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SOIL MOISTURE INVESTIGATION AND CLASSIFICATION OF SEVEN SOILS IN THE MBEYA REGION, TANZANIA

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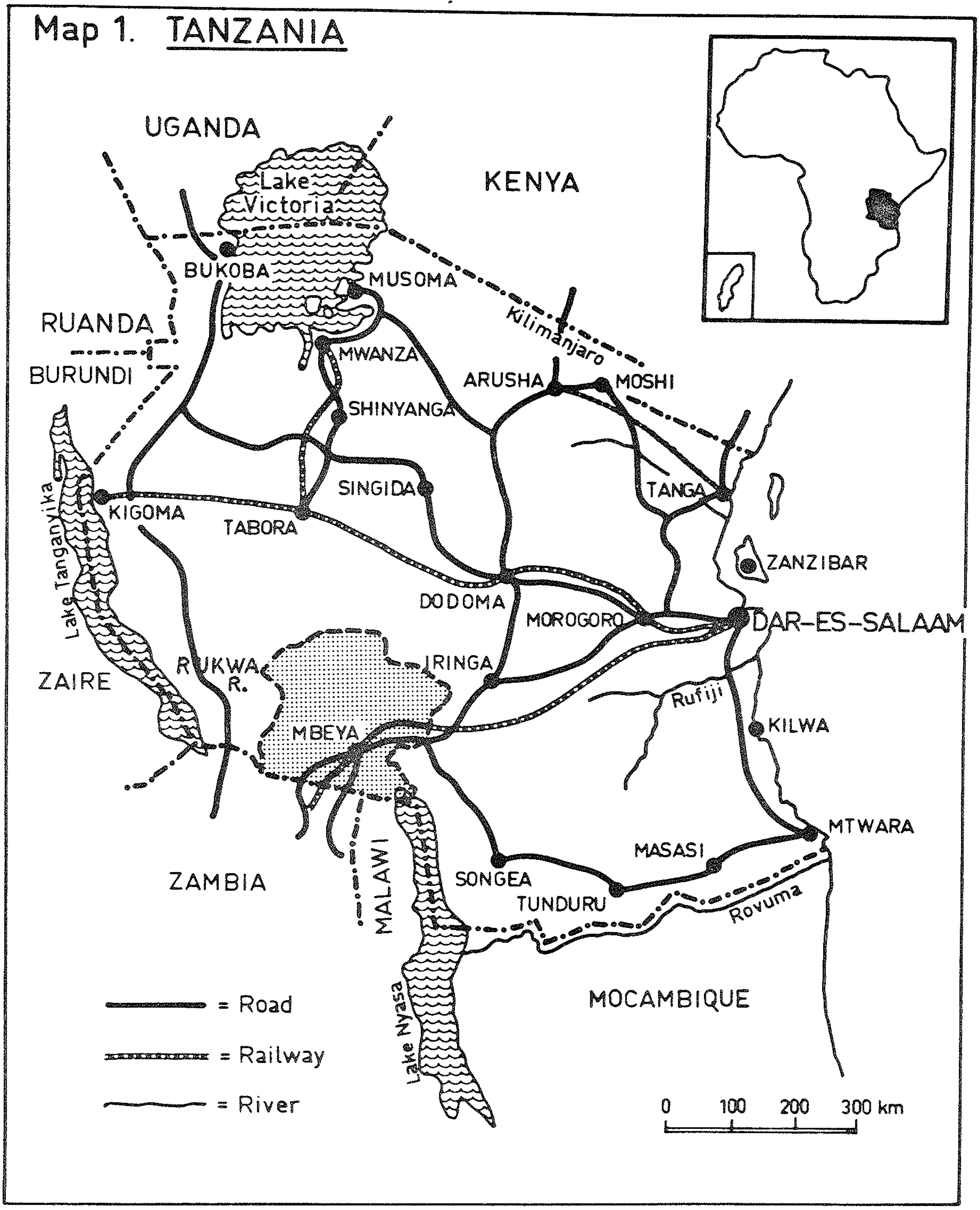
CONTENTS

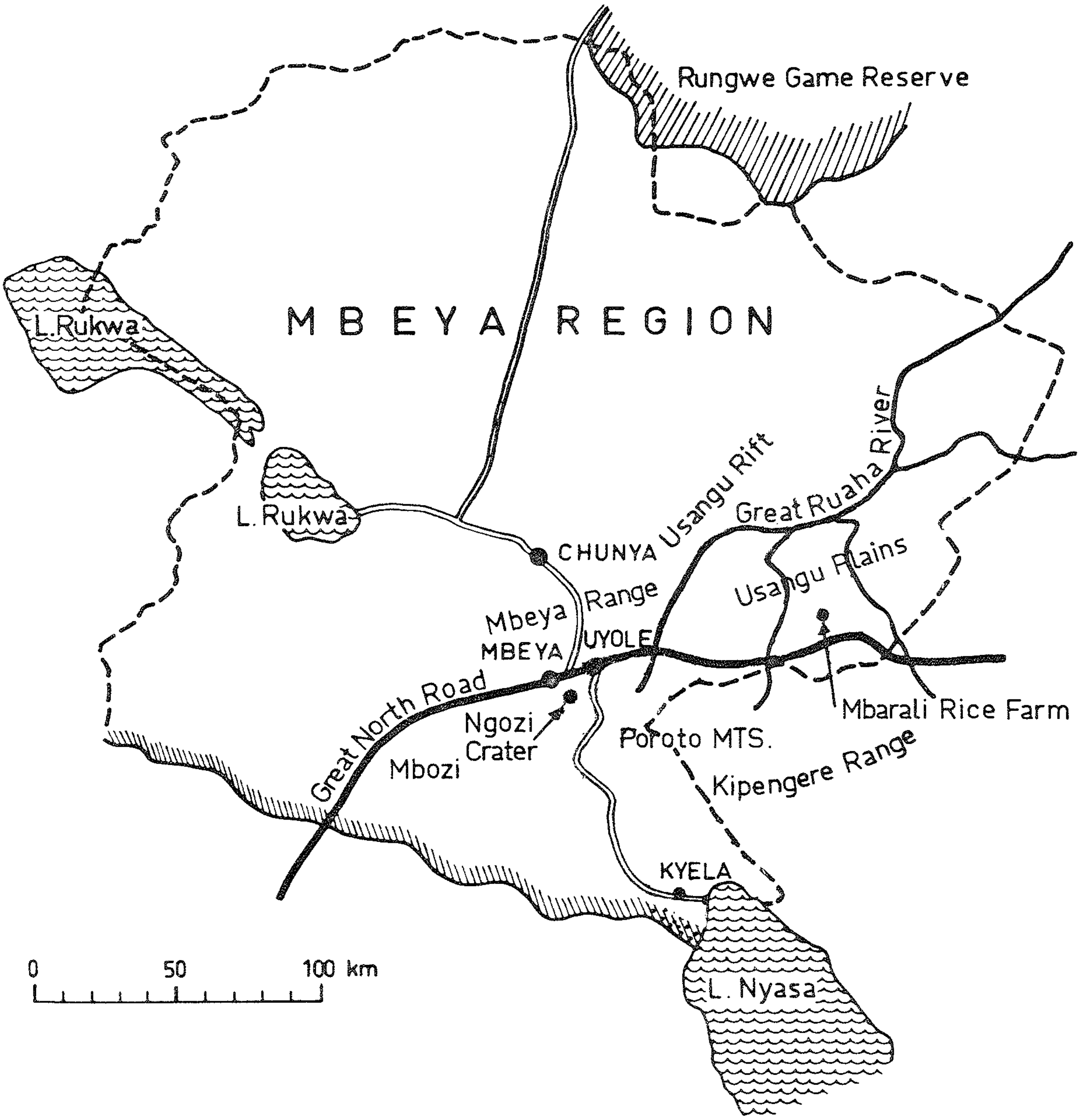
1 PREFACE

This report is based on soil profile studies in Tanzania 1979-1981. The author of the report spent three months in Tanzania 1979 (Aug.-Oct.), and one month in Oct. 1980. Some additional information was collected by geologist Jan Lindström, who spent one month in Tanzania 1981 (Jan.-Febr.). Mr. Lindström has also assisted in this research task with carrying out the physical analyses of the soil samples which were brought back to Sweden. Furthermore, he has contributed to this report in the description of methods (part 5). Agronomist I. Messing has also contributed in analysing the soils and with fruitful discussions over the results. The economical means necessary to make this work possible have been funded through SAREC (Swedish Agency for Research Cooperation with Developing Countries). The supervisor of this very limited research project was Senior Field Research Officer Janne Eriksson at the Department of Soil Sciences, Division of Hydrotechnics, Swedish University of Agricultural Sciences. Mr. Janne Eriksson has been of great help and the author owes him many thanks.

In Tanzania, the research counterparts were Mr. J.A. Kamasho and Mr. C.W. Rombulow-Pearse at the Soil Science Department, Uyole Agricultural Centre, Mbeya. I wish to express my great appreciation towards these two persons, who have done everything to make my visits interesting and rich in experiences.


Map 1. TANZANIA
UGANDA
KENYA
Lake Victoria
BUKOBA
MUSOMA
RUANDA
BURUNDI
MWANZA
Kilimanjaro
ARUSHA
MOSHI
SHINYANGA
SINGIDA
TANGA
KIGOMA
TABORA
Lake Tanganyika
ZANZIBAR
DODOMA
MOROGORO
DAR-ES-SALAAM
ZAIRE
RUKWA R.
IRINGA
Rufiji
MBEYA
KILWA
MTWARA
MASASI
ZAMBIA
MALAWI
SONGEA
TUNDURU
Rovuma
MOCAMBIQUE
Lake Nyasa
= Road
= Railway
= River
0 100 200 300 km

Map 2. Mbeya Region



3 INTRODUCTION

3.1 Physical Environment

The Mbeya Region is strongly affected by the Rift faulting. The western and eastern brances of the Rift Valley System join in the south of the region and continue southwards through Lake Nyasa. The rifting caused volcanic activity which brought about the formation of the Poroto Mountains. These highlands include the famous Njombe and Rungwe volcanoes at an altitude of 2500-3000 m. The latest eruption took place only about 200 years ago, and the area is still volcanic active with a great number of small craters. The soils in the highlands are very fertile and intensely cultivated.

Volcanic ash was spread by the winds far away from the mountains; westward to Mbozi, northward to the Mbeya Range and north-eastward to the southern parts of the Usangu Plains.

In the north and north-west of the region, there are vast areas of "Miombo" (Brachystegia-Julbernardia) woodland. The main soil types here are old reddish, leached lateritic soils. The predominant agricultural system is shifting cultivation.

The east of the region is dominated by the land systems of the Usangu Plains. This area was formed from lacustrine deposits by sedimentation in a lake which was situated here about 1-2 million years ago. The outlet of the lake was dammed southwards when the Rungwe volcanoes were formed. The plains are poorly drained, and the area is flooded every year during the rain period, which brings about a deposit of riverine alluvium.

3.2 Soil Survey in the Mbeya Region

Soil survey work based on "FAO Framework for Land Evaluation" (1976) has been carried out in two regions in Tanzania, the Rukwa Region and the Mbeya Region. The survey is performed in co-operation between BRALUP (Bureau of Resources Assessment and Land Use Planning) at the University of Dar-es-Salaam and Soil Science Department at Uyole Agricultural Centre.

The Rukwa Region (west of the Mbeya Region, see Map 1) Soil Reconnaissance Survey was completed and published in 1979. The field work of the survey in the Mbeya Region is now completed and will be published during 1982. Two more regions will be surveyed the coming years: the Iringa and the Ruvuma Regions.

For each soil survey, land suitability maps are published at a scale of 1:500 000. These maps give basic data for the regional authorities in their planning of food production in the future.

The soil survey work is done according to the following outline (BRALUP, 1979):

1. Land system analyses of satellite imagery.

2. Soil Surveying. The soils are described according to international standards (FAO and USDA classification systems).

3. Vegetation classification.

4. Correlation of the soils with the land systems, followed by land classification and publication of land suitability maps for irrigation and for specific crops at a scale of 1:500 000.

The following land qualities are used in the Tanzanian approach to land classification:

rooting depth	limitation	"r"
available soil moisture	"	"m"
available nutrients	"	"n"
oxygen availability in the root zone	"	"o"
soil temperature	"	"t"
erosion potential	"	"e"

Each soil unit is graded into the following four classes (FAO, 1976): Highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N) for the intensive production of specific arable crops and irrigated rice.

To indicate the limitation, i.e. the main reason why the soil unit was graded for instance S2 instead of S1, a letter suffix is placed after the class symbol. Consequently, the symbol S2r means that rooting depth is not sufficient. With improvement of rooting depth, the soil will be upgraded to S1.

The discussion in this paper is restricted to the important physical property "soil moisture holding capacity". In the Rukwa Region Survey (BRALUP, 1979), the following criterias for available soil moisture were used:

A drought index adapted from Dagg (1965) was calculated from rainfall (R) and potential evapotranspiration (E_o) data. The index is based on the percentage of years, in which the ratio of R/E_o is less than 0.5 in months critical for local maize varieties (Papadakis, 1970). "R" is the total of the monthly rainfall and the moisture store in the preceding month, and "E_o" is Penman E_o (Woodhead, 1970). The critical months were the month of planting (December), the month of tasseling (February) or the month following tasseling. The index was used for rating the climate as follows in relation to areas which are known to be liable to drought, some consideration also being given in freely drained soils to the vegetation and the ecological zones of Kenya (Pratt and coworkers, 1966).

Rating of drought index:

Grade 3 (marginal): the drought index is equal to or exceeds 20 %. Vegetation generally dry forms of woodland. *A. tortilis* subsp. *spirocarpa* woodland or *Sterculia* - *Sclerocarya* - *Lonchocarpus* woodland.

Grade 2 (moderately available): the drought index is less than 20 %. Vegetation generally *Brachystegia-Julbernardia* type woodland.

Grade 1 (very available): drought index 0; assumed to occur with "moist forest".

In addition, these grades were modified as follows:

(a) Ferric Luvisols were assumed to have a good moisture holding capacity and to make use of a moisture store during dry months (Young, 1976).

(b) Well drained alluvial soils, influenced by ground-water with usually giant grasses in the vegetation were assumed to be grade 1. The grasses often *Pennisetum* and trees *A. albida* and *A. polycantha* subsp. *campylacantha*.

3.3 Objectives

Unfortunately, the series of rainfall data are not always complete or long enough to be reliable for more than a few places in each region. In the Mbeya Region this is a serious drawback, since the climate is varying very much. For instance, the yearly rainfall varies from 600 mm to about 3000 mm. In addition, the drought index used in the classification can only give a very rough estimate of the water available for plant growth in a large area.

More specific are the vegetation indicators mentioned. However, it demands a very trained eye and a great experience to collect and evaluate the composition of the trees, herbs and grasses at each soil profile site.

In this work, a few examples are given on the water holding capacities of soils in the Mbeya Region in Tanzania. Seven main soil types have been analysed at different water retentions, the water content being recorded at each pressure level. The soils are presented in tables and figures in chapter 6.

The literature review will give a background to a suggested additional classification of the soil moisture properties in the Mbeya Soil Reconnaissance Survey.

Soil moisture characteristics are especially important in regions where good conditions for irrigation prevail. This is definitely the case in some parts of the Mbeya Region. There are several waterways in the region. Furthermore, the rainfall is very high in some parts.

4 REVIEW OF LITERATURE

4.1 Available water

The estimation of available soil moisture in tropical soils can be carried out in many various ways. According to recent publications on this subject (Hillel, 1980; FAO Soils Bulletin No 42, 1979), none of the existing methods give very accurate figures. In this chapter, some classification methods used in other countries in East Africa will be reported, along with some general statements.

Field capacity has often been calculated from the water content at a tension of 1/3 bar or 0.3 bar. However, a study in Zambia by Maclean and Yager (1972) showed that soil moisture tensions between 0.1 and 0.2 bar approximate actual field capacity better than 0.3 bar. Greenland (1981) also quotes an investigation in Nigeria, which showed that the most appropriate tension for approximating field capacity of tropical soils may be less than 0.1 bar.

Wilting point is generally estimated to the water content at a suction of 15 bars. Even though the plants do not wilt at lower suctions than 15 bars, they can suffer a great deal from water stress. This will reduce plant production considerably. Lal & Greenland (1979) have therefore suggested pF 3.7 (5.0 bars) as the lower limit of "productive available water". The soil classification criterias will be denoted later in this chapter.

Available water is usually expressed in terms of mm/meter. Thus, for each 10 cm-layer of soil the water content expressed in % by volume equals the corresponding number expressed in mm.

Table 1 gives approximate values of the Available Soil Water within the tension range 0.2 - 15 bars for different soil types.

Table 1. Relation between textural class and available soil water in mm/m soil depth. Source: FAO Irrigation and Drainage Paper no 24, 1977; table 38.

Texture class	Available soil water in mm/m soil depth
Fine textured soils	
Heavy clay	180
Silty clay	190
Loam	200
Silt loam	250
Silty clay loam	160
Average	200
Medium textured soils	
Sandy clay loam	140
Sandy loam	130
Loamy fine sand	140
Average	140
Coarse textured soils	
Medium fine sand	60

In FAO (1977) the concept "available water" is also discussed. In this paper the authors state that the level of maximum soil water tension or maximum soil water depletion tolerated to maintain potential crop growth varies with type of crop. Some crops, such as vegetables, potatoes, onions and strawberries, require relatively wet soils to produce acceptable yields; others such as cotton, wheat and safflower will tolerate higher soil water depletion levels. The tolerated depletion level varies also greatly with crop development stage; for most crops a reduced level of depletion should be allowed during changes from vegetative to reproductive growth or during heading and flowering to fruit setting. Readers specifically interested in these variations between crops are referred to FAO Irrigation and Drainage Paper No. 24 (periods when crops are sensitive to soil water shortages are given in Table 32, p. 63).

4.2 Rooting depth and evapotranspiration

The total available water in a soil profile is of course closely related to the rooting depth of the crop. In Table 2 the rooting depths and fractions of total available soil water (field capacity - wilting point), allowing optimal crop growth for different crops, are listed. In an irrigation scheme, the soil water depletion level may not fall below the fractions listed.

