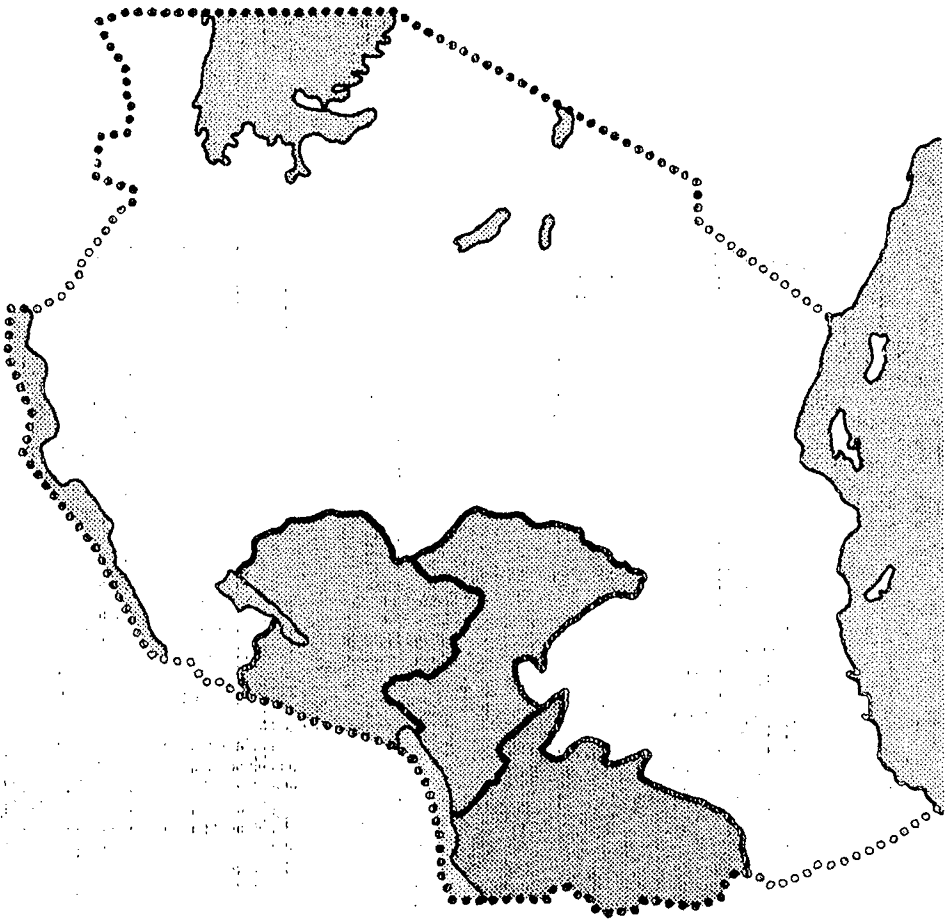
UNITED REPUBLIC OF TANZANIA

DANISH INTERNATIONAL DEVELOPMENT AGENCY • DANIDA

WATER MASTER PLANS FOR IRINGA, RUVUMA AND MBEYA REGIONS

HYDROGEOLOGY

VOLUME 9



CARL BRO ▫ COWICONSULT ▫ KAMPSAX - KRÜGER ▫

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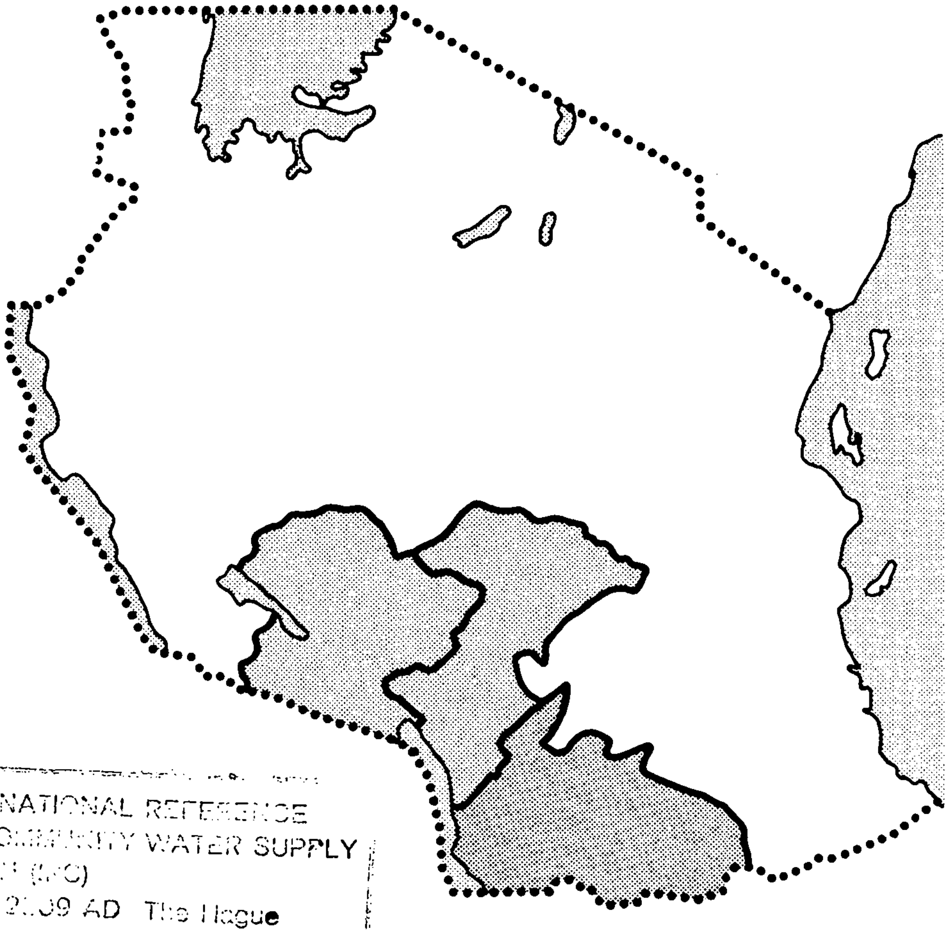

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GUIDE TO WATER MASTER PLANS FOR IRINGA,RUVUMA AND MBEYA

VILLAGE WATER SUPPLIES

DEVELOPMENT FRAMEWORK

POPULATION	3/2, 4A/2/4, 12/3
LIVESTOCK	3/2, 4A/2/3/5, 12/2
AGRICULTURE	3/2, 4A/3/5, 11/3, 12/2
INDUSTRY	3/2

VILLAGES AND EXISTING WATER SUPPLY

INVENTORY	5A/1, 12/4
DEVELOPMENT	4A/4
TRADITIONAL W.S.	4A/6, 12/5
IMPROVED W.S.	4A/6

WATER USE AND DESIGN CRITERIA

HUMAN CONSUMPTION	3/5, 5A/4, 12/8
LIVESTOCK DEMAND	3/5, 5A/4, 12/9
TECHNICAL ASPECTS	3/5, 5A/4

WATER SUPPLY PLANNING CRITERIA

TECHNOLOGY OPTIONS	5A/5, 12/7
WATER QUALITY	3/5, 4A/6, 4B/7, 5A/3, 12/5/10/11
SOURCE SELECTION	3/6, 4B/7, 12/5
PRIORITY CRITERIA	3/5, 5A/2, 12/12
COST CRITERIA	5A/2/6, 12/12

PROPOSED SUPPLIES

REHABILITATION	4B/8	
SINGLE VILLAGE SCHEMES	4B/8	
GROUP VILLAGE SCHEMES	4B/8	
SCHEME LAY-OUT AND DETAILS	5B, 5C, 5D, 5E	IRINGA
SCHEME LAY-OUT AND DETAILS	5B, 5C, 5D	RUVUMA
SCHEME LAY-OUT AND DETAILS	5B, 5C, 5D	MBEYA

COST

ECONOMIC COST	3/6, 4B/9/10, 5B, 5C, 5D, 5E	IRINGA
ECONOMIC COST	3/6, 4B/9/10, 5B, 5C, 5D	RUVUMA
ECONOMIC COST	3/6, 4B/9/10, 5B, 5C, 5D	MBEYA
FINANCIAL COST	3/6, 4B/9/10	

IMPLEMENTATION

STRATEGIES	3/6, 4B/10
PROGRAMME	3/6, 4B/10
ORGANISATION	3/6, 4B/11, 12/6
PARTICIPATION	3/6, 4B/10/11, 12/6

WATER RESOURCES

HYDROLOGY

RAINFALL	3/3, 7/3
EVAPORATION	3/3, 7/4
RUNOFF	3/3, 7/5/6
MODELLING	3/3, 7/7
BALANCES	3/3, 7/7/8

HYDROGEOLOGY

GEOLOGY	3/4	9/5
GROUNDWATER DOMAINS	3/4	9/7
GEOPHYSICS	3/4	9/8
CHEMISTRY	3/4	9/9
GROUNDWATER DEVELOPMENT	3/4	9/12
DRILLING	3/4	9/11

WATER-RELATED PROJECTS

WATER RELATED PROJECTS

IRRIGATION	11/4, 12/9
HYDROPOWER	11/4

NOTES

THE CHAPTERS REFERRED TO ARE THOSE WHERE THE MAIN DESCRIPTIONS APPEAR.

THE REFERENCE CODE 5A/6 MEANS, VOLUME 5A, CHAPTER 6.

CONTENTS Page

(cont'd)

CONTENTS

CONTENTS

(cont'd)

CONTENTS

(cont'd)

CONTENTS

References

DRAWINGS (C.F. BOX II)

1. INTRODUCTION

In preparing the hydrogeology part of the Water Master Plans for Iringa, Ruvuma and Mbeya Regions, it was decided not to produce separate volumes for the regions. This is because the geology of the regions is so closely related that describing each region separately would lead to unnecessary repetitions, and the risk of losing the overall view. Whenever possible the descriptions has, however, been done under the regional headings.

The report is presented in three volumes, which are organised in the following way:

Volume 9, the main volume, describes the findings of the study and gives recommendations, while Volume 10 is an associated data volume. For the sake of convenience Volume 10 is split up into Volume 10 A and 10 B.

Volume 10 A contains 4 Appendices. Appendix 1 is a description of the methods of investigations applied. Methods described in the literature are made factual, whereas analyses of pumping tests with decreasing discharge are described in more detail, as these methods have been developed by the Consultants. Appendix 1 also includes a Chapter, which describes the hydrogeological terms commonly used in Volume 9.

Appendix 2 is the presentation and interpretation of the pumping test data from existing wells and wells drilled by the Consultants.

Appendix 3 presents the results of the geophysical investigations (geoelectric and seismic surveys, and borehole logging).

Appendix 4 is a list of springs, obtained from the village inventories.

Volume 10 B contains all data pertaining to existing boreholes and boreholes drilled by the Consultants. It comprises three Appendices which are:

- Appendix 1, Borehole Completion Form,
- Appendix 2, Borehole Location Forms, and
- Appendix 3, Groundwater Chemical Analyses.

Six Drawings describing the hydrogeology and related fields are presented in Box II. They are:

Drawing II-8 : Geology
Drawing II-9 : Geomorphology
Drawing II-10: Cyclogram Map

Drawing II-11: Groundwater Chemistry
Drawing II-12: Dambos, Springs and Main Faults
Drawing II-13: Groundwater Development Potential.

Working papers have been prepared and submitted to MAJI and DANIDA during the course of the study, and key decisions and results have been discussed with MAJI - and DANIDA officials during the study.

2. APPROACH AND ORGANISATION OF WORK

2.1 Approach

The main purpose of the hydrogeology study has been to describe the groundwater occurrences in qualitative and quantitative terms, and to determine the most efficient ways of locating and evaluating the groundwater resources.

In the initial phase, therefore, existing data were collected and examined. The planning of the initial field investigations was based on these existing data, mainly borehole data.

As the study progressed it was realised that erosion and weathering had a decisive influence on the hydrogeology and groundwater conditions across the Basement Complex, which occupies 68% of the study area. It was, therefore, decided to use a geomorphological framework in describing the hydrogeology of the regions. Although the geomorphological approach was found most applicable in describing the subsurface conditions of the Basement Complex, the approach immediately identified groundwater domains in the remaining parts of the study area, so the whole area was divided into groundwater domains with particular geomorphological characteristics. It is on these geomorphological units that the description of the hydrogeology is based.

2.2 Organisation of Work

In the field and in the office, each expatriate hydrogeologist worked with mainly the same counterpart throughout the study.

The work in the field was centred around field investigations and supervision of the MAJI CME Auger Rig 53. The field investigations were geophysical surveys (geoelectric and seismic surveys, borehole logging), siting boreholes for Rig 53 and the MAJI Schramm T64 Rig 45. Sites for the latter rig were all determined according to the results of a geophysical survey. This was also the case for some sites for Rig 53, but the majority of these holes were sited during field reconnaissance only.

Field reconnaissance was also carried out to delineate geomorphological units and to study geology.

In connection with the geophysical surveys existing boreholes were located, and geoelectric soundings were performed at the drilling sites in order to establish a correlation between the borehole and georesistivity results.

Supervision of Rig 45 was carried out by the Drilling Engineer solely, while the hydrogeologists supervised Rig 53 in cooperation with the Drilling Engineer to solve the logistical problems of having the rigs operating in different regions at the same time (Iringa and Mbeya Regions). In Ruvuma Region supervision of both rigs were carried out by the Drilling Engineer assisted by the counterparts.

The pumping test programme was carried out by the Pumping Test Engineer or the Drilling Engineer assisted by the counterparts.

The office work was done in Mbeya which was the hydrogeologists' duty station. This work was treatment and interpretation of data, transfer of borehole data to data sheets to establish a borehole record file, interpretation of satelite imageries and air photos, construction of maps and writing of reports and working papers.

During all phases of the study it was tried to include the counterparts in all aspects of the hydrogeological work. This was achieved through having them carry out a number of different assignments in the field and in the office. In this way no parts of the study in Tanzania were carried out without each counterpart having been involved in it at some stage.

3. SUMMARY OF BASIS DATA

3.1 Borehole Data

3.1.1 Existing Borehole Data

All existing data on wells drilled in the regions have been collected from Dodoma and the regional MAJI Headquarters. These include information on wells drilled by MAJI and other agencies since the start of the Project.

The bulk of these wells have been drilled during the past ten years as shown in Figure 3.1. Until 1970 about one well has been drilled in the regions each year since 1936.

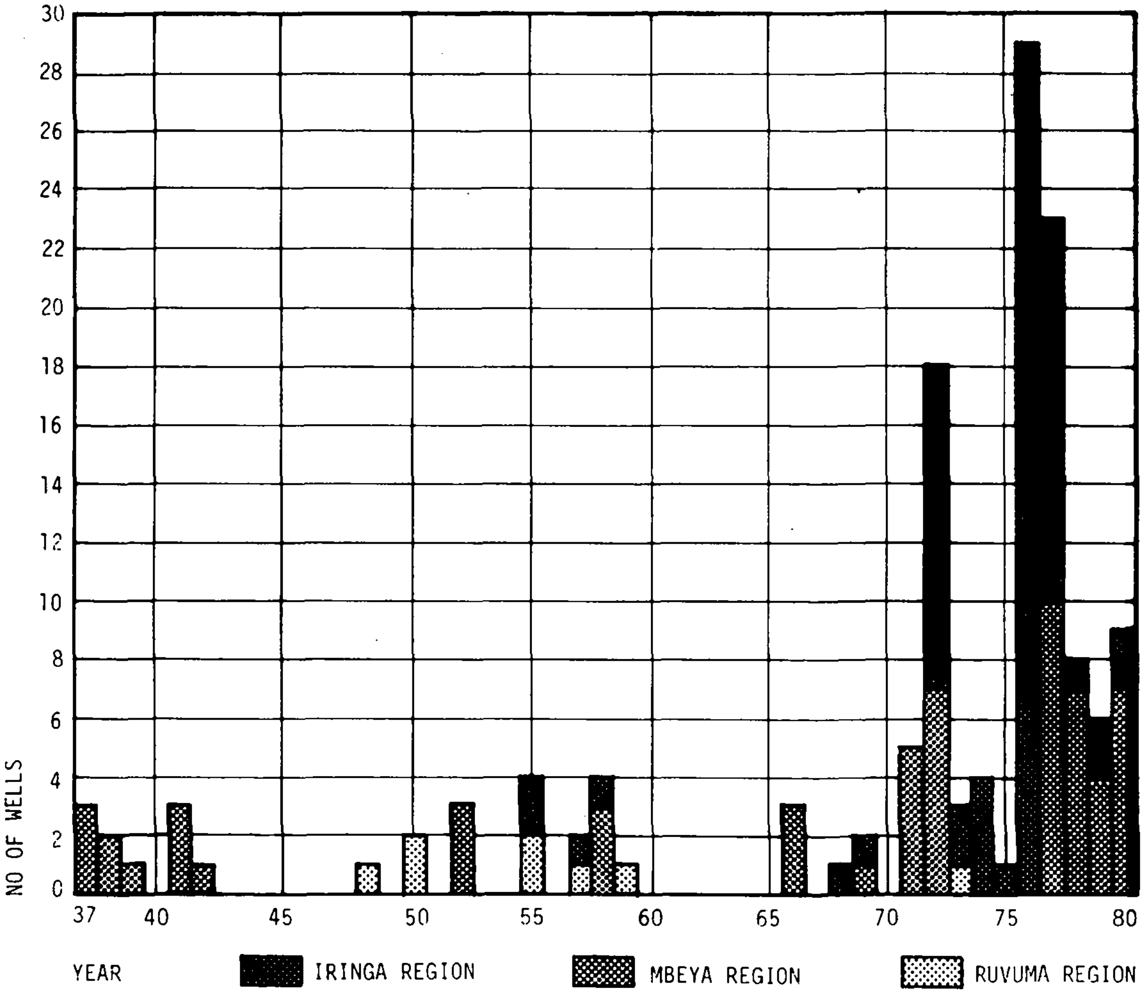


Figure 3.1 Number of recorded boreholes during 1936-1980.

A total of 140 well files have been obtained of which 71 are from Iringa, 65 from Mbeya, and 4 from Ruvuma Region.

According to information obtained in the regions, however, more wells seem to have been drilled, but it has not been possible to obtain any information on them. Therefore, the 140 well files form the basis for the evaluation of existing hydrogeologic data.

125 of these have information on the drilling depth, and it may be assumed that the remaining 15 wells have not been drilled, or the completion form has not been filed in Dodoma or in the regions. A histogram showing the drilling depths of existing wells is shown in Figure 3.2. Well location and borehole data are shown on the Cyclogramme Map (Drawing II-10).

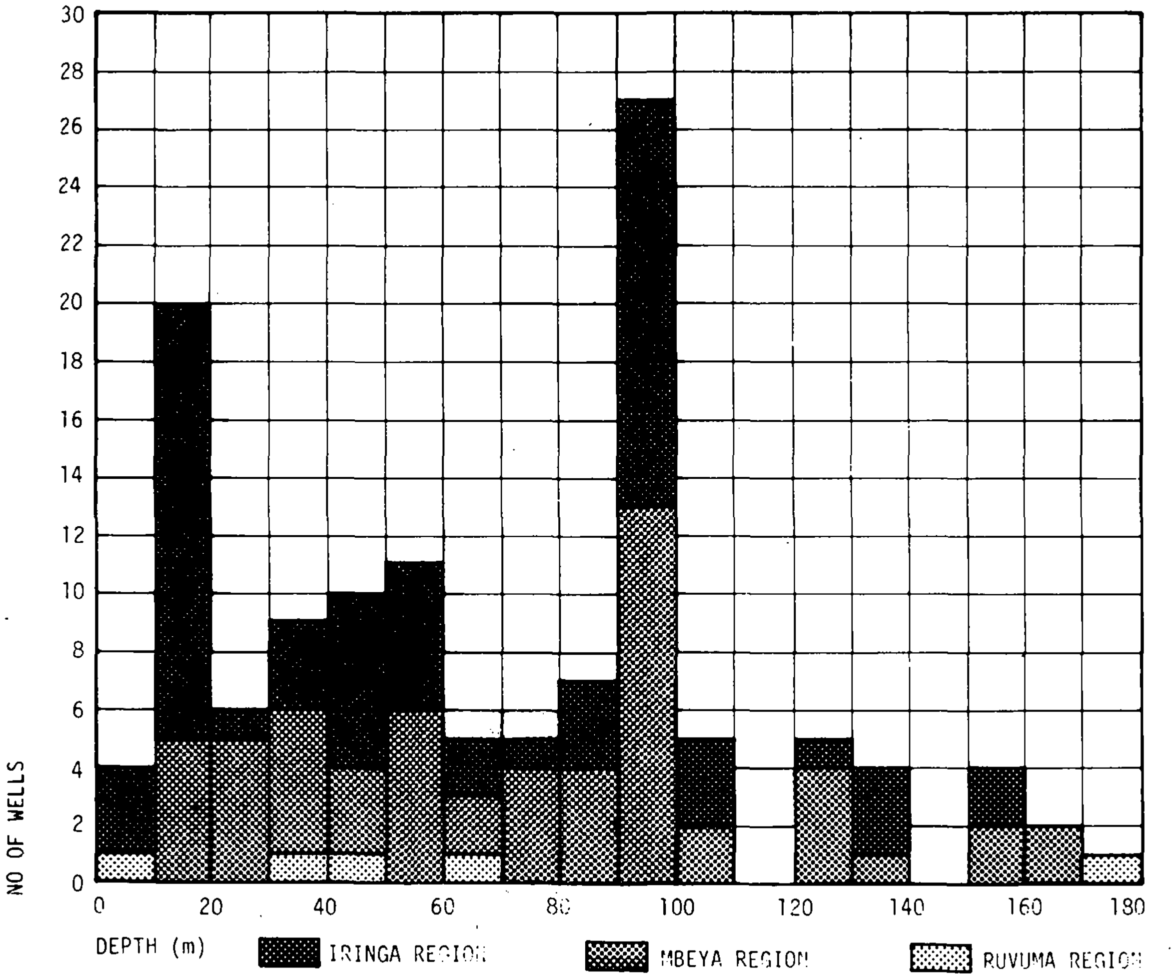


Figure 3.2 Drilling depths.

The majority of wells is between 30 and 100 metres deep, and wells shallower than 20 metres may generally be considered abandoned because of technical difficulties. The comparatively large number of wells with depths 90 to 100 m (300 feet) are due to the fact that 300 feet have been a standard depth of drilling. This figure does not reflect the depth necessary to drill a successful borehole.

58 wells have information on the tested yield and corresponding drawdown: 44 of these have data sufficient to determine the saprolite or aquifer thickness. Finally for 33 wells controlled pumping tests have been carried out with frequent measurements of drawdown and yield These tests have been carried out using predominantly air lifting, and the discharge decreases during the tests. To interprete the results from these tests a special method of analysis has been developed as explained in Volume 10 A, Appendix 1, Chapter 6.

All data available are listed on borehole completion records as regards existing wells and wells drilled by the Consultants (Volume 10 B, Appendix 1). Borehole location records have been made for the existing wells that could be found, and for all wells drilled by the Consultants (Volume 10 B, Appendix 2).

3.1.2 Borehole Data from Wells Drilled by The Consultants

Two drilling rigs have been available to the drilling programme, one CME Auger Rig (Rig 53) and one T64 Schramm Rig (Rig 45). A total of 70 wells have been drilled in the three regions, as shown in Table 3.1.

	IRINGA	RUVUMA	MBEYA
Rig 45	6	11	3
Rig 53	14	12	24
Total	20	23	27

Table 3.1 Number of boreholes drilled by the Consultants and their regionwise distribution.

Of these holes eight were dry, nine were not cased because casing was not available at the time of drilling, 13 holes were blocked, abandoned or collapsed. The auger holes in Ruvuma were drilled mainly as observation holes close to the deep holes and few were, therefore, tested. A total number of 27 holes were successfully pump tested, of which 13 were deep holes. The pumping test results are shown in Volume 10 A, Appendix 2.

3.1.3 Chemical Data

Chemical data on groundwater quality have been collected from MAJI, Ubungu, and from the regions. Some partial analyses have been found in the borehole files at Dodoma.

Samples from boreholes drilled by the Consultants have been analysed in one of three ways:

- Using a Hach Kit in the regions
- MAJI, Ubungo
- Laboratory in Denmark

A total of 125 chemical analysis including existing analyses have been collected as shown in Table 3.2. Some are repeated analyses from the same borehole, so the chemical data are based on information from 106 different boreholes.

IRINGA REGION		RUVUMA REGION		MBEYA REGION	
No. of Analyses	No. of B.H.	No. of Analyses	No. of B.H.	No. of Analyses	No. of B.H.
40 (30)	32	10 (5)	9	75 (41)	65

Table 3.2 Chemical analyses collected. Numbers in brackets denote the number of analyses on existing wells.

The quality of the individual analyses varies considerably. In some cases only the amount of Total Dissolved Solids is given, the majority of the analyses, however, includes enough information on the constituents to determine the potability of the water.

The chemical analyses have been transferred to data sheets and are presented in Volume 10 B, Appendix 3. The complete chemical analyses are shown as pie-diagrammes on the Chemical Map (Drawing II-11).

3.1.4 Down-the-Hole Logging

Down-the-hole logging was carried out as an aid in defining lithological contacts and placing screens in wells. One well (25/81) drilled by MAJI was logged. The remaining existing wells located by the Consultants could not be logged because they were sealed and in most cases equipped with a borehole pump. In all, 13 geophysical logs have been carried out in boreholes. The results are shown in Volume 10 A, Appendix 3.3.

3.2 Geophysical Surveys

3.2.1 Existing Geophysical Surveys

Geoelectrical Surveys

In connection with siting boreholes in Mbeya and Iringa a few geoelectrical surveys have been carried out. These were collected and studied at an early stage of the study to get an idea of the general results obtained and the applicability of geoelectrical surveys in the regions. The instruments used were not always in good working order and often not powerful enough to provide reliable measurements. These surveys are, therefore, not presented in the Report.

Airborne Geophysical Surveys

A preliminary gravity map of Tanzania has been available to the Project through existing literature. Further, aeromagnetic maps were made available to the Consultants. These maps have been used mainly to outline the boundaries and evaluate qualitatively the thicknesses of the Lake Beds and the two main Karroo basins in the Ruvuma Region.

3.2.2 Supplementary Geophysical Surveys

Geoelectrical Surveys

A total of 218 geoelectrical soundings has been performed, of which 33 have been carried out at existing wells to establish a correlation base. The remaining part of the soundings has been carried out to investigate in general the geological and hydrogeological conditions in the regions, and to determine well sites.

In addition 12 constant separation traverses (CST) have been performed as an alternative method to determine a well site.

Seismic Surveys

50 seismic profiles have been carried out to investigate the applicability of this method to map the succession of sub-surface strata. A comparatively large number (17) of the profiles was carried out in the Karroo Basins as the method was expected to be very useful in these continental deposits.

A list of the geophysical surveys carried out is given in Table 3.3.

	IRINGA	RUVUMA	MBEYA
Geoelectr. sounding	80	52	80
CST	1	-	11
Seismic profiles	9	31	10

Table 3.3 Geophysical surveys performed.

4. PHYSIOGRAPHY

4.1 Topography

Iringa, Ruvuma and Mbeya regions form the south-western part of Tanzania. The regions lie between 32° and 38° eastern longitude, and between 7° and 12° southern latitude, and have common borders with Mocambique, Malawi (Lake Nyasa) and Zambia. The total area covered by the three regions is approximately 177,000 km^2, of which Mbeya covers 60,500 km^2, Iringa 56,500 km^2 and Ruvuma 60,000 km^2 (cf. Figure 4.1).

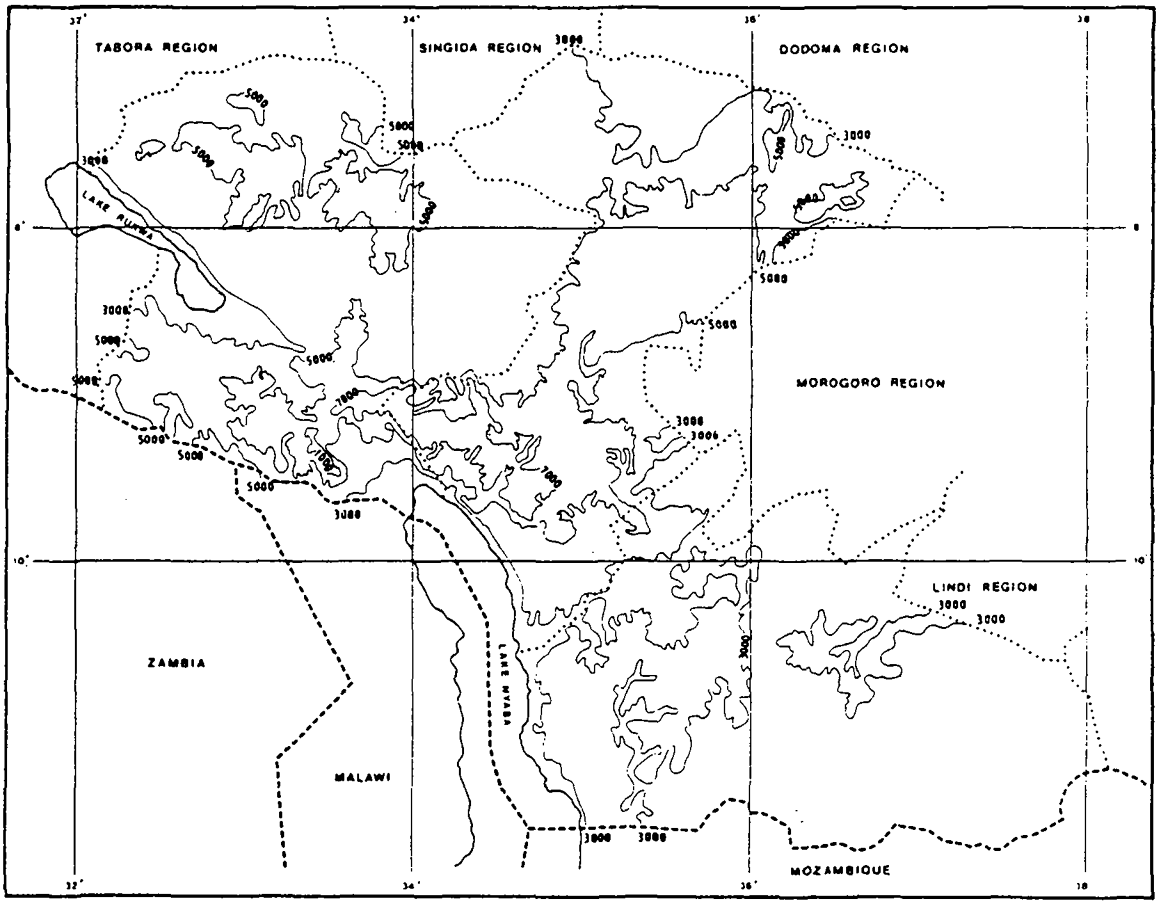


Figure 4.1 - Main Topographic features.

The area is generally known as the Southern Tanzanian Highlands, a mountainous and hilly area dominated by the Mporotos and Mbeya ranges in Mbeya, the Kipengere and Livingstone mountain ranges in southern Iringa region, and the Udzungwa mountains separating Iringa and Morogoro regions. Northern Iringa and Mbeya regions are relatively flat, high plains, cut by the eastern Rift Valley in which the Great Ruaha river runs, and the western Rift Valley with Lake Rukwa.

The mountainous areas of Ruvuma region are of lesser altitudes than those of Iringa and Mbeya regions and most of the region is covered by undulating hills. The mountain areas are found in the western part of the region bordering Lake Nyasa.

Altitudes vary from below 500 m to well over 2000 m above sea level in the Mporoto and Kipengere ranges. The highest peak of the Southern Highlands is the (no longer active) volcano Mount Rungwe with an altitude of 2960 m above sea level.

The characteristic features of the regions, apart from the Rift Valley system, are the surrounding uplifted and warped plateaus. Covering nearly 90% of the total study area, the plateaus represent by far the most common land form. They are separated by fault-lines and erosion scarps, and are the result of steady erosion that has taken place since the Late Jurassic period.

The oldest plateaus are found at the highest levels from 1800 to 3000 m above sea level (i.e. the Mporoto and Kipengere ranges in Mbeya and Iringa Regions). They are remnants of the oldest landforms, the Gondwana, and overlook a vast, very smooth pediplain, the African erosion surface, at 1200 to 1800 m above sea level. Compared to the surrounding plateaus, the African surface is extremely flat and is characterised by wide valleys, in which rivers have now reached a mature state.

The post-African surface, another pediplain, situated about a hundred metres lower than the African surface, is moderate to heavily dissected, thus forming a more irregular and unstable terrain. This is due both to its younger age, and to faulting in connection with the Rift Valley system.

The remaining parts of the regions are occupied by areas where deposition of material has taken place notably the Rukwa Trough, the Usangu Flats and the Rungwe Volcanics in and around Rungwe District.

The Rungwe Volcanics, with the Rungwe Mountain (2960 m a.s.l.) as its centre of eruption, forms an area of pronounced topographical relief. The craters, lava flows and volcanic ash cover make the volcanic area completely different from the rest of the study area.

In contrast, the two main depressions the Usangu Flats and the Rukwa Trough, are very flat because of their depositional nature, with the exception of minor local erosion features. These flats occupy parts of the valley floors of the eastern and the Rukwa-Nyasa rifts, which during an early period joined at location of the Rungwe Volcanic Province.

4.2 Climate

The climate of the project area is determined by its location close to the equator, and the Indian Ocean.

Located between 7 and 12 degrees southern latitude the climate is tropical, with high temperatures in the lowland areas, low wind speeds, high humidity of the air and no cold season.

The vicinity of the warm Indian Ocean places the three regions in an area in which the general circulation of the atmosphere exhibits large seasonal changes, thus creating considerable seasonality in rainfall, cloudiness and surface wind conditions.

A brief account of the main climatic features of the project area follows. The significance of these features for the rainfall pattern in the regions is briefly discussed in Volume 7, Chapter 3.

Four distinct periods characterise the general circulation, and hence the climate of the study area.

From December through February the area is situated between a relatively high pressure over northern Africa and the Arabian peninsula, and a large low pressure at about 10 to 15 degrees South. Air masses moving from high to low pressure areas in this period give rise to the rather dry north-east monsoon (Kaskazi), which despite its relative dryness does produce considerable rainfall in the regions. One of the reasons for this is the encounter between the north-east monsoon and air masses from the south-east at the inter-tropical convergence zone, the effect of which frequently extends north into southern Tanzania.

From about March this zone moves northward towards the equator, placing the regions under the influence of the convergence between air masses from the southern and northern hemispheres. This situation dominates the climate through May and causes the heaviest rains of the year.

From about June to September the synoptic situation shows relatively little variation. During this period the study area is under the influence of the south-east monsoon (Kusi) which carries air from a large high pressure area over South Africa and adjacent parts of the Indian Ocean to a very strong low pressure over Saudi Arabia. Coming largely from the South African winter this monsoon is rather dry and cold, and the regions experience a pronounced dry season in this period.

The main convergence returns to Tanzania in October, reaching the project area in November and causing the onset of the rainy season. The convergence zone traverses the country rather quickly on its southward journey to its "summer" location south of the country.

The rainfall regime in the project area is typically of the unimodal type with a single rainy season from November through May, and dry conditions the rest of the year. In the northeastern part of the area, at Iringa, there is a tendency to a bimodal pattern with less intense rains in January-February. However, the entire period November through May is still rainy, and there is no bimodality in the resulting runoff pattern.

Figures 4.2, 4.3 and 4.4, which indicate the spatial and temporal variation of rainfall, potential evapotranspiration and temperature.

As explained above the majority of the rainfall occurs in the rainy season from November through May. Mean annual rainfall varies from less than 500 mm per year in northern Iringa Region to more than 2600 mm per year in the wet area north of Lake Nyasa. In any given year, however, the actual rainfall may vary significantly from the figures in Figure 4.2, which are averages over long periods of record. Rainfall in the area is subject not only to high spatial variability due to the characteristic convectional pattern explained above, but also to considerable variation from year to year, the actual range of annual rainfall in the regions being from less than 250 mm per year to more than 3100 mm per year.

The figures in Figure 4.3 represent potential evapotranspiration, i.e. the potential rate of combined evaporation and transpiration from a vegetated surface. This rate is some 20% lower than the corresponding evaporation from a free water surface, while the actual evapotranspiration from the area, due to water stress in the dry season, is in the range of only 40-60% of the potential rates shown in Figure 4.3, whereas the potential evapotranspiration varies only little from year to year, the spatial variability is considerable, ranging from more than 2200 mm per year in the dry and warm northern Iringa, to less than 850 mm per year in the cool and wet highland in southern Mbeya and Iringa regions.

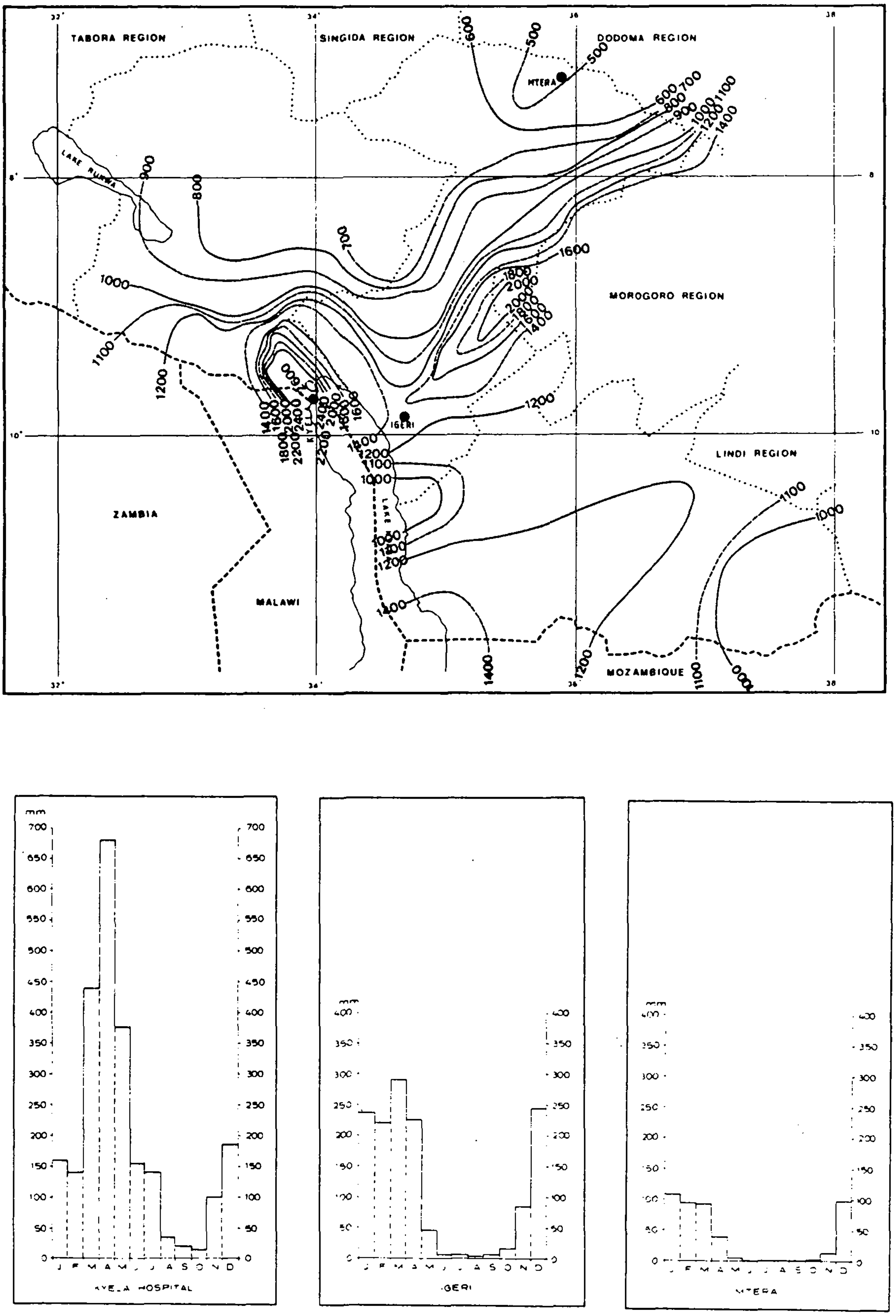


Figure 4.2 - Mean annual rainfall and mean monthly rainfall variation at selected locations.

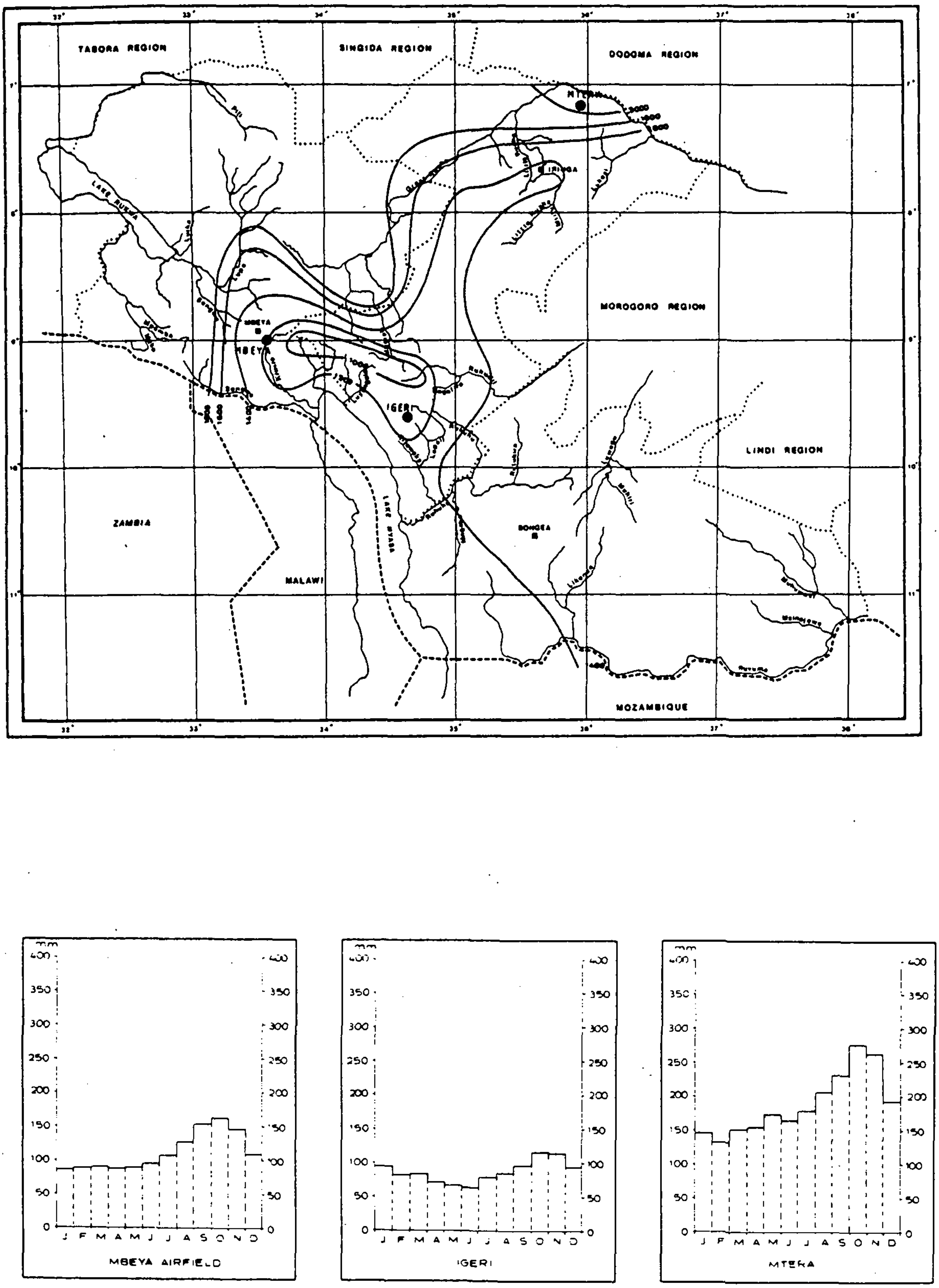
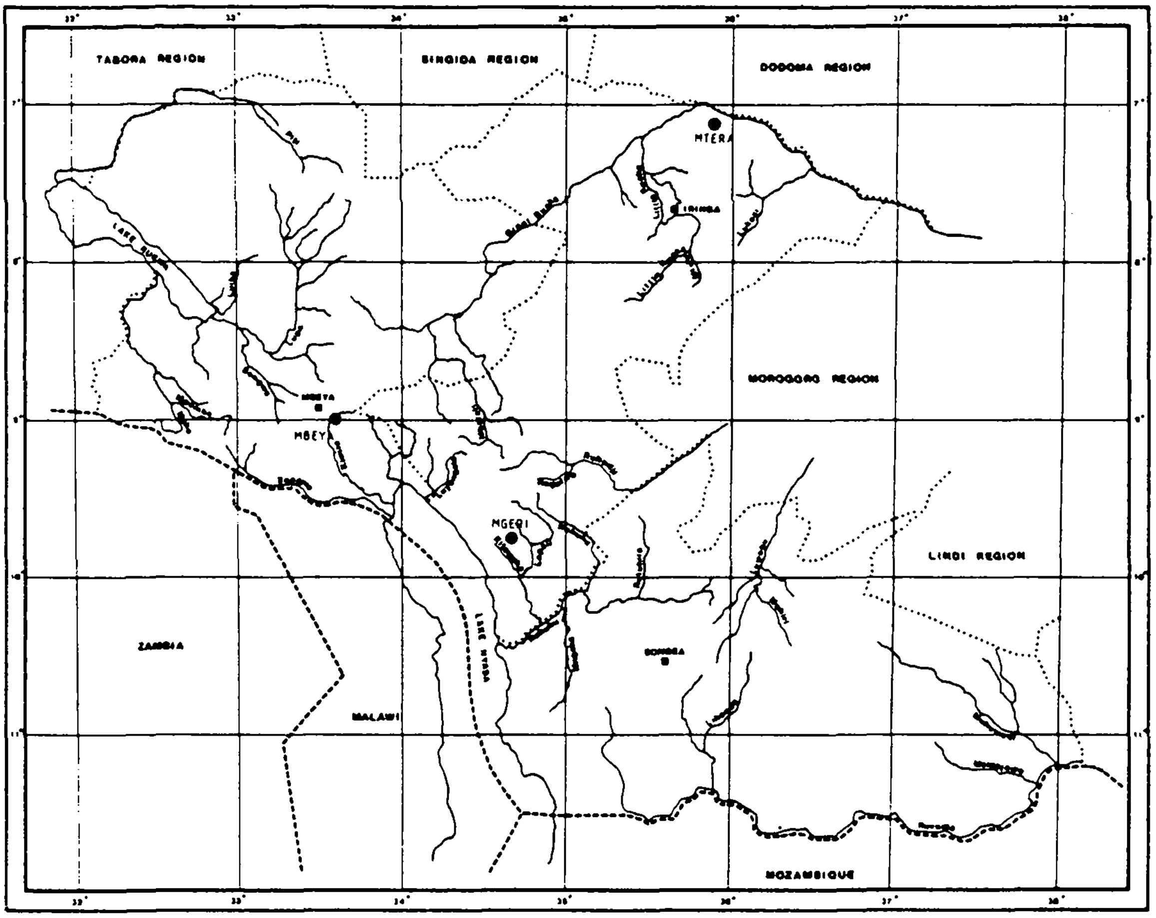


Figure 4.3 - Mean annual evapotranspiration, and mean monthly evapotranspiration at selected locations.



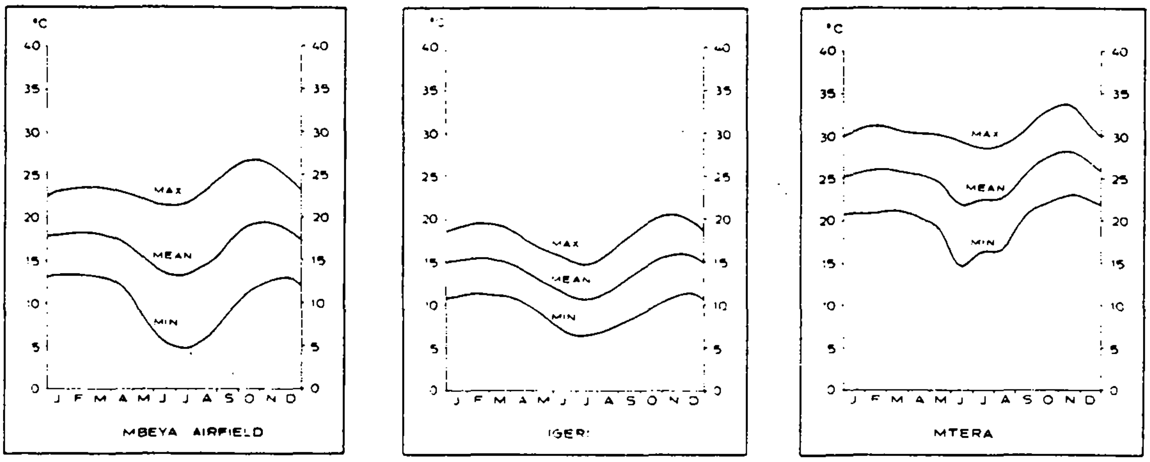


Figure 4.4 - Minimum, maximum and mean monthly temperature variation at selected locations.

Finally Figure 4.4 indicates the variation of temperature at selected locations in the regions. Again the extreme variation is found between the northern parts of Mbeya and Iringa regions where mean annual temperatures exceed 25°C, and the southern mountainous parts of these regions where mean annual temperatures at places are below 14°C. The temperature varies over the year from the cool June-July where, mean monthly temperatures in the mountains may approach 10°C, to the warm October-November where mean monthly temperatures in the northern areas approach 30°C. However, the typical variation over the year of mean monthly temperature for a given location is moderate, generally only 5-6°C. At the extremes mean daily temperatures range from less than 5°C in June-July in the mountainous areas, where frost occassionally may occur, to more than 35°C in October-November in the northern areas.

4.3 Surface drainage

Five major drainage basins divide Tanzania: The Lake Victoria basin, the Lake Tanganyika basin, the Northern Internal basin, the Lake Rukwa internal basin and the Indian Ocean drainage basin. Iringa and Ruvuma regions, and more than half of Mbeya region, fall within the Indian Ocean drainage basin, while the remaining part of Mbeya region drains to Lake Rukwa. Within these major drainage basins sub-divisions are made according to the catchments of major rivers and their principal tributaries. A drainage map indicating the major drainage systems of the Iringa, Ruvuma and Mbeya regions is shown in Figure 4.5.

In Iringa region the central plateau largely divides the rivers into a northern drainage part and a sourthern drainage. The rivers draining north all merge into the Great Ruaha which in turn is part of the Rufiji system. The rivers draining south reach Ruhudji/Kilombero which again has a confluence with Rufiji river. The southernmost part of Iringa drains to Lake Nyasa, which through the Shire and Zambesi rivers is connected to the Indian Ocean.

The northern part of Mbeya drains towards Lake Rukwa while the southern part drains towards Lake Nyasa. Finally the eastern part of Mbeya is in the Rufiji system and drains to this through the Great Ruaha.

As for Ruvuma the largest part drains to the Ruvuma River, while a small part drains to Lake Nyasa and another small part drains to the Rufiji through Luwegu River.

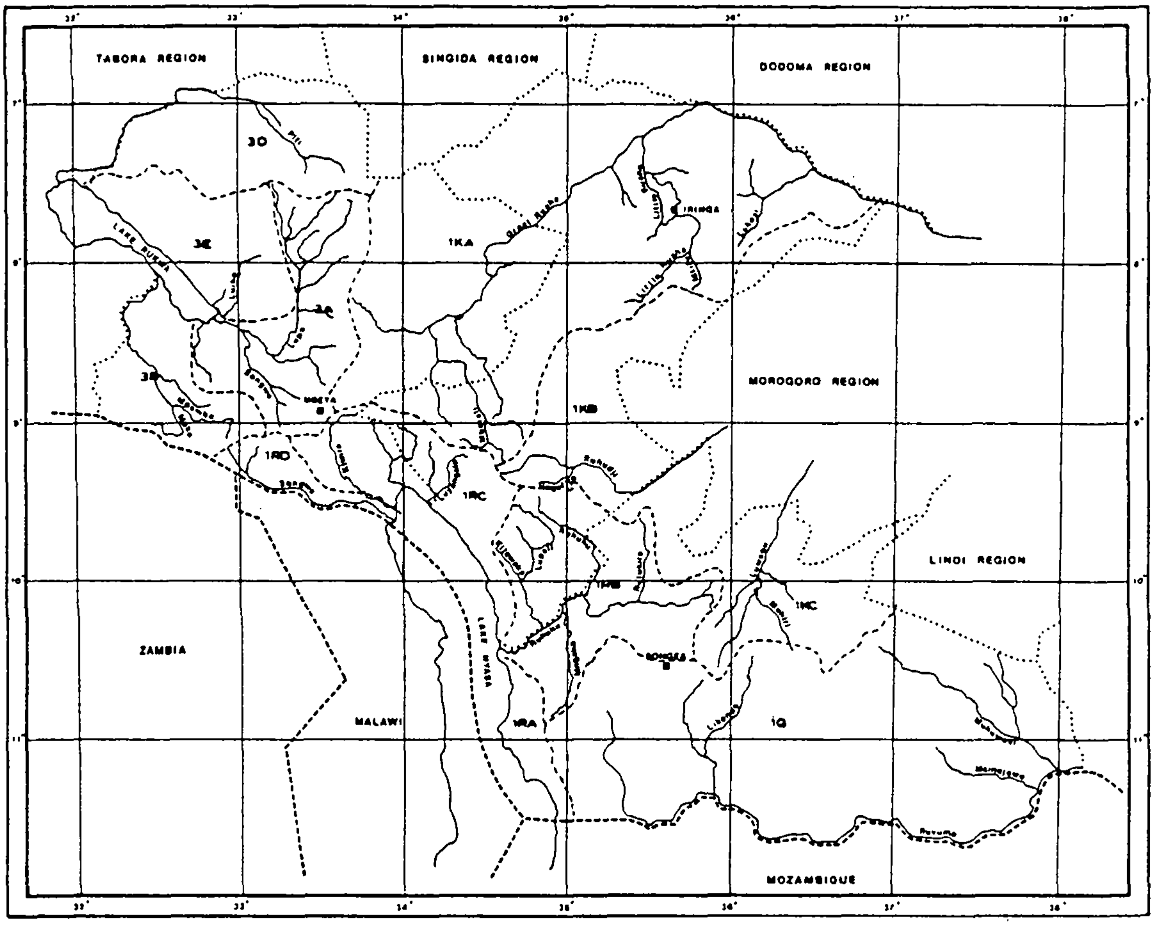


Figure 4.5 - Drainage map for Iringa, Ruvuma and Mbeya Regions.

