An attempt to identify 9 separate storm layers was made in pit A (nrs. 1—9).

The overall erosion rates, determined by calculations of volumes of sediment accumulation in Kisongo reservoir, vary between 481 and 640 $m^3/km^2$ year. These variations are probably a reflection of variations in sediment yield in response to variations in rainfall and grazing intensity.

Attempts to determine the relative importance of each erosion type through direct measurement of erosion types failed due to problems with instrumentation. Calculations of gully volumes in 1970 show that less than 19 % of the reservoir sediments can be attributed to gullying. Grain size analyses and measurement of areas affected by sheetwash both support the contention that sheet erosion is the major source of sediment.

Most of the sediments in Kisongo reservoir are fine grained, with little evidence of deltaic sedimentation. Individual storm flows lead to the formation of varve-like structures which could be used to determine annual sediment accumulations.

## Economic implications

Accelerated soil erosion in the Kisongo area developed as a result of changing land use in the 1950's. This erosion has been intensified in the vicinity of Kisongo reservoir as stock numbers rose in response to the new water supply. The consequent increase in pressure on available grazing has led to a progressive increase in the severely eroded area. A second effect of the reservoir has been the formation of a new set of stock routes leading to the cattle troughs, with related erosional problems.

Both these responses have led to a reduction in the area of available grazing land in Kisongo catchment. The initial effect of the water supply was to increase grazing capacities through the elimination of stock deaths from drought. When the water supply begins to dry up within the next 3 or 4 years the carrying capacity will drop to a lower level than before the reservoir was completed, due to the drop in available grazing areas.

Kisongo is a prime example of the need for integrated planning in rural development. Provision of water supply alone does not guarantee development, and may in the long run lower the economic potential of the surrounding areas.

## Acknowledgements

I am deeply indebted to Anders Rapp for his role in helping me complete this study. Since his guidance in selecting a suitable field area, he has been a constant source of ideas. From January 1971 he has provided considerable financial assistance, both in Tanzania and in Uppsala, from the Tercentenary Fund of the Bank of Sweden.

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*Mr. D. Hammond Murray-Rust, Department of Geology and Geography, City of London Polytechnic, London EC 3, England.*

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# THE RUFIJI RIVER, TANZANIA HYDROLOGY AND SEDIMENT TRANSPORT

BY PAUL H. TEMPLE AND ÅKE SUNDBORG

Department of Geography, University of Dar es Salaam and
Department of Physical Geography, University of Uppsala

ABSTRACT Sediment transport by large tropical rivers has generally not received adequate study due to deficiencies in recorded data on discharge and sediment load. This paper is a case study of sediment transport in the Rufiji river, which drains a varied catchment of 156,600 km$^2$, and is the largest river in Tanzania.

Data on suspended sediment load spans the period 1955/56 to 1961/62, while discharge data covers the period 1954/55 through 1969/70. During this period, daily discharges ranged between 6637 m$^3$/sec and 69 m$^3$/sec. Floods with a discharge of 5000 m$^3$/sec have a return period of approximately 5 years. Suspended sediment load data fortunately covers the extremes of the river record as well as more normal conditions. Suspended sediment load data indicates a maximum daily transport of approximately 1,000,000 tons during the investigated period. Sediment-rating-curve and duration-curve analyses indicate that some 250—300 mill. tons of suspended sediment have passed through Stiegler's gorge in the 16 years covered by discharge records. To this figure should be added the bed load transport and probably also a certain increase due to inaccuracy in the sampling and analysis procedures.

Heaviest loads of sediment are related to sudden flash floods in the rising limb of the annual hydrograph. The suspended sediment peaks are out of phase with the flood peaks, indicating an early annual flushing of sediment from the system with the onset of the flood season. The sources of this sediment and the characteristics of the tributary basins in terms of relief, geology, seasonal rainfall regimes, and vegetation are discussed.

Geomorphological and economic implications are discussed in general but will be covered more fully in a later report.

## Introduction

The erosional and depositional processes in the downstream part of a river are intimately connected with the geomorphological processes in the headwater areas. Heavy soil erosion in the upper part of the catchment may add considerably to the total sediment yield and radically increase the morphological activity within the lower part of the river. The building of hydroelectric power plants, the creation of big reservoirs and other artificial measures may, on the other hand, decrease the sediment load and completely change the depositional environment of the lower flood plain and delta. A river must be regarded as a compound unit, in which the small scale features are integrated parts of a single dynamic system.

The research described in this volume is mostly concerned with erosion and sedimentation processes at the erosion plot scale and within small to medium sized catchments. This report by contrast describes the hydrology and sediment yield of the largest river of Tanzania.

The Rufiji river is currently being developed for hydroelectric power. The Kidatu dam on the Great Ruaha will be completed in 1974. A further dam is planned at Mtera, upstream from Kidatu, while a decision has yet to be finalized on the largest scheme of all—the construction of a dam and power station at Stiegler's gorge with a firm capacity of the order of 500 mw.

Such dams and reservoirs will act as sediment traps for all material transported as bed load and for much or most of the suspended load. Other studies in this volume have highlighted the problem of sedimentation in small reservoirs for urban water supply, irrigation, and livestock. This study focusses upon the problems of changing flow and sediment regimes relevant to large dams and reservoirs in big rivers.

The main purpose of the Rufiji investigations is to study the water and sediment discharge characteristics of the river and their influence on the morphology and soils of the lower flood plain and delta. This paper presents a short analysis of the available data on hydrology and sediment load; the flood plain and delta will hopefully be the subject of a later article.

The recent availability of new topographic maps, excellent semi-controlled mosaics at a scale of 1 : 50,000 and air-photographs at a scale of 1 : 40,000, together with less complete data on water discharge, suspended sediment concentration and geology has provided good basic information for this study, which should not however be looked upon as a completed



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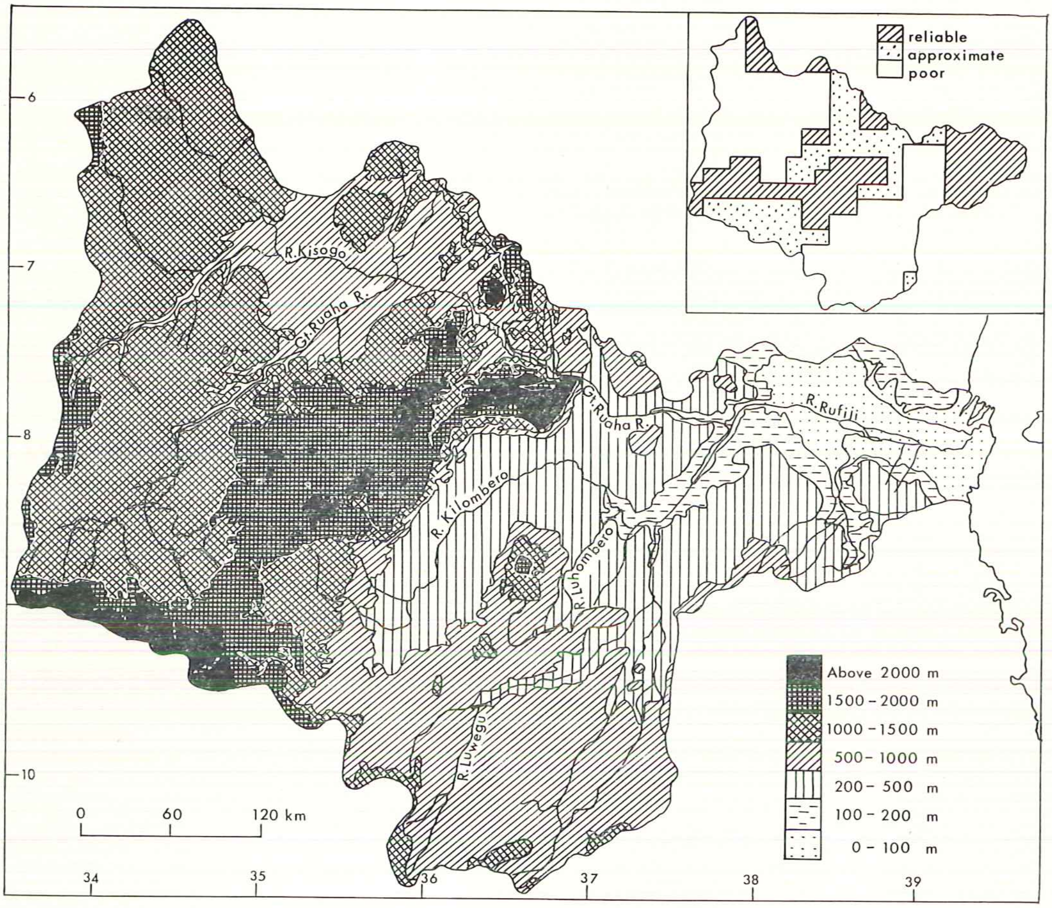


Fig. 1 The topography of the Rufiji basin: inset map indicates the reliability of the topographic information.

Table 1. Area-altitude analysis of the Rufiji basin and its principal components; areas in km², altitudes in m. Data from 1:1,000,000 sheets.

| Altitude interval | 0–100 | 100–200 | 200–500 | 500–1000 | 1000–1500 | 1500–2000 | 2000–2500 | >2500 | Total |
|---|---|---|---|---|---|---|---|---|---|
| Great Ruaha above | — | — | — | 11,300 | 43,156 | 11,085 | 2235 | 187 | 67,963 |
| Mtera; IKA 5 | | | | 16.6 | 63.5 | 16.3 | 3.3 | 0.3 | 100 % |
| Great Ruaha above | — | — | 327 | 14,518 | 47,298 | 13,854 | 3202 | 219 | 79,418 |
| Kidatu; IKA 3 | | | 0.4 | 18.3 | 59.6 | 17.4 | 4.0 | 0.3 | 100 % |
| Kilombero above | — | — | 11,664 | 7,619 | 5,686 | 5,616 | 1114 | 11 | 31,710 |
| Swero; IKB 17 | | | 36.8 | 24.0 | 17.9 | 17.7 | 3.5 | 0.1 | 100 % |
| Luhombero catchment | — | 60 | 1,843 | 1,801 | 251 | 21 | — | — | 3,976 |
| | | 1.5 | 46.4 | 45.3 | 6.3 | 0.5 | | | 100 % |
| Luwegu catchment | — | 83 | 5,067 | 21,047 | 658 | — | — | — | 26,855 |
| | | 0.3 | 18.9 | 78.4 | 2.4 | | | | 100 % |
| Rufiji above Stiegler's | 201 | 2836 | 28,518 | 47,104 | 53,913 | 19,491 | 4316 | 230 | 156,609 |
| gorge & Pangani | 0.1 | 1.8 | 18.2 | 30.1 | 34.4 | 12.5 | 2.8 | 0.1 | 100 % |
| rapids; IK 3 & IK 3A | | | | | | | | | |
| Total Rufiji catchment | 8277 | 7284 | 33,683 | 47,652 | 53,913 | 19,491 | 4316 | 230 | 174,846 |
| | 4.7 | 4.2 | 19.3 | 27.3 | 30.8 | 11.1 | 2.5 | 0.1 | 100 % |

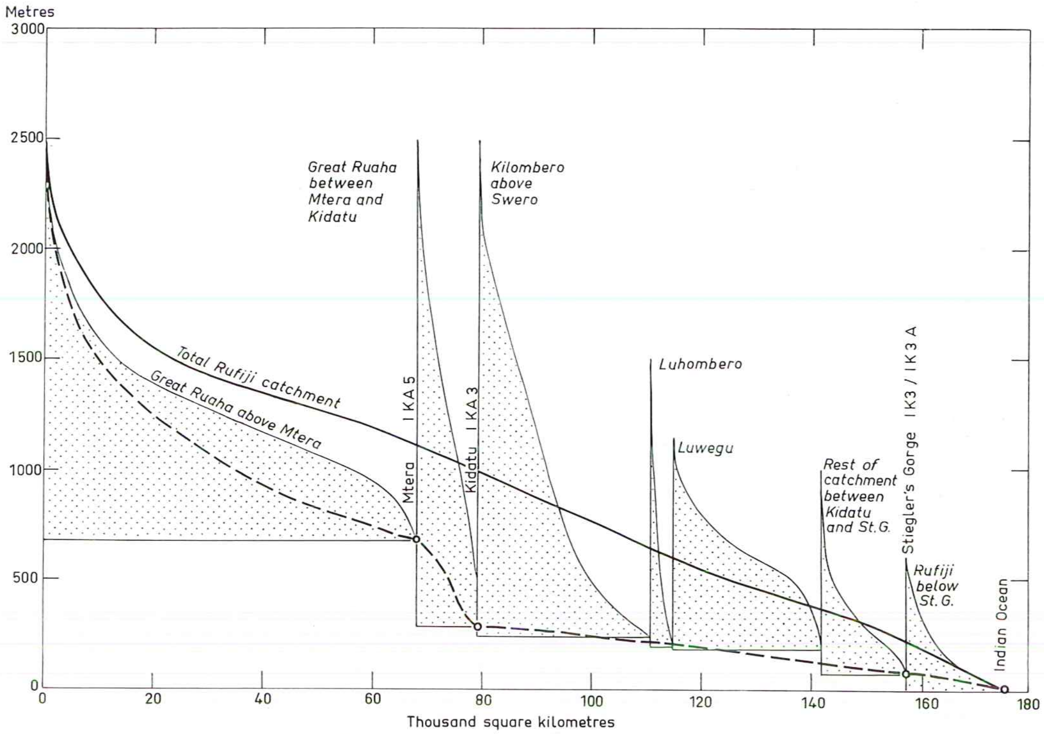


Fig. 2 Hypsographic analysis of the Rufiji basin showing the hypsographic curve of the total catchment, a curve showing area—elevation relationships along the main thalweg and hypsographic curves for major catchment units in sequence.

project. It is mainly a reprocessing and re-evaluation of previously existing data and a preliminary report of present results. Further studies within an integrated multipurpose research project should be given high priority in a development plan for the region.

## THE RUFIJI BASIN

### Relief and geology

The Rufiji catchment is the largest river basin in Tanzania. The river drains a basin of 174,800 km$^2$. Upstream of the major hydrological station at Stiegler's gorge (station 1 K3) it has an area of 156,600 km$^2$.

Within this extensive catchment there are wide contrasts of relief, slope, lithology, climatic conditions, vegetation, and land use. The identification of major controls on sediment yield from this catchment can thus only be attempted in general terms, and in relation to the broad characteristics of the component drainage basins.

Fig. 1 shows the outline and gross topography of the Rufiji basin. Parts of this map, as the inset shows, are based on detailed mapping, but large areas are illsurveyed and unmapped. The basin has a maximum latitudinal extent of 625 km around 8°S and a maximum meridional extent of 485 km around 36°E.

The river is known as the Rufiji only in its downstream section below the confluence of the rivers Kilombero and Luwegu at Shuguri falls. The Rufiji collects water from three principal subcatchments: (a) the Kilombero river system; (b) the Great Ruaha river system and (c) the Luwegu-Luhombero rivers. These components show considerable variation in run-off characteristics.



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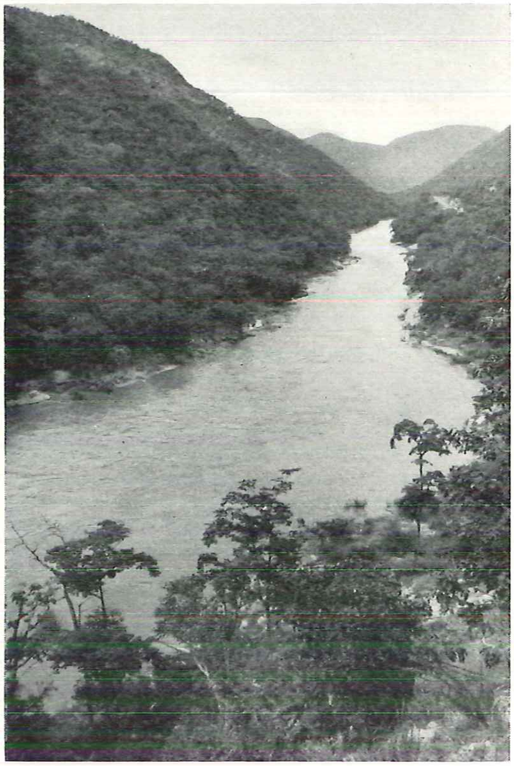

Fig. 3 View of the gorge section of the Great Ruaha river in the Kiberege mountains, 8 km upstream of gauging station 1 KA 61. Photo P. H. Temple, Dec. 1972.

Table 1 presents data on the area-altitude relationships within the Rufiji basin and its principal components. These data form the basis of the hypsographic analysis shown in Fig. 2. The solid line in Fig. 2 indicates the normal hypsographic curve for the whole catchment, indicating the small area of the basin below 200 m a.s.l. (c. 9 per cent) and the contrasting great extent of intermediate or plateau elevations between 500 and 1500 m (almost 60 per cent).

From a hydrological viewpoint, the dashed line, showing the relation between area increase and river elevation along the main thalweg is more significant. This curve is obviously compounded of three distinct sections: (1) a characteristic upper section above Mtera, concave-upwards, representing the limited but high mountain rim of the Great Ruaha basin and the dominance of plateau levels between 800 and 1200 m; (2) the sudden sharp break between Mtera and Kidatu, representing the antecedent gorge section of the river through the Rubeho and Kiberege mountains (Fig. 3); (3) the flat, slightly convex, lowest section of major confluences above Stiegler's gorge and the abrupt descent to the lower flood plain.