When the rate of water flow to the roots falls below the rate needed to meet the demand caused by the climatic conditions, the potential crop evapotranspiration and also the crop growth will be reduced. The effect of soil water content on evapotranspiration varies with crop and is conditioned primarily by type of soils and their water holding characteristics, crop rooting and the meteorological factors influencing transpiration. If the potential evapotranspiration of the crop does not exceed 5 mm/day, for most field crops the evapotranspiration is likely to be little affected at soil water tensions up to one atmosphere (10 m wc) (corresponding approximately up to 30 volume percentage of available soil water for clay, 40 for loam, 50 for sandy loam and 60 for sand). At much lower potential evapotranspiration rates than 5 mm/day, the crop may transpire at the predicted crop evapotranspiration rate even though available soil water depletion is greater; when higher than 5 mm/day, the crop evapotranspiration will be reduced, since the rate of water supply to the roots is unable to cope with transpiration losses. This latter situation will be more pronounced in heavy textured than in light textured soils (FAO, 1977; p. 59).

Table 2. Typical root-zone depths of full grown crops and fraction of available soil water at which evapotranspiration will be reduced. Source: FAO Irrigation and Drainage Paper No. 24, Table 39.

Crop	Rooting depth (m)	Fraction of available soil water *)	Crop	Rooting depth (m)	Fraction of available soil water *)
Alfalfa	1.0-2.0	0.55	Peas	0.6-1.0	0.35
Banana	0.5-0.9	0.35	Peppers	0.5-1.0	0.25
Beans	0.5-0.7	0.45	Potatoes	0.4-0.6	0.25
Cabbage	0.4-0.5	0.45	Rice	0.5-0.7	
Cacao		0.2			
Carrots	0.5-1.0	0.35	Sisal	0.5-1.0	0.8
Clover	0.6-0.9	0.35	Sorghum	1.0-2.0	0.55
Cotton	1.0-1.7	0.65	Sugar cane	1.2-2.0	0.65
Deciduous orchards	1.0-1.7	0.65	Sweet potatoes	1.0-1.5	0.65
Grains (small)	0.9-1.5	0.6	Tobacco	0.5-1.0	
			early		0.35
Grass	0.5-1.5		late		0.65
Groundnuts	0.5-1.0	0.4	Tomatoes	0.7-1.5	0.4
Lettuce	0.3-0.5	0.3	Vegetables	0.3-0.6	0.2
Maize	1.0-1.7	0.6	Wheat	1.0-1.5	0.55
Onions	0.3-0.5	0.25	Wheat, ripening		0.9

*) When crop evapotranspiration is 3 mm/day or smaller, increase values by some 30 %; when crop evapotranspiration is 8 mm/day or more, reduce values by some 30 %, assuming non-saline conditions.

4.3 Classification of soil moisture storage capacity in Zambia and Kenya

The soil survey classifications in the other countries in East Africa have followed somewhat different paths than the one being carried out in Tanzania. Since the climates and the soils are quite closely related to each other, it may be useful to study the soil moisture criteria being used in some of the other East African countries, as compared to the Tanzanian land evaluation. The following text summarizes briefly the criteria used in Zambia and in Kenya (FAO, 1978).

Zambia

The land classification system in Zambia is correlated to the FAO Framework for land evaluation (1976). It is developed to evaluate the land in its capacity to produce crops in a general land use over a long period of time without deterioration.

The following limitations/subclasses are used in the land capability system for irrigated agriculture:

a - alkali and/or salt
d - depth
e - erosion
f - fertility
m - termite mounds
s - slope
t - texture (either cracking clays or deep sands) or infiltration rate
w - wetness (drainage - permeability)

Table 3. Criteria for determining land classes for irrigation in Zambia: subclass w(wetness) or t (texture). Source: FAO World soils Resources Reports No. 51, 1979; table 2, p. 24.

Criteria	Irrigability class				
	I Good	II Moderately good	III Marginal	IV Not irrigable except under special management	V Unsuitable
Permeability (w or t subclass)	moderate	moderately slow to moderately rapid	slow to moderately rapid	very slow to rapid	lands which do not meet the requirements in the higher classes
Available min. moisture holding capacity*) (mm) (w or t subclass)	100	80	60	40	"
Drainage and max. wetness (w subclass)	well drained	somewhat excessively to moderately well drained	somewhat excessively to imperfectly drained	excessive to very poorly drained	"

*) If the soils are deeper than 90 cm the rating depth is assumed to be limited at 90 cm.

Kenya

The Kenya Soil Survey uses the FAO land evaluation system described in "Framework for Land Evaluation" (1976), which has been modified and adapted for Kenyan conditions. Examples of land utilization types which are included in the survey are:

- Small-holder, rainfed mixed farming, intermediate technology
- Large-scale, rainfed, mixed farming, advanced technology, medium altitude
- Large-scale sugarcane production under rainfed conditions, intermediate and advanced technology
- Forestry (silviculture)
- Extensive range management
- Small-holder irrigation
- Tourism

The following land qualities (comparable to "limitations/subclasses") are used:

- climate
- soil moisture storage
- chemical soil fertility
- possibilities for the use of agricultural implements (possibilities for mechanization)
- resistance to erosion
- presence of hazard of water logging (availability of oxygen for root growth)
- hindrance by vegetation
- presence of overgrazing
- availability of foothold for roots

The soil moisture storage land quality includes the following land characteristics:

- soil depth
- total productive available moisture (TPAM)
- profile hindrance to root development (rootable depth)

Rating for soil moisture storage capacity:

The rating of the moisture storage capacity in the rootable zone depends on the total productive available moisture (TPAM), which is a function of soil depth, texture and hindrance to root development. To calculate TPAM, the productive available moisture (PAM) is calculated first (moisture at pF 2.3 minus moisture at pF 3.7). Then the TPAM is calculated for effective soil depth. The final rating is adjusted taking into account hindrance to root development. In case of pronounced argillic horizon or pronounced sedimentary stratification, the rating is downgraded by one class, and in case of planic and sodic horizons (abrupt textural change), the rating is downgraded by two classes.

Table 4. Rating for soil moisture storage capacity in Kenyan soils. Source: FAO World Soils Resources Reports 51 (1978), page 39.

Rating	TPAM (Total Productive Available Moisture)	
1	160-200	very high
	120-160	high
	80-120	moderate
	40-80	low
	less than 40	very low

The rating system for soil moisture storage capacity used by the Kenya Soil Survey is commented further by Lal & Greenland (1979). The following table shows step by step how TPAM is calculated. However, Lal & Greenland presents a slightly modified version of the classification.

Table 5. Subratings and final rating for soil moisture storage capacity.
Source: Lal & Greenland (1979), table 7.18.

Soil Depth	Subratings: Average productive available moisture in topsoil (0-50 cm, pF 2.3- pF 3.7)	Profile hindrances to root development
0. >180 cm	1. >15 vol.%	1. None: e.g. oxic horizons
1. 180-120 cm		
2. 120-80 cm	2. 15-12 vol.%	2. Slight: e.g. oxic-argillic transitional horizons, cambic horizons
3. 80-50 cm	3. 12-8 vol.%	3. Moderate: e.g. distinct sedimentary stratification
4. 50-25 cm	4. 8-5 vol.%	4. Strong: e.g. pronounced argillic horizon, pronounced sedimentary stratification *)
5. <25 cm	5. <5 vol.%	5. Very strong: e.g. planic and sodic horizons

From the subrating points, a total sum is calculated to get the final rating:

Final rating

Class	Total of subrating points	TPAM (Total productive readily available moisture) (mm)
0. Except. high	2	>180
1. Very high	3-4	180-130
2. High	5-6	130-90
3. Moderate	7-8-9	90-60
4. Low	10-11-12	60-35
Very low	13-14-15	<35

*) High contents of exchangeable aluminium (60 % Al saturation of ECEC) in the soil are unfavorable for root development. This land characteristic has not yet been used in the present rating system.

Lal and Greenland do not discuss why the limits for "productive available moisture" have been chosen at pF 2.3-pF 3.7. However, according to what have been reported earlier in this chapter, the pF 2.3 for field capacity is well correlated to field measurements. pF 3.7 is considerably lower than the traditional wilting point at pF 4.2. The high evapotranspiration rates in East Africa and in other tropical countries give, on the other hand, a high stress factor on the vegetation. The water content at pF 2.3 - pF 3.7 can therefore be suspected to give a more accurate value of the actual available soil moisture in tropical and subtropical climates.

4.4 Soil moisture holding properties of six soils in Kenya

In fig 1 the soil moisture holding properties of some soils in Kenya are illustrated.

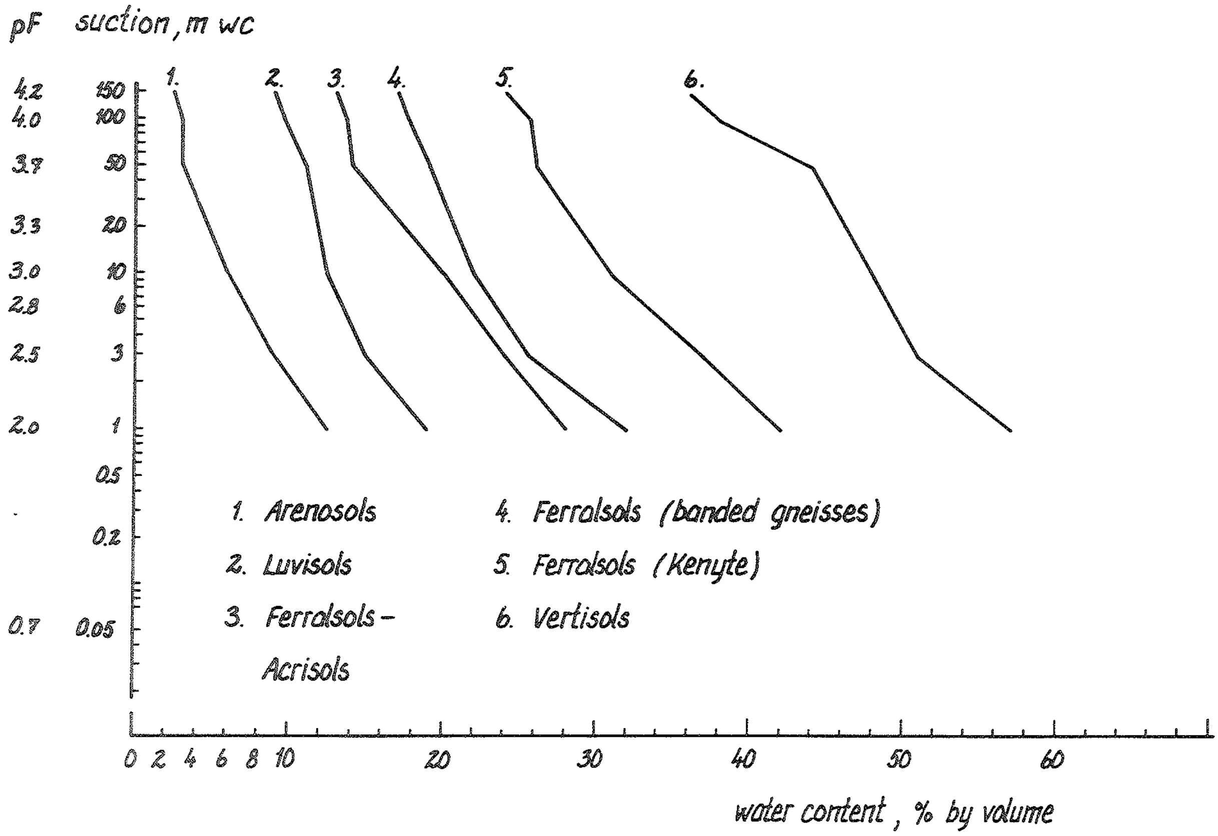


Figure 1. Volume percentage water held in the topsoils of some typical soils in Kenya. The soil classification is according to the FAO/UNESCO Soil Map of the World Legend. Source: Lal & Greenland (1979).

The sandy Arenosols hold very little water compared to Ferralsols and Vertisols. It is obvious that the sequence of pF-curves is arranged mainly according to clay content. However, organic matter content in the soil also have a great influence on the water holding properties. According to Greenland (1981), soil organic matter content increases water retained at lower tensions, thereby increasing the available water capacity. A high clay content, on the other hand, affects the water retention positively both at low and high tensions.

Other factors influencing the water holding properties of the soil are type of clay mineral, silt percentage and bulk density.

5 METHODS USED IN THE STUDY OF SOILS IN THE MBEYA REGION

5.1 Field methods

The locations of profile sites were selected to represent the different soil types in the Mbeya Region. The soils were analysed to gain sufficient information for the classification according to the FAO system.

From the pits, two cylindrical core samples were taken out from each horizon. The volume of the core samples were 98.5 cm^3. The cylinders were to be used for determinations of physical characteristics: soil moisture retention curves, bulk density and pore space. Also, from each horizon a sample of about 0.5 kg soil was collected to be used for texture and chemical analyses.

The field methods used for soil profile descriptions were based on FAO Guidelines for soil description (undated). Further information on these methods can be found in Karlsson and Messing (1980).

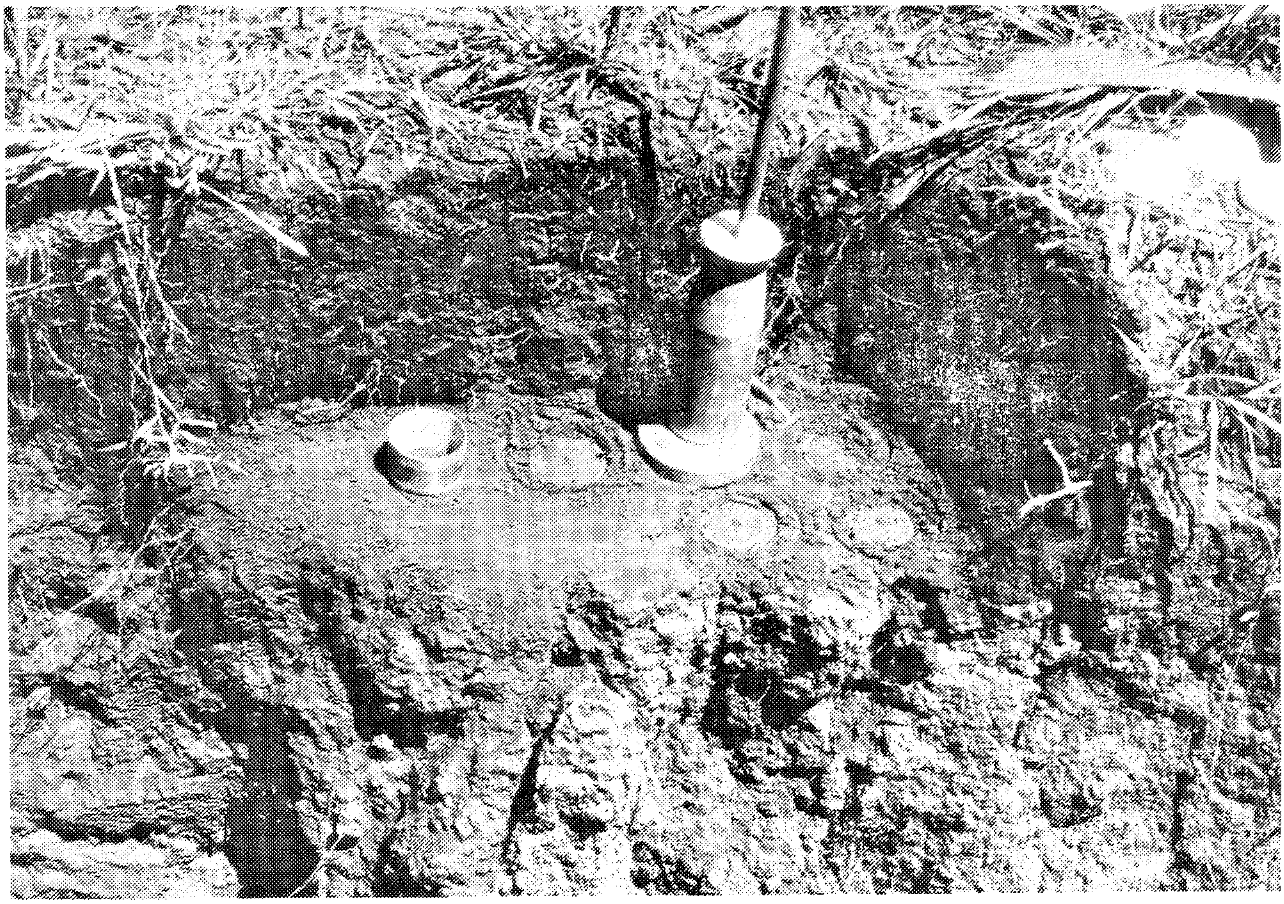


Figure 2. Core sampling in a Mbeya soil. Photo: Jan Lindström.

5.2 Laboratory analyses

5.2.1 The basis of mechanical analysis

Mechanical analysis is used to determine the size distribution of the particles which make up a soil.

Large particles can be separated into groups by means of sieves. However, no sieve is fine enough to effect the necessary subdivisions of the smaller particles. The methods commonly used to separate these particles of finer grain are based on the fact that small particles fall more slowly through a column of water than do larger particles.

When interpreting the speed of settling, one assumes that the particles are spherical. Hence, the size range r_1 to r_2 is defined by a measured settlement velocity range v_1 to v_2, and the size is calculated from the velocity by an application of Stoke's law:

$$v = \frac{2}{9} \; g \; r^2 \, \frac{(\rho_1 - \rho_2)}{\eta}$$

or $$v = k\, r^2$$

v = settling velocity (cm/s)
g = gravity acceleration (981 cm/s)
r = radius of the particle sphere (cm)
ρ_1 = density of the settling sphere (g/cm^3)
ρ_2 = density of the water (g/cm^3)
k = constant
η = the viscosity of the water (0.01 pois at 20^oC)

The constant k is depending on the nature of the liquid and the particle. If the liquid is water and the temperature is held constantly at 20^o C, k mainly depends on the density of the settling sphere.

At a conference in 1927, the International Society of Soil Science decided that the value of ρ_1 can be set to 2.6 g/cm^3, from which follows that k = 34722.

The equation can now be written

$$v = 34722\, r^2$$

The smallest silt particle (0.002 mm in diameter) will, according to this, fall 10 cm in 8 hours.