The surface runoff pattern in the regions corresponds rather closely to the general unimodal rainfall pattern. Streams start rising in November-December, experience a maximum flow in March-April, and have their recession period from May to October-November. In the warm and dry northern part of Iringa and Mbeya regions, with annual rainfall below 500-800 mm, streams run dry every year, and the mean annual runoff is generally below 2 $l/s/km^2$. At the other end of the scale in the south-western highlands, where annual rainfall is in the range of 1200-2600 mm, streams and rivers are perennial, and mean annual runoff exceeds 10 $l/s/km^2$. In this area the Kiwira river, for example, has a mean annual runoff of 40 $l/s/km^2$ from the 1660 km^2 catchment at Kyela.

Between these extremes, in areas like eastern Ruvuma, western Mbeya and Mufindi receiving 800-1200 mm of rainfall annually, streams are perennial or intermittent (i.e. only occasionally dry), and mean annual runoff is in the range 2-10 $l/s/km^2$. An example of a river in this regime is the Little Ruaha which from its catchment of 759 km^2 at Makalala yields a mean annual runoff of 6 $l/s/km^2$.

The general spatial and temporal variation of runoff is illustrated in Figure 4.6.

4.4 Vegetation and land use

Although large areas of the regions are now cultivated, the vast majority of the land is still covered by natural vegetation.

The most predominant natural vegetation in the three regions is the "Miombo" woodland, which is associated with rainfalls between 800 and 1200 mm per annum, and covers most soil groups, with the exception of very alkaline and poorly drained soils.

Areas with less rainfall and semi-desert conditions, namely northern Iringa and Mbeya regions, support wooded grassland and bushlands of dense thickets. The most predominant trees in these areas are acacias and other thorny trees, which are sufficiently sturdy to withstand long periods of drought.

Areas with higher rainfall, like the Rungwe and Kyela districts and the Dabaga area, support forests. In a few of these areas primeval rainforest still exists, but in most places extensive deforestation has taken place for agricultural purposes.

Rainfall regime is a dominating factor also with respect to land use and vegetational patterns. Distribution of the main cultivation areas is to a large extent determined by soil fertility and water availability, and it is characteristic that the agricultural areas in Mbeya, Iringa and Ruvuma regions coincide with areas of high rainfall. Hence, in Iringa region the cultivated area is found along the African Plateau from Iringa to the Njombe area in which the majority of the cultivation takes place. In Mbeya region cultivation is concentrated in the southwestern highlands, while in Ruvuma region, the Mbinga-Songea area and to some extent also the Tunduru area account for the majority of the agricultural production.

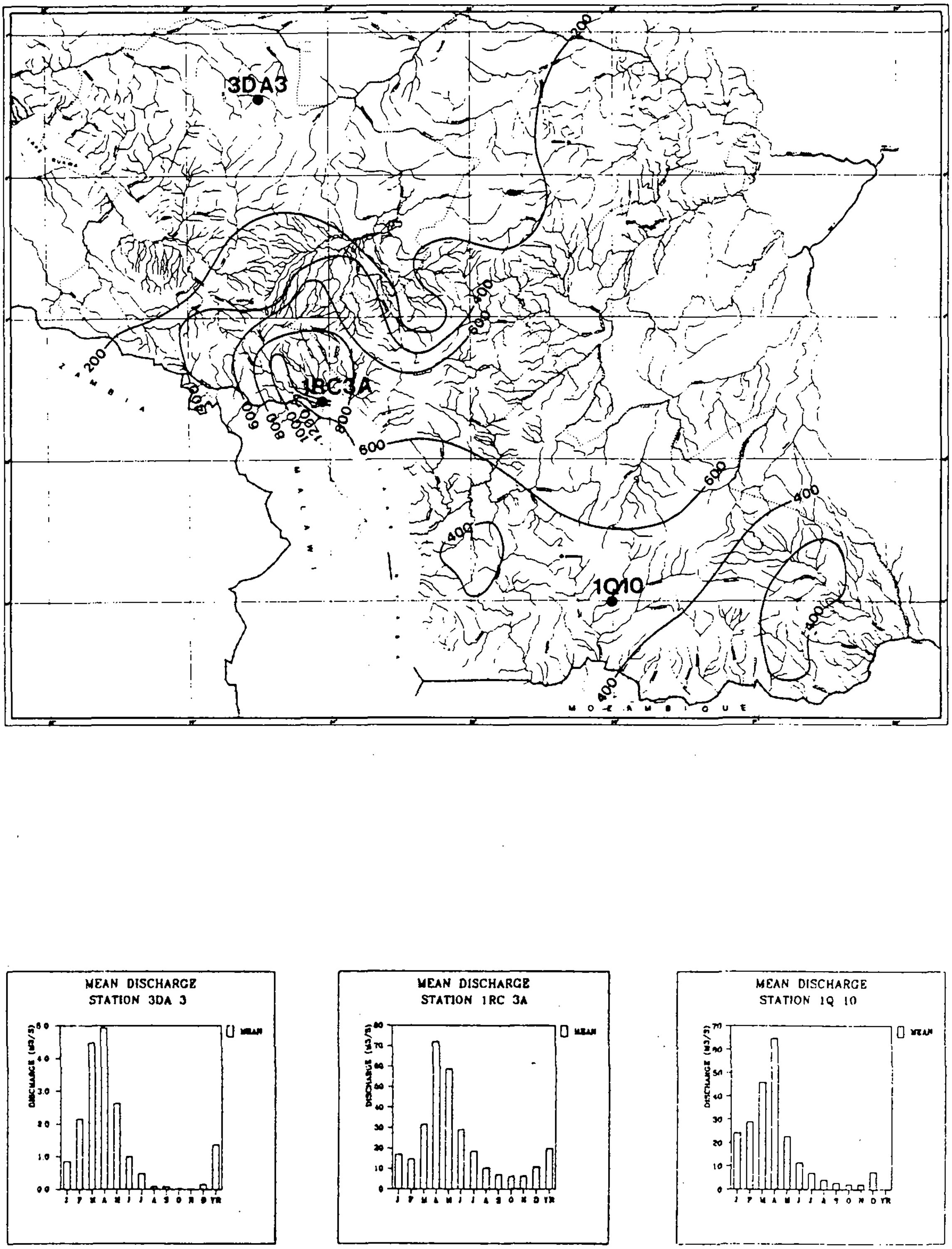


Figure 4.6 - Mean annual runoff, and mean monthly runoff at selected locations.

In order of importance the main crops grown in the three regions are: maize, wheat, beans, bananas and cassava in Iringa, maize, paddy rice, wheat, beans and bananas in Mbeya, and maize, cassava, wheat, beans and bananas in Ruvuma. Cash crops grown in the three regions are: tea, tobacco, pyrethrum and wattle in Iringa, coffee, tea, tobacco, pyrethrum, rice and citrus fruits in Mbeya, and coffee, tobacco and cashews in Ruvuma. Cash crops are generally cultivated on plantations, whereas, food crops are grown on smaller, individually held plots, often on a rotation basis with some land tracts lying fallow for a number of years to be cleared again when needed for further cultivation. (Slash and cut cultivation).

An outline, land use and vegetation map, based on Cook (1974) is shown as Figure 4.7.

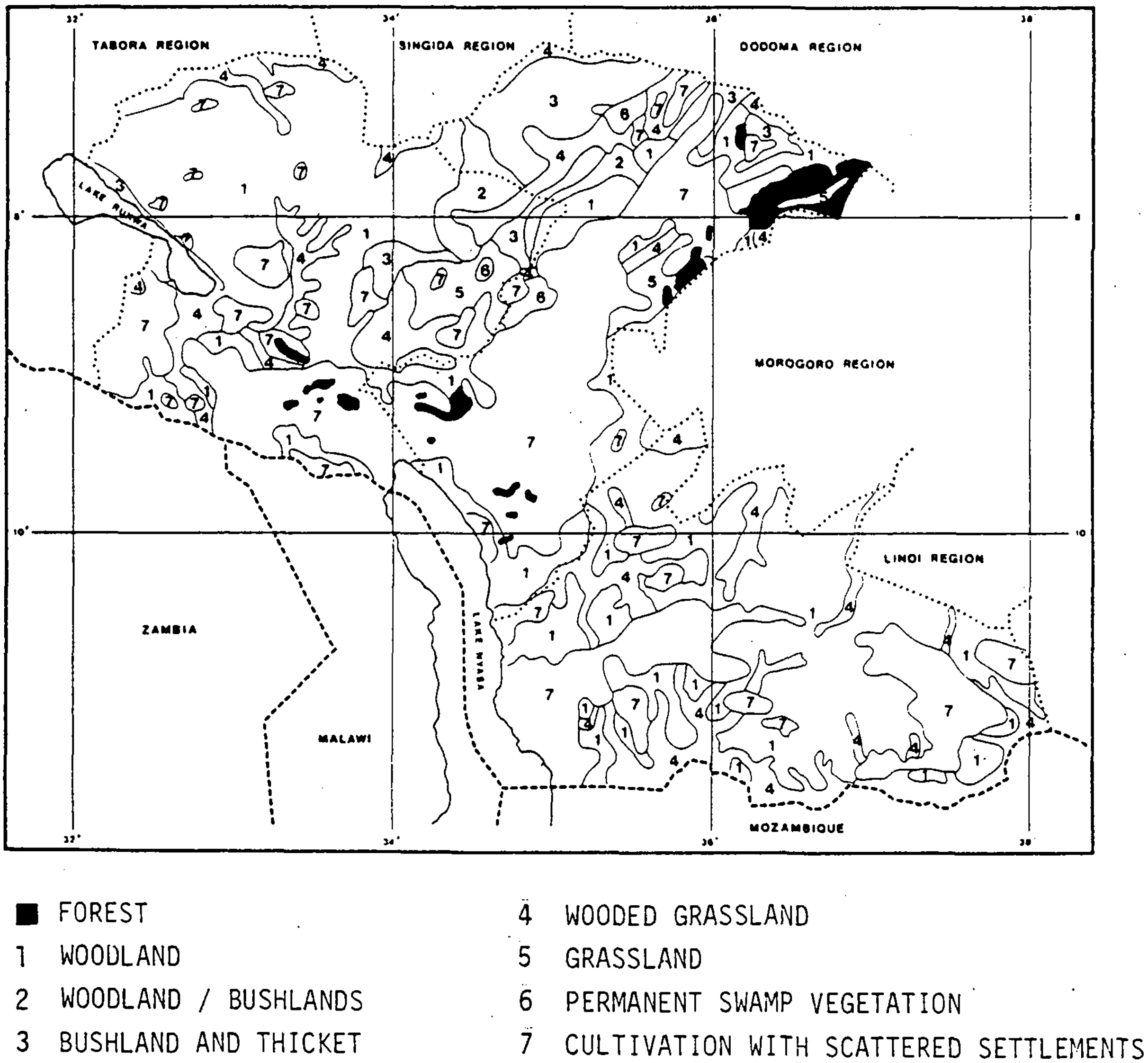


Figure 4.7 - Land use and vegetation.

4.5 Soils

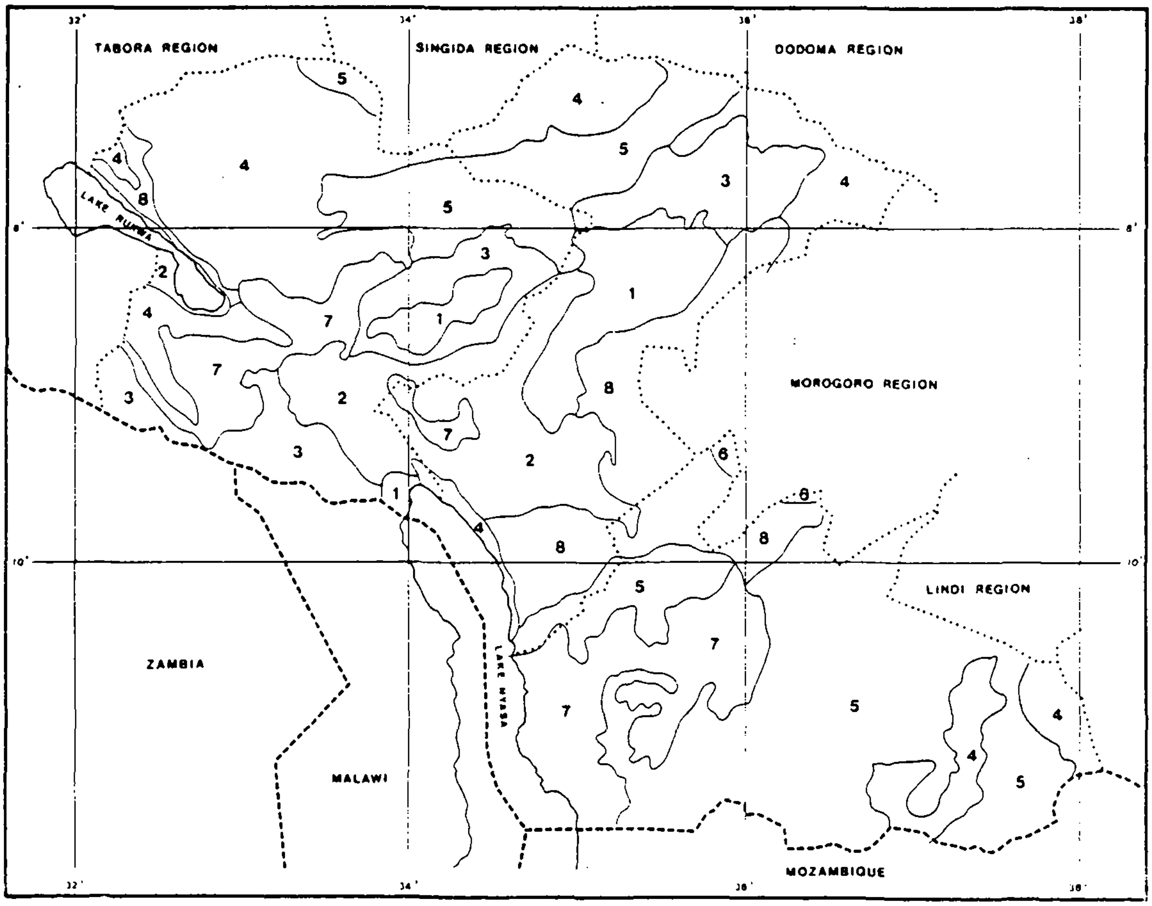
The soils of the three regions are generally well drained sands, clays, loams and mixtures of these. Only three areas are characterized by imperfect or poor drainage. These areas are the lake deposits of the Rukwa Trough, the Usangu Flats, and the flood plains north of Lake Nyasa in Kyela District.

Eight different soil classes have been identified for Tanzania as a whole, of which all eight are found within the study area. This classification relates to the soil texture of the upper 30 cm of the profile, the most predominant classes in Tanzania are loamy sands and sandy loams. These are also the most common classes in the three regions, covering most of Ruvuma, nearly half of Mbeya and some of Iringa in the Rift Valley.

The areas of highest elevation, the Mporotoes and the Kipengere ranges with their well-drained loamy soils, the Mbeya Range and hilly areas of western Ruvuma with a soil cover of clayey loam with good drainage, constitute the best agricultural lands in the three regions.

Other soil classes such as sands, sandy clay loams, sandy clays and clays make up smaller portions of the regions.

A soil map, based on R.M. Baker (1970), is shown in Figure 4.8.



1 CLAY 2 SAND 3 LOAM 4 SANDY LOAM
5 LOAMY SAND 6 SANDY CLAY 7 CLAY LOAM 8 SANDY CLAY LOAM

Figure 4.8 - Distribution of soils in Iringa, Ruvuma and Mbeya Regions.

5. GEOLOGY

5.1 Introduction

The rocks found within the regions can be divided by their geological age into three main groups: Neogene deposits, Karroo sediments and pre-Cambrian rocks (Table 5.1).

The pre-Cambrian rocks are collectively referred to as the Basement Complex and they occupy roughly 68% of the study area. They are, therefore, the most important geologic unit, and the majority of the water supply from groundwater in the regions will inevitably have to be derived from these rocks. The continental deposits of the Karroo System occurring almost exclusively in Ruvuma Region underlie 21% of the study regions (61% of Ruvuma region). A water supply from groundwater in Tunduru District would for a large part depend on the Karroo Rocks. The remaining 11% of the regions are covered by Neogene Lake deposits (Usangu Flats and Rukwa Trough) and Neogene rocks of the Rungwe Volcanic Province. All these are located mainly within Mbeya Region.

The distribution of the rocks in the regions is shown on Drawing II-8, Geology. The basic information that has been applied to construct the Geological Map is discussed in detail in Volume 10 A, Appendix 1, Chapter 4.

5.2 Stratigraphy and Distribution of Rocks

The stratigraphy and local distribution of the major rock types and rock groups in the region are given in Table 5.1, together with details on age, geological system and lithology.

5.2.1 Pre-Cambrian - Basement Complex

Metamorphic and Sedimentary Rocks

The pre-Cambrian has been divided into the Archaean and the Proterozoic, the transition between the two having been estimated to roughly 1,500 mill. years B.P. Although the absolute time ranges of all groups in the pre-Cambrian is still undetermined, the succession shown in Table 5.1, is generally accepted.

The oldest rocks in Tanzania are of Early Archaean age and they occupy much of the central plateau. These rocks form the old nucleus of Eastern Africa on to which younger pre-Cambrian fold belts were superimposed. The Early Archaean rocks may be divided into three main areas, the Dodoman Belt, the Nyanzian Belt between Singida and Geita, and the Nyanzian Belt further north in Mara Region. The Nyanzian System is not represented in the regions.

The Dodoman metamorphic series, comprising gneisses, granulites, migmatiles, amphibolites, quartzites and schists, occurs in the northern parts of Mbeya and Iringa Regions.

The Late Archaean rocks form the Ubendian and Usagaran fold belts. These occupy large areas in south-west and east Tanzania. They are found in east Iringa and south Njombe districts in Iringa Region. In Mbeya Region these rocks are found covering large parts of Ileje, Mbozi and Chunya districts. The rocks of this system are high-grade metamorphic gneisses, quartzites, granulites, charnochites and schists.

Late Archaean rocks also underlie most of Ruvuma Region, where they are known as the Mozambique Belt.

They outcrop in East Tunduru District and are found as inliers in the Tunduru Karroo Basin. They also occupy the greater part of Mbinga District.

The Early Proterozoic Karagwe-Ankolean System of metasediments, including the Ukingan System is found mainly along the western and eastern Rift Valleys, as very long narrow belts. These low-grade metamorphic rocks are of limited occurrence within the regions and are located in the south-western part of Njombe District (Ukinga and Upangwa), north of Sao Hill (Ndembera Series), along the Ruaha Valley (Konse Series) and as an east-west trending discontinuous belt in the central part of Chunya District.

In the Ukinga area, argillaceous rocks with intercalations of arenaceous horizons are predominant. The Ndembera Series are predominantly moderately metamorphosed volcanic products, while the Konse Series show a succession of quartzites, schists and phyllites interchanging with highly metamorphosed gneisses.

ERA	PERIOD	SYSTEM AND FORMATION	SYMBOL	ROCK TYPES	LOCALITY BY REGION		
					IRINGA	RUVUMA	MBEYA
	METAMORPHIC AND SEDIMENTARY ROCKS						
Kainozoic		Neogene	N_a	Alluvial deposits, mbugas	Widespread	Widespread	Widespread
			N_t	Residual soils			
			N_e	Lake beds	Mtera Depression	-	Rukwa Trough, Usangu Flats
Mesozoic	Cretaceous	Cretaceous	C	Red sandstones and siltstones	-	Are referred to as Karroo	Kiwira and Galula coal fields. Possibly the entire Rukwa Trough.
Palaeozoic	Jurassic	Jurassic	J		-	-	-
	Lower Jurassic to Upper Carbonferous	Karroo	K	Conglomerates, sandstone, mudstone, siltstone marls, carbonaceous shales and coals	Ruhuhu Trough	Ruhuhu Trough, Tunduru District, Songea District	Kiwira, Galula and Ivuna coal fields. Possibly at depth in Rukwa Trough and Usangu Flats
Pre-Cambrian	Proterozoic	Bukoban	B	Sandstone, quartzite, shale	Kipengere Range, Gofio Plateau	-	North of Lake Rukwa, Kipengere Range, Poroto Mts.
		Karagwe-Ankolean	G	Quartzite, schist, gneiss (Konse Series), metalavas, metatuffs (Ndembera beds)	Mloa over Nyangala to Mtera. Between Sao Hill and Idodi	-	Chunya District. E. Mbeya District (Ndembera)
		Ukingan	G	Quartzite, slate schist and phyllite	W. Njombe District	-	-
	Archaean	Ubendian and Usagaran	X_b	Gneiss, migmatite granulite, schist, quartzite, anorthosite	Most of Ludewa District, west of Makambako	Most of Mbinga District, N. Songea District	Mbozi and Ufipa Plateaus, Ileje District, S.E. Chunya District, Rukwa Scarp
			X_s	Gneiss, quartzite, granulite	E. Iringa, Mufindi and Njombe Districts	South of Songea, Tunduru District (outcrops and at depth)	-
		Kavirondian and Nyanzian			-	-	-
		Dodoman	D	Gneiss, schist, quartzite, migmatite	N. Iringa District	-	N. Chunya District
	PLUTONIC ROCKS						
Pre-Cambrian	Early Proterozoic to Archaean	Granite	g	Granites, granodiorites, often gneissic and migmatitic	Central and SE Iringa District, central and W Mufindi District. Central Njombe Distr.	Frequent in Mbinga and Songea Districts	Mainly Chunya District, but frequent throughout the region
		Basic and ultrabasic rocks	pb	Gabbro and anorthosite (partly metamorphic)	Livingstone Mountains	-	Mbozi Plateau mainly
	VOLCANIC ROCKS						
Kainozoic		Neogene	N_v	Extrusive basalt, lava flows and pyroclastics	Poroto Mountains, Kipengere Range	-	Rungwe Volcanic Province

Table 5.1 Lithostratigraphy and location of rocks.

In Chunya District, a variety of rocks are represented. The main types are sandstones, quartzites, shales, schists and phyllites.

The Bukoban belt being the youngest pre-Cambrian formation consists of the least metamorphosed rocks. This belt is found mainly parallel with and to the east of the Western Rift. The Bukoban rocks are found on Kipengere Range and along the Rukwa Scarp following the trend of the Rukwa Rift. They are predominantly sedimentary mudstones, shales, phyllytes, quartzites, and occasionally limestones.

Plutonic Rocks

Archaean and Early Proterozoic granitic shields occupy the central part of Tanzania. They are found covering most of the northern part of Mbeya Region, the central part of Iringa and Njombe Districts, and large areas in Mbinga and Songea Districts. The rock types are predominantly granites, granodiorites and migmatites.

Basic and ultrabasic pre-Cambrian intrusives have a scattered and limited occurrence within Tanzania and the study area. They are found bordering the Mbozi Plateau to the south (the Ihanda Block) where the rocks are predominantly gabbros and metagabbros. Similar rocks are also found in west Njombe District following Bukoban and Ukingan trends.

5.2.2 The Karroo System

The origin and lithological affiliation of substantial parts of the sedimentary series of Ruvuma Region, in particular the deposits in eastern Songea District and most of Tunduru District is subject to controversy.

It is generally agreed that the sedimentary series of the Ruhuhu Trough fronting Lake Nyasa, the outcrops along the Songwe Scarp in the Rukwa Trough, and the outcrops west of Kyela belong to the Karroo System. The drilling carried out by the Consultants in the sedimentary beds in Ruvuma Region indicates a close correlation between the Ruhuhu and the Tunduru Beds, and accordingly the Tunduru sedimentary basin is referred to as Karroo.

The Karroo period is interesting in that it followed an era of which no records are retained in East Africa. During the deposition of the Karoo rocks, Southern Africa was part of Gondwanaland, and deposition occurred close to the present continental margin and in inland basins as well. The Karroo sediments were laid down on mainly pre-Cambrian crystalline rocks, which have been exposed to weathering in pre-Karroo times. Due to pre-Cambrian and early Karroo movements, the pre-Karroo land surface had considerable relief which is particularly evident in the Tunduru Basin. Later vertical movements subsequently took place along existing fault lines. The Karroo rocks are, therefore, generally undisturbed except by tilting and faulting along the edges of the basins.

In the Ruhuhu depression, the sediments are believed to have thicknesses up to 3,000 metres. The magnetic signature of the Tunduru Basin is similar to that of the Ruhuhu Basin, it may, therefore, be concluded that the sedimentary series in the Tunduru Basin is at least as thick. Karroo rocks are believed to occur at depth in the Rukwa Trough and possibly below the Lake Beds of Usangu Flats as well. Lithologically the Karroo rocks are mudstones, siltstones, sandstones, conglomerates, varved clays, carbonaceous shales and coals. A more detailed description of the lithology is given in Section 7.8.

5.2.3 Cretaceous Rocks

The occurrence of Cretaceous rocks is limited in Tanzania. They follow the unconformity of the Karroo Series, but are probably part of the same sedimentary cycle. In the study area they are found in Mbeya Region in connection with the Rukwa-Nyasa Rift. The outcrops are described as red sandstones and have not been penetrated by drilling. They are believed to underlie the entire Rukwa Trough and have been found in a borehole at Ivuna. Their thickness is not known, as geophysical methods available do not distinguish between the Cretaceous and the suspected underlying Karroo rocks.

5.2.4 Neogene Deposits

The Neogene sedimentary deposits within the study area of hydrogeological importance are alluvial and colluvial deposits and Lake Beds.

Alluvium and colluvium occur in connection with escarpments, where rivers dispose of their sediment load as they flow across the topographically level terrain below the scarp. Alluvial deposits are found in many places, but due to the large proportion of eroded plateaus of little topographical relief in the study area, the alluvial deposits are limited in areal extent. Only in the northern end of the Ruaha Valley and in Kyela District large alluvial plains have been observed. The alluvial deposits form good aquifers with high hydraulic conductivities, due to the frequent occurrence of well sorted, coarse sediments. Colluvial deposits are poorer aquifers due to the higher content of clayey and silty material, but are still, where found, prospective areas for groundwater exploitation.

Lake Beds are found in the Rukwa Trough and across the Usangu Flats. The geological and structural setting of these two areas are described in more detail in Sections 7.10 and 7.9, respectively.

Before the Neogene rift faulting, the area occupied by the present Usangu Flats was a mature, probably post-African pediplain, which was drained to Lake Nyasa by the Ndembera River. The Rungwe volcanic eruption effectively blocked the discharge and Lake Buhoro was formed. This Lake persisted until it drained via the Great Ruaha River at Utengule, and the Flats were left behind.

The thickness of the Lake Beds is not known, but the airborne geophysical surveys carried out suggest a thickness of a few hundred metres at the most. The Lake Beds consist of soft sandstones, siltstones and tuffaceous sediments. Towards the centre of the Flats outcrops of white soft calcareous diatomite have been recorded.

The Lake Beds of the Rukwa Trough occupy a much larger area. The Rukwa Trough now forms the central part of the dischargeless Rukwa Basin. Downwarping of the Trough, probably during the Neogene Rifting, terminated the discharge from the Lake into Lake Tanganyika through a gap at Karema.

The Lake Beds may be divided into Older and Younger Lake Beds. The Older Lake Beds are found in the Songwe Trough and were deposited when the Lake occupied the whole of the Depression and reached a level 150-200 m higher than the present one. They are of green clays and sandy diatomite clays, with inclusions of volcanic material. The thickness of the Older Lake Beds, were fully developed, has been estimated to be 180 m (Coster, 1960).

The Younger Lake Beds occupy the central part of the Trough and consist of fine sands and silts. The shifting courses of the main rivers may be responsible for interbedded coarse material encountered at various depths. From boreholes at Ivuna (BH Nos 18/52 and 30/52) the Younger Lake Beds are known to be 70-80 m thick. They are underlain by red Cretaceous sandstones which are possibly underlain by Karroo sediments at depth.

The rocks of the Rungwe Volcanic Province are usually divided into the Older and the Younger Extrusives. The centres of eruption responsible for the deposition of the Older Extrusives have not been located exactly but a study of the drainage and structural features indicates that much of the material originated from the Katete and Poroto groups of volcanoes. The Older Extrusives rocks are lavas in the trachyte to phonolyte range and a large variety of basaltic rocks.

The Younger Extrusives can be associated with three centres of eruption, Tukuyu, Kiejo and Rungwe. Basalts and phonolitic trachytes are the main rocks. Widespread pumice and ash from the final activity of Rungwe forms an obscuring cover of the volcanic province and the surrounding Basement Complex and Lake Beds.

5.3 Structure

The principal tectonic events, that have affected the rocks of southern Tanzania are summarised in Table 5.2. The Table applies to most of the events controlling the structures in the study area, and thus relates the geomorphological and structural history of the study area to the overall system of Tanzania. The structures of Iringa, Ruvuma and Mbeya Regions are discussed in more detail below. They are also shown on Drawing II-8, Geology.

5.3.1 Pre-Cambrian Folds

The structural setting of Tanzania and in particular in the study area is dominated by the pre-Cambrian orogenic episodes and subsequent rift faulting which has taken place since the late pre-Cambrian.

The rocks of the old East African nucleus, of which only the Dodoman system is present in the regions have a predominantly east-west fold trend. The surrounding Ubendian and Usagaran fold belts have at least two principal fold-trends indicating that at least two orogenies have

	PERIOD	TANZANIA
KAINOZOIC	Quarternary	Eustatic changes in sea-level. Vulcanicity of western rift zone. West rift faulting along pre-existing pre-Cambrian structures. East rift faulting along pre-existing pre-Cambrian structures. Erosion of Congo land surface.
	Tertiary	Maturation of Coastal Plain erosion surface with subsequent warping.
		Rejuvenation of rift faulting and warping.
		Maturation of post-African erosion surface with subsequent warping.
		Regional uplift and minor movement along faults.
MESOZOIC	Cretaceous	Maturation of African erosion surface. Regional uplift. Maturation of post-Gondwana erosion surface.
	Jurassic	Maturation of Gondwana erosion surface. Deposition throughout Cretaceous. Break-up of Gondwanaland. Trough faulting and uplift of interior, down faulting and warping of coastal regions.
PROTEROZOIC-PALAEOZOIC	Karroo	Rejuvenation of major rift faults along margins of troughs. Formation of basins with partly faulted margins.
		Uplift, erosion, Karroo continental deposition.
	Bukoban	NW-SE, NE-SW major rift fault trends, initated possibly along older trends.
		Uplift, erosion and sedimentation.
	Karagwe-Ankolean	NNE trending folding and NNW thrusting Ukingan rocks. Granite intrusion. Volcanism.
		Uplift, erosion and sedimentation.
ARCHAEAN	Ubendian Usagaran	Ubendian NW trending isoclinal folding)NW-SE Usagaran N trending isoclinal folding)Mozambiquian fold trends
		Uplift, erosion and sedimentation.
	Nyanzian-Kavirondian	E trending isoclinal folding of Nyanzian Belt. Slight metamorphism and migmatisation.
		Uplift, erosion and sedimentation.
	Dodoman	ESE intense regional folding, metamorphism, granitisation and migmatisation.

Table 5.2 Principal tectonic events in southern Tanzania.
(After Saggerson, 1969)

been impressed upon these rocks. The western fold belt (Ubendian) trends north-west/south-east along the Rukwa Trough and swings south along Lake Nyasa. The Usagaran fold belt of East Iringa Region trends predominantly north-east/south-west and north-south in Tunduru District. The Usagaran and Ubensian Systems converge in Ruvuma Region and continue into Mozambique as the Mozambique Belt which occupies the entire area between Lake Nyasa and the coastal sedimentary belt to the east.

The Karagwe-Ankolean orogeny is the last major folding episode in the area. The thick sedimentary series of Ukingan rocks was intensely sheared and folded following the already established Usagaran south-east/north-west trend. The Karagwe-Ankolean orogeny was responsible for the folding and metamorphism of the Ndembera Beds and the Konse Series along a north-east/south-west trend.

Following the Karagwe-Ankolean orogeny, the tectonic activities are characterised by major rift faulting and associated tearing and fracturing established in the Bukoban Period. The Nyasa and Rukwa rift fault lines are considered established with a north-north-west/south-south-east trend during the Bukoban.

5.3.2 Faults

Throughout the late Palaeozoic, Mesozoic and Kainozoic, a series of events happened that affected the structural pattern. Regional uplifting, block and trough faulting, sedimentation, rifting and warping along the eastern coast took place.

By the mid-Jurassic, Gondwanaland started to break up. This resulted in the formation of new coast-lines, and a number of erosion cycles was initiated. These resulted in the transport of material and were followed by deposition, uplifts and warping. Movements took place predominantly along zones of weakness already established during the Bukoban of the late pre-Cambrian.

Major movements along these faults have taken place during several periods since the Bukoban in the late-Cretaceous, Tertiary and Quaternary. The present linear topographic expression of the faults was established during Pleistocene times. The faults are shown on Drawing II-8, Geology, and the main fault lines are also shown on Drawing II-12, Dambos, Springs and Main Faults.

The faults dominating the area are those defining the two Rift Valleys, the Eastern and the Western Rift Valley (Figure 5.1).

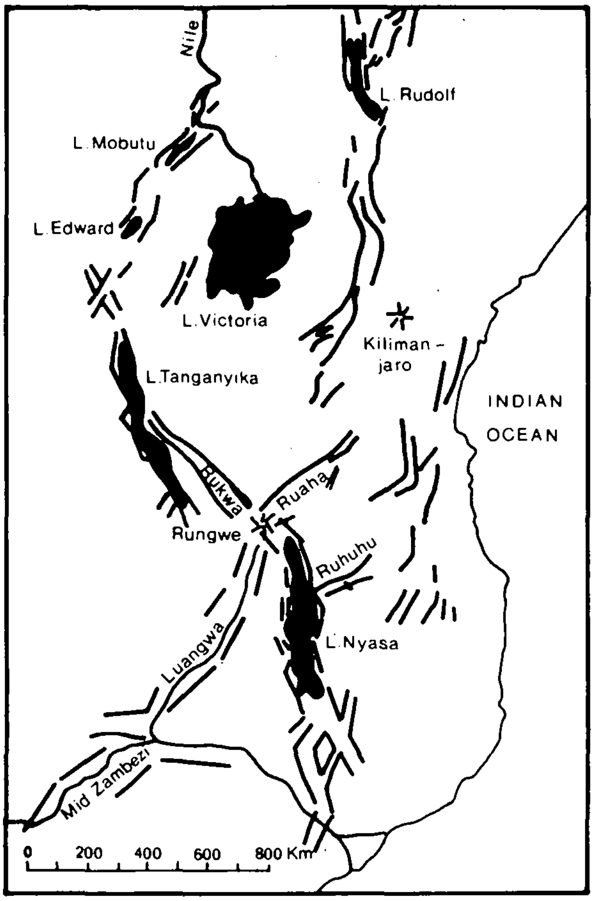


Figure 5.1 The East African Rift Valleys.
The Luangwa-Mid Zambesi rifts are older features now largely filled in with Karroo sediments. (After Holmes, 1978)

The Eastern Rift Valley runs from Lake Rudolf south towards Dodoma and continues further south to Mbeya. The Western Rift Valley follows Lake Edward, Tanganyika, Rukwa and Nyasa.

Parallel to the Ruaha Rift are the Ruhuhu Trough and the Kilombero Valley. These are results of reactivation of structural lines established during the Usagaran orogeny.

The mainly north trending faults along the margins of the Karroo Basin and sub-basins in Tunduru are a continuation of the faults defining the margins of the Karroo Basins in Morogoro Region.

Thus, there is a close relation between the fault type tectonical activity whether it is pre- or post-Karroo, and the trends established during the pre-Cambrian Period. Faults will be following north-west/south-east pre-Cambrian structural lines in the western part of the study area, north-east/south-west trends in central and south-east Iringa Region and north trending structural lines in Ruvuma Region.

As a result of the complex structural history of Tanzania in general and of the study area in particular, all rocks older than Quarternary may be expected to be intensely faulted and fractured. This has a considerable bearing on the hydrogeology of the regions. Weathering profiles will be shallow in recently disturbed areas due to erosion, and deep in areas not affected by Neogene faulting. Juvenile water may be expected in association with rift faulting, and this may, in certain areas, impose restrictions on the groundwater development potential. However, large areas are apparently unaffected by Neogene faulting, and here groundwater may constitute a prospective source.

5.4 Rock Weathering and Erosion

Rock weathering is the physical breaking down of rocks, and can take place in two ways, mechanically and chemically. Erosion is the process by which weathering products are removed and transported either mechanically or in solution.

Weathering and erosion are governed by the geology (both lithology and structure) and by climate and environmental conditions. Variations in these results in the production of the characteristic land forms observed in any given area. The study of the results of the interplay of these variables is Geomorphology.

When a land surface has been subjected to mechanical weathering and erosion until a well developed pediplain has been formed, the area will become mechanically stable and from then on only chemical weathering and solution transport can take place. This is the weathering and erosion equation found over the high African Plateaus which geomorphologists have defined as the African and post-African Pediplains or land surfaces. In addition it is found that the chemical weathering and erosion over these two land surfaces has a profound influence on the occurrence and availability of groundwater. It is, therefore, important to examine the chemical weathering process.

Chemical weathering is the process of breaking down the rock forming minerals by chemical reactions in a liquid (or rarely gaseous) environment, and the result is a more or less disintegrated rock with physical properties completely different from the parent rock. For Basement Complex rocks this means that some of the minerals of the parent rock, mainly quartz, persist, others are completely destroyed and form clay minerals. The result is that a permeable and porous rock replaces the original fresh rock and a potential aquifer is developed in the weathered zone, known as the saprolite. Chemical rock weathering depends on several parameters the most important of which are time, climate (rainfall and temperature), degree of jointing and the original mineral composition of the parent rock. The main agent of chemical weathering is circulating groundwater and its chemical composition is again important in the process.

5.4.1 Time

Time is the most important parameter of them all. The longer a land surface has been exposed to weathering the deeper the weathering and the thicker the resulting saprolite will be. The different erosion surfaces encountered in East and Southern Africa have been developed during particular periods of geological history and differ up to 150 million years in age. Therefore, there is a distinct difference between saprolite thicknesses from one erosion surface to another, although differences do occur within each erosion surface because of the time factor. The application of the geomorphological concepts and analysis immediately enables a delineation of the areal extent of the erosion surfaces, and, all other factors being equal, the aquifer thicknesses can be reliably predicted.

5.4.2 Climate

The climate, especially the rainfall variation, gives rise to a differential weathering from surface to surface and within a given surface. The rainfall variation actually could cause a variation in borehole yields to occur, but to prove this, a much larger amount of borehole data than is presently available should be obtained. Historical variations in climate have also be shown to be of great importance (Hadwen, 1972).

5.4.3 Jointing

The original jointing of the parent rock plays an important role for the weathering process. Water percolates through the joints and chemical weathering is thus facilitated. Different rocks are jointed to different degrees, which may again cause differential weathering over short distances, but only in terms of depth, and the resulting effect on the aquifer transmissivity may be only a factor two or three.

5.4.4 Mineral Composition of Parent Rock

The mineral composition varies considerably between rock types, but within rocks of the Basement Complex the variation is limited, and the weathering products become similar. This uniformity of weathering products of Basement rocks leaves a geological approach to the hydrogeology of the Basement Complex with little value, because the geological significance in terms of groundwater hydraulics is not preserved once the rock is weathered.

The mineral composition of different igneous rocks is shown in Figure 5.2.

Within each rock group there are variations in mineral composition, and more specific names than shown here, are used for individual rocks.

From different quarter degree geological map sheets from the study regions the following rock analysis have been obtained as shown in Table 5.3.

The variation between the rock groups is not large, and once the rock is weathered down, the physical properties of the weathering product as a water bearing medium become even more uniform from rock to rock.

There is a pronounced difference in how quickly individual minerals weather down, but the weathering products for granitic and gneissic rocks are always quartz and clay minerals.

In Table 5.4 the weathering products and the stability of the most common minerals are listed. From this table and Figure 5.2 it is possible to characterise the different rocks most commonly encountered within the study regions, and also give a qualitative estimate of the water bearing quality of the resulting saprolite.

A list of the most common rock types of the Basement Complex is given in

Table 5.1, and a description of the weathering products is given in Tables 5.5 and 5.6.

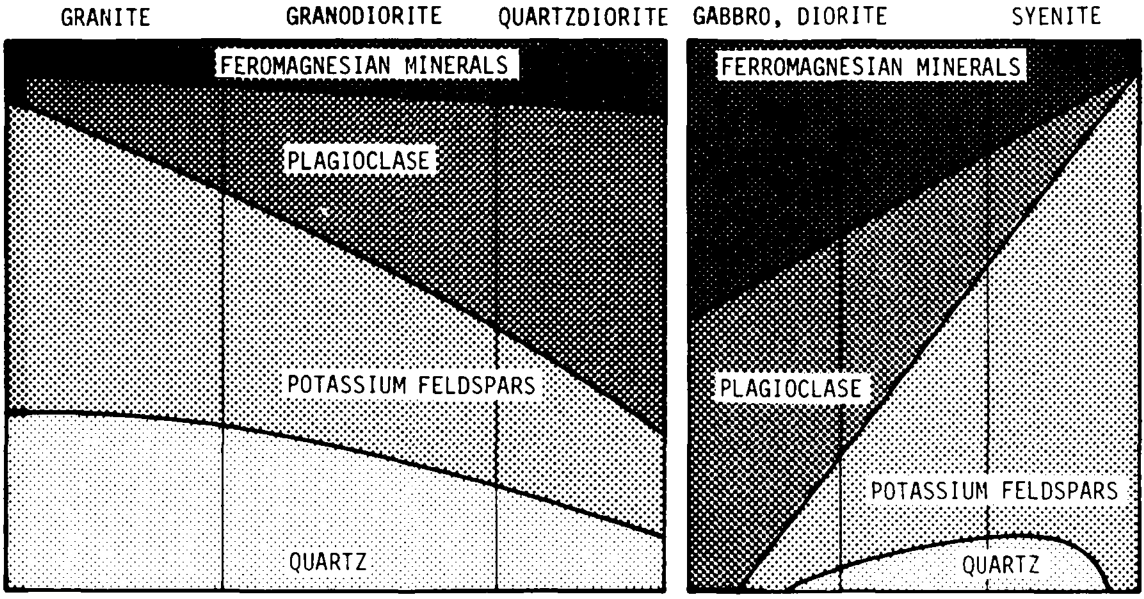


Figure 5.2 Schematic representation of the mineral composition of different igneous rocks. (After Graff-Petersen, 1960)

	Older Granite	Younger Granite	Quartzo-Feldspatic Gneiss	Biotite Gneiss
Quartz	35	41	28	35
Potassium Feldspars	25	41	37	19
Plagioclase	34	13	26	26
Micas	4	4	7	14
Accessories	2	2	2	5

Table 5.3 Mineral composition in per cent of different rocks of the Basement Complex.

Before studying the details of the tables, it is worth noting that 97% of the Basement Complex rocks which cover 68% of the study area are psammitic (quartz rich) metamorphic rocks or acidic plutonic rocks covering a large range of gneisses, granites and migmatites which when weathered usually form good aquifers. The remaining Basement rocks are pelitic (clay rich) metamorphic rocks like schists and phyllites, or basic and ultrabasic plutonic rocks and basic and intermediate extrusives, all of which have poor water-bearing qualities in their weathered form.

Mineral in Order of Increasing Stability	Weathering Product	Primary Minerals That Persist
Olivine	Clay minerals	
Calcium - rich plagioclase	Clay minerals	
Augite	Clay minerals	
Calcium-Sodium plagioclase	Clay minerals	
Hornblende	Clay minerals	
Sodium - rich plagioclase	Clay minerals	
Biotite	Clay minerals	Some mica
Potassium feldspar	Clay minerals	
Muscovite	Clay minerals	Some mica
Quartz	-	Quartz

Table 5.4 Mineral stability and weathering products. (After Flint and Skinner, 1974)

It appears, that the best aquifers are found where the parent rock contains abundant quartz, but even schists, which are metamorphosed clay minerals, may yield water because of weathering along the schistosity planes.

From the considerations above the aquifer set-up in Basement areas in Tanzania is comparatively simple. The lower part of the saprolite forms the water bearing strata. Below is, apart from joints and fractures, impermeable bedrock, and above is in situ weathered soil, consisting mainly of clay minerals, rendering the aquifer confined. On a mature pediplain, this single aquifer system will be as shown in Figure 5.3.

The depths of the various sections of the profile are approximate. Weathering is deeper across the African land surface compared to the post-African land surface.

Parent Rock	Texture	Jointing	Weathering Products	Depth of Weathering	Water Bearing Quality
Granite	Coarse-grained, uniform size grains.	Richly	Clay minerals. Quartz and some mica persist.	Deep	Good
Granodiorite	Coarse-grained, uniform size grains.	Richly	Clay minerals. Quartz and some mica persist.	Deep	Good
Microgranite	Medium grained, uniform size grains.	Well	Clay minerals. Quartz persist.	Deep	Good
Diorite	Corase grained, uniform size grains.	Well and regular	Clay minerals and iron oxides.	Moderate to deep	Poor
Syenite	Coarse grained, uniform size grains.		Clay minerals.		Poor
Trachyte	Fine-grained		Clay minerals.		Fair
Gabbro	Coarse-grained, uniform size grains.	Little	Clay minerals, often montmorillonite	Moderate	Poor
Pyroxenite Peridotite Serpentinite Amorthosite.	Coarse-grained, uniform size grain.		Clay minerals.		Poor
Rhyolite	Coarse-grained, uniform size grain.	Well	Clay minerals. Quartz persist.	Shallow	Poor
Andesite	Fine-grained, uniform size grain.	Little	Clay minerals.	Shallow to moderate.	Fair
Basalt	Fine-grained, uniform size grain.	Well, often columnar.	Clay minerals and iron oxides.	Moderate to deep, but very variable.	Poor
Dolerite	Fine-grained, uniform size grain.	Well and regular.	Clay minerals and iron oxides.	Moderate to deep.	Poor

Table 5.5 Weathering and weathering products of common igneous rocks within the Regions. Partly from Carrol (1980) and Flint and Skinner (1974).

Parent Rock	Texture	Jointing	Weathering Products	Depth of Weathering	Water Bearing Quality
Quartzites	Fine - to coarse - grained	Well	Mechanical weathering	Shallow	Poor to very good
Gneiss Biotite gneiss Augen Gneiss Granite gneiss etc.	Coarse - grained	Moderate	Clay minerals. Quartz persists	Moderate to deep	Good
Slate, phyllite, shist	Breaks into flakes	'Schistosity'	Clay minerals. Some crystals	Moderate to deep. Depends on topography.	Poor to fair
Migmatite	Coarse - grained	Well	Clay minerals. Quartz persists	Deep	Good
Amphibolite	Oriented flakes	Cleavage	Clay minerals	Deep	Fair
Ferro - magnesium schists	Foliated	Cleavage, 'Schistosity'	Clay minerals	Deep	Poor

Table 5.6 Weathering and weathering products of common metamorphic rocks within the Regions Partly from Carrol (1970) and Flint and Skinner (1974).

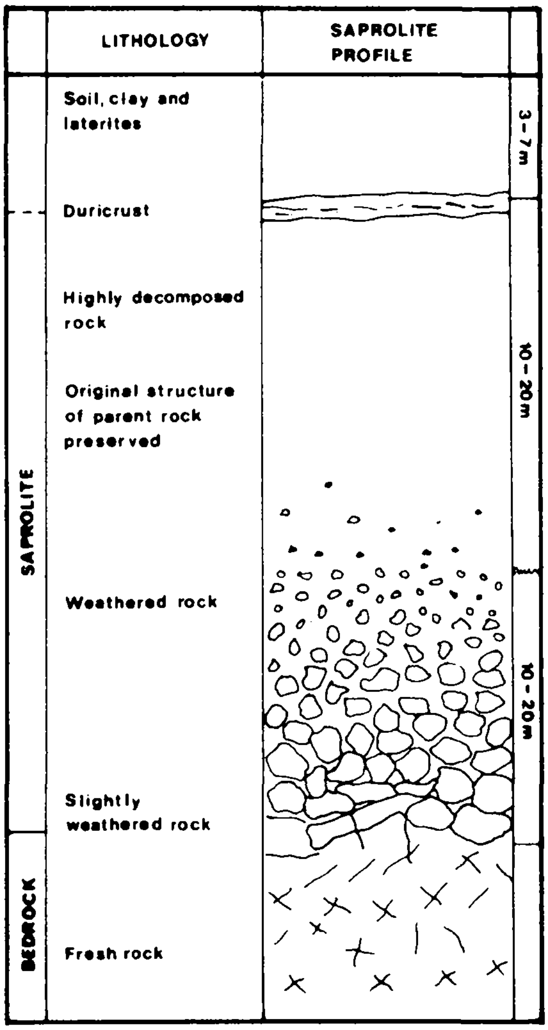


Figure 5.3 A typical saprolite profile in the Basement Complex.

To get an impression of the depth of weathering across the Basement Complex as a geological unit, data have been collected from other regions of Tanzania. The erosion surfaces are predominantly African and post-African. The saprolite thickness frequency distribution is shown in Figure 5.4

It appears from Figure 5.4 that weathering profiles deeper than about 70 metres are exceptional (less than 5%) and that the mean is around 30 metres. The data used are from wells drilled predominantly for village water supplies, and geomorphological considerations have probably been little applied in selecting the well sites. It will be shown in Chapter 7, that saprolite thicknesses are a function of the geomorphological history of an area, and that this concept is very useful in determining the hydrogeological conditions across the Basement Complex.

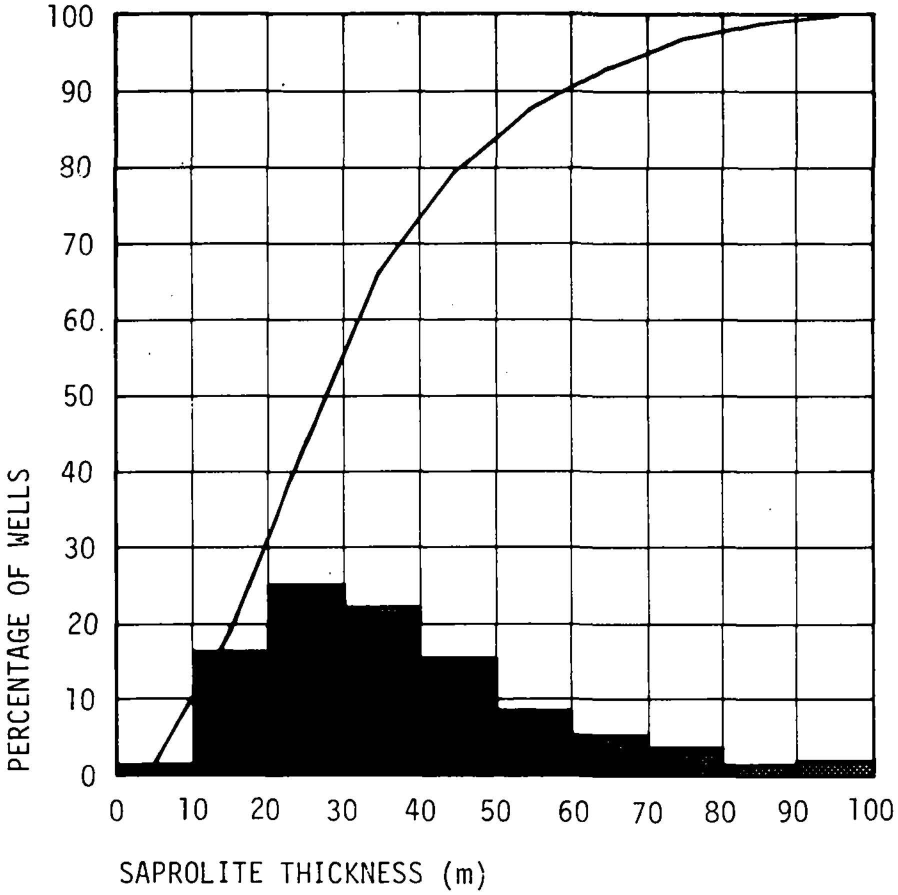


Figure 5.4 Saprolite thickness frequency distribution across the Basement Complex of Tanzania. Data from 236 wells from Iringa, Ruvuma, Mbeya, Mtwara, Lindi, Shinyanga, Tabora and Lake Regions.

6. GEOMORPHOLOGY

6.1 Introduction

Much of East Africa has been exposed as continental land above sea level for over 200 million years. The landscape, therefore, is among the oldest found on the earth. East Africa and in particular the areas covered by the study regions are characterised by extensive elevated plateaus interrupted by isolated highlands and broad linear valleys of tectonic origin. The plateaus are a result of erosion processes operating since the late Jurassic (Table 5.2), and 90% of the area covered by the regions can be referred to particular erosion surfaces.

68% of the study area is underlain by crystalline rocks belonging to the Basement Complex. The remaining 32% is underlain by sedimentary rocks of the Karroo System (21%) or by younger deposits, mainly of Neogene age.

Intensive in-situ chemical weathering by circulating groundwater has produced a thick mantle of overburden across the plateaus. This overburden in some places effectively masks the exact geological nature of the underlying rocks, as well as their tectonic and structural features.

At an early stage of the study, it became apparent that in the Basement Complex, groundwater occured in the lower part of the in-situ weathered rock zone, and that the distribution of landforms played an important role in determining the hydrogeological conditions. The factors controlling the hydrogeology of the Basement Complex were, therefore, found to be uniquely related to the geomorphology of a given area, and by means of a geomorphological classification it became immediately possible to describe qualitatively the groundwater conditions in most areas. The description would become complete once enough borehole data was available to express the groundwater occurrences in quantative terms.

It is, therefore, necessary to describe the geomorphology in detail. The description is based mainly on King (1962), who gives a comprehensive account of the processes of landscape evolution and the physical laws controlling them.

6.2 The Erosion Cycle Concept

A landscape is primarily a result of the processes trying to change it, and the topographical characteristics of the study area are related strongly to the erosion cycles which have prevailed over the continent. A cycle of erosion includes several stages of landscape evolution. The first stage is of extreme mechanical erosion with deep stream incision which is characteristic for a youthful landscape. Then follows mechanical erosion in the form of scarp retreat and resulting pedimentation which characterises a mature landscape. The final stage is further planation with less mechanical and more chemical erosion which results in a senile landscape of extremely low relief.

To achieve a senile landscape topography requires very long periods of stable erosion base levels, tens of millions of years. The erosion base level is usually the prevailing sea level in relation to the land surface. If the sea level goes up in relation to the land, sedimentation takes place, if it goes down, accelerated erosion takes place.

When tectonic events establish a new base level of erosion, a new erosion cycle starts its work of denudation from the coast towards the interior. All stages of erosion are present.

Such tectonic movements have happened several times during geologic history of Tanzania and several erosion cycles can be identified. Each erosion cycle operates at a lower level than the former one, and the erosion cycles are, therefore, separated by escarpments which may be more or less well defined.

