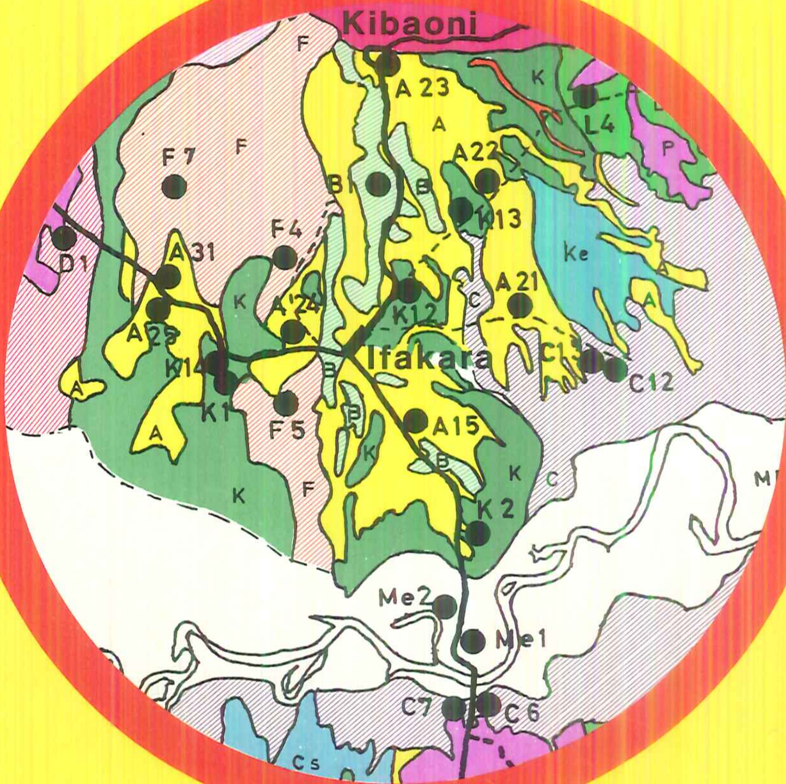

Helmut Bonarius

PHYSICAL PROPERTIES OF SOILS

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Cover page shows a map of the Ifakara-Project-Area

PHYSICAL PROPERTIES OF SOILS IN THE KILOMBERO VALLEY (TANZANIA)

HELMUT BONARIUS

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Eschborn 1975

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PHYSICAL PROPERTIES OF SOILS IN THE KILOMBERO VALLEY (TANZANIA)

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PREFACE

Several reports describing the economic conditions, institutional aspects and physical conditions of the Kilombero valley in the south western part of Tanzania have already been published, the best known of which are those of Telford (1929), FAO (1961), Jätzold and Baum (1968) and the studies of the Dutch consultant ILACO (1966, 1968 and 1970).

The FAO report of 1961, in seven volumes, presents a broad term development plan for the improvement and conservation of land in the catchment areas of the Rufiji Basin. The establishment and management of the joint Tanzanian-German Kilombero Agricultural Training and Research Institute (KATRIN), only few kilometres from Ifakara, is associated with the rural land use programme designed for the Kilombero valley. To a great extent, the efforts of the KATRIN-Project aim at evaluating crops to be grown profitably under irrigation and at carrying out irrigation methods applicable to the climatic and soil conditions in the valley.

The purpose of this paper is to provide additional information on the physical properties of the Kilombero basin soils and to assist in discussions on possible land utilization with regard to both irrigated and rainfed farming, given the present situation in the valley.