Along this dashed line, graphs in sequence present diagrammatically the contrasted hypsographic characteristics of the major subcatchments. The curves for the Great Ruaha catchment between Mtera and Kidatu, for the Luhombero and Luwegu are of particular significance. Both the Mtera-Kidatu and the Luhombero graphs indicate a large elevation range associated with a rather limited catchment area, in great contrast to the graph of the Great Ruaha catchment above Mtera. Other factors being equal, this suggests that these subcatchments may be prone to rapid discharge fluctuations (see below). The Luwegu curve presents a further contrast, with rather limited elevational contrasts; the basin is dominantly a plateau with extensive areas of intermediate elevation linked to the main river rather far down its course. Other characteristics, eg. thalweg gradient, of this particular catchment function to exaggerate its influence on total Rufiji discharge (see below).

The Kilombero hypsograph is more normal. Although there is a considerable elevation range in the catchment, the river basin is extensive in its lower section, as the smooth concavity of the lower part of the curve indicates. This area exerts a severe damping effect on the river discharge, particularly significant because of its major contribution to total flow in the main river.

Most of the plateau and mountain sections of the catchment are underlain by gneissic and schistose metamorphic rocks, but several major structural depressions, such as the Usangu flats, the Great Ruaha basin above Mtera and the Kilombero trough, form extensive areas of alluvium. The southeastern section of the basin, the Luwegu catchment, and the Stiegler's gorge section are underlain by arenaceous stratified rocks mainly of Karroo age. Details of the geology of the basin with particular reference to proposed dam sites are provided by Haldemann (1962) and thus not reviewed here.

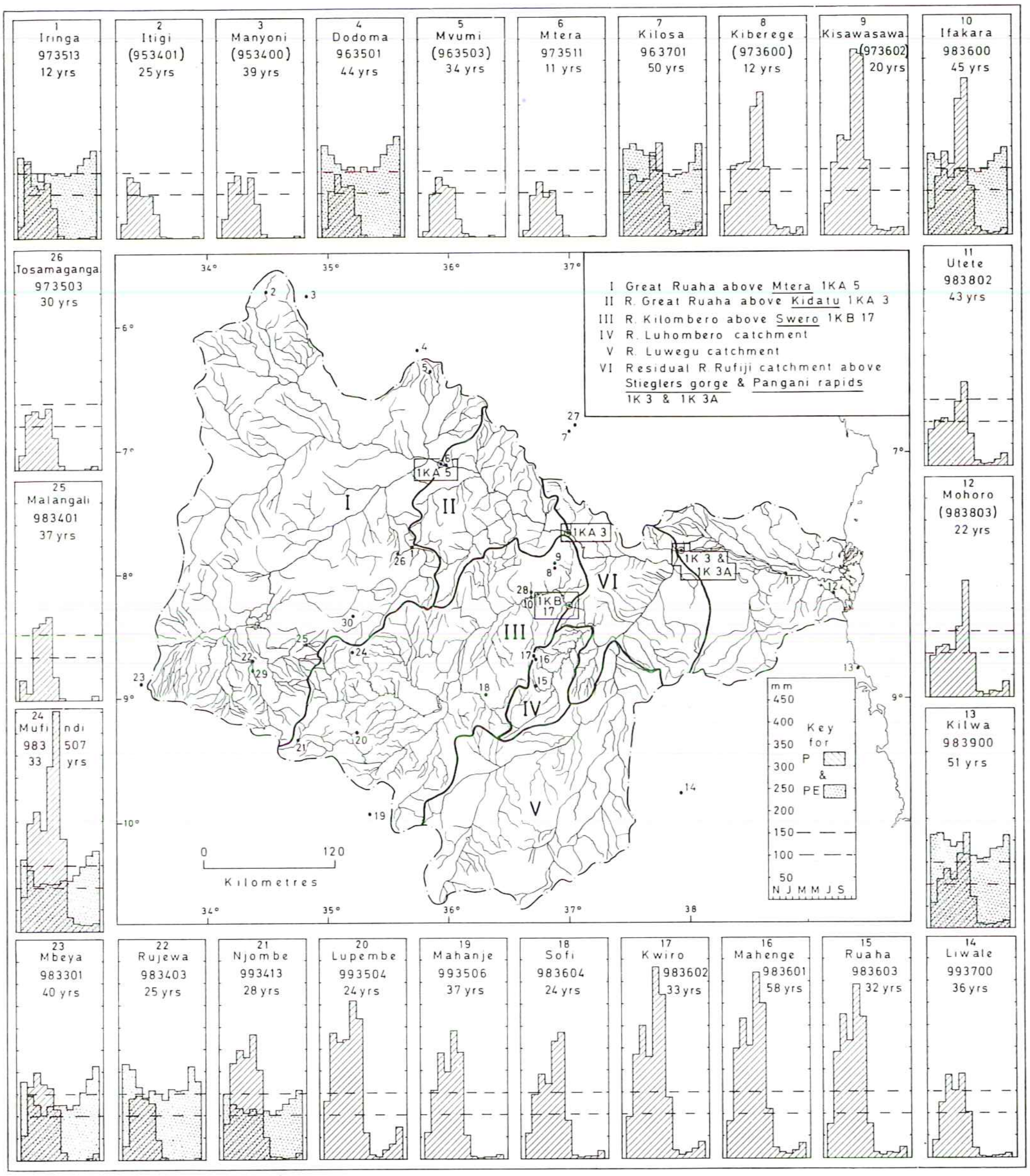


Fig. 4 Drainage network of the Rufiji basin, showing the locations of the main gauging and rainfall stations. Bar graphs show average monthly rainfall (P) and potential evaporation (PE) where data are available (see text). Closed stations bracketed.

## Hydrometeorology and vegetation

Fig. 4 shows the drainage network and watersheds of the Rufiji catchment and the location of gauging stations discussed. Bar graphs show the average monthly rainfalls for 26 selected precipitation stations within or closely peripheral to the basin. Potential evaporation data are also given for some stations (P. W. Porter, personal communication).

It will be seen from Fig. 4 that the meteorological network is not adequate to give more than a schematic overview of conditions in

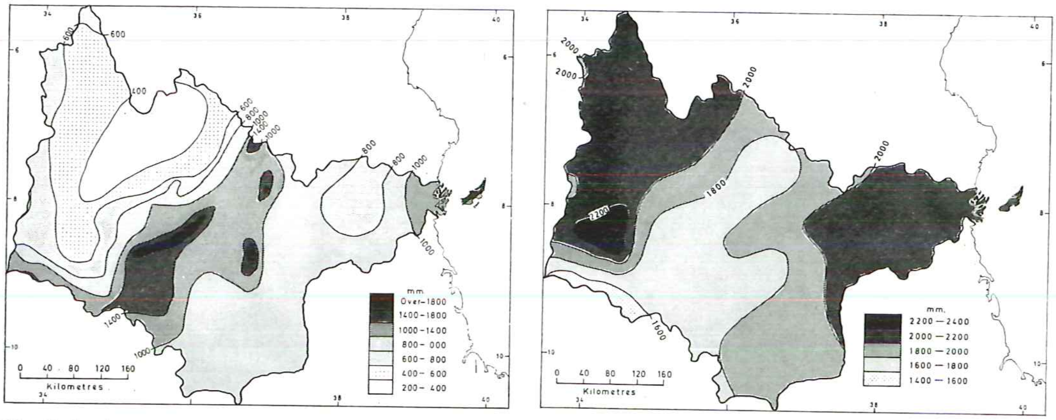


Fig. 5 A. Average annual rainfall over the Rufiji basin (to the left).

B. Average annual potential evaporation (Penman $E_0$) from open water over the Rufiji basin after Woodhead, 1968 (to the right).

some sections of the basin, particularly the southeastern part. In Figs. 5A and 5B schematic general maps of the distribution of precipitation and potential evaporation are presented, the latter according to Woodhead (1968).

Over the southeastern area the rainfall pattern appears uniform and precipitation varies between 800 and 1000 mm annually. The high-rainfall areas extend diagonally across the catchment in association with the mountainous zones. Here precipitation averages over 1000 mm and rises over significant areas to above 1400 mm. The Kilombero trough also receives over 1000 mm annually. Inland of this well-watered area, the interior plateau is dry, large areas being very dry and receiving less than 500 mm annually.

Over large areas potential evaporation (computed by Woodhead for open water surfaces according to the Penman formula) exceeds precipitation supply in every month of the year on average. In fact only the zones of greater elevation and reduced potential evaporation, the Rubeho and Mahenge mountains and the west-facing Southern Highland escarpments, are major zones of mean annual water surplus.

More significant for the analysis of hydrological characteristics and sediment transportation is the seasonal distribution of rainfall. The bulk of the catchment above Mtera normally has rains between December and March. The southern part of this area, excepting the small mountainous rim in the extreme south, has 4 months with over 150 mm on average. The rest of the catchment has a similar number and distribution of rainy months but rainfall amounts decrease northward. The plateau areas east of the Mbarika and Mahenge mountains, primarily the Luhombero and Luwegu basins, have a similar rainy season, starting in December but extending through April. Most of this region experiences on average 3 months with over 150 mm.

The Kilombero and the Great Ruaha catchment between Kidatu and Mtera show a different pattern: over this area the rainy season is longer by a month, extending from December through May with, over a large section of the Kilombero catchment, 5 months with over 150 mm on average.

Fig. 6 shows the vegetation of the catchment according to data by Gillman (1949).

Forty per cent of the total Rufiji catchment is woodland and a further 32 per cent either intermediate between woodland and bush or wooded grassland. There are striking contrasts between the vegetation of different parts of the catchment. Deciduous woodland, bush, and wooded grassland offer limited protection against soil erosion at the onset of the rains, before a leaf cover is developed: if such vegetation mantles easily erodible sedimentary rocks or steep slopes, as it does over 63 per cent of the Luwegu catchment, sediment yield may be large. Forest and swamp distribution is also significant in reducing rapid runoff and decreasing sediment transport. This is partic-

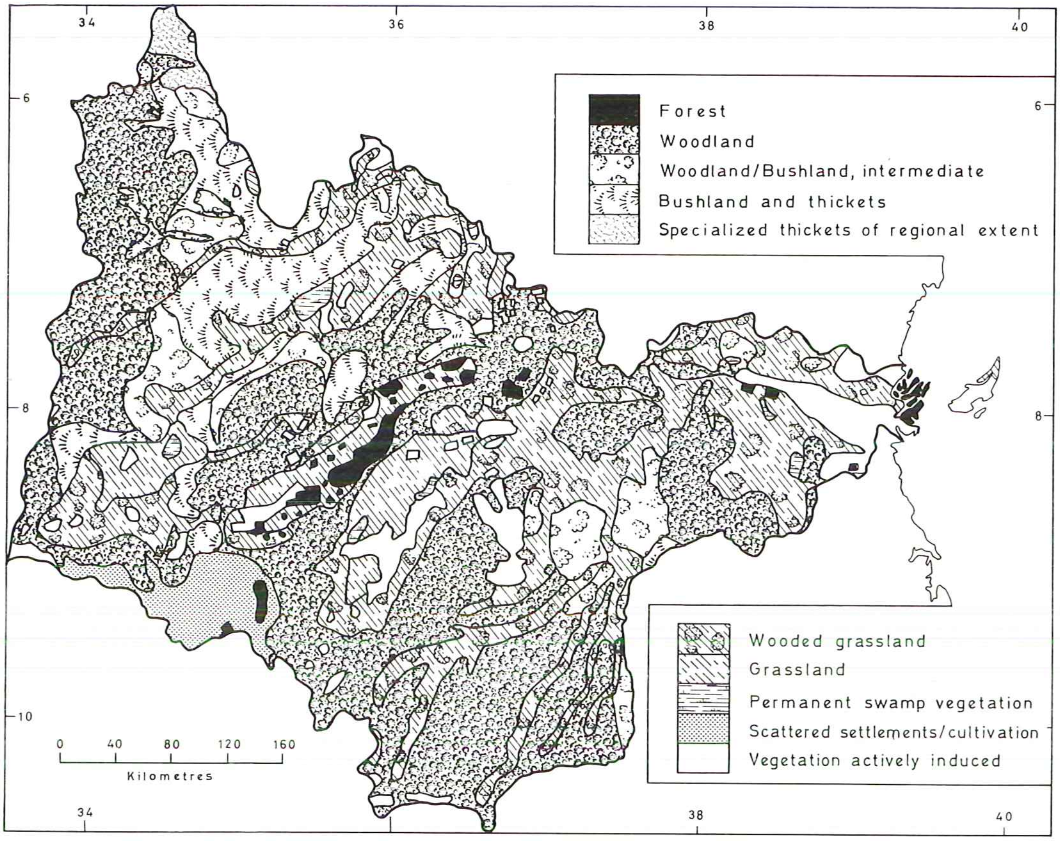


Fig. 6 Vegetation of the Rufiji basin (modified after Gillman, 1949).

ularly true of the Kilombero catchment. The poor cover of much of the interior plateau of the Great Ruaha above Mtera should be noted, sections of it in the north being thorn thicket, though the majority is under woodland and bush.

## The Rufiji river system

In terms of total flow contribution, the Kilombero river is the principal tributary of the Rufiji, accounting on average for over half its discharge though draining only one fifth of the total catchment. The Kilombero headwaters drain the wellwatered east-facing escarpment of the Southern Highlands but these streams discharge into the flat trough of the middle Kilombero valley where flow is regulated before the junction with the Luhombero and Luwegu.

The Luhombero drains a much smaller catchment, 13 per cent of that of the Kilombero, but discharges the runoff from the seaward-facing slopes of the Mahenge mountains over steep gradients into the lower Kilombero and is unreliably gauged, even over a limited period.

The Luwegu river drains the southeastern part of the Rufiji catchment and contributes approximately one fifth of the Rufiji discharge: as the river is not gauged, this value is an estimate. The Luwegu catchment, though not high, is hilly and the river thalweg is considerably steeper than that of the Kilombero and Great Ruaha. It is argued in this paper that the discharge of the Luwegu is generally of critical importance for the understanding of the flood hydrograph and sediment transport at Stiegler's gorge.

The major area, 47 per cent, of the Rufiji basin is drained by the Great Ruaha river system: but its average contribution to the Rufiji discharge is only approximately 13 per

Fig. 7 Aerial view of Stiegler's gorge between Pangani rapids (1 K3 A) and station 1 K3: river flow right to left. Photo P. H. Temple, April 1972.

cent. Although the river rises in the Poroto and Kipengere mountains at elevations close to 3000 m, most of the runoff from this area is lost by flooding and evaporation in the swamps of the Usangu plains. Other important headwaters drain the western flanks of the Southern Highlands but again their waters are largely dissipated in swamps below the junction of the principal tributary (the Little Ruaha river) with the main river. These swamp areas reduce potential discharge and damp flood peaks from the tributaries. The main Great Ruaha catchment is a dry plateau characterized by low and seasonally intermittent drainage. But the river moves this seasonally fluctuating water volume through a mountainous and well-watered catchment area between Mtera and Kidatu (Fig. 1), which in some years produces heavy flash runoff.

The Great Ruaha river joins the Rufiji 24 km upstream of Stiegler's gorge. In Stiegler's gorge the river falls approximately 35 m in 16 km through a deep (80 m) and narrow canyon (Fig. 7). At the outlet of the gorge the river enters its flood plain some 160 km from the ocean.

## HYDROLOGY OF THE RUFIJI RIVER

### Hydrological stations and available data

A comprehensive statement of the existing gauging network and available hydrological data are given in a separate technical report (Temple and Sundborg 1973). Therefore only a brief summary is presented here.

Fig. 4 shows the Rufiji basin and the hydrological stations used for this analysis. The nature of these stations is set out in the above-mentioned report. Only selected stations have been examined in our analysis.

It will be seen from Fig. 4 that a major section of the basin drained by the Luwegu and Luhombero rivers is not properly monitored.

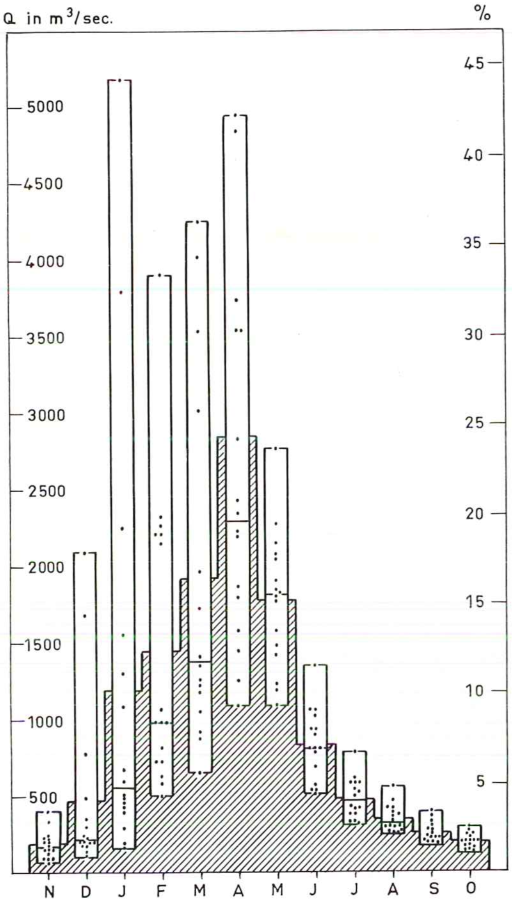


Fig. 8 Dispersion graphs of mean discharge values by month (m³/sec.) for the Rufiji river at stations 1 K3 and 1 K3 A for the 16-year period 1954/55 to 1969/70. Mean monthly discharge shaded with percentage scale to the right.