The standard scarp caused by erosion has four elements (Figure 6.1): a crest, a scarp, a debris slope and a pediment.

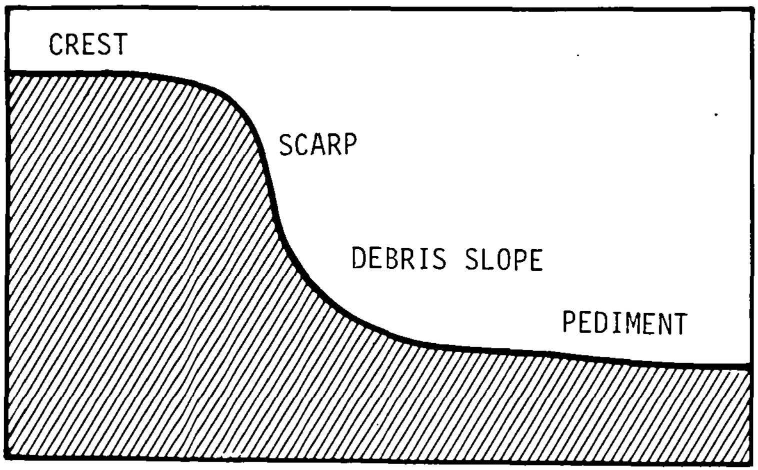


Figure 6.1 The morphological elements of a standard hillslope. After King (1962).

The crest is the summit area over which there is little mechanical erosion. It forms a convex surface, and since the gradient is very small there is a critical distance away from the scarp beyond which no mechanical erosion can take place, because the turbulence of the flowing water is not strong enough to overcome the cohesion of the soil.

The scarp is the steepest part of the hillslope, and here bare rock usually outcrops. The scarp is where most mechanical activity takes place in the erosion cycle. The whole scarp is eroded backwards resulting in a retreating hill face. Generally such a retreating scarp parallels the neighbouring coast line.

The debris slope is where mechanically weathered rock material derived from the crest of the scarp is deposited, having been deposited by gravity or by high energy streams. The material along the debris slope is deposited as talus, conglomerates or alluvial fans. Material is removed from the debris slope by erosion, and therefore, it usually retreats with the scarp face.

The pediment is the lower part of the hillslope, usually with a concave surface. Once established, the pediment will be further smoothed by erosion due to sheet flow of water and mass movement of soil.

The pediment is hydrogeologically the most important part of the landscape. It forms 68% of the study area and is the result of scarp retreats, which have increased the pediments below the scarps and reduced the crest areas above.

The pediplanation described above is best developed in hard rock areas in a semi-arid environment, where heavy seasonal rainfall results in river and overland runoff strong enough to conduct erosion effectively.

Once a landscape has been reduced to a pediplain it may remain so until uplift, tilting or isostacy creates a new base level. Then streams start incising again, and a new cycle of erosion is initiated.

If not for local tectonic changes, erosion surfaces could be traced and correlated over vast distances, even intercontinental, based on their level alone. To construct a morphological map, local geological structures, therefore, must be examined to avoid errors in correlating surfaces, even over short distances. Faults on a pediplain may be misinterpreted as an erosion scarp indicating two different cycles of erosion. If such faults have existed sufficiently long, erosion may have moulded them so much that they appear as normal erosion scarps.

A landscape which is a result of several cycles of erosion having passed over it, is polycyclic. The study area is polycyclic, the earliest cycle originated during the Jurassic. The following is a description of these cycles, starting from the oldest. The map accompanying the description (Drawing II-9, Geomorphology) has been drawn by means of geological and topographical maps, landsat imageries, existing maps on morphology and physiography, and finally from field reconnaissance.

6.3 Erosion Cycles in the Regions

Up to the early Cretaceous Period, Africa, South America, Australia, India and the Antarctis were one huge continent which has been given the name Gondwanaland. Compared with today, the Gondwana landscape was at a rather low level. During the whole of the Jurassic Period, this landscape was denuded, and the erosion cycle responsible for this planation is the Gondwana Erosion Cycle.

Due to later uplifts, remnants of the Gondwana planation are preserved as high plateaus which form the crests of the present African watersheds. The Gondwana pediplain is generally heavily dissected by later erosion cycles. It is in many places, therefore, identified as high remnants standing out above the African pediplain (see below).

During the early Cretaceous Period, continental drift caused Gondwanaland to break up to form the continents of today. The eastern and western coasts of Africa were created, and monoclinal flexing, or hinge down-warping towards these coasts created a new base level for the existing rivers. This initiated a new cycle of erosion known as the post-Gondwana Cycle. The post-Gondwana Cycle is today seldomly seen as broad pediplains, but merely as broad valleys dissecting the Gondwana Plateaus. These two cycles are very difficult to separate, because they operated at more or less the same level. Hydrogeologically these two plateaus are also very similar, and in the following they are, therefore, discussed together.

Continental uplift and further monoclinal flexing along the coasts during the late Cretaceous initiated a third new cycle of erosion that lasted until the late Oligocene Period, i.e. throughout the early Cainozoic era. This is the major erosion cycle across Eastern and Southern Africa and is known as the African Cycle. The cycle base level was stable for 40-50 million years between the late Cretaceous and the Oligocene, and this has resulted in the extremely flat pediplained African Surface. This plateau offers the datum best suited for mapping erosion surfaces in Africa. In many places it is responsible for the heavy dissection of the post-Gondwana Surface. Above it stands the Gondwana and occasionally the post-Gondwana remnants and plateaus, and below one finds the late Cainozoic cycles (post-African Surface), valleys belonging to late Pliocene planation (Coastal Plain Surface) and the most recent Quarternary (Congo) planation.

During the end of the Oligocene and again late Miocene, moderate vertical isostatic uplift caused by the unloading of the continental surface by erosion of material created a new base level for the rivers. This resulted in the post-African Erosion Cycle. It is responsible for the destruction of large parts of the African Surface. The post-African Surface covers a large part of the interior African Plateau, and is a gently undulating landscape with broad shallow valleys cut down into the African pediplain. The less well developed post-African Surface results from a short formative 15 million year period, when compared with the African Cycle. While the post-African surface is polycyclic, it is extremely difficult to identify each erosion cycle within this plateau, because the scarps are indistinct, and in the following the post-African surface is, therefore, treated as the result of one erosion cycle only.

Powerful uplift and warping during the Pliocene Period resulted in elevation of the interior of the continent. This and outward tilting at the coast due to cracking of the crest (the Rift Valley System) started a new erosion cycle, the Coastal Plain Cycle. As the name implies, this planation is found mostly in the coastal hinterlands, but in some cases rivers have cut valleys into the interior plateaus.

In the study area, coastal planation is limited and not easily distinguishable from the Quarternary Congo Planation, so these two erosion cycles are hereafter treated as one.

6.3.1 The Gondwana and Post-Gondwana Erosion Cycles

The Gondwana and post-Gondwana land surfaces occupy a comparatively large fraction of the study area. Mostly they are only preserved as remnants now appearing as heavily dissected mountain ranges, the summit of which is the Gondwana Surface, while the post-Gondwana Surface is represented by valley floors cutting into the Gondwana Surface above.

In Iringa Region, the Gondwana and the post-Gondwana cycles are found on the Livingstone Mountains, the Kipengere Range and the Gofio Plateau, the Mufindi Highlands, and the area north-east of Iringa.

The Gofio Plateau is an extensive Gondwana erosion surface standing at just below 3000 metres. It is surrounded to the east, south and west by an even more extensive plateau belonging to the post-Gondwana land surface. The Livingstone Mountain part of this surface is heavily dissected, but for a large part it consists of a well pediplained erosion surface.

In the north-eastern part of Iringa Region, a large area is occupied by Gondwana and post-Gondwana landscapes. They are everywhere heavily dissected, the summit level at around 2500 metres representing the Gondwana pediplain. Remnants of these erosion cycles are generally widespread in this part of Iringa Region, and are much more common than indicated on the geomorphological map, e.g. around Iringa town.

A large area belonging to the post-Gondwana cycle of erosion and standing around 2000 metres are the Mufindi Highlands. These are now heavily dissected by the African cycle of erosion. They are separated from the Kilombero Valley by a bold fault scarp several hundred kilometres long.

In Ruvuma Region, only remnants of the Gondwana and post-Gondwana erosion cycles are present, and they are found in Songea and Mbinga Districts. Their summit levels are lower than in the rest of the study regions, around 1500-2000 metres. Throughout the region, Gondwana remnants are preserved as steep-sided bare rock hills, Inselbergs, which are very common on the African Surface.

In Mbeya Region these cycles are found in the northern part of the region, on Mbeya Range, Poroto Mountains and bordering the Mbozi Plateau to the north, east and south-east.

In the northern part of the region the comparatively large area covered by the Gondwana is heavily dissected, presumably much should be referred to as a post-Gondwana land surface. Few extensive Gondwana Plateau remnants are preserved, but division of the area into Gondwana or post-Gondwana erosion surface is not easy due to the remoteness and inaccessibility of these areas.

The post-Gondwana Surface in Makete District with the Gondwana Surface of the Kipengere Range in the background.

As above.

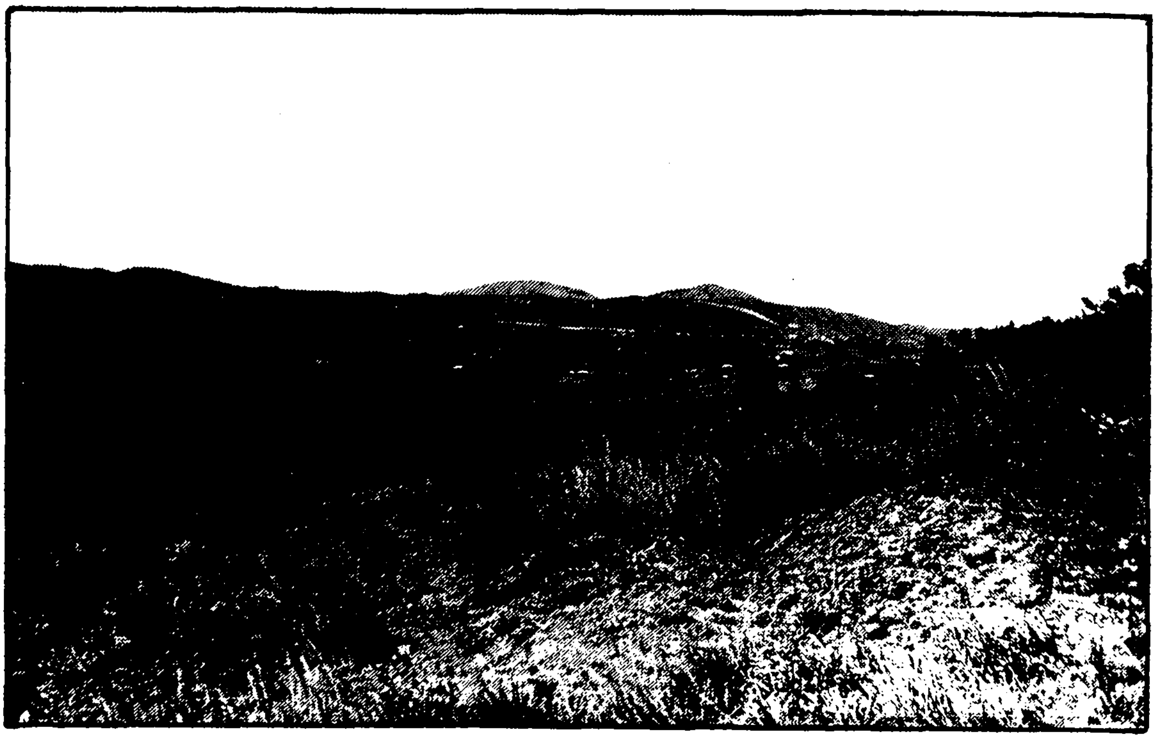
PLATE II

A heavily dissected Gondwana plateau in Makete District.

A dissected Gondwana landscape in Makete District. In the background, the Gofio Plateau, overlooking the post-Gondwana land surface. In most of the valleys, springs emerge.

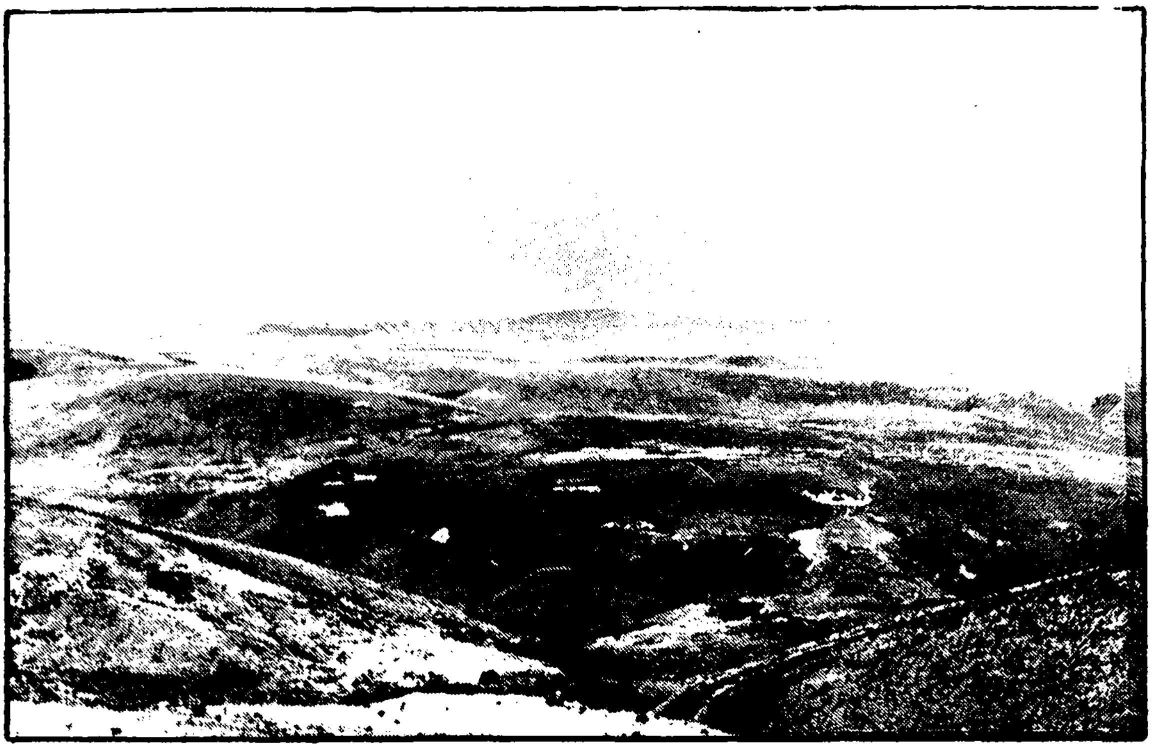
PLATE III

A typical post-Gondwana landscape in Makete District. In the background, remnants of a Gondwana plateau.

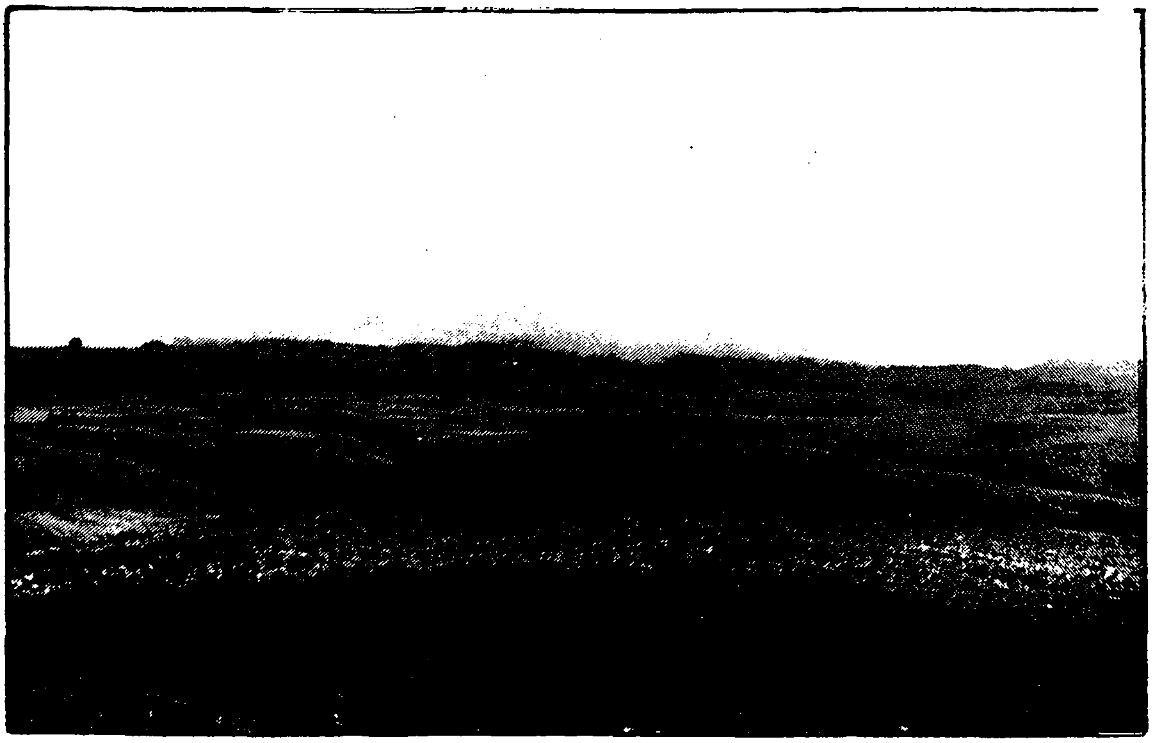


As above.

PLATE IV



The Gondwana Surface of the Gofio Plateau.



As above.

In the Mbeya Range, the summit levels at almost 3000 metres represent the Gondwana land surface. It is now so heavily dissected that no plateau areas remain. Remnants of several later pediplains are visible on the mountain range because of the differential uplift which has taken place here, probably dating back to the Ukingan Period (Table 6.2).

On the Poroto Mountains, the Gondwana land surface stands as a smooth pediplain at about 2500 metres. In some places, the surface is heavily dissected. Large parts of the Poroto Mountains are covered by an obscuring layer of volcanic ashes from the Rungwe eruptions.

Found bordering the Mbozi Plateau to the north is an extensive dissected post-Gondwana land surface, the summits of which stand around 1900 metres on the Chumwa Range. To the south-east of Mbozi the Umalila and Bundali Hills represent the Gondwana erosion cycle at around 2700 metres. This area is also heavily dissected by the post-Gondwana erosion, but it is nevertheless assigned to the Gondwana cycle of erosion because of its significant level.

6.3.2 The African Erosion Cycle

Except where major tectonic movements or eruptions from the Rungwe volcanic province have disrupted the pattern, the Gondwana and the post-Gondwana land surfaces are bordered by extensive surfaces belonging to the African erosion cycle.

The African Surface forms the extremely smooth landscape so characteristic of large parts of Africa. Because of the senile state of the landscape, rivers flowing on the African Surface have generally reached a state of equilibrium, and very little erosion takes place now.

The African Surface generally stands at about 1300-1500 metres. Only where local uplifting has occurred does the African Surface rise above this level. The rift valley system of East Africa has completely disrupted the African Surface. Thus, the valley floors of Lake Nyasa and the Rukwa Trough are down-warped African Surfaces.

A characteristic feature of the African Surface is the occurrence of Inselbergs. These are extremely hard rock remnants left behind by scarp retreat during the denudation of the previous land surface, i.e. the Gondwana/post-Gondwana Surface. Also the occurrence of dambos are very common (Section 7.4). The abundancy of dambos in an area bears strong evidence that the land surface belongs to the African cycle of erosion, and that this particular area has been exposed to little tectonic disturbance.

In Iringa, the central part of the region and the area north of the Usangu-Fufu Scarp is formed by the African Surface, covering about 50% of the region.

In Ruvuma, the larger part of the region, about 85%, forms part of the African Surface. This includes the Karroo Formation (61% of the region) which is treated as a separate hydrogeological unit.

King (1962) in his provisional geomorphological map of Africa has taken the southern part of Tunduru District as a post-African Surface, but observations during field trips there and the general occurrence of large Inselbergs indicate that this area belongs to the African Surface.

About 50% of Mbeya Region belongs to this denudation period. The African Surface is found in the northern part of the region and on the Mbozi and Ufipa Plateaus.

6.3.3 The Post-African Erosion Cycles

These late Cainozoic cycles can be treated as one, and they cover about 20% of Mbeya Region, 15% of Iringa Region, and only a small part of Ruvuma Region.

In Mbeya Region the post-African Surfaces are found south of the Mbozi Plateau, around Chunya and Makongolozi, and in the rift valley surrounding the Usangu Flats. This land surface continues into Iringa Region, and is further met bordering the Kilombero Valley in the west.

The post-African Surface today mostly appears as a young pediplain much more hilly and incised than the African Surface. This is mainly due to the rejuvenation of rivers which has taken place in connection with the rift faulting. The surface is rather unstable, and erosion is still taking place. Bedrock is frequently outcropping, showing the youthfulness of the land surface. Proper dambos are not found as frequently as they are on the African Surface.

The post-African surface has been influenced in the same way by the rift system as has the African Surface. Thus the floor of the Great Ruaha Valley and the Kilombero Valley are down-warped post-African land surfaces now partly covered by deposits of modern origin.

6.3.4 The Coastal/Congo Erosion Cycles

These cycles occupy only a minor part of the study regions and, therefore, hydrogeologically, play a minor role. Because of the large distance from the coast, the Coastal Plain Erosion Surfaces are not likely to be present within the study region, except very locally. These two cycles of erosion, therefore, will be treated as one surface, denoted the Congo Surface in the following.

Lake Nyasa is completely rimmed by this surface. The Ruhuhu River has dissected the Livingstone Mountains and formed an extensive pedimented valley of Congo Surface in the Ruhuhu Trough, cutting down into the easily erodible Karroo sediments.

Finally, narrow belts of Congo surfaces are present along the Great Ruaha River along the boundary between Iringa and Morogoro Regions.

To illustrate the succession of erosion surfaces, a schematic cross section is shown in Figure 6.2, which shows the pediplains as they may be found from the interior to the coast.

6.3.5 Scarp Areas

The scarp areas form the transition between one erosion surface and the next. The majority of the scarps shown on the geomorphological map are results of faulting connected to the rifting. Most of these faults have been initiated before Neogene times, and were reactivated in the Quarternary when the present day Rift Valleys were formed.

Normal erosion scarps are found in many places, e.g. around the Gofio Plateau, the Kipengere Range, the Mbozi Plateau, around the Gondwana land surface in the northern Mbeya Region, and in North Western Iringa Region. In these places, all elements of the standard erosion hillslope may be found.

Many of the fault scarps show considerable erosion as well, and often a geological map must be consulted to determine the nature of the scarp.

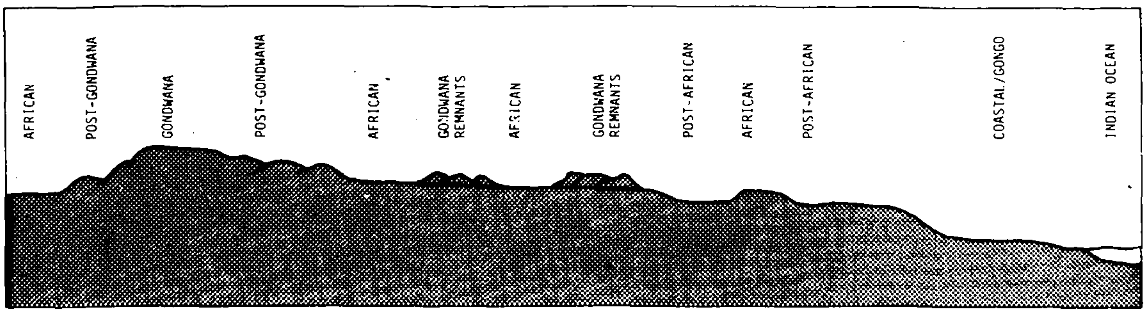


Figure 6.2 Schematic cross section showing erosion surfaces from the interior to the coast.

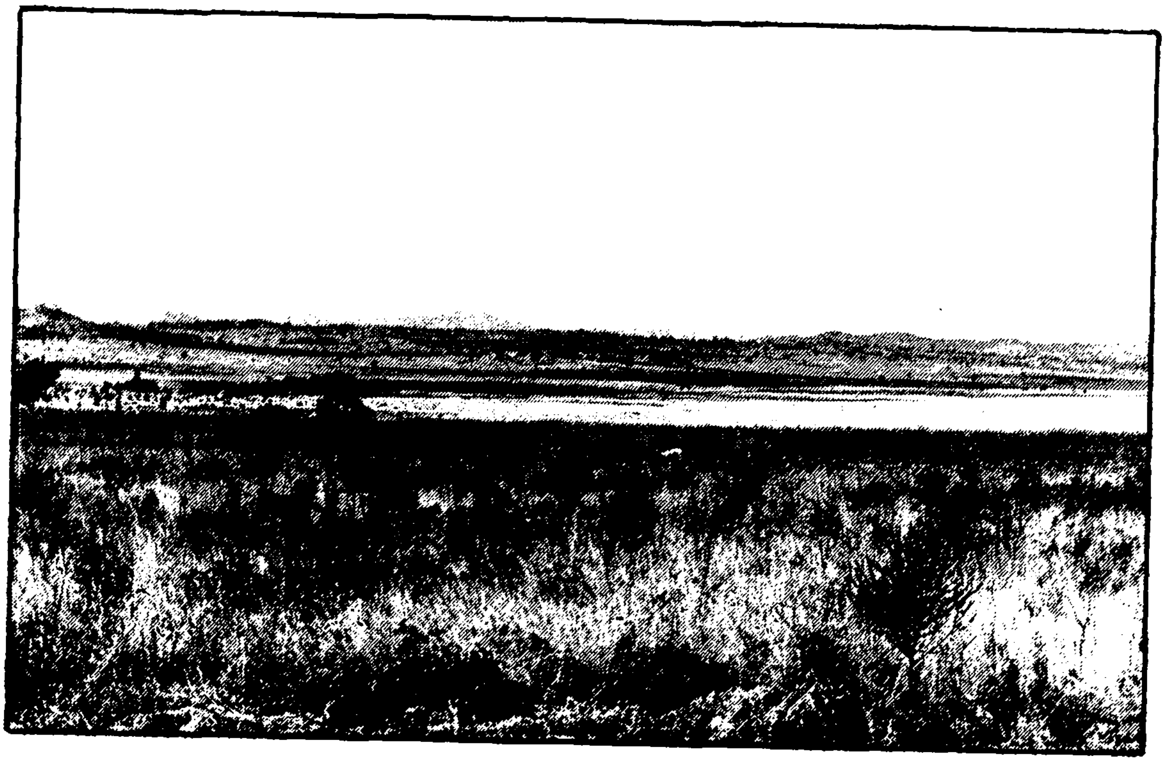
The scarp mapped are determined by inspecting satellite imageries at a 1:500,000 and 1:250,000 scale. Therefore, only scarps of reasonable areal coverage are included. The scarp dividing the African and the post-African Surface is not very pronounced except where the scarps coincide with the rift system.

However, hydrogeologically, the scarp areas shown are very alike, except for one very important factor. Where faults have caused the escarpment, mineralised juvenile groundwater of deep-seated origin is likely to occur, which is not normally found along erosion scarps.

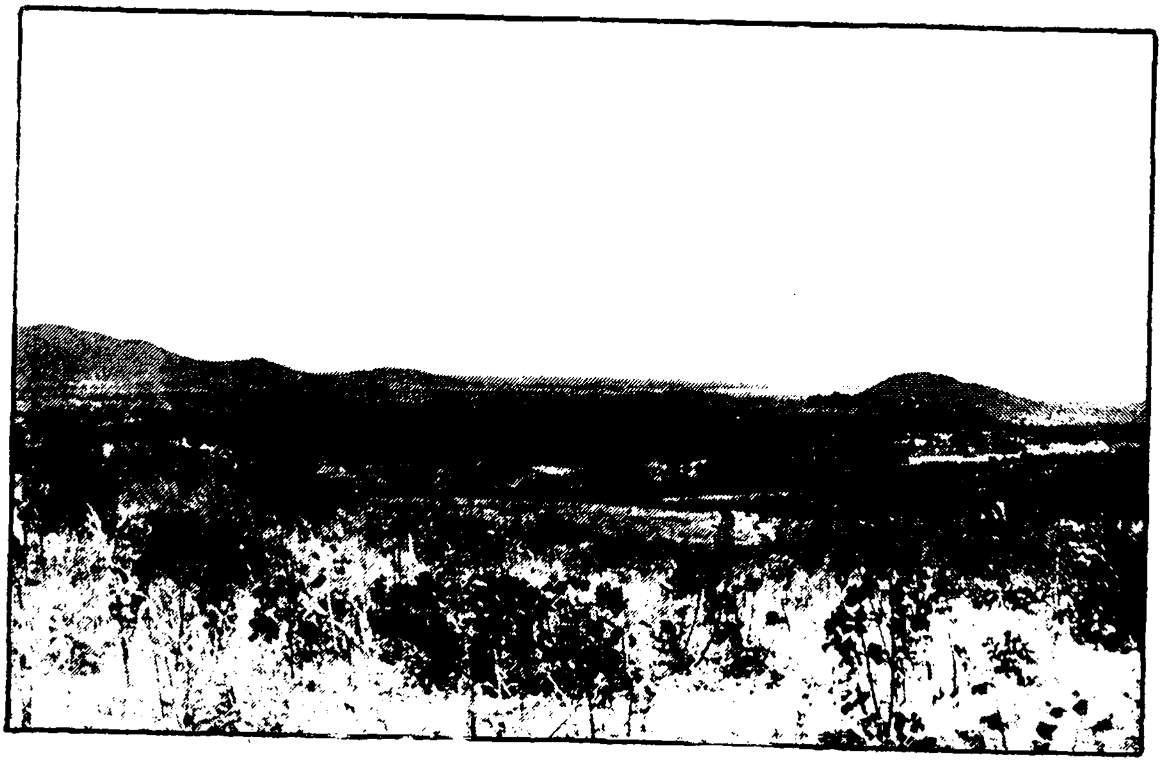
The characteristic features of the scarp areas are the frequent occurrence of springs. The heavily dissected slopes form a hydrogeological domain far different from the plateau areas or pediplains.

6.3.6 The Karroo Formation

Even though they fall in the African surface, the predominantly unmetamorphosed clastic sedimentary rocks of the Karroo System in Ruvuma are treated as a separate hydrogeological unit. The Karroo rocks are easily eroded as clearly demonstrated by the incision of the Ruhuhu River through the Livingstone Mountains, and many erosion scarps exist within the Karroo Formation as a result of the work of rivers, many of which are perennial. The land surface in the Karroo terrain, therefore, includes all the geomorphological features of an erosion land surface, from smooth pediplains to narrow valleys and sharp escarpements.

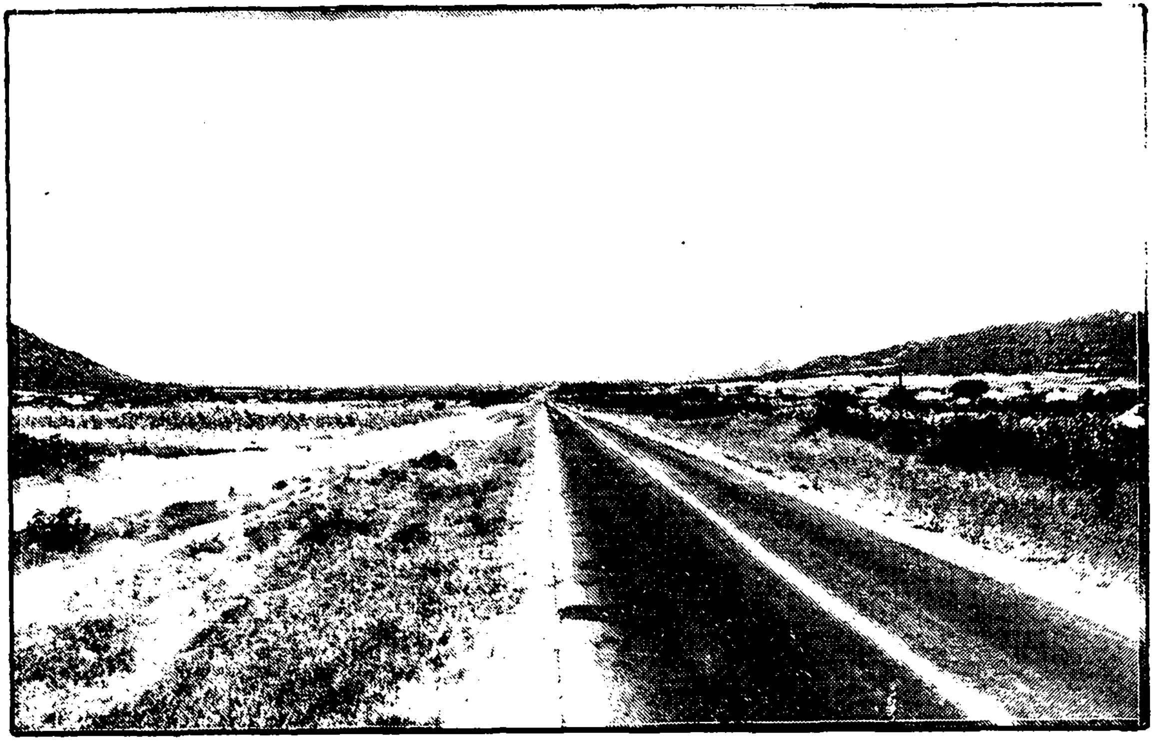


The African Surface surrounded by Gondwana Plateau remnants. North Iringa Region, seen from the Great North Road.

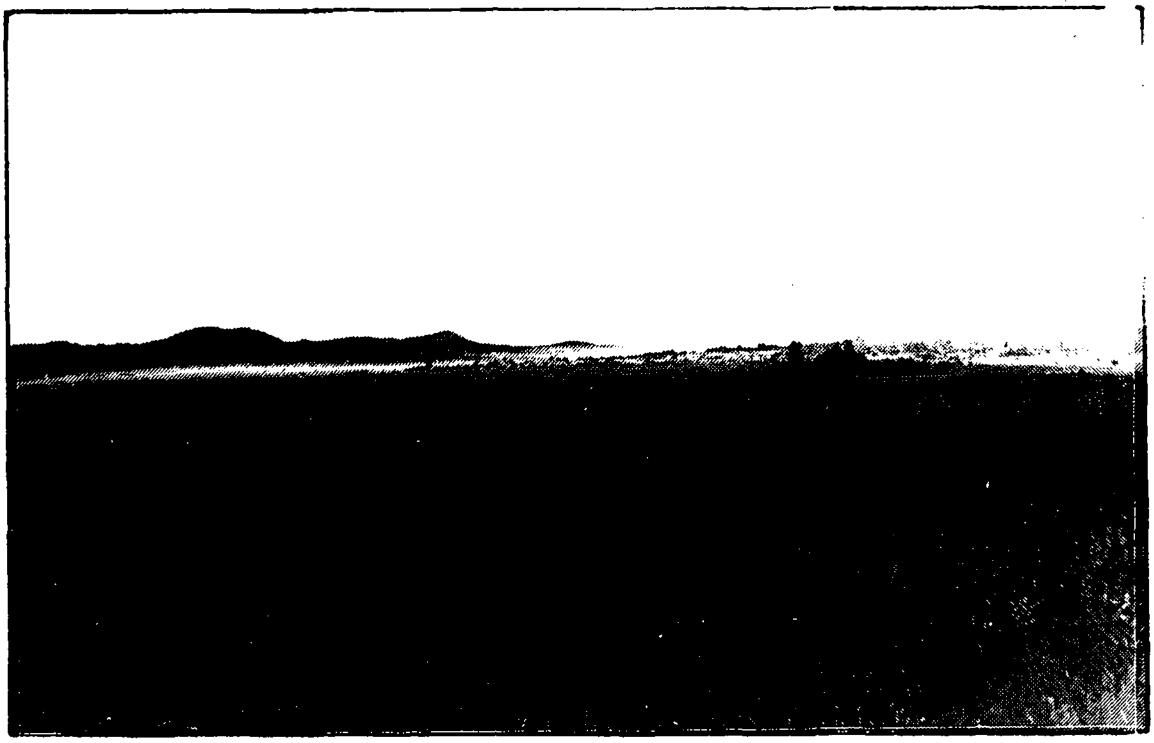


As above.

PLATE VI

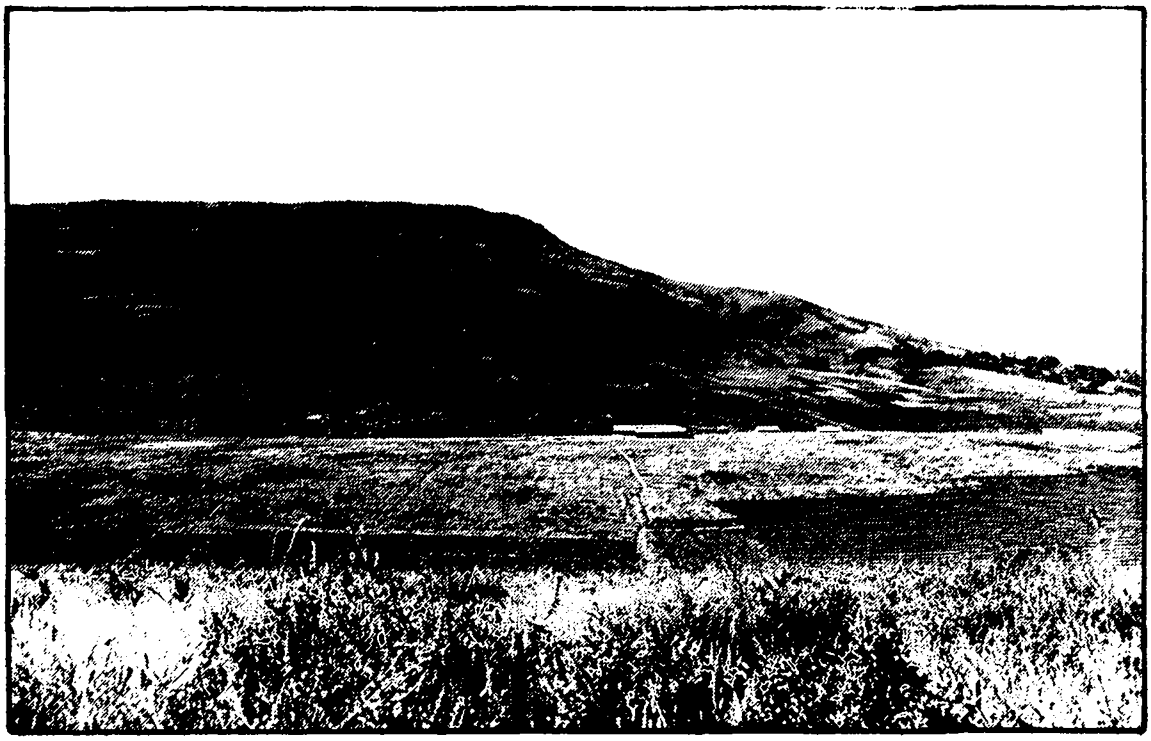


The Great North Road on the African Surface in Iringa District.

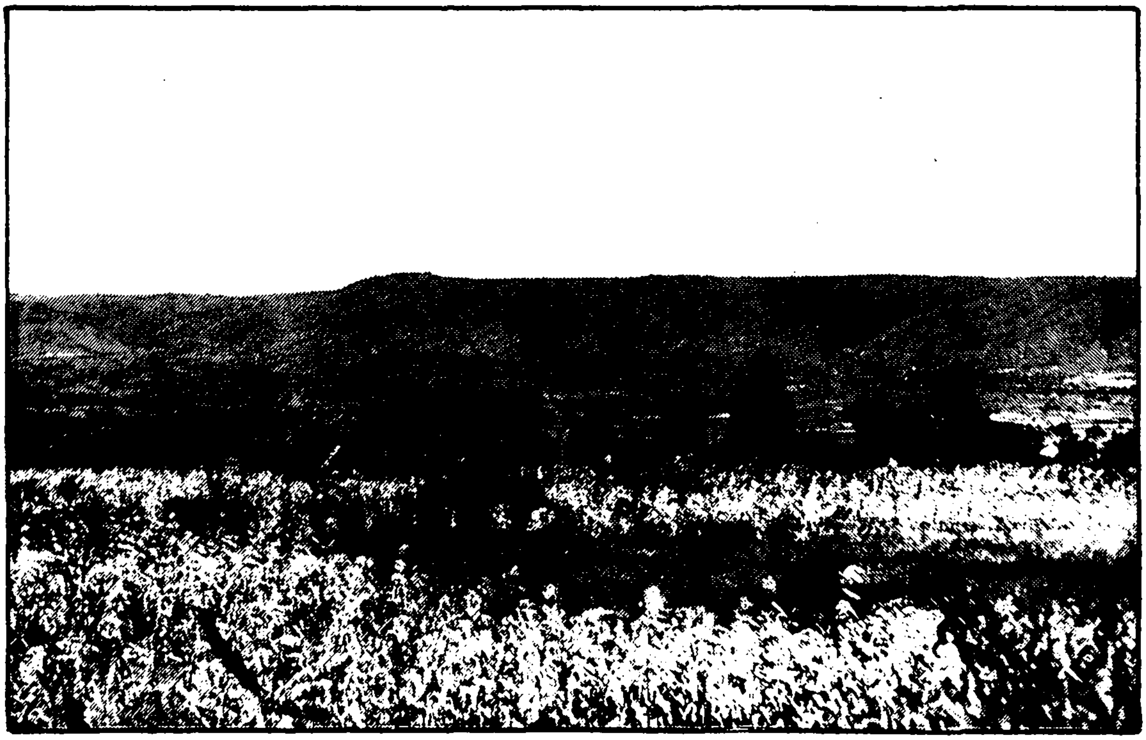


The African Surface of the Mbozi Plateau. In the background the Gondwana Plateau remnants of the Bundali Hills.

PLATE VII

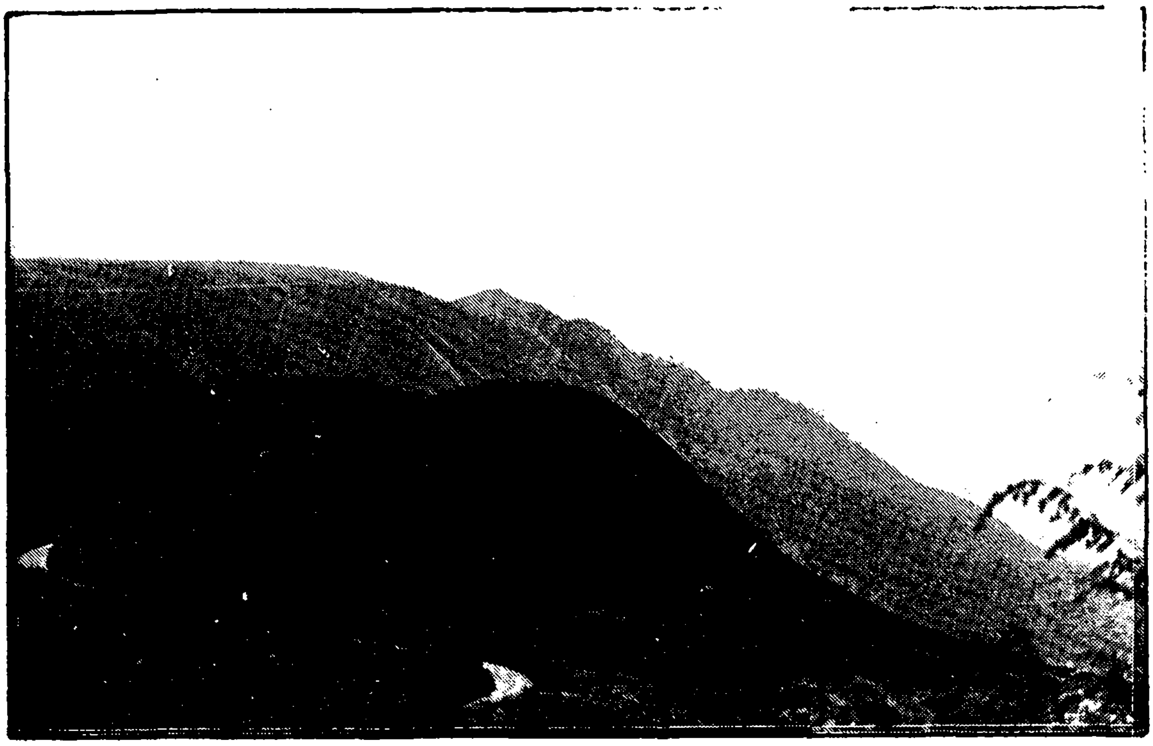


Erosion scarp. The eastern edge of Kipengere Range. The crest of the scarp is the Gondwana Surface, the pediment the post-Gondwana Surface.

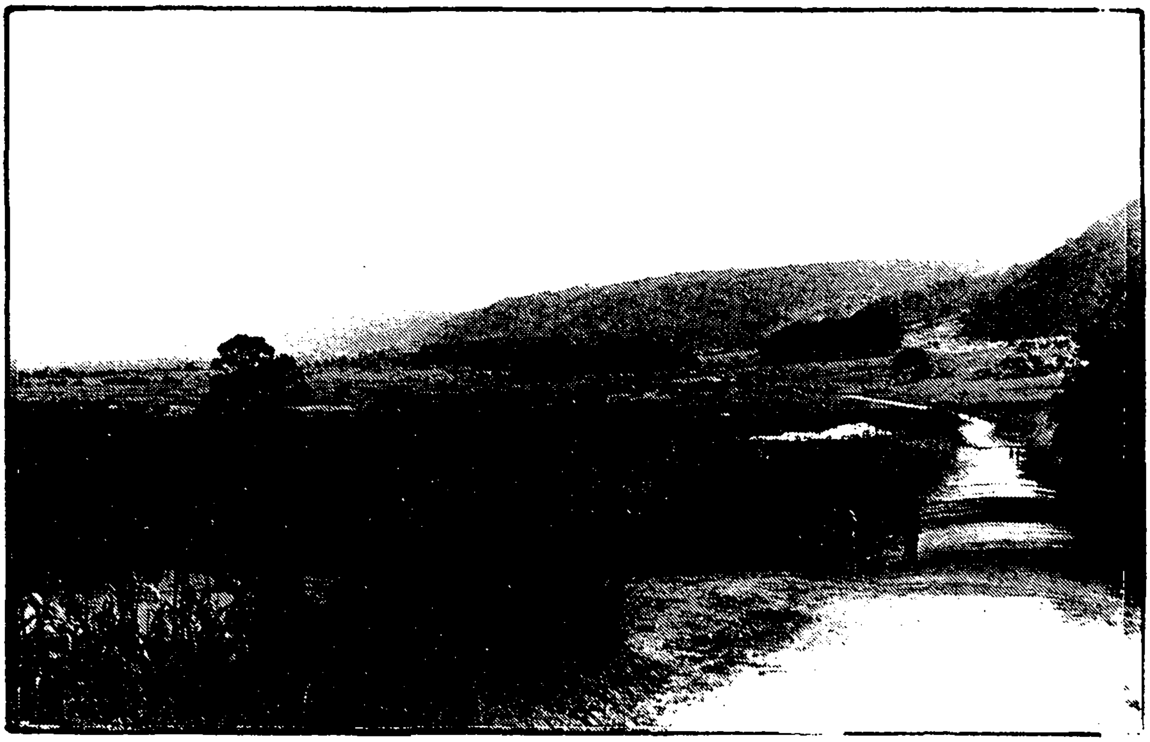


The Songwe scarp seen from the Songwe Valley. The plateau above the rift fault is the post-Gondwana Surface bordering the Mbozi Plateau.

PLATE VIII



The Usangu scarp separating the African Surface from the Usangu Flats.



A fault scarp on the African Surface in Iringa District. Numerous springs emerge along the foot of the scarp.

6.4 Aggradational Land Surfaces

The opposite event to erosion or denudation is sedimentation or aggradation, the process of building up a surface by deposition. Two different aggradational surfaces are present within the regions, the Lake Deposits and the Rungwe Volcanics, both recent in terms of geological age.

6.4.1 Lake Deposits

The lake deposits are found in the Rukwa Trough and the Usangu Flats; both fall within Mbeya Region. Because of their mode of origin, both areas are extremely flat with rivers having eroded deeply into their rather soft deposits, especially in the Rukwa Trough. The Usangu Flats are drained to the east by the Great Ruaha River, while the Rukwa depression forms part of the enclosed Lake Rukwa Drainage Basin.

6.4.2 The Rungwe Volcanics

The Rungwe volcanic deposits cover most of the area between Lake Nyasa and the Mbeya Range. The topography of this area is extremely irregular with the three main eruptive centres Rungwe, Kiejo and Tukuyu, and numerous small explosion craters. The soft volcanic ash is easily eroded, and the area is heavily intersected by deep valleys incised by the large number of rivers present. Nearly all rivers originate as springs, which is an indication of a considerable amount of groundwater in storage throughout the year.

7. HYDROGEOLOGY OF GROUNDWATER DOMAINS

7.1 Introduction

In describing the regional hydrogeology of a large area it is essential to establish a framework in which the groundwater occurrences can be related to the geological, geomorphological and hydrological features of the area.

Several approaches are possible. A framework based on geology has often been successfully used to describe uniform stratiform sedimentary aquifers, while the application of a hydrological framework leads to a rapid understanding of the hydrogeology of a karstic terrain.

In the regions under study, however, no extensive stratiform or karstic aquifers exist. Much of the area (68%) is underlain by a great variety of crystalline rocks of the Basement Complex.

The hydrogeological work demonstrates that the extensive geomorphological land forms have a greater influence on the hydrogeology of the regions than the usually expected geological factors.

The framework chosen for this study, therefore, is based on major geomorphological land forms.

There are several advantages connected to this approach, some of which are:

- The study area is reduced to a few geomorphological units, each with distinct hydrogeological characteristics.
- Aquifers show a uniformity within each geomorphological unit. The aquifers of the Basement Complex are predominantly the lower part of the in-situ weathered rock zone. The aquifer properties are a result of the time during which the rock in question has been exposed to weathering.
- The geomorphological units in the study area are described in the literature. Topographical maps, air photos and satellite imageries can be used to delineate the units accurately.
- A geomorphological classification reflects the geological history of the study area and acts as a connection between geology and hydrogeology.

- The geomorphological units classified as groundwater domains and recognised in this Report, are:
  The Gondwana and post-Gondwana Surfaces
  The African Surface
  The post-African Surface
  The Congo Surface
  The Scarp Areas
  The Karroo System
  The Usangu Flats
  The Rukwa Trough
  The Rungwe Volcanics
  The Alluvial and Colluvial Deposits.
  Of these classified domains only that of the Karroo can be necessarily identified as coinciding with a strict geological subdivision.

7.2 Defining the Aquifers

7.2.1 The Saprolites of the Basement Complex Pediplains

As the major part of the study area is underlain by rocks of the Basement Complex these areas will inevitably have to be investigated and developed as the major source of groundwater supply. It is, therefore, of paramount importance to locate the water bearing strata within this geological environment.

Groundwater in Basement areas occurs mainly in the blanketing in-situ weathered rock mantle, known as the saprolite. A description of the saprolite is not complete without involving the geomorphology of the area, because the time factor is the most important one in developing the in-situ weathered soil profile. The saprolite obtains a more mature state on older rather than younger cyclic land surfaces, and many of the chief properties of saprolite are determind by its topographic site. The weathered zone is thinner and possesses only the lower horizons of the profile on steep slopes, whereas it may obtain considerable thickness on the pediplains where all the elements of the weathering profile are preserved.

A typical saprolite profile, as it may be observed on an anciently planed land surface, is shown in Figure 7.1.

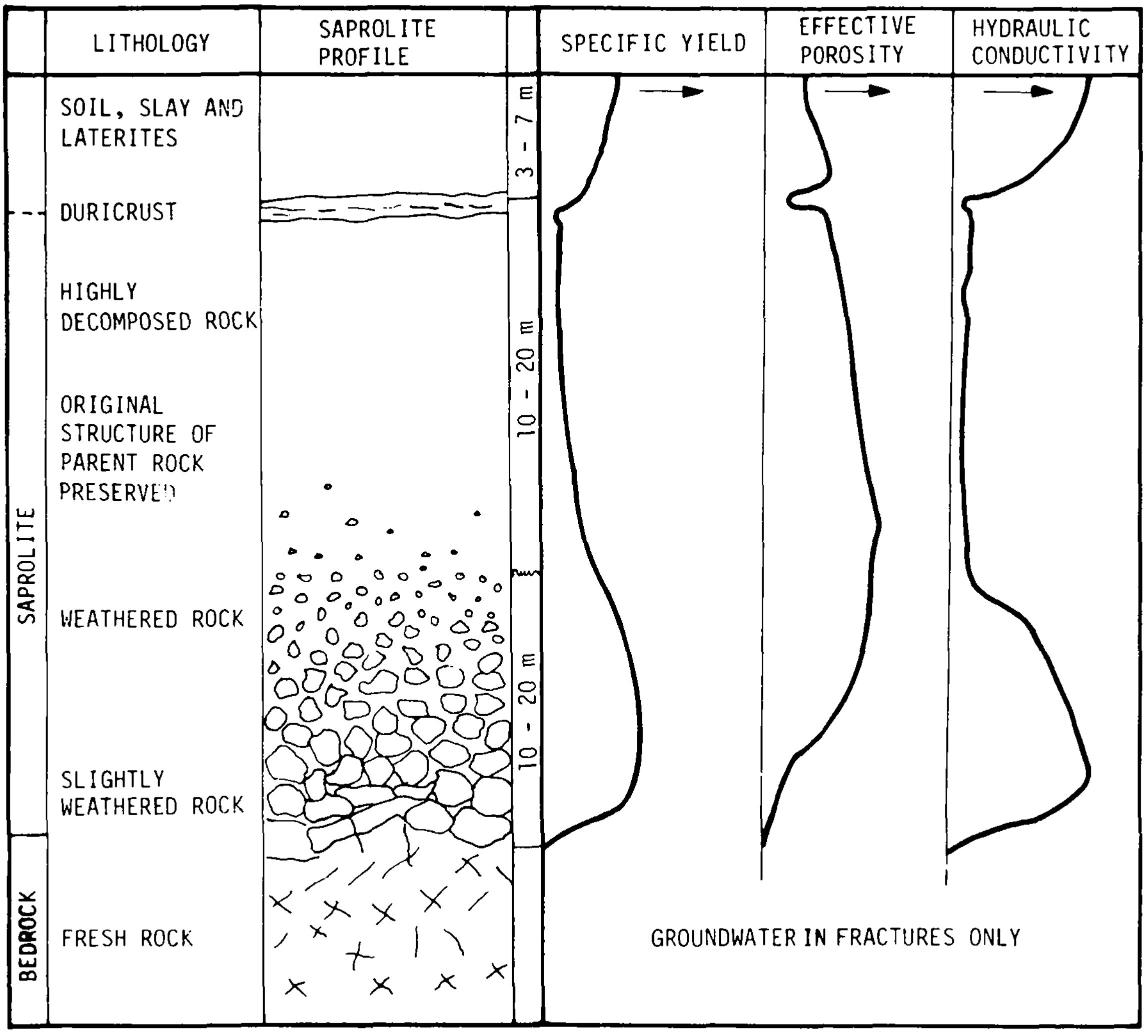


Figure 7.1 A typical saprolite profile and its hydraulic properties as found on an old pediplain.