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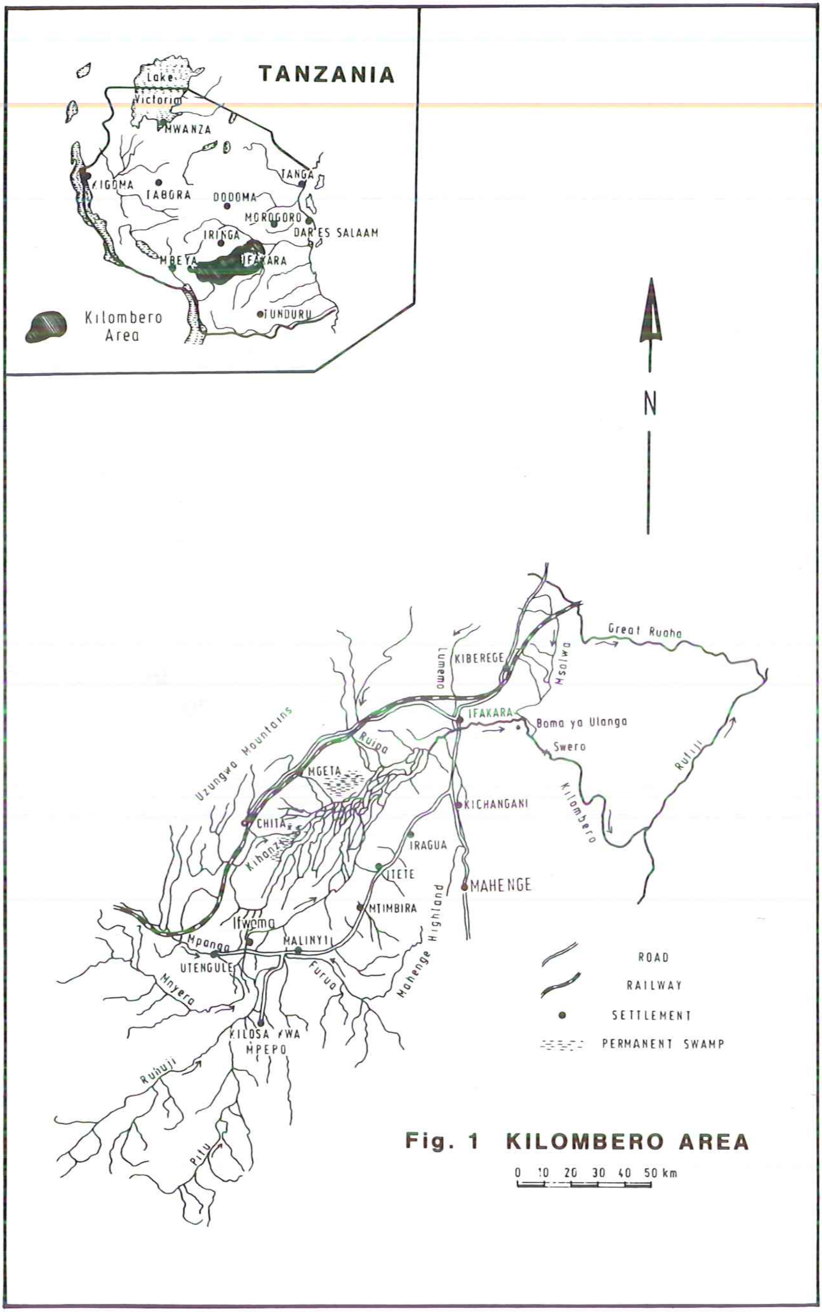

Fig. 1 KILOMBERO AREA

FEATURES OF THE KILOMBERO VALLEY

The Kilombero valley (Fig. 1) features a topographical depression running roughly south-west to north-east. From Boma ya Ulanga the Kilombero river flows in a narrow valley southwards. In northern continuation, this "Rift Valley Depression" follows the Msolwa river valley in the section from Ifakara up to the banks of the Great Ruaha river. The adjoining Uzungwa mountains in the north-west rise abruptly to an altitude of 2000 m, but in the south-east the ascent is at first gentle changing after several miles to the steep Mahenge mountain block 900 to 1500 m high.

The Kilombero basin floor lies on average 270 m above sea level covering $^1/_4$ of the whole Kilombero catchment area, i. e. about 11,500 km^2. The change in level in longitudinal section from Ifwema to Swero is about 0.4 ‰. Just at Swero is a rock bar, which largely determines the soil and hydrological features of the Kilombero river alluvial plain.

Three main rivers, the Ruhuji, Mnyera and Mpanga, form the Kilombero river itself. The more important tributaries of the Kilombero river up to Boma ya Ulanga are Furua on the right bank and Kihanzi, Ruipa, Lumemo and Msolwa on the left bank. The slope of the tributaries down to the foot of the escarpments ranges from 5 to 40 ‰. The steep relief causes rapid water flow, and with entrance into the valley, the river gradients are decreased by $^1/_{10}$ to $^1/_{100}$ of the original gradients with a resulting formation of alluvial fans bordering the floodplain.

The extensions of the different alluvial fans are not uniform even though mainly almost semicircular in shape, correlating with the river gradient. On the south-west side of the valley the alluvial fans are best developed, forming an extensive piedmont alluvial plain or bajada. These considerable extensions indicate sparse vegetation and torrential rainfall with advanced soil erosion in the catchment areas of these rivers. Suspended loads of up to 1 kg per m^3 were measured (Furua river 1958/59). However, on the north-west side the rivers form smaller, but in general more fertile alluvial fans penetrating and overlying the comparatively poor, non-alluvial sand-flats on the edge of the floodplain (FAO, 1961).

The Kilombero valley is enclosed in the Usagaran System of the Basement Complex, an asymmetrical rift valley depression, caused by Pliocene faultings (Jätzold, 1968). The Usagaran System itself consists chiefly of migmatitic gneiss and acid granulites (FAO, 1961). The gneiss, rich in biotite, weathers very easily to fine grits and coarse sands; the granulites disintegrate to stony material and fine grits. With continuous modification the parent material becomes loamy gravelly in a transitional stage, then loamy sand and sandy loam soils (Fiedler, 1964).

The economic infrastructure, and with it the rural development of the Kilombero valley, is rendered more difficult because of periodic floodings, the result of rainfall patterns in the surrounding mountain ranges. About $^1/_3$ of the total plain, i. e. 400 km^2, is semi-perennially or prennially flooded.

With maximum emergence in March—April, the flood level may then be one to three meters above ground. The flooding along the Mgeta-Iragua line in the central portion of the extensive braided river zone may have a width of 24 km but downstream in the meander zone along the Ifakara-Kichangani line, a width of only 3.4 km, correlating with the varying topographic features from and to the adjacent uplands (Telford, 1929). Proposals made in the FAO report of 1961 would implement flood control and extensive, dry-season irrigation by constructing seven storage dams at the Kigogo-Ruaha-, Mnyera-, Ruhuji-, Mpanga-, Kihanzi-, Ruipa- and Lumemo-rivers.