This lack of data on 20 per cent of the catchment and two important tributaries of the main river represents a serious data gap. Some data exist on the river Luhombero but the rating curve is unreliable.

An FAO report (Otnes, 1960) on the Rufiji basin presented a detailed description and analysis of available hydrological data for a 5 year period. Data on water discharge presented and discussed in this article represent an additional 11 year period over and above the data available to the FAO team. Together with the FAO data the records cover a period of 16 years. While 16 years of record for a major tropical river are not adequate for a proper discussion of its flow characteristics, it was considered valuable to process the data at this time because they might render some additional information useful as a basis for scientific discussions and planning decisions.

The most important hydrological stations for the discussions in this paper are those at Stiegler's gorge (Station 1 K3) and at Pangani rapids (Station 1 K3A), which is some 8.5 km upstream of Stiegler's gorge. The Stiegler's gorge station was established in October 1954. Since the establishment of the Pangani rapids station in December 1959 at a more stable control, Stiegler's gorge has been used mainly for gauging, while water levels are recorded at Pangani rapids. In this analysis, the stations are regarded as practically identical, catchment size difference being 200 km² or only about 0.1 % of the basin area.

## Main hydrological characteristics

Fig. 8 presents dispersion graphs of mean water discharge values by month for the Rufiji river at Stations 1 K3 and 1 K3 A for the total recorded period. The shaded columns behind the dispersion graphs in Fig. 8 show the mean monthly discharge values.

Average daily discharge is highest in April and lowest in November. On average, as Fig. 8 shows, the April discharge accounts for nearly 25 per cent of the annual total compared to 2 per cent in November.

The maximum value for mean monthly discharge was recorded in January 1961 (5173 m³/sec) and the minimum in November 1959 (76 m³/sec). The dispersion graphs indicate that, over the recorded period, the month of January was subject to by far the greatest fluctuations of mean discharge and the month of October to the least. The graphs also indicate that, on average, the months June through November are not subject to floods. The period December through May has experienced high average discharges, in excess of the highest floods of some dry years of the record.

It is apparent from Fig. 8 that the most damaging floods, and, as will be seen below, those responsible for heavy transportation of sediment occur in the period late December to mid-April.

## Annual hydrographs of the Rufiji, Kilombero, and Great Ruaha

Figs. 9A—D present as examples the annual

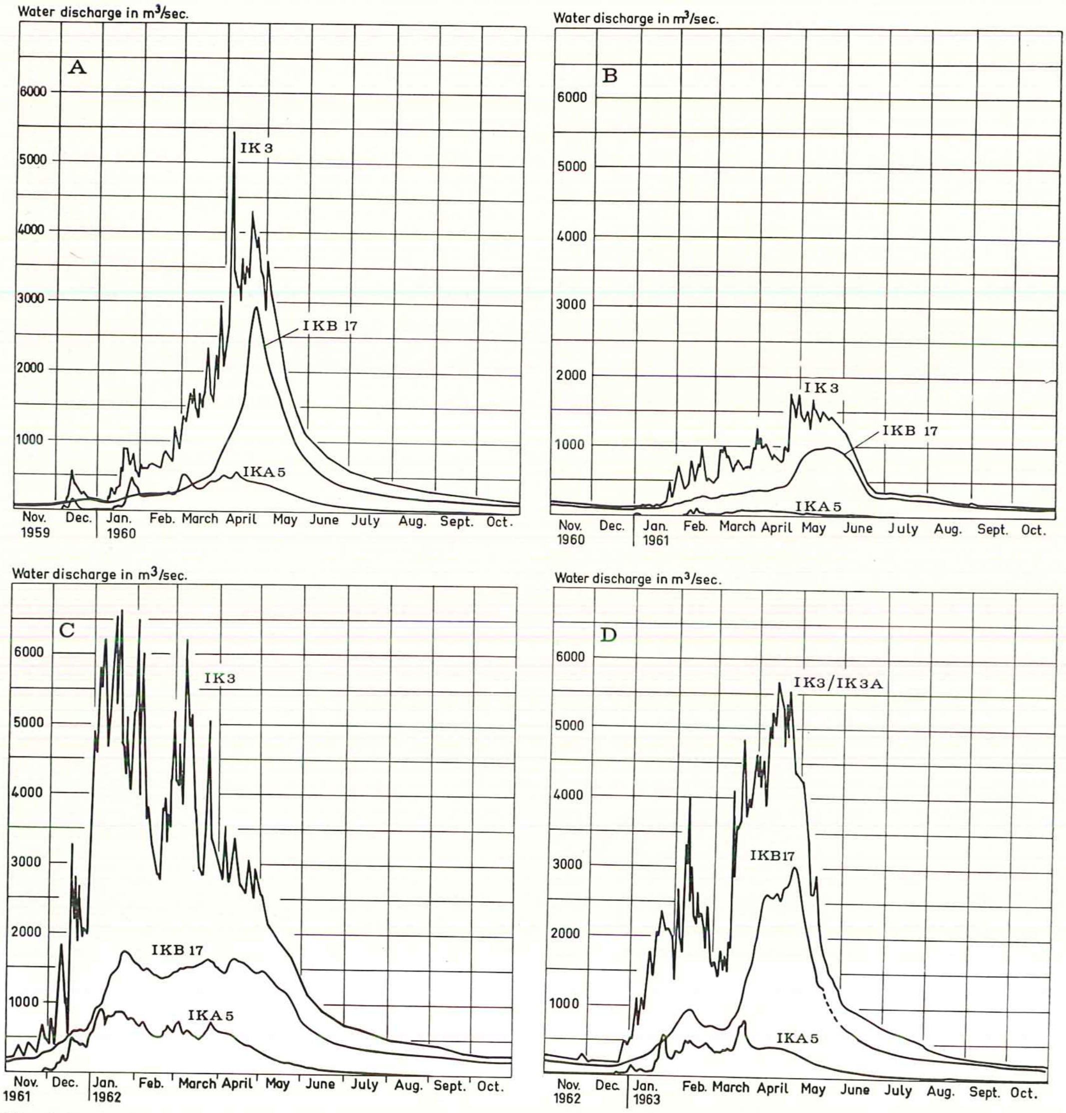


Fig. 9 Hydrographs of the Rufiji river at Stiegler's gorge (1 K3 and 1 K3 A), Kilombero river (1 KB 17), and Great Ruaha river (1 KA 5) for the hydrological years 1959/60 (A), 1960/61 (B), 1961/62 (C), and 1962/63 (D).

hydrographs 1959/63 of the Rufiji river at Stiegler's gorge (stations 1 K3 and 1 K3 A). For comparison the hydrographs of the Kilombero (1 KB 17) and Great Ruaha (1 KA 5) rivers are added. Data used for the construction of these curves are daily averages and therefore significantly smooth the actual fluctuations. Automatic recorders have been installed at both Rufiji stations but their trace is too short for analytical purposes, and several times they have been swept away under flood conditions. Generalization from the whole series of 16 hydrological years suggests several normal relationships:

a) all hydrographs indicate that the initial sector of storm runoff is made up of flash floods occurring at variable time and spacing, sometimes as early as late November but more commonly from late January, superimposed on a slowly rising base flow;

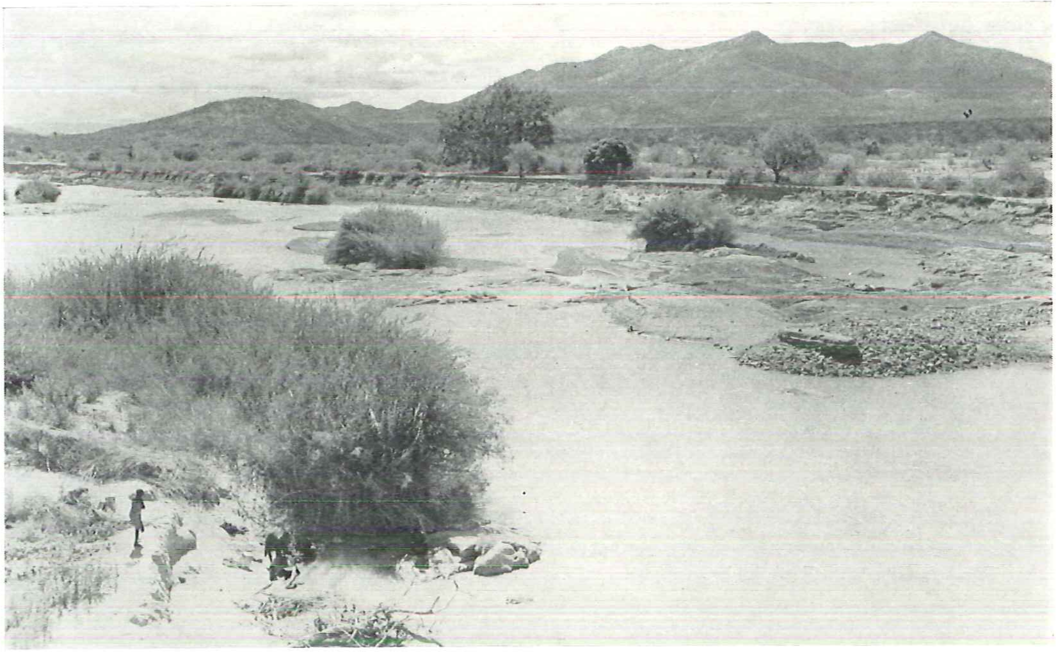

Fig. 10 The Great Ruaha river at Mtera: view downstream from gauging station 1 KA 5: low flow stage. Photo P. H. Temple, Sept. 1968.

b) from November through December, flood peaks are always rather small;
c) extreme variations of discharge over very short intervals of time are frequent for much of the flood period, January through April; differences of over 3 000 $m^3$/sec between two consecutive 24 hour averages and up to 4 000 $m^3$/sec over 72 hours are recorded on the rising limb and discharge reductions of over 2 000 $m^3$/sec over 24 hours on the falling limb;
d) the similarities between different years are most striking in the recession curves from late May to the end of October and often to the end of December.

Many of the above characteristics are of great relevance to the analysis of the sediment transportation conditions and to an understanding of the sediment sources.

The discharge characteristics of the Rufiji at Stiegler's gorge can be compared with the hydrographs for the Kilombero at Swero (1 KB 17) controlling a subsidiary catchment of 31,700 $km^2$. The Kilombero discharge is very even (Figs. 9A—D), reflecting the damping influence of the river's tortuous middle course and the large swamp areas of this fault depression. No flash floods derive from this source and the sediment yield has been shown to be very small due to the low gradient, sluggish flow and swamp traps. The Kilombero provides a considerable volume of water discharge to the Rufiji, the amount ranging between c. 40 and 60 per cent of the total Rufiji flow (Fig. 11). The addition of the Kilombero water mainly supports the latter part of the flood peak of the lower Rufiji.

There is a striking dissimilarity between the annual hydrographs of the Rufiji, which are very flashy, and those of its main tributary the Kilombero with generally only one well-defined peak.

The Rufiji hydrographs can also be compared with the hydrographs for the Great Ruaha at Mtera (Fig. 10), controlling a component catchment of 68,000 $km^2$ (1 KA 5). The Great Ruaha annual discharge at Mtera normally forms between 4 and 35 per cent of that of the Rufiji flow (see below). It is important for the sediment transport because the flood starts early and is rather irregular in the critical period January—March.

Fig. 11 shows, by means of the heavy lines, the average monthly discharges of the rivers

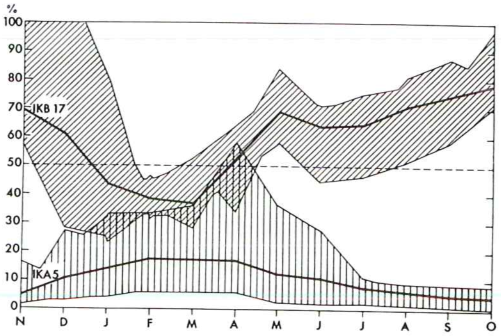


Fig. 11 Monthly discharge values (million m³) for the rivers Kilombero (1 KB 17) and Great Ruaha (1 KA 5) as percentages of the Rufiji for the period 1957/58 to 1969/70. Shaded areas indicate the full range of fluctuations; heavy lines indicate the average relationship for each river.

Kilombero (1 KB 17) and Great Ruaha (1 KA 5) as percentages of the total Rufiji flow. The upper curve indicates that the Kilombero flow averages over half that of the Rufiji for 9 months of the year and falls below the 50 per cent line only for the period January through March. In the normal recession period of the water year, May through December, it averages over 60 per cent of the Rufiji discharge volume. The lower curve indicates that the Great Ruaha flow at Mtera averages over 10 per cent of the Rufiji flow only from December through June.

The shaded areas on the figure show the extreme ranges of monthly flows for both rivers compared to the Rufiji discharge. One exceptional feature of the Kilombero discharge is apparent: that during some months it has actually been in excess of that of the Rufiji (eg. November 1958 and 1959 and December 1968). This occurs during the periods of minimum flow of both rivers.

The Great Ruaha envelope curve covers a comparable period of record and this conceals one exceptional feature: the river has been almost completely dry during some months of the longer record (eg. November and December 1954). The Great Ruaha discharge compared to the Rufiji on a monthly basis thus varies between 0 and 58 per cent. Over the whole years plotted on Fig. 11, its discharge ranges between 4 and 36 per cent of the Rufiji total, while the Kilombero ranges only between 42 and 63 per cent. As the hydrographs discussed above indicate, the Kilombero provides a generally uniform and steady flow, while the Great Ruaha, even at Mtera, is liable to very wide flow fluctuations.

## Flow duration analysis and flood frequencies

The problem of forecasting the sediment yield of a river is often a critical problem in water resource planning within catchments with a high sediment production. Especially in developing countries the sediment transport records are often very short or defective, whereas water discharge measurements may be available for a somewhat longer period. Thus the problem arises of how to process the sediment data to obtain improved information about sediment yield from the headwater areas.

Normally there is a rather good correlation between figures for sediment transport and water discharge. This has been shown in a great number of investigations. The conventional method of determining the relation between the hydrological conditions and the quantitative transport of suspended material is to ascertain the relation between water discharge and suspended sediment load. This relation, the so-called sediment-rating curve, can then be used, together with the flow-duration values, to produce a forecast of the probable transport of material during a longer period. Such a method has been applied to forecast the probable sedimentation within the Euphrates reservoir in Syria (Sundborg 1964 a and b). Recently Nordin and Sabol (1973) have given convincing data showing that "the estimate of the average annual sediment yield can be improved by developing a linear regression model between the logarithms of the flow and the sediment discharge and estimating the sediment yield for the period when only flow records are available" (cf also Nilsson 1972).

With this approach to the sediment transport problem a satisfactory knowledge of the probability and duration of different water-discharge figures is of fundamental importance. As already mentioned water discharge values are available from the river Rufiji for the 16-year period 1954/70. Most complete are the data from Stiegler's gorge (1 K3) and Pangani rapids (1 K3A). These data are also the most relevant for the treatment of the main Rufiji river.

On the basis of the 24-hour mean discharge

Table 2. Water discharges (m³/sec.) with different duration. Stations IK 3 and IK 3A, 1954/55 to 1969/70.

| Year | Ann. Max. | 5 % | 10 % | 20 % | 30 % | 40 % | 50 % | 60 % | 70 % | 80 % | 90 % | Ann. Min. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1954/55 | 2662 | 1930 | 1780 | 1470 | 1090 | 730 | 450 | 270 | 170 | 120 | 100 | 90 |
| 1955/56 | 6265 | 3210 | 2730 | 2170 | 1890 | 1140 | 660 | 450 | 340 | 230 | 130 | 87 |
| 1956/57 | 2930 | 2340 | 2000 | 1130 | 925 | 760 | 500 | 365 | 280 | 240 | 210 | 129 |
| 1957/58 | 3084 | 2350 | 1930 | 1340 | 860 | 520 | 360 | 290 | 245 | 200 | 160 | 103 |
| 1958/59 | 1709 | 1390 | 1250 | 1110 | 830 | 540 | 425 | 335 | 250 | 180 | 120 | 72 |
| 1959/60 | 5440 | 3420 | 2660 | 1500 | 850 | 610 | 500 | 390 | 275 | 200 | 155 | 69 |
| 1960/61 | 1766 | 1435 | 1280 | 830 | 630 | 400 | 280 | 240 | 220 | 210 | 200 | 116 |
| 1961/62 | 6637 | 5320 | 4580 | 3410 | 2800 | 1960 | 1025 | 630 | 475 | 380 | 310 | 199 |
| 1962/63 | 5660 | 4720 | 4070 | 2410 | 1790 | 1050 | 700 | 475 | 360 | 260 | 200 | 168 |
| 1963/64 | 5712 | 4230 | 3620 | 2540 | 1910 | 1200 | 790 | 600 | 485 | 380 | 265 | 201 |
| 1964/65 | 3720 | 2530 | 1870 | 1010 | 685 | 520 | 380 | 275 | 240 | 230 | 220 | 176 |
| 1965/66 | 3338 | 2320 | 1850 | 1140 | 820 | 620 | 395 | 285 | 250 | 220 | 195 | 167 |
| 1966/67 | 3432 | 1710 | 1285 | 930 | 620 | 485 | 420 | 365 | 320 | 310 | 260 | 162 |
| 1967/68 | 5754 | 5010 | 4720 | 3830 | 2670 | 2025 | 1480 | 765 | 530 | 405 | 260 | 176 |
| 1968/69 | 2572 | 1870 | 1590 | 1080 | 895 | 560 | 295 | 230 | 220 | 205 | 185 | 170 |
| 1969/70 | 4935 | 2920 | 2320 | 1700 | 1340 | 640 | 380 | 270 | 250 | 230 | 210 | 160 |

values from these gauging stations, flow duration curves have been constructed for each of the 16 hydrological years. Typical data from the 16 individual duration curves are given in Table 2.