The relationship between depth and the hydraulic properties are shown schematically. It appears, that the aquifer is the lower zone of the saprolite. As shown in the section on weathering (Chapter 5) different types of parent rock weather down to aquifers which can be expected to have different hydraulic properties. To estimate quantatively the hydraulic characteristics of an aquifer, therefore, knowledge is required of the parent rock and its weathering products.

7.2.2 Scarp Areas

With only the lower horizon of the saprolite preserved on steep hillslopes and because of the steep topography, the hydraulic gradient will be large in these areas. The result, therefore, is a rapid drainage of groundwater, so in areas of pronounced topographical relief, perennial groundwater is expected to be found only in valley bottoms and along foothills. Because of limited saprolite thickness, alluvial deposits, where found, may prove to possess the best groundwater prospects. In general, these groundwater occurrences are found in old river beds, alluvial fans, talus and colluvium in the valleys and along escarpments.

7.2.3 The Karroo System

The continental deposits of the Karroo System consist of sandstone which, according to the drilling results do not weather. Groundwater conditions here should, therefore, be fairly uniform, in the statistical sense with the primary permeability of the sandstone as the limiting factor controlling groundwater abstraction.

7.2.4 Aggradational Surfaces

n the aggradational surfaces the situation is different. In the Rukwa Trough and on the Usangu Flats, groundwater away from the escarpments must be found in the Lake Beds which consist of very fine grained material with a comparatively low permeability. Here special considerations must be applied taking into account the sedimentation of the basins.

The Rungwe Volcanic Province is another subdivision where special conditions prevail. Because of the young age of the extrusives and their resistance to weathering, groundwater here should be found in the volcanic ash, tuffs and pumice which may occasionally reach considerable thicknesses (more than 100 metres).

7.3 The Gondwana and Post-Gondwana Land Surfaces

7.3.1 Physiography

The Gondwana and post-Gondwana land surfaces occupy the higher parts of the study regions (except for the Rungwe volcanic area). Rainfall is high (1000-1600 mm/year) except for the Gondwana land in northern Mbeya (800-1000 mm/year). Some parts lie above the tree line and are characterised by extensive grass cover (e.g. Kipengere Range, Poroto Mountains and the Gofio Plateau). Rain forest is found occasionally, otherwise the vegetation is bush and scattered trees. In the valleys, numerous springs command the growth of small groups of trees.

The population is sparse on the Gondwana and the post-Gondwana land surfaces, except in the Makete District and parts of the Poroto Mountains. The abrupt topography and the frequent outcrop of rocks makes agriculture difficult. Other factors are the remoteness and inaccessibility of much of these areas.

7.3.2 Geology and Structure

The most common rocks are granites and gneisses, but shales and schists do occur. Because of the pronounced topographical relief, the saprolite is thin or non-existing on the slopes, and rock frequently outcrops. On the plateaus proper, however, the saprolite may attain considerable thickness.

The Gondwanaland adjacent to the rift valleys has been subject to intense echelon faulting in Neogene times. Most of this faulting is a reactivation of older faulting. Away from the rifts little faulting has taken place, as is the case in the northern Mbeya Region where the Gondwana Surface differences are a result of lithological competance to erosion and tectonics. Aeromagnetic survey results show a multitude of pre-Neogene faults which, having no surface expression, are virtually impossible to detect by any other means.

7.3.3 Infiltration and Drainage

The drainage of the Gondwana and post-Gondwana land surfaces is controlled by the geomorphological set-up. In dissected and sloping country the majority of discharge is directed by overland flow towards the valley bottoms. The transit time of this type of discharge is prompt and measured in hours.

Interflow plays a minor role on drainage of the strongly sloping hillsides, but becomes of importance on plateau areas and in areas where the slope is less than a critical value which allows for direct infiltration.

The base flow regime is a function of the contributions from cascading springs, seeps, bank storage and artesian discharge, of which the artesian discharge from aquifers may be the smallest part. Springs are very common in the Gondwana and post-Gondwana landscape, and constitute the major discharge contribution during the dry season, rendering most water courses perennial.

It follows that a typical hydrograph of a river draining the Gondwana/ post-Gondwana land surface will have a pronounced difference between peak and minimum flow, the magnitude of which depends on the rainfall intensity. A comparatively slow initial recession follows the rainy season, and a base flow controlled by springs, seeps and to some extent bank storage during the early dry season. During the late dry season the base flow regime is purely controlled by springs.

This is illustrated in Figures 7.2 and 7.3. Figure 7.2 is Station 1RB 4A (Drawing II-1) on the Kitiwaka River as it flows down the escarpment to the Ruhuhu Trough. The catchment area is 2480 km^2, on the post-Gondwana land surface, and the mean annual rainfall 1100 mm/year. The peak discharge based on monthly means is about 20 l/s/km^2, and the mean minimum flow (base flow) is on an average around 1 l/s/km^2. Thus, the *minimum net groundwater recharge increment is around 30 mm/year, or* about 3% of the rainfall.

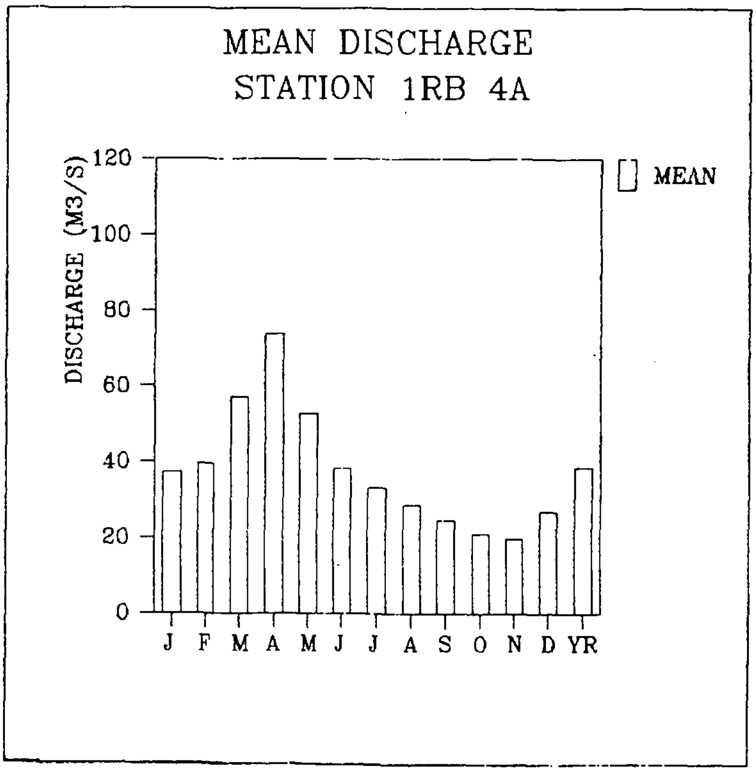


Figure 7.2 Hydrograph of the Kitiwaka River at Station 1RB 4A.

Figure 7.3 is Station 1RC 13 on the Lumbira River as it discharges the Livingstone Mountains to Lake Nyasa. The catchment area of 1414 km^2 is exclusively situated on the post-Godwana land surface, and the mean annual rainfall is about 1500 mm. The peak discharge based on monthly mean values is 54 $l/s/km^2$, and the mean minimum flow around 11 $l/s/km^2$. The minimum groundwater recharge increment accordingly is around 66 mm/year, or about 4% of the rainfall. The recession curve is almost linear from July to October indicating more than one mode of base flow. The same is observed on inspecting the previous hydrograph (Figure 7.2).

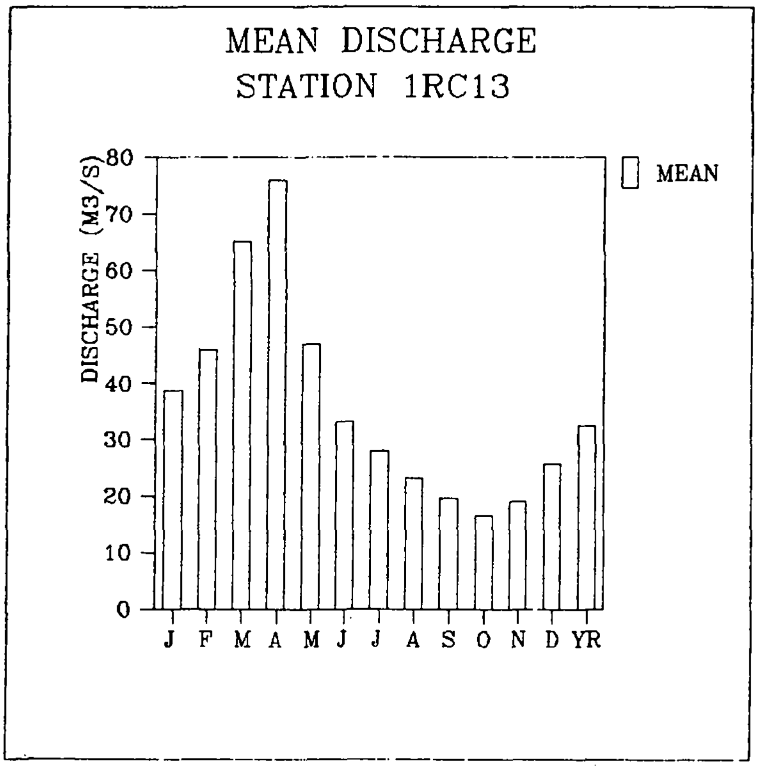


Figure 7.3 Hydrograph of the Lumbira River at Station 1RC 13.

7.3.4 Groundwater Level and Movement

The groundwater movement and level are related to the geomorphology. The groundwater catchments are defined qualitatively by the surface water catchments, but because of topographic and geologic factors the groundwater storage basins are generally much smaller, especially following recession during the dry season.

The groundwater flow is very much directed towards the surface water drainage courses, and steep groundwater gradients are very much to be expected. It follows that groundwater is shallow along the rivers and in the valleys but is located deeply under hills and plateaus.

7.3.5 Yield of Wells

Four wells have been drilled over the post-Gondwana land surface. Of those two wells (57/80 and 68/80 in Mbeya Region) were dry. In one well (22/59 in Iringa Region) the rest water level was 48.7 m.b.g.l. and the yield 0.36 m^3/hr, which from a water supply point of view must be considered a dry well. The fourth well (127/77 in Iringa Region) had a static water level 9.1 m.b.g.l. and yielded 21.2 m^3/hr with a 6.1 m drawdown.

Drilling across the Gondwana and post-Gondwana land surfaces is considered difficult and great care should be taken in siting wells. Siting can be based on geomorphological interpretations. Drilling is recommended only in the lowest part of valleys, and even this might prove unsuccessful if there are topographically lower nearby valleys.

Because of the topographical relief, alluvial deposits in the valleys are mainly coarse. Saprolite is seldom present in great thickness, because of erosion. Thus, the only places that offer good groundwater prospects are the valleys where alluvium or the weathered zone can yield water. Drilling depths will typically be 30-40 metres. Drilling to greater depth will mean drilling in fresh rock with only the prospect of striking fractures that may yield water. However, due to the numerous springs there usually is little problem in finding water. The present water supply in these areas is mainly from these springs, and it seems that such sources which are mostly perennial and reliable in terms of yield will continue to offer the most useful groundwater source across the Gondwana and post-Gondwana land surfaces. Only where springs or perennial streams are absent is it recommended that a groundwater development by drilling should be considered.

7.3.6 Groundwater Chemistry

Little is known of the chemical quality of groundwater over the Gondwana/ post-Gondwana Surfaces. However, it may be expected that the water quality in the alluvial deposits in the valleys will be good and of a comparable quality to that of known springs, the quality of which is generally extremely good.

7.4 The African Land Surface

7.4.1 Physiography

The African land surface is the most extensive erosion surface within the study regions. In remote areas where population is scarce and the land uncleared, the surface is covered by miombo forest. This is replaced by evergreen thicket on the highest parts. Large parts of the surface, however, are now under cultivation.

The variation in rainfall over the large area covered by the African Plateau is considerable. Parts of northern Iringa Region have a mean annual rainfall below 400 mm, and the climate borders a semi-arid one. In Njombe, Mufindi and Iringa Districts rainfall can exceed 1600 mm annually. In the north of Mbeya Region the mean annual rainfall is around 900 mm which is also the case in most of Ruvuma Region, except for the western mountainous part where rainfall occasionally exceeds 1600 mm a year.

7.4.2 Geology and Structure

Except for the areas underlain by Karroo deposits, the African Surface is underlain chiefly by rocks of the Basement Complex which are divided into two main groups, granites and gneisses. As these two groups of rocks are composed of the same basic minerals in varying quantities, the saprolites derived from the parent rocks will have very similar geohydraulic properties.

This saprolite offers the most reliable and persistant aquifer horizon across the African land surface. The resultant weathering renders the exact lithology of the parent rock less important in the hydrogeological context. The degree of weathering is a function of the geomorphological history of the locality and will have a critical control over the water bearing characteristics of the saprolite.

Figure 7.4 shows the saprolite thickness frequency distribution across the African Surface. The saprolite is generally 30-60 metres thick. In 70% of the cases the saprolite thickness is less than 50 metres.

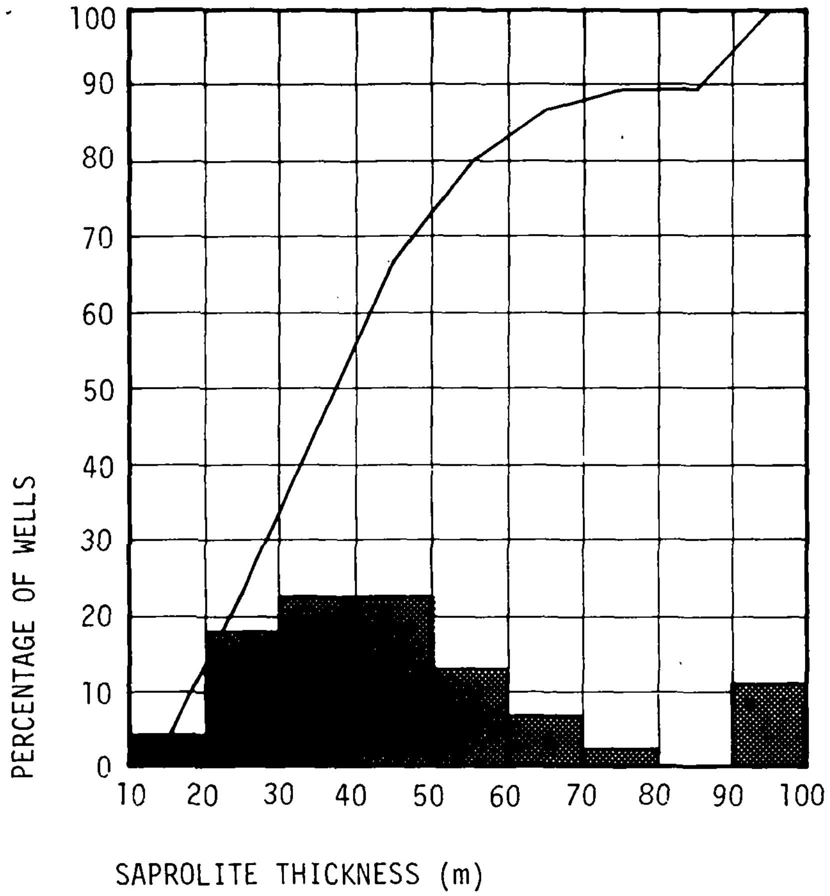


Figure 7.4 Saprolite thickness frequency distribution across the African land surface. Data from 45 wells.

Because of the extremely long denudational period of the African erosion only major faults and structures have a surface expression and can be readily identified. Minor faults of old age have now lost their topographical significance, and in many cases they are revealed only by the drainage pattern they control. Their existance, though, is confirmed by aeromagnetic surveys.

Faults and fractures, however, are believed to be of minor importance on the African Surface because the weathering will often have destroyed the fracture permeability, and a systematic search for fractures in connection with faults will mostly prove fruitless because the weathering process may have destroyed the traces and hydraulic benefit. The faults and fracture systems that can be readily seen, often have been recently rejuvenated and there are high chances that drilling will strike mineralised water, (e.g. north-east Iringa Region). Many faults shown across the African Surface on the geological quarter degree sheets are inferred from linear courses of rivers.

7.4.3 Infiltration and Drainage

Across the generally extremely smooth African erosion surface the discharge pattern is that of a plateau area.

The infiltration capacity of the top soil is good, and this together with the flat topography reduces overland flows when compared to more hilly terrains. The African land surface is chiefly stable, and rivers have mostly reached a mature state with little erosion and a low sediment transport.

Interflow is an important part of the river discharge with a rather large time scale. In areas with sufficient rainfall, the main rivers are perennial with dry-season run-off consisting of base flow derived from mainly springs and seeps. Bank storage is important, especially during the early dry season. Artesian discharge is uncommon along the rivers in the upland areas but may be common along the lower course.

A typical hydrograph of rivers draining the African Surface, therefore, should have moderate differences between peak and minimum flow, and the recession of the base flow regime should be relatively long.

This is illustrated in Figure 7.5 which shows the hydrograph of the Little Ruaha River at Station 1KA 2A (Drawing II-1). The catchment area is 2920 km^2, solely on the African land surface. The mean annual rainfall in the catchment is 950 mm. The hydrograph shows a moderate peak flow and a long recession period from April-May to December. The peak discharge based on monthly mean values is 13 $l/s/km^2$ and the minimum flow about 2 $l/s/km^2$, corresponding to a minimum annual groundwater recharge increment around 65 mm, or about 7% of the rainfall.

As an example of a catchment with a comparatively low rainfall the hydrograph of the Huhuni River at Station 1KA 23A is shown in Figure 7.6. The mean annual rainfall is about 800 mm, and the catchment area is 803 km^2 on the African Surface. The peak discharge based on monthly means is about 5 $l/s/km^2$, and the mean minimum flow as low as 0.26 $l/s/km^2$, corresponding to a minimum groundwater recharge as low as 8 mm/year, or 1% of the rainfall. Although this catchment may be near an extreme, the basic characteristic of a catchment on the African land surface is preserved: a smooth and long recession period.

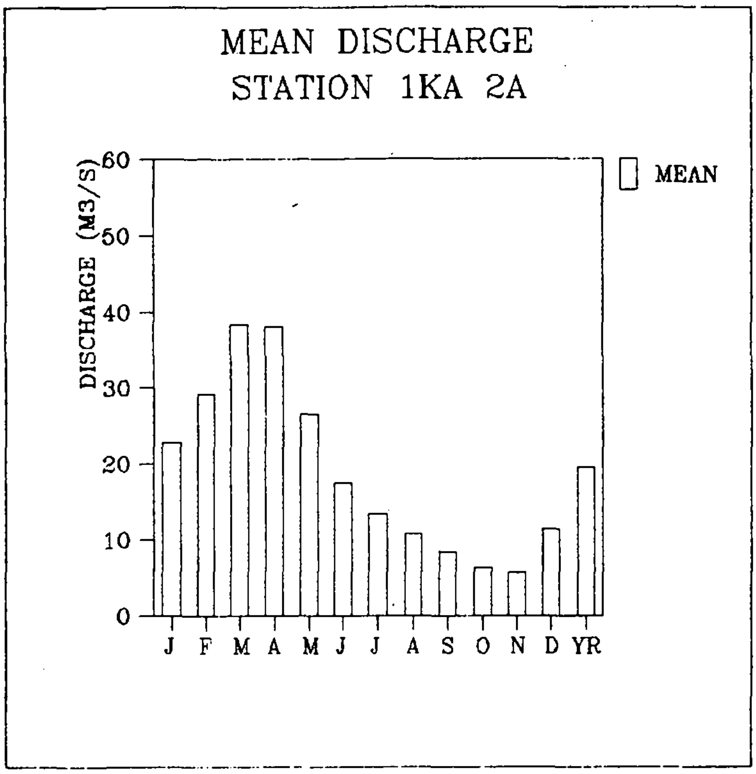


Figure 7.5 Hydrograph of the Little Ruaha River at Station 1KA 2A.

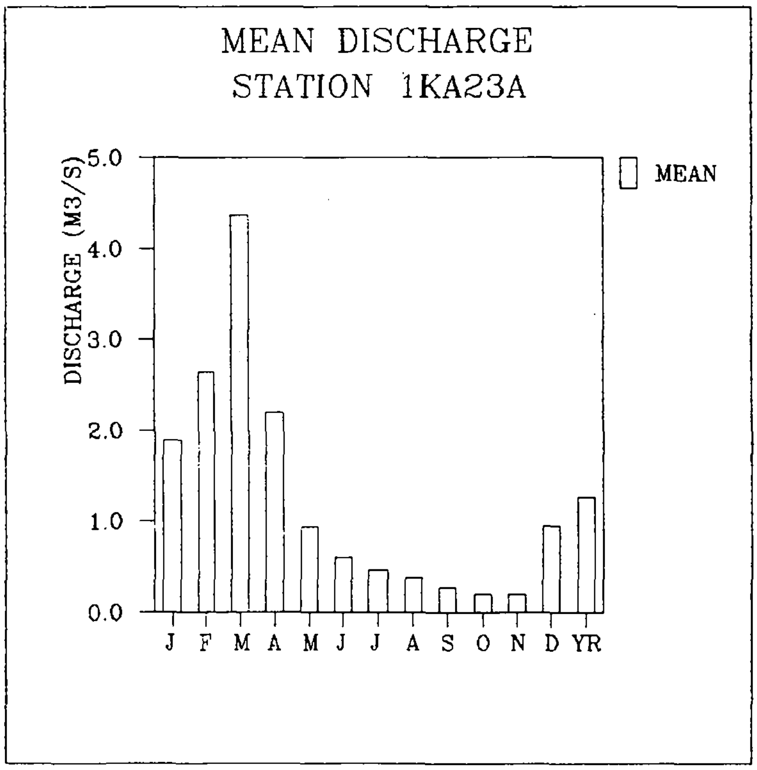


Figure 7.6 Hydrograph of the Huhuni River at Station 1KA 23A.

The drainage found across the African land surface shows a variety of patterns. In areas affected by recent tectonic activity, trellis and rectangular drainage (Volume 10 A, Appendix 5) is often observed (e.g. the Ufipa Plateau in Mbozi District, Mbeya Region). In tectonically undisturbed areas the drainage is dendritic as shown in Figure 7.7. (cf. Volume 10 A, Appendix 5).

Dambos

A very characteristic feature on the African erosion surface is the occurrence of dambos. They form the upper watershed drainage pattern and bear evidence of the underground drainage pattern as well, since they are situated in depressions. The occurrence of dambos in the study regions is shown on Drawing II-12, and a typical dambo pattern is shown on Figure 7.7. They are grass-covered almost treeless flat areas following river courses. Seen from the air they have a tree-like appearance and are most easily recognised in forest areas. They are areas of sheet flood during the rainy season. During the dry season no well defined river course can be seen.

Their mode of origin is not completely understood, but since they are found chiefly on the African Surface, time must have a controlling influence together with the topography.

It appears from Figure 7.7 that the dambos start near the headwaters of the river and typically terminate quite a distance further downstream. It follows that there must be a critical relationship between the slope of the land, which in turn affects the energy level of the surface run-off, and the formation of dambos. Therefore, the upper formation of the dambos is due to mass waste sheet washed down from the gently sloping hills. Field observations show that run-off in dambos occurs as relatively slow moving sheet flows. Such flows have little mechanical erosion capacity, and hence dambos are typically extremely stable geomorphological features. When land slopes steepen further downstream from the headwaters mechanical erosion can take place, and the dambos stop at a well marked nick point.

Under favourable circumstances the hill slope and the slope of the river may result in the formation of dambos again downstream.

A cross section through a dambo may, therefore, be like shown in Figure 7.8.

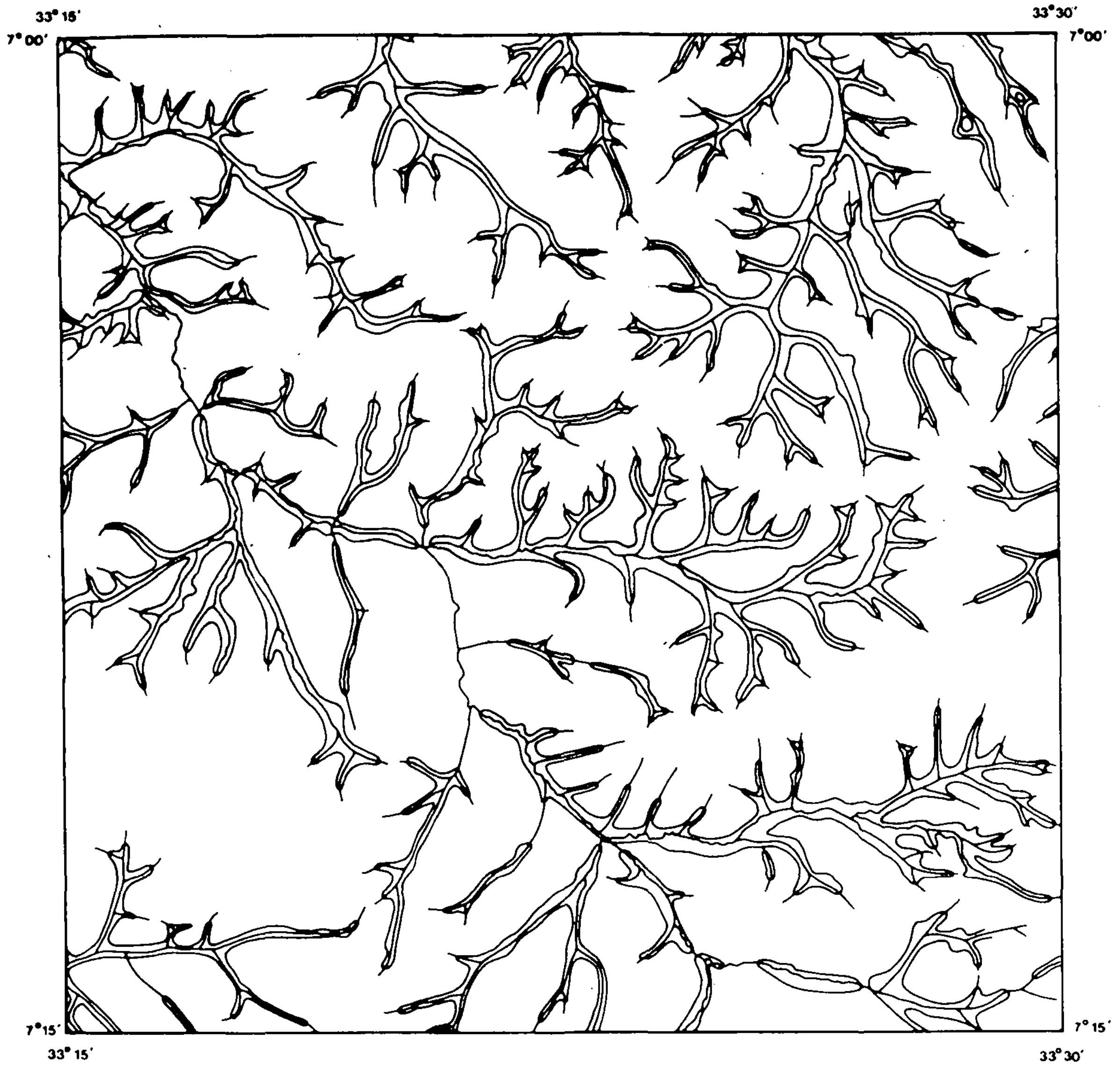


Figure 7.7 A typical dambo pattern as found on the African land surface. Chunya District, North Mbeya Region, showing dendritic drainage.

The process described above can only happen in a geomorphological environment where chemical rather than mechanical weathering and erosion have taken place for a considerable time, that is on a mature pediplain with gentle topographical relief. This is the reason why the dambos are so characteristic for the African erosion surface. Across the post-African Surface the topography is generally too pronounced and the weathering not deep enough to produce a similar effect.

Dambos are characteristically more common in areas which have been less disturbed by tectonic activity. Therefore, dambos are very common in

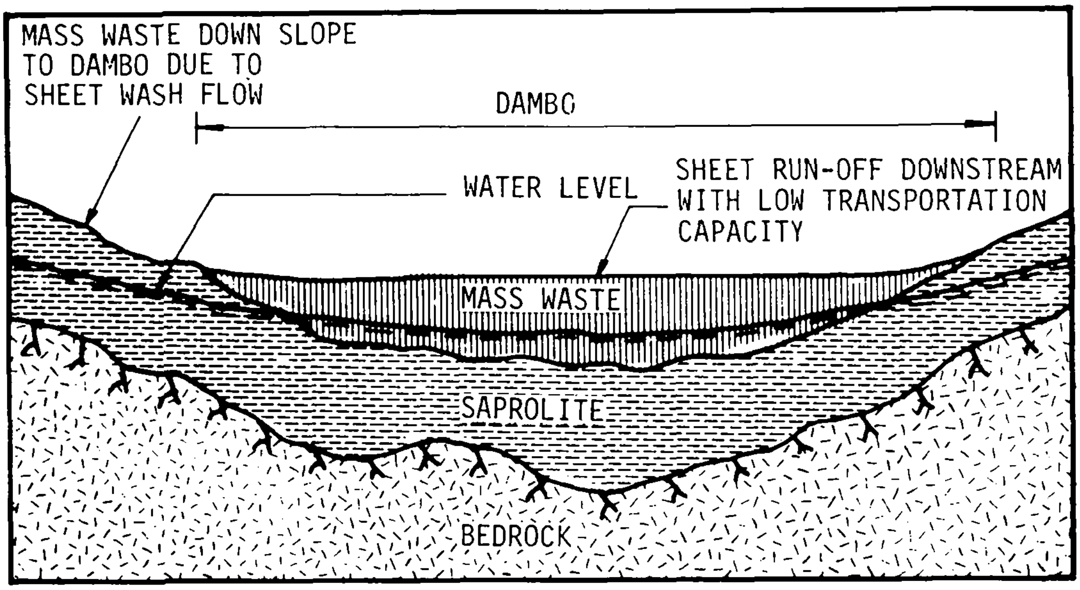


Figure 7.8 A schematic section through a dambo.

the tectonically stable northern Mbeya Region. In central Iringa Region, however, in the area along the Great North Road, frequent rejuvenation of old faults combined with consequent rejuvenation of streams has destroyed the dambo pattern. The same is the case in the Basement Complex in Mbinga and Songea Districts in Ruvuma Region.

In a tectonically undisturbed area the drainage pattern and, consequently, the dambo pattern is dendritic, as it appears from Figure 7.7.

7.4.4 Groundwater Level and Movement

Data on the groundwater levels across the African land surface are obtained from existing wells and wells drilled by the Consultants. Generally, water is struck in the lower part of the saprolite, and the water level rises closer to the surface revealing confined conditions.. A secondary water table is normally encountered in the upper clayey part of the saprolite. This water body is rather stagnant due to the low permeability of the clay, but it provides leakage to the main lower aquifer in the in-situ weathered rock.

Figure 7.9 shows the frequency distribution of water levels in wells across the African Surface. The water level in the wells rises to a comparatively shallow depth below ground. 50% of the wells are found to have standing water levels less than 4 metres below ground, and for 70% of the wells the figure is 6 metres.

Less than 10% of the wells have water levels deeper than 20 m.b.g.l. These wells are all situated in highly faulted areas and have penetrated the fractured rock, where drainage is unpredictable. As the majority of the data presented in Figure 7.9 is from wells drilled for water supply purposes for villages situated along or near the surface water divides, the general depth to water in such areas can be assumed to be less than 8 metres. Water levels should be generally less than 4 metres below ground lower down the valley slopes and in or around the dambos.

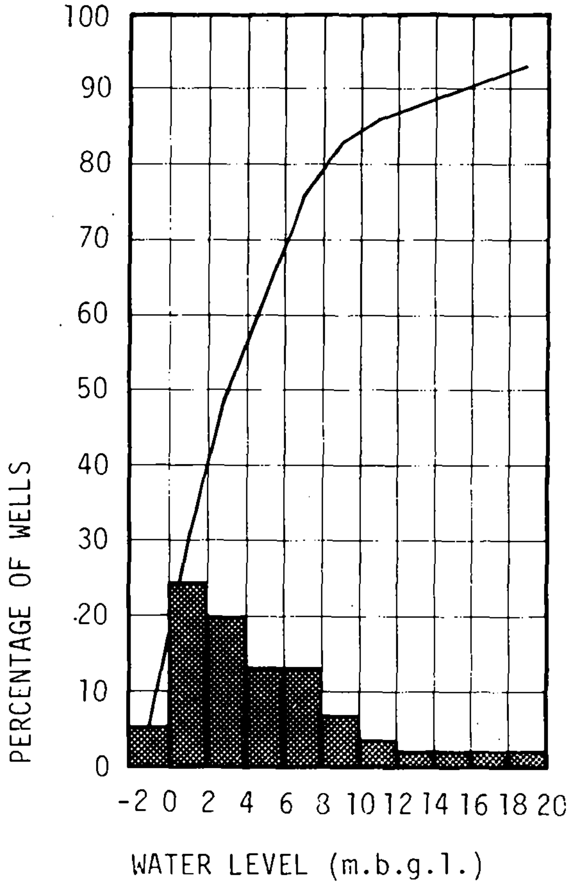


Figure 7.9 Water level frequency distribution (in metres below ground level) in wells across the African land surface. Data from 58 wells.

The standing water level, therefore, reflects the variations of the topography in a damped fashion, and groundwater movement is controlled by the topography. Groundwater flows are from the watershed areas towards and along the depressions to the point where it discharges to the rivers as artesian groundwater along their lower stretches, or as springs or seeps.

There are no long term records of the water level variations in wells within the study region. The water level variations in BH No. 113/80 (MS 1) at Nkhangamo, Mbozi District, which was monitored for one year, are shown in Figure 7.9. The well was drilled by the Auger rig, and drilling was stopped in the weathered rock at the top of the productive part of the saprolite. The well is situated very close to a water divide.

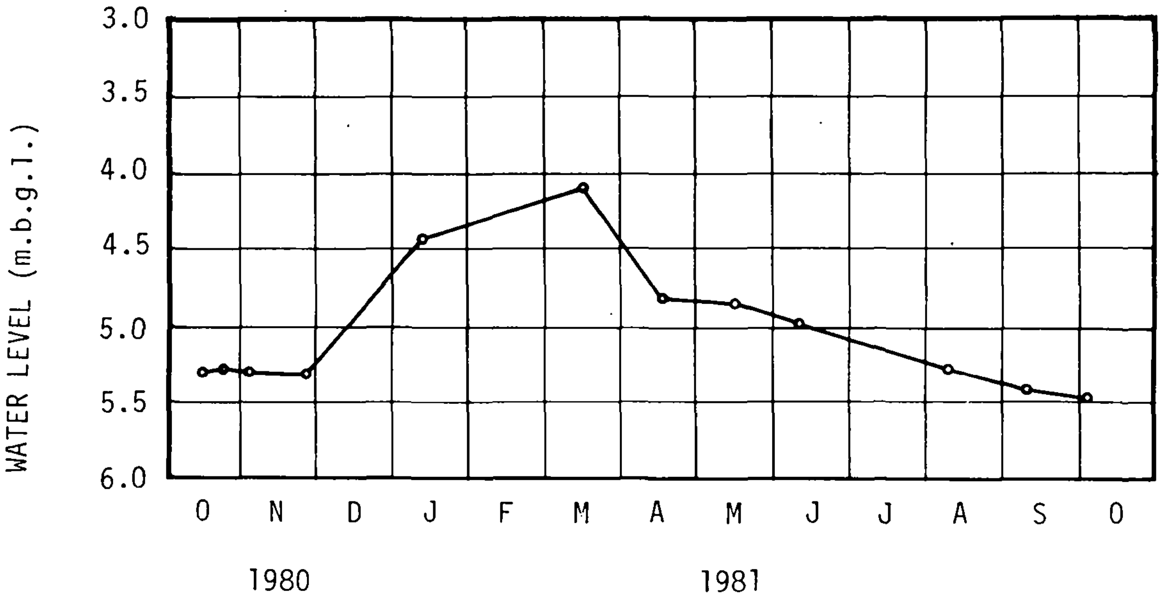


Figure 7.10 Water level fluctuation in BH.No. 113/80 (MS 1), Nkhangamo, Mbozi District, Mbeya Region.

The annual fluctuation, about 1.4 metres, seems to be less than would be expected. The water level variations coincide with the rainy season reflecting groundwater recharge by infiltrating rain.

Experience from neighbouring countries shows that the water level in the lower saprolite across the Basement Complex may generally vary between 2 and 4 metres over the year, depending on the topographical siting and the local rainfall. Fluctuations are larger in the watershed areas than in the depressions and, further, they are proportional to the magnitude of the net recharge.

7.4.5 Yield of Wells

Across the African Surface 68 wells have information on drilling depth, 51 have reported yields, and 38 of the latter wells have drawdown records.

The drilling depth frequency distribution is shown in Figure 7.11. 60% of the depths are less than 70 metres, and comparing Figure 7.11 with the recorded saprolite thicknesses (Figure 7.4) it is evident that the saprolite is the common productive aquifer horizon.

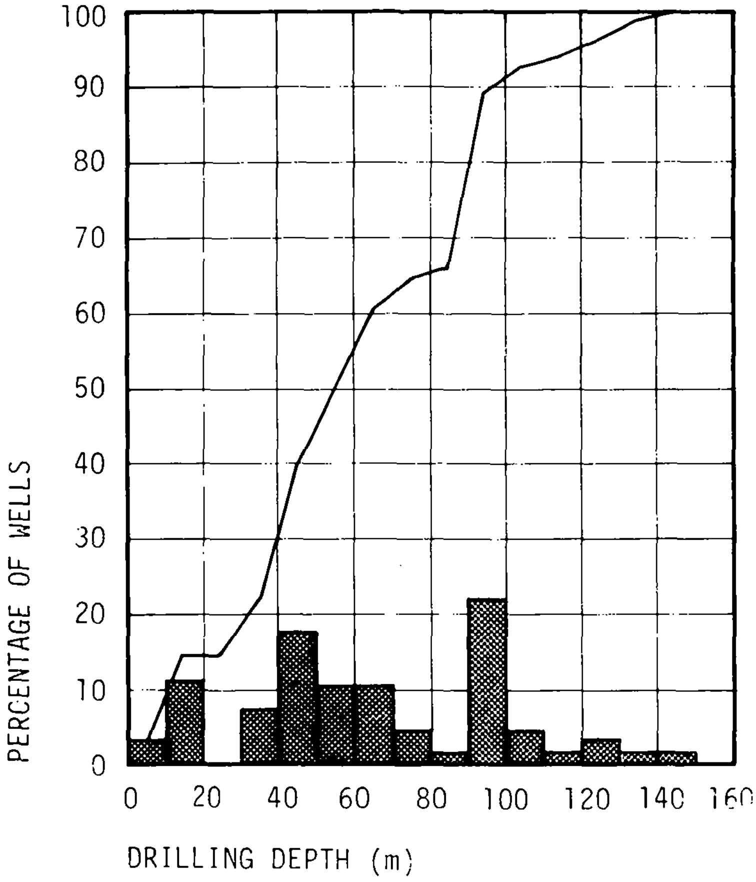


Figure 7.11 Drilling depth frequency distribution across the African land surface. Data from 68 wells.

Wells shallower than 20 metres can in most cases be considered abandoned because of drilling difficulties. A relatively large proportion of the wells (14) are drilled to between 90 and 100 metres (300 feet). To some extent that can be explained by recorded saprolite thicknesses of that magnitude (5 wells), but it seems that 300 feet is a drilling depth based on rule of thumb experience, probably because this depth was found to ensure a successful well in most cases. That 300 feet is a depth of preference becomes more evident on the post-African Surface, where the saprolite thickness in no cases exceeds 80 metres (Section 7.5).

To investigate the relationship between depth and yield, these two parameters have been plotted against each other in Figure 7.12.

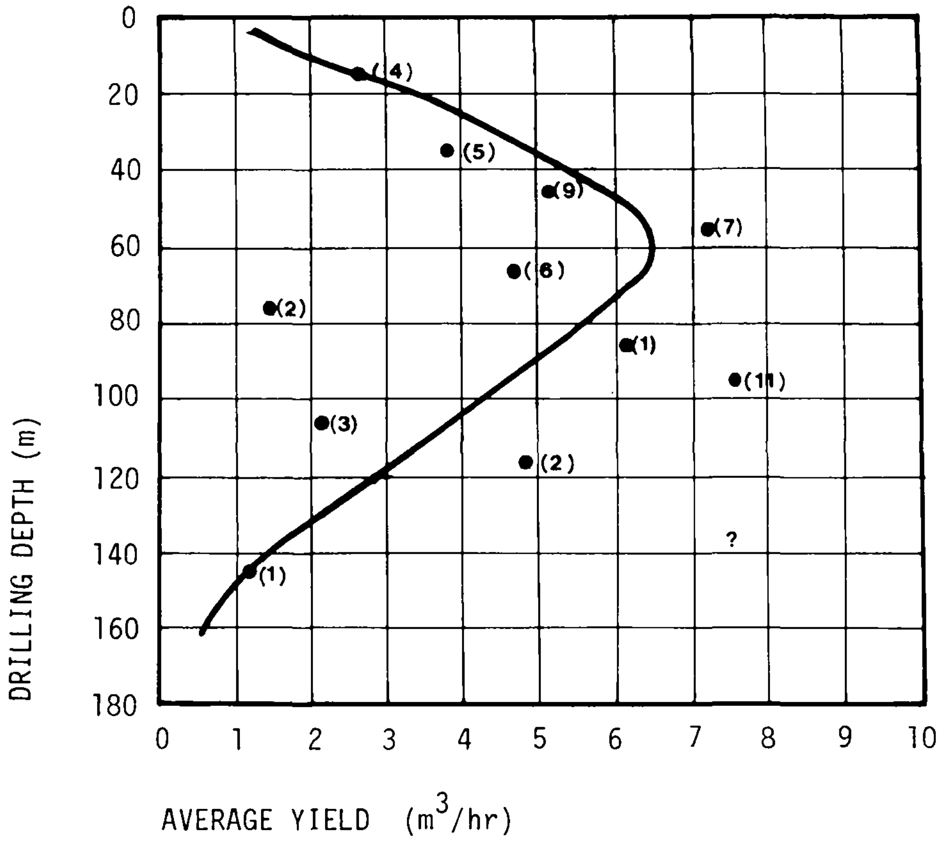


Figure 7.12 Average yields versus drilling depth for wells across the African land surface. The numbers in brackets denote the number of wells within each 10 m interval of depth.

The graph shows that the larger yields are obtained from wells drilled to depths ranging from 50 to 70 metres. The maximum average yields are obtained from the interval 90-100 metres, but these yields are most probably obtained from the saprolite and not from the lower 30-40 metres of the borehole. The economic drilling depths on the African Surface, therefore, would in most cases not exceed 60 metres, and the range of average yields from successful wells would be 4-7 m^3/hr.

It should be noted that unsuccessful boreholes are not included in the analysis because it seldom appears from the records why the wells have no reported yields. Some wells have struck water, but no information is given on the water level depth or yield. The fact that no yield is reported is not equivalent to assuming that the borehole is dry.

Dambos are generally not chosen for drilling by tradition, but since the dambo depressions are synonymous with the groundwater drainage pattern, wells drilled here are expected to have yields exceeding the ones shown in Figure 7.12. The range of average yields here would probably be 5 to 10 m^3/hr.

The hydraulic performance of a well is expressed by its specific capacity, that is the well yield divided by the drawdown caused by pumping. The specific capacity frequency distribution of wells across the African Surface is shown in Figure 7.13. It appears that most of the 38 wells analysed obtain their yield from the saprolite, and thus the graph mainly shows the specific capacity of wells completed in the in-situ weathered rock.

The graph in Figure 7.13 shows that 50% of the wells have a specific capacity of larger than 0.17 m^3/hr/m, and for 70% the figure is 0.08 m^3/hr/m. Allowing for 20 metres of drawdown the corresponding yields are 3.4 and 1.6 m^3/hr, respectively. If such wells were equipped with handpumps, which can yield up to 1 m^3/hr, the drawdown would on an average be about 8 metres. Adding the water level depth, water should be lifted 11-14 metres, so 40-50 m deep holes equipped with handpumps offer a technically feasible solution to abstract groundwater for village supplies across the African erosion surface.

7.4.6 Aquifer Hydraulic Parameters

Across the African Surface, 19 controlled pumping tests have been carried out on existing wells drilled into the rocks of the Basement Complex. Data from 13 of these were of a sufficiently good quality to allow for interpretation by either the type curve method or the straight line method. Data from six wells drilled by the Consultants have also been analysed.

The results of the interpretations are shown in Table 7.1. The transmissivity of the aquifers is within the range 2.0-11.0 x 10^{-5} m^2/s, which accounts for the comparatively low specific capacities obtained.

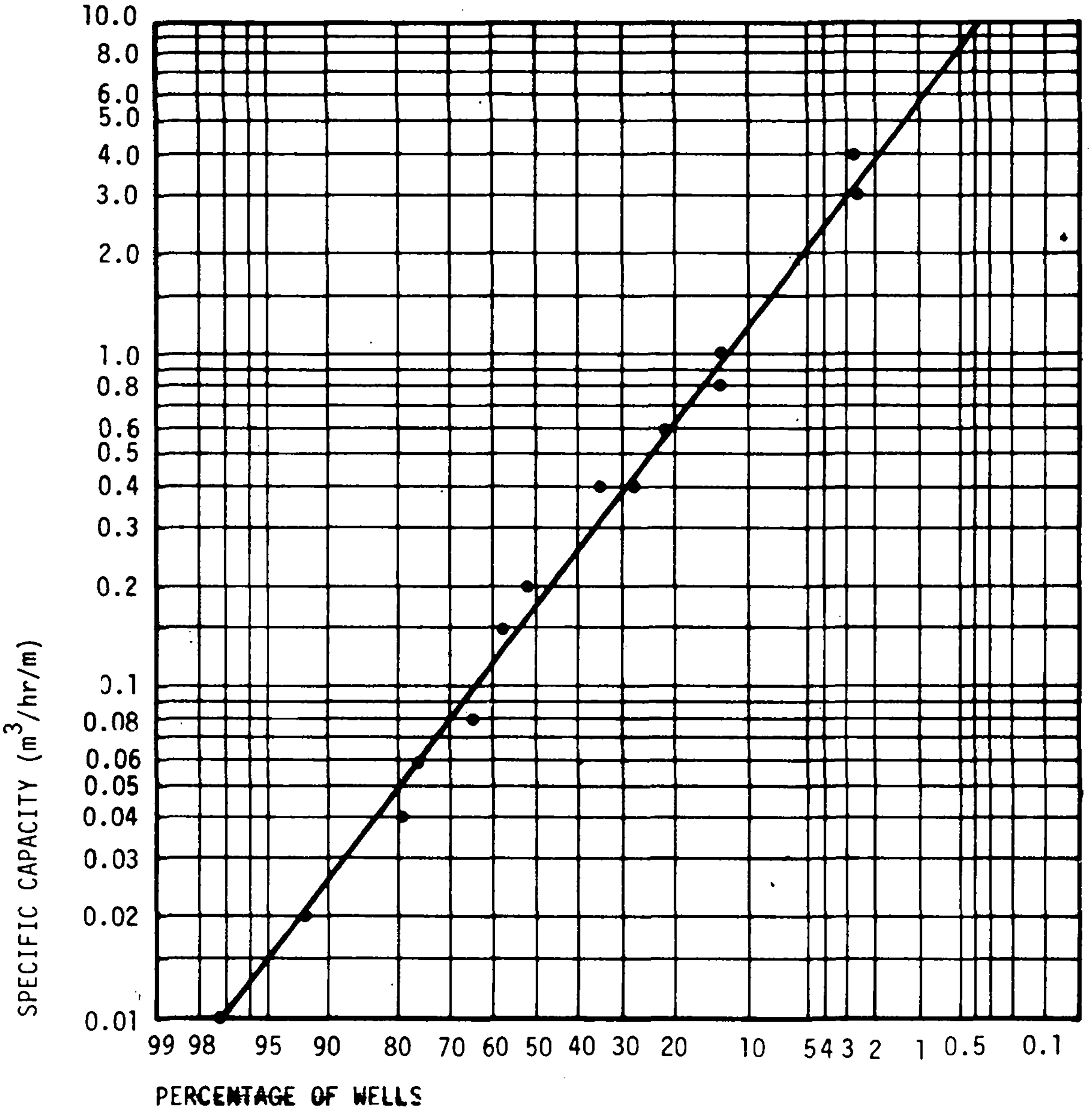


Figure 7.13 Specific capacity frequency distribution for wells across the African land surface. Data from 38 wells.

Theoretically, the specific capacities and the transmissivities should be proportional, except for a weak variation with the diffusivity T/S. The scatter of data points can be explained by the effects of well losses, well damage, etc.

The relationship between the calculated transmissivities and the specific capacities is shown in Figure 7.14, and is found to be $T = 8.5 \times 10^{-5} Q/s_w$ m^2/s. The scatter of the data points is moderate which shows

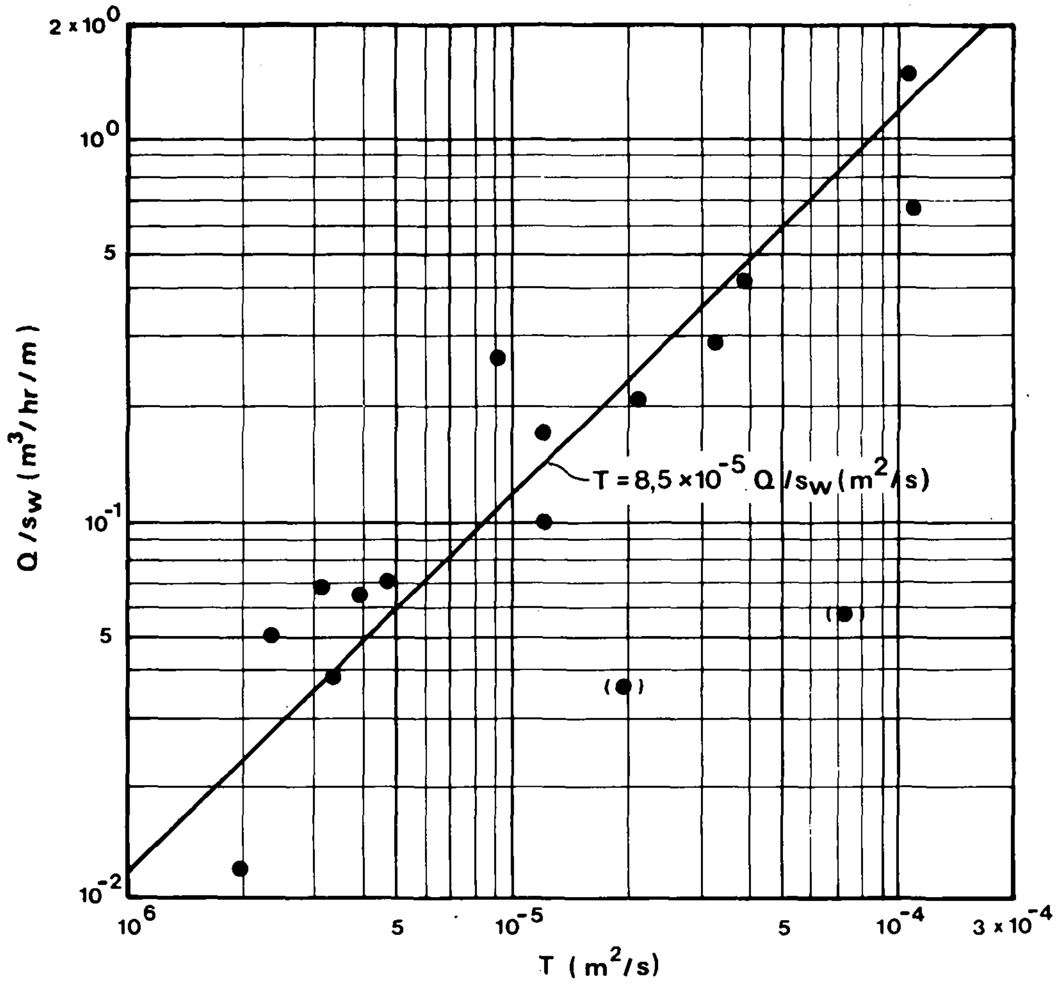


Figure 7.14 Relationship between specific capacities and calculated transmissivities for wells across the African land surface.

that the tests have been carried out in a satisfactory way, and that data are influenced only moderately by the effects mentioned above, mainly due to the low yields.

The storage capacity of the aquifers expressed as $r_w^2 S$, r_w being the effective radius of the well, is quite large, the only explanation being that the effective radius of the well is large, in the order of magnitude of several metres. The value of $r_w^2 S$ in a granular artesian aquifer would normally be around 10^{-5} m^2, but the range observed here is 1.5-160 x 10^{-3} m^2, the larger figure reflecting water table conditions.

BH.No.	$T \times 10^5$ (m^2/s)	$r_w^2 S \times 10^3$ (m^2)	$r_w^2 P'/m' \times 10^6$ (m^2/s)	Q/s_w ($m^3/hr/m$)
6/66	4.0	11.0	-	0.43
118/71	0.35	8.4	-	0.039
13/76	0.24	7.3	-	0.05
29/76	2.1	21.0	-	0.21
54/76	0.20	11.0	-	0.012
67/76	0.92	1.5	-	0.27
70/76	4.0	6.5	-	0.43
216/76	0.48	7.6	-	0.07
217/76	1.2	3.6	-	0.17
232/76	1.2	11.0	-	0.10
247/76	11.0	1.5	-	0.60
126/77	0.83	29.0	33.0	-
130/77	1.7	160.0	38.0	-
2/81	11.0	-	-	1.4
3/81	0.32	2.7	-	0.067
76/81	2.2	3.4	-	0.035
262/81	3.4	-	-	0.29
263/81	7.6	-	-	0.056
276/81	0.39	43.0	-	0.064

Table 7.1 Aquifer hydraulic properties calculated from type curve or straight line method. Data from wells across the African land surface. Symbols used are explained in Volume 10 A, Appendix 1, Chapter 5.