INVESTIGATIONS

The soil reconnaissance maps of Anderson (FAO, 1961) were used to select sites representative of the physiological land units found in the Kilombero valley. Measurements and soil samplings were done along roads and tracks passable by Landrover and in the floodplain along the Kilombero river, which is navigable by motor boat. The infiltration rate measurements were conducted in the field. Hydraulic conductivity, soil-moisture availability and bulk density were determined in the laboratory. Only the surface 20 cm of the soil profile was investigated.

Infiltration rate

By this method the downward flow of water from the surface into the soil is determined. The soil takes in water rapidly, when water is first applied. As the water application continues the surface soil gradually becomes saturated and the inflitration rate decreases until it reaches an almost constant value. The data presented here are based on this constant values as obtained under saturated flow conditions. The measurements were carried out according to the Double-Ring Infiltrometer method of Swartzendruber and Olson (1961).

Hydraulic conductivity

This measurement is used to describe the ease with which soil transmits water under saturated soil-water conditions. The measurements were made in the laboratory using 250 cm^3 cores placed in a Constant-Head-Permeameter. Four replicate samples were tested for each site.

Soil-moisture availability

The available soil moisture was determined on undisturbed soil samples placed in soil-moisture extractors at pF 2.0 (equal to 1.4

p.s.i.) and pF 4.2 (equal to 225 p.s.i.). The Field Capacity (FC) ranges between pF 1.8 and 2.5, at which pF 2.0 was applied as the average value. The tension of pF 4.2 has been adopted by many soil scientists for the Permanent Wilting Point (PWP). The soil moisture content between Field Capacity and Permanent Wilting Point is considered as the soil water available to the plants. Four replicate samples were tested for each site.

Bulk density

This is defined as the ratio of the weight of a given volume of dry soil, air space included, to the weight of an equal volume of water.

Bulk density is needed for the determination of soil moisture contents on volume percentage basis. Moreover, the bulk density may be generally interpreted as a significant indication of the soil structure.

Two cores per sampling site, each of 100 cm^3, were dried at 105°C, then weighed and bulk density calculated.

RESULTS

The results of the infiltration rate and available water content measurements have been classified, taking into account the soil types as reported in the soil reconnaissance survey of Anderson (FAO, 1961), the land use and natural vegetation as mapped by the author, and the physiographic units as described by Jätzold and Baum (1968) for the Kilombero valley. With these background data a detailed interpretation of the results is possible. Attempts have been made to find a functional relation between infiltration rate and hydraulic conductivity as well as between available water content and bulk density.

Infiltration grouping in accordance with the soil classification units

The results of 109 infiltration tests are illustrated in a histogram (Fig. 2), grouped according to the infiltration classes given in Table I.

Table I: Infiltration rate and its classification (according to Kohnke, 1968)

Class	Infiltration Rate cm/hr
very slow	< 0.1
slow	0.1 – 1.0
moderate	1.0 – 10.0
rapid	10.0 – 25.0
very rapid	> 25.0

The infiltration rates vary widely between the individual soil groups. However, the mean values do exceed 10.0 cm/hr. Therefore, regardless of variation the infiltration rates of soils in the Kilombero valley may be classified by reference to their averages as rapid to very rapid.

It is of particular interest that 40–50 % of the results for soil groups A, K+KL and C+Cs+Cn+Me are lower than 10.0 cm/hr and are therefore in the range of slow to moderate infiltration. This is unlike the results for soil groups B, P+Pm+L+G and F+T+W, where only 10–15 % of the sites show infiltration rates below 10.0 cm/hr. Generally, infiltration rates under 0.1 cm/hr do not occur. The areas consisting mainly of clayey soils, as described by Anderson (FAO, 1961), belong to soil groups with significantly lower infiltration.

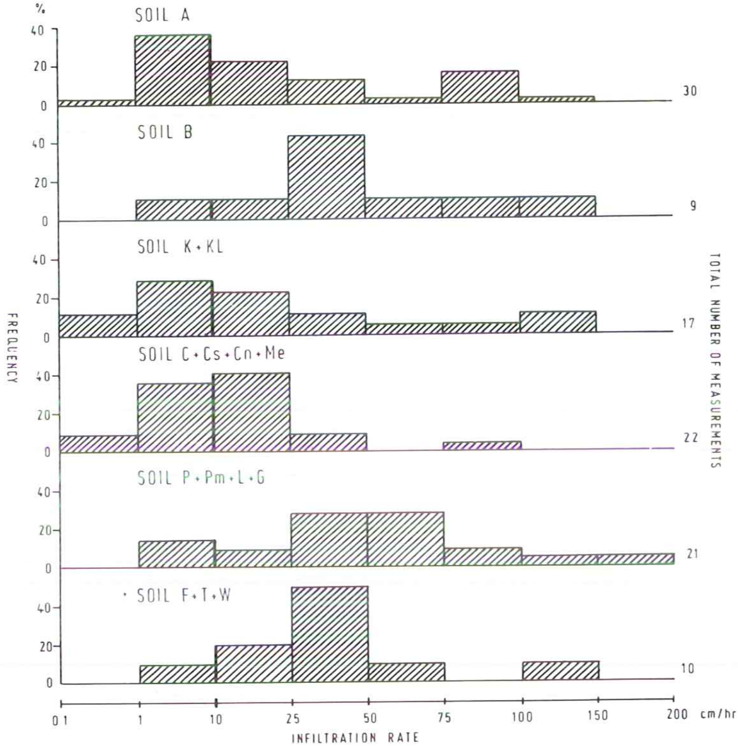

Fig. 2: Infiltration Rate of the Soils in the Kilombero Valley
(see Appendix for Soil Description)