Two widely used texture analysis methods are based on the sedimentation velocity of soil particles in water. "The hydrometer method" measures the suspension density. The second method uses a pipette to take out samples from an initially stirred soil-water suspension at a given depth and a given time. This "Pipette method" was originally developed by Robinson (1922) and Jennings, Thomas and Gardner (1922).

The pipette method is used for routine texture analysis at the Division of Hydrotechnics, Department of Soil Sciences at the Swedish University of Agricultural Sciences. It is also used in the Soils Laboratory of the Uyole Agricultural Centre in Tanzania.

After pipetting, the sand fraction is determined by wetsieving. Loss of ignition can be determined by heating the soil to 600^oC. To get an approximate value of the organic matter content from this,the percentage loss of ignition must be reduced by the amount of water which is present within the clay minerals in crystallized form.

For classification of the soil on the basis of fractional composition, the textural triangle was used (see fig. 3).

Particle density was determined on soil which was ground and heated to 105^oC. Ethanol was used to drive out enclosed air from the soil sample.

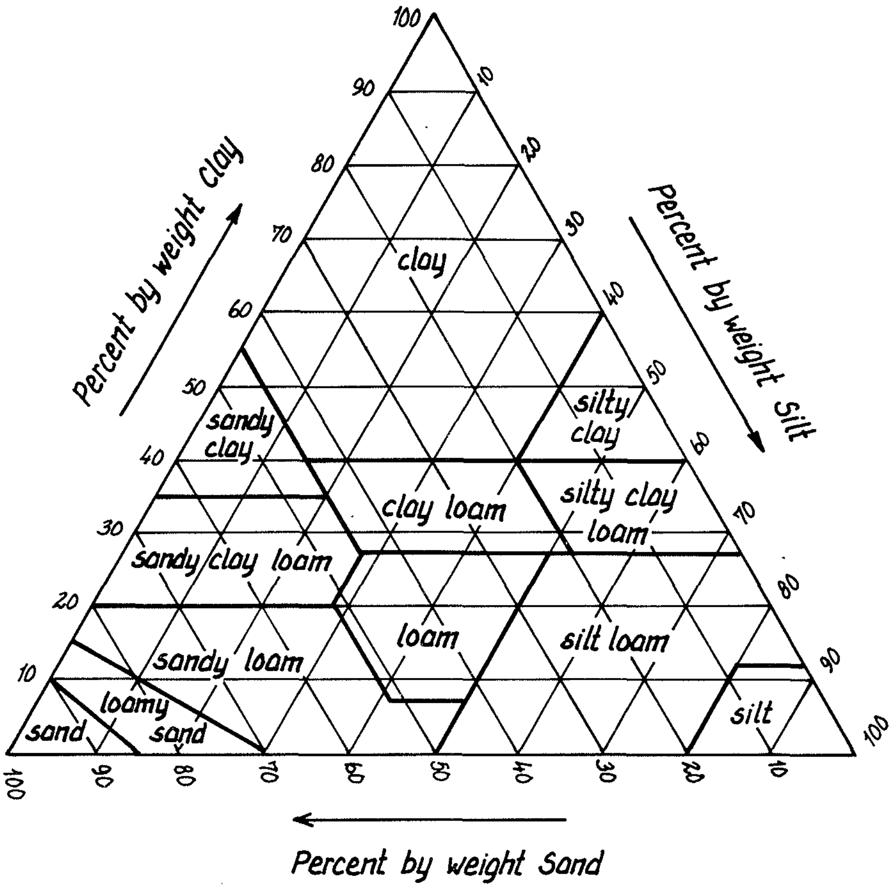


Figure 3. Guide for textural classification according to USDA (clay <0.002 mm, silt 0.002 - 0.05 mm, sand 0.05 - 2.0 mm).

5.2.2 Procedure for mechanical analysis (pipette method) used in the laboratory at the Uyole Agricultural Centre

Preparation of soil. The air-dried sample is ground in a soil mill, where the soil passes through a 2 mm sieve. The material which does not pass the sieve is weighed and recorded as percentage of the whole sample.

The particle-size analyse of the soil only include the mineral particles. Thus, the organic matter has to be removed, otherwise it will disturbe the pipetting procedure. A 20 g sample is weighed in a 600 ml beaker and 50 ml 10 % H_2O_2 is added. The beaker is covered with a watch-glass and heated on a waterbath until the organic matter has become oxidized (it takes about 1 - 4 hours). The H_2O_2 (30 %) treatment is repeated until no more reaction occurs.

50 ml dispersing agent ($Na_4P_2O_7 \times 10\ H_2O$) is then added and the suspension is mixed about 20 minutes in a mixer. The sample is transferred to a sedimentation cylinder (1000 ml) and is filled up with deionized water.

Analyses of soil suspension. Pipettings are made for the silt and clay fractions. The pipetting depth is 10 cm. A Kuhn-pipette of 10 ml with a filling time of about 3 seconds is used.

Before the first pipetting the suspension is stirred with a plunger for 60 seconds. The plunger is made out of plexiglass, with a perforated plate (4 holes) at the end of the rod. Just before the sedimentation is completed, the pipette is lowered into the suspension at 10 cm depth. The pipette is then filled and emptied into a steel crucible. The procedure is repeated, i.e. the pipettings are made twice.

The pipette is rinsed with deionized water and the sample is dried in an oven at 105 C. After the pipettings the suspension in the sedimentation cylinder is carefully poured out, and the bottom sediment is transferred to a 600 ml beaker.

The sand fraction is separated by repeated decantations. The beaker is filled up with deionized water to a hight of 10 cm. The content is then stirred and after 4 minutes and 48 seconds (at $20^{o}C$), the suspension is poured out. The sand fraction has now sedimented to the bottom of the beaker. The procedure is repeated until the suspension is limpid (about 10 times). The sand fraction is finally separated into fine sand (0.02 - 0.2 mm) and coarse sand (0.2 - 2.0 mm) by using a sieve. The samples are dried at $105^{o}C$ and weighed.

Calculations of the results. 1. Clay and silt pipetted fractions:

Clay pipetted fraction (g) = A
Clay + silt fraction = B
Dispersing agent (0.100 N $Na_4P_2O_7 \times 10\ H_2O$) = 1.331 g/l

$$\text{Clay \% by weight} = 100\ \frac{(100\ A - 1.331)}{20}$$

$$\text{Silt \% by weight} = 100\ \frac{(100(B - A))}{20}$$

2. Sieved sand fractions

Fine sand (g) = C
Coarse sand (g) = D

$$\text{Fine sand \% by weight} = 100\ \frac{C}{20}$$

$$\text{Coarse sand \% by weight} = 100\ \frac{D}{20}$$

(clay + silt + fine sand + coarse sand + loss of ignition) = 100 %

5.2.3 Soil moisture retention analysis

Two undistorted sampling cores were selected from each soil profile horizon. The volume of these cylindrical cores were 98.5 cm^3 with lids at each end.

The moisture characteristics can be defined as the relationship between the moisture content of a soil and the tension applied. Porous ceramic plates containing water under suction are usually used. To obtain a continuity of water between the sample and the suction plate, a thin layer of fine-grained material is applied.

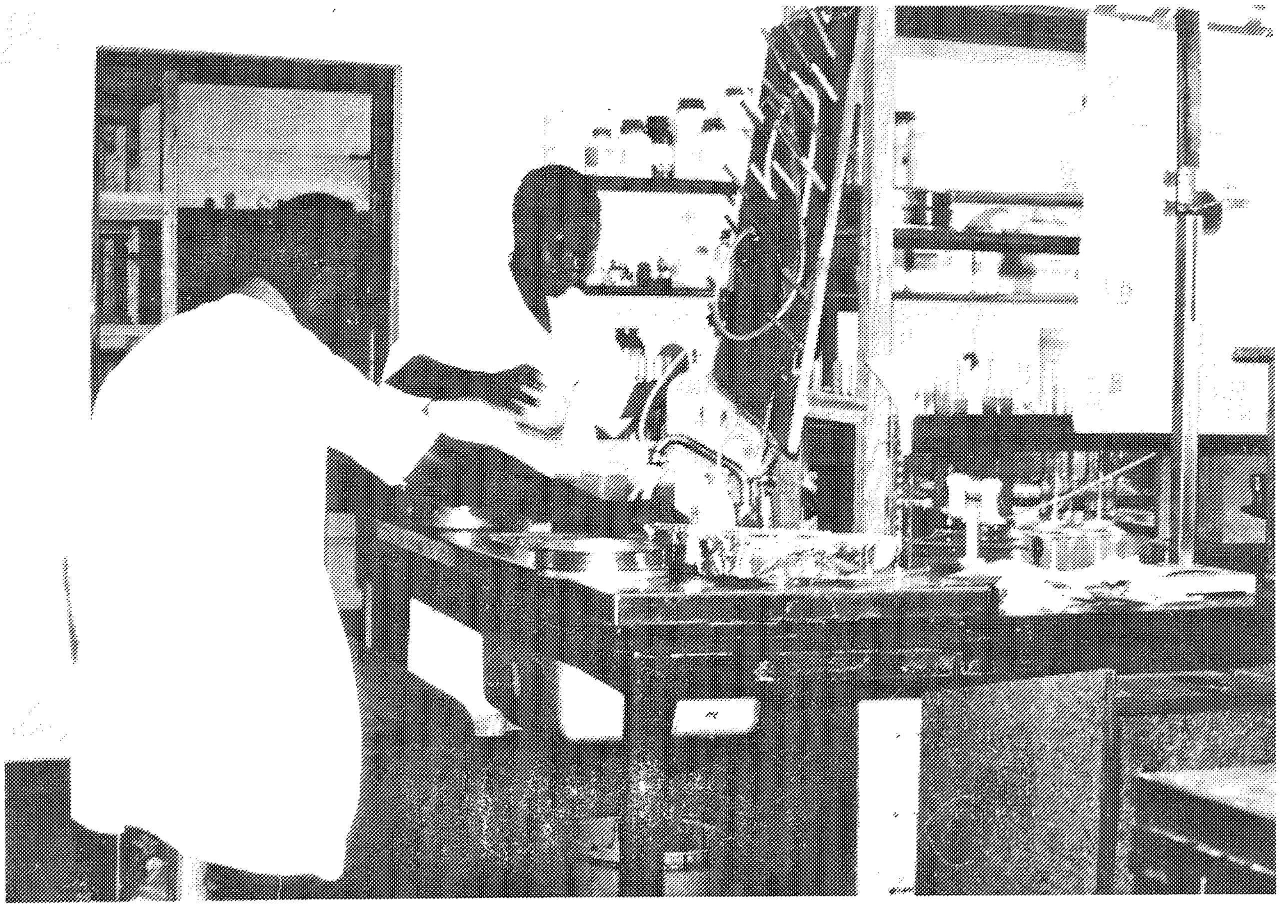


Figure 4. Interior from the soils laboratory at Uyole Agricultural Centre, Mbeya. Photo: Jan Lindström

Procedure:

The samples were brought to saturation by capillary wetting on a suction plate. For each suction step, the amount of water removed from the soil sample was recorded at a time when no more water would drain from the soil (i.e. when the suction forces and the water retention forces were at equilibrium). After this, the following (higher) suction was applied.

The suctions were applied in the following way:

The suctions 0 - 1.0 m wc (0 - 0.1 bar): A ceramic plate with a hanging column control of suction.

The suctions 1.0 - 6.0 m wc (0.1 - 0.6 bar): A ceramic plate with vacuum control of suction.

The suctions 6.0 - 150 m wc (0.6 bar - 15 bar): Pressure equipment using ground soil samples.

All water contents were determined gravimetrically.

Finally, the soil sample was dried in 105°C and weighed. Dry bulk density was determined by dividing dry weight of soil by the volume of the cylinder. Moisture content at each suction step was multiplied by the soil dry bulk density to convert to moisture content by volume.

The moisture contents were determined at the following suctions:

0.025 (or 0.05)	meter	water	column
1	"	"	"
3	"	"	"
6	"	"	"
150	"	"	"

5.2.4 Errors in moisture retention analysis

Moisture retention analysis of soils with pronounced swelling and shrinking properties are very difficult to perform. The soil profiles US 37 and US 59 (described in chapter 6) are soils with such properties due to the high clay content, 50 % resp. 80 %. The clay minerals in these soils are mainly of montmorillonitic origin.

Two major concerns are listed below:

1. The dry bulk density determination will be dependent upon the water content of the soil at the time of sampling. Since the sampling took place during the dry period, the values obtained from the determination of the dry bulk density may be too high. Preferably the site should be wetted to saturation before sampling on a heavy clay soil. However, this would probably have taken several days in these cases and was therefore considered to be practically and economically impossible.

2. The core sample will swell when saturated with water at the start of the soil moisture retention analysis. Since the swelling can only take place upwards and downwards inside the sample cylinder, the structure within the sample will be disturbed. As the soil sample is moved to higher tension steps, it will gradually shrink inside the cylinder.

   To compensate for this shrinkage, the soil core volume was measured at each tension step. In spite of these efforts, there is a risk that the soil moisture retention curves of US 37 and US 59 are slightly unreliable. Hall et al. (1977) states that the errors resulting from ignoring shrinkage at lower suctions will be almost negligable. At 15 bar suction, the error due to shrinkage is unlikely to exceed 12 per cent.

5.2.5 Chemical analysis

pH of the soil was determined in a soil - $CaCl_2$(0.02 N) suspension at a 1:5 ratio.

Difficultly soluble Phosphorus and Kalium were determined with the HCl extraction method (Kungl. Lantbruksstyrelsens Kungörelser m.m. nr 1, 1965).

Accessible Phosphorus and Kalium were determined using the Egnér Ammonium-Lactate method (Kungl. Lantbruksstyrelsens Kungörelser m.m. nr 1, 1965).

The cation exchange capacity (CEC) was determined using NH_4Ac to replace the cations Na^+, K^+, Mg^{2+}, Ca^{2+} and H (Ståhlberg et al.,1978).

The exchangeable cations Na^+, K^+, Mg^{2+} and Ca^{2+} were determined with an atom absorption spectrofotometer (AAS) (Ståhlberg et al., 1978).

The base saturation of the soil was calculated from the determinations of exchangeable cations and the cation exchange capacity. The total of metal cations (Na^+, K^+, Mg^{2+} and Ca^{2+})was divided by the CEC and multiplied with 100 to get a percentage value.

The condictivity of the soil was measured on soil dispersed in destilled water on a conductivity meter. The cell constant of the electrode was 0.7 cm^{-1}.

Organic carbon content was determined using the Walkley and Black method.

6 PRESENTATION OF SEVEN STUDIED SOIL PROFILES

6.1 General remarks

The soil profile descriptions have been done according to the FAO system (FAO Guidelines for soil description, undated). For each soil profile, figures describing particle-size distribution, pore space distribution with suction curves and pF-curves are presented. The figures are designed according to Andersson (1955).

The soil texture terms, "silty clay" etc., in the soil descriptions are based on field determinations. In brackets the texture terms according to the laboratory texture analyses are noted.

However, this latter texture classification is done with definitions of silt and sand differing slightly from the texture triangle (fig. 3) definitions:

Laboratory analysis	silt	= 0.002 mm - 0.06 mm
	sand	= 0.06 mm - 2 mm
Texture triangle	silt	= 0.002 mm - 0.05 mm
	sand	= 0.05 mm - 20 mm

The following remarks should be taken into account when reading the tables on analytical data following each profile description:

1. The suctions in meter water column (m wc) equals the following pF-values: 0.025 = pF 0.4; 0.05 = pF 0.7; 1.0 = pF 2.0; 3.0 = pF 2.48; 6.0 = pF 2.78; 150 = pF 4.18.

2. The texture classes according to British Standards Institute and following the Swedish texture classification. Particle diameters: clay $<$0.002 mm; fine silt 0.002 - 0.006 mm; medium silt 0.006 - 0.02 mm; coarse silt 0.02 - 0.06 mm; fine sand 0.06 - 0.2 mm; medium sand 0.2 - 0.6 mm; coarse sand 0.6 - 2 mm.

6.2 Soil Profile Descriptions

6.2.1 Profile RU 7. Described 79-11-23

The profile is situated in Ndaga village in the mountains north of Lake Nyasa at 33° 34' 30" E and 9° 04' 00" S. The altitude is 1920 m. In the surroundings all land is cultivated. Common crops are maize, European potatoes, wheat, peas and pyrethrum. The farmers consider this soil to be very fertile. The slope is 0 - 1 % on a gently undulating plain on a lava plateau.

The soil was named an Eutric Regosol (FAO) and an Andeptic Troporthent (USDA).

Soil profile horizons:

1. Ap, 0 - 20 cm: Black (5YR 2/1) moist and brown (10YR 5/3) dry; fine sandy loam (silt loam); strong very fine angular blocky structure, aggregated into weak fine subangular blocky; slightly sticky, slightly plastic, very friable consistence; the sand fraction is derived from pumice with few visible pumice sand fragments; abundant medium to very fine roots; gradual smooth boundary.

2. AC, 20 - 45 cm: Brown - olive (2.5Y 5/3) moist and pale yellow (2.5Y 7/4) dry; loamy fine sand (silt loam); single-grain structure; non-sticky, very slightly plastic, very friable, soft consistence; few very fine tubular pores; fresh pumice fragments concentrated to the lower part of the horizon; few fine and very fine roots; gradual boundary.

3. C, 45 - 140 cm: Greyish brown (2.5Y 5/2) moist and white (2.5Y 8/2) dry; fine sandy loam (silt loam); slightly sticky, slightly plastic, very friable consistence: pores as above with more common tubular pores: the sand fraction is derived from pumice: faint brownish streaks and spots in pores and root holes: very few fine and very fine roots: clear boundary.

4. 2 Bwb, 140 - 180 cm: (Buried, altered B horizon). Dark brown (7.5YR 3/4) moist and yellowish brown (10YR 5/4) dry; loamy sand to sandy loam; nonplastic, nonsticky, very friable, soft consistence; single-grained structure; common fine simple tubular pores; hard grits (small ash and pumice fragments) are common; common fine and very fine roots; clear wavy boundary.

5. 2 Cb, 180 - 217 cm: Light yellowish brown (2.5Y 6/4) moist and white (5Y 8/2) dry; pumice gravel and grits with some dark grey ash fragments; almost unrooted.