The leakage coefficient expressed as $r_w^2 P'/m'$ shows a similar behaviour. It is found to be 3-4 x 10^{-5} m^2 /s. Although some inaccuracy may be connected to the calculation of the actual value, this possible inaccuracy cannot explain a deviation of 2-3 orders of magnitude from the expected values. The effective radius of the well has some influence, but the main reason is believed to be that the upper part of the saprolite from where the leakage originates is extremely unconsolidated and releases large amounts of water upon lowering the hydrostatic pressure.

According to Carrol (1970) it is generally found that rocks weather without volume change, and some researchers tend to believe that swelling may occur. This results in consolidation and consequently release of water during pumping.

Inspection of the drawdown curves (Volume 10 A, Appendix 2) reveals that a steady state in cases of leaky aquifers is obtained generally within 100 minutes of pumping, which lends support to the extraordinary amount of leakage observed.

It should be observed, however, that the steady state condition referred to is a pseudo or quasi-steady state condition which lasts as long as there is water available for leakage in the upper strata. When this source starts to become exhausted further drawdowns will occur, and the long term state will start. This long term situation will operate at a non-steady state until an independent source is reached which may eventually provide a true steady state. The source in question may be a large perennial river, a swamp, or a lake.

7.4.7 Groundwater Chemistry

Because of the mature state of the African Plateau the groundwater has generally obtained a state of chemical equilibrium in which the transformations from one groundwater type to its ultimate stable type has been already achieved. The iron and manganese content is normally below the maximum permissible, fluoride also is generally found in acceptable quantities.

This situation may be reversed in areas influenced by Neogene tectonic activity. Here groundwater is often found to be locally polluted by juvenile water issuing from fractures and fissure zones. Such areas are typically following the escarpments separating the African Surface from the Rift Valley floors, e.g. the Ruaha Valley Escarpment and the escarpment separating the Msangano Trough from the Mbozi Plateau (cf. Chapter 10).

To conclude this Section, the data presented above demonstrate that the aquifer across the African Surface is the deeply in-situ weathered rock, the saprolite, and that groundwater is available in adequate quantities for rural domestic supplies. Since the occurrence, thickness, and water bearing qualities of this saprolite are controlled by weathering, and weathering is explained in terms of geomorphology, all available data lead to the conclusion that geomorphology is the key to the description of the hydrogeology, not only on the African Surface but on other erosion surfaces as well.

7.5 The Post-African Land Surface

7.5.1 Physiography

Areally the post-African land surface is the second largest geomorphological unit within the regions. Except where cultivated, the land surface is covered by bush forest which gives place to thick thornbush in low-lying areas. Only in few places does the post-African pediplain appear as a continuous mature erosion surface, otherwise it forms a dissected and topographically irregular terrain.

The rainfall variation across the post-African Surface is large. Along the flank of the Kilombero Valley the land surface benefits from the orographic effects of the Mufindi and other highlands, giving a mean annual rainfall around 1200 mm. In the Ruaha Valley rainfall is low. The climate here is close to semi-arid with less than 400 mm rainfall in the area around the Ruaha National Park. Vast areas here are infested by tsetse flies. Most tributaries to the Great Ruaha River in the valley are non-perennial.

7.5.2 Geology and Structure

The post-African land surface found in the regions is atypical as compared to most other areas in Central and East Africa. This is due to the fact that the post-African land surface in Iringa, Ruvuma, and Mbeya Regions all fall within or flank the Quarternary Rift Valleys. The Neogene rift faulting has dissected the older pediplains so they now appear in places more like scarp areas than eroded land surfaces. Rejuvenation of rivers has taken place to a large extent, so mechanical erosion is now very pronounced, and the broad valleys which are so characteristic on the African land surface are seldom seen.

Because of the faulting and the resulting change of base level of erosion, alluvial plains and fans of Neogene age are common, especially in the Ruaha Valley.

The rocks underlying the in-situ weathered rock mantle across the post-African land surface are exclusively granites and gneisses of the Basement Complex. These rocks should have a fairly uniform depth of weathering across the land surface, variations, when found, being due to mainly rainfall variations and Neogene erosion. Because of the younger age of the pediplains, the saprolite thicknesses are less than those found across the African Surface.

The saprolite thickness frequency distribution is shown in Figure 7.15. In 50% of the cases the saprolite thickness is less than about 20 metres compared to 40 metres across the African land surface. As explained later, this has a considerable bearing on the reliability of the saprolite as an aquifer across the post-African land surface.

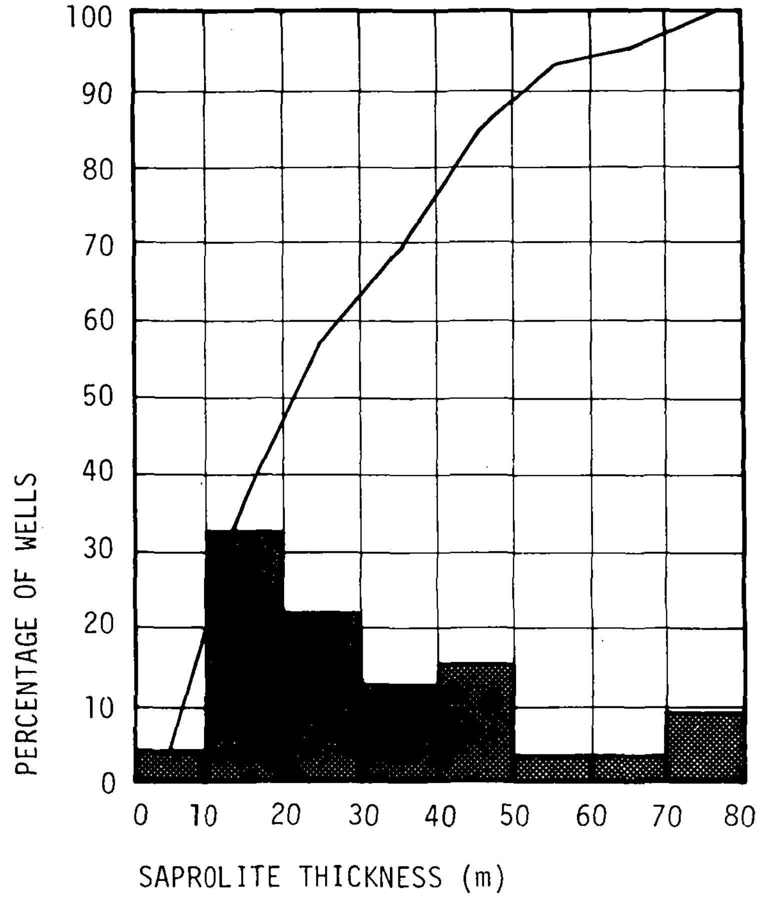


Figure 7.15 Saprolite thickness frequency distribution across the post-African land surface. Data from 33 wells.

7.5.3 Infiltration and Drainage

Because of the irregular topography, the actual groundwater recharge varies considerably across the land surface. In the well pedimented areas the discharge pattern is that of a pediplain plateau area, and the land surface is comparatively stable. The general picture, however, is that erosion is very active. Where the surface has been recently rejuvenated, rivers run in narrow valleys and carry a large amount of sediments.

The clay minerals are often washed out of the top soil leaving a sandy surface behind. This would allow for good possibilities of direct infiltration by rainfall. However, there still is a critical hillslope which when exceeded causes a high incident of surface run-off. Since most tributaries of the main rivers across the post-African land surface do not carry water during the dry season, it may be concluded that the hillslopes exceed the critical gradient, and that surface run-off is predominant. Groundwater recharge, therefore, occurs on the summit areas where it reaches the aquifer situated in the saprolite. From there groundwater flows by gravity into the valleys where it is finally discharged by rivers.

On the higher parts of the hills the topography often does not allow perennial aquifers to exist, and there are no secondary perched aquifers to supply the lower part of the saprolite with groundwater. Weathering has not been going on for a period long enough to establish a clay horizon with sufficient thickness and storage capacity as is the case on the African land surface.

The groundwater catchment boundaries across the post-African land surface, therefore, usually vary over the year. During the rainy season the groundwater catchment area matches that of surface water but is reduced to occupy the lower parts of the land surface at the end of the dry season. This is a major difference between the African and the post-African erosion surfaces. While across the mature African Surface water is struck virtually everywhere throughout the year when drilling, great care must be taken in siting wells across the post-African surface in order not to drill wells that could run dry at the end of the dry season.

The hydrograph of a typical river draining the post-African land surface, therefore, in qualitative terms should be as follows:

- The ratio between the peak and the minimum discharge is large, because the minimum discharge is low.
- The interflow component has a quick recession, in the order of magnitude of a few days.
- The base flow recession period is long but at the end of the dry season low in magnitude because of decreasing catchment area.

The baseflow regime is that of artesian discharge. Springs and seeps are uncommon on the post-African land surface. They are, where found, associated with major fault lines. Some are saline or hot, and the springs in general have little or no influence on the base flow regime.

The hydrograph of the Ndembera River, Station 1KA 33A, based on monthly means, is shown in Figure 7.16. The catchment area is 2190 km^2 situated exclusively on the post-African land surface. The mean annual rainfall is around 600 mm.

The hydrograph shows a very quick recession. After the long rains have terminated in April, already by May the flow regime is purely from groundwater. The minimum flow is 0.82 $l/s/km^2$, indicating a minimum net annual groundwater recharge increment around 26 mm or about 4% of the rainfall.

The hydrograph of the Ruaha River at Station 1KA56 is shown in Figure 7.17. The catchment area is 151 km^2, mainly on the post-African land surface. Parts of the upland area form part of the African Surface. The mean annual rainfall is around 850 mm.

The pattern is the same as before, but slightly more pronounced. One month after the termination of the rains the flow regime is again purely base flow.

The minimum flow is 1.4 $l/s/km^2$, indicating a minimum net annual groundwater recharge increment around 44 mm, or about 6% of the rainfall.

Data from the two stations used here are not as reliable as could be desired, but they are included since these Stations are the only two representing catchments over the post-African Surface.

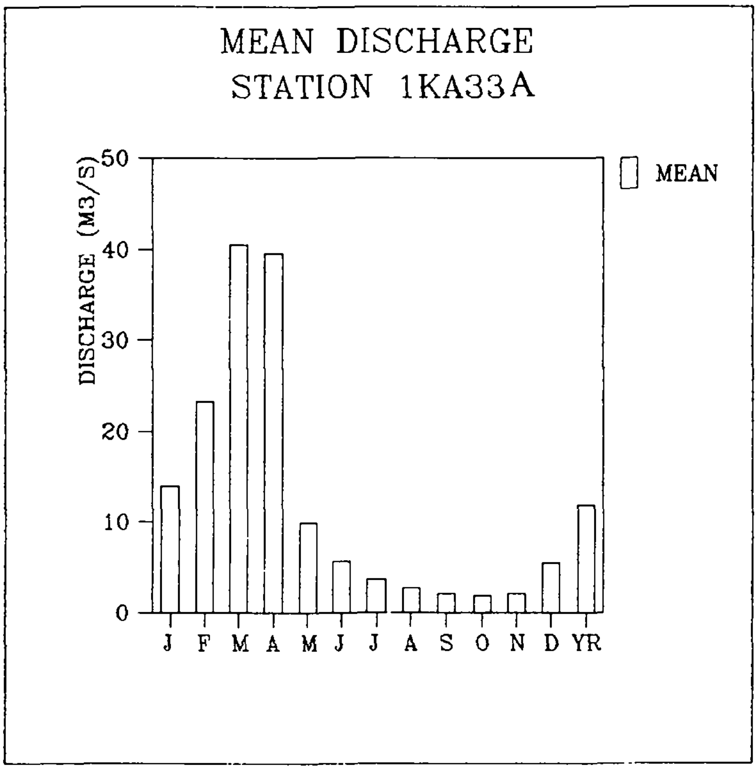


Figure 7.16 Hydrograph of the Ndembera River at Station 1KA 33A.

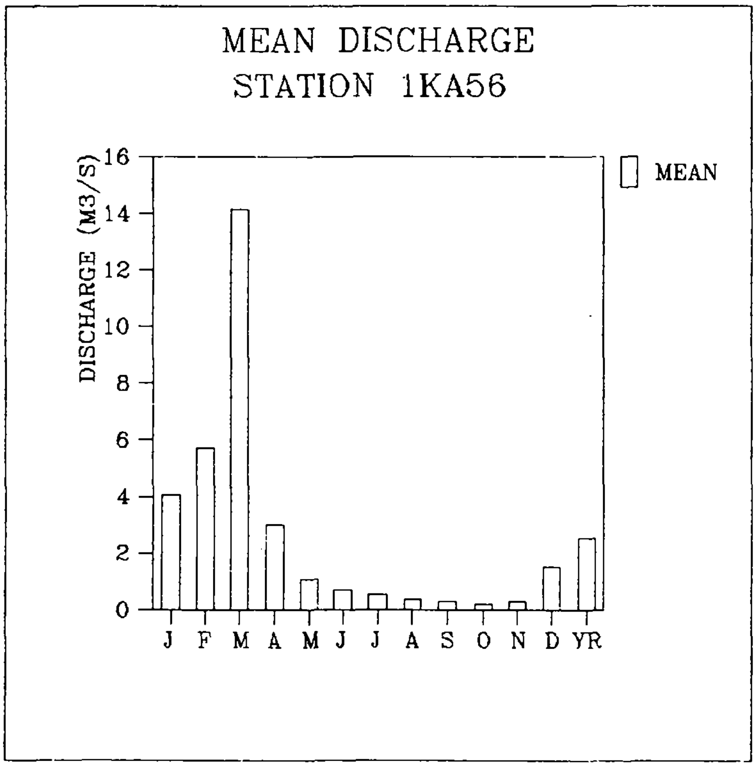


Figure 7.17 Hydrograph of the Ruaha River at Station 1KA56.

7.5.4 Groundwater Level and Movement

Data on the groundwater levels across the post-African land surface is obtained from existing wells and wells drilled by the Consultants. Wells drilled in low-lying areas usually strike water in the upper part of the saprolite, and the water level rises closer to the surfaces revealing confined conditions. This is also the case over the more elevated areas during the rainy season.

Figure 7.18 shows the frequency distribution of water levels in wells across the post-African land surface. The water levels in the wells are comparatively shallow, 50% of the wells having a standing water level less than 5 metres below ground level and 70% of the wells having standing water levels less than 8 metres below ground level. This is slightly lower when compared to the African land surface, as expected from topographic differences between the two surfaces.

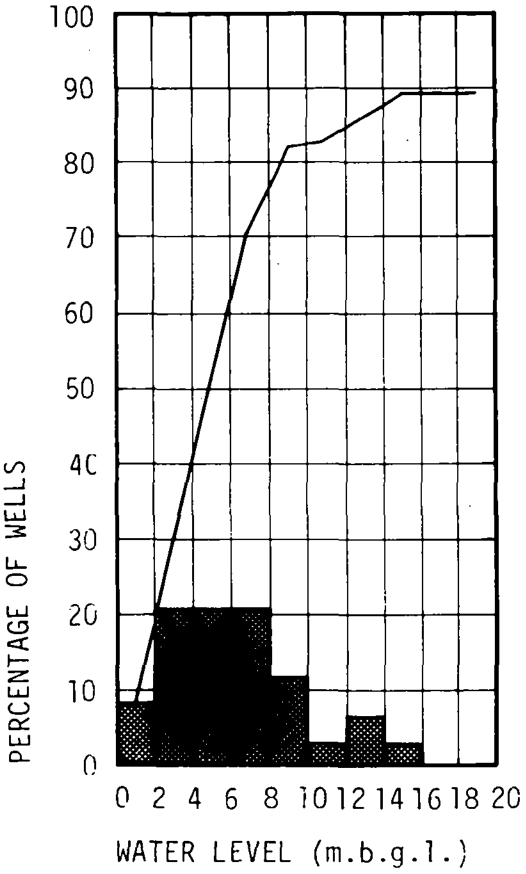


Figure 7.18 Water level frequency distribution (in metres below ground level) in wells across the post-African land surface. Data from 34 wells.

From Figure 7.18 it is likely that successful boreholes are drilled mainly in the low-lying areas. Only a few wells have rest water levels deeper than 10 metres, and these are probably drilled in a more elevated terrain.

As on the African Surface the water level reflects the topography. The groundwater flows from the high to the low areas where it is discharged by rivers as long as the groundwater level is above the river bed. When this is no longer the case the river runs dry, but groundwater can still be found in holes dug into the river bed. In many areas these are the only source of water available during the late dry season.

No records of the water level variations across the post-African land surface exist from the regions. From the considerations above, the water level fluctuations should be somewhat larger than found on the African Surface. The likely range would be 3-6 metres depending on topography and local rainfall. The fluctuations are largest in the watershed areas and smallest in the river valleys and, further, they are proportional to the net groundwater recharge.

7.5.5 Yield of Wells

Across the post-African land surface 38 wells have information on drilling depth, 26 have reported yields, 18 of which have records of drawdown.

The drilling depth frequency distribution is shown in Figure 7.19.

60% of the depths are less than 85 metres. Some wells shallower than 20 metres are in most cases abandoned because of drilling difficulties.

The distribution partly shows the difficult drilling conditions in general and partly some lack of understanding of the groundwater conditions across the post-African Surface. From Figure 7.15 it would appear that the economic drilling depth should be 40 metres, which in 70% of the cases would ensure that the saprolite was penetrated.

However, drilling is carried out to much larger depths indicating that the saprolite encountered has not contained enough water, or that the saprolite has not been the main target of drilling. It is evident, as was the case across the African Surface, that the interval 90-100 metres (300 feet) is the depth derived by rule of thumb experience.

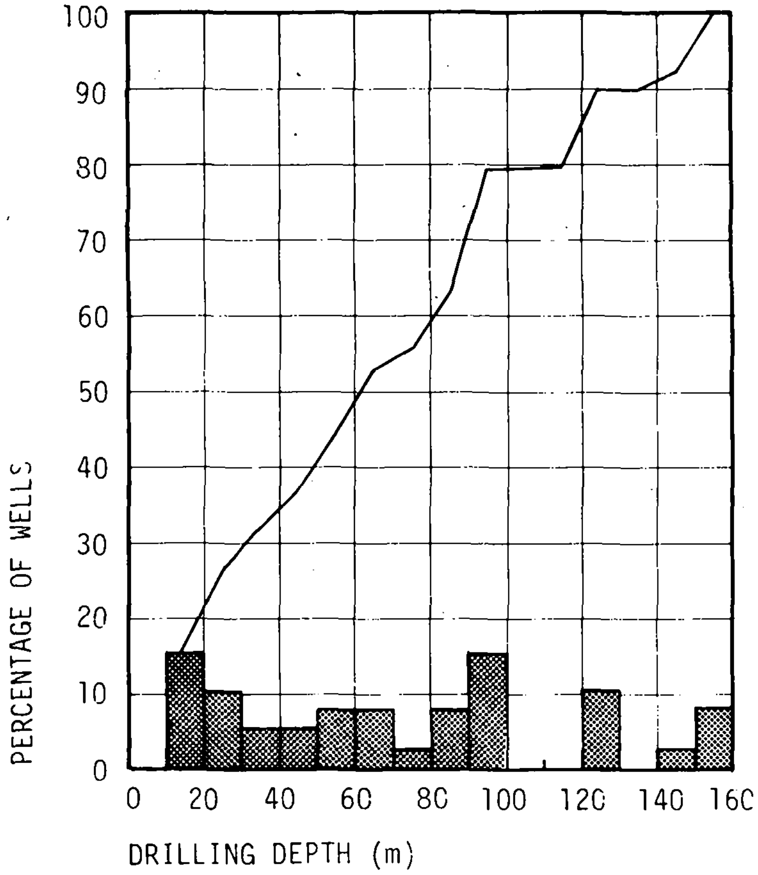


Figure 7.19 Drilling depth frequency distribution for wells across the post-African land surface. Data from 38 wells.

That the saprolite is the main aquifer also across the post-African land surface becomes obvious when inspecting Figure 7.20 which shows the relationship between the drilling depths and the yields from each 10 metre interval.

The maximum yields are obtained between 30 and 50 metres which is exactly where the water should be found on geomorphological considerations. The amount of data in Figure 7.20 may not seem sufficient to make such a statement but comparison with the experience of the Basement Complex over the post-African Surface everywhere else in East and Central Africa, the pattern is the same.

Wells drilled deeper than 50 metres show yields decreasing with depth, clearly demonstrating the poor yields that can be expected from fresh bedrock.

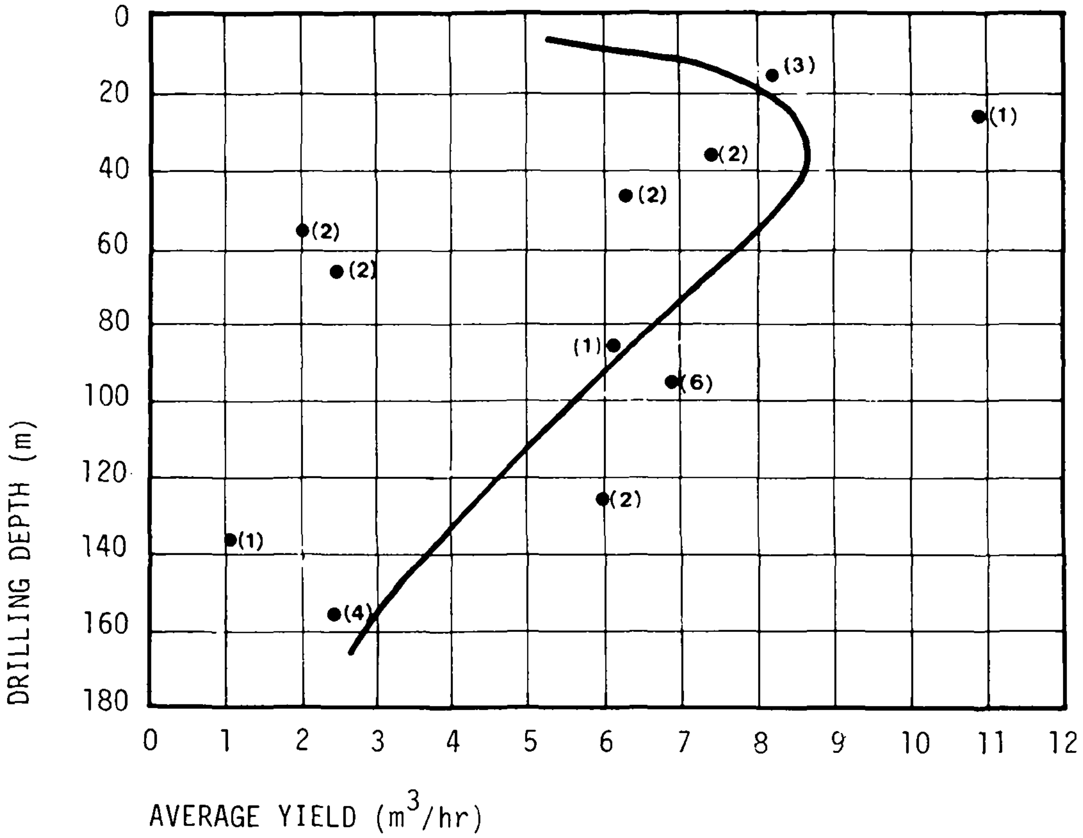


Figure 7.20 Average yield versus drilling depth for wells across the post-African land surface. Numbers in brackets denote the number of wells within each 10 metre interval of depth.

The hydraulic performance of the wells is described by the specific capacity. The specific capacity frequency distribution for wells across the post-African land surface is shown in Figure 7.21.

50% of the wells have specific capacities larger than 0.17 m^3/hr/m, and for 70% the figure is 0.08 m^3/hr/m. These are the same figures that were found representing the African Surface, and since the water level distribution is more or less the same, the expected yields of wells will be as described for the African Surface (cf. Section 7.4.5).

Comparing Figure 7.21 with Figure 7.13 it is seen that the lines are coinciding. This demonstrates the uniformity of the aquifer properties found in the weathered zone of the Basement Complex.

7.5.6 Aquifer Hydraulic Parameters

Across the post-African Surface 15 controlled pumping tests have been carried out on existing wells and wells drilled by the Consultants. Data from 14 of these existing wells is of sufficient quality to allow for interpretation by the type curve method or the straight line method.

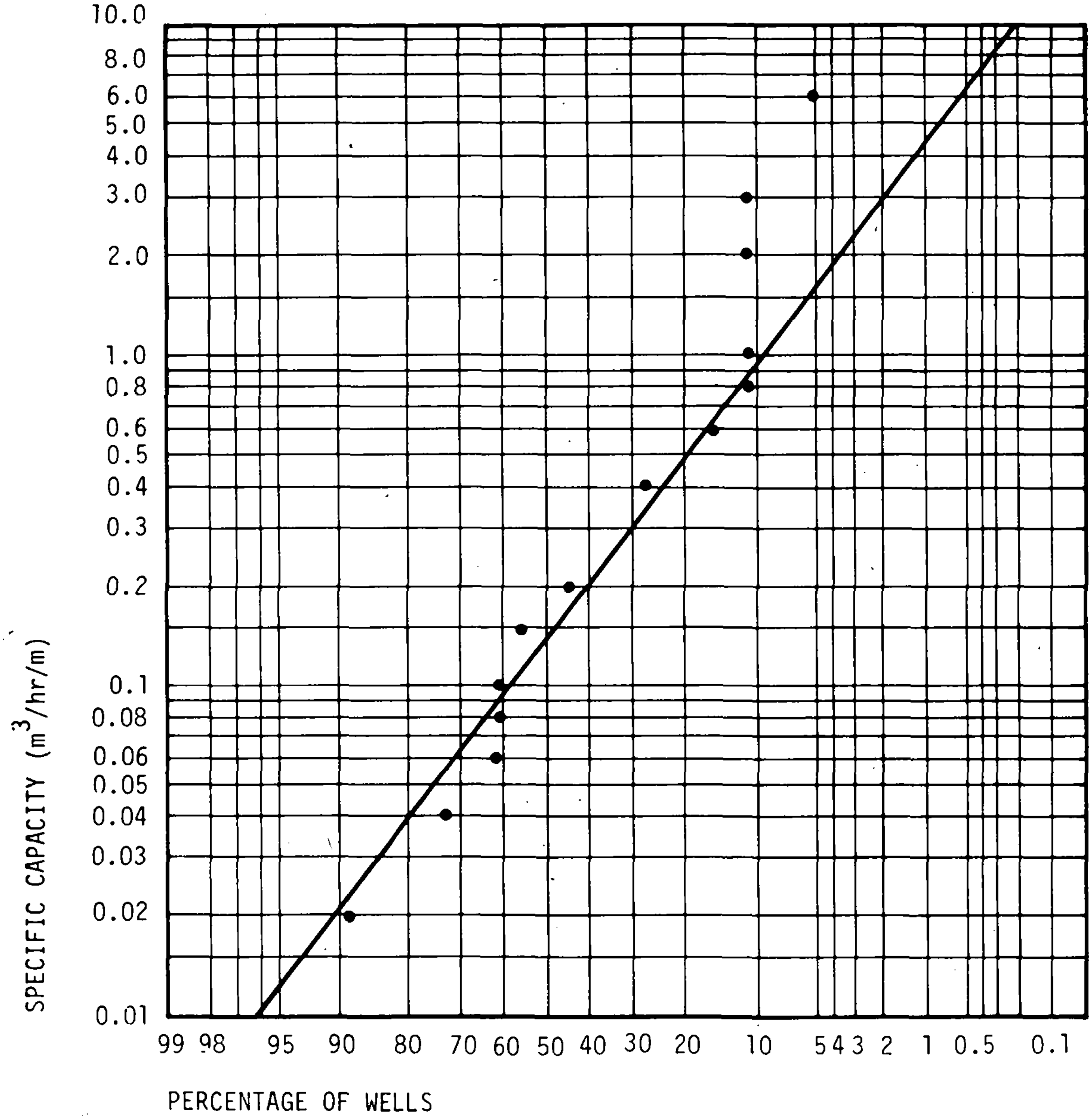


Figure 7.21 Specific capacity frequency distribution for wells across the post-African land surface. Data from 18 wells.

The result of the interpretation is listed in Table 7.2. The transmissivity of the aquifers is within the range 0.056-74.0 x 10^{-5} m^2/s. The relationship between the specific capacities and the calculated values of the transmissivity is shown in Figure 7.22.

BH.No.	$T \times 10^5$ (m^2/s)	$r_w^2 S \times 10^3$ (m^2)	$r_w^2 P'/m' \times 10^6$ (m^2/s)	Q/s_w ($m^3/hr/m$)
55/76	6.0	17.0	-	0.49
71/76	0.056	0.77	-	0.0076
226/76	0.84	15.0	4.1	0.26
265/76	0.33	19.0	-	0.044
21/77	0.94	140.0	-	0.18
65/77	2.1	15.0	-	0.16
173/77	0.32	2.0	-	0.047
194/77	0.27	1.4	-	0.022
195/77	0.48	4.9	-	0.12
209/77	1.4	4.9	2.2	0.28
223/77	74.0	84.0	-	4.0
227/77	3.5	63.0	-	0.40
4/81	0.76	0.38	-	0.026
77/81	0.76	-	-	0.041

Table 7.2 Aquifer hydraulic properties calculated from type curve or straight line method. Data from wells across the post-African land surface. Symbols used are explained in Volume 10 A, Appendix 1, Chapter 5.

The empirical relationship between the calculated transmissivities (T) and the specific capacities (Q/s_w) is $T = 8.5 \times 10^{-5}\ Q/s_w$ (m^2/s), exactly the same as found for the African Surface, which is not surprising since the relationship is based strictly on flow conditions in weathered saprolite zone.

The values of $r_w^2 S$ are within the range $0.77-140 \times 10^{-3}\ m^2$. The average value is somewhat higher than found on the African Surface, lending support to the previous statement that water table conditions are more common across the post-African Surface than across the African Surface.

The values of $r_w^2\ P'/m'$ are an order of magnitude smaller than found for the African Surface. The probable reason for this is that the saprolite is thinner across the post-African land surface, and accordingly the groundwater in storage in the upper part of the saprolite is smaller and provides a smaller source of leakage.

The remarks on the pseudo steady state of leaky aquifers and the possible true steady state in Section 7.4.6 apply to the post-African land surface as well as to the African Surface.

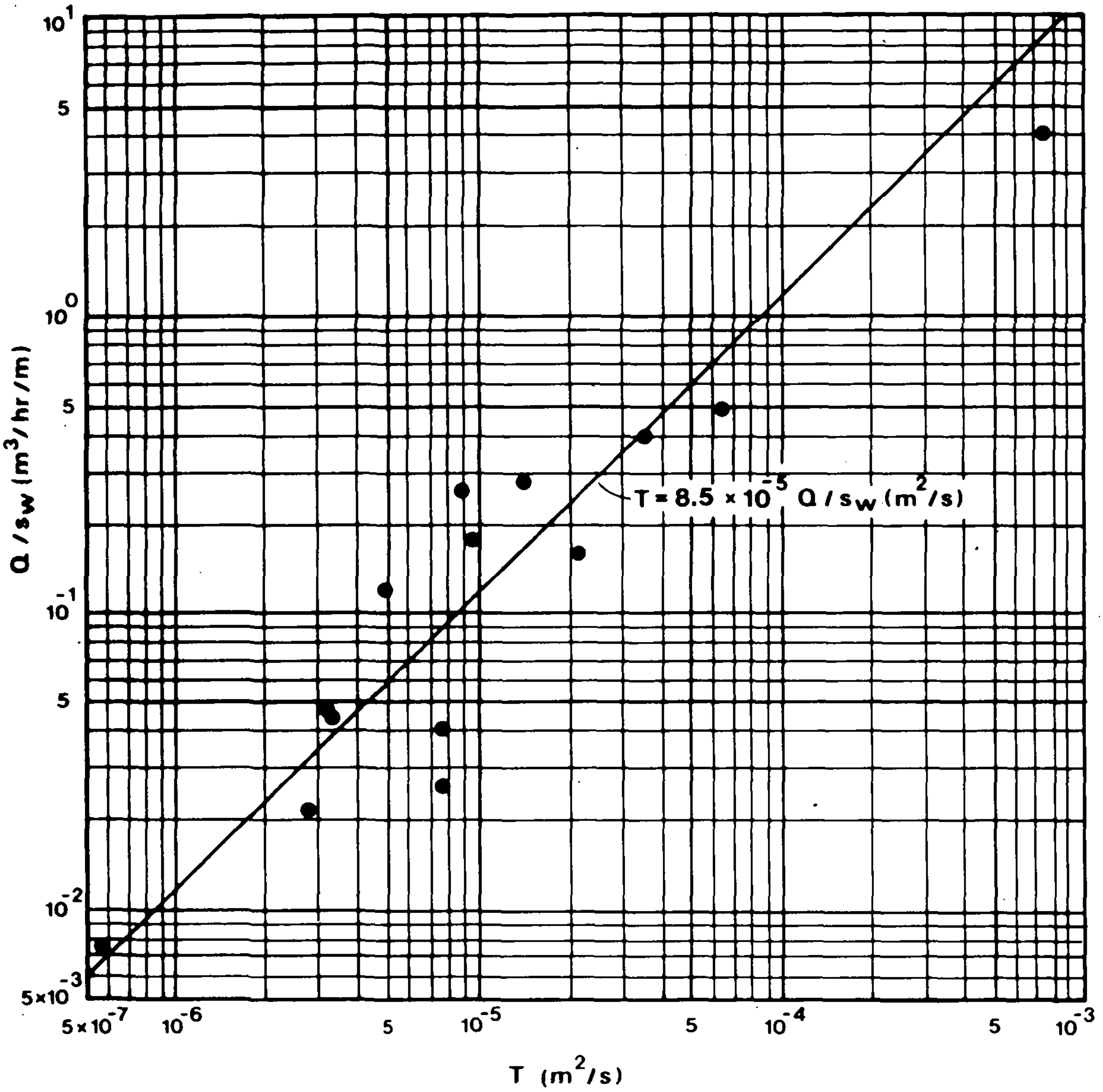


Figure 7.22 Relationship between specific capacities and calculated transmissivities for wells across the post-African land surface.

7.5.7 Groundwater Chemistry

The groundwater quality found across the post-African Surface is chiefly the same as found over the African Surface (Section 7.4.7). A large proportion of the post-African Surface is situated close to the rift faults, so it may be expected that many boreholes may have water with traces of juvenile constituents. The majority of boreholes drilled here, however, has indicated the existence of groundwater qualities compatible with accepted standards.

In concluding this Section, it may be stated that the saprolite is generally thinner across the post-African Surface compated with the African Surface. This means that less groundwater is in continuous storage. Also the more pronounced topographical relief means that perennial groundwater in places must be located in the lower areas. However, data show that groundwater exists and can be utilised in many areas.

7.6 The Congo Land Surface

7.6.1 Physiography

The Congo land surfaces are found along the shore line of Lake Nyasa, in the Ruhuhu Depression, and along the Great Ruaha River Valley where it borders Morogoro Region. The Congo surfaces benefit from the rainfall on the surrounding highlands, and the mean annual rainfall is about 2000 mm in Kyela District, around 1400 mm along the Great Ruaha River, and somewhat lower in the Ruhuhu Depression where the mean is around 1000 mm per year.

The vegetation across the Congo land surfaces is mainly grassland and scattered bush. Baobabs are common along the Great Ruaha River, and palm trees along Lake Nyasa.

Except for the northern end of Lake Nyasa the areas occupied by the Congo land surfaces are relatively thinly populated. Access to the Ruhuhu Depression and the eastern shore of Lake Nyasa is difficult during the rains as steep escarpments have to be passed, while the Great North Road provides easy access to the villages situated along the Great Ruaha River.

7.6.2 Geology and Structure

The occurrence of the Congo erosion surface this far from the coast is a result of tectonic events associated mainly with the rift faulting.

The erosion surfaces are very young and have not existed long enough for a thick in-situ weathered profile to be established. The pediplains in the Great Ruaha Valley and along the Lake Nyasa are very narrow and cannot be compared hydrogeologically with the much older pediplains of the African or post-African Surfaces.

The Great Ruaha River runs through the highlands of the Northern Iringa Region along antecedent gorges, and the river valley is in places extremely narrow. The steep valley and the frequent rock outcrops in the river bed clearly indicate the youthfulness of the river.

The Ruhuhu Depression is considered an ancient erosion valley infilled with Karroo sediments (Haldeman, 1956). These are separated from the surrounding pre-Cambrian rocks by well defined post-Karroo fault-line scarps.

The erosion of the soft Karroo sediments during the Quarternary has resulted in areas of very low topographic relief within the depression. In other places the Karroo sediments have been more protected from erosion and areas resembling dissected scarp areas have been created.

The thickness of the remaining Karroo beds are not explored by drilling, but gravity and aeromagnetic maps suggest thicknesses of more than several hundred metres.

7.6.3 Infiltration and Drainage

Due to the topographical position and the areally small extent of the Congo land surface the infiltration and drainage is controlled by local conditions to a much larger extent than across the mature and old pediplains.

Direct infiltration probably plays a minor role, but recharge mainly originates from the rivers flowing down the escarpments from the surrounding highlands. Many of these rivers have small alluvial fans where recharge takes place throughout the year, but the recharge during the dry season is important. The alluvial deposits along the escarpments separating the Congo land surfaces from the highlands surrounding them will generally contain groundwater in continuous storage. In the Ruhuhu Depression and in the narrow Great Ruaha Valley groundwater is drained by the Ruhuhu and the Great Ruaha Rivers, respectively. Along the Lake

Nyasa shore the groundwater level is controlled by the water level of Lake Nyasa. The major part of the groundwater is discharged directly into the Lake, the rest drains first into the rivers which then drain into the Lake. Weathered rock of sufficient thickness to store groundwater cannot be expected to exist, so groundwater must be located solely in alluvial and hill outwash deposits.

An exception is the Karroo sediments over the Congo Surface of the Ruhuhu Depression. Drilling in the Karroo Formation in other places has shown that enough groundwater is available for rural water supply, and the topographical position of these deposits in the depression makes the Karroo sediments an obvious target for groundwater abstraction. Due to the remoteness of the Depression, no systematic drilling has been carried out here. The sediments belong to the lower part of the Karroo sequence which have not been drilled into in the other Karroo Basins in Ruvuma Region. Therefore, the lithology of these lower beds in terms of hydraulic conductivity is unknown. Future drilling will show if the yields of boreholes will be sufficient for village water supply.

7.6.4 Groundwater Level and Movement

As groundwater is considered only to be found in alluvial deposits and, in the case of the Ruhuhu Depression, also in the Karroo sediments, the groundwater conditions can be considered largely the same as found in alluvial deposits in other parts of the regions (Section 7.12). The groundwater level is shallow, 1-4 m.b.g.l., except where the Karroo sediments are not eroded down to a smooth surface. Here the depth to the groundwater will be mainly a function of the actual level above the valley bottoms. During the rainy season the Congo surface of the northern end of Lake Nyasa is often flooded, and wells here must be carefully sited to avoid the water logged areas, and wells must be effectively protected from pollution by surface water by means of concrete slabs.

In this area and along the Lake Nyasa shore the direction of groundwater flow is towards the Lake. In the topographically well defined Great Ruaha Valley and the Ruhuhu Depression groundwater flows towards the rivers draining the valleys.

7.6.5 Yield of Wells

The expected yield of wells can be based on results from drilling in alluvial deposits elsewhere in the regions, and the findings presented in Section 7.12 can be directly used. Expected yields from wells drilled in Karroo sediments can for similar reasons be obtained from Section 7.8.

7.6.6 Aquifer Hydraulic Properties

For estimating the hydraulic properties of alluvial deposits and Karroo sediments reference should be made to the results given in Sections 7.12 and 7.8, respectively.

7.6.7 Groundwater Chemistry

The groundwater quality in alluvial and outwash material is expected to be good since the retention time of groundwater is too short for major chemical reactions between infiltrating water and the porous matrix to take place. The Karroo sediments are known from drilling elsewhere in these sediments to have high-quality groundwater.

7.7 Scarp Areas

7.7.1 Physiography

There are two types of scarps within the regions, fault-line scarps and erosion scarps. The fault-line scarps occupy by far the larger area of the two. They mark the transition between the plateaus and the Rift Valleys and other major tectonic features. Rejuvenation of river systems on the plateaus above the scarps has in many places dissected the scarps heavily and extended their area.

The erosion scarps are found separating erosion surfaces of different ages. On a geological time scale their development has taken considerably longer than the fault-line scarps, and tectonics are not involved in their development. Therefore, no rejuvenation of rivers has taken place and the area associated with the erosion scarps is very small. Usually, erosion scarps can be distinguished from fault-line scarps in the field because of the presence of the erosion scarp hill slope elements as described in Chapter 5.

The vertical displacement of the fault-line scarps can be up to 800 metres, while the difference in level between the two plateaus on each side of an erosion scarp is about 200 metres or less. The most pronounced erosion scarps are those separating the Gondwanaland and the African erosion surfaces. The scarp between the African and post-African erosion surfaces are less pronounced and may in places not clearly be observed in the field.

The vegetation in the scarp areas is normally scattered bush or miombo forest, except in areas of high altitude where the rainfall is sufficient to produce rain forest.

Scarp areas are normally only accessible where they are crossed by main roads, and the population is sparse and scattered. Along the foot of the scarps, however, rural settlements are more common.

7.7.2 Groundwater Occurrence

Groundwater in scarp areas is difficult to locate and often does not exist at all. Because of the topography, rainfall runs off directly. Very little water recharges possible groundwater bodies.

Erosion is effective, and little or no groundwater circulation can be established to produce a saprolite of sufficient thickness to store groundwater.

The greater chance is to find shallow groundwater in the alluvial deposits in valleys having perennial rivers, but such valleys are seldom of large areal extent.

The most common sources in the scarp areas are the springs, especially along the fault-line scarps. They may be found anywhere in the scarp area. Springs connected with faults, however, are often hot or saline, whereas fresh water springs are mainly the result of lithological discontinuities, e.g. those formed by the transition from weathered to fresh rock.

Fresh springs will, apart from perennial rivers, constitute the major water source in the scarp areas. They discharge good quality groundwater and are in most cases perennial as they have comparatively large catchments on the plateau above.

Talus slopes and other mass waste from the scarps and the plateaus above offer a prospective groundwater source. These deposits are treated in Section 7.12.

Limited groundwater occurrences occur in intensely fractured and fissured zones related to the actual faulting movements along the scarps. These zones may produce small quantities of groundwater to drilled or dug wells.

7.8 The Karroo Sediments

7.8.1 Physiography

Only the two southern Karroo outcrops, the Tunduru or Eastern Basin and the Ruhuhu or Northern Trough, are discussed in this section. These outcrops fall almost entirely within Ruvuma Region with only a small overlap into Iringa Region.

The Karroo occurrences in Mbeya Region are discussed in the section on the Rukwa Trough (Section 7.10).

The Tunduru Basin covers some 32,000 km^2 in Ruvuma Region, the Ruhuhu Trough some 5,300 km^2. Except where the Ruhuhu Trough cuts through the Livingstone Mountains fronting Lake Nyasa, the topography of both outcrops is very similar. Both have an elevation of between 600 and 900 metres above sea level and both give the appearance of flat even plateaus similar to the African Surface Basement Complex Plateaus when viewed from a distance. In detail, however, the Karroo outcrops have an irregular rolling topography with steep rises and declivities resulting from a dense dendritic drainage pattern. Although this topography is sharp, the local differences in elevation are only moderate, usually in the order of 20 and 60 metres between valley floors and valley crests.

Together with the rest of Ruvuma, the Karroo Basins have a very equable climate. The rainy season is generally from mid November to late April. The mean annual rainfall is between 800 and 1200 mm. It is drier and rainfall is less reliable to the north-east and east.

Thick loamy sand soils cover most of the Karroo Basins reflecting the arenaceous lithology of much of the Karroo sediments. These soils have good drainage, and standing water is seldom seen even after heavy rainfalls. Heavy clayey soils are found over the lower Karroo mudstones and shales.

Both basins have a dense deciduous miombo forest cover.

In terms of settlement and land use, very large areas of the Karroo basins are empty. The only areas of intense agricultural activity are around Tunduru where cashew nuts are the main commercial crop, and in the Ruhuhu Trough near Lake Nyasa. Communications across both basins are poor. The main roads between Njombe and Songea, and between Songea and Tunduru can be impassible during the rainy season despite following the main water divides. There is a well developed feeder road system around Tunduru but apart from this, access is limited to hunter and forestry tracks.

7.8.2 Geology

The Tunduru Basin

Virtually no published information is available on the geology of the Karroo rocks in the Tunduru Basin.

Results from recent airborne geophysical surveys have, however, made it possible to delineate the area underlain by the Karroo and to define the major structural features. These are shown on Drawing II-8, Geology. Regional geological mapping is now required to establish lithological and stratigraphical information. This is presently being carried out by Madini.

Without this mapping six main observations can be made on the nature of the Karroo rocks of the Tunduru Basin:

- They are of continental origin. Lithologically they are arenaceous i.e. sandstones, siltstones, arkoses, and conglomerates. They exhibit both current and dune bedding.
- They were deposited on a pre-Karroo land surface of considerable topographic relief. Younger Karroo beds are seen to overlap the pre-Karroo surface along the Songea-Tunduru road around 'kilometre 160'.
- It is not possible to estimate the thickness of the Karroo system in the Tunduru Basin. Large areas have

a magnetically quiet signature which would indicate a thickness of a few thousand metres.

- The same survey shows that the Tunduru Basin is composed of several north-east to north trending subbasins. On the ridges between the subbasins the Karroo can be very thin.
- Movement along pre-Karroo fault lines took place during the sedimentation of the Karroo. Such movements appear to have influenced the formation of the subbasins.
- There is no evidence of subsequent major post-Karroo movements along these faults.

Of the boreholes drilled by the Consultants, six (Nos 256/81 to 261/81) are considered having penetrated the Karroo rocks immediately above the contact zone with the Basement. The lithological logs of three of these holes are given in Table 7.3. Interpretation of these logs indicates a considerable saprolite cover over some of the pre-Karroo Basement land surface.

The lithological log for borehole No. 258/81 which was drilled into well developed Karroo sandstones of the Tunduru Basin is given below.

BH No. 258/81 NANDEMBO: LITHOLOGY LOG

DEPTH (m)	LITHOLOGY
0-12	Brick red lateritic clayey sand. Quartz grains fine to medium, angular to sub-rounded. Colour becomes paler with depth, and frequent, very weathered, white feldspar grains occur.
12-15	Pale brick red to cream, medium to coarse, quartz sand with weathered feldspars. Some clayey laterite (weathered arkose).
15-28	Cream fine to medium grained sand of quartz and weathered feldspars. Very minor micas. Angular to sub-angular. Becomes much coarser with depth (arkose).
28-35	As above, but with clayey matrix.

35-46	Reddish light tan clayey arkosic conglomerate, fine, medium and coarse grained/angular.
46-47.5	Light yellow brown fine/medium fine grained sub-angular to rounded well sorted sandstone.
47.5-53	Light yellow brown fine/medium fine very clayey sandstone.
53-59	Light yellow brown fine/medium grained sub-angular to sub-rounded sand. Fairly frequent biotite mica flakes. Well sorted.
59-67	Red medium/medium fine sub-rounded to rounded, well sorted sandstone with abundant magnetite and some white very weathered feldspars.

The lithologies recorded in this borehole log are essentially similar to the lithologies of exposures seen in cliffs and cuttings along the Songea-Tunduru road.

BH No. 256/81 NDENYENDE No. 1		BH No. 257/81 NDENYENDE No. 2		BH No. 261/81 SISIKWASISI No. 2	
DEPTH m	LITHOLOGY	DEPTH m	LITHOLOGY	DEPTH m	LITHOLOGY
0-5	Red medium/fine grained very clayey soft friable sandstone.	0-26	Brick red lateritic clayey sand medium/fine grained angular to sub-rounded, well sorted some crystalline quartz.	0-8	Orange brown/orange limonitic clayey sand. Quartz grains angular to sub-angular.
5-24	Light yellow buff, fine grained well sorted micaceous arkosic sandstone.	26-35	Light yellow/buff limonitic clayey sand, medium/fine grained angular/sub-rounded.	8-11	As above but becoming lateritic.
24-30	Dark greenish grey sandstone, 15% black biotite medium coarse grained.	35-41	Orange/Yellow very clayey limonitic sand grading to sandy clay with depth.	11-17	Mottled white and red clayey sands abundant kaolin nodules.
30-37	Very dark grey biotite and quartz crystalline rock.	41-73½	Buff sandy clay - frequent biotite mica and white weathered feldspar. Pyrite and magnetic grains.	17-35	Mid grey plastic kaolinite clay with some red laterite streaking.
37-42	Light red/pink quartz - feldspathic rock with very minor micas.			35-41	Red plastic clay with some mottling.
				41-48	Light to mid grey plastic clay with red mottling and some silty layers.
				48-60	Light yellow/brown medium coarse quartz sand.
INTERPRETATION					
0-24	Basal Karroo clayey sands (weathered arkose).	0-41	Lower Karroo continental clayey sands.	0-11	Lower Karroo continental sands.
24-30	Weathered saprolite of pre-Karroo Basement land surface.	41-73	Basal Karroo equivalent to 0-24 m in BH No. 256/81.	11-60	Very weathered basal Karroo grading into very weathered saprolite of pre-Karroo Basement land surface.
30-37	Quartz biotite gneisses.			60-67	Basement saprolite.
37-47	Feldspathic gneisses.				

Table 7.3 Lithological logs and interpretation of boreholes drilled in the Tunduru Karroo Basin.

The lithologies of the shallow wells drilled south of Tunduru (BH Nos 271-275/81) are considered as representative of a lower horizon in the same Karroo sequence recorded in the log of borehole No. 258/81.

A typical log is:

BH No. 274/81	Azimio Kalnido
0.0- 1.5 m	Light brown silty sand
1.5- 3.0 m	Brown fine to medium sand
3.0- 8.0 m	Brown fine to coarse clayey sand
8.0-11.5 m	Light brown fine to coarse clayey sand
11.5-13.5 m	Dark brown fine to coarse clayey sand
13.5-22.0 m	Wet, light brown medium to coarse clayey sand
22.0-23.5 m	Wet, light brown fine to medium clayey sand
23.5-26.0 m	Yellow brown silty sand

The essential lithological variation would appear to be related to the depositional environment: These lower sediments appear to have been laid down under fairly stable, fluviatile conditions while the higher sediments appear to have been deposited either sub-aerially or under a spate-flood regime. At the western end of the Tunduru Basin Stockley (1932) gave the following general stratigraphic succession for the Songea Karroo series:

	Top
K 7-8	Current bedded grits and sandstone, mudstone
K 5-6	Mudstone, sandstone, local limestone and bone beds
K 1-4	Conglomerate, sandstone and mudstone including upper and lower coal measures.

It is not possible to correlate the eastern project borehole lithologies with Stockley's western succession.

The Ruhuhu Trough

The Ruhuhu Trough is a well defined structural and physiographical unit lying between the Njombe Highlands and the Songea African Surface Plateau.

The Trough is recognised as an old rift feature. The original rifting took place in the pre-Cambrian, and subsequent movements took place during the Karroo, the Tertiary, and in the Neogene. The Neogene movements along the Nyasa Rift and the preservation of the older north-east trending rift have resulted in the spectacular Ruhuhu Valley cutting through the Livingstone Mountains. The Neogene movements also rejuvenated the faults to the east along the northern edge of the Trough. Movement further occurred along the southern boundary faults during the Neogene. In this area there is no single fault line but rather a broad fault zone.

The geology of the western end of the Ruhuhu Trough, where coal deposits are of economic importance, is well established: It is covered by two Quarter Degree Geological Map Sheets, Nos 285 and 297. The geology of the areally larger eastern end of the Ruhuhu Trough, where the groundwater resources are of great interest and where the Project Boreholes were drilled, is less well known.

The stratigraphic succession established by Stockley (1932) and revised by Harkin, McKinlay and Spence (no year) for the Ruhuhu Coalfields near Manda Bay is:

	Top	
K 8	Manda Beds)	Pink and purple coarse current bedded
K 7	Kingosi Sandstone)	grits and sandstones.
K 6	Lower Bone Bed	Coarse feldspathic sandstone with bone fragments.
K 5	The Ruhuhu Beds	Grey-green mudstones, siltstones and fine sandstones.
K 4	Upper Coal Measures	Shales, mudstones, thin coal bands.
K 3	Intermediate Mudstone and Sandstone	Soft red-green mottled sandstones and mudstone.
K 2	Lower Coal Measures	Sands with subordinate shales and coal.
K 1	Basal Conglomerate and Sandstone	Sandstones with conglomerates at base. Occasional green shales.

The maximum thickness of these formations near Manda Bay is in the order of 1500 metres.

As indicated, little stratigraphic information is available for the eastern end of the Ruhuhu Trough. Table 7.4 gives the lithology logs for boreholes No. 253, 254, 255, and 267/81. These logs would indicate that boreholes No. 253 (Hanga River) and 255 (Mtukano) are drilled in lithologies equivalent to K 7-8 of Stockley's succession, and holes No. 254 (Gumbiro) and 267 (Mtapa) which are very near the southern boundary of the Trough are lithologically equivalent to the K 5 horizon.

Towards the northern boundary of the western and central area of the Ruhuhu Trough yellow and red variegated marls are seen to outcrop near the Lutukila River. These probably also belong to K 7-8. Further north of the Lutukila River the surface geology is confused by large quantities of colluvial material being deposited along the foot and the northern fault line scarp. A similar but less readily discernible situation is seen along the southern fault boundary zone near Gumbiro.

In general the Karroo occuring south of Songea and west of 36^{o}E appears to be closely correlatable. The Karroo east of 36^{o} in the Tunduru Basin, however, appears entirely continental and probably of K 7-8 age. At one time these formations were considered of Cretaceous age (Gillman 1943).

7.8.3 Infiltration and Drainage

The essentially similar arenaceous nature of the majority of the Karroo formations in Ruvuma means that hydrogeologically and hydraulically the Karroo found in the Tunduru and Ruhuhu Basins is virtually identical.

The most characteristic topographic feature of both Karroo basins is the irregular rolling topography of sharp rises and declivities resulting from the dense dendritic river drainage pattern. Figure 7.23 reproduces part of the contoured 1:50,000 maps from both basins, and shows this characteristic topography. Both sections of maps also show more active erosion advancing across the Karroo land surface from the east in the Ruhuhu section where drainage is to the Rufiji River, and from the south in the Tunduru Basin where drainage is to the Ruvuma River.
Of further importance is the abundant occurrence of depression springs in the bottom of these more active valleys. Frequently at the heads of these valleys springs are discharging groundwater at the foot of extremely steep cliffs.

Due to the comparatively high infiltration capacity of the top soils, groundwater recharge in the Karroo basins is expected to be high as compared to the Basement Complex plateaus.