Infiltration grouping in accordance with land use and natural vegetation

The method of interpretation used in relation to the soil classification units will also be applied in the case of the land use forms and natural vegetation associations. A total of 120 measurements are subdivided into six groups as presented in Fig. 3.

On average, all infiltration rates exceed 10.0 cm/hr. The soils with mbuga + grassland occupy an exceptional position. With average infiltration of 13.5 cm/hr, these soils tend towards the 10.0 cm/hr boundary. 58 % of the sites with infiltration between 0.1 and 10.0 cm/hr (slow to moderate infiltration rate) are on mbuga + grassland whereas 44 % are under sugar cane. 20–30 % of the land used for rice, intercropping, as well as the areas with miombo- and forest-vegetation, have infiltration rates of less than 10.0 cm/hr, but only 20 % of the soils with scrub and scattered trees have infiltration of between 0.1 and 10.0 cm/hr.

A significant finding of the present investigation is, that mbuga and grassland association, which prevails on soil C, can be regarded as having a relatively slow water transmission.

Infiltration grouping in accordance with physiographic units

It is useful to divide the Kilombero valley into physiographic units to provide relevant data for the rural development planning in the valley. For this reason the following subdivisions of physiographic units as described by Jätzold and Baum (1968) were used:

- South West Alluvial Fans (in the terrain between the tributaries Ruhuji and Luri)
- North West Alluvial Fans (in the terrain between the tributaries Mpanga and Ruipa)

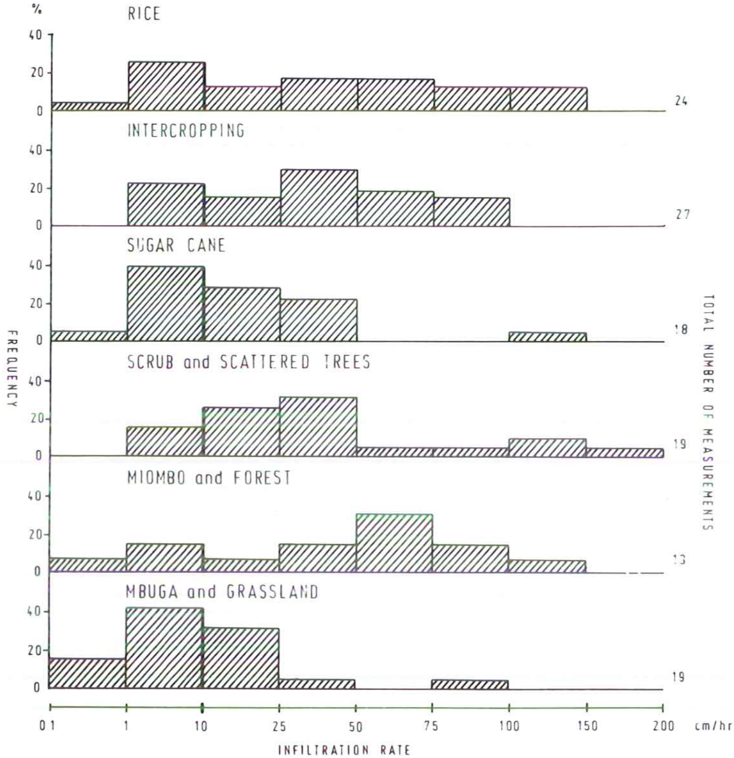

Fig. 3: Infiltration Rate grouped in Accordance with the Land Use and Natural Vegetation

- North West Alluvial Fans (in the terrain between the tributaries Idete and Lumemo)
- Msolwa Alluvial Fans (all tributaries of Msolwa river included)
- Kilombero River Zone
- Savanna Plains
- Miombo Plains

Hitherto the alluvial fans in the area, from the fanhead to three quarters down their slope have been mainly used as arable land. To some extent peasant farming extends into the savanna and miombo plains.

The comparative test of the average infiltration rates for the different physiographic units was done according to Wilcoxon (1949). The test revealed a significantly higher infiltration rate for the miombo plains (56.4 cm/hr) and a significantly lower one for the Kilombero river zone (6.2 cm/hr) compared with the remaining units which had relatively rapid inflitration rates ranging between 25 and 40 cm/hr.