Table 6. Analytical data from soil profile No RU 7.

Horizon Depth (cm)	1. Ap 0-20	2. AC 20-45	3. C 45-140
Dry bulk density, g/cm^3	0.72	0.87	0.98
Particle density, g/cm^3	2.35	2.42	2.42
Porosity, % by volume	71	63	57
Water content, % by volume at suctions (m wc):			
0.025	66	58	54
1.0	44	41	42
3.0	40	34	35
6.0	34	29	28
150	12	5	6
Particle size distribution, % by weight:			
clay	11	3	5
fine silt	10	11	13
medium silt	25	34	37
coarse silt	20	23	27
fine sand	6	7	5
medium sand	12	14	8
coarse sand	5	5	3
loss of ignition	11	3	2
pH ($CaCl_2$)	6.1	6.1	6.8
P-HCl, mg/100 g soil	100	26	15
K-HCl, mg/100 g soil	335	400	430
Exchangeable cations, me/100 g soil:			
Ca	11.68	3.84	2.66
Mg	2.44	0.68	0.93
K	5.37	5.69	5.54
Na	1.20	1.84	1.84
CEC, me/100 g soil	34.6	14.3	11.3
Base saturation, %	60	79	97

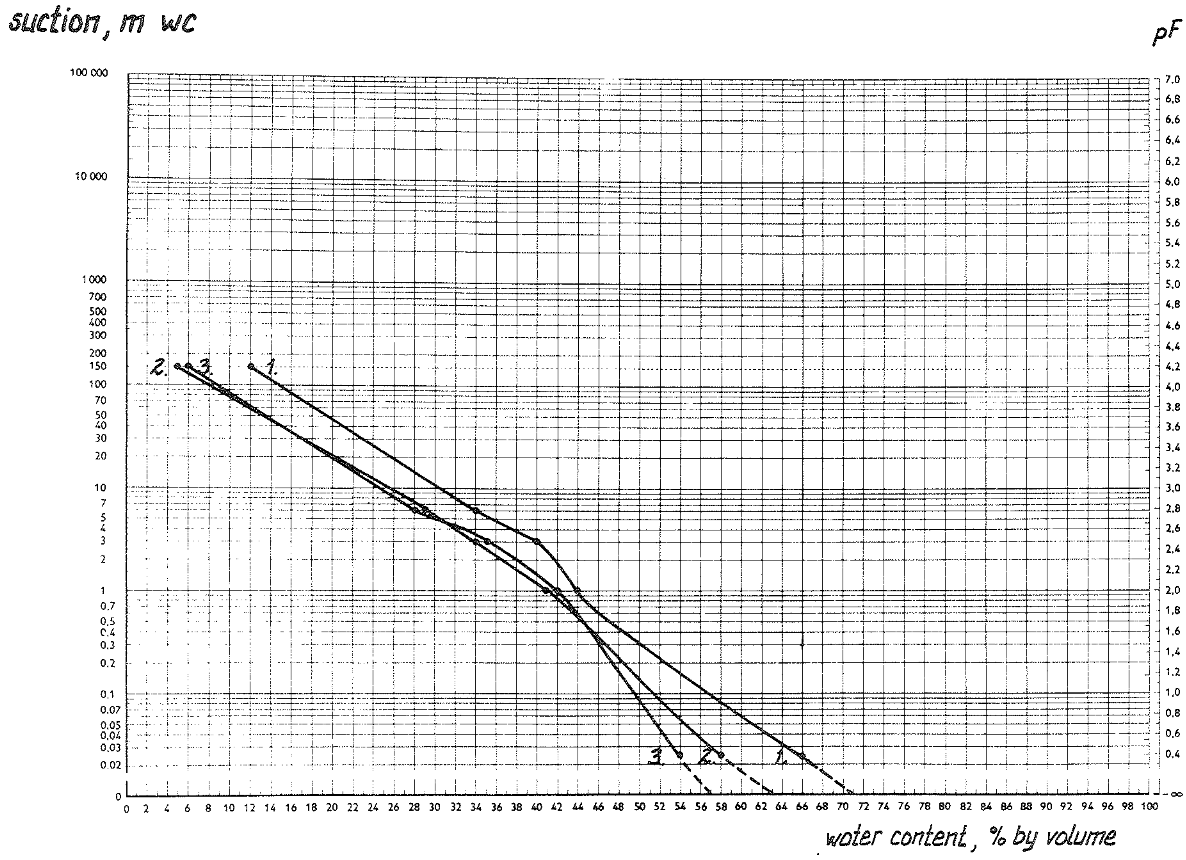


Figure 5. Soil moisture retention curve of profile RU 7.

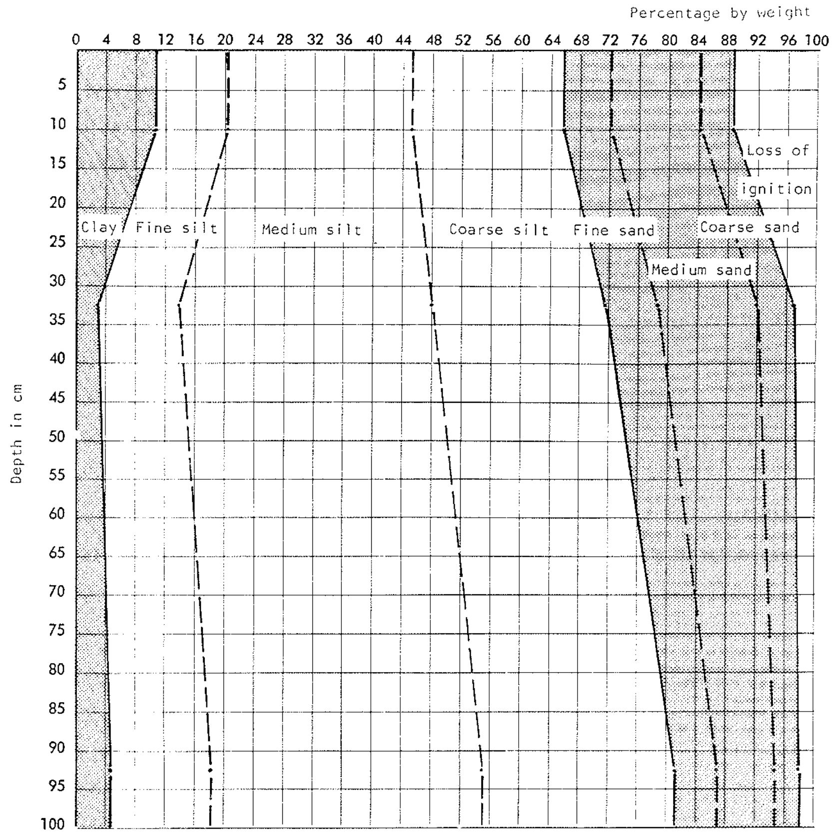


Figure 6. Profile RU 7. Particle-size distribution.

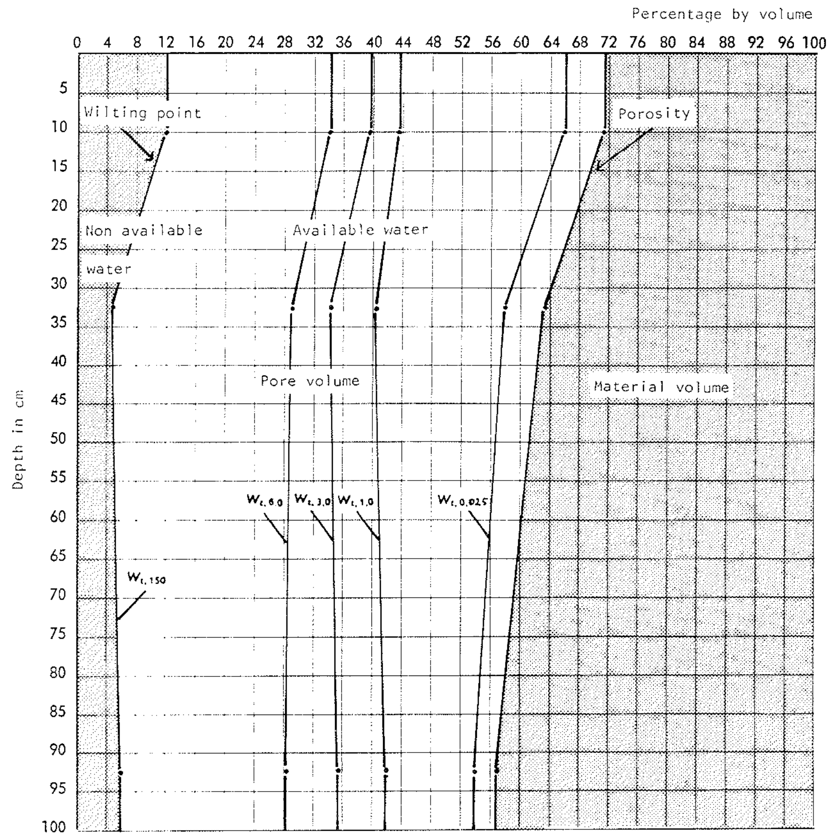


Figure 7. Profile RU 7. Pore space distribution with five suction curves.

6.2.2 Profile MA 2. Described 79-08-29

The following profile is situated in the Poroto Mountains in Ijombe Juu village at 33° 35' 14" E and 8° 55' 40" S. The altitude is 1998 m. Natural vegetation at the site is Erythrina abyssinica which occur sparsely in a landscape dominated by cultivated crops. The latter are mainly maize, wheat and peas. Montane forest remnants can be seen about one km from the profile site, indicating a rainfall of about 1400 mm per year. The soil has a volcanic origin.

The soil was named a Mollic Andosol (FAO) and a Typic Eutrandept (USDA).

Soil profile horizons:

1. Ap 0 - 25 cm	Dark reddish brown (5YR 2.5/2) moist and yellowish brown (10YR 5/4) dry; sandy loam (silt loam); slightly massive when dry; strong fine granular structure when moist; slightly sticky, slightly plastic, very friable, soft consistence; common very fine tubular pores; very few fresh angular pumice gravel fragments; the sand fraction is soft, probably also pumice; many medium to very fine roots; clear smooth boundary.
2. 2 Ab 25 - 60 cm	Dark reddish brown (5YR 3/2) moist and brown (7.5YR 4/4) dry; loam (clay loam); moderate medium to fine subangular blocky and fine granular structure; slightly sticky, slightly plastic, friable, hard consistence; pores and mineral fragments as above; common very fine roots; clear wavy boundary.
3. 2 Cb 60 - 70 cm	Brownish yellow (10YR 8/4) moist and very pale brown (10YR 8/1) dry; medium and fine subangular and fine rounded pumice gravel; very few very fine roots; clear wavy boundary.
4. 3 Ab 70 - 105 cm	Colours, texture, structure, consistence, pores and mineral fragments as 2.Ab, but plastic consistence; very few very fine roots; diffuse smooth boundary.
5. 3 A b2 105 - 190 cm	Dark reddish brown (5YR 3/2) moist and dark yellowish brown (10YR 4/4) dry; clay loam (silt loam); structure as above; sticky, plastic, friable, slightly hard consistence; many fine and very fine simple tubular pores inside the peds; very few weathered angular pumice gravel fragments; sand as above; very few very fine roots; black streaks, probably derived from old tree roots.

Table 7. Analytical data from soil profile No MA 2.

Horizon Depth (cm)	1. Ap 0-25	2. 2 Ab 25-60	3. 2 Cb 60-70	4. 3 Ab 70-105	5. 3 A2b 105-190
Dry bulk density, g/cm^3	0.84	0.80	0.42	0.78	0.68
Particle density, g/cm^3	2.47	2.56	2.42	2.56	2.54
Porosity, % by volume	67	70	65	72	72
Water content, % by volume at suctions (m wc):					
0.025	63	65	-	72	72
0.05	-	-	37	-	-
0.3	-	-	36	-	-
0.5	-	-	34	-	-
1.0	45	39	33	42	46
3.0	41	35	28	37	42
6.0	37	33	26	35	39
150	19	20	8	19	17
Particle size distribution, % by weight:					
clay	15	23	-	10	8
fine silt	13	16	-	12	11
medium silt	23	19	-	29	24
coarse silt	16	13	-	22	26
fine sand	2	4	-	4	6
medium sand	14	11	-	9	11
coarse sand	5	4	-	5	5
loss of ignition	12	10	-	9	9
pH ($CaCl_2$)	5.7	5.7	5.9	6.0	5.9
P-HCl, mg/100 g soil	103	51	51	57	42
K-HCl, mg/100 g soil	155	200	255	200	200
Exchangeable cations, me/100 g soil:					
Ca	11.18	7.79	5.54	9.12	8.34
Mg	2.86	1.99	1.25	2.46	2.20
K	1.93	3.12	3.05	3.62	3.89
Na	0.04	0.04	0.13	0.18	0.23
CEC, me/100 g soil	30.1	27.0	18.8	23.7	28.0
Base saturation, %	53	48	53	65	52

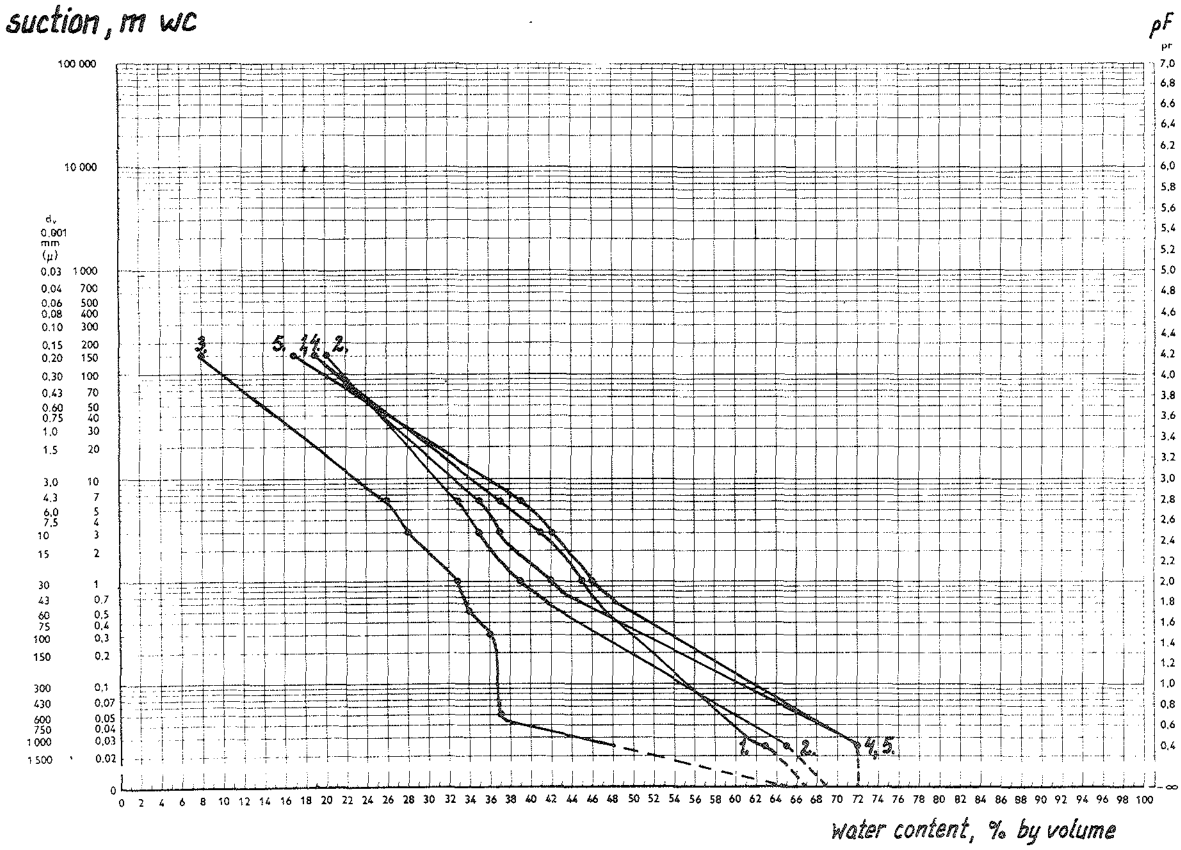


Figure 8. Soil moisture retention curve of profile MA 2.

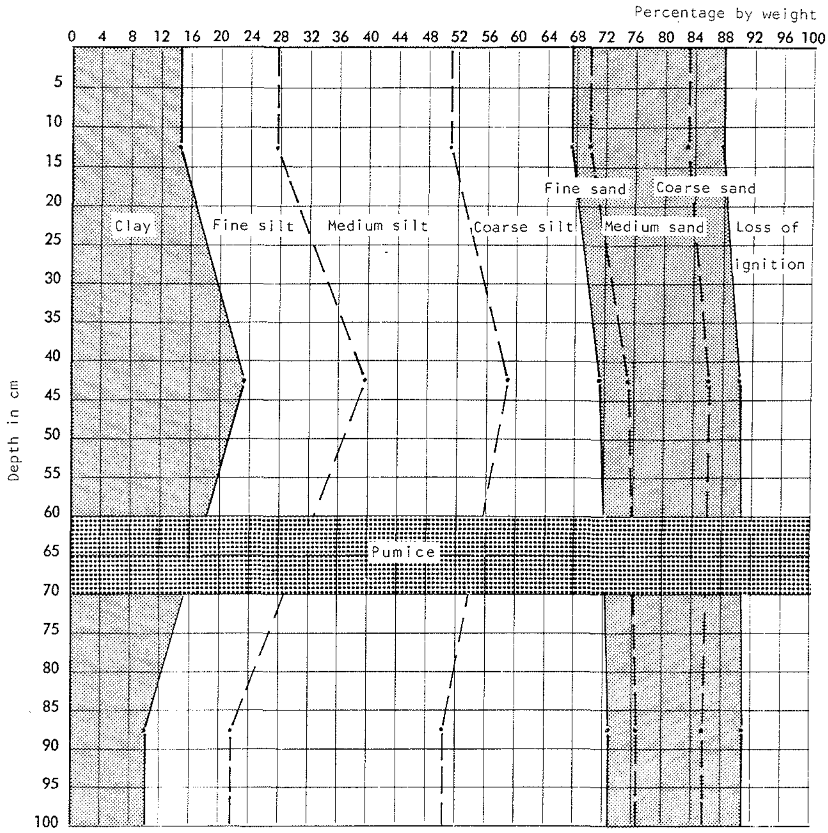


Figure 9. Profile MA 2. Particle-size distribution.