The table shows the discharge values for each water year with durations of certain percentages. For example, in 1961/62, 5 % of the year had discharges in excess of 5320 m³/sec; whereas in 1960/61, the discharge value with 5 % duration was only 1435 m³/sec. Maximum and minimum daily average discharges are also shown in the table. From these data it appears that the range of daily discharges recorded is between 6637 and 69 m³/sec.

The 16-year observation period is too short to permit a reliable analysis of the probability and duration of flows with different water discharge values. It is difficult to establish whether the investigated period is representative of a longer period or not, both as regards mean values and dispersion. However, it is still of great importance to consider the character of the individual hydrological years compared with the general conditions during the 16-year period. Therefore a further analysis has been performed of the duration curves and the data in Table 2.

For this analysis it is necessary to make an assumption concerning the probable type of statistical distribution for the discharge values with different durations, which are given in the table. The number of years is too small for an opinion to be expressed with any certainty on the basis of the available values. In the analysis of flood data it is usual to employ a probability function with a logarithmic transformation of the variate or some similar function, e.g. Slade's function or Pearson's probability functions (cf. Foster 1948, p. 360, IASH 1969, p. 185, etc.). In this case also it was considered most suitable to assume and apply a normal logarithmic distribution, both for the annual maximum discharge and for the discharges of various durations.

The frequencies of different values for maximum discharge and for discharges with different durations have been determined using an approximate gradation method. The data were arranged in order of magnitude, the highest being placed first. Then the frequency can be calculated from either of several approximate formulas:

$$P = \frac{m}{n+1}; \quad P = \frac{3m-1}{3n+1} \quad \text{or} \quad P = \frac{2m-1}{2n};$$

where P is frequency, n the number of data and m the rank in sequence.

All formulas have the disadvantage that they give the same frequency value independently of the magnitude of a certain observation relative to other observations. In this case and for the present purpose, however, it is scarcely worthwhile using a more refined method.

In this particular case the formula P =

$\frac{2m-1}{2n}$ has been used. The observed discharge values with a given duration have been plotted on logarithmic probability paper using the frequency values calculated according to the formula. Then the regression line has been drawn for the data of each duration. A similar procedure has been used for data of all duration values and maximum and minimum discharges as well.

The regression lines make it possible to estimate discharge values with different durations and for different probability values. On the basis of the computed figures flow-duration curves were constructed for different probability values: 1, 2, 10, 25, 50, 75, 90, 98, and 99 %. The duration curves are given in Fig. 12. The curves for 1, 2, 98, and 99 % probability are dashed, indicating high uncertainty within the range of the extended period.

Actually the plots are not flow-duration curves in the strict sense, because they do not describe the duration conditions during an individual hydrological year. But they give the probability figures for the durations of any discharge value. They also give the probable durations of any discharge and for different probabilities. The diagram indicates, for example, a 10 % probability that the water discharge during a hydrological year will be 2000 m³/sec or more for a period corresponding to 30 % of the year.

Flood frequencies or approximate return figures for different discharges can also be estimated from the diagram. Floods with discharges of 5000 m³/sec have, for instance, a return period of about 5 years and floods with discharges of 7000 m³/sec a return period of about 13 years.

Although the curves in Fig. 12 are not flow-duration curves in the strict sense, they are useful as a basis for the discussion of the characteristics of individual hydrological years. In Fig. 13A—D the annual duration curves for the hydrological years 1954/55 to 1969/70 have been plotted with the computed curves from Fig. 12 as a background. From the diagrams it is easy to distinguish in what respects the individual hydrological years are normal or exceptional.

The year 1967—68 for instance has a rather high maximum water discharge, ca 5700 m³/sec, but this maximum is by no means exceptional. The probability value seems to be about 17 %. What is quite exceptional, however, is the 50 % duration of a water discharge of ca 1500 m³/sec or higher. In a similar way the characteristics of any year can be distinguished. This is especially useful for evaluating the characteristics of the years for which sediment transport data are available (cf. below).

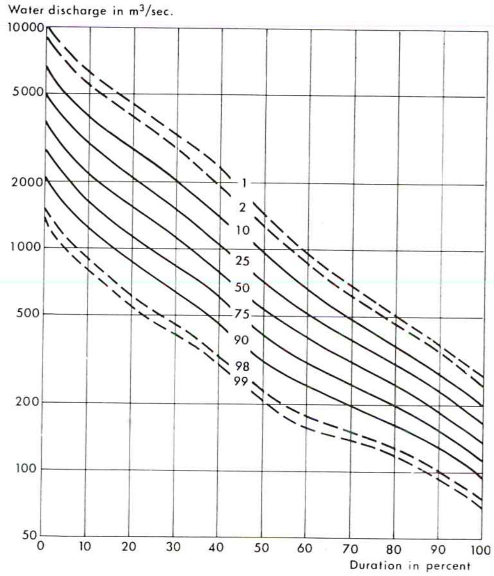


Fig. 12 Computed flow duration curves for different probability values (see text). Dashed curves indicate high uncertainty for 1, 2, 98, and 99 % probability. Basic data from stations 1 K3 and 1 K3 A. This matrix is shown as a background in Figures 13 A—D.

## SEDIMENT TRANSPORT IN THE RUFIJI RIVER

### Sediment sampling stations and sediment sampling procedures

Water sampling in the Rufiji river and its tributaries was begun under the initial direction of the FAO team in 1956 (Raadsma 1960). The purpose was to study the sediment production within different parts of the catchment including the total sediment yield to the lower Rufiji at Stiegler's gorge. After some years the sampling programme was taken over entirely by the WD & ID. The programme lapsed in 1961/62. At present no regular water sampling is being conducted on any river in Tanzania.

The FAO team selected as sampling stations

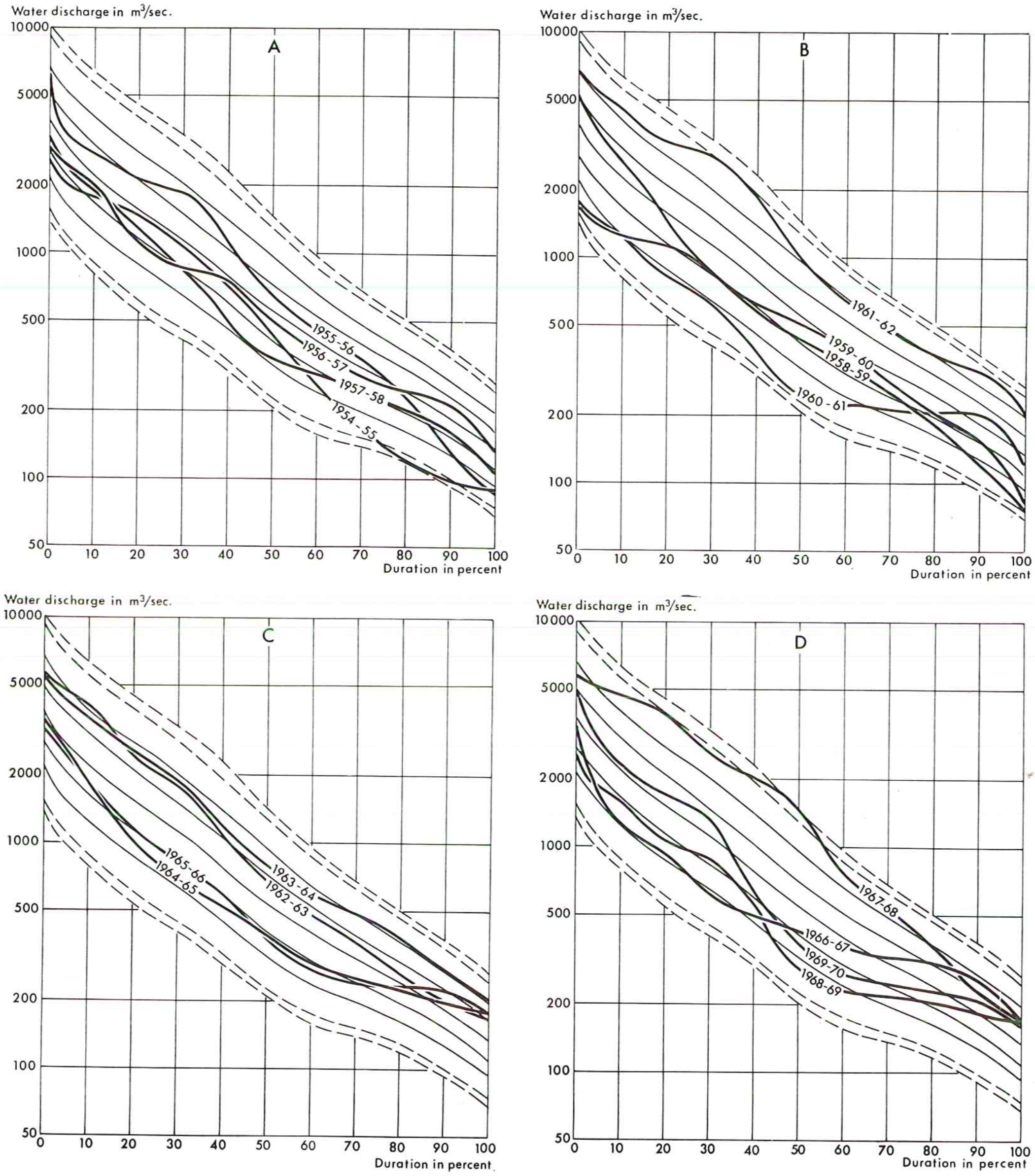


Fig. 13 Annual flow duration curves for the Rufiji river at station 1 K3 and 1 K3A for the hydrological years 1954/58 (A), 1958/62 (B), 1962/66 (C), and 1966/70 (D). The matrix from Figure 12 shown as a background.

within the basin those river gauging stations nearest to proposed reservoirs and sites of potential water development (Raadsma 1960, p. 200). Twenty-seven sampling stations on twenty rivers were utilized. Some of the stations were used only during very short periods, whereas others show data records for up to six years. In this article only one of these sampling stations is studied in detail: the Rufiji station at Stiegler's gorge.

The sampling procedure was rather simple due to lack of an adequate number of proper sampling devices. It involved "filling water directly into a bottle" with a capacity of 500 $cm^3$ and an opening of 4 cm. "In rivers with waterfalls or rapids at or near to a gauging station, samples were collected by immersing the bottles into the turbulent flowing water by hand. At stations with more calmly flowing water, samples were taken in the middle of the stream at six tenths of the depth below the surface" (p. 200).

This crude method of sampling may involve several sources of error. Some are discussed in the FAO report, which also includes the results of an evaluation of the sampling procedure against more sophisticated methods. According to this evaluation, the simple bottle sampling method shows reasonably reliable sediment concentration figures, with a correlation coefficient of 0.98 between comparable data obtained by the two methods.

It is not possible to analyse the reliability of the sediment concentration data in any detail now more than ten years after the investigations, but there is no reason to believe that the general statements on reliability in the FAO report should not be valid. Although individual sediment concentration figures may deviate considerably from the true concentration values, the general trend is certainly correct. As the samples normally were taken from the bank of the river, the results may on average be lower than the correct values: this bias is difficult to assess without new investigations.

The sampling design called for weekly samples at each selected gauging station, with additional samples, if possible, during floods. This programme was not adhered to even at Stiegler's gorge, where there are large gaps in the record due to sampling and analytical difficulties. All analytical work covering sediment concentration and chemical analysis was done in Dar es Salaam by the Government Chemist.

## Available data on sediment transport

Unfortunately the FAO report does not contain the results of the analyses of individual samples for any of the stations but presents only a general table indicating monthly sediment transport, sediment concentration as a percentage of runoff, and sediment production in tons per square mile (Raadsma 1960, Table 10, p. 206). The figures are based on an interpolation procedure that conceals the basic data and makes further statistical treatment difficult.

Detailed analytical results for part of the record are, however, available by courtesy of WD & ID in Dar es Salaam. These data comprise results from water sampling at Stiegler's gorge on the Rufiji, from the Great Ruaha at Mtera and Kidatu and from the Kilombero at Swero. The data considered in this report refer to samples taken at Stiegler's gorge with related water discharge figures. The Great Ruaha and Kilombero data are discussed only cursorily.

Two hundred and sixty samples in total are available from Stiegler's gorge, spanning the period January 1956 to March 1962. This approximates to one sample on average every 9th day. Only part of these data, samples 1—192, were used in the FAO analysis. Data for the hydrological years 1959/60, 1960/61, and 1961/62 were not examined at all.

This means that more than 25 % of the available analytical data has not been scrutinized at all in earlier investigations. In only one of the four water years analysed was the total water discharge in excess of the 16 year average and the annual maximum flow above the mean annual maximum. Three of the four years were relatively dry.

Thus data for the years 1959/60, 1960/61, and 1961/62 add significantly to the understanding of the sediment transport processes, especially as these years are, in sequence: average wet, extremely dry and extremely wet (cf. Fig. 9A—D). They also make it possible to extend the calculations beyond a simple interpolation procedure and to establish relationships between water discharge, sediment concentration, and sediment load during different periods of the hydrological year. A more detailed analysis of the sediment data is therefore viable.

## Water discharge, sediment concentration and sediment load analysis

All available basic data on sediment concentration and related values for water discharge and sediment load at Stiegler's gorge are tabled in the technical report (Temple and Sundborg 1973). In order to illustrate the relationship between the parameters in a visual manner the data for the hydrological years 1955/56 to 1958/59 have been plotted graphically in Fig. 14A—D.

As the water sampling is generally spaced at seven day intervals or more, whereas water discharge is given as daily mean values, the hydrographs are much more detailed than the

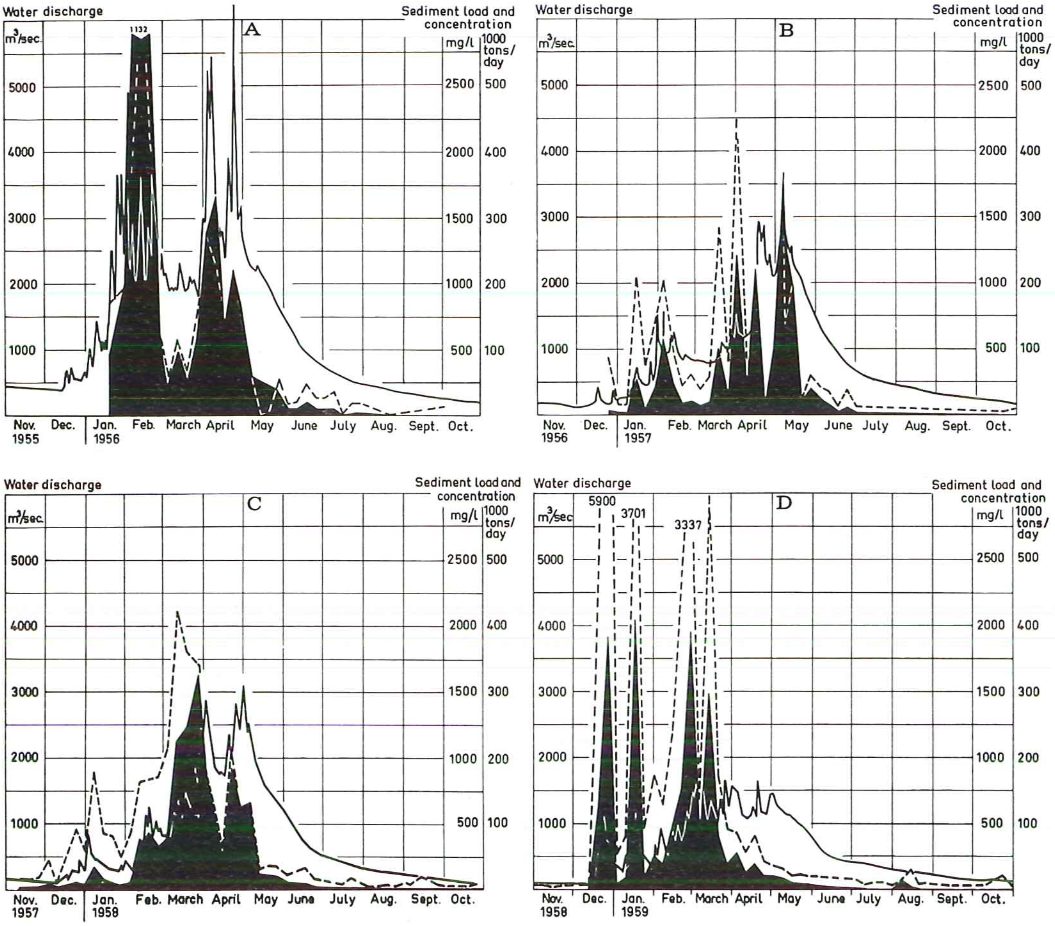


Fig. 14 Water discharge, sediment concentration, and sediment load for the Rufiji river at Stiegler's gorge. Solid line water discharge, broken line sediment concentration, shaded curve sediment load:
A. 1956/57; B. 1957/58; C. 1958/59; D. 1959/60.

curves for sediment concentration and load. Yet it is quite clear that some general statements can be made on the relationships between the plotted parameters and time.