Hydraulic conductivity

In measuring and interpreting infiltration rates, only the steady-state infiltration or final infiltration capacity was quoted. Downward infiltration into an initially unsaturated soil generally occurs under the combined influence of tension and gravity gradients. As the water moves deeper in the soil, the upper zones become saturated and their tension gradient becomes negligible. The gravitational gradient is eventually the only force moving water downwards. The flux therefore tends to settle down to a steady rate, which approaches the hydraulic conductivity values of the upper soil horizons determined under saturated conditions. Corresponding to these phenomena a significant correlation between the steady-state infiltration and hydraulic conductivity may be expected.

There was a linear relationship between hydraulic conductivity (m/day) and infiltration rate (cm/hr). The regression equation was $y = 10.53 + 6.38x$, the regression coefficient $r = 0.24$ and the number of tested sites $n = 51$. However, the relation between both variables should in practice be more significant. The deviations are caused on one hand by the heterogeniety and structural instability of the soil profile and on the other hand, by inevitable inadequacies of hydraulic conductivity measurements with cores of small diameter, since only a limited soil column is tested, which is not necessarily absolutely accurate.

The statistical test according Wilcoxon (1949), applied to compare the mean hydraulic conductivity of different physiographic units has demonstrated that the hydraulic conductivity in the topsoil of the Kilombero river zone is 0.45 m/day (1.9 cm/hr), which is significantly lower than that of the other units, which exceed 1 m/day (4.2 cm/hr). The hydraulic conductivity of the Kilombero river zone is therefore moderately slow whereas it is rapid to very rapid for the rest of the units.

Bulk density

The bulk density is affected by the soil structure, i. e. its looseness or degree of compaction. With increasing looseness, i. e. enlarged volume fraction of pores, comparable soil samples become lower in bulk density. It can be assumed that a soil which is ideally loose shows at the same time a high attraction for moisture retained against gravitational potential, but available to plants. This means that bulk density and available moisture content are relatively correlated (Fig. 4).

17 % of the 72 sites investigated have a bulk density under 1.0 which indicates a higher proportion of organic matter in the topsoil layer (compare FAO, 1961). The soils in the area of the alluvial fans between Mpanga and Ruipa rivers are characterized by bulk density below 1.0. Soils with bulk density above 1.4 indicating

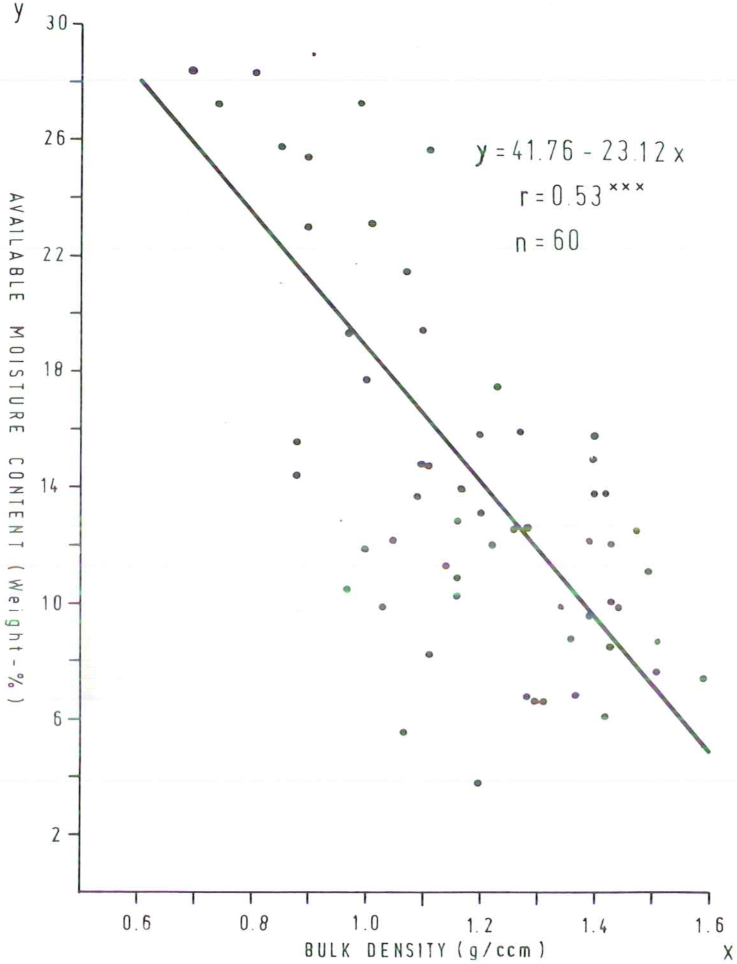

Fig. 4: Relation between Available Moisture and Bulk Density of the Soils in the Kilombero Valley

sandy non-aggregated soils and compacted well-grades soils are found predominately in the P+Pm+L+G soils and along the Kilombero river in the river zone.

Available moisture grouping in accordance with soil classification units

The data on soil-moisture availability have been evaluated in a similar manner to those of infiltration and are presented in Fig. 5. The classification stated in Table II was applied for the interpretation of the results.

Table II: Soil-moisture availability to plants and its classification (according to Fiedler and Reissig, 1964)

Class	Available Moisture Content Vol.-%
very low	<5
low	5 – 10
medium	10 – 15
high	15 – 20
very high	>20

A total of 68 tests were conducted. The tests on the B as well as on the F+T+W soils are not included in Fig. 5, since only four B soils and five F+T+W soils were tested. On average the A and C+Cs+Cn+Me soils as well as the F+T+W soils fall into the category of high available moisture content. Among them, the A soils contain 19.5 Vol.% available moisture. The soil-moisture availability of the rest of the soil groups falls into the medium category.