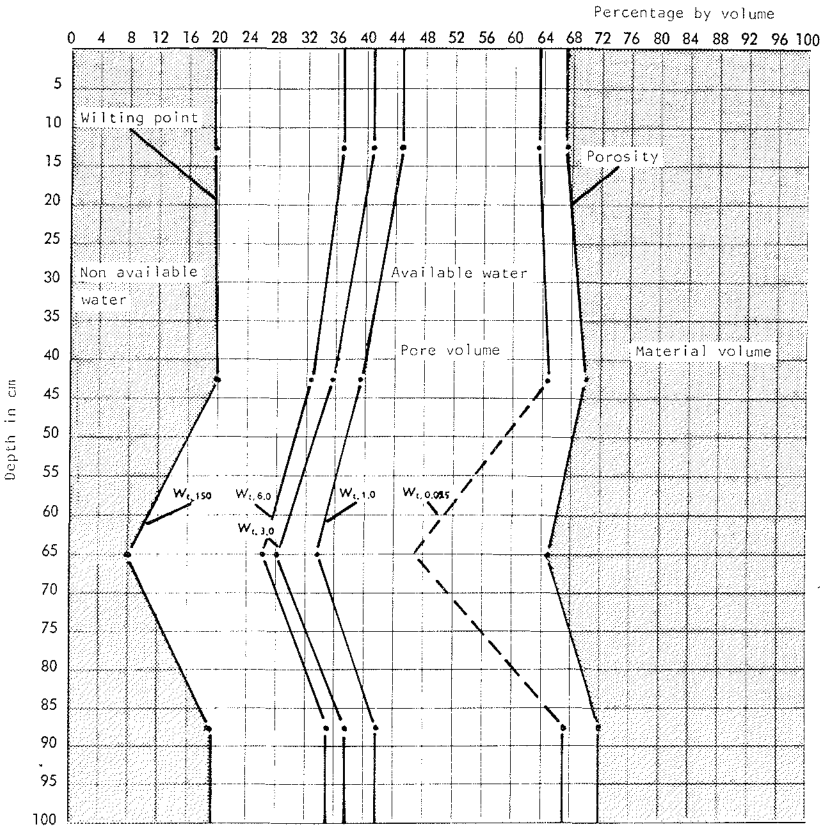


Figure 10. Profile MA 2. Pore space distribution with five suction curves.

6.2.3 Profile MA 53. Described 80-10-30.

The profile MA 53 is situated 100 m west of the plant nursery at Kawetire Forest Station north of Mbeya town. The landscape is characterized by a rolling land form and the profile lies on a slightly convex slope of 6 - 13 %. Pinus patula trees were planted here 1964, the average height of the trees now being 24 m. The soil is assumed to have been developed from hillwash material, probably with some ash included, overlaying basalt rock.

The soil was named a Luvic Phaeozem (FAO).

Soil profile horizons:

1. O 0 - 8 cm	Litter (needles from P. patula). 0-5 cm nonhumified, 5-8 cm humified organic matter.
2. A 8 - 25 cm	5YR 2.5/1 moist and 10YR 3/2 dry; loam (clay loam); moderate granular fine to very fine structure; slightly sticky, slightly plastic, firm consistence; few fine, common very fine and common medium pores; few rounded weathered and strongly weathered pumice and trachyte gravel; worms and fungihyfes present; few coarse, few medium and few fine roots; gradual wavy boundary.
3. Bt 1 25 - 55 cm	5YR 3/3 moist and 5YR 3/3 dry; clay loam (clay loam); strong medium to fine subangular blocky structure; sticky, plastic, firm, hard consistence; continuous thin clay skin on ped faces; many micro- and very fine pores; very few coarse roots and few fine and medium roots; gradual wavy boundary.
4. Bt 2 55 - 100 cm	5YR 3/2 moist and 5YR 3/4 dry; clay loam (clay loam); strong medium to fine subangular blocky structure; sticky, firm, hard consistence; continuous thin (barely visible) clay cutans; common very fine and micropores; very few sand sized fresh angular quarz and feldspar mineral fragments; very few coarse to fine roots; smooth and diffuce boundary.
5. Bt 3 100 - 150 cm	5YR 3/2 moist; silty clay loam; moderate medium to fine subangular blocky; sticky, plastic, slightly hard consistence; many very fine and micropores; mineral fragments same as above; very few coarse to fine roots.

Table 8. Analytical data from soil profile No MA 53.

Horizon Depth (cm)	2. A 8-25	3. Bt 1 25-55	4. Bt 2 55-100
Dry bulk density, g/cm^3	0.99	0.98	1.02
Particle density, g/cm^3	2.40	2.59	2.59
Porosity, % by volume	60	58	65
Water content, % by volume at suctions (m wc):			
0.05	58	55	55
1.0	40	38	41
3.0	37	36	38
6.0	34	34	36
150	21	25	35
Particle size distribution, % by weight:			
clay	29	38	36
fine silt	13	13	13
medium silt	14	15	16
coarse silt	9	6	9
fine sand	9	8	9
medium sand	10	8	5
coarse sand	5	2	1
loss of ignition	11	10	11

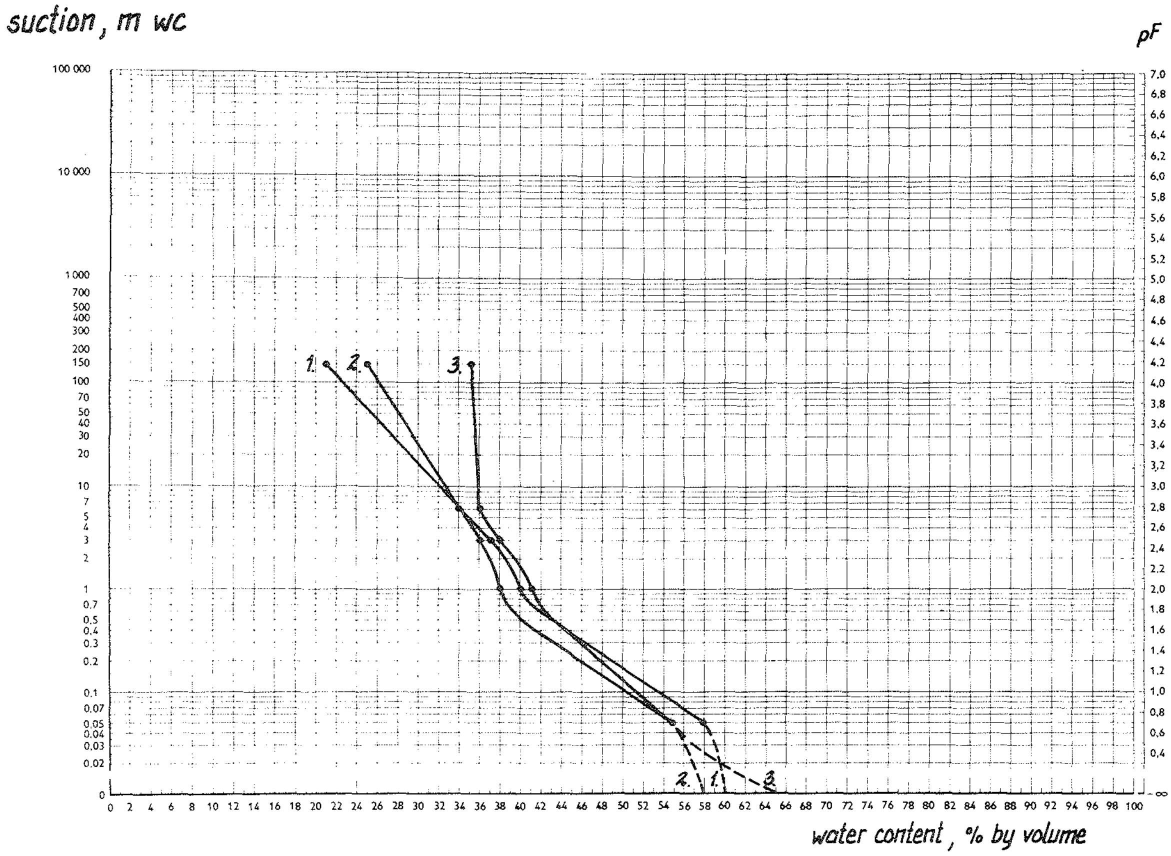


Figure 11. Soil moisture retention curve of profile MA 53.

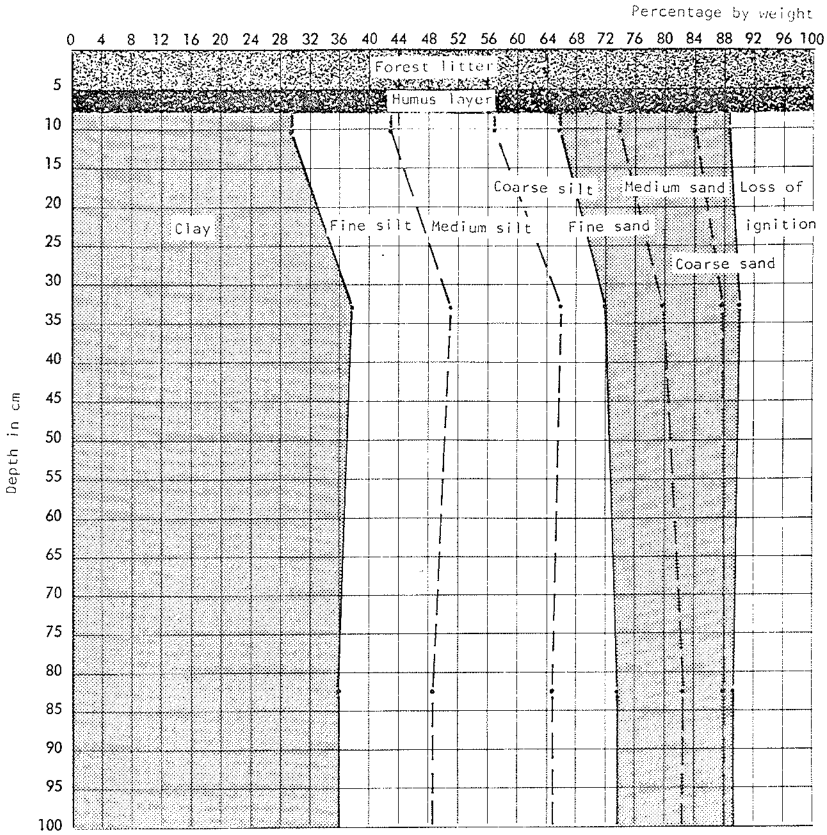


Figure 12. Profile MA 53. Particle-size distribution.

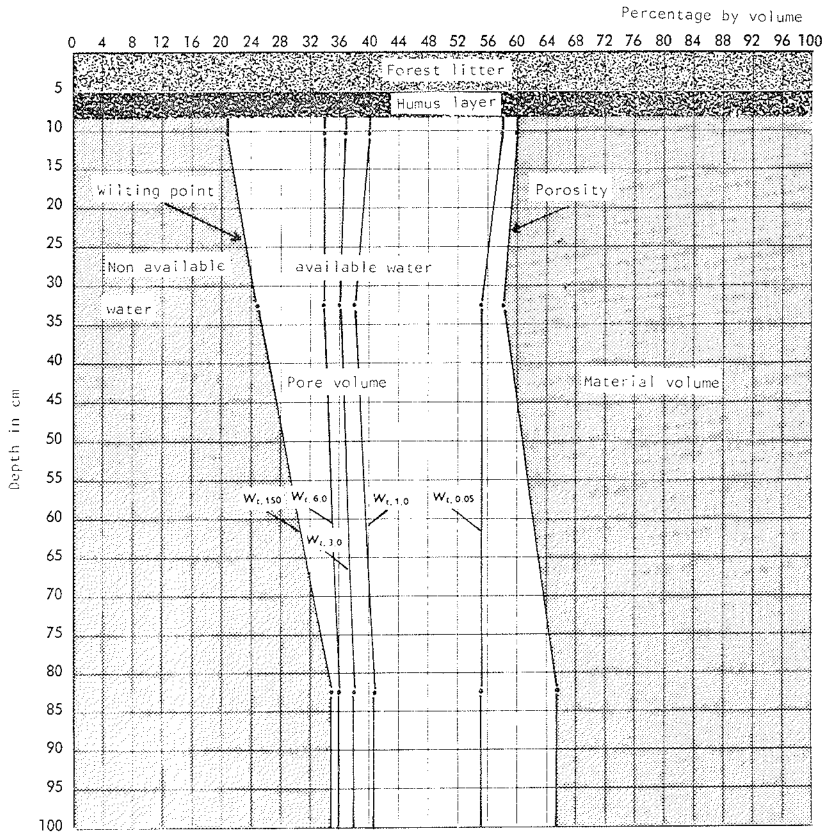


Figure 13. Profile MA 53. Pore space distribution
with five suction curves.

6.2.4 Profile US 37. Described 79-10-07

The following profile, US 37, is situated half-way along the road from the northern tip of the new state farm to the Great Ruaha River at 34^{o} 14' 30" E, 8 30' 40" S at an altitude of 1020 m. It lies in Acacia tortilis wooded Cynodon short grassland at a slope of 0 %. There are sinkholes up to 1 m deep, 2 - 3 m wide and 10 - 30 m apart. Much of the ground is bare of vegetation, indicating severe sheet erosion from which the drainage is interpreted as excessive.

The soil was named an Eutric Fluvisol (FAO) and an Ustic Torrifluvent (USDA).

1. A
   0 - 20 cm

   The upper 3 cm are a crust which shatters into small prismas, 1 - 2 cm in diameter. Very dark greyish brown (10YR 3/2) moist and dark greyish brown (10YR 4/2) dry; sandy clay (clay); strong, very coarse, prismatic - breaking into fine prismatic and subangular blocky structure; cracks up to 0.5 cm in width, about 15 cm apart define the coarse prisms; sticky, plastic, friable, very hard consistence; common very fine simple tubular pores within the peds; very few quartz fragments of grit size; sand fraction composed of quartz; few common very fine roots; gradual wavy boundary.

2. AC
   20 - 120+ cm

   Very dark grey (10YR 3/1) moist and dry; unmottled yellowish brown (10YR 5/2) streaks, possibly representing old cracks filled with more recent sediments; sandy clay (clay); strong medium and fine prismatic structure; very sticky, plastic, friable and extremely hard consistence; very difficult to dig; patchy shiny ped surfaces which probably are pressure faces; common fine simple tubular pores within the peds; very few angular quartz fragments of grit size; few small grit sized white and yellow angular and rounded slightly hard non-calcareous fragments; few very fine roots in the top 20 cm, some of them flattened between the peds, the horizon becoming unrooted with depth.

Table 9. Analytical data from soil profile No US 37.

Horizon Depth (cm)	1a. A 0-5	1b. A 5-20	2. AC 20-120+
Dry bulk density, g/cm^3	1.54	1.66	1.69
Particle density, g/cm^3	-	-	-
Porosity, % by volume	52	48	47
Water content, % by volume at suctions (m wc):			
0.025	49	47	47
1.0	41	44	47
3.0	39	38	43
6.0	38	38	43
150	25	35	43
Particle size distribution, % by weight:			
clay	46	56	60
fine silt	7	8	8
medium silt	9	8	9
coarse silt	13	9	11
fine sand	11	7	2
medium sand	6	4	2
coarse sand	2	1	1
loss of ignition	6	7	7
pH ($CaCl_2$)	5.8	5.7	6.6
P-HCl, mg/100 g soil	16	15	18
K-HCl, mg/100 g soil	235	270	330
Exchangeable cations, me/100 g soil:			
Ca	11.31	11.45	20.25
Mg	7.01	6.17	9.03
K	1.16	1.56	1.93
Na	2.36	4.04	3.06
CEC, me/100 g soil	25.9	31.5	36.0
Base saturation, %	84	74	95
Org. C, % by weight	0.80	0.82	0.51
Conductivity, mhos x cm^{-1} x 10^{-5}	10.1	5.8	6.3

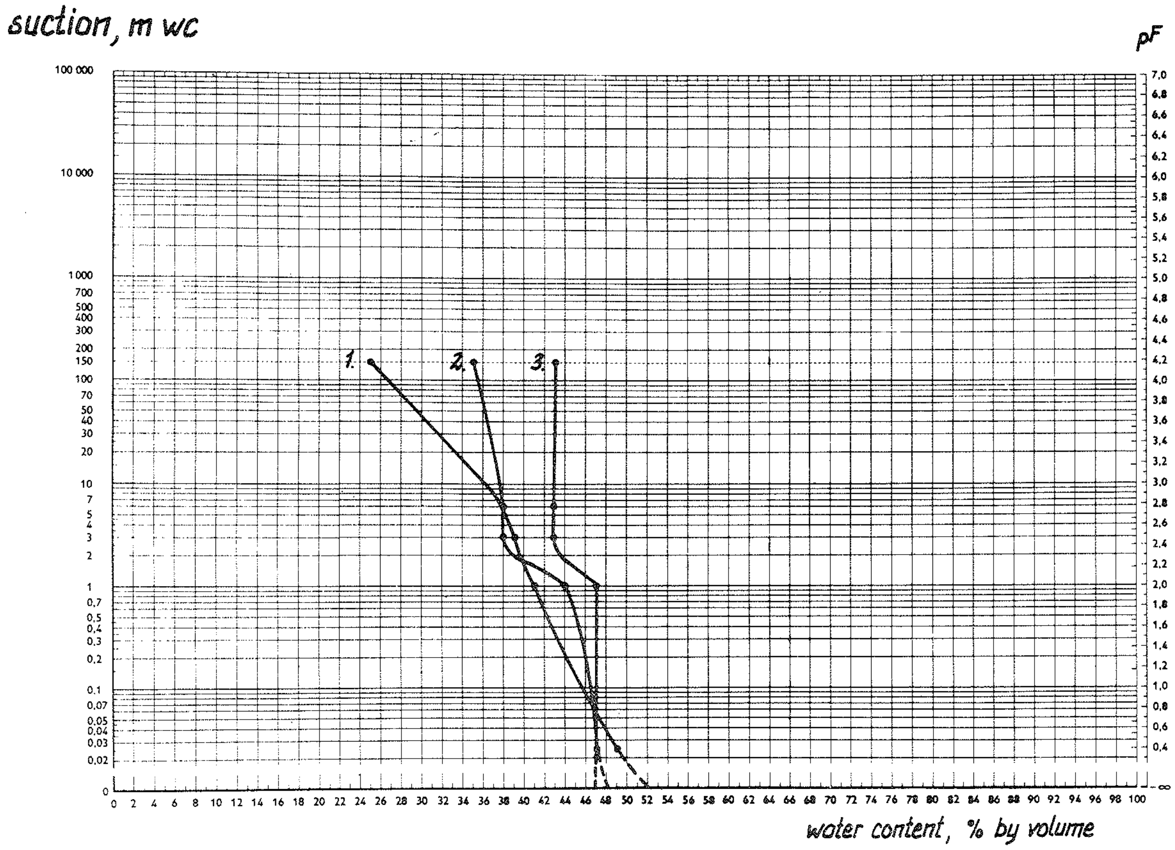


Figure 14. Soil moisture retention curve of profile US 37.