Sediment concentrations are highest in association with sudden flash floods on the rising limb of the hydrograph, particularly in its lower part when base flow is low. At low discharges on the recession limb (generally May through October) the sediment concentrations are moderate to low. The highest reported sediment concentrations are associated with years of relatively low total water discharge but flashy rises (eg. 1958—59 and 1960—61). Maximum recorded sediment concentration is 5900 mg/1 (PPM).

From the pattern of sediment concentration, it follows that the heaviest sediment loads are associated with peaks on the rising limbs of the hydrographs. The peak water discharge occurs much later than the peak sediment transport—often as much as about two months. The curve of sediment load falls more rapidly than the recession curve of water discharge, and sediment load is often very small while water discharge, though falling, is still relatively high. From the end of April through November the sediment yield is generally very low.

Already, from a simple graphical comparison of the three curves, some conclusions can be drawn on the geomorphological processes responsible for the variations in sediment yield.

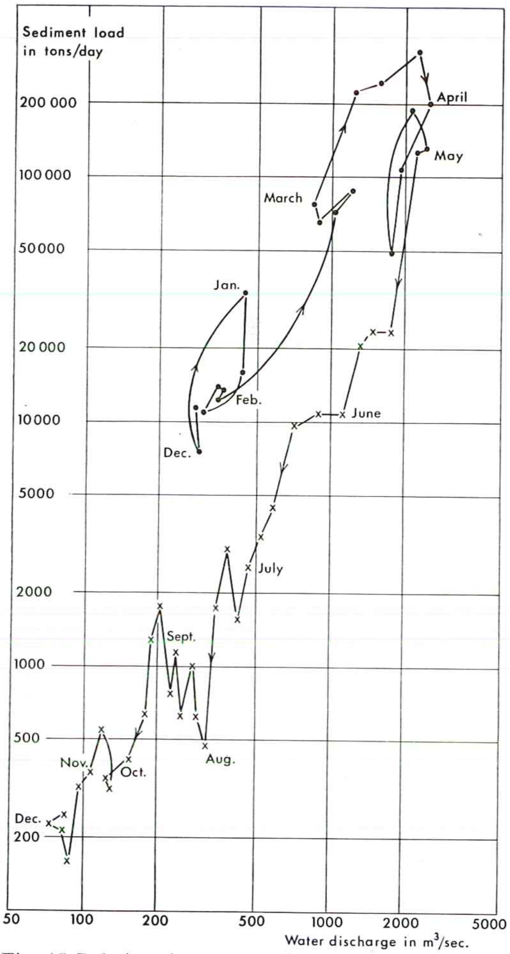

Fig. 15 Relation between sediment load and water discharge during the hydrological year 1957/58 at station 1 K3 (Stiegler's gorge).

The high concentrations and high sediment loads well in advance of the discharge peak indicate an early and rather rapid flushing out of sediment from the system. As has been pointed out earlier, the flashy floods normally originate from the lower parts of the Rufiji catchment, especially from the Luwegu and Luhombero sub-catchments. As the sediment concentration generally rises in connection with these floods, the Luwegu and Luhombero catchments seem also to be principal sediment-producing areas. This is confirmed by the sediment concentration values from the Great Ruaha (Mtera and Kidatu) and the Kilombero (Swero), which are relatively low compared to the concentrations at Stiegler's gorge.

Apparently the relation between sediment load and water discharge follows a regular rhythmic annual course, although random variations are considerable, especially during flood season. In order to illustrate the changing conditions during the hydrological year, a diagram has been constructed showing the relation between sediment load and water discharge at individual samplings during the period Dec. 1957—Dec. 1958 (Fig. 15).

During rising water stage sediment load is generally high (cf. also Fig. 14). Even if the variations from day to day are considerable, there exists a marked correlation between water discharge and sediment concentration, reflected also in the discharge—sediment load relation. After the high-water period, with variable flow and flashy floods, the sediment concentration decreases and the recession curve is characterized by low, stable, and slightly decreasing sediment concentration figures and a very good correlation between discharge and sediment load.

The pronounced seasonal variation in the relation between sediment load and water discharge, reflected in Fig. 14, justifies a division of the year into two typical periods: the *flood period* and the *recession period*. The data on sediment transport have therefore been grouped into 12 consecutive periods, characterized either by highly variable but generally rising water discharges or by smoothly decreasing discharges. The beginning of a flood period is generally easily recognized by the occurrence of flash floods, superimposed on a slowly rising base flow. The beginning of the recession curve may sometimes be a little more difficult to distinguish, but generally-speaking the periods are relatively easy to define.

## Sediment rating curves for flood and recession periods

According to the principles stated above, the 260 samples available for the period January 1956 to March 1962 have been grouped into 7 flood periods and 5 recession periods. For each period the sediment discharge rating curve has been computed using the same methods and the same computer programme as were developed by Nilsson in his investigations of sediment transport in Swedish rivers (Nilsson 1971 and

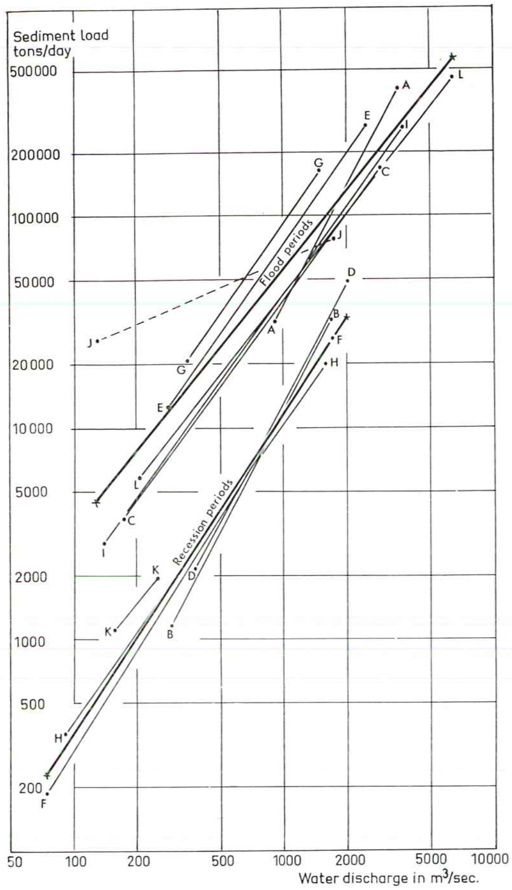


Fig. 16 Sediment rating curves for different flood and recession periods at Stiegler's gorge (see text). Coarse lines indicate sediment rating curves computed from all available flood period data and for all available recession period data.

1972). The sediment transport has been expressed by the equation

$$\log T = A + B \log Q$$

where T is sediment transport, Q water discharge and A and B constants. The regression lines (sediment rating curves) are all included in Fig. 16 and characteristic data for the lines reported in Table 3.

As can be seen from Fig. 16, the sediment rating curves for the 7 flood periods form a group that is clearly distinguishable from the group of curves for the 5 recession periods. The internal dispersion is higher within the group of flood periods than within the group of recession curves. As might be expected, the coefficients of correlation are also considerably

Table 3. Characteristic parameters for the regression lines.

| Period | Type | N | r | $\sigma$ |
|---|---|---|---|---|
| A | Flood | 16 | 0.80 | 0.23 |
| B | Rec. | 16 | 0.86 | 0.25 |
| C | Flood | 34 | 0.77 | 0.35 |
| D | Rec. | 23 | 0.88 | 0.24 |
| E | Flood | 26 | 0.91 | 0.22 |
| F | Rec. | 31 | 0.96 | 0.18 |
| G | Flood | 19 | 0.51 | 0.43 |
| H | Rec. | 32 | 0.94 | 0.18 |
| I | Flood | 21 | 0.84 | 0.40 |
| J | Flood | 9 | 0.61 | 0.23 |
| K | Rec. | 12 | 0.48 | 0.16 |
| L | Flood | 21 | 0.94 | 0.23 |
| $\Sigma$ | Flood | 146 | 0.80 | 0.36 |
| $\Sigma$ | Rec. | 114 | 0.93 | 0.22 |

N = number of samples
r = correlation coefficient
$\sigma$ = residual variance

higher for the recession periods than for the flood periods, with their highly variable flow conditions.

With the exception of periods J and K, which each include a very small number of samples and period G, representing the exceptionally dry flood season 1958—59, all periods have coefficients of correlation in the order of 0.8 or higher. The correlation coefficient for the regression line including all available flood period data is 0.80 and the correlation coefficient for the combined recession period data is as high as 0.93. Although the correlation is not particularly good, it is considered satisfactory. The random variation in the results of the sediment sampling is not higher than is quite normal in data from rivers investigated by much more sophisticated methods. Although there may be some systematic errors due to the sampling and analysis procedures, the general sediment transport conditions are probably rather well elucidated by the data already available.

In Fig. 17 are plotted all available observations on sediment transport for flood seasons during the period January 1956 to March 1962. The regression line is also shown in the diagram and, for comparison, the regression line for the recession periods is marked as a dashed line. The dots show considerable scatter, corresponding to the relatively low correlation coefficient, but it is also evident that the sedi-

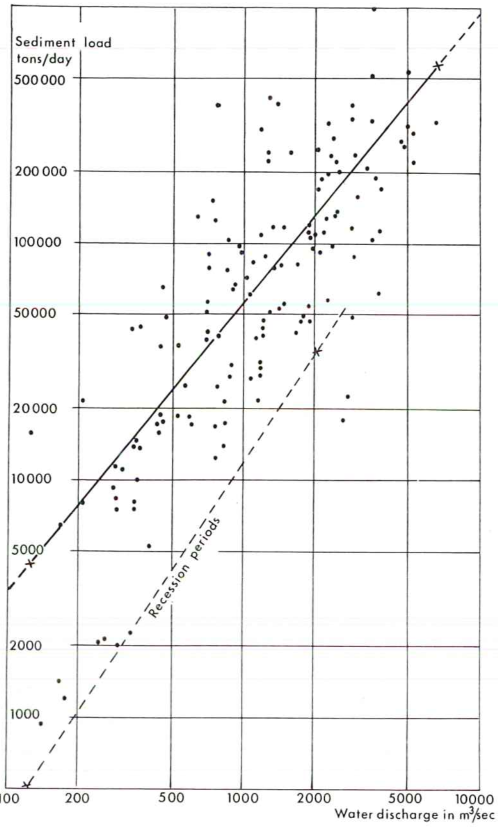


Fig. 17 Sediment rating curve for flood periods at Stiegler's gorge. Dashed line shows rating curve for recession periods.

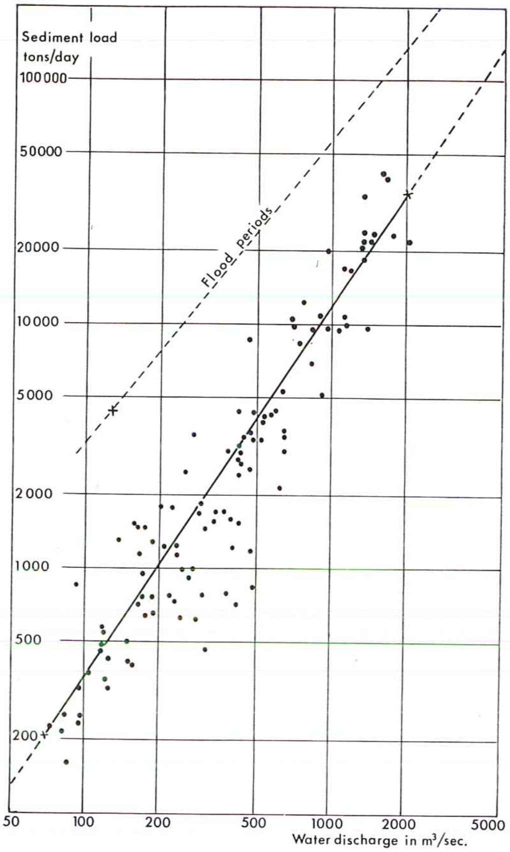


Fig. 18 Sediment rating curve for recession periods at Stiegler's gorge. Dashed line shows rating curve for flood periods.

ment rating curve for the recession periods is clearly separated from the observations during floods.

The corresponding data for the recession periods are shown in Fig. 18. The correlation is much better for these periods of the year, and the points certainly belong to a statistical population other than that of the flood-period data. Thus the division of the year into a flood period and a recession period seems quite appropriate in the analysis of the sediment transport conditions.

## Sediment transport over different time intervals

From the computed sediment-rating curves the probable sediment load can be estimated for different water discharge conditions and for different seasons. The normal procedure used in the analysis of sediment transport is to apply the sediment-rating curve to the flow-duration curve to calculate the quantity of suspended material during a certain period. An estimate of the long-term average sediment yield may also be obtained (Sundborg 1964).

The sediment-rating curves computed have in this case been applied to the whole 16-year period, for which water discharge data are available. In the division between flood periods and recession periods, the criteria mentioned above have been used. In this way calculated daily values for the suspended sediment transport have been obtained. Using the daily values, probable monthly sediment transport totals throughout the 16-year period have been computed and are given in Table 4.

The calculation gives a mean annual suspended sediment transport during the 16-year period of 16.6 mill. tons. The period 1955/56 to

Table 4. Calculated monthly suspended sediment transport values at Stiegler's gorge (Pangani rapids) for the 16-year period 1954/55 to 1969/70 (in thousand tons).

| Year Month | N | D | J | F | M | A | M | J | J | A | S | O | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1954/55 | 54 | 56 | 272 | 1995 | 2447 | 3,881 | 4074 | 483 | 255 | 167 | 119 | 96 | 13,899 |
| 55/56 | 75 | 441 | 2,971 | 4556 | 3672 | 7,021 | 2288 | 341 | 144 | 84 | 48 | 32 | 21,673 |
| 56/57 | 20 | 181 | 635 | 1344 | 1352 | 3,206 | 2740 | 315 | 123 | 75 | 45 | 28 | 10,064 |
| 57/58 | 16 | 177 | 501 | 938 | 2347 | 3,884 | 1739 | 218 | 85 | 46 | 27 | 15 | 9,993 |
| 58/59 | 8 | 444 | 663 | 1075 | 2198 | 1,937 | 632 | 119 | 71 | 45 | 27 | 17 | 7,236 |
| 59/60 | 6 | 215 | 557 | 956 | 2989 | 6,961 | 1729 | 223 | 110 | 63 | 40 | 28 | 13,877 |
| 60/61 | 20 | 13 | 172 | 694 | 1114 | 1,641 | 2057 | 183 | 58 | 38 | 23 | 25 | 6,038 |
| 61/62 | 387 | 2983 | 11,472 | 7355 | 8420 | 5,278 | 1279 | 274 | 146 | 98 | 65 | 43 | 37,800 |
| 62/63 | 34 | 138 | 2,649 | 3883 | 6030 | 10,212 | 3241 | 257 | 150 | 71 | 45 | 34 | 26,744 |
| 63/64 | 467 | 1126 | 4,225 | 3627 | 7250 | 7,429 | 1064 | 227 | 120 | 88 | 56 | 38 | 25,717 |
| 64/65 | 27 | 46 | 966 | 677 | 1969 | 4,396 | 1163 | 119 | 55 | 42 | 29 | 26 | 9,515 |
| 65/66 | 22 | 625 | 848 | 1364 | 2015 | 4,213 | 1639 | 129 | 65 | 39 | 28 | 23 | 11,010 |
| 66/67 | 87 | 343 | 596 | 590 | 901 | 2,633 | 2602 | 281 | 89 | 52 | 34 | 25 | 8,233 |
| 67/68 | 132 | 3900 | 7,210 | 3678 | 9044 | 10,461 | 4044 | 470 | 221 | 132 | 76 | 49 | 39,417 |
| 68(69 | 35 | 31 | 261 | 1343 | 1630 | 2,317 | 3077 | 313 | 84 | 50 | 33 | 27 | 9,201 |
| 69/70 | 20 | 25 | 1,735 | 3721 | 4497 | 3,703 | 422 | 113 | 58 | 42 | 32 | 24 | 14,392 |
| Mean | 88 | 672 | 2,233 | 2362 | 3617 | 4,950 | 2112 | 254 | 115 | 71 | 45 | 33 | 16,552 |

1958/59, which was used by the FAO team in their measurements, shows a mean value of 12.2 mill. tons per year. It is generally true that the average value for a representative time period increases somewhat with increasing length of the period, due to the non-linear relationship between sediment load and water discharge and to the higher probability that extraordinary hydrological conditions will occur during a longer period. On the other hand, Raadsma's computations show values for the 4-year period corresponding to an annual transport of 17.2 mill. tons. If Raadsma's computations are correct, the mean annual transport for the whole 16-year period will be still higher, probably more than 20 mill. tons per year. However, the difference between the quantitative data given by Raadsma and the results of this analysis is not particularly significant.