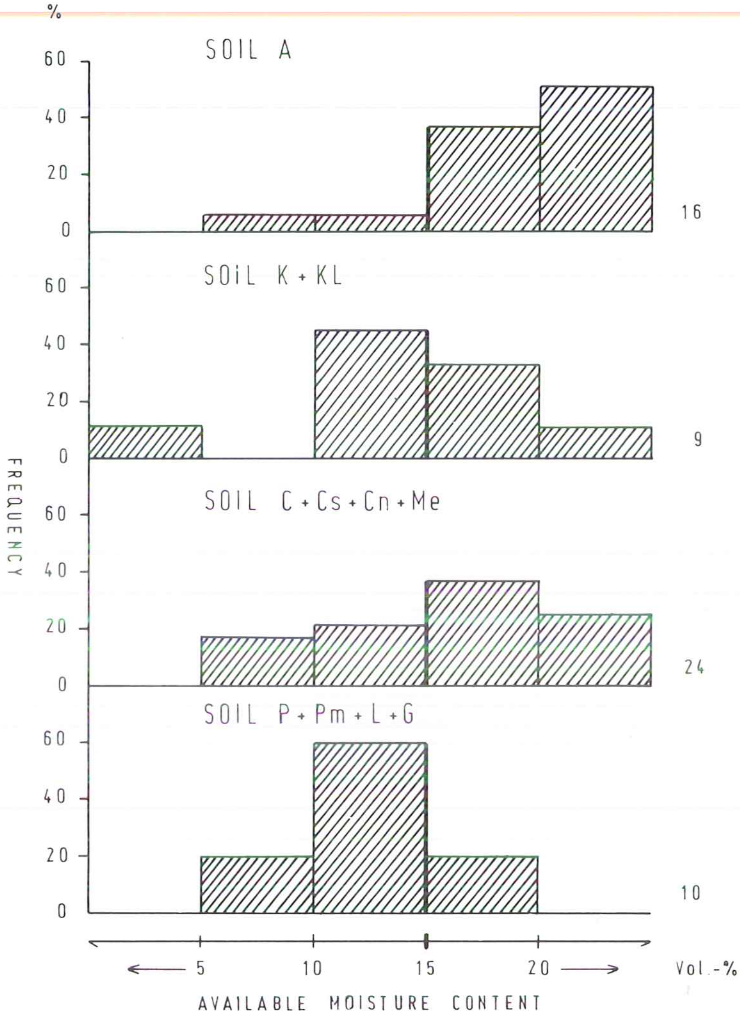

Fig. 5: Available Moisture Content of the Soils in the Kilombero Valley
(see Appendix for Soil Description)

In general, compared with the deeper layers of a soil profile, a more favourable soil-moisture availability may be expected in the surface layers owing to the higher proportion of organic matter.

For the A soils, 88 % of the sites have more than 15 Vol.-% available moisture which is the boundary between high and very high content of soil moisture. Next are the C+Cs+Cn+Me and F+T+W soils where 58 % and 60 % of the sites respectively have more than 15 Vol.-% available moisture. In both K+KL and P+Pm+L+G soils less than 50 % of the sites have more than 15 Vol.-% available moisture. The lowest moisture content is found in the colluvial sandy to loamy sand P+Pm+L+G soils.

Available moisture grouping in accordance with land use and natural vegetation

The results obtained are represented graphically in Fig. 6. Of the 72 measurements made, the investigations in the areas with miombo, scrub and scattered trees as well as forest were considered too few for presentation in Fig. 6.

The average soil-moisture availability of all vegetation and land use units ranges between 15 and 20 Vol.-% which is classified as relatively high. Only 39 % of the sites with rice cultivation are suitable for supplying plants with more than 15 Vol.-% soil moisture. However, for soils with intercropping, sugar cane and mbuga + grassland 60 % of the sites have more than 15 Vol.-% available moisture.

Available moisture grouping in accordance with physiographic units

The rapid statistical test according to Wilcoxon (1949) has demonstrated that the alluvial fan soils in the stretch between Mpanga and Ruipa rivers are with 23 Vol.-% highest in available