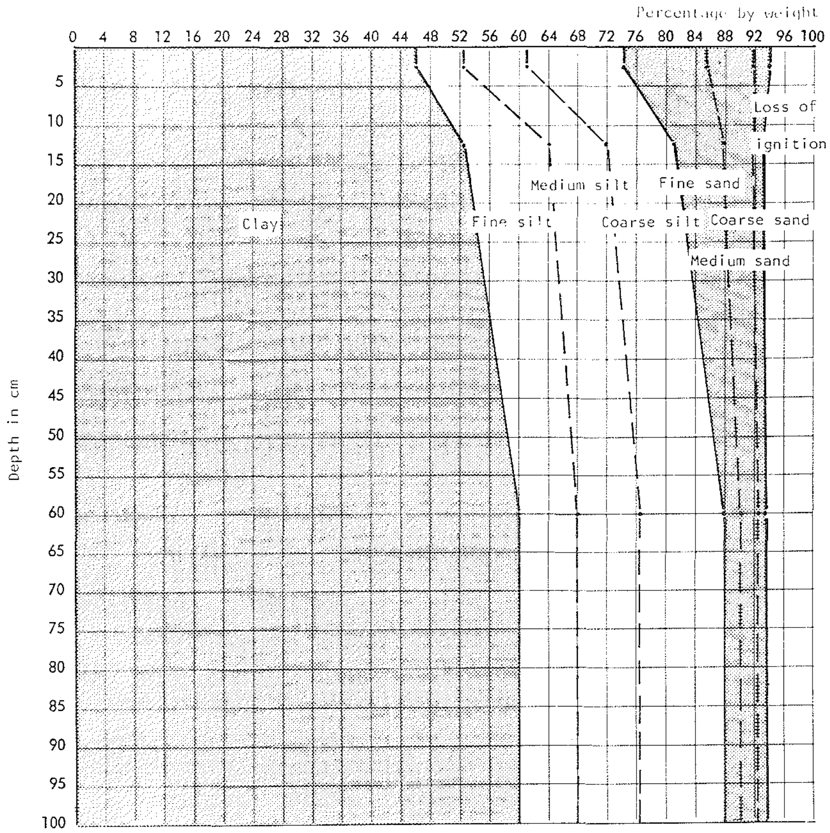


Figure 15. Profile US 37. Particle-size distribution.

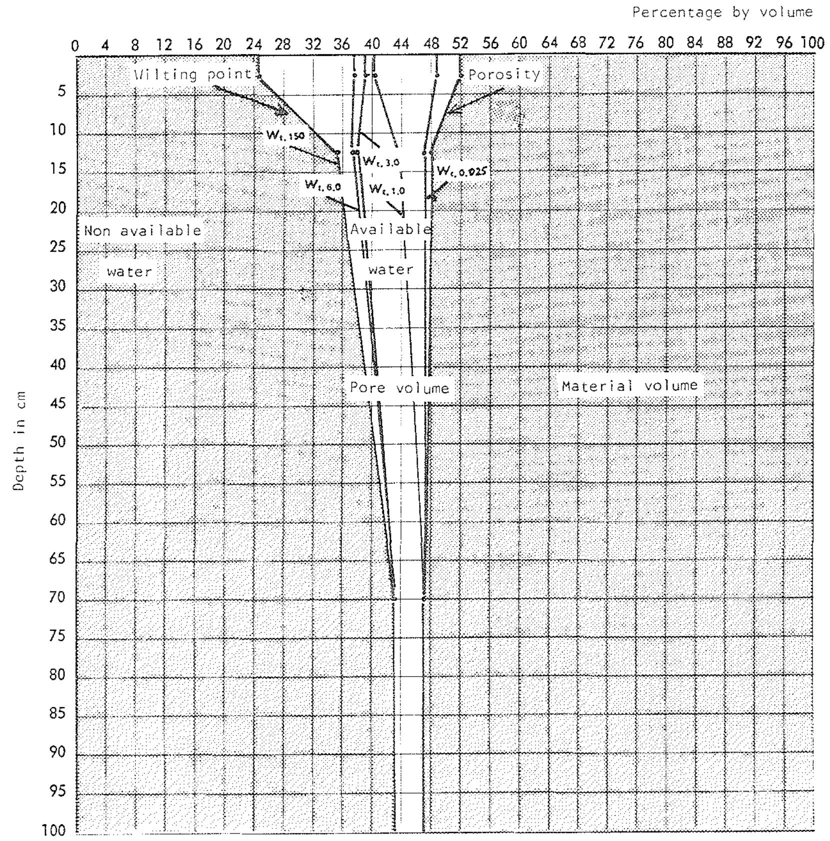


Figure 16. Profile US 37. Pore space distribution with five suction curves.

6.2.5 Profile US 59. Described 79-11-11.

Profile no. US 59 lies 6 km north-west of Ikoga village at an "mbuga" (seasonally flooded plain) on the Usangu Plains. It is situated on a low floodplain bench with a land form that is almost flat. The slope is 1 %. The microtopography can be described as a lattice of low ridges (about 20 cm high), 3 - 4 m apart. The natural vegetation is named "kiwunduwe" in the kihehe language and "malowoto" in the kisukuma language. This means seasonally waterlogged grassland. The site was not cultivated, but the land was used for wasukuma cattle grazing. Parent material is riverine alluvium. The soil is very poorly drained, the internal drainage being very slow. It was named a Pellic Vertisol (FAO).

Soil profile horizons:

1. A 0 - 20 cm	Very dark grey (7.5YR 3/0) moist; heavy clay (clay); very sticky, very plastic, extremely hard, very firm consistence; cracks up to 20 cm apart separate very coarse prisms which break up into smaller ones near the cracks; some shiny ped surfaces on the smaller peds; few small and large irregular rounded calcareous nodules; underneath the surface a mat of grass rhizoms has developed; abundant fine and very fine grass roots; gradual smooth boundary.
2. Bw 20 - 82 cm	Black (7.5YR 2/0) moist; heavy clay (clay); very sticky, very plastic, extremely hard, very firm consistence; cracks closer together than above enclosing coarse prisms up to 15 cm long and 10 cm wide, breaking into medium and fine prisms with conspiciously shiny pressure faces and angular faces. The smaller prisms become wedgeshaped and blocky with depth. The faces appear like small slickensides on the profile wall; nodules same as above; common fine and very fine roots; diffuse smooth boundary.
3. C 82+ cm	Colour, texture and consistence as above, very coarse blocks, enclosed by intersecting slickensides, breaking into coarse to small wedgeshaped blocks with very shiny pressure faces; few very fine roots.

Table 10. Analytical data from soil profile No US 59.

Horizon Depth (cm)	1. A 0-20	2. Bw 20-82	3. C 82+
Dry bulk density, g/cm^3	1.48	1.58	1.52
Particle density, g/cm^3	2.62	2.66	2.66
Porosity, % by volume	56	63	66
Water content, % by volume at suctions (m wc):			
0.025	56	63	66
1.0	55	63	66
3.0	49*	57*	58*
6.0	49*	57*	58*
150	49	57	58
400	25	27	28
Particle size distribution, % by weight:			
clay	82	85	86
fine silt	3	1	2
medium silt	1	2	1
coarse silt	2	1	1
fine sand	0	0	0
medium sand	0	1	0
coarse sand	0	0	0
loss of ignition	12	10	10

*) Because of the high shrinkage, these water contents have been adjusted.

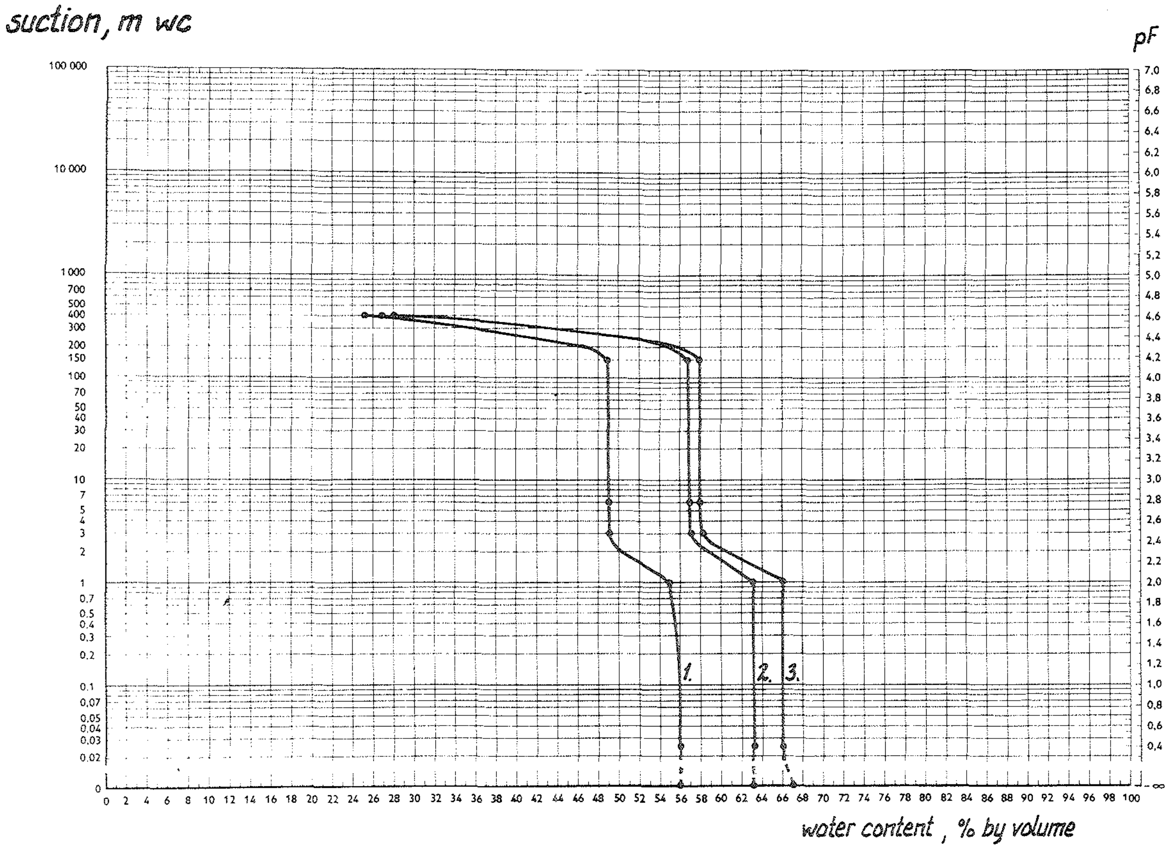


Figure 17. Soil moisture retention curve of profile US 59.

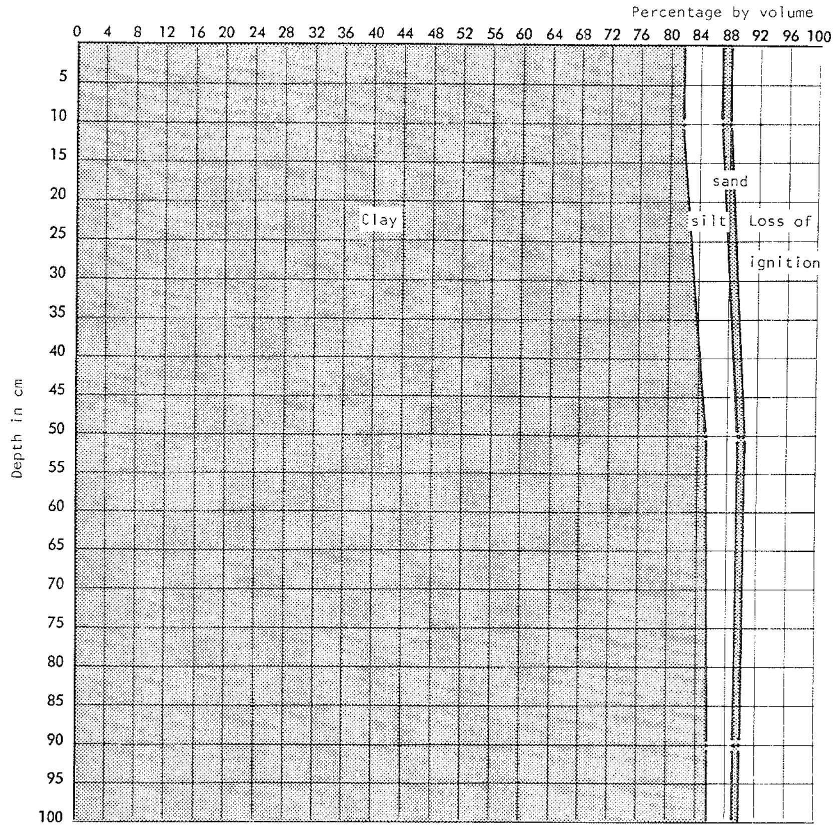


Figure 18. Profile US 59. Particle-size distribution.

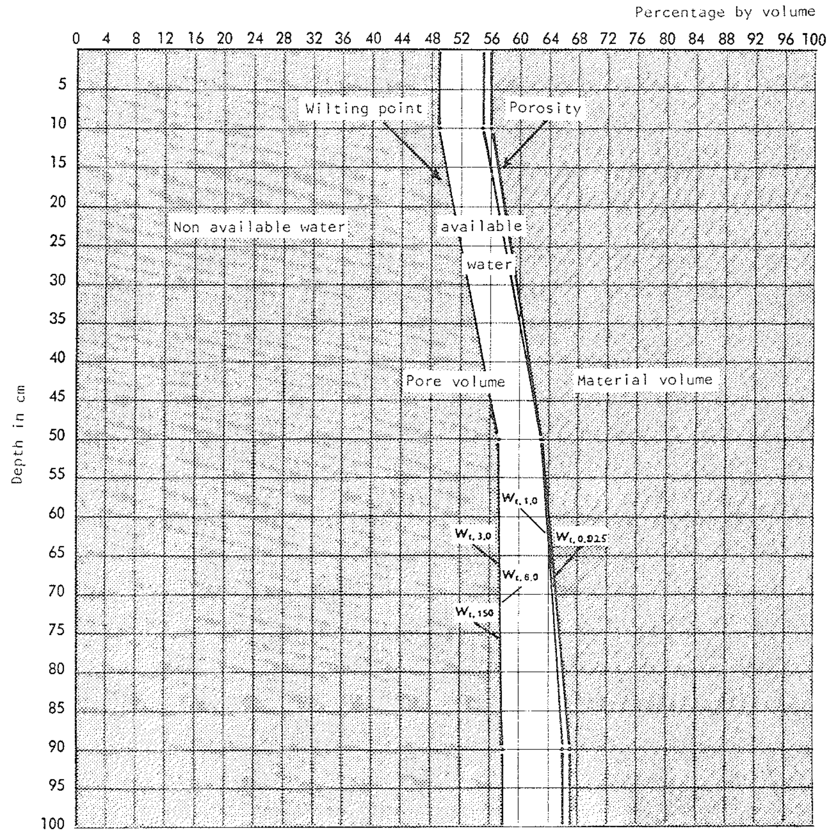


Figure 19. Profile US 59. Pore space distribution
with five suction curves.

6.2.6 Profile US 65. Described 79-11-14

The following profile is situated north of the Usangu Plains at Idunda village, 0^o 15' E and 8^o 10.6' S. The land form in the surrounding area is an undulating plain. The profile lies on an upper midslope on an interfluve at a slope of 5 %. The dominant vegetation is "Miwanga" woodland with some "Mjagara" (*Julbernardia paniculata*). The profile was described at a place recently cleared but not yet cultivated. The soil has probably been formed in place from gneiss and it is well drained.

The soil was named an Orthic Ferralsol (FAO).

1. Ah 0 - 9 cm	Weak red (2.5YR 4/2) moist and reddish brown (2.5YR 5/4) dry; sandy loam to loamy sand (Loamy sand); weak subangular blocky and very fine granular structure with some single grain- and massive structure; quartz of sand size present; abundant very fine to medium roots; gradual, smooth boundary.
2. Bt 9 - 31 cm	Reddish brown (2.5YR 4/4) moist and red (2.5YR 4/8) dry; sandy loam (sandy clay loam); nonsticky, non-plastic to slightly plastic, slightly hard, very friable consistence; weak medium and fine subangular blocky (appears massive) and fine granular structure; common very fine tubular pores; few grit and sand sized quartz fragments; common very fine roots.
3. Bt 2 31 - 150+ cm	Dark red (10R 3/6) moist and bright red (10R 4/8) dry; sandy clay loam (sandy clay); weak medium subangular blocky and granular structure - appearing massive -; sticky, slightly plastic, hard to very hard consistence; quartz grits; common very fine roots; few fine tubular pores.

Table 11. Analytical data from soil profile No US 65.