It should be remembered that the values for sediment transport discussed above do not include material carried as bed load or in solution. No measurements of the bed load transport exist, and no calculations with conventional bed load formula have been performed so far. A very rough estimate, based on the general character of the Rufiji river and the sediments transported and using the classification by Maddock (Lane and Borland 1951), seems to indicate a bed load transport in the order of about 25 % of the suspended sediment transport. However, this estimate may be rather far from the true order of magnitude.

In conclusion it can be stated that, on average, a suspended sediment discharge of c. 17 mill. tons per year is yielded to the Rufiji lower flood-plain and delta downstream of Stiegler's gorge. This figure is probably on the low side, due to inaccuracy in the sampling and analysis procedures. Bed load and dissolved material is not included.

As the average annual water discharge volume during the 16-year period is 30,600 mill. m$^3$, the mean concentration is slightly more than 500 mg/l (PPM). According to present knowledge of the total sediment yield to the oceans of the world this figure seems to be somewhat higher than the average sediment concentration of all rivers in the world (cf. Sundborg 1972). It would therefore be correct to say that the sediment yield of the Rufiji at Stiegler's gorge is high but not extremely high. In his report in 1960 Raadsma gives some qualitative evaluations of sediment concentration and load. He considers "the very low sediment load concentration of the investigated rivers" (p. 202) and states as a final conclusion that "the suspended sediment concentration is low for all the rivers investigated" (p. 205).

Raadsma's statement is true only if the Rufiji is compared with extremely turbid rivers; it is definitely not true taking average global conditions into consideration. Compared with concentrations in most European rivers, the sediment concentration in the Rufiji is very high. Raadsma's qualitative statement may be quite misleading. It is therefore important that it does not overshadow the quantitative data given in his report, which by contrast seem to present a rather good idea of the order of magnitude of the sediment transport.

## GEOMORPHOLOGICAL CONCLUSIONS

### Denudation of the catchment

An annual sediment discharge of approximately 17 mill. tons from a catchment of 156,000 km² represents an overall soil denudation rate in the order of 0.06 mm/year. This is a rather low figure. It should be realized however that most of the soil loss and sediment yield recorded at Stiegler's gorge derives from a small part of the whole catchment. Applied to the area downstream of Swero and Kidatu, these values represent a much higher soil denudation rate.

The data presented elsewhere in this volume on small catchment sediment yields show greater denudation rates by several orders of magnitude, reflecting the significance of scale in the interpretation of results. Processes operative in large river basins are much more variable in type, magnitude, and effect than those in small catchments (Slaymaker 1972).

While it is therefore clear from the data presented that areas of soil erosion are localized within the catchment, the sampling procedures discussed above are inadequate to locate these areas except in the broadest terms. In fact soil erosion is probably locally most severe in sections of the catchment which show very low sediment yields as measured at sampling stations some way downstream—eg. the Iringa area of the Little Ruaha catchment and the Poroto mountains of the upper Great Ruaha catchment.

### Sediment and water yield to the flood plain

The average quantities of sediment transport involved have been outlined in previous sections. A more extended discussion of this question will hopefully be presented in a later paper, the main points of which can be briefly summarized.

A high proportion of the coarse-grained sediment transported through Stiegler's gorge is deposited downstream of the gorge section in the proximal part of the flood plain. Consequently, in this section, the river is excessively braided (Anderson 1960).

Some portion of the finer sand fractions is transported further downstream as is indicated by the well-developed levees, point bars and scroll bars of the middle flood plain. Such levee features are absent in the tidal section of the flood plain. Aerial reconnaissance indicates, however, that heavy minerals (probably ilmenite and rutile) reach the coastal delta to be reworked, sorted and enriched by marine action.

Much of the suspended silt and clay fraction of the load reaches the lower flood plain. Probably there is a large deflection of flood water and associated suspended sediment towards the Ruvu system to the north some km below Stiegler's gorge in the upper flood plain.

The finest part of the river load is deposited by overbank flow at flood periods into flood basins, where it renews the fertility of the flood plain soils and provides soil water for the growth of the main staple crop, rice, or the main cash crop, cotton (Yoshida 1972).

Flocculation and tidal ponding effects are also of great importance within the mangrove swamps and submarine sections of the delta (Temple 1970). This is evidenced by cartographic comparisons of the extension and modification of the delta form over a period of 80 years and by reconnaissance observations of delta lobes and sea water discolouration.

The consequences of interference with these inputs to the natural flood plain system are considered below.

### The effects of dam construction: some geomorphological and economic considerations

*Reduction of planned reservoir storage capacity*

It has been shown above that the Rufiji river currently transports large quantities of sediment into its flood plain. The mean annual suspended sediment transport is estimated here at 15—20 mill. tons with recorded sediment yields in one day of well over 1 mill. tons associated with high floods. It has been suggested above that only a rather small proportion of this sediment originates from the Great Ruaha system.

With the completion of the Kidatu dam, almost all Ruaha sediment will be trapped at Kidatu. Nonetheless this will have little impact at Stiegler's gorge, due to the rather small amounts involved, and may not be important even at Kidatu, a supposition which calls for further investigation.

Most of the sediment currently transported by the river through Stiegler's gorge will, in the event of a dam being built there, be deposited in the reservoir, with the following consequences:

The initial storage capacity will be reduced at a rate approximating 10—15 mill. $m^3$ annually. This figure is a first approximation and will need to be verified by reference to the reservoir design and operation plans. This progressive storage reduction will shorten the life of the reservoir, but will probably not have serious economic consequences.

Aggradation will occur in the river valley upstream of the reservoir. The river bed upstream will be raised as a consequence: flooding may result and water levels will be higher. Neither the one nor the other are likely to be of major significance for this project.

*Reduction of sediment transport into the flood plain after reservoir construction*

Naturally there will be a very pronounced decrease in the sediment load transported into the flood plain and delta zone of the river. The dam and its operation will also affect the regime of the river. The likely consequences of these facts are as follows:

Erosion will occur downstream of the reservoir when the river, deprived of its supply of coarse- and medium-grained sediment, entrenches its channel towards a reduced gradient or greater water depth. This may have serious effects on engineering works downstream such as bridges and water intakes.

Loss of water by irrigation and from the proposed reservoir surface by evaporation will reduce total water flow in the lower river. This could be important at seasons of low discharge and might permit increased tidal incursions of sea water into the lower flood plain with consequent deterioration of water and soil there. Experiences from, for instance, the Houghly river system in West Bengal in India indicate important effects on the tidal areas.

Loss of sediment by reservoir detention together with control of floods by reservoir operations will terminate the natural cycle by which the soils of the flood plain and delta are renewed and kept fertile, viz. by deposition of silt and water. The whole agricultural economy of the flood plain is currently dependent upon this annual cycle. Artificial fertilizers will be needed for the flood plain soils once the reservoir is built and new methods, presumably extensive irrigation schemes, will have to be developed to ensure an adequate water supply to crops once natural flooding is reduced or eliminated. Loss of sediment supply to the delta will cause coastal erosion along the delta front. Potentially valuable deposits of mineral sands may therefore be destroyed.

## Conclusions and recommendations

In contrast to previous evaluations presented in official reports and available to the authors, this paper has demonstrated that sediment transport through Stiegler's gorge is by no means insignificant. We consequently recommend that sediment transport needs very full consideration in any feasibility study concerned with water development on the river. In particular this process needs to be examined in relation to the proposed hydro-electric project at Stiegler's gorge and to development projects, eg. irrigation undertaken downstream of Stiegler's gorge both before and after reservoir construction.

The above study indicates a severe lack of information vital to the proper development of the Rufiji flood plain, particularly of information on discharge characteristics and sediment transportation in the Luwegu and Luhombero rivers. We therefore recommend the urgent establishment of gauging stations to monitor accurately the regimes of these rivers.

In conformity with the proposals of SWECO, we recommend the re-establishment of the water quality and sediment sampling programme for the Rufiji, initiated by FAO, but with a more limited operational schedule concentrating on Stiegler's gorge, the Luwegu river and the Luhombero river.

We also recommend as full an analysis as possible of the probable sedimentation in the proposed Stiegler's gorge reservoir, using the data on sediment transport provided in this report. The analysis may be performed according to the methodology set out by Sundborg (1964a). Because vital data on water temperatures, solution load and bed load are not available, this analysis would be preliminary but should reveal the extent of the problem.

These recommendations are put forward only as unsolicited comment on the results and conclusions of the report presented above.

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*Professor P. H. Temple, Department of Geography, University of Birmingham, P.O. Box 363, Birmingham, U.K. Professor Åke Sundborg, Department, of Physical Geography, University of Uppsala, Box 554, S-751 22 Uppsala, Sweden*

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Note:
After this paper went to press, information has been received that some of the lowest water discharge values relating to sediment samplings may be slightly incorrect due to discrepancies in water stage heights. This will not change any of the conclusions in the paper. Revised figures, if necessary, will be published in the full technical report.

# MEAN DAILY RAINFALL INTENSITY AND NUMBER OF RAIN DAYS OVER TANZANIA

BY IAN J. JACKSON

Department of Geography, University of New England, Australia
formerly University of Dar es Salaam

ABSTRACT. The significance of rainfall characteristics in relation to a number of topics, particularly soil erosion, is discussed.

Average daily rainfall intensity and numbers of rain days for four months are presented to serve both as background material for more detailed studies and also to suggest areas where further work may be worthwhile. With the exception of April, average monthly rainfalls are associated more with numbers of rain-days than with daily rainfall intensity. Considerable spatial variations in daily rainfall intensity and numbers of rain days exist. The results indicate that careful selection of rainfall stations for analysis is necessary and that caution is needed in generalising from detailed analyses to a wider area.

## Introduction

Rainfall conditions over periods of 24 hours or less are of great significance in Tanzania. Soil erosion is influenced by rainfall amounts, intensity, and frequency of occurence for short time periods. Water balance, especially in relation to agriculture is also very sensitive to these aspects as is streamflow, particularly in smaller catchments. Short period data are also important for planning storm water drainage systems and flood control design.

The relation between rainfall and soil erosion is an extremely complex one and can be considered only briefly here. Soil aggregates, generally too large to be easily removed by runoff, tend to be broken up and moved by rain drop impact and the fine particles detached may be more easily carried away in suspension. In addition, the fine particles tend to block the soil pores and this compacting effect on the soil surface considerably reduces infiltration capacity. The influence of raindrop action has been demonstrated experimentally by Ellison (1945) and Hudson (1957). These effects will tend to increase as rainfall intensity and therefore kinetic energy of the raindrops increase.

Important as the effects of high intensity rainfall are in terms of soil erosion however, the picture is much more complicated than this. Surface runoff is important to soil erosion and this involves the relation between rainfall intensity, variable infiltration capacity and the time available for infiltration to occur. Intensity data alone therefore may not be very adequate indicators of erosion by surface water. Infiltration capacity is a function of a number of factors amongst them soil type, conditions and soil moisture content. In general terms, infiltration capacity decreases as soil moisture increases and therefore not only rainfall intensity but also its duration, frequency of occurrence and interval between storms are of great significance in determining surface runoff.

The seasonal occurrence of heavy storms is likely to be of importance in a country such as Tanzania with marked wet and dry periods. If heavy storms occur at the start of a wet season when vegetation cover is sparse and soil is not well protected, compaction effects, discussed above, may lead to considerable surface runoff and erosion. On the other hand the development of cracks in the soil during the dry season and general low moisture content may allow considerable downward movement of water at first. Heavy storms at the middle and end of the wet season, when vegetation protects the soil, will not have so much impact upon soil surface characteristics. The slope of the land and the nature of the vegetation cover influence the rate of movement of surface water and therefore the time available for infiltration to occur.

It must also be remembered that sub-surface water movement may be of considerable significance to erosion, this depending very much on the characteristics of the underlying soil layers.

In summary therefore, rainfall intensities, duration, frequency of occurrence, interval between storms, and seasonal occurrence may all influence the rate of soil erosion. In addition however, factors such as soil type and condition, cultivation practices, slope and type of vegetation cover are also of great importance (cf. Temple & Rapp 1972).

Various aspects of rainfall over periods of 24 hours or less in Tanzania and East Africa have been analysed. Sansom (1953) and Lumb (1971) examined probable maximum precipitation in East Africa for durations up to 24 hours, and Thompson (1957) and Anon (1968), presented data on the diurnal variation of precipitation. Rainfall intensity, duration and frequency data have been analysed by Taylor and Lawes (1971). The paper by Taylor and Lawes (1971) included a map showing the maximum 24 hour rainfall amounts recorded in East Africa. Apart from this map, both that particular paper and the others listed above were concerned with data for individual representative stations.

The aim of this paper is to present basic data on daily rainfall conditions in Tanzania, particularly the spatial variations, which it is hoped will serve a number of purposes both in terms of rainfall analysis and also in studies where short period rainfall is significant. These purposes may be considered to be as follows:

1. to serve as background material for existing and future more detailed studies of short period rainfall. Such studies, of extremes for example, will in many cases be limited to analyses of individual stations and it is important to have some means of relating these 'point' analyses to regional variations.
2. to focus attention on particular aspects of short period rainfall or areas of the country which warrant further investigation.
3. to serve as a background for other work e.g. on soil erosion. The data may be useful in relating experiments or case studies to the rest of the country.
4. to focus attention on areas of the country where further analyses in a related field such as soil erosion may be worthwhile.

The reason for choosing daily values rather than shorter period ones was the wider availability of data for 24 hour amounts. Whilst extreme values are important, it was considered worthwhile here to present average figures which could serve as a base on which to build studies of the former characteristic. The presentation of values at different times of the year was also considered worthwhile.

## The data and methods of analysis

Data for 133 stations were analysed, the bulk of them being taken from the East African Meteorological Department (E.A.M.D.) summary for the years 1931—60 (1966). The spatial distribution of these latter stations was examined and supplemented by other stations having a reasonably long period of observation in order to give an adequate coverage. Of the stations, 112 were in operation for a period of 30 years, or more, 12 for between 25 and 29 years, six between 20 and 24 years and only three for a period of 15—19 years. The distribution of the stations is indicated in Fig. 1.

The analysis was limited to four months which it was thought could be considered as representing the variety of conditions throughout the year. The four months were January, April, July and October the essential characteristics of rainfall during these months being described elsewhere (Jackson 1971).

Two aspects of daily rainfall were examined:

a) average number of rain-days (defined by the E.A.M.D. as a day with at least 0.25 mm).
b) average rainfall *per rain day* (termed here mean daily rainfall intensity).

The relationships between both these parameters and average monthly rainfall were analysed. The spatial variations of the two parameters are shown in Figs. 2—9.

## Discussion of the results

*Relation between average monthly rainfall, average number of raindays and mean daily rainfall intensity*

In all four months, there was a clear relationship between average monthly rainfall and average number of rain days. For January, July and October the relationship was linear. For April, a plot of average number of rain days against the square root of average monthly rainfall was more linear. Correlation coefficients, regression lines and standard errors of regression estimates are presented in Table 1.

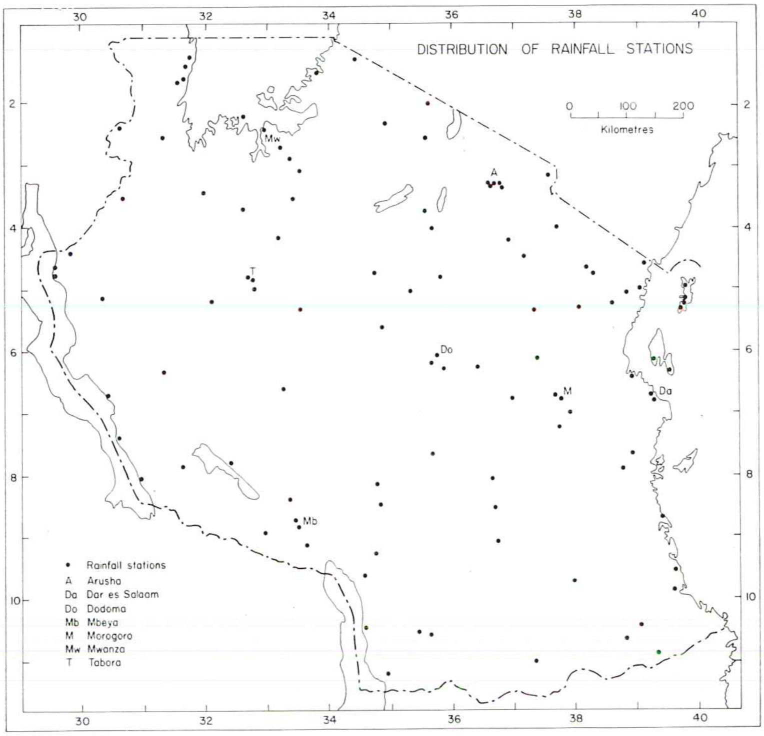



Fig. 1. Distribution of rainfall stations.

With the exception of April, the relationship between average monthly rainfall and mean daily rainfall intensity was not so apparent, correlation and regression parameters being presented in Table 2. During July, a considerable number of zero values occurred and inclusion of these in the regression tended to suggest a reasonable relationship which was not so apparent in a plot of intensity against average monthly rainfall. Accordingly, a second regression, excluding zero values, was calculated, both equations being presented in Table 2.