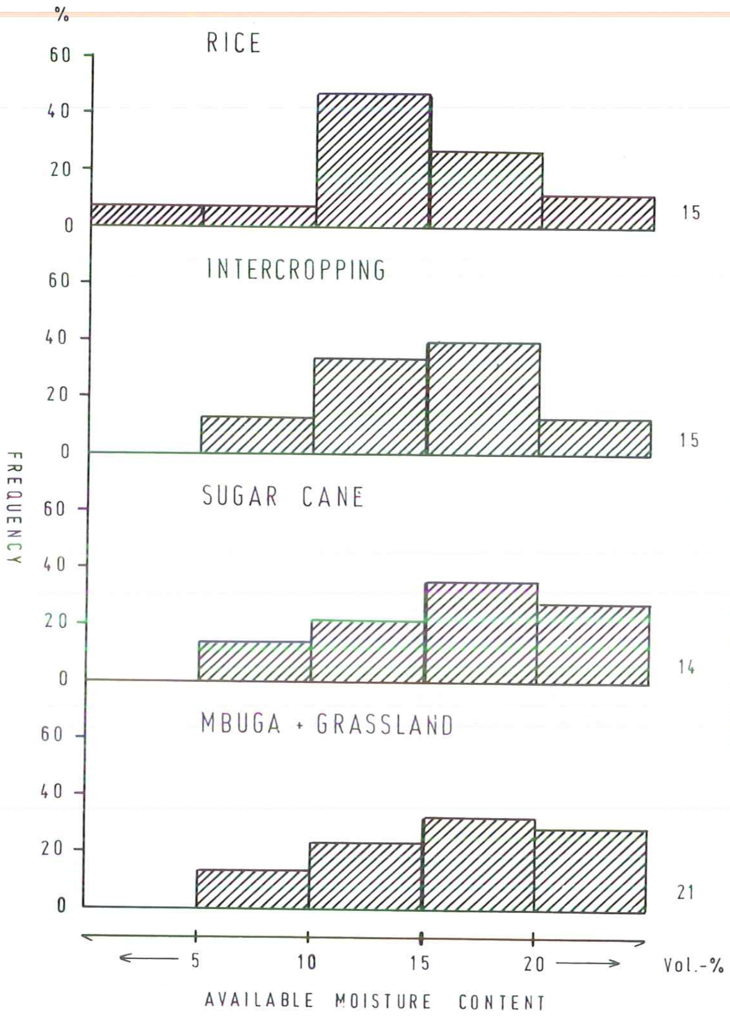

Fig. 6: Available Moisture Content grouped in Accordance with the Land Use and Natural Vegetation

soil moisture. In contrast, the alluvial fans between the Idete and Lumemo rivers, as well as the savanna and miombo plains, have less than 15 Vol.-% soil-moisture availability, which is significantly inferior to that of the other units. The south west alluvial fans, the Msolwa alluvial fans and the Kilombero river zone show on average a high water availability which ranges between 15 and 20 Vol.-%.

DISCUSSION

Soil types and their distribution are defined as dynamic sets of genetic processes conditioned first of all by topographic features, parent material and climatic conditions. The complex interrelationship of these factors in turn determines the external and internal drainage and the kind of vegetation developed in the area.

With concept of soil forming processes in mind, and in attempting to find a more generalized approach to the landscape characteristics of the Kilombero valley, three main zones are distinguishable:

- The braided and meandering river zone in the widespread central alluvial plain
- The alluvial fans laid down by streams entering the valley
- The marginal colluvial sand-flats or miombo plains

The braided and meandering river zone is semi-perennially or perennially flooded. According to Anderson (FAO, 1961) the soils of this zone consist mainly of clay and clay loam. The clay is somewhat weathered, implied by slight perpetual deposition with suspended matter of the flood water.

The hydraulic conductivity of the topsoil of the central alluvial plain is significantly lower than that of the other two zones, classified as moderately slow on the strength of the results. The hydraulic conductivity of the top layers of the alluvial fan soils as well as marginal sand-flat soils exceed 1 m/day (4.2 cm/hr) and is considered rapid to very rapid water transmission capacity. The infiltration rate of marginal sand-flats or miombo plains is 56.4 cm/hr which is comparatively rapid.

The alluvial fans are semi-perennially or non-flooded, and their proportion of little weathered minerals is remarkably high because of periodical overlay with eroded material.

The marginal sand-flats or miombo plains on the lower slopes of the mountains surrounding the valley are of colluvial origin according to Anderson (FAO, 1961). The soils are coarser and already leached.

By reason of actual hydrological circumstances in parts of the alluvial fans and miombo plains, rice is cultivated here during the rainy season, as other crops could scarcely adapt to the seasonal submergence and shallow groundwater levels occuring in these stretches. The soils used for paddy are mostly confined to the K+KL and P+Pm+L+G units, which are soils with low soil-moisture availability and weak structure. The most unsuitable soil properties are found in the marginal sand-flats where the rural population has been forced to settle because of the inundation of extensive areas. The area suitable for intensive agricultural use is restricted to the alluvial fans, predominantly sandy loam to loam in texture. Their infiltration rate is rapid to very rapid and the relatively high water holding capacity in the surface soil layers is apparently due to higher proportions of organic matter (FAO, 1961). These are the soils preferably used for intercropping which includes tree crops, bananas, paw paw, pineapples, sugar cane, maize, sorghum, sesame, cassava, sweet potatoes and vegetables, as well as for pure sugar cane plantations. Rice is also grown on those stretches affected by waterlogging, which occur predominantly along the lower boundaries of the alluvial fans. However, the data on available moisture show significant variations between the individual alluvial fans recognized in the Kilombero valley.