Horizon Depth (cm)	1. Ah 0-9	2. Bt 9-31	3. Bt 2 31-150+
Dry bulk density, g/cm^3	1.51	1.38	1.42
Particle density, g/cm^3	2.64	2.65	2.65
Porosity, % by volume	48	53	45
Water content, % by volume at suctions (m wc):			
0.025	42	47	42
1.0	19	23	31
3.0	15	17	26
6.0	13	15	24
150	4	8	17
Particle size distribution, % by weight:			
clay	8	22	43
fine silt	1	2	1
medium silt	2	3	0
coarse silt	4	5	4
fine sand	25	23	9
medium sand	34	25	14
coarse sand	14	17	23
loss of ignition	12	3	6
pH ($CaCl_2$)	5.7	4.0	4.0
P-HCl, mg/100 g soil	5	7	9
K-HCl, mg/100 g soil	35	35	60
Exchangeable cations, me/100 g soil:			
Ca	1.05	0.26	0.13
Mg	0.79	0.25	1.58
K	0.20	0.20	0.49
Na	0.04	0.04	0.09
CEC, me/100 g soil	3.4	4.0	5.9
Base saturation, %	60	19	39

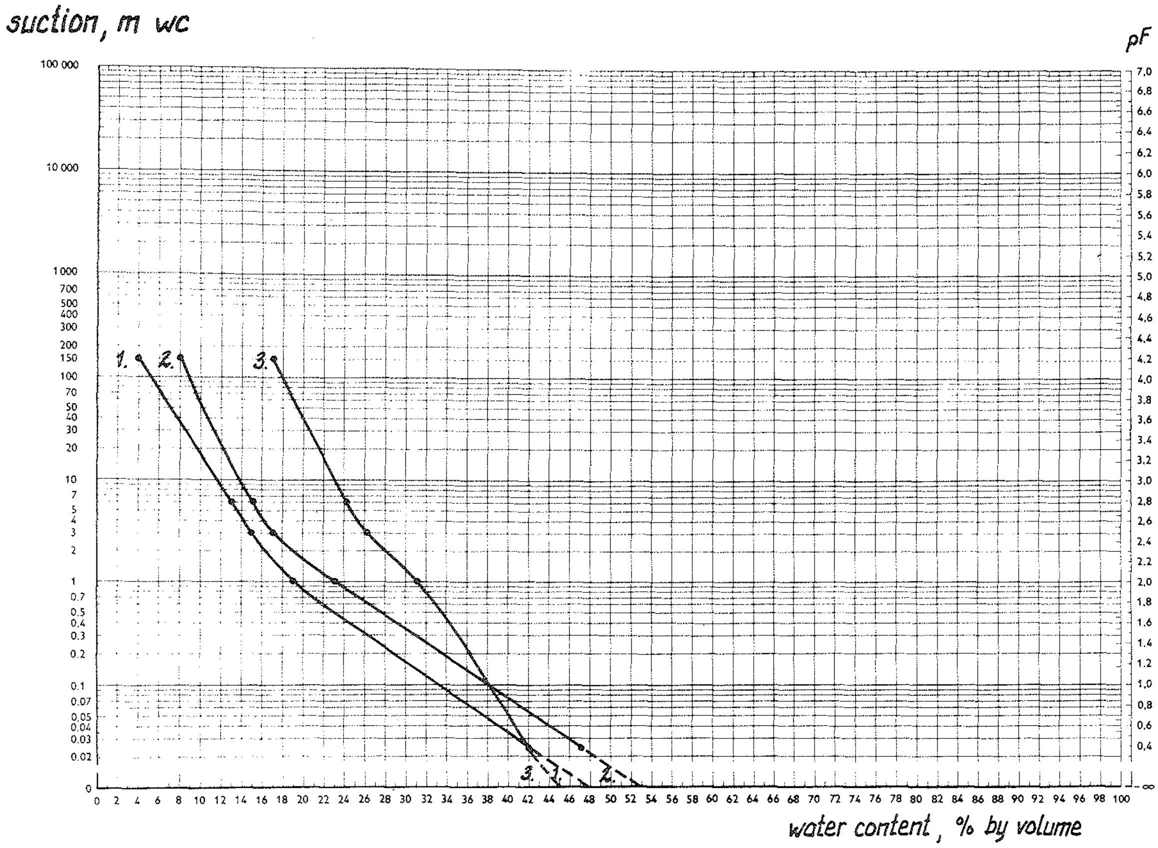


Figure 20. Soil moisture retention curve of profile US 65.

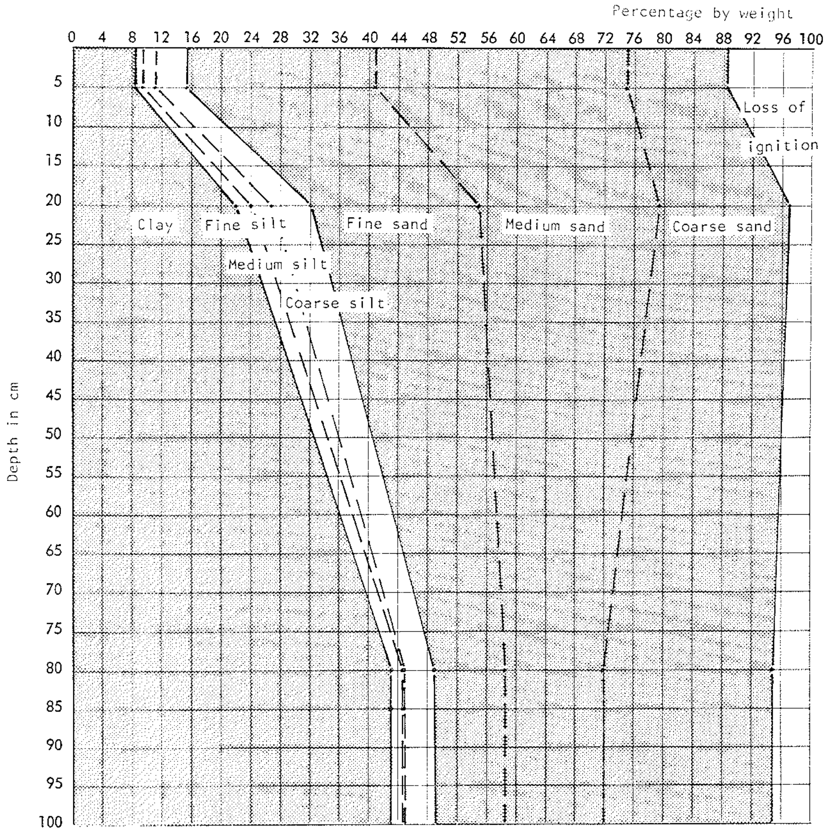


Figure 21. Profile US 65. Particle-size distribution.

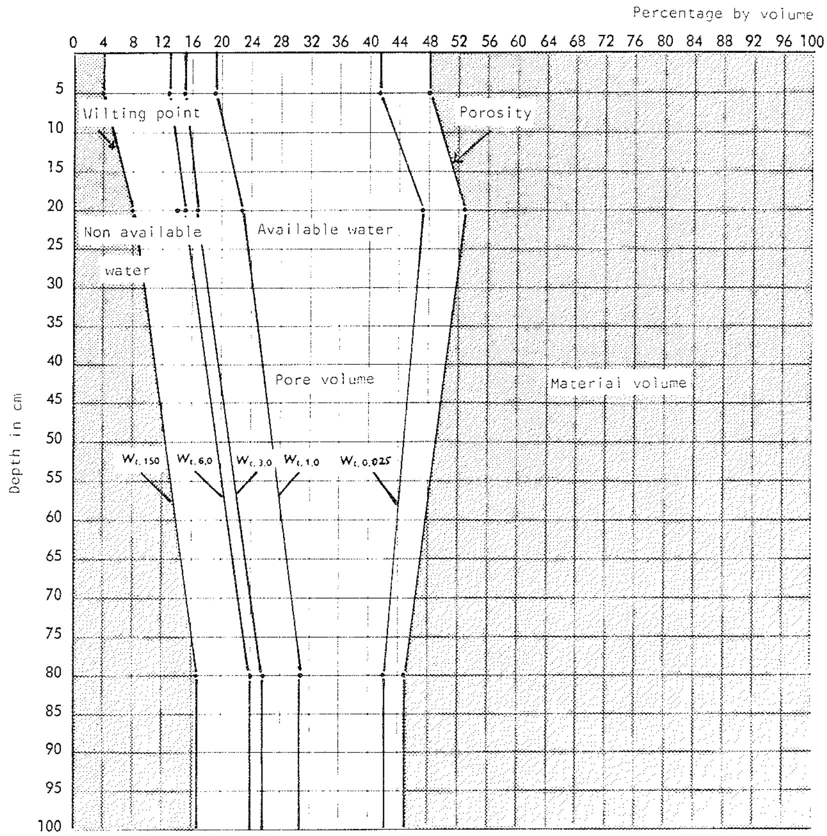


Figure 22. Profile US 65. Pore space distribution
with five suction curves.

6.2.7 Profile KY 7. Described 79-08-21

The profile was described at Mahengi close to Lake Nyasa at 33° 56' 30" E and 9° 26' 30" S. The altitude is 500 m. KY 7 is situated on a high floodplain bench on a lacustrine plain. The microtopography consists of rice field ridges. The slope is 0 %. The soil was cultivated but scattered *Bauhinia* could be seen. Common crops are rice, cashew, pigeon pea and bananas. The soil has not been analysed chemically, but is estimated to be fairly fertile. The origin of the soil is alluvial material derived from volcanic material. The soil is poorly drained and at the sampling time it was moist from 15 cm depth and downwards. The depth of ground water was 135 cm.

The soil was named an Eutric Fluvisol (FAO).

Soil profile horizons:

1. Ap 0 - 15 cm	Brownish black (10YR 3/1) moist and brownish grey (10YR 4/1) dry; silt loam (silty clay loam); strong coarse prismatic structure; sticky, slightly plastic, very hard consistence; many prominant coarse clear ferric oxide mottles; moderately thick broken ferric oxide cutans in pores and on ped faces; weakly cemented by iron; few medium, fine and many very fine pores; common fine and very fine roots; abrupt wavy boundary.
2. Bw1 15 - 48 cm	Brownish black (10YR 2/2) moist and dark brown (7.5YR 3/3) dry; silt loam (clay loam); coarse prismatic, strong medium subangular blocky structure; sticky, slightly plastic, slightly hard consistence; few fine and many very fine pores; in the lower parts some yellow ants were seen; few fine and very fine roots; gradual smooth boundary.
3. 2 Bw2 48 - 65 cm	Strong brown (7.5YR 5/8) moist; clay loam (silty clay loam); sticky, plastic, friable consistence; coarse subangular blocky structure; abundant medium and fine tubular pores; few medium and fine roots; clear wavy boundary.
4. 3C 65+ cm	Brown (10YR 5/3) moist; fine gravelly loamy sand (sandy loam); single grain structure; nonplastic, slightly sticky, loose consistence; porous; pumice gravel and few lava fragments; few large roots.

Table 12. Analytical data from soil profile No KY 7

Horizon Depth (cm)	1. Ap 0-15	2. Bw1 15-50	3. 2 Bw2 50-65	4. 3 C 65+
Dry bulk density, g/cm^3	1.17	1.16	1.08	1.06
Particle density, g/cm^3	-	-	-	-
Porosity, % by volume	52	58	61	58
Water content, % by volume at suctions (m wc):				
0.025	51	57	60	57
1.0	51	41	41	42
3.0	48	38	39	37
6.0	44	36	37	36
150	22	20	23	16
Particle size distribution, % by weight:				
clay	32	30	26	11
fine silt	10	10	12	6
medium silt	17	15	14	12
coarse silt	19	17	23	7
fine sand	6	14	9	7
medium sand	5	5	5	19
coarse sand	1	1	2	32
loss of ignition	10	8	9	6

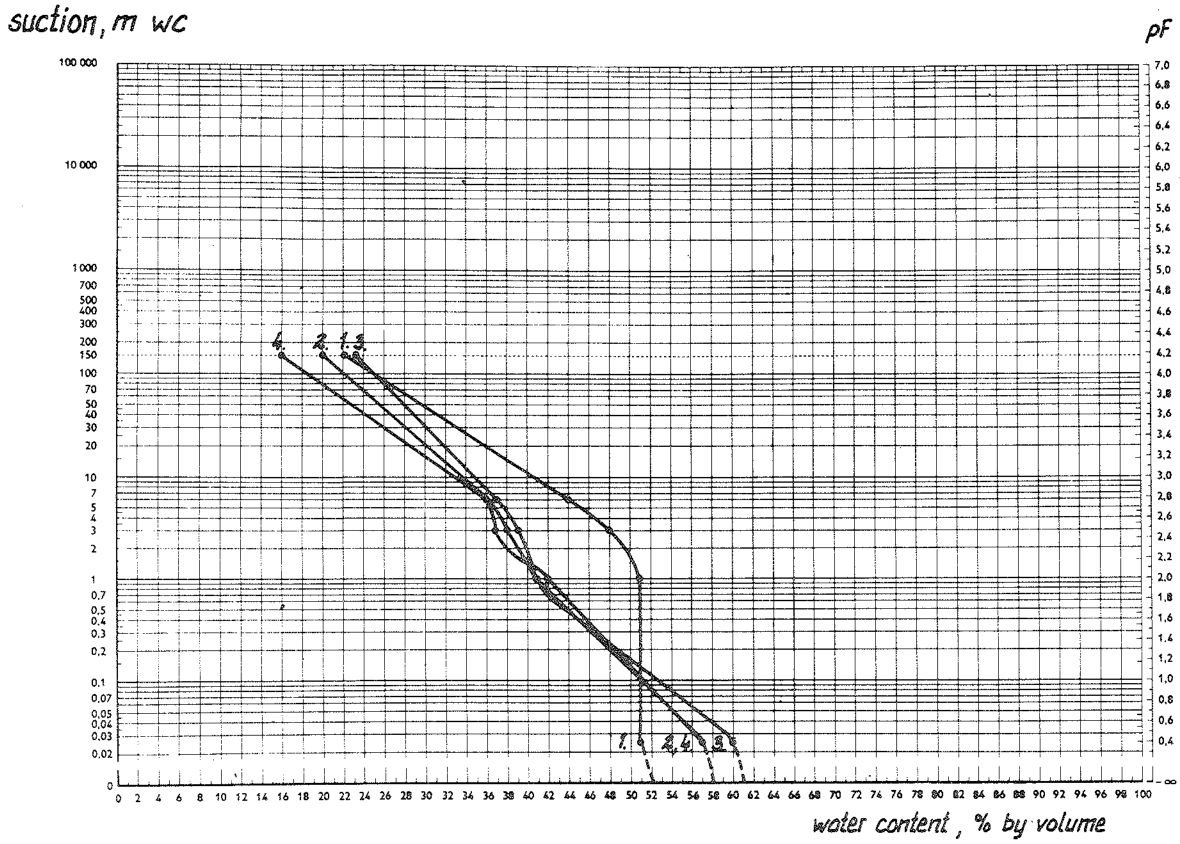


Figure 23. Soil moisture retention curve of profile KY 7.

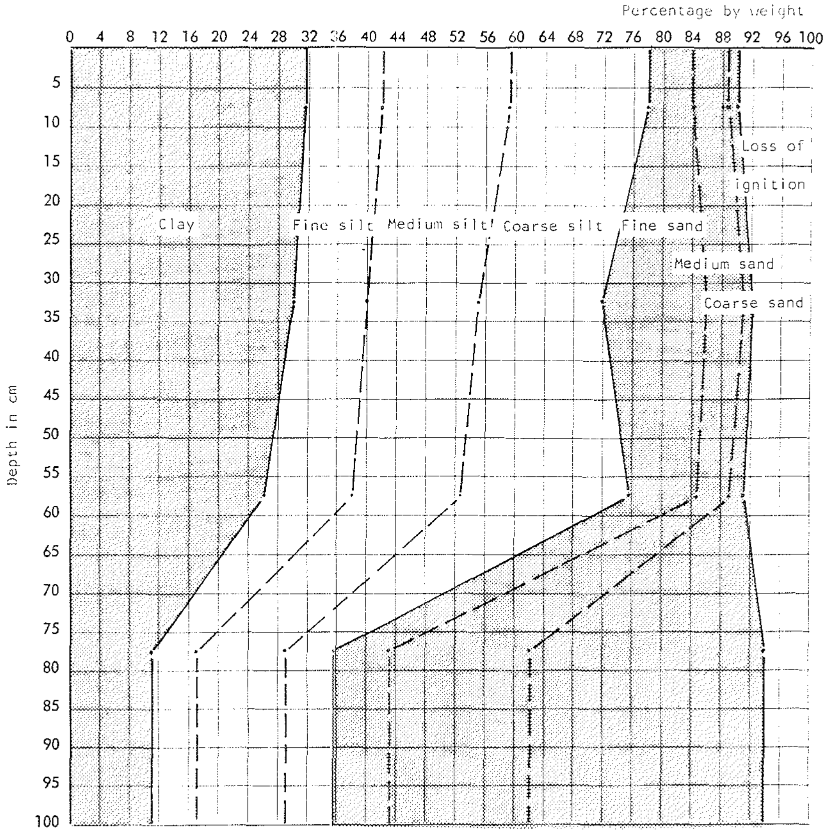


Figure 24. Profile KY 7. Particle-size distribution.

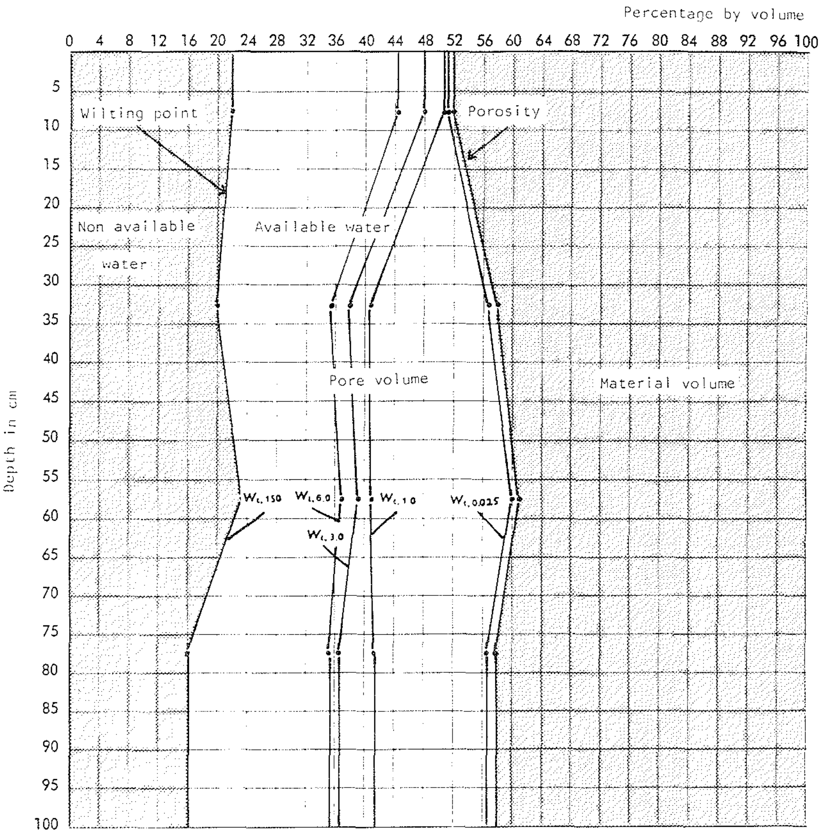


Figure 25. Profile KY 7. Pore space distribution with five suction curves.