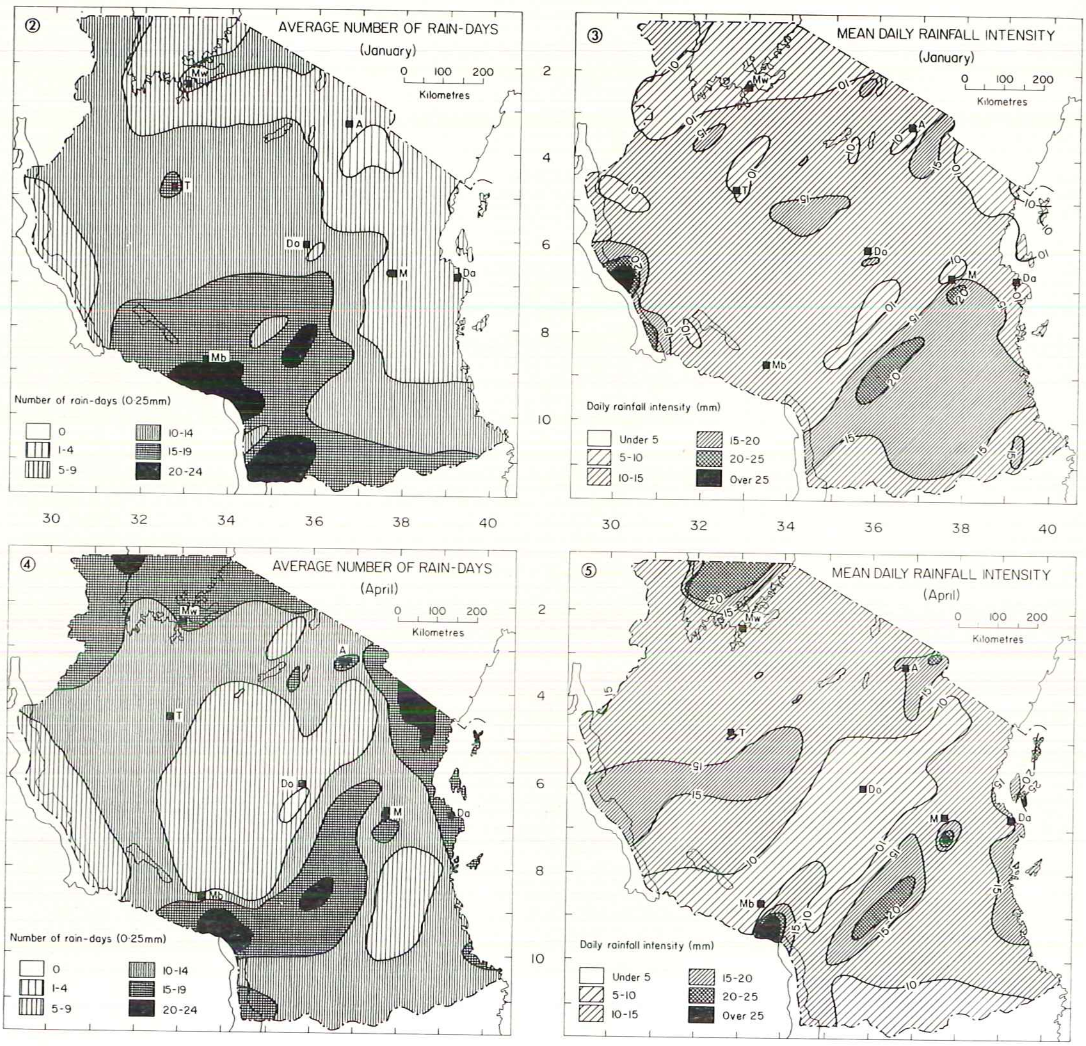
Table 1. Average number of rain days against average monthly rainfall, correlation coefficients (r) and regression lines. $S_y$ = standard error of regression estimate, x = average monthly rainfall, y = average number of rain days.

| Mth | r | r² | Regression eqs. | $S_y$ |
|---|---|---|---|---|
| Jan. | 0.841 | 0.707 | $y = 0.0594x + 2.8805$ | 2.41 |
| Apr. | 0.845 | 0.714 | $y = 1.0104\sqrt{x} + 0.6507$ | 2.50 |
| Jul. | 0.949 | 0.901 | $y = 0.1562x + 0.1799$ | 1.34 |
| Oct. | 0.930 | 0.865 | $y = 0.0907x + 0.6936$ | 1.27 |

From the above results therefore, it would seem that in January, July and October, higher average monthly rainfalls are associated with greater numbers of rain days rather than higher intensities (i.e. in wetter areas, it rains more often rather than more heavily than in drier areas). April however, represents a departure from this pattern. A feature particularly ap-

Table 2. Mean daily rainfall intensity against average monthly rainfall. Correlation coefficients (r) and regression lines. x = average monthly rainfall, y = mean daily rainfall intensity, July 1 = all stations, July 2 = stations with zero values excluded, $S_y$ = standard error of regression estimate.

| Mth | Correlation coefficient r | r² | Regression eqs. | $S_y$ |
|---|---|---|---|---|
| Jan. | 0.438 | 0.192 | $y = 0.0239x + 9.1464$ | 3.04 |
| Apr. | 0.862 | 0.743 | $y = 0.0319x + 6.8948$ | 2.26 |
| Jul. 1 | 0.553 | 0.306 | $y = 0.0751x + 2.5417$ | 2.92 |
| Jul. 2 | 0.382 | 0.146 | $y = 0.0418x + 4.3638$ | 2.74 |
| Oct. | 0.287 | 0.082 | $y = 0.0322x + 7.8637$ | 3.79 |



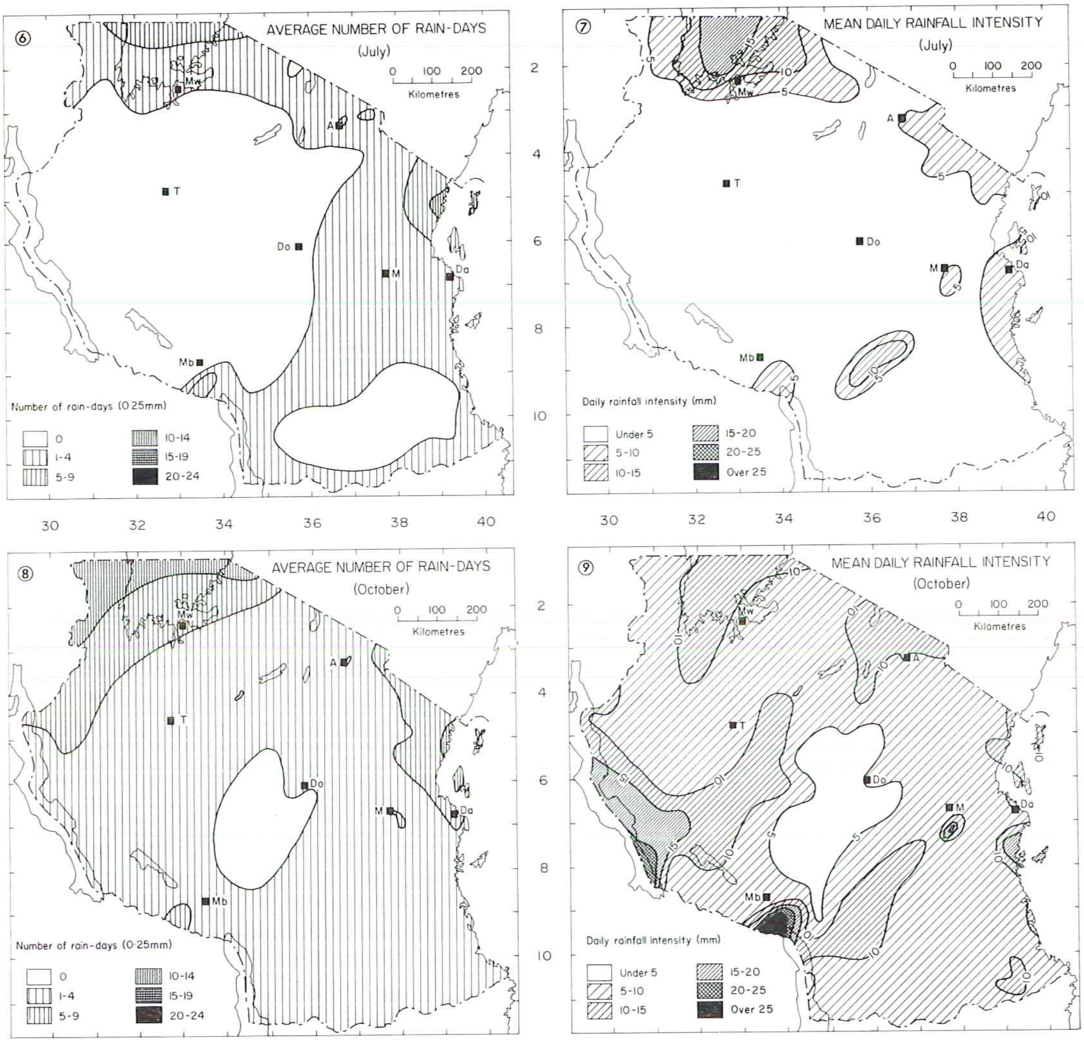

Figs. 2—5.

parent in July and October is that stations with the highest mean daily rainfall intensities are those with low average monthly rainfall. This indicates the occurrence of infrequent heavy showers in these dry areas (usually only one rain day per month on average).

*The spatial variation of average number of rain days and mean daily rainfall intensity*

Since there is a close relationship between numbers of rain days and average monthly rainfall, it would be expected that the former would present a spatial pattern similar to that of average monthly rainfall. Except for April, this would not apply so much to mean daily rainfall intensity. Figs. 2—9 are best examined by treating each month separately. It should be emphasised that in the absence of data, conditions shown over the Lake areas, particularly Lake Victoria are very tentative.

*January*. Following the average monthly rainfall pattern, the south-western part of Tanzania has the highest number of rain days (+ 20) falling off to the north and east where some parts have four days or less. The area east of Lake Tanganyika has comparatively




Figs. 6—9.

few rain days (5—9). The spatial variation in mean daily rainfall intensity is rather different and quite complex. There are two major areas of high intensity; the southern Lake Tanganyika area and the south eastern part of the country. The Lake Victoria area and the north-east have relatively low intensities. Much of the rest of the country has intensities of between 10—15 mm per rain day.

*April.* There are three fairly extensive areas with comparatively few rain days covering an area east of Lake Tanganyika (as in January), the central area of the country and an area inland from the south coast. The Lake Victoria area, the north east, and an area extending north east from the Southern Highland have a substantial number of rain days, between 15—19 days, rising to 20—24 in some parts. As would be expected from the regression (Table 2), the intensity pattern bears more relation to the average monthly rainfall pattern than is the case in the other months. There are two areas of relatively low intensity (5—10 mm); a central wedge and the extreme south of the country. Highland areas, Lake Victoria, coastal areas, and the area north west of Lake Nyasa have high intensities.

*July*. A large part of the west of the country and the south have an average of 0 rain days. Most of the rest of the country has only 1—4 rain days except for the extreme north east and northern Lake Victoria area, which have 5 or more. Most of the country has daily intensities of under 5 mm except for highland areas, the Lake Victoria area and the coast.

*October*. In October, most of the country has between 1—4 rain days, the exceptions being the north west and north east with more and a central area with 0. The intensity pattern is much more complex. There is again a central area with low values (under 5 mm). Lake areas, highland areas and the coast have relatively high intensities (more than 10 mm) and the rest of the country has between 5—10 mm.

*Percentage of the total area having particular mean daily rainfall intensities*
The above data indicates seasonal and spatial variations in rainfall intensity and numbers of rain days. For Tanzania as a whole, in terms of say application to soil erosion studies, it may also be of interest to have some indication of the proportion of the country experiencing certain mean daily rainfall intensities. The areas were measured on the maps by means of a planimeter and the results are presented in Table 3.

During the two wetter months of January and April, no part of the country has a mean daily intensity of less than 5 mm and about 80 % of the area has intensities in excess of 10 mm. 61 % of the country has mean intensities of 10—15 mm. Only 3—4 % of the area has high intensities of more than 20 mm in these two months. During July, 94 % of Tanzania has mean daily intensities of less than 10 mm, the corresponding figure for October being 73 %. In July, over 80 % of the country has intensities of less than 5 mm.

Table 3. Percentage of total area having particular mean daily rainfall intensities.

| | Intensity mm | | | | | |
|---|---|---|---|---|---|---|
| | <5 | 5−10 | 10−15 | 15−20 | 20−25 | >25 |
| Jan. | 0 | 16 | 61 | 20 | 2 | 1 |
| Apr. | 0 | 20 | 61 | 15 | 3 | 1 |
| Jul. | 82 | 12 | 4 | 2 | 0 | 0 |
| Oct. | 8 | 65 | 22 | 3 | 1 | 1 |

## Conclusions

The general aims of the paper were set out in the introduction. No discussion of the meteorological conditions responsible for the variations in daily rainfall conditions is presented here although it is possible that the data, particularly as shown in Figs. 2—9, may suggest possible interpretations or aspects for further analysis.

With the exception of April, it appears that wetter areas are more likely to be associated with more rain days rather than with greater daily rainfall intensities. In July and October, the greatest daily rainfall intensities occur at stations with low average monthly rainfall.

The great spatial variations in intensity and number of rain days in each of the months is illustrated by Figs. 2—9. During the two wetter months of January and April, a very large part of the country has daily intensities of 10 mm or more. As would be expected from the results of the regression analysis (Tables 1 and 2), whilst the spatial pattern of number of rain days resembles that of average monthly rainfall, in January, July and October, the same is not true for mean daily rainfall intensities.

## Acknowledgement

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*Dr. Ian Jackson, Dept. of Geography, The University of New England, Armidale, N.S.W. 2351, Australia.*

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# CONCLUSIONS FROM THE DUSER SOIL EROSION PROJECT IN TANZANIA

BY ANDERS RAPP

Department of Physical Geography, University of Uppsala

The 15 papers of this volume form an integrated geographical study of soil erosion and sedimentation in some tropical environments under heavy human influence. The main approach of the project is geomorphological and hydrological. Surface runoff, erosion, and sedimentation were documented in a number of catchment basins. The catchment studies are supplemented by earlier data from erosion plots, either collected from unpublished reports in Tanzanian archives or compiled from published papers. To widen the perspective in time and space, the history of land use and soil conservation has been reconstructed as far as possible. Furthermore, a number of papers in the volume deal with special studies—rainfall over Tanzania, soils on Mt. Meru, and sediment transport of the Rufiji river—thus widening the perspective also in a methodological sense.

The most important message that this volume contains is about the necessity to observe critically the reactions of the environment upon exploitation, and to draw rational conclusions for a better land use from these observations. Every land development scheme should to some extent also be a research project. As such it should from the planning stage be designed to allow scientific observations, comparisons, and conclusions concerning its impact on environment and man. In other words, for long-term success, development schemes must be combined with accurate documentation, so that through later comparisons, initial mistakes can be recognized and corrected. Schemes of water and soil conservation must be provided with reliable maps, profiles, reference photographs, and descriptions documenting the situation before the project, so that accurate and inexpensive evaluation of environmental changes during the progress of the work can be made (e.g. changes in erosion, reservoir sedimentation, afforestation, grassland reclamation, stock numbers, and human population).

Any environment under heavy human influence is nevertheless to a certain extent under the control of natural structures and processes.

This is quite evident in the two types of marginal tropical lands—deforested mountains and overgrazed semi-arid grasslands—which we have studied in this project. However, both in the industrialized world and in developing countries man has increasingly neglected the limits of the environment and tried to conquer instead of cooperate with nature. Hence the world of to-day is facing a global ecological crisis. One part of this world-wide pattern is the crisis of land use in the developing countries, another is that of pollution in the industrialized world.

We have in the DUSER project made a particular effort to present carefully documented and illustrated cases, which we hope are understandable and convincing, not only to scientists, but also to decision makers, planners, and farmers. We have in the cases studied tried to document the kind and rate of erosion and sedimentation. On the basis of our diagnosis of the illness of the catchments, we have also recommended methods for their continued observation and treatment. However, we have intentionally avoided going deeply into the details of the cures, because such details should be further discussed with agronomists, foresters, conservationists, water development planners, and economists before being transformed into actual development schemes.

Two important points have been stressed in our approach to catchment studies: (1) the spatial interaction of landscape factors such as relief, soils, and vegetation, and (2) the importance of long-term variations in processes, particularly rainfall extremes, and floods.

The selected study areas represent two different ecological zones: (1) steep, cultivated mountain slopes with perennial stream flow, and (2) semi-arid savanna plains with a long, dry season, severe shortage of water, and seasonal streamflow.

## Mountain areas

The studies of the catchments at Morogoro and Mgeta show that small landslides and mudflows triggered by extremely intense rainstorms are important processes affecting steep cultivated slopes in the western Ulugurus. The case study of a rainstorm at Mgeta showed an average landslide denudation of 14 mm over an area of 20 km$^2$ from this single storm. Erosion by landslides and mudflows is also active under forest and woodland, but is greatly accelerated on deforested slopes, as the data from Mgeta show. The recurrence interval of such events on deforested slopes in the Ulugurus is probably one to a few decades, judging from analyses of records of rainfall intensity.

The "normal" annual erosion from splash and sheet wash in the Morogoro catchment corresponds to a general denudation of 0.26 mm or 260 m$^3$/km$^2$. A tenfold higher intensity of denudation by slopewash is likely on the 10 % of area that is under cultivation within the catchment. This conclusion is supported by erosion plot records from Mfumbwe in the Ulugurus. Further information concerning the erosion and runoff on slopes in areas of high rainfall is provided from soil erosion tests in plots at Lyamungu and Tengeru in northern Tanzania.