BH No. 253/81	Hanga River	BH No. 254/81	Gumbiro
DEPTH m	LITHOLOGY	DEPTH m	LITHOLOGY
0-6	Yellow brown clayey sand.	0-14	Chocolate very fine firm to brittle clayey siltstone and very fine sandstones.
6-30½	Red medium fine clayey sandstone.	14-54	Dark brown mudstones, reddish brown micaceous siltstones.
30½-59½	Red mottled sandy marls with occasional sands.	54-60	Grey/dark grey siltstones and very fine sandstones & mudstones.
59½-154½	Variegated red fine grained siltstones, marls, sandstones and arkoses.		

BH No. 255/81	Mtukano	BH No. 267/81	Mtapa
DEPTH m	LITHOLOGY	DEPTH m	LITHOLOGY
0-20	Red variegated sands and arkoses.	0-12	Light to mid brown silts.
20-22	Mottled red/grey claystone.	12-30.9	Dark grey to black mudstone.
22-30	Red medium to coarse arkose.		
30-35	Mottled red/yellow clayey sandstone.		
35-41	Mid to dark grey claystone.		
41-51	Red variable arkoses and sandstones with occasional conglomerate horizons.		

Table 7.4 Lithological logs for boreholes drilled in the Ruhuhu Trough.

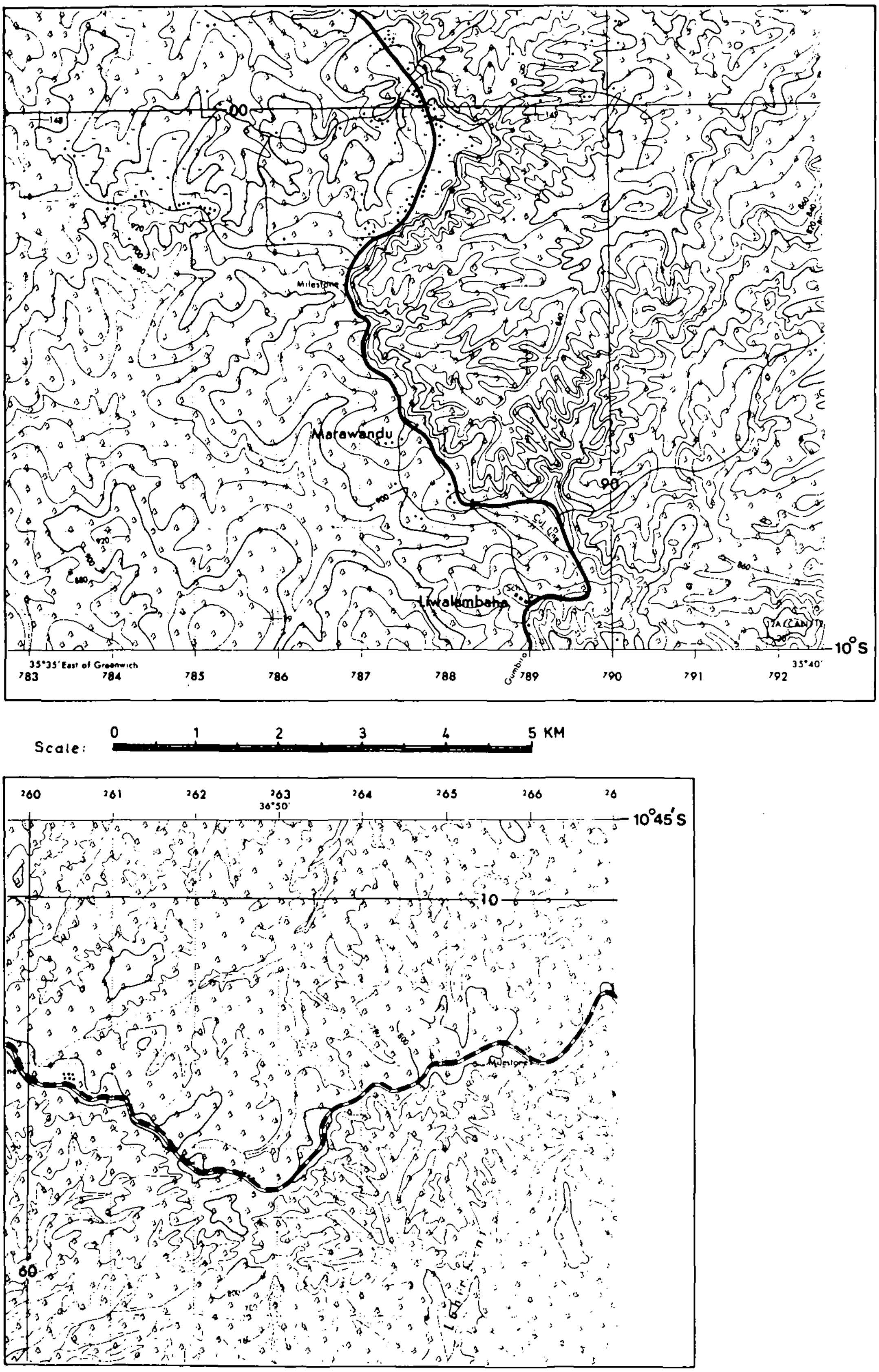


Figure 7.23 Sections showing characteristical Karroo topography and drainage patterns along the Njombe-Songea Road crossing the Ruhuhu Trough (top) and along the The Songea-Tunduru Road crossing the Tunduru Basin (bottom).

The base flow regime of the rivers is predominantly influenced by springs throughout the year and predominantly at the end of the dry season. Groundwater is discharged to the rivers along the lower courses as the groundwater level coincides with the water level in the rivers. Thus, a river draining the Karroo sediments should have a slow recession and percentagewise a high base flow component.

As an example the hydrograph of the Hanga River at Station 1RB11 is shown in Figure 7.24. The catchment area is 1400 km^2, mainly covering Karroo sediments in the eastern Ruhuhu Trough. The mean annual rainfall is 1200 mm. The peak discharge based on monthly mean values is about 41 l/s/km^2, and the minimum flow is 3 l/s/km^2 in October. This indicates a minimum groundwater recharge around 90 mm/year or about 8% of the rainfall.

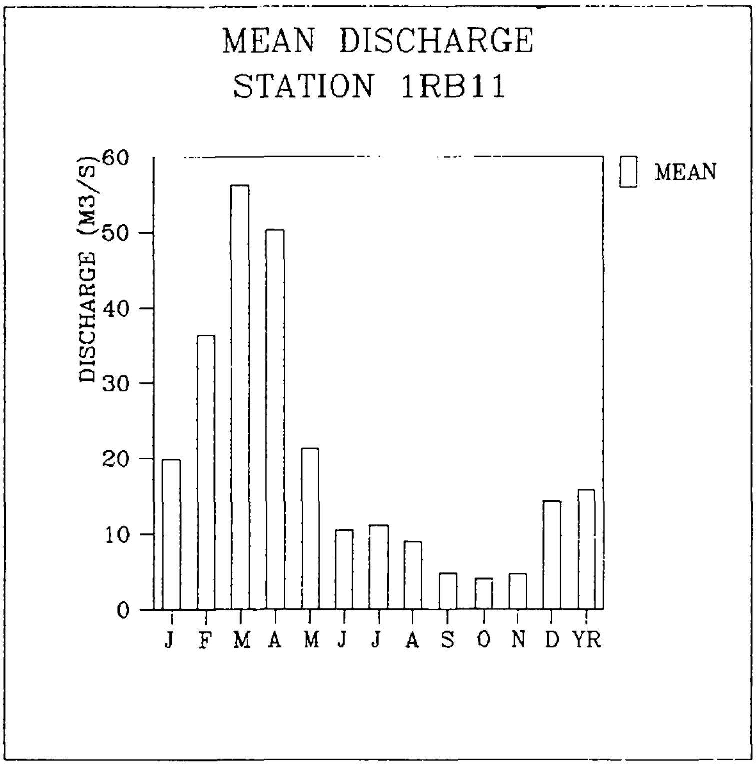


Figure 7.24 Hydrograph of the Hanga River at Station 1RB11.

To illustrate the base flow pattern in the Tunduru Basin, the hydrograph of the Muhowesi River at Station 1Q4 is shown in Figure 7.25.

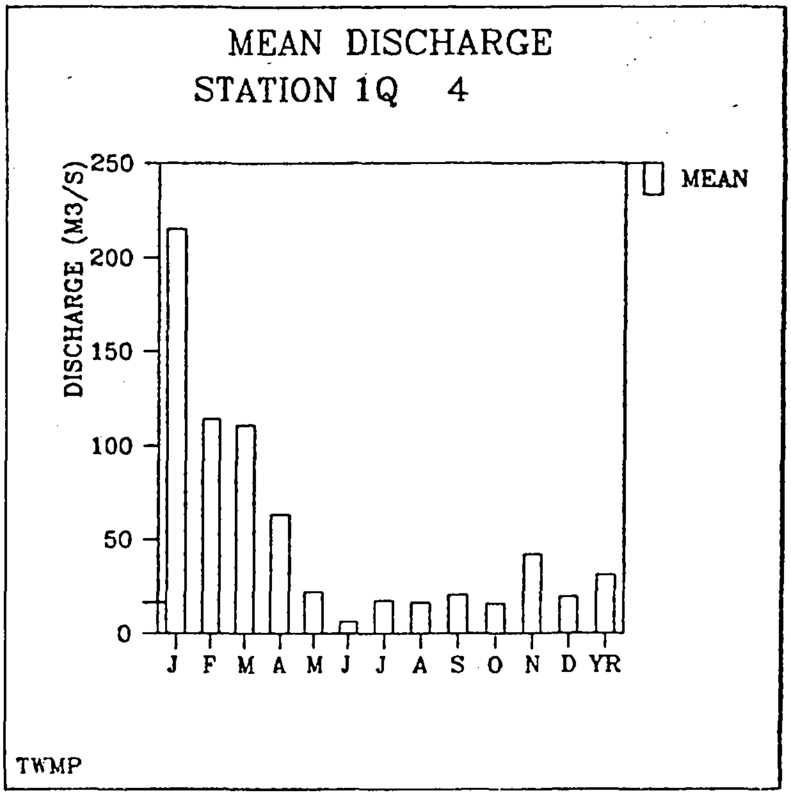


Figure 7.25 Hydrograph of the Muhowesi River at Station 1Q4.

The catchment area is 5960 km^2 solely on the Karroo. The mean annual rainfall is about 1000 mm. Based on montly mean values the peak discharge is about 36 $l/s/km^2$ and the minimum in October about 3 $l/s/km^2$. The minimum annual groundwater recharge accordingly is again about 90 mm or 9% of the rainfall.

Further observation of the streamflow hydrographs show that both exhibit a significant drop in discharge in June in relation to the May and July discharge. This is probably due to a consumptive use of the stream flows by large tracts of dense vegetation in the extensive swampy areas immediately upstream of the discharge stations.

7.8.4 Groundwater Level and Movement

The Karroo aquifers are principally intergranular aquifers with primary porosity. Secondary fissures were also struck in several boreholes. Over large areas the aquifers are considered stratiform although in detail they are composite aquifers with rapid vertical and horizontal changes in lithology and hydraulic properties.

Persistant clayey or marl horizons are found and these, if areally extensive, may result in overflowing artesian conditions as observed at Borehole No. 207/73 in the Tunduru District. Here overflowing groundwater was struck at 171 metres below ground.

The results of the Consultants' test drilling showed most of the water struck to be semi-confined. In no cases could water table (unconfined) conditions be definately identified.

The general depth to the piezometric water level in the boreholes drilled proved to be closely related to the local topography and local spring lines.

At Nandembo (BH.No. 258/81) in Tunduru and Mtukano (BH.No. 255/81) confined water was struck which had standing levels some 26 metres below ground; both holes are situated some 30 metres above the local spring lines.

The Karroo mudstones in Borehole No. 254/81 (Gumbiro) proved to have fracture porosity with water being struck at 36 metres and rising to 19 metres below ground. This hole was drilled within 30 metres of the local water divide.

The presence of local spring lines along many of the valleys cutting into the Karroo indicates the close hydraulic continuity between the surface and groundwater over most of the Karroo Basins. Groundwater flow is strongly directed towards the springs and depressions.

In the low-lying areas the rest water levels are shallow as would be expected, predominantly less than 4 m.b.g.l.

Based on one existing borehole (BH.No. 207/73) and the ones drilled by the Consultants, the water level frequency distribution has been calculated in Figure 7.26.

The limited number of wells available makes conclusions tentative, but it seems probable that the water levels are generally within reach of hand pumps.

7.8.5 Yield of Wells and Aquifer Hydraulic Properties

Five holes drilled in the Karroo were tested, three of these (BH.No. 253, 254 and 255/81) were drilled in the Ruhuhu Trough, and two (BH.No. 256 and 258/81) were drilled in the Tunduru Basin. In terms of geology and

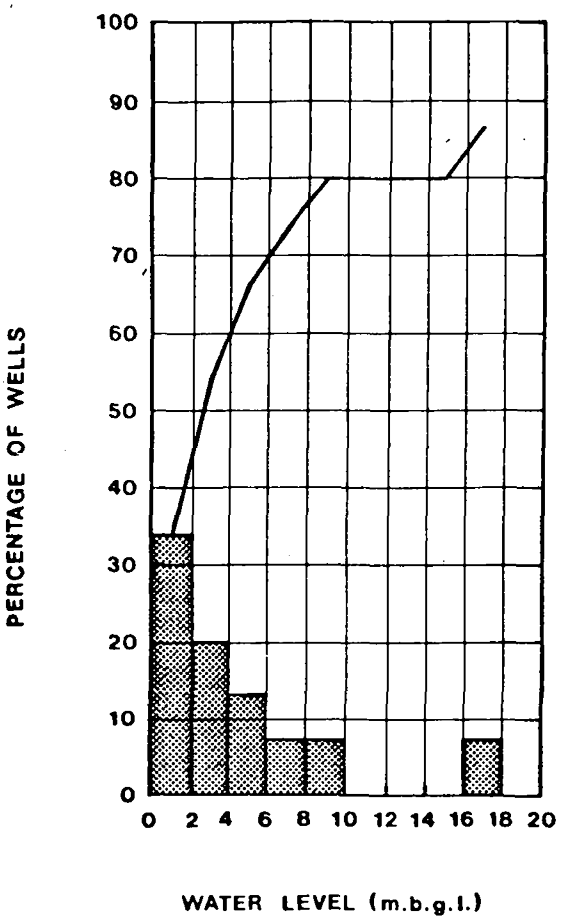


Figure 7.26 Water level frequency distribution (in metres below ground level) in wells drilled in the Karroo. Data from 15 wells.

aquifer characteristics three holes (BH.No. 253, 255 and 258/81) were drilled in the most typical Karroo arenaceous aquifers. These holes yielded 2.4 m^3/hr, 3.6 m^3/hr, and 5.3 m^3/hr, respectively.

Hole No. 254/81 was drilled into Karroo mudstones considered belonging to the Ruhuhu Beds and this less favourable aquifer resulted in a slightly lower yield of 2.1 m^3/hr.

Hole No. 256/81 was drilled into a basal member of the Karroo close to a basement high and yielded 5.3 m^3/hr.

Borehole No. 207/73 which is overflowing artesian was drilled in 1973 and gave on test 4.5 m^3/hr.

These results indicate that sufficient water for village water supplies can be expected from the Karroo. There is not sufficient data to make a reliable statistical analysis of the specific capacities. The specific capacities are listed in Table 7.5 together with the calculated values of hydraulic parameters.

BH No.	$T \times 10^5$ (m^2/s)	$r_w^2 S \times 10^3$ (m^2)	Q/s_w ($m^3/hr/m$)
207/73	0.45	1.2	0.045
253/81	-	-	0.037
254/81	0.43	-	0.066
255/81	20.0	-	0.60
256/81	5.4	5.1	0.48
258/81	77.0	-	8.03

Table 7.5 Aquifer hydraulic properties calculated from the straight-line method. Data from wells drilled in the Karroo. Symbols used are explained in Volume 10 A, Appendix 1, Chapter 5.

The specific capacities can be expected to be generally higher in the Karroo than in the Basement. The transmissivities are in the range of $0.4-77.0 \times 10^{-5}$ m^2/s and the coefficient of storage moderate.

7.8.6 Groundwater Chemistry

The analyses performed on water samples all show groundwater of high quality. Iron, manganese and fluoride have in all cases been clearly below accepted standards. Also the conductivity of the water is generally lower than found elsewhere in the regions.

In concluding this Section, it may be stated that the Karroo sediments appear to be a promising groundwater source. Perennial groundwater can be generally found. Rest water levels depend on the topography and are comparatively deep in elevated areas and shallow in the low-lying areas. Yields from tested wells indicate that the water bearing qualities of the Karroo are sufficient for village water supplies.

7.9 The Usangu Flats

7.9.1 Physiography

The Usangu Flats occupy the western end of the Buhoro or Ruaha Rift Valley. They lie in the east of Mbeya Region. The Flats are an area of recent deposition (an aggradational surface). They have a very low topographic relief and once formed the bed of Lake Buhoro.

During late Cretaceous and Palaeogene times the Usangu/Buhoro basin drained to the south. The Ndembera was then the major river of the basin. The southern drainage was dammed by the Neogene Rungwe Volcanic eruptions and Lake Buhoro was formed. Ultimately in the Neogene, Lake Buhoro overflowed through the narrow rock barrier at Utengule into the Ruaha River system. Lake Buhoro was then drained leaving the Usangu Flats behind.

The general elevation of the Flats is around 1065 metres and the elevation at Utengule where the Ruaha River leaves the Flats is just below 1020 metres.

The Flats cover some 4,500 sq.km. They are 150 km long and have a maximum width of 65 km. The mean width is 40 km.

The Flats may be divided into 5 main physiographic or geomorphological zones:

- The central seasonally flooded zone. This includes the Utengule Mbuga.
- The intermediate zone lying between the central zone and the outwash zone.
- The outwash zone fronting the steep scarps along the western end of the Flats.
- The Kimbi and Kioga Alluvial Fans, and
- The Madibira zone at the eastern end of the Flats.

These zones are shown on Drawing 7.1.

The Flats lie within the upper catchment of the Great Ruaha River. Seasonally flooded, the central parts of the Flats are poorly drained by a tangled and braided network of streams. The main rivers meander across the Flats, frequently changing their courses and beds. Figure 7.27 shows a typical segment of the central drainage pattern. An extensive mbuga or seasonal lake (Utengule Mbuga) occurs upstream from Utengule.

In the south, several major rivers rising in the Poroto Mountain and the Gofio Plateau cut across the intermediate zone of the Flats. These rivers carry a heavy sediment load and may change course during exceptional floods. Figure 7.27 shows a typical section of a river course crossing the intermediate zone (the Mporo River). To the north there are few large rivers cutting across the Usangu Escarpment from the African Surface to the Flats. Many short, ephemeral streams drain the Usangu Escarpment (Figure 7.27). These have deposited outwash and talus material along the foot of the scarp.

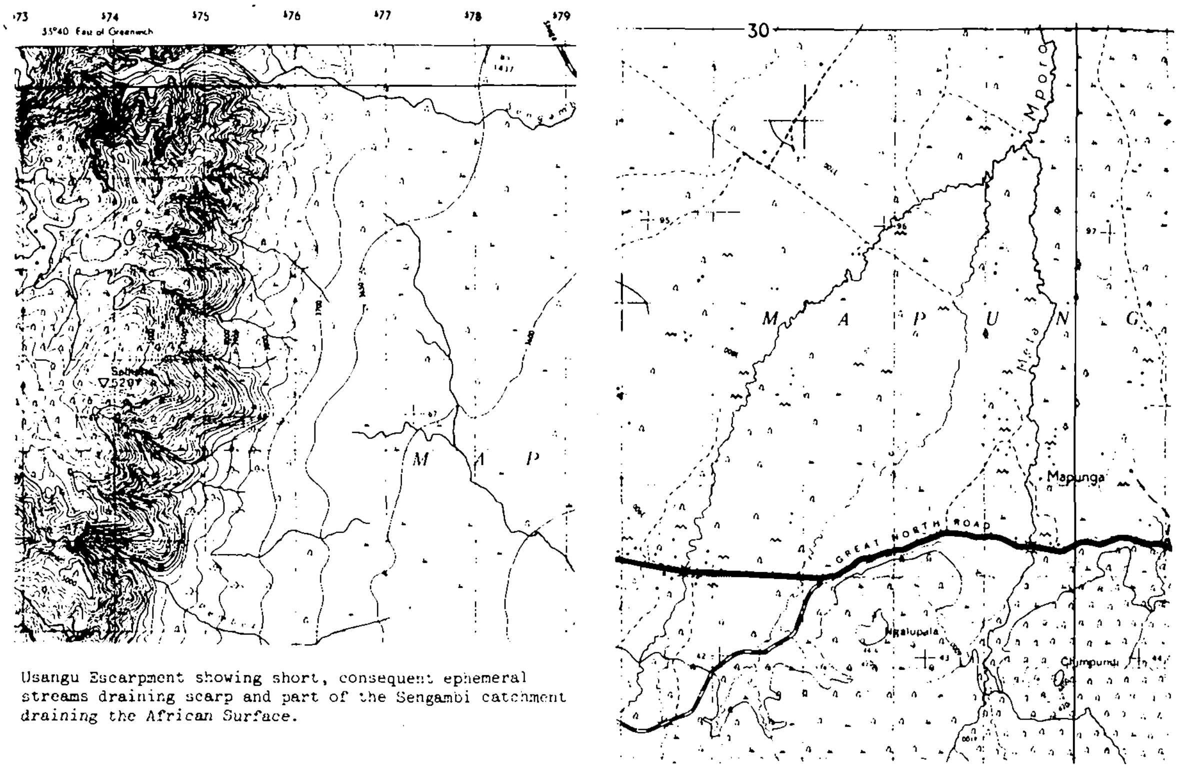
Figure 7.27 also shows the drainage pattern near the toe of the Kioga alluvial fan.

The eastern end of the Flats, the Madibira Zone, is a much more mature and well graded land surface, the rivers draining the surrounding post-African Surface having broad, shallow valleys opening out gently on to the Flats.

With an erratic and unreliable seasonal rainfall of between 400 and 600 mm, most of the Flats border from being sub-humid to semi-arid. The western end of the Flats, however, benefit from the aerographic effects of the Usangu Escarpment and the Poroto Mountains and has a rainfall approaching 800 mm.

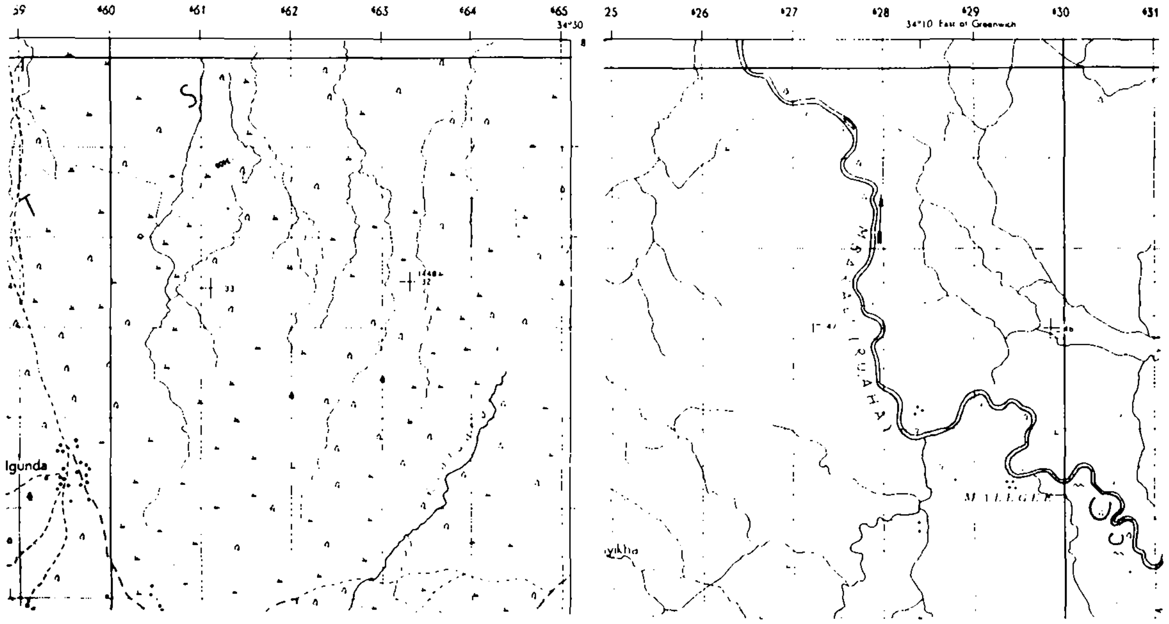
The soils across the Flats are derived from recently deposited colluvium and alluvium. The central areas of the Flats liable to flooding have dark grey, montmorillonoid soils with abundant calcium carbonate modules and concretions. These soils include the poorly drained mbuga or black cotton soils. On the slightly higher ground, forming the interfluves between the flooded areas, are light to medium brown, fine to medium grained sandy, silty alluvial soils.

The central, seasonally flooded areas have a persistant grass cover and are nearly treeless. The slightly higher interfluves have a thin to moderate thornbush (Acacia Fistula) scrub cover. The intermediate zone and low lying outwash zone of the Flats have a thick thorntree (Acacia Spirocarpa) and combretum thicket cover.



Usangu Escarpment showing short, consequent ephemeral streams draining scarp and part of the Sengambi catchment draining the African Surface.

Intermediate zone drainage.



Part of the Kioga alluvial fan.

Drainage of the central seasonally flooded area of Flats.

Scale 0 1 2 3 4 5 KM

Figure 7.27 Usangu Flats - Drainage Patterns. Areas shown are located on Drawing 7.1.

Considerable small scale irrigation farming practiced along the intermediate zone in front of the Chimala Escarpment and two large scale irrigated rice schemes are located in the same zone at Mbarali and Madibira.

7.9.2 Geomorphology, Geology and Structure

The provisional gravity map of Tanzania (Atlas of Tanzania (1967)) shows a characteristic negative Bouguer gravity anomaly associated with downwarped rifts for the area of the Usangu Flats. Regional mapping also indicates that the Buhoro rift faulting trend was initiated in the Bukoban Period of the late pre-Cambrian.

Subsequent tectonic movements along this rift took place in Karoo times, in the mid Tertiary and in the Neogene. These periods of rifting relate the Buhoro Rift with the Luangwa and mid-Zambezi Rift Valleys, see Figure 6.1. Little is known of the geological impact of the Karoo and mid-Tertiary movements along the Buhoro Rift. It is quite feasible, however, when comparison is made with the Luangwa, Rukwa and Ruhuhu rifts that a substantial thickness of Karroo sediments underlie the Buhoro Lake deposits.

The effects of the Neogene movements can be seen to the north and south of the western half of the Flats. In the north-west and north, the 300 metre high Usangu Escarpment marks the northern, normal rift fault, e.g. the Buhoro Rift. While this fault escarpment loses height to the east, it can be traced along the entire northern length of the Usangu Flats separating them from the post-African Surface (Drawing 7.1).

To the south, the normal Chimala Fault fronts the Poroto Mountains for some 15 km. The south western end of the rift is buried under various volcanic rocks of the Neogene Rungwe eruptions.

The south-eastern and eastern end of the Flats appear to have been little disturbed by the Neogene movements and they give way gently to the surrounding post-African Surface and the lower Ndembera river valley. (Cf. Section CD, Drawing 7.1)

Prior to the onset of the Neogene tectonics and the Rungwe Volcanics, the Usangu area had been relatively stable since the mid-Tertiary. The area was probably a mature pediplain and formed part of the post-African

Surface. The proto-Ndembera River draining southwards would have been well graded and very little erosion or sedimentation was taking place along its course. It may, or may not have been flowing over a Karroo outcrop.

The first phase of the Neogene tectonics resulted in sharp uplift of the areas around the western end of the Flats. These movements caused rapid rejuventation of rivers and heavy erosion in the Poroto Mountains, The Usangu Escarpment and the Mbeya Range. Piedmont alluvial and talus fans would have started to form and expand at the foot of the rift scarps in these areas. These piedmont deposits would have been in part reworked during Lake Buhoro times. The onset of the Rungwe Volcanic eruptions soon blocked the western end of the rift with basaltic and trachytic lava flows. Deposition in Lake Buhoro across the western part of the Usangu Flats would now include volcanic ash layers of various thicknesses interbedded with alluvial material. 16 metres of such horizontal lake beds comprising soft sandstones, siltstones and tuffaceous sediments are recorded around Chamoto Hill.

Towards the centre of the Flats an unknown thickness of white, soft, very light density, calcareous diatomite outcrops in the bed of the Mkoji River near Yala. This diatomite has been eroded and rounded by river action and has been re-deposited as a conglomerate immediately above the bedded diatomite. The conglomerate has an extremely fine silty clay matrix.

Ultimately Lake Buhoro both silted up and overflowed into the Great Ruaha river system at Utengule and the Usangu Flats were formed.

Since then medium and coarse alluvial and talus material continued to be deposited close to the scarp areas surrounding the western parts of the Flats while fine to very fine silts and muds were being deposited in the central areas. This fine material represents the suspended sediment load which is deposited as the slow moving rivers cross the central area.

Five boreholes (BH.Nos 205-209/81) were drilled in the central zone or along its edge by the Consultants. All the samples showed very fine grained sands and a large content of silt and clay. As a typical sequence, the strata log from BH.No. 209/81 is given below:

0- 1.5 m	Light cream, fine grained silt and sand of quartz and mineral fragments.
- 3.0 m	Dark grey silt.
- 4.6 m	Blackish grey clayey silt.
- 7.6 m	Off-white, very light grey calcareous sand, fine grained.
-15.2 m	As above, medium fine grained sand.
-18.3 m	As above, with some clay material.
-21.3 m	Light grey mud with some sand.
-24.4 m	Light grey mud and clay with dark brown lignitic/peaky material.
-30.5 m	Greenish grey clay with large calcareous modules and calcareous bands (limestones?).

Water was struck at 19.7 m b.g.l. and rose to 11.6 m b.g.l.

As indicated before the eastern and south-eastern end of the Flats were less disturbed by the Neogene Tectonics, indeed there is some geomorphological evidence that a north-west/south-east trending flexture axis runs across the Flats as indicated on Drawing 7.1. Two large alluvial fans, the Kimbi and Kioga Fans are found to the east of the flexture and it is possible that Buhoro Lake deposits are absent in the Madibira Zone or are at least confined to the very centre of the Flats.

The main evidence for this flexture axis is:

- The flexture fault mapped along the Halili River on Geological Map Sheet No. 247.
- The marked gravity anomaly interpreted as limiting the eastern limit of the down-warped area of the Buhoro Rift in Kennedy's draft map of the Tanzania Rift System (Kennedy, 1965).
- The evidence that the final elevation of the bed of Lake Buhoro in the western end of the Flats was above the present level of the Flats. There is an elevated tabular feature west of the Usanji River which is considered a remnant of the former Lake bed as are the Lake bed deposits preserved around Chamoto Hill. Late movement along the flexture caused the western parts of the Flats to rise relative to the eastern parts.
- Clearly defined fault traces are seen on ERTS imagery to the east of the flexture axis on the northern margin of the Flats near the Kimbi Fan.

Drawing 7.1 shows the main geomorphological feature and divisions recognized in and around the Flats and cross-sections A-B and C-D show the steep topographic contrast in the western end and the shallower contrast at the eastern end.

7.9.3 Hydrogeology

Due to the paucity of the groundwater data only a general assessment of the hydrogeology can be made.

The identification of the most likely aquifers in the Usangu Flats requires an appraisal of the unconsolidated Buhoro lake deposits and the alluvial and colluvial deposits. The water yielding properties of these unconsolidated sediments are controlled by their grain size and degree of sorting. Well sorted gravels and coarse sands are the best aquifers, fine grained muds and silts while having high porosities, have very low permeabilities and form aquifuges rather than aquifers.

From the outline of the geomorphology and geology given in the previous section it is possible to sub-divide the Usangu Flats into provisional hydrogeological zones. These are shown on Drawing 7.1.

Before discussing the hydrogeology of these zones it is necessary to consider briefly the factors controlling the deposition of the unconsolidated sediments across the Flats.

These factors are:

- The greater topographic relief between the highland areas surrounding the western end of the Flats compared to the eastern end. This means that vastly more outwash and alluvial material derived from the surrounding highlands has been deposited in the western end compared to the eastern end.
- The rivers draining from the Poroto Mountains are considerably larger and drain an area of very much sharper relief than the rivers draining to the flats from the north and east. Hence there should be better developed and coarser alluvial material extending along the south western parts of the intermediate zone of the Flats.
- The possible extent of Lake Buhoro. The Lake undoubtedly occupied the whole of the western end of the Flats but may not have covered

the entire eastern end. Lake deposits are usually very fine grained and often do not form good aquifers. Wave action on the lake shores also would have caused a reworking and redistribution of existing alluvial material, although alluvial fans would have extended from the western scarps into the Lake. It is possible that no great thickness of Lake beds have been preserved under the Flats.

- The spasmodic nature of the Rungwe Volcanic eruptions. This would have caused various thicknesses of ash beds to be deposited across the western end of the Lake beds. It is not known how far the volcanic ashes extend to the east.
- The palaeoclimatic changes of the area. Past pluvial periods would have produced more erosion and hence the deposition of thicker alluvial and outwash beds. Possible the Kimbi and Kioga Fans are a product of the last pluvial period (15-10,000 years BP) as they both now appear to be subject to erosion by their parent rivers, the Kimbi and the Kioga.
- Pluvial palaeoclimatic conditions meant more frequent changes in the river courses and hence a more favourable distribution of likely alluvial aquifers especially to the west of the Flats.
- At present it is not possible to determine the thickness of the unconsolidated material underlying the Flats, they have been stated to be more than 50 feet (15 metres) (Coster, 1961) but may be several hundred metres deep across the western end of the Flats. To the east of the Halili flexture, however, it is unlikely that any great thickness of unconsolidated material exists.

The Outwash Zone

This is the zone of talus and outwash fans that form the piedmont deposits along the western escarpments. The width of the zone varies from a few hundred metres to several kilometres. The thickness of the deposits are unknown. The deposits, though poorly sorted, are very permeable and have good porosity. The groundwater occurrence is intergranular and unconfined.

The upper parts of the fans are areas of high influent seepage of surface waters. The toe areas of the fans are zones of shallow groundwater or even groundwater discharge. The Yowela Spring (Drawing 7.1) for example is one of many springs discharging along the toe areas of the southern part of the outwash zone. In terms of groundwater resources these southern toe areas of the outwash zone are the most readily developed. Groundwater quality appears good (see analysis of Yowela Spring Water, Table 7.6). The situation along the outwash zone at the foot of the Usangu Escarpment is less clear. The zone is much narrower here though it may extend further out from the scarp under the alluvial material of the intermediate zone. There is some scant evidence that the water quality here may be only fair to poor. It is possible that saline juvenile water has ascended along the Usangu Rift Fault and is mixed with the meteoric groundwater (see analysis results for Mtiu, Mapogoro and Makondo - Table 7.6).

The Intermediate Zone

Over this zone vast amounts of medium to fine grained alluvial sediments have been deposited by the rivers draining the highland areas surrounding the Flats. Individual aquifers in this zone are mostly expected to be buried channel deposits. The subsurface position of these aquifers is hard to predict, the buried channels retain the same sinuous and interconnected courses as the modern surface channels. The thickness of the alluvial sediments across the intermediate zone is not known. It is possibly in the order of several tens of metres. If so there should be large thicknesses of water yielding strata distributed across the zone and most wells should encounter suitable aquifers even though the exact location of the aquifer zone cannot be predicted.

The groundwater occurrence in these aquifers is intergranular and semi- to completely confined. Well yields should be relatively high. The alluvial materials in the intermediate zone are expected to be best developed in the south-west in front of the Chimala Escarpment.

Water quality in the intermediate zone close to the Usangu Rift Fault may be poor for the same reasons as given for the outwash zone. There is a possibility of Rungwe volcanic and Buhoro Lake deposits being interbedded with the alluvial sediments of the intermediate zone. With no information available, however, only future drilling will establish whether this is so and what influence they have on the hydrogeology.

The Central Zone

On the surface, this zone is dominated by fine to ultra fine grained deposits, siltstones sands and clays. Much of the area is seasonally

Location of Sample		YOWELA SPRING	YOWELA SPRING	MAKONDO	MAPOGORO	MPIU
Coordinates		34°52'E 8°45'S	34°52'E 8°45'S	33°47'E 8°30'S	33°44'E 8°34'S	33°44'E 8°31'S
Source		SPRING	SPRING	DUG WELL	DUG WELL	DUG WELL
Date of Analysis		29.08.69	29.08.69	12.11.69	12.11.69	12.11.69
Appearance		Turbid	Slighty turbid	Turbid	Slighty turbid	Turbid
pH		7.4	7.1	7.7	9.0	8.6
Conductivity	m mhos	234	160.1	980	750	1400
TDS	ppm	178	135.	854	845	569
Calcium	ppm	4.0	4.8	36.0	8	30
Sodium		62.0	42.0	175.2	259.2	147.2
Potassium	-	10.5	8.5	8.61	33.2	14.7
Magnesium	-	3.8	13.0	17.0	4.9	19.5
Metals (Fe+Mn)	-	NIL	NIL	NIL	Fe 2.6 Mn 0	Fe 1.24 Kn 0
Chloride	-	4.0	4.0	15.7	14.7	14.7
Sulphate	-	-	NIL	5.8	45.2	35.0
Nitrate	-	trace	NIL	0.01	NIL	0.05
Carbonate	-	-	-	-	-	-
Fluoride	-	0.4	NIL	0.48	1.16	0.24
Free Amonia		0.88	0.01	0.039	0.078	NIL
Albuminoid Ammonia		1.30	0.40	-	-	-
Nitrite		0.2	NIL	0.01	NIL	0.09
Alkalinity as $CaCo_3$		108.0	88.0	574	716	424
Carbonate Hardness		30.0	66.0	210	40	155
Non-Carbonate Hardness		-	-	-	-	-
Total Hardness as $CaCo_3$		30.0	66.0	210	40	155
Remarks		Signs of organic pollution	Signs of organic pollution			

NB: Analysis performed at least 1½ months after date of sampling

Table 7.6 Groundwater chemical analyses from the intermediate zone flooded and concretionary material has collected at or very near the surface.

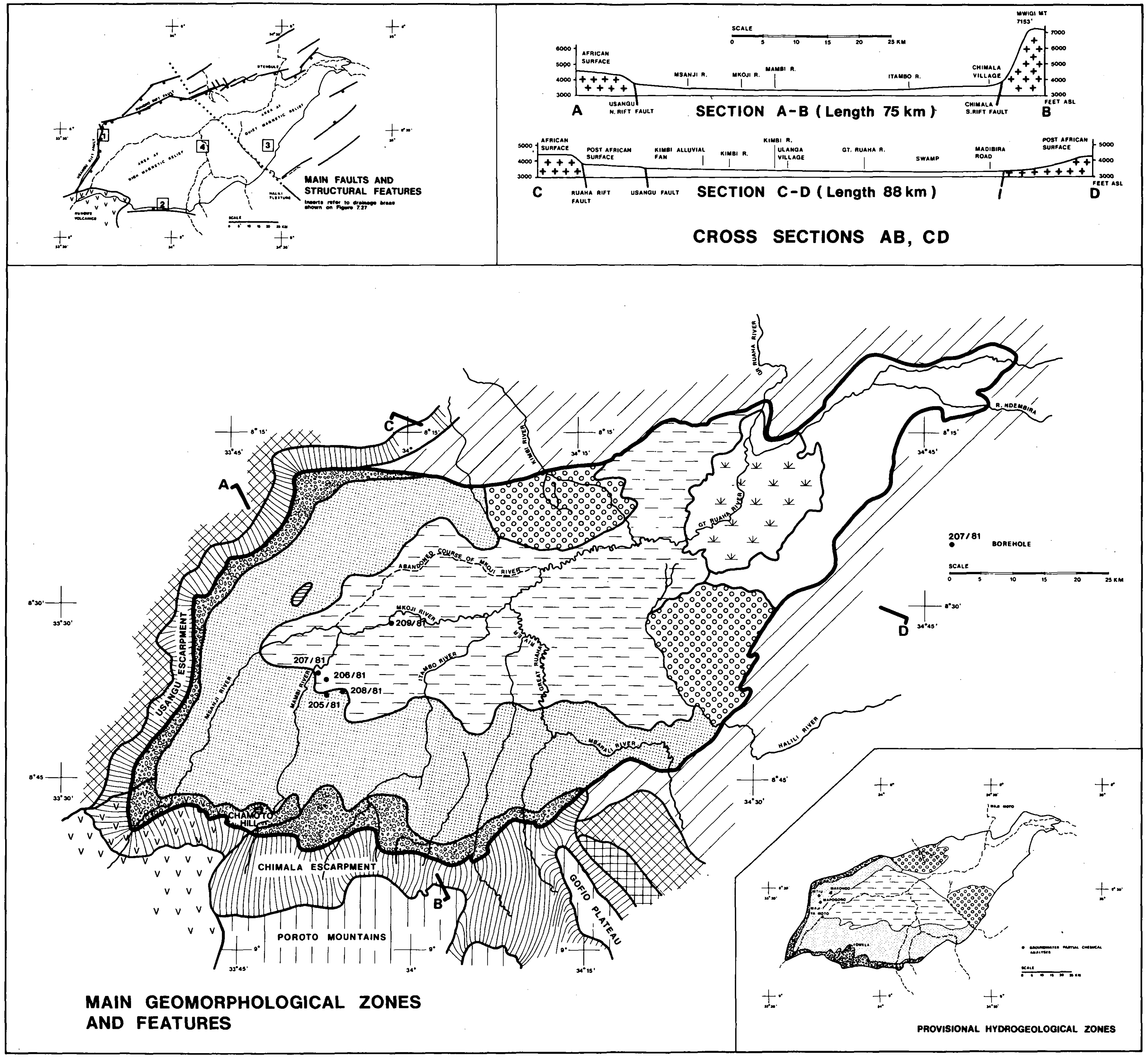
Even the main rivers crossing this zone carry only suspended material. No bedload of clastic material appears to be carried into the zone under present climatic conditions. The position may have been different during past pluvial periods and buried channel aquifers may occur at depth. The position of such potential aquifers is even more difficult to predict than in the intermediate zone. Once again, the thickness of the unconsolidated material across this zone is unknown. The Rig 53 drilling shows depths of more than 30 m, but the actual depths may be several hundred metres. There is evidence that the central zone is recharged by the rivers crossing it. Flow records show that the Great Ruaha river loses water as it flows across the Flats. This groundwater recharge from the influent streams and rivers probably reappear in and around the Utengule Mbuga. It may therefore be expected that there are large groundwater bodies at depth across the Flats, suitable for development.

The chemical analysis from the Project boreholes in the central zone show that groundwater is meteoric mixed with juvenile water. The in places high content of fluoride is an indication of juvenile water issuing from fractures below the Lake beds, and this seems to be the only factor that might constrain a future groundwater development across the Flats.

The Kimbi and Kioga Alluvial Fans

These two fans have very little topographic expression: They are, however, clearly distinguished on ERTS imagery. Lithologically the fans appear to be composed of medium fine to fine sands. Both the Kimbi and Kioga rivers flow across mature post-African surfaces although Neogene Tectonics has caused some major rejuvenation of erosion along parts of their courses.

This coupled with past pluvial periods, may have introduced coarse sediments with the fan deposits and there will be major aquifer prospects. Apart from numerous water holes that are recorded along the toe of the Kimbi fan no other groundwater information is available at present. It is felt, however, that the Kimbi fan in particular may prove to have a valuable groundwater resource suitable for development.



THE USANGU FLATS

LEGEND

MAIN GEOMORPHOLOGICAL ZONES AND FEATURES

GONDWANA SURFACE
POST - GONDWANA
AFRICAN SURFACE
POST-AFRICAN SURFACE
SCARP
OUTWASH ZONE
INTERMEDIATE ZONE
CENTRAL ZONE
UTENGULE MBUGA
KIMBI AND KIOGA FANS
LAKE BED REMNANT
MADIBIRA ZONE
RUNGWE VOLCANICS

PROVISIONAL HYDROGEOLOGICAL ZONES

OUTWASH ZONE
INTERMEDIATE ZONE
CENTRAL ZONE
MADIBIRA ZONE
KIMBI AND KIOGA FANS

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Drwg. no. 7.1

The Madibira Zone

As previously discussed this zone is considered to have been relatively stable during the Neogene. The Kimbi and Kioga Fans are considered to have been laid down on the stable Madibira part of the Flats. Otherwise sedimentation across this zone will have been controlled by palaeoclimatic changes and recent tectonic activities along the Madibira, Ndembira, and other rivers draining the African and post-African Surfaces to the east and north. Considerable amounts of surface water are brought on to this zone by these rivers and any aquifers that may exist should provide good quality and reliable groundwater supplies.

7.9.4 Yields of Wells

Knowledge about the yields of wells drilled into the Lake beds is limited to the information obtained from the test pumping of the three successful Project boreholes (205, 208, 209/81). The discharge from these wells were 1.0-1.9 cu.m/h, but would have been considerably more, had the Rig been able to drill deeper.

The expected specific capacity frequency distribution for wells across the Flats can be read from Figure 7.31, which includes data from wells drilled into alluvium, colluvium and Lake beds. The experience so far indicates a sufficient potential for a groundwater solution across the Usangu Flats, and more than 90% of the wells striking water will have sufficient yields for a hand pump implementation.

7.10 The Rukwa Trough

7.10.1 Physiography

The Rukwa Trough is situated in the western part of Mbeya Region and is an approximately 380 km long section of the Western Rift Valley. Being of recent deposition the Lake Beds in the trough form an aggradational surface.

The mean width of the trough is about 45 km. A maximum width of about 68 km is reached in the southern part just before the trough is divided by the Mbozi Plateau into the Songwe and Msangano Troughs (Drawing 7.2) The Trough covers some 15,000 km^2, about 20% of which is occupied by the retreating Lake Rukwa. Some 7000 km^2 of the Trough are situated within the Mbeya Region.

Because of its mode of origin the floor of the Trough has a very low topographic relief with a general elevation of 915 m.a.s.l. The southern part of the Songwe Trough is somewhat more elevated because of later uplifts where Lake Beds are found at a level up to 1065 m.a.s.l.

The Rukwa Trough may be divided into four physiographic or geomorpholoical zones (Drawing 7.2):

- The central seasonally flooded zone. The area of this zone is highly variable. After several consecutive dry years the Lake divides into two parts.
- The Younger Lake Beds.
- The Older Lake Beds and fluviatiles.
- The outwash zone fronting the Rukwa and Ufipa Scarps and Mbeya Range.

These zones are shown on Drawing 7.2. The central zone is drained by a tangled and braided network of streams. The main rivers: Songwe, Sira, and Momba meander across the Trough changing their course during exceptional floods.

The rainfall across the trough is between 700 and 800 mm in the Mbeya part of the Trough. Evaporation and evapotransporation consume a large part of the rainfall. The part that recharges groundwater bodies is finally evaporated from the Lake.

The upper metre or so of the Lake Beds have been reworked to form a soil cover of fine sands and silts. In the Songwe Valley the Lake Beds have an obscuring ash cover. Outwash material is areally limited because of the high levels of the Lake during the Pleistocene pluvial periods. Along the Rukwa Scarp these deposits are predominantly alluvial fans but along the Ufipa Scarp they are mass waste.

In the central part of the Trough the soils have imperfect drainage, and the remaining part soils have moderately good drainage.

Seasonally flooded marsh and swamp border the Lake and extend up the lower course of the Momba River. Open grassland covers the central part of the trough. The slightly higher surrounding areas have a thorn bush and thorn tree cover.

7.10.2 Geomorphology, Geology and Structure

Structurally, the Rukwa Trough is a continuation of the Nyasa Rift Valley, and is defined by the north-west/south-east Rukwa and Ufipa Fault Scarps. The movement on the rift faults began in pre-Karroo times and continued intermittently until recent times.

The three main fault lines resulting in the Rukwa, Ufipa, and Songwe Scarps (Drawing 7.2), respectively, are of mainly late-Tertiary, Jurassic and pre or early-Cretaceous age.

The Rukwa fault-line scarp rises 100-170 m above the Lake Beds and is remarkably fresh partly because it has been protected by the high level of the Lake. The fault has been reactivated during the Neogene and fault lines can be observed cutting the fans along the foot of the scarp.

The Ufipa Scarp, rising to about 1500 m above the Trough, has been subject to little erosion and it is, therefore, believed that the main movement along this fault also took place during the Neogene.

The Songwe Scarp is a mature feature and probably has not been reactivated in Neogene times because no faulting is observed in the Cretaceous and Karroo rocks along the foot of the scarp.

The transition from the Mbozi Plateau to the Msangano Trough is gradual due to a large number of parallel faults. They are believed to be of pre or middle-Cretaceous age because the escarpments are planed off by the late-Cretaceous pediplanation (the African erosion cycle).

The provisional gravity map of Tanzania (Pallister, 1965) and aeromagnetic mapping indicates a considerable thickness of 2000-2500 metres of Cretaceous and post-Cretaceous aged sidements. These are possibly underlain by Karroo sediments. Prior to the onset of the Neogene tectonics the area was a mature pediplain and formed part of the African Surface.

Up to Pleistocene times Lake Rukwa discharged into Lake Tanganyika through a narrow gap at Karema. Downwarping of the Trough in the Pleistocene then created the dischargeless Rukwa Basin. The sedimentation of the Lake has happened quietly, resulting in fine grained Lake Beds.

The Older Lake Beds were deposited when the lake occupied the whole of the depression, and consist of green clays and sandy diatomite clays (Coster 1960). They are present in the Songwe Trough and are estimated to be up to 180 m thick. Their level in relation to the central part of the Trough indicates that they have been uplifted.

The Younger Lake Beds occupy the central part of the Trough and consist of fine sands and silt. The shifting courses of the main rivers may be responsible for interbedded coarse material at various depths. The thickness of the Younger Lake Beds can be estimated from the two boreholes at Ivuna (BH No. 18/52 and 30/52) where the Lake Beds obtained thicknesses of 70 and 80 m, respectively.

BH No. 161/78 at Magamba showed 69 m of Lake Beds. This hole was hole was still penetrating the Lake Beds when drilling stopped.

Along the foot of the scarps alluvial fans and talus deposits are present to some extent. The infrequent occurrence of these deposits are due to the fact that the Lake level has been high during the pluvials, thus protecting the scarps against erosion. The main alluvial fans are found along the Rukwa Scarp and hill outwash and talus occur along the Ufipa Scarp and along Mbeya Range fronting the Songwe Valley.

7.10.3 Hydrogeology

As with the Usangu Flats, the hydrogeology of the Rukwa Trough must be based mainly on geological considerations since little borehole data is available.

Based on the geomorphology and geology given in the previous section the Rukwa Trough is subdivided into four provisional hydrogeological zones which follow the physiographical zones discussed earlier.

The water bearing qualities of the deposits across these zones are determined by the factors controlling the deposition of the sediments. These factors are:

- Rejuvenation of the rivers draining the plateau to the east of the Rukwa Scarp which has resulted in alluvial fans. The rivers draining this plateau have larger catchments than the rivers draining the Ufipa Plateau, and carry more sediments. Hence there should be better developed and coarser alluvial deposits extending along the Rukwa Scarp.
- The Rungwe volcanic eruptions have caused various thicknesses of ash beds to be deposited across the Songwe Trough. It is not known how far the ashes extend into the Trough.
- Pluvial palaeoclimatic changes have resulted in frequent changes in the river courses with a possible favourable distribution of alluvial aquifers, especially in the areas of the Songwe and Momba Rivers.

The Outwash Zone

The most prospective outwash zones are the alluvial fans along the Rukwa Scarp. These have been deposited after the Lake has retreated and may be some 20 metres thick. Across these fans rivers are influent, and the aquifers are replenished by seepage. The alluvial material is coarse and well suited for groundwater development. The outwash zones along the Ufipa Plateau and Mbeya Range are more mass waste than alluvial deposits. They are still prospective groundwater sources, although in terms of hydraulic permeability they are not as good as the fans.

The Older Lake Beds

As these Beds were formed when the Lake filled the Trough, they consist of very fine material which forms poor aquifers. They are overlain for a large part by basaltic lava flows and fluviatile deposits containing volcanic silts. Rivers have eroded deeply into the Lake Beds, and due to the elevation of these Beds in relation to the central part of the Rukwa Trough, groundwater is expected to be deep, and the rivers are most probably influent across this zone. The Discharge Station 3A17 on the Songwe River clearly shows a loss in relation to stations up stream as the river flows across the Lake Beds. This water later appears again in the central part of the Trough as groundwater.

The Younger Lake Beds

Areally the Younger Lake Beds occupy the largest part of the Rukwa Trough. Over large parts the meandering rivers are believed to be influent, and accordingly groundwater recharge should occur from this source. Also groundwater that is ultimately evaporated from the Lake crosses this zone. From a resource point of view the younger Lake Beds, therefore, offer a good prospective of groundwater development. The water levels in the three wells drilled in this zone (BH'No.18/52, 30/52, and 161/78) show that groundwater is situated 8-10 m below ground level. The shifting river courses may have resulted in the deposition of coarse alluvium at various depths. The sand and gravel deposits found in BH No. 161/78 are probably one of such buried river channels.

The drainage of the Younger Lake Beds is in many places intermittent towards the scarps, indicating groundwater recharge by influent streams. In the central part many small streams appear again discharging groundwater to the Lake.

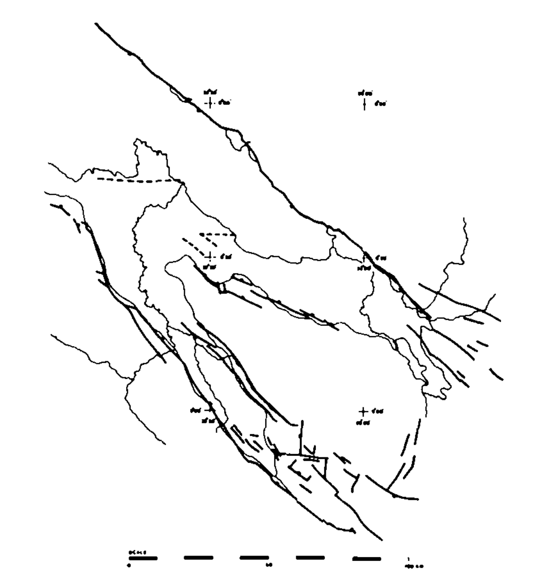
The Central Zone

In the central seasonally flooded zone the slowly flowing rivers have deposited the finest sediments, silts and mud. The water bearing quality of the Lake Beds in the central zone may be considered the poorest in the Trough. The prospect for tube wells is not promising but it may be possible to obtain groundwater from large diameter ring wells. It has not been verified by drilling whether the Lake itself is effluent or influent. It can be expected that the Lake level represents the groundwater level of the central zone, and accordingly groundwater would be shallow.