7 GENERAL DISCUSSION

7.1 Soil Moisture Classification

The profile descriptions in chapter 6 give the basic data which are needed for evaluating the moisture holding capacities of the soils. Figure 26 is compiled from these data. The figure shows the water retention characteristics of the topsoils.

RU 7, MA 2 and MA 53 are all soils which have a volcanic origin. This fact has influenced the water holding properties of these soils considerably. The very high amount of available water is caused by several specific physical properties:

low bulk density - high porosity
the clay fraction consisting of amorphous clay minerals
the sand fraction consisting mainly of pumice particles.

US 65 is a Ferralsol, situated on a midslope. The water holding properties of this soil are good in spite of the low porosity. This type of soil can therefore be expected to give high yields of agricultural crops, provided the wet period give sufficient precipitation (possibly supplimented with irrigation applications), and provided fertilizers are applied. The natural fertility of this soil is very low (see Table 11).

Profile KY 7 also has a good water holding capacity. It is a Fluvisol with quite high clay content, situated on a floodplain bench north of Lake Nyasa. The geological composition of this soil is strongly influenced by volcanic material, which has been brought down from the mountains and carried to the floodplains by the water ways. The ash and pumice particles have very good water holding properties, as mentioned above.

The two profiles US 37 and US 59 are both situated on the Usangu Plains. They have very high clay contents and they do not release much of their water even at the high tension of 150 m wc (pF 4.18). The evaluation of these soils show that the soil moisture storage capacities are low to very low (see Table 14). On land where traditional farming is performed, grazing is the only realistic land use. However, at places with regular flooding during the wet season, wet rice can be cultivated. In addition to the drought susceptability, the soils are also extremely difficult to work with the traditional agricultural tools.

The soils have been classified with respect to soil moisture storage capacity according to the system presented by Lal & Greenland (1979) (see Tables 13 and 14). The classification system is reported in chapter 4, Table 5. An important part of the evaluation is the determination of "average productive available moisture in topsoil" (pF 2.3 - pF 3.7). The water contents at this point of the pF-curve have been approximated from the soil moisture retention analysis for each soil.

The classification of the soil moisture storage capacities is recorded in tables 13 and 14.

With this method, variations in soil moisture characteristics of different soil types can be easily distinguished. Thus, specific feasability studies in smaller areas within a region can be evaluated with good accuracy with respect to soil moisture retention. In the planning of irrigation schemes, this is of course of particular interest. In addition, introduction of crops with specific demands on soil moisture also require this kind of information.

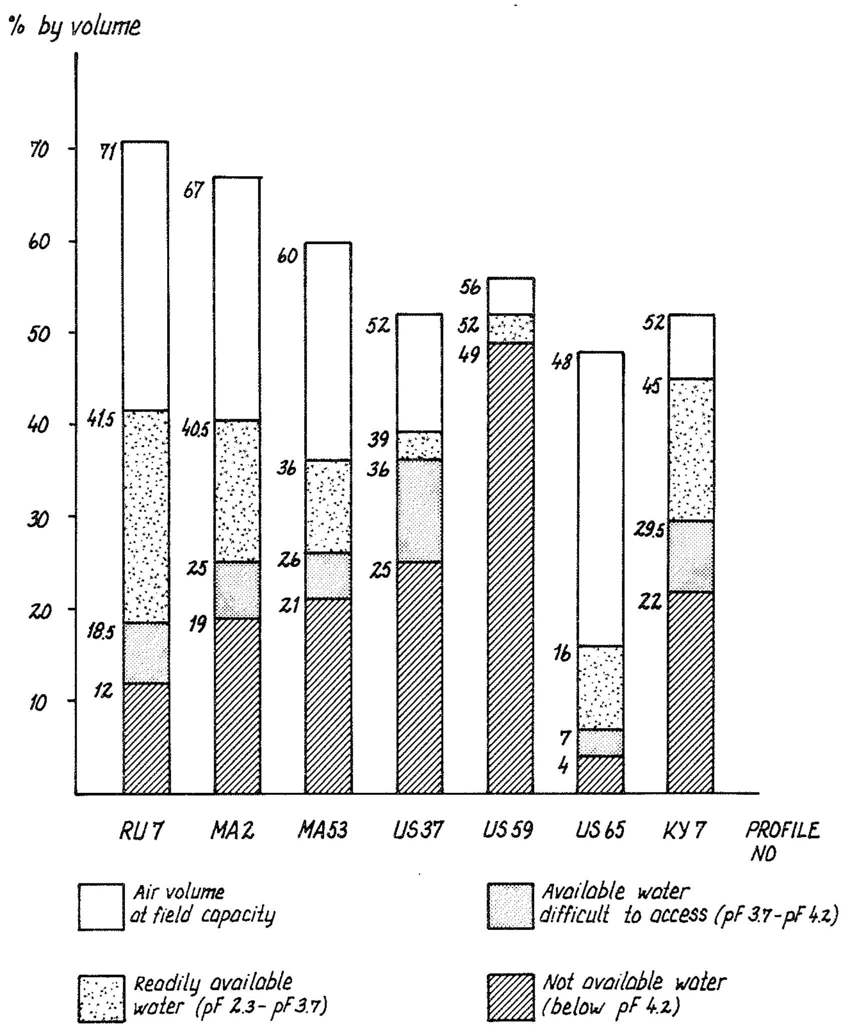


Figure 26. Porosity, fraction of air and fractions of water at different suctions in the topsoils (0-30 cm) of seven Mbeya soils at field capacity (pF 2.3).

The classification system used here need to be tested further at different levels of survey and in different land use systems.

Table 13. Subratings of the soil moisture storage capacity of seven soils in the Mbeya Region, Tanzania.

Profile no.	Soil depth cm	Average productive available moisture in topsoil pF 2.3-pF 3.7; % by vol.	Profile hindrance to root development
RU 7	180	23	none
MA 2	190	15.5	none
MA 53	150	10	slight (argillic horizon)
US 37	40	3*	strong (all horizons in sodic phase)
US 59	82	3*	strong (no roots below cracking depth due to the high clay content)
US 65	150	9	none
KY 7	65	15.5	slight (sedimentary stratification; gr. water level at 135 cm in dry period)

*High swelling and shrinking capacity give somewhat unreliable soil moisture retention data.

Table 14. Final rating of the soil moisture storage capacity of seven soils in the Mbeya Region, Tanzania.

Profile no.	Class	Total of subrating points	Total productive readily available moisture (mm)
RU 7	0. Except. high	2	>180
MA 2	0. Except. high	2	>180
MA 53	2. High	6	90-130
US 37	Very low	13	<35
US 59	4. Low	11	35- 60
US 65	1. Very high	4	130-180
KY 7	2. High	6	90-130

The final evaluation of the soils must of course include the specific demands of the crop. For instance, vegetables and cacao need soils which hold a high amount of available water during the growing season. Sisal and cotton, on the other hand, grow well on soils which have less favorable soil moisture holding properties (see table 2 in chapter 4).

7.2 Estimations of soil moisture characteristics

It is possible to estimate soil moisture characteristics without the expensive and time-consuming analysing of water content over the whole pF-range. The estimation can be made from correlations between, for instance, wilting point and clay content on a certain type of soil. Similar relations can be found for water content at various lower tensions and clay content. If multiple regression analysis is used, factors such as clay content, silt content, bulk density and organic matter content can also be correlated to soil moisture characteristics.

Several soil scientists have presented different regression equations for estimation of soil moisture properties. In the following, four different regression equations will be tested on the soils presented in this report. The equations will be restricted to estimation of water content at wilting point. Also, the equations will only include soil samples in horizons underlying the topsoil. This is to avoid the high variation due to the different organic matter contents in the topsoils.

Each equation will be transformed to give the value of the water content at wilting point in % by volume. This is done in order to simplify the comparison in Fig. 24. The average dry bulk density is assumed to be 1.4 g/cm^3.

1. FAO, 1974a

$Y = 10 + 0.234C$ $\qquad$ $r = 0.645$, $n = 24$

$Z = 1.4Y$

Y = 15-bar water content, % by weight
C = clay content, % by weight
Z = 15-bar water content, % by volume
r = correlation coefficient
n = number of soil samples

The equation is based on soil samples from oxic horizons of Ferralsols. It is not mentioned in the FAO publication where these soils are located.

2. Greenland, 1981.

$Y = 0.48X + 4.5$ $\qquad$ $r = 0.77$***

$Z = 1.4Y$

Y = Permanent Wilting Point, % by weight
X = clay content, % by weight
Z = Permanent Wilting Point, % by volume
r = correlation coefficient

This equation is based on water retention data from West African soils. Greenland states that the correlation between clay content and water content at 15-bar suction is less than twice the clay content, in contrast to the value of 2.5 x clay content found for many temperate zone soils. The reason for the lower water retention per unit weight of clay is, according to Greenland, "probably an effect of the dominance of the larger kaolinite clay minerals than the normally dominant micaceous minerals in most temperate zone soils".

The number of samples on which the equation is based is not specified.

3. Hall et al, 1977.

(15) = 1.48 + 0.84C - 0.0054C   variance accounted for 83 %
n = ca 480

(15) = 15-bar water content, % by volume
C = clay content, % by weight
n = number of samples

The equation is based on a great number of subsoil samples from soil profiles in England and Wales. The relationship was found not to be linear. For this reason, a quadratic regression analysis is used. The increasing scatter of $\theta_v(15)$ values at high clay contents is probably, according to the authors, due to a mineralogy factor.

4. Wiklert, 1964.

$$W_{t,150} \pm 2.5 = 1.5 + 0.32L \qquad n = \text{ca } 750$$

$$Z = 1.4\, W_{t,150}$$

$W_{t,150}$ = 15-bar water content, % by weight
L = clay content, % by weight
Z = 15-bar water content, % by volume
n = number of soil samples

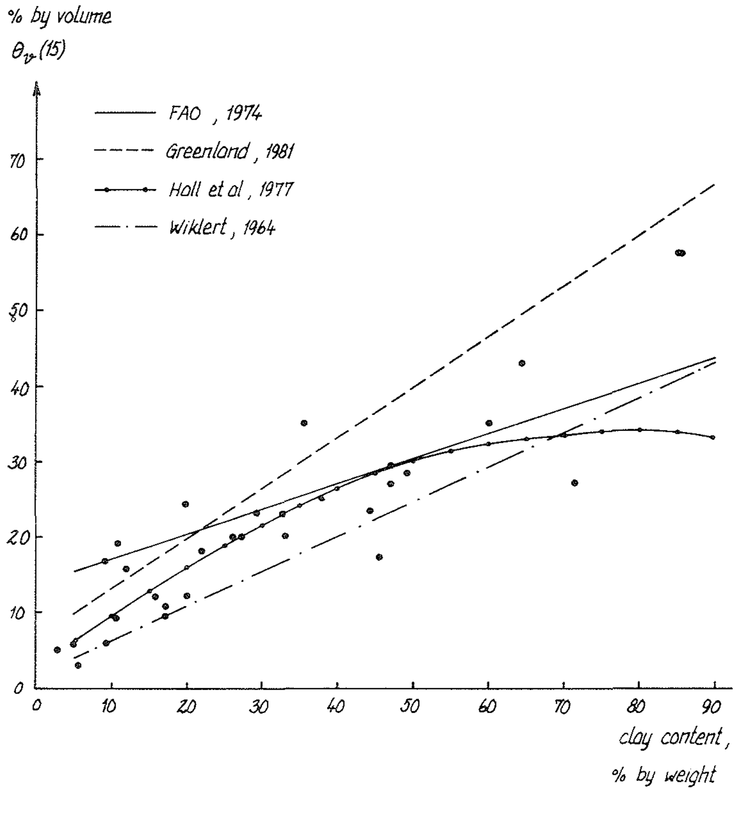


Figure 27. Regression curves showing the relation between 15-bar water content and clay content.

The equation No. 4 is a simplified version of a regression equation in which the fine silt fraction also was built in. The numerous soil samples are all cultivated soils from Sweden.

The four equations are presented in Fig. 27. Tanzanian subsoils reported earlier in this paper are placed in the same diagram. A few other soils from the same region in Tanzania are also included. It is evident that it is very difficult to find a regression curve which fits all the soils. On the other hand, these soils are very different both with respect to geological origin and climatic conditions.

A regression equation based on the Tanzanian subsoil samples which were plotted both in Fig. 27 and Fig. 28 is illustrated in Fig. 28. The equation follows below:

$Y = 5.10 + 0.50X$ $\qquad\qquad$ $r = 0.91,\ n = 31$

Y = 15-bar water content, % by volume
X = clay content, % by weight
r = correlation coefficient
n = number of samples

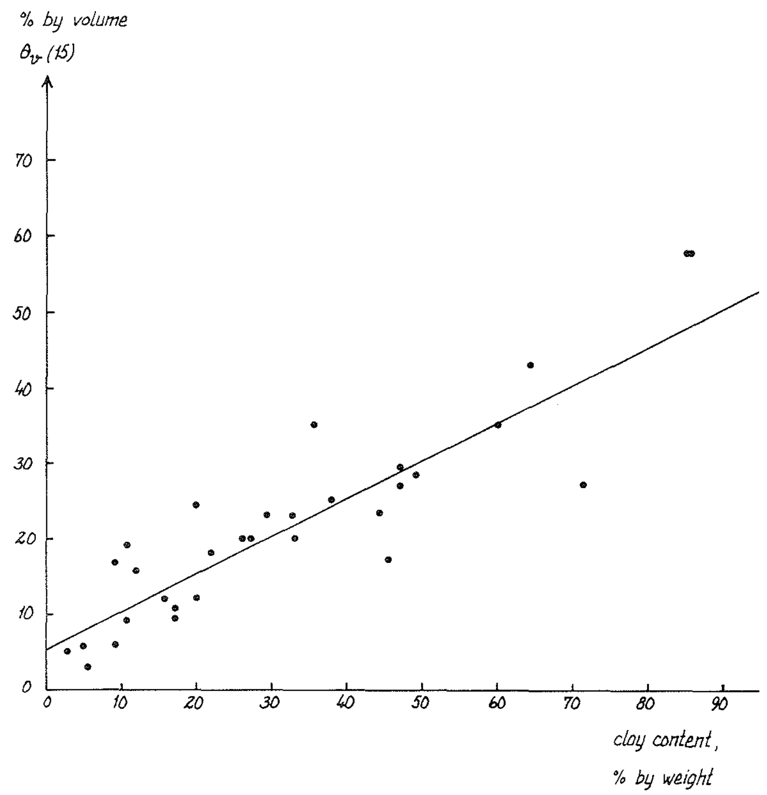


Figure 28. Regression curve based on soils from the Mbeya Region, Tanzania. The figure shows the relation between 15-bar water content and clay content.

This regression equation is quite close to equation No. 3 in Fig. 25 up to a clay content of 50 %. The variations are, however, quite high. Considering the great differences between the soils, the equation can possibly be used for rough estimations of Permanent Wilting Point of Tanzanian soils. Much better regression analysis can be worked out if each main soil type is analysed and treated separately. Such regression equations can probably use soil information also from other countries in East Africa. The number of soil samples should not be less than 50-60 for each soil type.

This type of estimations can be useful for soil moisture classification at, for instance, reconnaissance level. More intensive studies need thorough soil moisture analysis to give accurate recommendations on land use etc.

8 SUMMARY

In this report, detailed descriptions of seven soils in the Mbeya Region in Tanzania are given. The soils are chosen to represent some of the main soil types in this part of East Africa: Andosols, Regosols, Phaeozems, Vertisols, Ferralsols and Fluvisols. The soil profile descriptions include physical and in some cases chemical analyses and are reported in chapter 6.

The seven soils are picked from the Reconnaissance Soil Survey recently undertaken in the Mbeya Region by BRALUP (Bureau of Reconnaissance Assessment and Land Use Planning) at the University of Dar-es-Salaam, and the Soil Science Department at Uyole Agricultural Centre in Mbeya, Tanzania. The object of the Soil Survey is a land evaluation of the soils in the region for several specific crops.

This report is an attempt to improve the classification of soil moisture storage capacities of the soils. The normal routine today for this classification is a drought index including potential evapotranspiration and rainfall data, completed with data on vegetation indicators (see chapter 3).

The suggested soil moisture classification is an application of a classification system described by Lal & Greenland (1979). This system is described in the literature review (chapter 4). It is based on the term "Productive available moisture", defined as the water content in the soil at pF 2.3 - pF 3.7.

The classification of the seven soils are presented in the tables 13 and 14. The highest amounts of "Total productive readily available moisture" were found in the soils derived from volcanic materials. The Ferrasol US 65 also has very good water holding properties; it was classified "very high". The Fluvisol KY 7 and the Phaeozem MA53 were classified "high" - these soils also include some material of volcanic origin. Finally, the soil profiles US 37 (Regosol) and US 59 (Vertisol) were classified "very low" and "low", respectively. The high clay contents of these soils cause an extremely high water retention. Thus, a very small amount of that water is available for plant production.

Finally, a regression equation relating 15-bar water content to clay content was calculated from Tanzanian subsoil samples. The estimations that are made from this equation can not, however, be recommended for use in detailed soil surveys. Further research is suggested, in order to work out regression analysis for different soil types in East Africa.

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