The most feasible means of controlling landslide erosion on such mountain slopes would be shelter belts of forest planted below ridge crests, along road cuts and along stream sides, to stabilize the soil and regolith with tree roots. Slopewash can be considerably diminished by use of cover plants, mulching, reduced burning, and change to perennial instead of annual crops.

In summary, we recommend continued and extended studies of water and sediment budget in mountain catchments of small size (1—20 km$^2$). Such studies are necessary as a basis for better knowledge of the following problems:

a) The loss of water, soil and plant nutrients from areas under different type of cultivation or grazing, as compared to forested catchments.
b) The importance of catastrophic erosional events due to heavy, infrequent rainstorms, as compared to average annual erosion losses; the so-called magnitude-and-frequency problem.
c) The time needed for recovery of soil, vegetation and economy after severe erosion.
d) The best inexpensive conservation practices, their implementation, and maintenance in a long term perspective.

## Semi-arid savanna lands

The rate of soil erosion and reservoir sedimentation is very high in the four catchments investigated near Dodoma and the one near Arusha. Reservoir sedimentation rates in the cases investigated correspond to annual sediment yields of 200—730 m$^3$/km$^2$ averaged over the longest periods of available records. The figures of sediment yield decrease with increasing drainage area, due to sedimentation in the catchment. Therefore sediment yields from small catchment basins, a few km$^2$ in area, reflect most closely the erosion in the catchment. The suspended sediment transport in the Rufiji river at Stiegler's gorge amounts to 15—20 million tons/year with the highest concentrations in the beginning of the rainy season, which is characterized by marked fluctuations in discharge, due to flash floods in the different tributaries.

The most important process of erosion in the Dodoma and Arusha catchments is sheet wash from overgrazed land and unprotected cultivations. Gully erosion is spectacular in some areas but a clear understanding of the mechanism and frequency of gully cutting could not be obtained during the short time of the DUSER project. Gully cutting is probably connected with rare and extremely intense rainstorms. Studies of when and how gullies are cut and how they function as drainage lines for water and sediment should continue and provide a basis for the establishment of efficient methods of gully control.

Judging from our studies the life lengths of reservoirs in the Dodoma and Arusha areas are very short due to rapid sedimentation. Reservoir surveys to document the rate and type of sedimentation and to establish the remaining life length of reservoirs should be undertaken as standard practice for all existing and planned reservoirs in semi-arid areas. Reservoir maps and profiles should be made, and sedimentation pegs established when a development project starts, so that through later comparisons one can determine how the project has affected the area.

Improved grass management in the semi-arid catchments is the best general method of decreasing soil erosion and increasing the life-length of the reservoirs.

In summary we recommend continued and extended studies of the water and sediment budget in catchments of all sizes in semi-arid regions. Such studies will provide a basis for better knowledge of the following problems:

a) The range of losses of water, soil and plant nutrients from areas under different types of land use, as compared to good grassland management.
b) The importance of catastrophic erosional events due to heavy infrequent rainstorms in comparison with average annual losses. Particular emphasis should be placed on the problems of gully erosion in relation to sheet erosion.
c) The time needed for recovery of soil, vegetation, and economy after excessive erosion.
d) The best and least expensive conservation practices in semi-arid lands, their implementation and maintenance in a long term perspective.
e) The rate of reservoir sedimentation and the distribution, texture, and structure of the deposits. Such studies provide important information for many purposes such as erosion in the catchment, prognosis of life-length of reservoir, and possible use of sand-filled reservoirs for ground-water storage.

STUDIES OF SOIL EROSION AND SEDIMENTATION IN TANZANIA

Edited by Anders Rapp, Len Berry, and Paul Temple.

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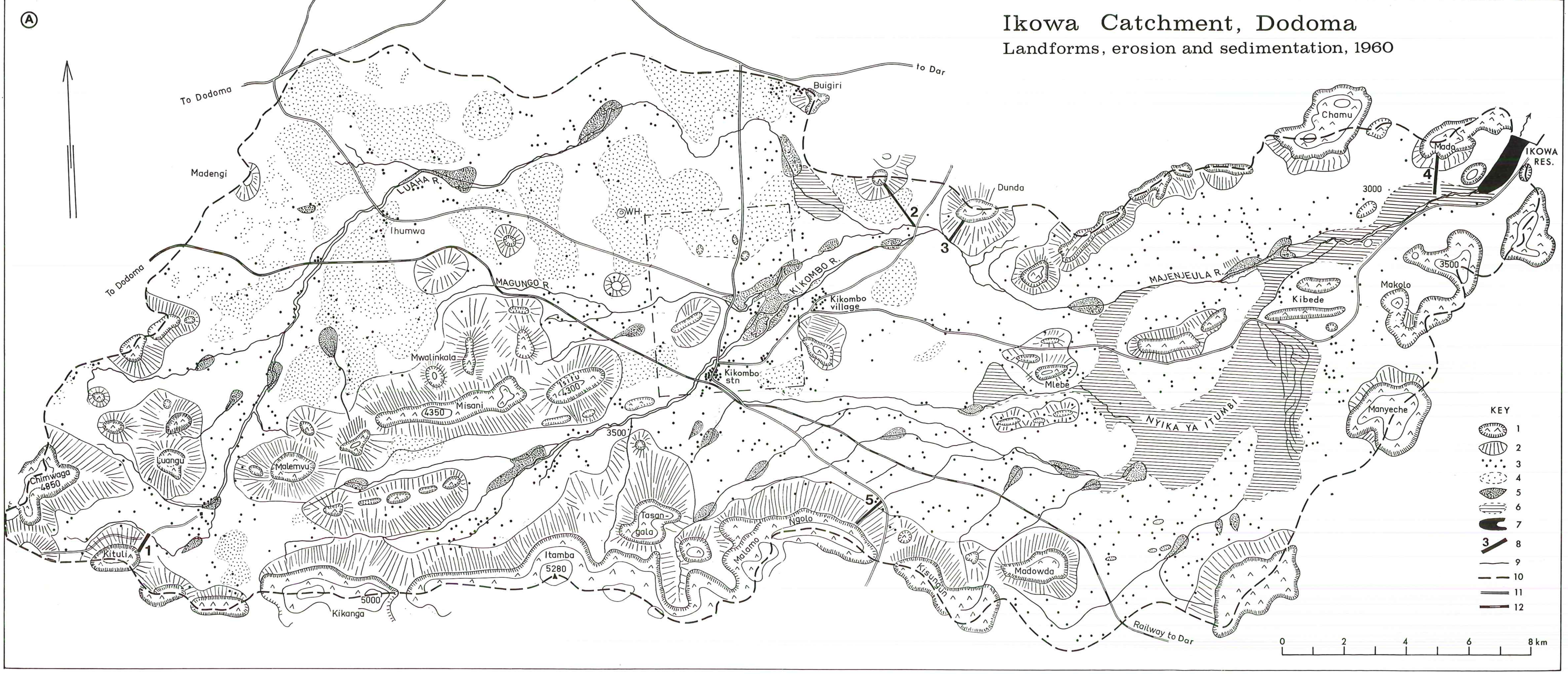
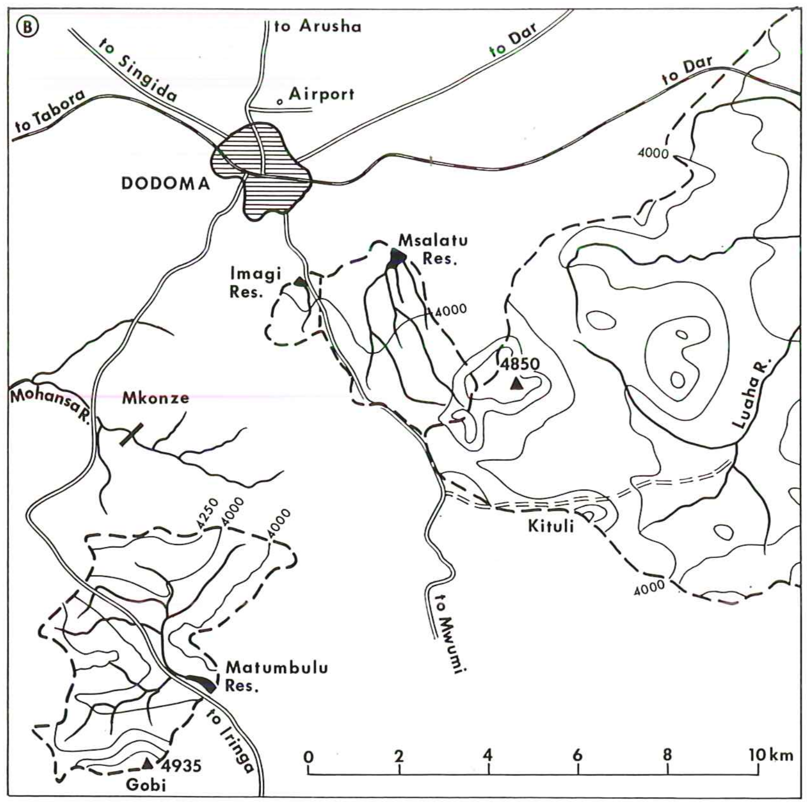


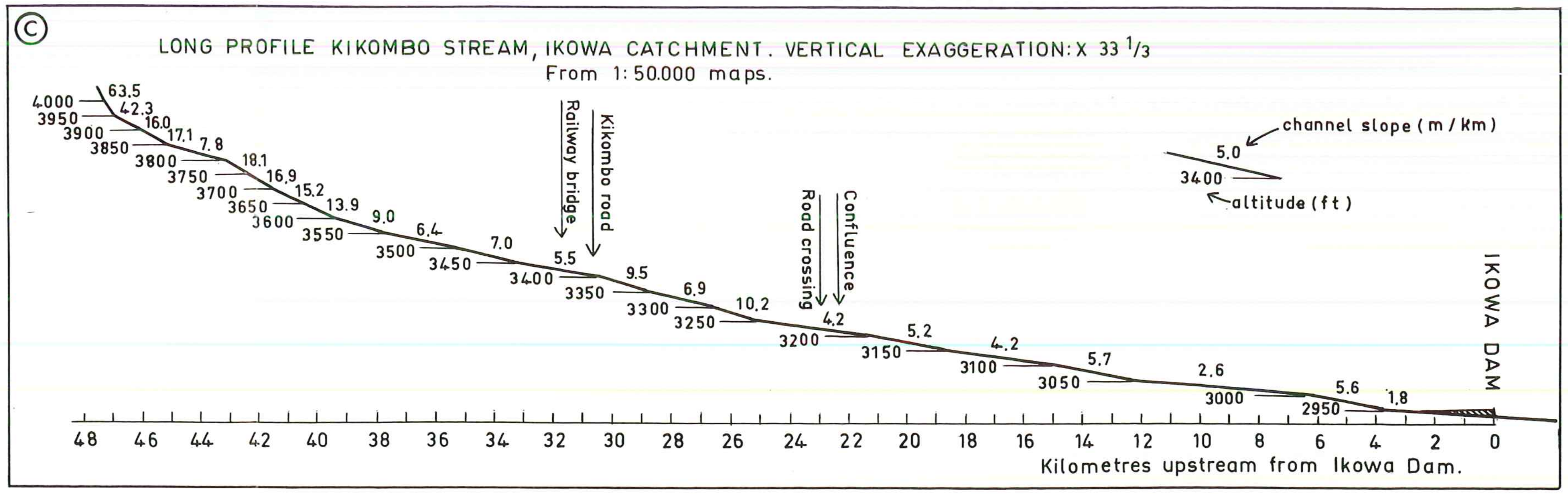
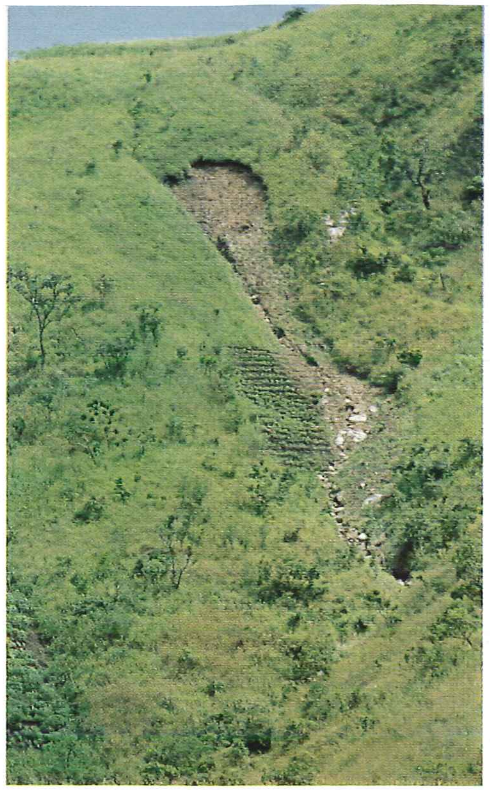




Plate 1A. Map of Ikowa catchment showing landforms and zones of erosion and sedimentation. Based on air photographs of 1960 and topographic map. Key: 1. Inselberg or other bedrock hill with miombo woodland. 2. Zone of dense gully patterns on upper pediment. Predominantly grazing areas. 3. Homesteads, most of them on lower pediment zone with much cultivation. 4. Area with many termite mounds and thicket. 5. Sand fan. 6. Mbuga floodplain with clayey sediments. 7. Ikowa reservoir. 8. Slope transect measured in 1971. 9. Stream channel. 10. Drainage divide. 11. Road or track. 12. Railway. Altitude figures in feet (3000—5280). Rectangle of dashed lines marks area of Fig. 12. South of Kikombo village is a terrace cultivation from the 1940s. Dar = Dar es Salaam.

Plate 1B. Location of Matumbulu, Msalatu and Imagi catchments near Dodoma and close to western part of the Ikowa catchment. Contour interval in catchments 250 feet. Black rectangle = proposed dam site at Mkonze.

Plate 1C. Long profile of the Kikombo and the Majenjeula stream channels, Ikowa catchment. Based on topographic map with contour interval 50 feet.



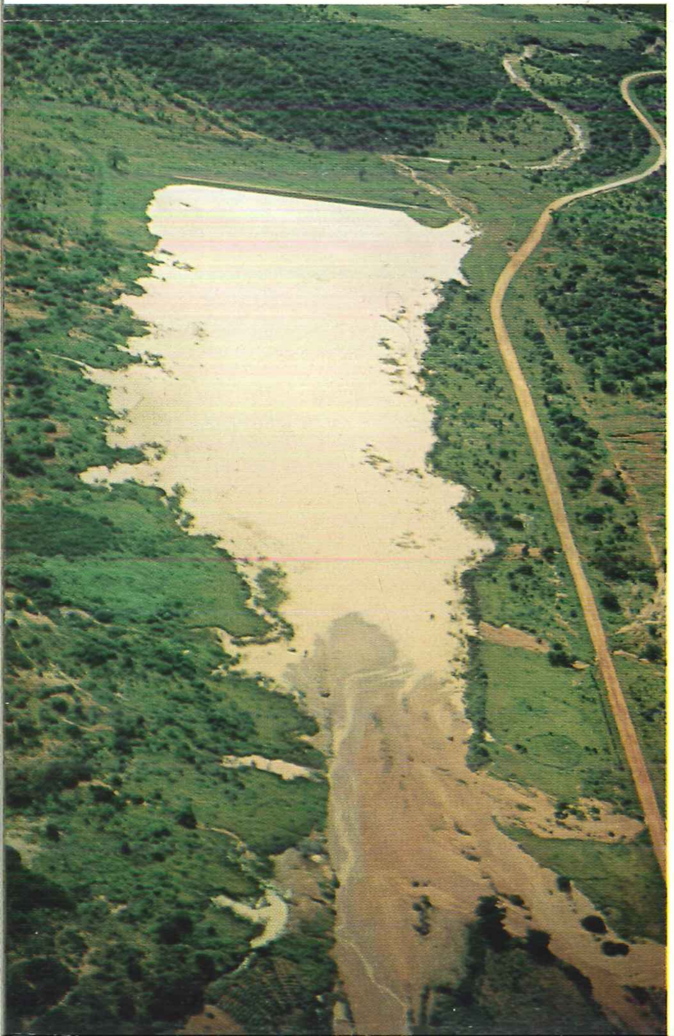


Plate 2A (above left). Debris slides and mudflows at Mgeta. Contrast the two slides originating in woodland reserve with the numerous small slides affecting cultivated land. Compare with Figure 13. The colour plate makes slide identification easier. Photo AR: 3/70.

Plate 2B (above right). Small landslide near Kidiva pass in the Mlali headwaters showing mudflow track below. Note typical position of slide scar below ridge crest and damaged *shamba* with ladder terraces. Photo AR: 3/70.

Plate 2C (left). Matumbulu reservoir showing delta lobes of sand. Photo AR: 3/70.

Plates 2D & 2E (opposite). Seasonal contrasts in the Ikowa catchment at slope transect 4, 3 km west of dam. Above, dry season, October 1969, Photo JMcK: Below, wet season, March 1970, Photo AR. Note zonation—miombo woodland, grazed & severely eroded area, maize *shambas, mbuga*.

Plates 2A and 2B: Temple and Rapp, Geogr. Ann., 1972, 3—4.

Plates 2C, 2D and 2E: Rapp, Murray-Rust, Christiansson and Berry, Geogr. Ann., 1972, 3—4.