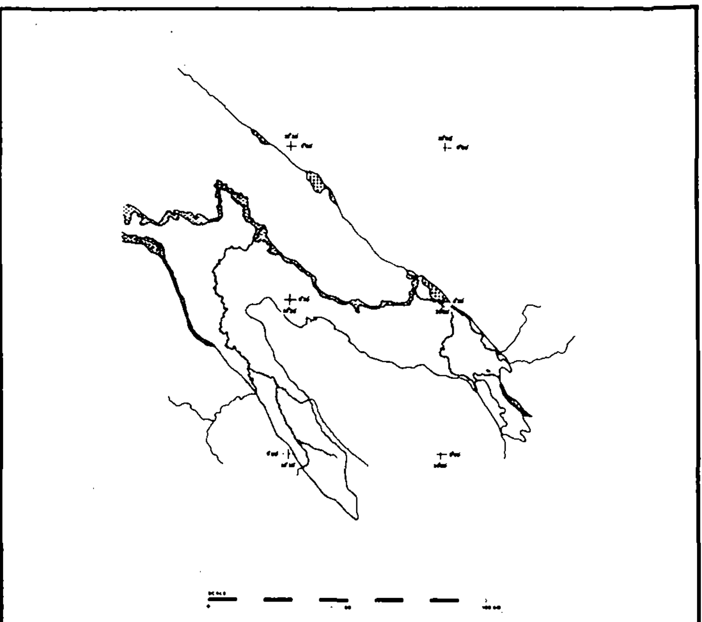
7.10.4 Yield of Wells

The aquifers in the Lake Beds of the Trough are intergranular, and the porosities and hydraulic conductivities accordingly follow the general statistical rules controlling the distribution of these parameters in such deposits.

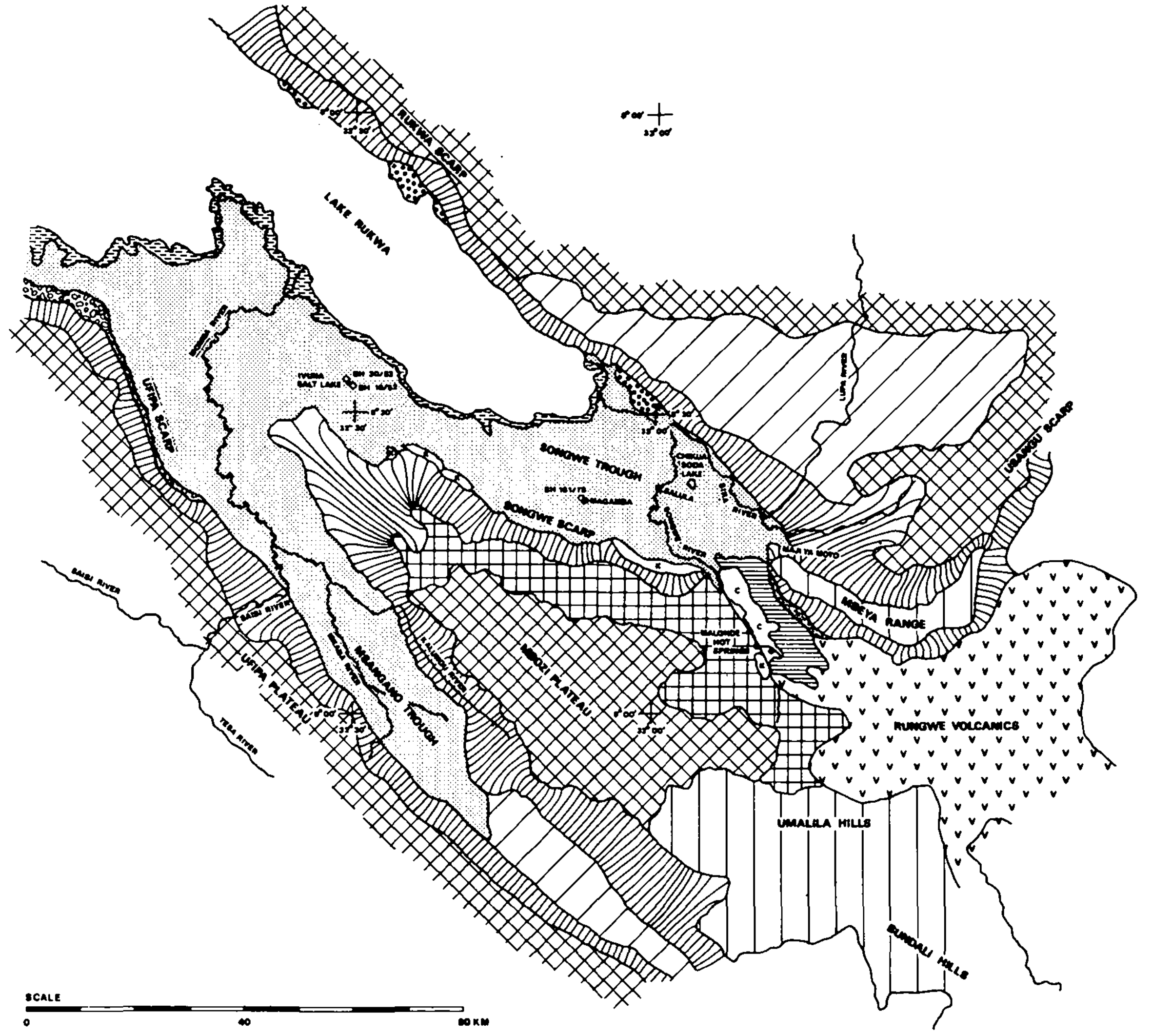
The yields from the three wells drilled in the Trough are in the range 2-12 m^3/hr. The specific capacity frequency distribution can be found from Figure 7.31 which includes wells from alluvium, colluvium, and



MAIN FAULTS AND STRUCTURAL FEATURES



PROVISIONAL HYDROGEOLOGICAL ZONES



MAIN GEOMORPHOLOGICAL ZONES AND FEATURES

THE RUKWA TROUGH

MAIN FAULTS AND STRUCTURAL FEATURES

— FAULT, MARK ON DOWNTHROW SIDE

- - - FAULT, INFERRED FROM AEROMAGNETIC MAP

PROVISIONAL HYDROGEOLOGICAL ZONES

☐ OLDER LAKE BEDS AND FLUVIATILES

☐ YOUNGER LAKE BEDS

▨ CENTRAL FLOODED ZONE

▨ ALLUVIAL FANS

▨ OUTWASH ZONE

MAIN GEOMORPHOLOGICAL ZONES AND FEATURES

○ BOREHOLE

▥ GONDWANA SURFACE

▦ POST-GONDWANA SURFACE

▩ AFRICAN SURFACE

▨ POST-AFRICAN SURFACE

▥ SCARP

▤ OLDER LAKE BEDS AND FLUVIATILES

▨ YOUNGER LAKE BEDS

▨ CENTRAL FLOODED ZONE

▨ ALLUVIAL FANS

▨ OUTWASH ZONE

v v v RUNGWE VOLCANICS

K K KARROO

C C CRETACEOUS

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Drwg. no. 7.2

Lake Beds. Experience so far indicates sufficient potential for a groundwater solution across the Rukwa Trough, and more than 90% of wells striking water will have sufficient yields for hand pump implementation.

7.10.5 Groundwater Chemistry

The chemical quality of the groundwater from the Rukwa Trough is not known in detail. The presence of the Ivuna Salt Lake which contains salt water issuing from a deep-seated fracture indicates that juvenile water may be expected. The Soda Lake in the Songwe Trough also bears witness of local poor groundwater quality. In general a large amount of dissolved solids can be expected in the groundwater due to the evaporation.

Where the groundwater flow is large, i.e. in coarse material such as buried river valleys, a considerable improvement of the groundwater quality may be expected in relation to the areas with poor permeabilities. The groundwater quality of the outwash zones and of the alluvial fans are expected to be good.

7.11 The Rungwe Volcanic Province

7.11.1 Physiography

The topography of the area is dominated by the volcanic activity during the Neogene. The largely uneroded volcanoes form the major topographical features with the largest central volcano, Rungwe, standing at almost 3000 metres above sea level.

Volcanic ashes from the Rungwe eruptions can be traced 30-40 km from the centre, leaving a very fertile soil cover over this area. This, combined with a mean annual rainfall up to 2400 mm at Tukuyu results in a very dense natural vegetation and a good agricultural potential. Tea, coffee, potatoes, bananas, and citrus fruits are the main crops. The natural vegetation is grassland in the more elevated areas. Forest is widespread, and on some craters and areas up to 2500 metres above sea level rain forest is found.

The temperatures in the area are because of the elevation moderate. The highest temperatures occur in the low-lying areas, but they seldomly are above 30°C. The elevated areas have temperatures up to about 25°C, and down to the freezing point during extremely cold nights.

7.11.2 Geology and Structure

The Rungwe Volcanics have been divided into two main groups, the Older and the Younger Extrusives. The volcanic activity associated with the Older Extrusives is assumed to have commenced in late Pliocene times. It has not been possible to locate exactly the particular centres of eruption, although much of the material came from the Poroto and Katete groups of volcanoes. The Older Extrusive rocks are lavas in the trachyte to phonolyte range and a large variety of basaltic rocks. Tuffs are found at the surface in the Kiwira River Valley and in the Elton Plateau, otherwise they are buried beneath lavas and tuffs originating from the Younger Extrusives.

The Younger Extrusives can be referred to the activity of three major centres of eruption, Tukuyu, Kiejo, and Rungwe. Basalts and phonolitic trachytes are the main rocks, and widespread pumice and ash from the final activity of Rungwe forms an obscuring cover of the volcanic province and the surrounding Basement Complex.

The structure of the area is heavily influenced by the rift faulting. All major faults are parallel to the faults forming the Nyasa Rift. Numerous explosion craters, some of which hold lakes, are situated on the fault lines as well as hot springs.

7.11.3 Infiltration and Drainage

The infiltration conditions and the drainage pattern of the Rungwe Volcanics differ considerably from those found elsewhere in the study regions. The volcanic ash cover which in some places attains considerable thickness provides a very porous soil surface with a high infiltration capacity. This, combined with a dense vegetation, reduces overland flow in relation to more clayey top soils. It also results in little soil erosion, and the landscape is still in a very young stage of development. Rivers run in narrow valleys, basaltic rocks are commonly seen in the river beds. Even during heavy rains the rivers carry almost clear water because of the little soil erosion, and the sediment transport and suspended load is consequently small.

The typical drainage pattern in the Rungwe Volcanics is consequent parallel drainage originating from the central volcanoes Rungwe, Ngozi, Tukuyu, and Kiejo, where the drainage pattern is initially radial. Practically all streams in the area are fed by springs and are perennial.

Because of their young age the volcanic rocks are little weathered, and groundwater can be stored only in fractures in the fresh rock or intergranularly in the volcanic ashes. Springs are of the contact and fissure type. Contact springs are the most common, the zone of contact being the sharp transition between ash and fresh rock.

Because of the heavy rainfall around the central volcanoes, rivers have a comparatively high peak discharge. Overland flow plays a minor role, and interflow is important only during a few days after a rain. Groundwater recharge is large, and the river runoff is purely base flow shortly after the rains have terminated. The base flow is largely sustained by springs.

The discharge pattern is illustrated in Figure 7.28 which shows the mean monthly discharge of the Mbaka River at Station 1RC3A which is situated on the alluvial plains at the northern tip of Lake Nyasa. The catchment area is 645 km^2, almost exclusively in the volcanic rocks, with a mean annual rainfall around 2200 mm.

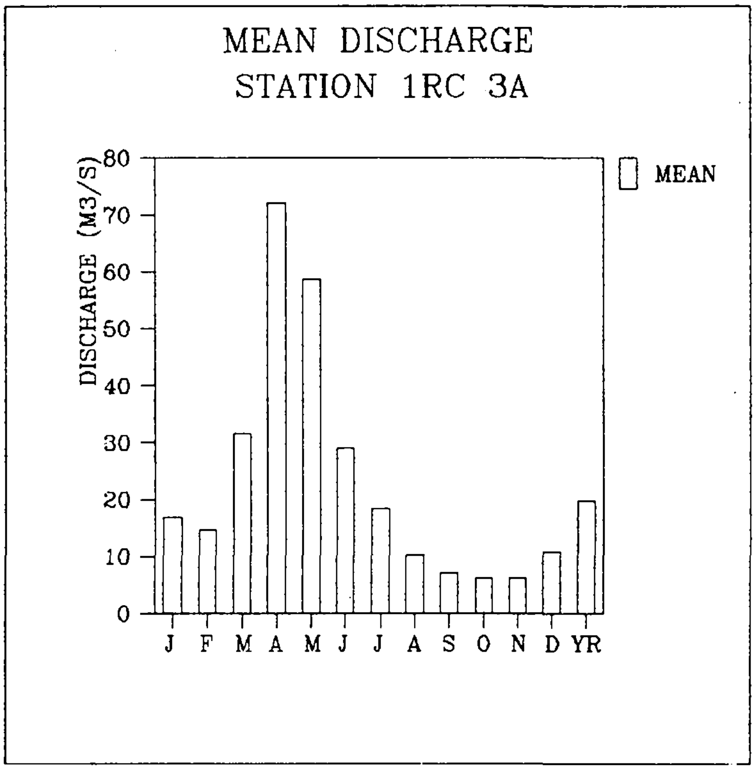


Figure 7.28 Hydrograph of the Mbaka River at Station 1RC3A.

The peak discharge is around 112 $l/s/km^2$, and the minimum discharge in October is around 10 $l/s/km^2$. This corresponds to a minimum annual groundwater recharge increment around 310 mm or about 14% of the rainfall.

At Station 1RC8A on the Kiwira River the mean annual rainfall is about 1700 mm and the catchment area of 655 km^2 is exclusively over volcanic rocks. The peak discharge (Figure 7.29) is about 100 $l/s/km^2$, and the minimum discharge in October is 14 $l/s/km^2$, corresponding to a minimum annual groundwater recharge increment around 440 mm or 26% of the rainfall.

The difference between these two catchments is explained by inspecting the hydrograph of the Kiwira River at Station 1RC2A situated about 50 km south of Station 1RC8A on the alluvial plain. Here the peak discharge is 106 $l/s/km^2$, and the minimum in October 13 $l/s/km^2$, corresponding to a minimum annual groundwater recharge around 416 mm. Between the two stations several tributaries join the Kiwira River, and excluding the possibility of major areal discontinuities within the Kiwira catchment the explanation must be a loss of surface flows to the groundwater bodies of the alluvial plains as the rivers cross the boundary between these and the volcanic rocks. The rivers (Kiwira, Mbaka and Lufirio) thus are influent across the alluvial plains, at least during the dry season, and the total loss is probably in the order of 100 mm/year.

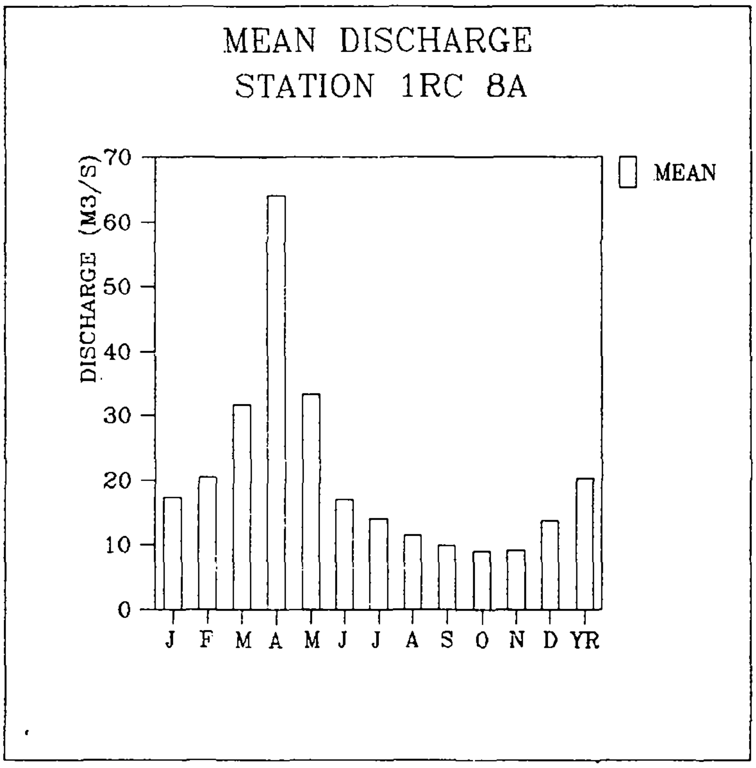


Figure 7.29 Hydrograph of the Kiwira River at Station 1RC8A.

From the Kiwira Index Catchment (Station 1RC5A) similar calculations indicate a minimum annual groundwater recharge of 405 mm/year. Hydrologic modelling (Volume 7) indicates a groundwater recharge of 639 mm/year in a medium wet year which shows that the minimum estimate of 405 mm made here would be closer to the actual values if they were increased with about 50%. This is due to an under-estimation of the groundwater recharge during the rainy season in the 405 mm value.

7.11.4 Groundwater Occurrences and Quality

Two water wells have been drilled in the Rungwe Volcanics, BH No. 3/40 and 15/69, both close to Mbeya. The yields were 3.6 and 9.1 m^3/h, respectively, and the standing water levels 36.6 and 80 metres, respectively. This indicates that the groundwater conditions in the volcanic rocks are unpredictable and probably controlled strongly by topography and structure.

Due to the young age of the volcanic rocks there is very little weathering, and accordingly, no saprolite horizon to store groundwater. Groundwater, therefore, must be found in the volcanic ashes, pumice and tuffs, or in fractures in the fresh rock. No drilling experience in the area is available to form a basis for guidelines, so at this stage it can only be stated that drilling in loose unconsolidated deposits should take place in low-lying areas, and that drilling in hard rock should be based on the occurrence of fractures, preferably in topographic lows as well.

At an early stage of the study it became apparent that the water supply in the Rungwe Volcanic Province should be based on the abundancy of fresh springs. The majority of villages can be supplied from this source by gravity systems, and since these springs are emerging groundwater of good quality it does not seem practical or economical to try to extract groundwater by means of wells.

In addition, the topography of the area makes a groundwater solution based on wells difficult and in many areas impossible. Spring water has a short retention time compared to deep-seated groundwater and is of much better quality. The deep and probably some of the shallow groundwater as well will often have a chemical quality unsuitable for human consumption because of high amounts of dissolved solids and in some places gases. This contamination is coming from deep-seated fractures leading to hydrothermal water sources. Where this occurs, locating aquifers with potable water is difficult, especially if there is no surface evidence of such hydrothermal contamination such as explosion craters or hot springs.

7.12 Alluvium and Colluvium

7.12.1 Physiography

Alluvium and colluvium are superficial deposits laid down by rivers or under the influence of gravity.

Alluvial plains and fans are because of their mode of deposition topographically very smooth areas. Colluvium is essentially weathered material transported by gravity or hill wash. It forms the transition between escarpments and plains or pediplains and has, therefore, gentle to steep hill slopes. Because the soils are predominantly coarse grained, especially in alluvial deposits, the vegetation across alluvium and colluvium is generally grass and bush.

These deposits are found everywhere along faults and escarpments. Notably they occur in the Rift Valleys where the most pronounced activity has taken place. The most extensive alluvial plain is situated in the northern end of the Ruaha Valley, but alluvium is common elsewhere in the valley. Large fans have developed along the escarpments defining the extent of the Usanga Flats.

Alluvial plains have good prospects for irrigation, but a conflict occurs because such plains are often liable to destructive flooding.

7.12.2 Lithology

Because alluvial deposits are a result of sedimentation by running water, the coarse material is deposited where the flow is most rapid, i.e. in the apex area(s). Alluvial plains and fans have a convex slope, and the thickness of the deposits decreases with the distance from the apex(es). Drilling in the regions indicate that the actual thickness in some places exceeds 30 m, and any thickness smaller than this can be found.

During the process of deposition of the sandy alluvium, clay and silt particles are carried away by the streams as suspended solid, and the alluvium is consequently mostly fine and coarse sands and gravel. The alluvial deposits in the regions have probably been developed during the last Pluvial Period of the Pleistocene, and in some cases erosion by their parent rivers has taken place. In some cases (e.g. along the

Rukwa Scarp) later tectonic movements have caused some minor rejuvenation.

Colluvium is a result of mass waste and consists of rock fragments, scree, and mud which have been moved down to the base of the slope by by the action of gravity. Therefore, these deposits do not exhibit the same degree of sorting as the alluvial deposits, and their water bearing qualities are accordingly poorer.

7.12.3 Infiltration and Drainage

The infiltration capacity of the alluvial deposits is very high compared with what is usually found across in-situ weathered soils or colluvials. Groundwater levels respond rapidly to rainfall and the recession is likewise quick.

The drainage pattern across the alluvial deposits is usually ephemeral parallel drainage close to the escarpments, and radial at the apex of the fans. Rivers commonly disappear and reappear. Further out in the alluvial plains the drainage is parallel, dendritic, or a combination of the two. Meandering of the main rivers is common.

During the dry season only main rivers may still carry water, and the base flow regime is supported by effluent groundwater discharge. Groundwater levels coincide with the water level of the river at the river bank.

Groundwater can usually be found year round in the alluvial deposits because there is a large storage capacity in the alluvial sands, and the groundwater body is often recharged by influent tributaries during a period after the rainy season.

7.12.4 Groundwater Level and Movement

The groundwater levels are usually very shallow in alluvial deposits. Some plains are flooded during the rains. Groundwater levels are then at the surface. At the end of the dry season groundwater is usually found less than 4 m.b.g.l., so the annual fluctuation is up to about 4 m.

Water levels obtained from existing wells and wells drilled by the Consultants across alluvial plains, fans, talus, and colluvium are shown in Figure 7.30. The water levels are those measured at the time of drilling so they reflect an average depth to groundwater over the year.

The direction of groundwater flow is chiefly the same as the surface gradient. Near the rivers, directions can change depending on the stage of the river and whether the river is effluent or influent over that part of its course.

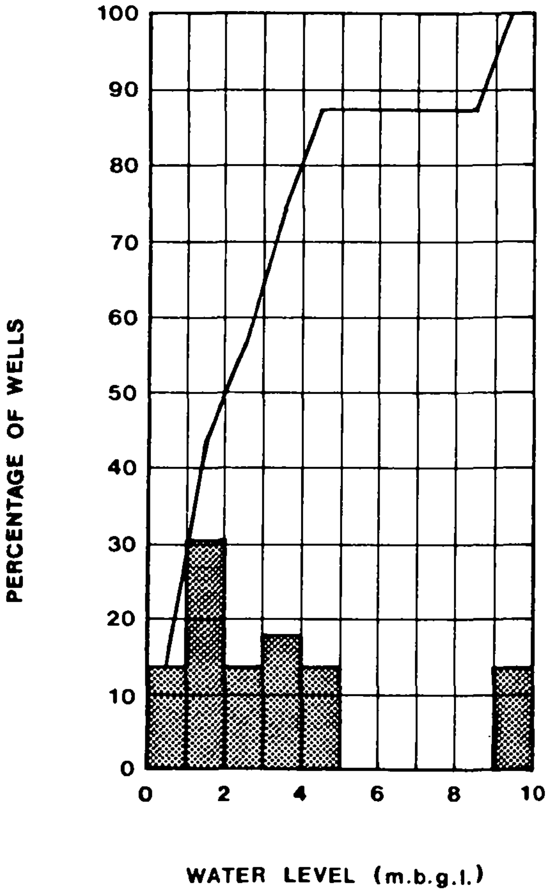


Figure 7.30 Water level frequency distribution (in metres below ground level) for wells drilled in alluvium and colluvium. Data from 24 wells.

7.12.5 Yield of Wells

In alluvial deposits there is not a uniform aquifer horizon to be found as in the Basement Complex. The average yield from wells in the regions is about 3 m^3/hr, but this figure could be larger since the majority of these wells was drilled by the Auger Rig which had a limited depth of drilling.

Coster (1960) as an average gives 7.5 m^3/hr based on 45 wells drilled into superficials and Lake Beds.

On inspecting the specific capacity frequency distribution shown in Figure 7.31 it is possible to give a better estimate of the expected yields from alluvium, colluvium, and Lake Beds. The Lake Beds have been included in the analysis because they hydraulically are similar to alluvial deposits. Taking the 50% fractile, the specific capacity is 1.2 m^3/hr/m. Allowing for 10 m of drawdown this would give an average yield of 12 m^3/hr.

The yields from these superficial deposits thus are considerably higher than from the Basement rocks.

From a hydraulic point of view the superficials offer the most prospective groundwater resources within the regions. Where they occur they should be the first target of drilling as the yields are good and drilling in these deposits is comparatively simple and cheap.

The major occurrences of these deposits is shown on the geological maps of the regions, and in more detail on the Quarter Degree Geological Map Sheets. These maps should be consulted and followed up by a field survey before decision is taken on where and how to drill in a given area. As the major alluvium and colluvium is connected to rift faulting, the areal distribution of these deposits is limited.

7.12.6 Aquifer Hydraulic Properties

The controlled pumping tests from superficials and Lake Beds were all carried out by the Consultants. From existing wells only specific capacities are available. Data from the tests are given in Volume 10 A, Appendix 2, and the results are listed in Table 7.7.

The range of the transmissivities is 0.065-14.0 x 10^{-3} m^2/s, the lower ones being from Lake Beds. Generally the values are higher than from the Basement Complex. The range of values of r_w^2S is 0.002-0.036 m^2 reflecting mainly unconfined aquifer conditions.

The relationship between the calculated transmissivities and the specific capacities is investigated in Figure 7.32. The functional relationship is found to be $T = 2.5 \times 10^{-4}\ Q/s_w\ (m^2/s)$. The difference as compared to that of the Basement Complex is explained by the difference in the physical flow conditions in the aquifers. The characteristic intergranular porosity is much larger in a saprolite aquifer than in a granular aquifer because of packing during sedimentation.

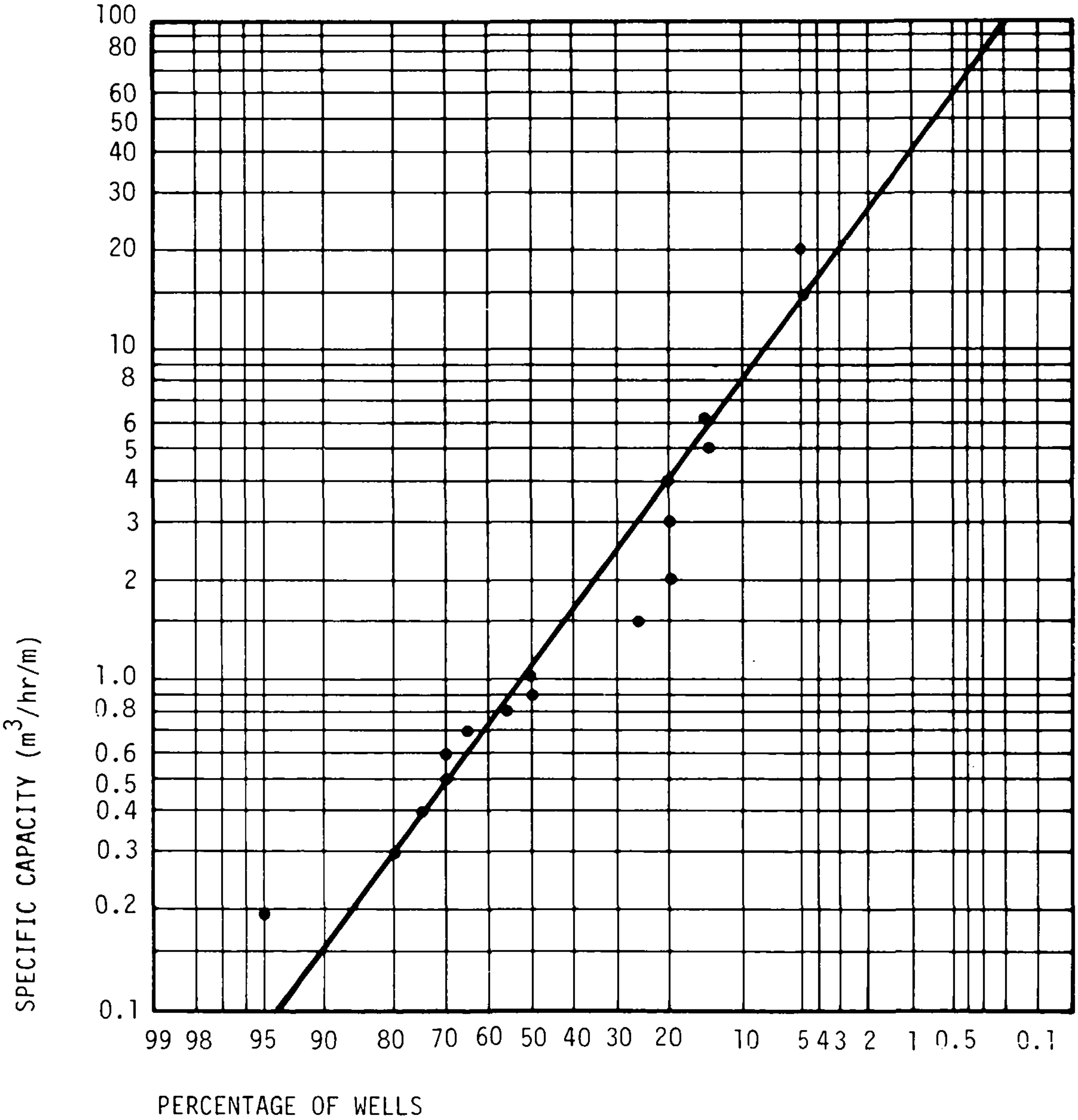


Figure 7.31 Specific capacity frequency distribution for wells in alluvium, colluvium, and Lake Beds. Data from 21 wells.

B.H. No.	CCKK No.	$T \times 10^3$ (m^2/s)	$r_w^2 S \times 10^2$ (m^2)	Q/s_w ($m^3/hr/m$)
19/81	MS 10	0.75	-	1.31
22/81	MS 13	0.2	-	1.48
24/81	MS 15	0.042	2.0	0.69
29/81	MS 16	5.6	-	20.8
30/81	MS 17	0.65	-	1.04
55/81	IS 1	1.40	-	3.1
56/81	IS 2	-	-	1.34
58/81	IS 4	0.022	3.6	0.22
73/81	MS 18	14.0	-	12.9
178/81	IS 11	0.25	-	1.4
205/81	MS 20	0.081	-	0.25
207/81	MS 28	0.0065	0.2	0.08
209/81	MS 24	0.028	0.51	0.32

Table 7.7 Aquifer hydraulic properties. Data from alluvial deposits and Lake Beds.

The data points are comparatively scattered, mainly due to difference in pumping periods and well losses.

7.12.7 Groundwater Chemistry

The groundwater found in alluvial deposits is usually very young on a geological time scale, so little chemical interaction has taken place with the surrounding porous matrix. There is usually a very shallow unsaturated zone to penetrate, and the retention time in the aquifer is of the order of magnitude of a few years.

The water samples analysed from alluvial deposits generally show good quality groundwater. Excessive iron and manganese is uncommon, and fluoride rarely exceeds the accepted limits.

Organic pollution is common in some places but this source of pollution can usually be eliminated by placing the screens as deep as possible and securing the well top effectively against leakage from the surface.

Organic pollution has been observed mainly in the Kyela District where the population density is high.

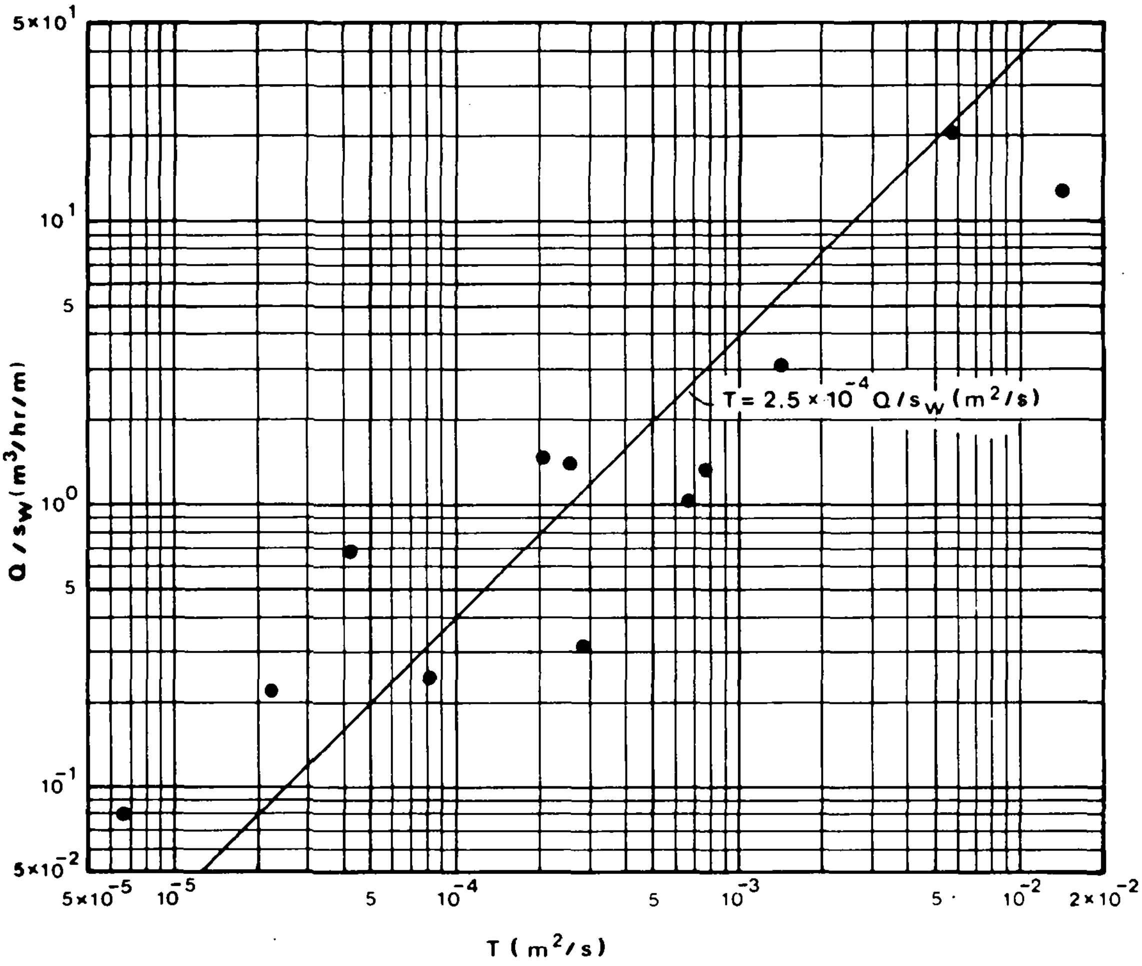


Figure 7.32 Relationship between specific capacities and calculated transmissivities for wells in alluvium and Lake Beds.

8. GEOPHYSICAL SURVEY

8.1 Introduction

The geophysical surveys carried out during this study comprise geoelectric and seismic surveys and down-the-hole logging. The purpose of these investigations has been twofold:

- to supplement the existing knowledge on geology and hydrogeology by surveying areas with little or no information, and by logging boreholes,
- to investigate the usefulness of geophysical surveys in siting boreholes.

The holes drilled by Rig 45 (deep holes) have all been located after a geophysical survey had been carried out. This is only partly the case for Rig 53 (auger holes) because most of these holes were drilled in alluvial deposits or Lake Beds where the stratigraphy is largely known beforehand.

As the Basement Complex and the Karroo continental deposits are the two major geological units within the study area, the majority of the geophysical surveys has been carried out in these areas. The geoelectrical survey consisted of geoelectric soundings and constant separation traverses (CST). The seismic survey was carried out as a profiling.

The geoelectric soundings and traverses measured are shown in Volume 10 A, Appendix 3.1, the seismic profiles in Appendix 3.2, and the geophysical logs in Appendix 3.3. A short description of methods and procedures is given in Volume 10 A, Appendix 1, Chapter 3. The location of the geoelectric and seismic surveys is shown on the Location Map, Drawing 8.1.

8.2 Geoelectric Soundings

The geoelectric soundings ideally give two types of information, the resistivity of formations and the position of lithological contacts. One factor may, however, make the interpretation very difficult and disrupt a possible pattern, namely the conductivity of pore water. Mineralised groundwater has a lower resistivity than fresh groundwater. A sand layer containing water with a high mineral content may be interpreted as a layer with much lower resistivity as for instance a clay layer.

Therefore, a correlation base has been established in the most widespread geological unit, the Basement Complex. This has been done by carrying out geoelectric soundings in the immediate vicinity of existing wells with a known stratigraphic log.

8.2.1 The Basement Complex

Saprolite Thickness

The target of a geophysical survey across the Basement Complex is the thickness of the in-situ weathered rock, the saprolite, blanketing the fresh rock. The lower part of the saprolite is the aquifer (Chapter 7), and wells should be drilled where the saprolite is found to be the thickest, geomorphological factors being equal.

To evaluate the applicability of the geoelectric soundings to define this thickness Figure 8.1 has been plotted. It shows the thickness of the weathered zone as determined from the well log (D_w) and from the geoelectric sounding (D_g) where fresh rock is defined as the layer with infinite or very large apparent resistivity.

From the graph it appears that the actual saprolite thickness is 2.1 times as thick as generally indicated by the geoelectric measurements. This is most probably caused by the fact that when the rocks start to be only little or slightly weathered the resistivity of the rock is practically the same as that of fresh rock.

On the graph the line representing equal thickness, $D_w = D_g$, indicates few measurements giving this information. The scatter of data points is due to numerous effects influencing the geoelectric measurements, and to some extent the difficulties encountered in defining the exact contact between weathered and fresh rock from the borehole logs.

Based on Figure 8.1 an attempt has been made to estimate statistically the saprolite thickness across the Basement Complex. Measurements taken across the African and post-African land surfaces are treated separately since they are expected to exhibit differences in saprolite thickness. The results are shown in Figures 8.2 and 8.3, and the thicknesses measured have been multiplied by 2.1 to obtain the actual thicknesses.

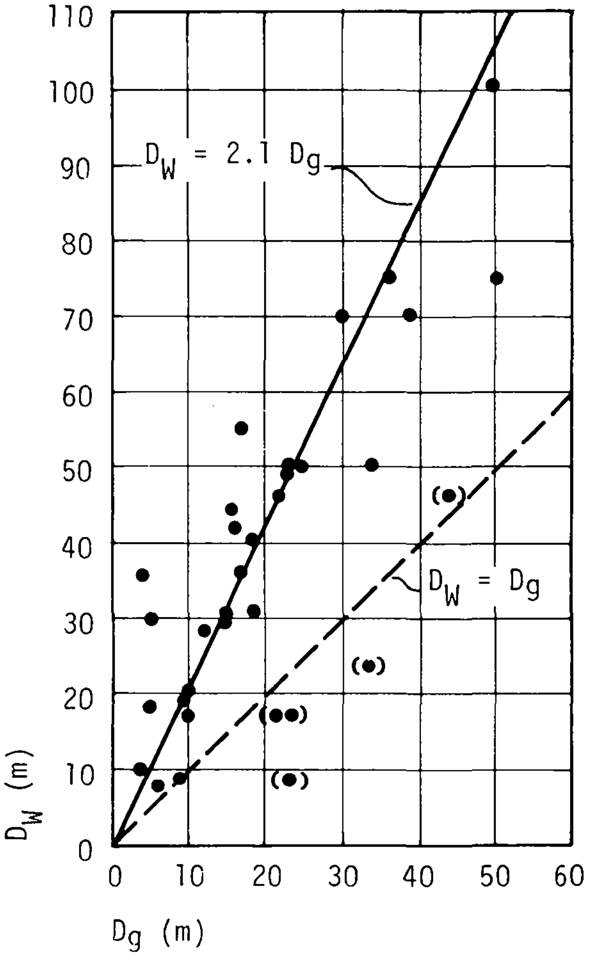


Figure 8.1 Correlation between saprolite thicknesses from well logs and geoelectric soundings.

Figure 8.2, representing the African land surface, shows a very evenly distributed saprolite thickness. Comparing with the distribution obtained from wells (Figure 7.4) the deep saprolite is apparently much more dominating the distribution of the measured thicknesses. The observed mean saprolite thickness is about 40 metres, and 50 metres from the geoelectric measurements. This is probably due to the principle of suppression. When the saprolite thickness is moderate the lower sapro-

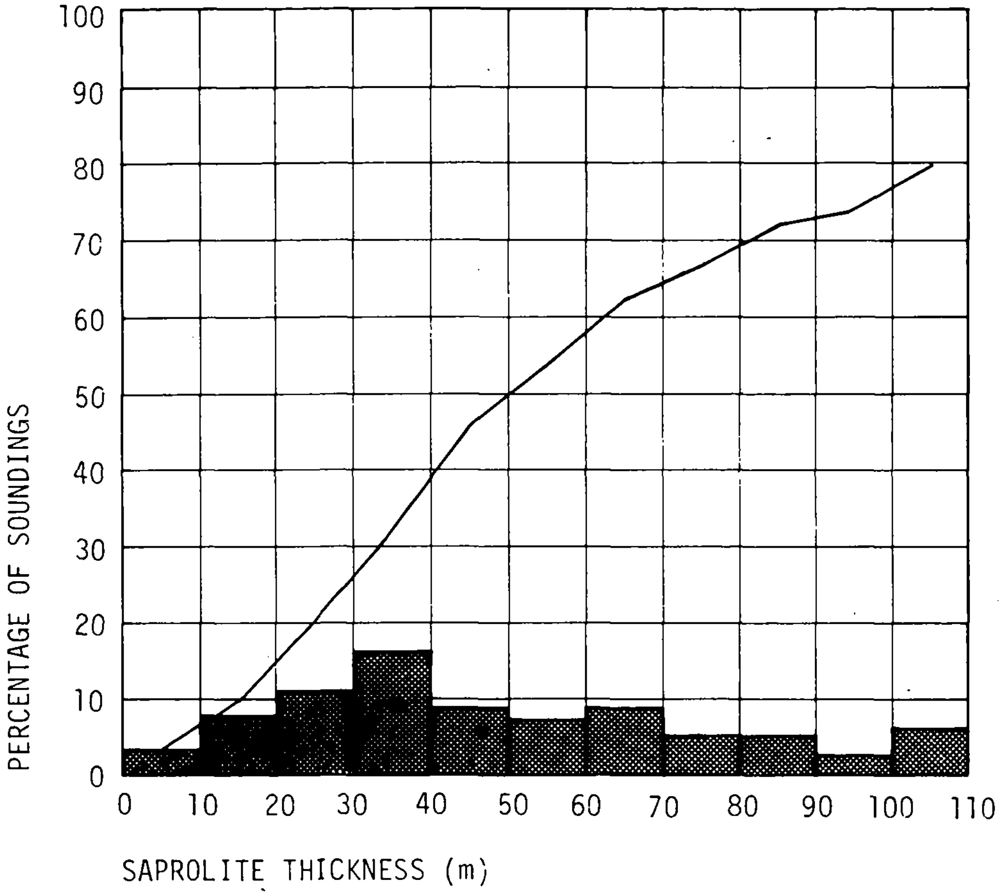


Figure 8.2 Saprolite thickness frequency distribution across the African land surface as determined by geoelectric soundings. Data from 81 soundings.

lite responds like fresh rock, but when the thickness is large the lower saprolite is suppressed because its thickness is small compared to total saprolite thicknesses. Therefore, the measured saprolite thickness is probably very close to the true one in cases of thick saprolite covers.

The correlation formula is strictly valid only for $D_g < 50$ m, resulting in saprolite thicknesses larger than about 100 m being overestimated.

On inspecting the individual geoelectric soundings it was found that the saprolite is generally thick across the African land surfaces of the Mbozi and Ufipa Plateaus, the southern Njombe District, and Mbinga District. In the Iringa and Njombe Districts along the Great North Road the pattern is irregular because of intense faulting in some places.

The results from the post-African land surface (Figure 8.3) are more straight forward. The saprolite thickness is less than across the

African Surface, the mean being about 25 metres. The observed mean (Figure 7.15) is about 23 metres, and the distribution functions of the two graphs are almost identical. The reason that the results are better across the post-African Surface is that the saprolite is comparatively thin, and suppression of the lower part of the saprolite seems not to be effective.

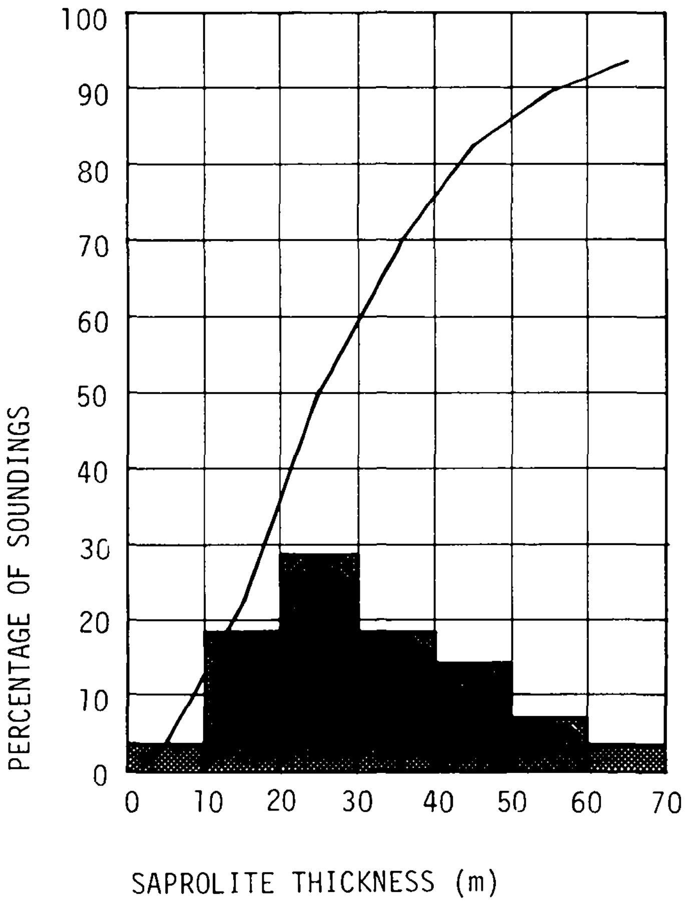


Figure 8.3 Saprolite thickness frequency distribution across the post-African land surface as determined by geoelectric soundings. Data from 28 soundings.

To provide an overall idea of the type of geoelectrical profiles that have been found, each profile if applicable has been grouped into one of four standard types as shown on Figure 8.4 These four types can conveniently be divided into two groups, the AH Group with increasing apparent resistivity with depth, and the KQ Group with decreasing apparent resistivity with depth. One of these letters is attached to the sounddings on the Location Map, Drawing 8.1, to show the shape of the resistivity curve.

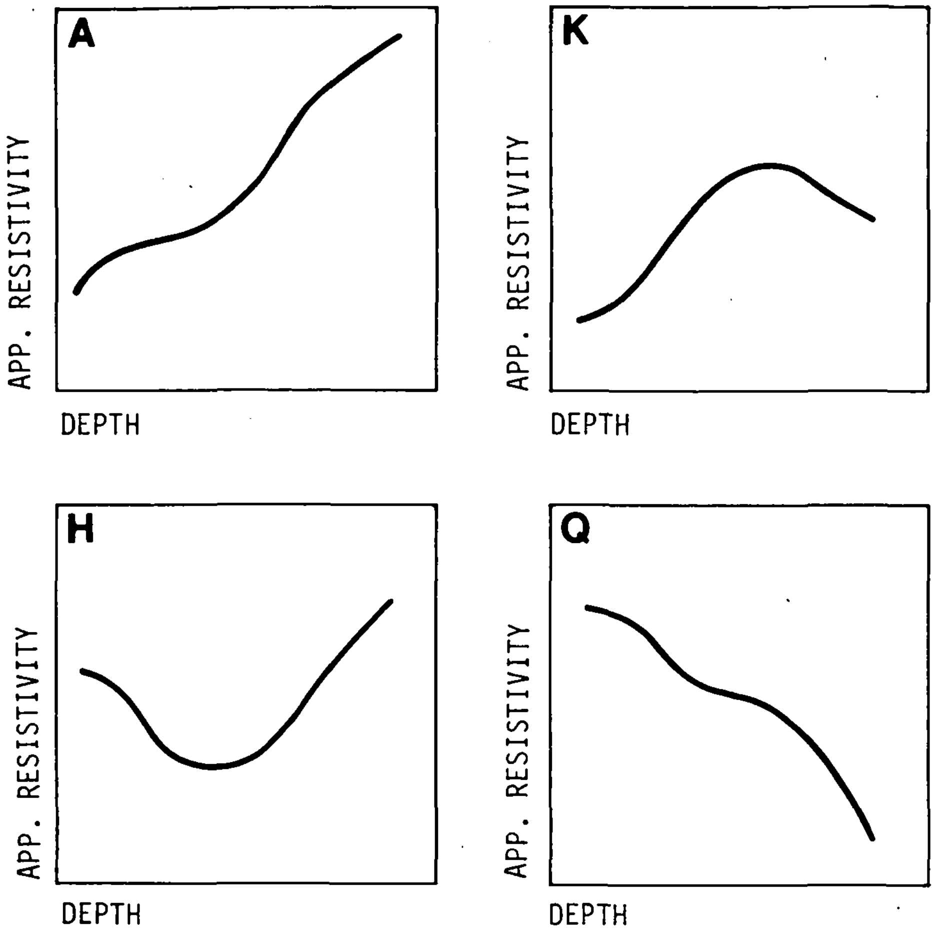


Figure 8.4 Grouping of the geoelectric soundings.

The predominant resistivity curve found across the Basement Complex is the H curve showing a dry top layer, a wet clay layer (saprolite), and finally bedrock. The A curve is found as well, but the KQ Group is rare and where found indicates the occurrence of juvenile water or highly conducting bodies at depth.

Characteristic apparent resistivities of the formations found across the Basement Complex are 100-300 ohm-m in the dry clayey top soil, 1-10 ohm-m in the completely decomposed rocks, 10-1000 ohm-m in weathered rock, and 5000- ohm-m in fresh rock. Table 8.1 gives a range of apparent resistivities of the common rocks in the regions.

It may be concluded that a geoelectric survey is an effective tool in determining well sites across the Basement Complex. The method gives reliable results as to the depth to fresh rock according to the method outlined here. If the depth to bedrock is large some difficulties may arise in the interpretation, but the method clearly indicates the variations of saprolite thickness across the Basement Complex.

8.2.2 The Karroo Basins

Geoelectric surveys have been carried out in the two Karroo Basins in Ruvuma Region, the Ruhuhu Basin and the Tunduru Basin. The interpretation of the results has been based on the drilling and the aeromagnetic maps without which a pattern would have been difficult to find.

As described in Section 7.8 the Tunduru Basin is subdivided into subbasins separated by Basement outcrops, so the Karroo sediments are alternately ranging between thick and very thin. This is reflected by the geoelectric soundings carried out.

In the Karroo, the H, K, and Q types of soundings are recorded exclusively, and there is a definite pattern controlling where the individual type of resistivity curve is found.

In the central parts of the main Basins and the Subbasins predominantly the Q curves and some K curves are situated. They show a dry (Q curves) or a moist (K curves) top layer underlain by an intermediate dry layer, and finally the saturated Karroo formations with apparent resistivities typically in the range 30-100 ohm, the range reflecting the lithology.

Along the edges of Basins predominantly K and H curves are found. The K curves show a comparatively high-resistivity upper layer (2-3000 ohm-m) underlain by a layer of very low resistivity (~ 0 ohm-m). This lower layer is the pre-Karroo Surface consisting of clay and shale found by drilling. The saturated Karroo formation of resistivity 30-100 ohm-m is not seen because it is suppressed by the underlying layer.

The H curves are located very close to the Basement outcrops, and the first part of these curves are actually K curves, but they are referred to as H curves because they reveal a fourth layer with very large or infinite resistivity, indicating bedrock.

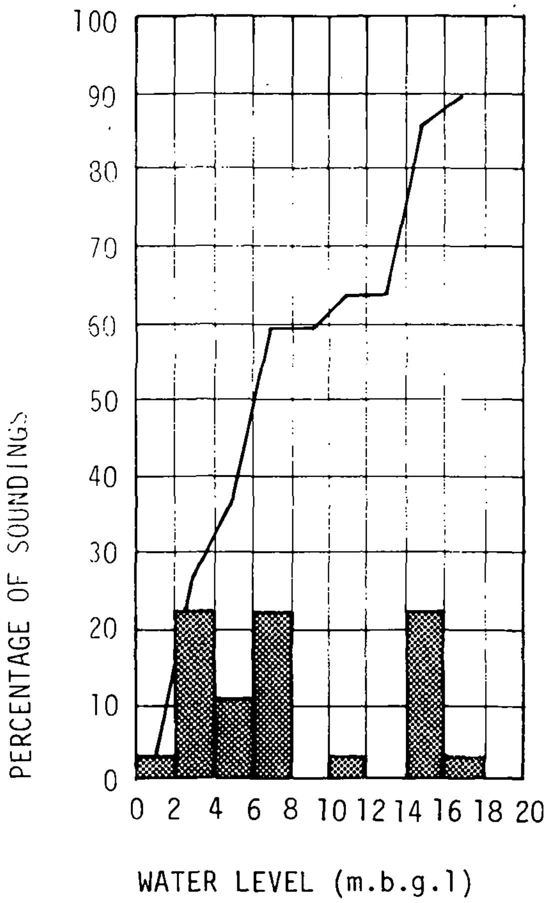


Figure 8.5 Water level frequency distribution across the Karroo Basins as determined from geoelectric soundings. Data from 27 soundings.

As soon as the boundary between the Karroo and the Basement rocks is crossed the geoelectric soundings are predominantly H curves as in the Basement Complex in general.

A determination of the water level in the Karroo sandstone should be possible where the aquifer is phreatic or where artesian aquifers are situated near the surface. According to the above this has not been possible in all profiles, but an estimate of the water level distribution could be done in 27 soundings, and the distribution of these is shown in Figure 8.5.

From the figure it appears that the water levels are either shallow or comparatively deep. The shallow levels are found in low-lying areas and the deeper ones in the more elevated areas. Comparing with the water level data from boreholes (Figure 7.26) which are drilled in mainly flat and low-lying areas the actual rest water levels appear to be even more shallow. This is probably because the artesian aquifers give high rest water levels and these are not possible to detect by the geoelectric method if the aquifers are deep-seated.

It may be concluded that the geoelectric soundings are useful for an initial geologic mapping of the Karroo Basins. The method reveals the thick Karoo sediments and the Basement rocks where the Karroo sediments are comparatively shallow. It is not possible to detect areas with shallow Karroo sedimentation from the satelite imageries. It should be mentioned that the interpretation would have been difficult without the results from the airborne magnetic survey.