The alluvial fan soils in the catchment area of the Msolwa river are fairly similar to the soils in the south west section of the valley from Luri to Ruhuji rivers. According to the investigations undertaken in these zones, 30—40 mm * availbale water can be stored in the surface 20 cm of the soil profile, quite a considerable amount. The soil-moisture availability of the alluvial fan soils from Idete to Lumemo rivers is in contrast only 11 Vol.-% or 22 mm in the topsoil layers and is considered relatively low. The north west alluvial fans from Mpanga to Ruipa rivers, with an available water content of 23 Vol.-% or 46 mm in the surface 20 cm, surpass all other physiographic units. With the construction of a railway line through the area the agricultural exploitation of this promising section is likely to be intensified.

Rice is still the staple food and cash crop in the Kilombero valley. The local farmers recognize the necessity of growing mainly rice in the areas subject to flooding, or where the groundwater table is so high during the rainy season that no other crops can be grown successfully. It is reasonable to expect that irrigated rice could be cultivated during the dry season in the braided river zone of the Kilombero river, provided that effective protection measures against wild animals are instituted. The soils of the river zone have a restricted hydraulic conductivity. In addition to that, groundwater occurs at high levels and there is an abundant network of surface water resources, which can be utilized by diverting or pumping the water from the courses. The Kilombero river itself is navigable for small boats. The beneficial use of this land would be confined to the dry season, because the ground is deeply flooded during the rainy season.

Sugar cane does well on soils rich in humus, sufficiently aerated and with adequate water availability. The cultivation of sugar cane could be extended from the Great Ruaha river through Ifakara up to Mpanga, provided the sugar processing is appropriatly guar-

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* 10 Vol.-% soil moisture for 10 cm soil thickness is equivalent to 10 mm soil water in this layer.

anteed. The railway already in operation in the northern strip of the valley is an advantage for sugar cane transport costs. Besides sugar cane, tree crops and bananas promise relatively high income on the north west alluvial fans and Msolwa alluvial fans.

Unlike the alluvial fans on the north west side of the valley, the south west alluvial fans are more extensive, with large areas of poorer sands occasioned by excessive soil erosion in the catchment area of the rivers (FAO, 1961). On the well drained sites, crops which can be stored over a longer period without damage (eg. maize, cotton, cashew nuts etc.) should preferably be grown, partly because of inadequate infrastructure facilities on that side of the Kilombero river; the roads crossing the Kilombero river are usually impassable for six months in the year.

The Mahenge Plateau represents an important area on this side for the cultivation of wheat and vegetables.

SUMMARY

To complement already published reports on soil conditions in the Kilombero valley, this study presents data on infiltration rates, hydraulic conductivity and soil-moisture availability, which should contribute to soil utilization programmes in rural development planning.

The results obtained were systematically grouped according to soil classification units, land use, vegetation forms and physiographic units.

The classification of the area into three main zones makes possible the formulation of certain conclusions relating to the nature and distribution of soils and their development potential.

The soils of the Kilombero river zone are of moderately slow hydraulic conductivity and are perennially or semi-perennially suit-

able for tillage, particularly for paddy cultivation during the dry season.

The soils of the alluvial fans show rapid to very rapid infiltration, but at the same time also a favourable soil-moisture availability to plants. They are semi-perennially or non-flooded and are prefered for agricultural use. However, qualitative soil structure differences have been established between the alluvial fans of various units, eg. the alluvial fans in the strip from Mpanga to Ruipa rivers are superior to the rest. Further rural development on the northern side of the Kilombero valley should benefit from the existence of a railway line and a road passable even during the rainy season.

The soils of the marginal colluvial sand-flats or miombo plains include some of the poorest soil structures in the area, with very rapid infiltration rate and low available soil moisture. The fact that these soils are in agricultural use indicates the limited amount of flood-protected, fertile land available, and reflects the pressures inherent in a steadily increasing rural population.

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APPENDIX

Key of Soils

According to the soil reconnaissance map of Anderson (FAO, 1961)

Alluvial

Sands, in ridges or banks	S
Sands, in seasonal watercourses	M
Sandy loams, usually including patches of sand	A
Loams	B
Recently deposited clays, subject to seasonal flooding	K
Recently deposited clays, above present flood level	Ke
Clays affected by weathering since deposition	C
Clays with partial overlay of sand	Cn
Complex of clay and sand ridges	Cs
Alluvial complexes, predominantly light-textured	Xt
Alluvial complexes, predominantly heavy-textured	Xh
Complex of light and heavy alluvial soils	Xm

Non alluvial

Red and brown soils of well-drained sites	R
Grey sandy soils, ill-drained, of foothills	G
Low-lying sandy soils seasonally flooded	L
Pale sands, with permanent water-tables	Pm
Pale sands, developed from underlying sediments	Ps
Other pale sands	P
Sandy clays of enclosed basins (mbugas)	D
Grey sandy clays on sloping ground	H
Bare rock and shallow stony soils	Z

Soil profiles which are composite in the top two feet of the profile

Sandy loam overlying clay	AC
Sandy loam overlying sand	AS
Recent clay overlying alluvial sand	KS
Recent clay overlying low-lying sand	KL

Soil groupings used by Loxton (exceptions to the above scheme)

Flood flow	F
Ferruginous sands	U
Groundwater forest soils	W
Shallow alluvial soils	T
Foothill catena	E

Soils not included in the soil reconnaissance survey of Anderson

Meander zone soils	Me

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