8.2.3 Neogene Deposits

The geoelectric soundings carried out in the Rukwa Trough and the Usangu Flats predominantly belong to the H and Q Groups. The H curves are found near the edges of the basins where bedrock is close to the surface, otherwise the resistivity is generally decreasing with depth. The resistivities are typically less than 10 ohm-m which has resulted in many erratic measurements. The lithology of the deposits is largely unknown so there is no basis for correlation.

Due to pronounced evaporation in the Rukwa Trough and the Usanga Flats the mineral content of the groundwater is comparatively high, and this combined with the clayey and silty nature of the deposits leaves geoelectric surveys in these areas without much chance of success in locating aquifers.

In the alluvial deposits the situation is largely the same. Rapidly changing clayey, silty, and sandy layers make it difficult to accurately describe the lithology, and result in low values of the apparent resistivity.

However, these factors are not considered crucial for the exploration of the Neogene deposits. The drilling has shown that groundwater is generally present at shallow to medium deep levels, and the success of drilling into the Lake Beds and alluvium does not depend on the existence of a geophysical survey.

In the Rungwe Volcanic Province the situation is similar. The groundwater quality is unpredictable, and the resistivities of the lava and pumice depend largely on the mineral content of the groundwater. There is not sufficient data to establish any correlation, so only few geoelectric soundings have been carried out in the volcanic deposits. Apart from this, groundwater is unlikely to be utilised in this area because of the abundancy of perennial springs of good quality water.

8.2.4 Resistivities of Rocks

Based on the geoelectric soundings and available borehole data, a list of resistivities of commonly occurring rocks within the regions has been prepared (Table 8.1).

As it appears the range is wide for many rock types, and care should be taken in interpreting geoelectric soundings strictly without prior knowledge of the general geologic environment.

8.3 Constant Separation Traverses

Constant separation traverses have been carried out in dambos to investigate the ability of this method to delineate the variation of saprolite thicknesses along the traverse.

On one occasion seismic profiles and a constant separation traverse have been measured along the same line, CST 189 (Volume 10 A, Appendix 3.1) and seismic profiles 101-107, Vwawa, Mbozi District (Volume 10 A, Appendix 3.2). The variation of the resistivity is seen to follow the depth to bedrock closely along the traverse. The geoelectric soundings 190 and 191 (Volume 10 A, Appendix 3.1) have been measured in the resistivity lows to estimate the saprolite thicknesses which were found to be 46 and 53 m, respectively. The average depth along the profile is according to the seismic results 50 m. The true depths are found by multiplying with the correcting factors found.

When interpreting the CST profile the actual value of the apparent resistivity is of no major interest, only the variation of resistivities along the line is important. Smooth variations reflect the variations in saprolite thicknesses whereas sudden resistivity peaks are caused by interbedded sands in the upper strata.

ROCK TYPE	APP.RESIST. (ohm-m)	REMARKS
Lake beds (clay, silt, mudstone)	0-10	Due to evaporation the mineral content of water is high and the resistivity low. In the Rukwa Trough the range may be higher because of volcanic colluvium in some places.
Decomposed rock (saprolite, predominantly clay)	0-10	Completely weathered down granites, gneisses, and schists.
Weathered rock (granites, gneisses)	10-1000	The range reflects the degree of weathering and the mineral content of groundwater.
Fresh rock (granites and gneisses)	5000-∞	Lower values may be observed where there is intensive fissuring and water of large mineral content.
Karroo (top soil and intermediate, dry)	500-3000	Range varies over the year, low during rains.
Karroo, as above, wet	30-500	
Karroo, saturated	0-100	Predominantly 10-30
Volcanic ashes and lavas, dry	500-700	
Do., wet	0-30	
Basalts	200-1000	Higher values where no fissures.
Sand, gravel, dry	300-5000	The ranges reflect clay content and mineral content of groundwater.
Sand, gravel, wet	10-150	

Table 8.1 Resistivity ranges of common rock types.

CST profiling is a comparatively quick method of locating thick saprolite profiles and seems to be well suited in dambos and other areas of low relief across the Basement Complex. In areas with irregular terrains caused by differential erosion and faulting the method cannot stand alone but must be supplemented by geoelectric soundings and maybe seismic profiling.

8.4 Seismic Profiles

The seismic survey ideally gives two types of information, the sound velocity of rocks and the lithological boundaries between them. The problem of the hidden layer (a layer with a lower velocity than the layer above) is the major disadvantage of the method and may lead to erroneous results.

The seismic soundings have been carried out generally to investigate the applicability of the method. No attempt has been made to carry out seismic surveys at existing boreholes, so it has not been possible to establish a correlation base as was the case with the geoelectric soundings. The results of the seismic investigations are, therefore, interpreted utilising the results of the geoelectric survey, the results of existing drilling and drilling carried out by the Consultants, and the general knowledge of geology and geomorphology.

8.4.1 The Basement Complex

Across the Basement Complex predominantly three layers are detected. The upper layer is the dry top soil with velocity 300-600 m/sec., then follows the decomposed clayey rock layer with velocity 1100-1600 m/sec. which in a few cases can be separated into two horizons, and finally follows a third (or fourth) layer with velocity in two distinct ranges. The most common range is 4500-5500 m/sec., but in a few cases velocities between 6000 and 9000 m/sec. have been measured. This layer is the bedrock, and the range found reflects the degree of fissuring and weathering of the rock.

The upper layer has a general thickness of 2-6 m. The thickness of this layer added to the thickness of the intermediate layer/layers gives the saprolite thickness. From 22 seismic profiles (44 depth soundings) the distribution of the saprolite across the African land surface has been calculated as shown in Figure 8.6.

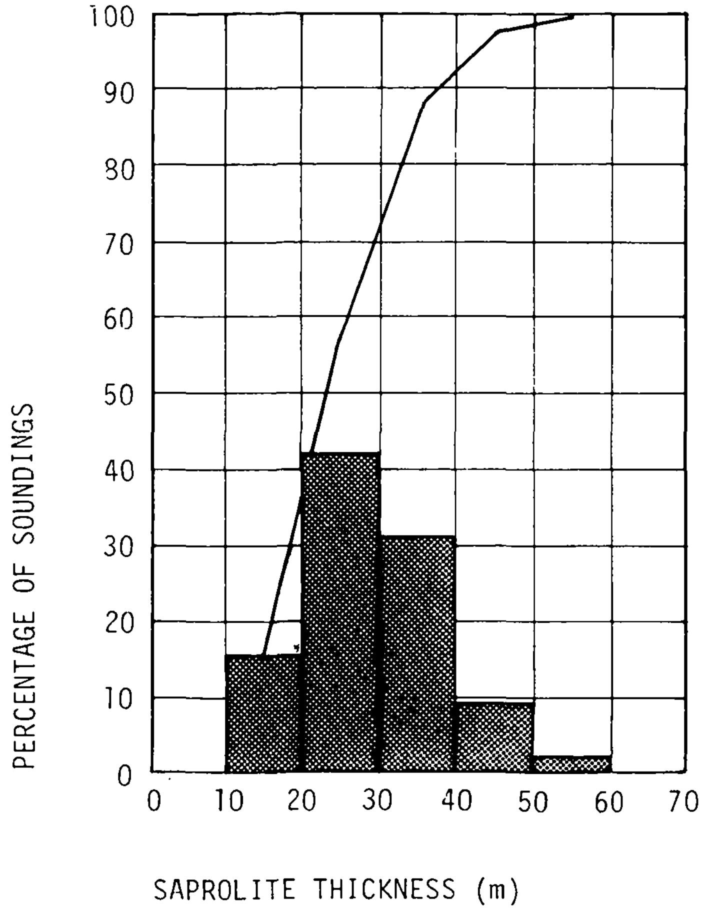


Figure 8.6 Saprolite thickness frequency distribution across the African land surface as determined by the seismic profiles. Data from 44 depth soundings.

Comparing Figure 8.6 with Figures 8.2 and 7.4 it appears that the seismic method records too shallow saprolite thicknesses. This is partly due to the limited penetration depth of the seismic waves. Layers below 60 metres cannot be recorded, and bedrock does not show on the seismograms. Another reason is probably that it is the slightly weathered rock that is recorded and not the fresh unweathered rock. This was the case with the geoelectric soundings as well. In general there seems to be no problem with a hidden layer because this would result in too large saprolite thicknesses. The mean saprolite thickness in Figure 8.6 is about 23 m compared to 40 m from borehole logs. This would call for a correction factor of about 1.7, so the relationship between true saprolite thicknesses according to well records (D_w) and those obtained from the seismic survey (D_s) would be $D_w = 1.7\ D_s$.

Too few profiles have been measured across the post-African land surface to make a similar comparison. The results, however, seem to be in agreement with the above, with saprolite thicknesses measured to about 15 m on an average.

8.4.2 The Karroo Basins

The travel time diagrams in the Karroo Basins can be divided into two main groups as was the case with the georesistivity curves: those in the central parts of the Basins and those on the edges.

In the Basins predominantly three layers are detected. An upper dry layer of loose sands with velocity 400-600 m/s and thickness 3-6 m, an intermediate layer of more consolidated dry sands with velocity 1200-1800 m/s and thickness 8-15 m, and finally a lower layer representing the saturated Karroo sandstone with velocity 1800-2500 m/s situated at 11-20 metres' depth. This general interpretation of the depth to the water table or water saturated artesian aquifer is in good agreement with the drilling and the results of the geoelectric survey.

Along the edges of the Basins the situation is the same as regards the top and intermediate layer, but the third layer has a somewhat higher velocity, 2000-3000 m/s, which can be interpreted only as the pre-Karroo land surface found during drilling and also recognised on the georesistivity curves. In a few cases a fourth layer is recognised with a velocity of 4000-7000 m/s. This layer represents the fresh rocks of the Basement Complex.

Along the edges of the Karroo Basins it has not been possible to clearly define the depth to the water saturated Karroo sandstone because the velocity contrast between this horizon and the clayey pre-Karroo land surface is too small. This same problem was found when interpreting the georesistivity curves.

8.4.3 Seismic Velocities of Rocks

Based on the results of the seismic survey and the knowledge of the nature of the rocks Table 8.2 has been compiled. It includes the velocities of the commonly occurring rocks within the regions. The ranges given reflect the effects of lithological differences and degrees of weathering.

ROCK TYPE	SEISMIC VELOCITY (m/s)	REMARKS
Sand, silt, top soil, dry	100-600	Velocity increases with clay content.
Sand, silt, clay (saprolite), saturated	900-1600	Velocity increases with clay content and consolidation.
Weathered rock (granites, gneisses)	2000-4000	Velocity decreases with increasing weathering.
Slightly weathered and fissured rock (granites and gneisses)	4500-5500	Velocity decreases with increasing fissuring and weathering.
Fresh rock (granites and gneisses)	6500-9000	
Karroo (top soil unconsolidated, dry)	400-600	
Karroo (intermediate, more consolidated, dry)	1200-1800	Range reflects degree of consolidation and cementing.
Karroo (sandstone, saturated)	1800-2500	

Table 8.2 Seismic velocity ranges of common rock types.

8.5 Down-the-Hole Logging

Geophysical logging was applied upon completion of drilling on all boreholes before installation of lining whenever feasible. Logging was performed with a Johnson-Keck Model SR 3000 logging equipment.

In the initial phase of the drilling programme, however, only few boreholes could be logged due to extremely high density of the residual fluid in the boreholes drilled by the Auger Rig. This high density made penetration by the logging probes impossible. The holes were cleaned later when a skid-mounted compressor was made available to the Consultants.

A total of 13 geophysical logs was performed during the study, of which 12 logs were run on wells drilled by the Consultants.

The logging equipment had persistant mechanical problems caused by transport shocks. Whenever this happened, an attempt to repair the equipment was made as soon as possible and in most cases successfully. The temperature log, however, was only successfully used once. Due to these problems a variable number of logs were run in the individual holes. The recorded logs are shown in Volume 10 A, Appendix 3.3.

8.5.1 Logging in Basement Complex

A total of five logs were recorded in boreholes drilled in the Basement Complex. Gamma logs show only minor deviations in radiation from penetrated layers and are thus of no great use to locate changes in lithology. The characteristic gamma curve as described above, however, confirms that the layers penetrated consist of the same basic minerals, but no information is given on the weathering of the rocks.

Resistivity logs were very useful to determine the thickness of the weathered zone due to the higher resistivity in fresh rock. The logs were recorded with electrode spacings of 3 m and 0.8 m giving different rock penetration, and both logs gave useful information.

A self-potential log was recorded in only one borehole (BH No. 4/81, Mloa, Iringa Region) but gave no information of value for the lithological interpretation.

A temperature log was recorded in BH No. 25/81 at Mbozi Mission in Mbeya Region and shows a temperature gradient of appr. 0.52°C per 100 m in the Basement. This gradient is surprisingly low and is probably caused by mixing of water due to gas being emitted from the formation penetrated. In this borehole the gamma log has not responded to lithology changes as indicated by the samples. This is most likely due to instrument failure.

8.5.2 Logging in Karroo Formations

A total of eight logs were recorded in boreholes drilled in the Karroo formation.

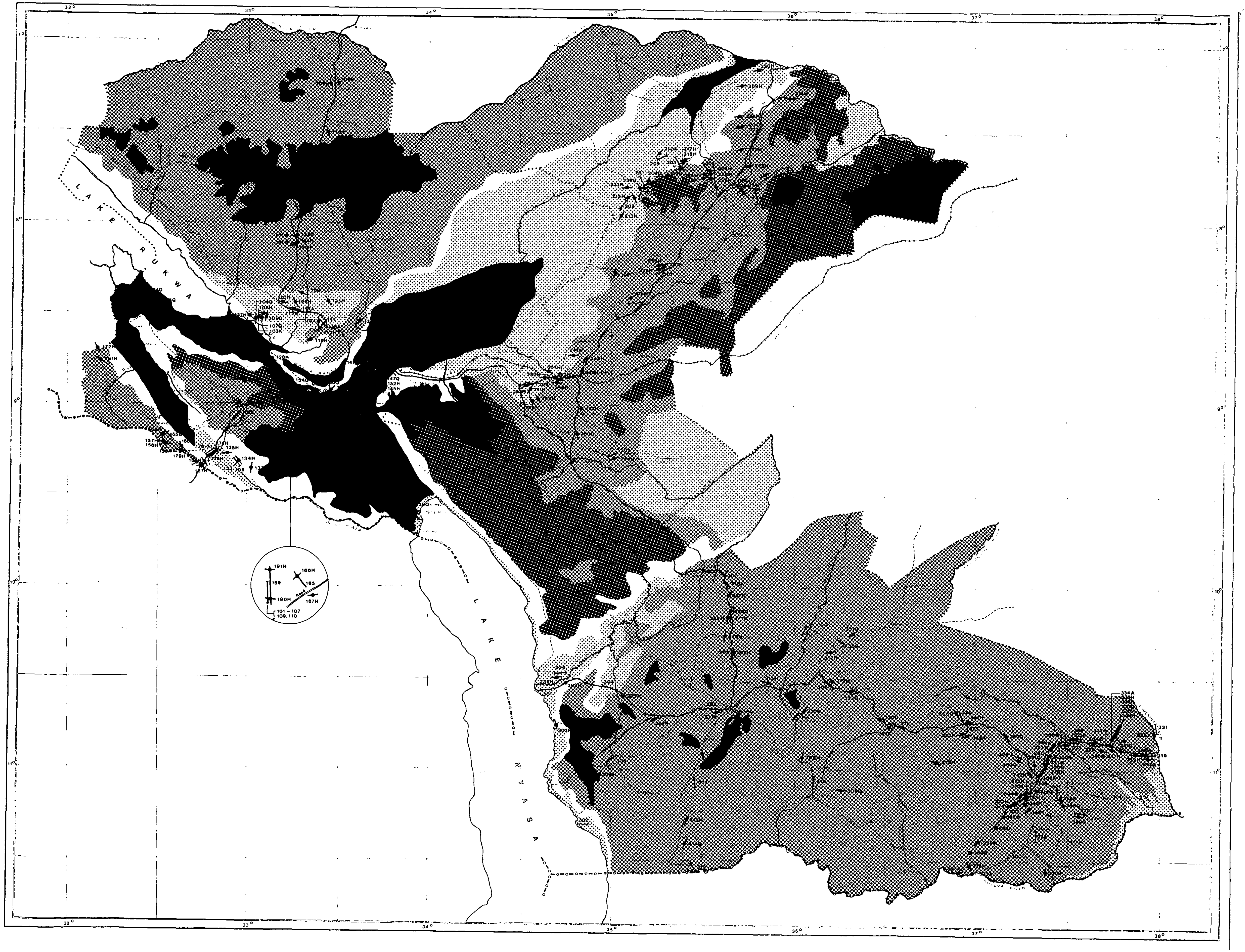
Gamma logs have generally been more useful in Karroo than in the Basement Complex as they clearly detect the increased radiation from mudstones and marls in relation to sandstone in the Karroo sediments.

Resistivity logs were useful also in the Karroo due to the difference in resistivity between sandstone and mudstone or marls.

A self-potential log was recorded in BH No. 253/81 at the Hanga River and gave useful information to define certain lithological contacts.

In general the recorded logs confirm that the combination of gamma and resistivity logs is very useful in defining the lithology in rapidly changing layers, whereas only resistivity logs are particularly useful in Basement areas because of the negligible changes in mineral composition in the crystalline rocks, whether they are fresh or weathered.

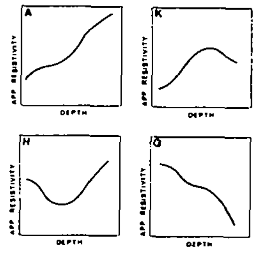
GEOPHYSICAL SURVEY LOCATION



LEGEND

125H	Site of geoelectric sounding with reference number and type of recorded curve (H) Soundings without letter attached do not classify for a group. Line indicates *bearing of sounding*
192	Site of constant separation traverse with reference number Line indicates bearing of sounding Length of line not to scale
207	Site of seismic survey with reference number Line indicates bearing of sounding Length of line not to scale

TYPE OF GEOELECTRIC SOUNDING



GEOMORPHOLOGY

EROSION SURFACES	AGGRADATIONAL SURFACES
■ GONDWANA	
▩ POST GONDWANA	
▨ AFRICAN	
PA POST - AFRICAN	
CO COASTAL PLAIN / CONGO	A *MODERN*
SC SCARP	RV RUNGWE VOLCANICS

CARL BRO•COWICONSULT•KAMPSAX-KRÜGER•CCKK 1982

0 50 100 150 200 km

SCALE 1:2,000.000

Drwg. no. 8.1

9. GROUNDWATER CHEMISTRY

9.1 Introduction

On Drawing II-11, pie-diagrams of selected groundwater analyses are shown. The chemical data are presented as Appendix 3 in Volume 10 B.

The explanation of the hydrochemistry is based on trilinear Piper-diagram. The basic principles of this method of plotting is explained in Volume 10 A, Appendix 1, Chapter 7.

Before discussing the various types of groundwater in the regions and the chemical reactions which may lead from one type to antoher, it is stated, that there are two main types of groundwater in the area.

One is the juvenile type, which is characterised by the strong acids, Cl, SO_4 and F. They plot in the upper half of the diamond shaped field of the Piper diagram (Figure 9.1). Usually this groundwater type is not potable. The other main type is the result of the reaction between infiltrating meteoric water and the rocks and soils. This type is characterised by the weak acids HCO_3 and CO_3. Usually this type of groundwater is potable.

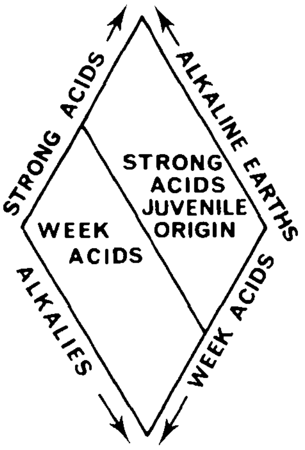


Figure 9.1 Piper-diagram showing the two main water types

9.2 Transformation of Groundwater Types

From the chemical analyses, 7 groundwater types have been recognised in the regions. They are:

Type 1. Strong Acids.

Type 2. Sulphate-reduction of strong acids with partial ion exchange.

Type 3. Strong acids with non-carbonate hardness.

Type 4. Strong acid water with non-carbonate hardness, partial ion exchange and sulphate reduction.

Type 5. Alkaline earths and weak acids.

Type 6. Weak acids with partial ion exchange of alkaline earths with alkalies.

Type 7. Carbonate alkalies (non juvenile).

Four main transformations have been recognised, as shown in Figure 9.2, which also shows the position of the water types in the Piper-diagram.

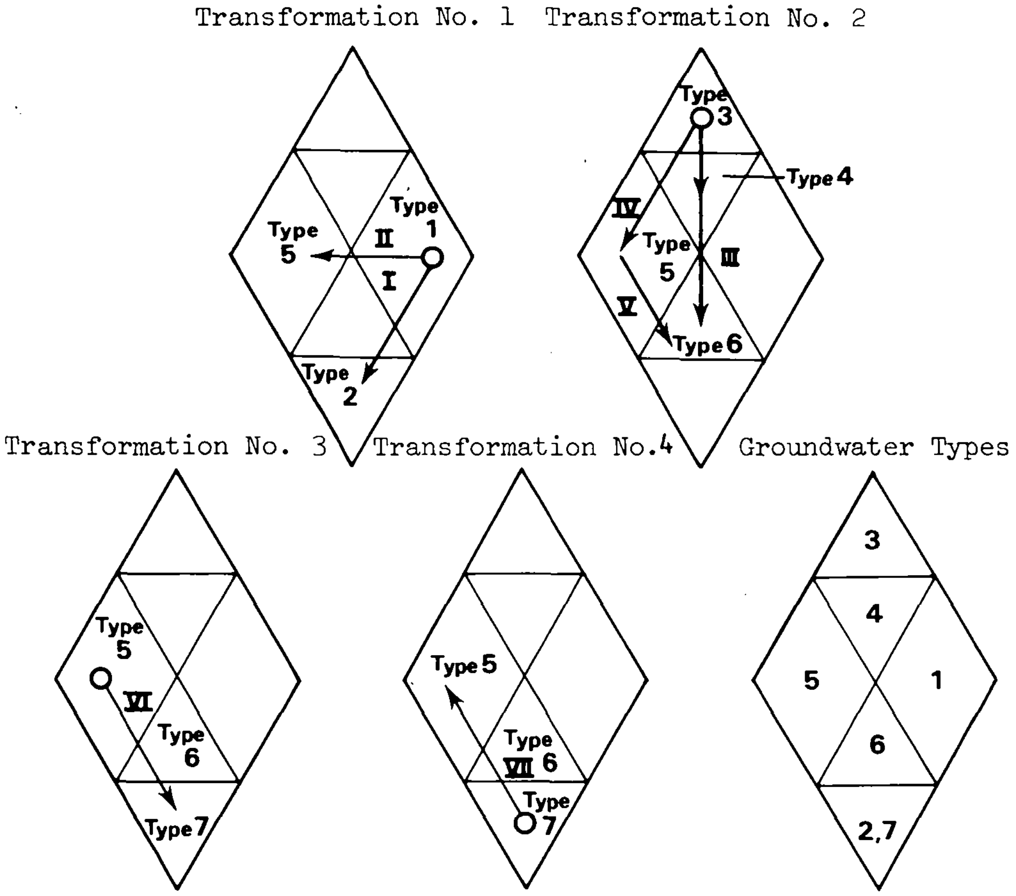


Figure 9.2 Transformation of groundwater types, and areas in which the individual groundwater types are plotted

9.2.1 Transformation No. 1

This transformation is recognised in scarp areas associated with Neogene Faulting. It transforms $NaHSO_4$ through the following reactions:

Reaction I, sulphate reduction with formation of $NaHCO_3$.

Reaction II, sodium ion exchange with calcium and magnesium with partial sulphate reduction.

The groundwater type moves from the strong acid juvenile to the weak acid part of the Piper-diagram.

9.2.2 Transformation No. 2

This transformation is recognised in scarp areas in Iringa Region, also as a result of Neogene Faulting. The result is again a shift from the strong acid to the weak acid part of the Piper-diagram.

The transformation occurs through the following reactions:

Reaction III, sulphate reduction with formation of HCO_3, calcium and magnesium ion exchange with sodium.

Reaction IV, sulphate reduction with formation of HCO_3.

Reaction V, Calcium and magnesium ion exchange with sodium.

9.2.3 Transformation No. 3

This transformation is common in the tectonically stable Basement Complex and is a transformation of alkali earth carbonate to alkali carbonate, through Reaction VI, calcium and magnesium ion exchange with sodium.

9.2.4 Transformation No. 4

This transformation is recognised in the alluvial plain in Kyela District. It transforms alkali carbonate to alkali earth carbonate through Reaction VII, sodium ion exchange with calcium and magnesium.

9.3 Groundwater Types

The positions of the individual groundwater types in Piper-diagram are shown in Figure 9.2.

9.3.1 The strong acid alkali type, Type 1

This groundwater is of deep seated juvenile origin. It is characterised by a high content of $NaHSO_4$, a high fluoride content and a relatively high content of iron and manganese.

The relatively high iron and manganese content indicates that the sulphate content is a result of sulphide oxidation (oxidation of pyrite). An example of this is BH No. 4/81 Mloa, Iringa District. The same type is found in BH No. 64/79 Kiejo, Rungwe District, but here iron and manganese are low.

The high sodium content opens for the possibility of ion exchange of sodium with calcium and magnesium.

The water type generally has a high fluoride content, from 2 to 6 mg/l. In the volcanic rocks, this may be even higher.

This groundwater is found in areas heavily influenced by Neogene Faulting (Rift faulting). It is not suited for water supply.

9.3.2 Sulphate reduction of strong acids with partial ion exchange, Type 2

This groundwater type plots in the weak acids part of the Piper-diagram, but is derived from Type 1. The juvenile origin is indicated by the conservative fluoride ion.

The groundwater is characterised by a high $NaHCO_3$ content, a high content of calcium and magnesium, and a very low content of iron, manganese and chloride.

The dominant process in this groundwater is the reduction to sulphide associated with the formation of a very high content of $NaHCO_3$. The sulphide reacts with the heavy metals forming metal sulphides. Therefore, the iron and manganese content will be very low.

The groundwater type is recognised in BH Nos. 205/81, 208/81 and 209/81 across the Usangu Flats. The presence of this type of groundwater indicates the existence of faults below the Lake Beds.

Also, a high SiO_2 content and a starting ion exchange of sodium with calcium has been recognised.

The same type of groundwater is found in BH No. 8/36, Makongolosi, Chunya District.

The groundwater is suited for village water supply, where the fluoride content is below accepted limits.

9.3.3 Strong acids with non-carbonate hardness, Type 3

This groundwater is characterised by a high content of calcium, magnesium, chloride and/or sulphate. There seems not to be an upper limit for the fluoride, but the content of this constituent is normally below 2 mg/l. The iron and manganese content seems to depend on local possibilities of oxidation of the respective sulphides.

In the Piper-diagram, the type plots in the juvenile part.

The water type is predominantly found in the northern part of Iringa Region in and near the rift faulted areas. Here, BH Nos. 71/76, 126/77, 87/77 and 22/55 belong to this type with chloride dominating the strong acids group. In BH No. 79/73 there is an equal amount of chloride and sulphate.

The conductivity of this groundwater is high, 2000-5000 micro S/cm. It is not suited for village water supply.

9.3.4 Strong acids with non-carbonate hardness and normal cation exchange and sulphate reduction, Type 4

This groundwater type also plots in the juvenile part of the Piper-diagram. It is derived from Type 3, and differs from this type by a lower conductivity, 1000-2000 micro S/cm. The groundwater may not be of juvenile origin, but it is at least contaminated by sources of juvenile origin.

The groundwater has been recognised in BH Nos. 24/55, 14/76, 67/76, 148/76 and 31/81, all in Iringa Region. It is not suited for village water supply.

9.3.5 The weak acids alkaline earths type, Type 5

This groundwater is common in the Basement Complex. It is characterised by calcium and magnesium dominance in the cation group, and by the carbonate system in the weak acids group. The groundwater type may be derived from Types 1, 3 or 2.

BH No. 178/81, Iringa Region, shows groundwater derived from Type 2. In BH No. 227/77, also Iringa Region indicates the same reaction after dilution with rain water.

In BH Nos. 54/76, 216/76, 3/81, 56/81 (Iringa Region) and BH No. 76/81 in Mbeya Region, most of which are situated close to or along Rift Valley faults, the groundwater is derived from Type 3.

The groundwater is suitable for village water supply, except where the fluoride content exceeds accepted limits.

The water type is found in many places in the Basement Complex in Mbeya Region without an indication of juvenile origin. It is accordingly well suited for village water supply.

9.3.6 Weak acids with partial ion exchange of alkaline earths with alkali, Type 6

This groundwater is derived from Type 5, and occurs in the same areas. It is suited for village water supply.

9.3.7 Carbonate alkali type, Type 7

This groundwater is characteristically soft water with $NaHCO_3$ and often aggressive CO_2. The iron and manganese content depends on local conditions, the fluoride content is low. This type has been recognised in the alluvial plain in Kyela District and is normally suited for village water supply.

In Figure 9.3, selected analyses have been plotted in the Piper-diagram to illustrate the distribution of water types within the study area.

9.4 Relation to Geology and Structure

The relationship between the groundwater types and the geology and structure is shown in Figure 9.4. Here, Piper-diagrams representing the geochemistry in single boreholes or groups of boreholes are shown where they occur. The main faults are also shown.

The potable groundwaters are generally found the the weak acids part of the diagram and the non-potable groundwaters in the strong acids juvenile part.

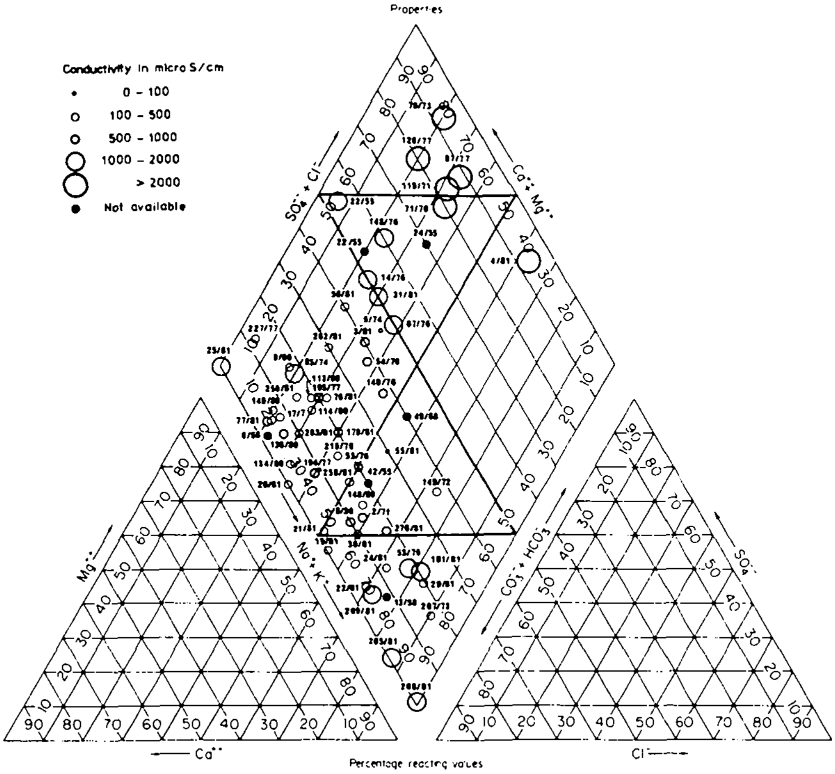


Figure 9.3 Distribution of groundwater types in the Piper-diagram

9.4.1 The Basement Complex

Juvenile water types are found in the Basement Complex close to or in areas affected by Neogene faulting. This is particularly evident along the faults defining the Eastern Rift Valley (The Ruaha Valley) to the south. The juvenile groundwaters are found in the same areas as the juvenile springs (Drawing II-12, Dambos, Springs and Main Faults).

Away from these areas, the scarp areas, groundwater is generally of non-juvenile origin and potable. But even in scarp areas chemical reactions occur, that makes juvenile water potable.

9.4.2 The Karroo Sediments

The groundwater in the Karroo seems generally not to have reacted with the rocks. Conductivity is low and groundwater potable.

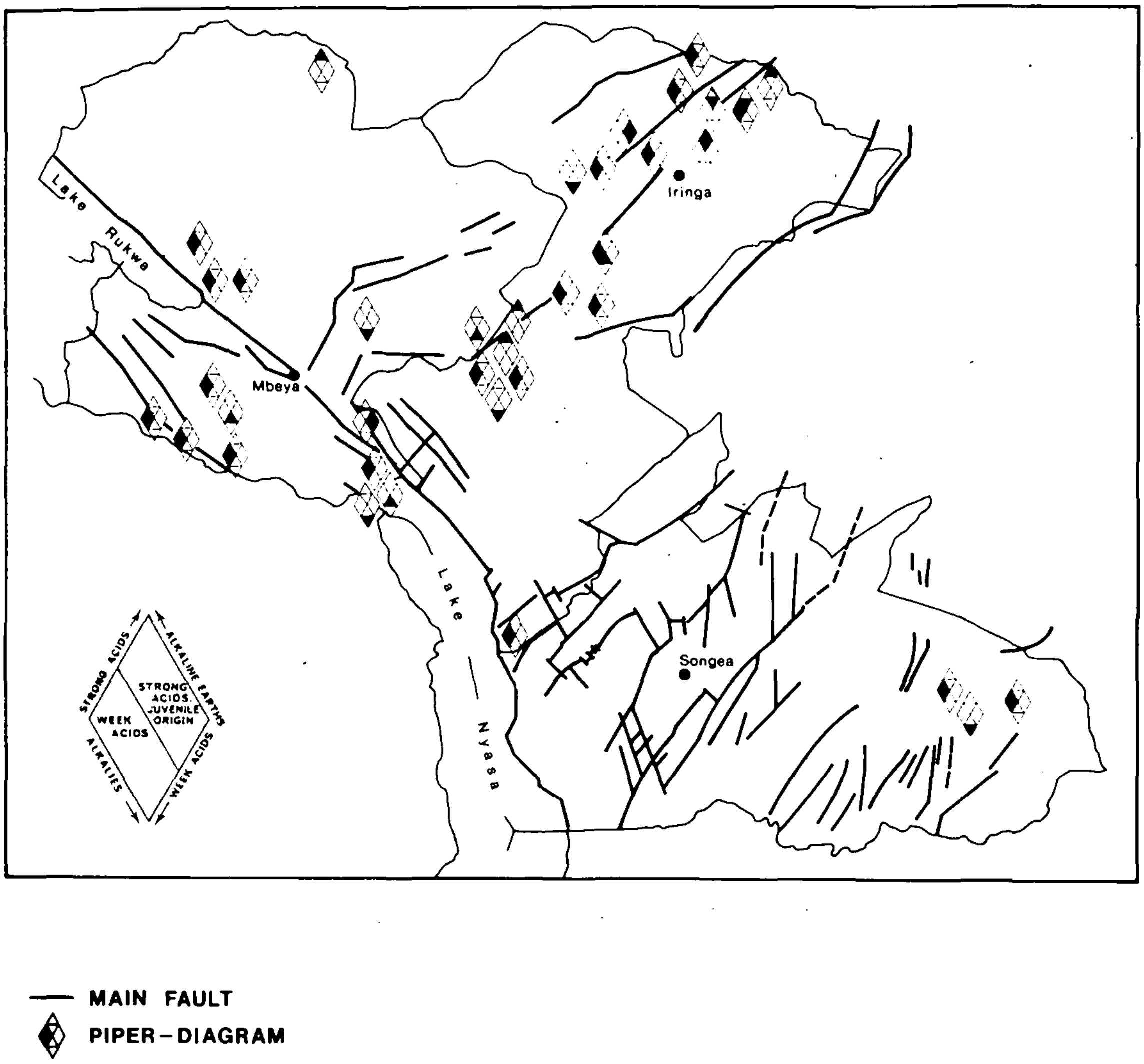


Figure 9.4 Groundwater types in the Regions represented by Piper-diagrams

9.4.3 The Lake Deposits

The groundwater across the Usangu Flats seems to be the strong acid type with sulphate reduction. The juvenile origin is revealed by medium to high fluoride contents. The potability of this groundwater depends on the local fluoride content.

In the Rukwa Trough there are indications of contamination by juvenile water.

The groundwater is expected to have a high concentration of NaCl and Na_2CO_3. The potability would be depending on local conditions.

9.4.4 Alluvial Deposits

The groundwater quality in the alluvial deposits is highly variable. Neogene faults will in places (the northern part of the Ruaha Valley) cause contamination by juvenile water. In the alluvial deposits in Kyela district iron and manganese may locally be too high. The alluvial deposits in general, however, have potable groundwater.

9.4.5 The Rungwe Volcanics

In the volcanic rocks, groundwater may be expected to be of juvenile origin predominantly. Information is too scarce to reveal any pattern presently.

10. SPRINGS

10.1 Introduction

As mentioned in Chapter 7, springs are of major importance in sustaining the base flow of rivers in many areas. At an early stage it was realised that a comprehensive field spring survey could not be undertaken as the number of springs in the regions is very large, so locating all springs would be beyond the scope of the Project.

It was, therefore, decided to use the village inventories and adopt the information on location and yields given there. The yields reported are referred to the date of visit, and since no springs have been monitored for a large period of time it is not possible at this stage to calculate the actual groundwater recharge over the spring catchment. In many cases maps have not been available to calculate the catchment area, and it is often found that the size of the catchment cannot explain the amount of discharge recorded because the spring drains fracture systems, the flow in which may have no relation to the surface topography.

However, from the recorded yields and the location of springs important conclusions can be drawn. If the yield is measured by the end of the dry season it represents the minimum groundwater recharge over the catchment, and yields recorded during the rainy season represent recharge larger than the average over the year.

Apart from the springs obtained from the village inventories the location of some springs are given on the geological Quarter Degree Sheets. Many of these springs have a geological significance as they are hot or saline.

10.2 Types of Springs

Springs can be divided into two main groups,

- gravity springs
- springs flowing due to agencies other than gravity (juvenile springs)

The gravity springs are numerous and by far the most common in the Southern Highlands. They can be further divided into three main groups: contact springs, artesian springs, and fissure springs.

The contact springs occur at the boundary between two lithologically different rocks with a pronounced difference in hydraulic conductivity. In the Southern Highlands these springs occur in dissected or faulted plateaus where the weathered rock overlies the fresh rock. They are also appearing across well eroded plateaus where sandy layers interbedded in clays outcrop.

Fissure springs, as the name implies, originate from fissures in the rocks and may, therefore, appear virtually anywhere in the lower areas.

Artesian springs originate from artesian aquifers and emerge at the surface along paths of low hydraulic resistance. They are found predominantly in depressions.

Springs flowing as a result of agencies other than gravity are usually of deep-seated origin and are often hot, saline, or carry large amounts of minerals in solution. They are almost inevitably associated with rift faulting and may contaminate large areas of groundwater bodies.

10.3 Location of Springs

The positions of the located springs are shown on Drawing II-12, Dambos, Springs and Main Faults, list of springs and data pertaining to them is given in Volume 10 A, Appendix 4. A total of 486 springs are included on the map, 179 of which are in Iringa, 123 in Ruvuma, and 184 in Mbeya Region. The actual number of existing springs cannot be given, but 1200-1500 could be a realistic figure.

On inspecting the distribution of springs it appears from Drawing II-12 that they are found mainly:

- along the escarpments defining the Rift Valleys and other major structures, and along erosion escarpments separating erosion surfaces,
- across the Gondwana and Post-Gondwana land surfaces
- across the African land surface
- across the Karroo sediments.
- across the Rungwe Volcanic Province.

10.3.1 Juvenile Springs

Along the rift valley escarpments and in the rift valleys themselves juvenile springs are commonly found. Hot springs are situated in the Songwe Valley in Mbeya District along the foot of the Usangu Scarp, in the Rungwe Volcanic Province and in the Ruaha Valley. Along the Rukwa Scarp in the north-west Mbeya Region one spring is radioactive. In the north-east Iringa Region many saline springs and water holes are shown on QDS 198. Most of them are found along the Mbungu River which has a high chloride content. In this area fresh springs are found as well.

Although the juvenile springs are small in number compared with fresh springs they are important from a water resource point of view. In areas where they are known to exist care must be taken not to drill into fracture systems that feed the springs, and further where they occur groundwater bodies may be contaminated.

10.3.2 Fresh Springs

Fresh springs are generally occurring across the post-Gondwana, Gondwana, and African land surfaces, and in the Rungwe Volcanic Province. The springs of the Gondwana Surfaces and the Rungwe volcanics are predominantly of the contact type. The springs in these areas are of paramount importance for rural water supply, partly because they are comparatively simple and cheap to implement, and partly because they are much more common than indicated on the map. Virtually all rivers in these areas offset as springs.

Across the African land surface springs are common as well, and here the springs are predominantly contact springs originating from within the saprolite, and artesian springs in depressions.

A number of springs have been located in the continental deposits of the Karroo system. These springs are probably contact springs as well as what could be termed depression springs, i.e. springs that appear due to a depression having been eroded into a local groundwater table in the soft Karroo sediments.

It is interesting to note that very few springs are found across the post-African Surface except for the juvenile ones. This is because Neogene erosion caused by rejuvenation of rivers in connection with the rift faulting has removed the saprolite in many places and, therefore, there is very little groundwater in storage compared to what is found across the older erosion surfaces.

10.4 Yield of Springs

Many of the springs recorded have low yields, and from field observations most of these should strictly not be classified as springs but rather as seepages. They are borderline cases and could as well be regarded as effluent streams. Yet they are included in the survey because, however small, they are revealing hydrogeological information. As a guideline, springs discharging less than 0.2 ltr/s could be considered seepages.

The range of spring discharge is very large, from fractions of one litre per second to more than one hundred. Across the Rungwe Volcanic Province, Gondwanaland, and the African Plateaus low as well as high yielding springs are found. The tendency is that springs in the Volcanic Rocks are the highest yielding, then follows Gondwanaland and the African Plateaus. This is in accordance with the findings on the base flow from these areas where the rivers in the Rungwe Volcanics have the highest specific base flow followed by rivers across Gondwanaland and the African Plateaus. Rivers having their catchments exclusively on the post-African land surface have accordingly little or no base flow by the end of the dry season.

No very high yields are recorded in the Karroo sediments. The highest one recorded is 8 ltr/s, but the majority of springs yields between 0.5 and 3 ltr/s. This indicates in spite of the comparatively low rainfall a large amount of groundwater in storage, as a result of the sandy top soils with a large infiltration capacity compared to the top soils of the Basement Complex. The small variation of yields further indicates very uniform hydrogeological conditions across the continental deposits of the Karroo system.

10.5 Chemistry of Spring Water

Gravity springs are, as a rule, of low salinity and potable. The retention time of the water from spring storages is very small on a geological time scale, and there has been too little time for the water to interact chemically with the porous matrix. In many cases the gravity springs contain kaolin which gives the water a slightly milky appearance. This has no bearing on the potability.

The juvenile springs are, as a rule, not potable. The total amount of dissolved solids is not always high, but a fluorine content of 4 p.p.m. or more is common. The saline springs may contain several thousands p.p.m. chloride. Hot springs have temperatures generally between 50 and 65°C. In the volcanic rocks the juvenile springs often contain gas (cf. the CO_2 exploration wells near Kiejo).

In some boreholes a high fluorine content indicates contamination from juvenile water. This may be the case in some places across the Usangu Flats where juvenile water may issue from fractures situated below the Lake Beds.

The results of the investigation of springs may be summarised as follows:

- Springs are common and constitute the major mode of groundwater discharge across the Gondwana/post-Gondwana and African land surfaces. This is also the case of the Karroo and the Rungwe volcanics.

  The yield of the springs varies considerably, but the majority of springs has yields high enough to make them important for an implementation.

- The chemical quality of springwater is generally very good.

11. DRILLING PROGRAMME

11.1 Introduction

The drilling programme was executed using two rigs, the MAJI T64 Schramm Rig No. 45 and the MAJI Central Mining Equipment (CME) Auger Rig No. 53. A total of 70 boreholes were drilled in the regions. Details on the holes are given in Table 11.1. The full borehole records are presented in Volume 10 B, Appendix 1. The location of the boreholes is shown on Drawing 10, Cyclogram Map, together with the location of existing boreholes in the study area.

11.2 Objectives

The purpose of drilling was to increase the knowledge of the subsurface conditions in the regions and to obtain reliable information which could be used in interpreting the results of the geophysical surveys. In more detail, the objectives of the drilling were as follows:

- To increase the areal knowledge of the hydrogeology of the Basement Complex, especially the African and post-African erosion surfaces. (Holes in Mbozi, Iringa and Tunduru Districts.) Also to see relationship between borehole site and topography. (Sadani and Mantanana.)
- To examine the groundwater quality in general, and in particular in the mid Ruaha Valley (Neogene faulting).
- To examine the depth of the water level in relation to the land surface.
- To investigate the hydrogeology of alluvial deposits and Lake Beds (Kyela District, Usangu Flats and Ruaha Valley).
- To investigate the areal distribution and lithology of the Karroo sedimentary basins (The Ruhuhu Trough and the Tunduru Basin).
- To establish a correlation base for interpretation of geophysical results.

11.3 Execution

11.3.1 Deep Boreholes, Rig 45

The approximate time spent on the various activities was:

1.	Moving, and demobilisation		55 days	16.0%
2.	Drilling		44 days	13.0%
3.	Reaming		2 days	0.5%
4.	Casing		12 days	3.5%
5.	Cleaning		18 days	5.0%
6.	Mechanical Repairs	126	135 days	40.0%
7.	Electrical Repairs	9		
8.	Fuel Procurement		36 days	11.0%
9.	Drilling Tool Collection		15 days	4.5%
10.	Drill Supplies Collection		8 days	2.0%
11.	Crew Changes and Holidays		16 days	4.5%

The actual distribution of the working time for Rig 45 is shown in Figure 11.1.

The notional productivity of the first 6 months of the drilling programme excluding down time was 1 borehole per 9 working days. The Ruvuma drilling was executed at 1 borehole per 2 working days. These figures include moving and site preparation time.

11.3.2 Shallow Boreholes, Rig 53

The time distribution for work on the shallow borehole programme is shown on Figure 11.2. Again for Rig 53 only about 15% of the time was spent on actual drilling.

The shallow borehole programme began in September 1980 and was completed in November 1981 with 4 to 5 holes being drilled per month.

11.4 Training

The training aspect of the project drilling programme was to a large extent curtailed by the continual mechanical breakdowns of the equipment. This fragmented many aspects of the training until the Ruvuma phase of the programme. Here it was possible for the project personnel to fully co-operate with the Maji crews. For future training, as well as on pure drilling methodology, three further aspects need to be taught. These are:

- Mechanical awareness and preventive maintenance
- The efficient use of the support vehicles to reduce the number of unnecessary journeys

- The need for complete and accurate record keeping on the drilling programme.

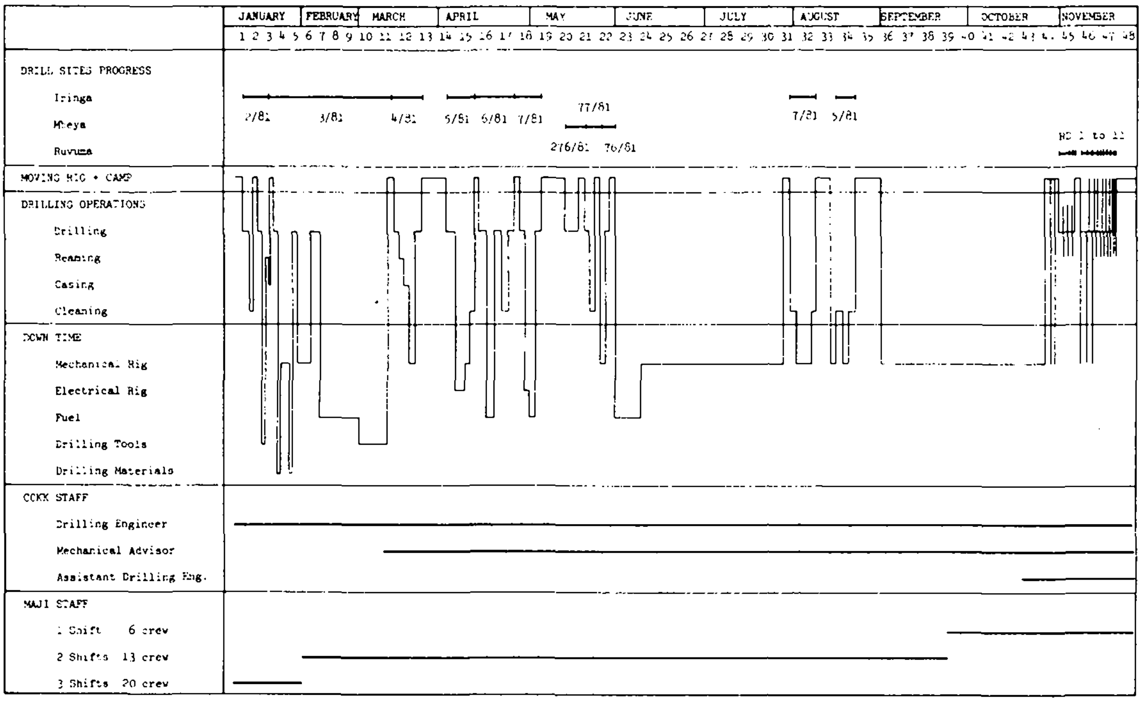


Figure 11.1 MAJI Schramm Rig 45: Deep drilling operations 1981.

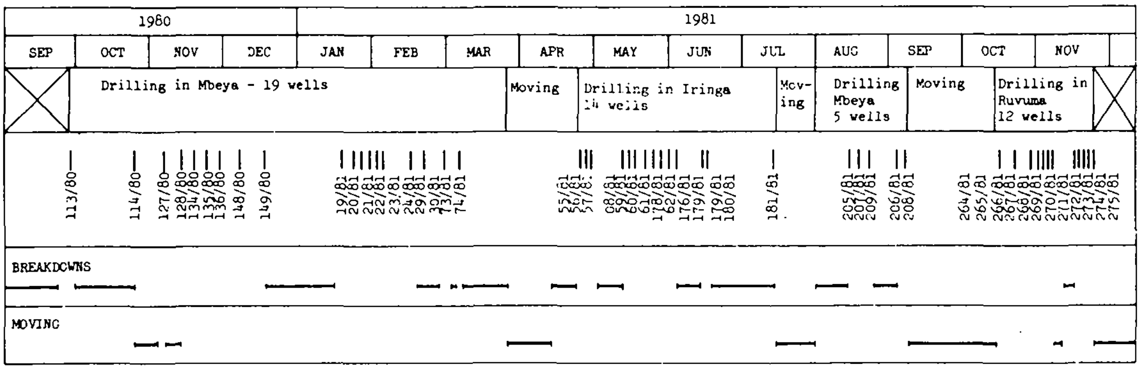


Figure 11.2 MAJI CME Rig 53: Summary of drilling, September 1980 - November 1981.

11.5 Results

Table 11.1 summarises the main results of the drilling programme. Full details of the boreholes are given in Volume 10 B, Appendix 1.

	No. of holes drilled	No. of dry holes	No. of holes abandoned	No. of holes completed	Holes since blocked	No. of holes tested	Average yield m^3/hr	Total metres drilled
SCHRAMM RIG 45								
Iringa	6	1	1	4	1	3	1.20	297.5
Mbeya	3	0	0	3	0	3	0.82	124.9
Ruvuma	11	3	3	9	1	7	2.96	747.45
CME RIG 53								
Iringa	14	1	8	6	0	5	3.32	340.0
Mbeya	24	3	1	16	2	9	2.98	623.4
Ruvuma	12	5	6	6	0	0	-	304.8
TOTALS	70	13	19	44	4	27	-	2438.35

Table 11.1 Summary of boreholes drilled.

12. GROUNDWATER DEVELOPMENT POTENTIAL

12.1 Introduction

The description of the groundwater resources of the regions shall in this context be understood as a description of the availability of groundwater in different geological formations in the regions. A general description of groundwater recharge and discharge and the controlling physical processes is given in Chapter 7 and will not be repeated here. The keywords of this chapter are, therefore, groundwater occurrence and well yields.

The groundwater development potential is shown on Drawing II-13. In constructing this map, the overall policy has been that wells should be drilled in places where the hydrogeological conditions allow for groundwater abstraction by means of hand pumps. The map, however, is equally valid if motor-driven pumps should be preferred in some places, but there is a significant difference between the two methods of abstraction.

There is a larger degree of freedom in siting a well meant for a motor-driven pump, but in addition there is a smaller success rate of drilling because the yield of the well must be larger compared with the yield required for implementation with hand pumps.

The implication of this is that if the groundwater resources maps are used for the purpose of implementing with motor-driven pumps, the differences between the classes shown on the maps become less distinct and the Geomorphological Map (Drawing II-9) could be used instead, and the hydrogeological interpretations given in Chapter 7 should be consulted for guide lines.

12.2 Definition of Terms

The description of the groundwater resources is aimed at shallow groundwater resources and deep groundwater resources. As there is no sharp distinction between the two a definition is necessary, and the following is used:

Shallow groundwater resources are those that can be developed by drilling with:

- Hand tools (digging or hand augering)
- Power augering

Such wells are not considered wells until they are lined with either concrete rings (ring wells) or ordinary casing and screen (tube wells). Usually the method of drilling dictates the depth of the wells although hand-dug wells can be very deep in consolidated sediments.

Deep groundwater resources are those that can be developed by drilling with:

- Percussion rigs
- Rotary rigs

In the study area these wells are mostly drilled into the hard rock of the Basement Complex and are, therefore, generally deeper than the first group although again there is no sharp distinction. In some cases shallow groundwater is being abstracted from wells drilled by rotary rigs because sufficient water was found in alluvial deposits or in the upper part of the saprolite. Such groundwater is shallow groundwater, and actually a different method of drilling could have been chosen. Deep groundwater resources generally cannot be abstracted from hand-drilled or power-augered wells, whereas shallow groundwater resources of course can be utilised by drilling wells with high technology rigs although this is generally not recommended.

12.3 Occurrence of Groundwater

The groundwater resources within the regions occur as deep groundwater and shallow groundwater. The deep groundwater resources are found mainly across the Basement Complex and in the Karroo sediments. The shallow groundwater resources occur mainly in superficial alluvial deposits.

12.3.1 Alluvial Deposits

The occurrence of alluvium is connected to river courses and escarpments. Often the areal extent of these deposits is very small and, therefore, only major alluvial deposits are shown on the maps. However, alluvial deposits are shown in more detail on the geological maps which should be consulted before siting wells for village water supplies. Wells in alluvial deposits have proven to have considerably better yields than wells drilled into the rocks of the Basement Complex. The occurrence of such deposits, therefore, should be closely investigated before hard rock drilling is proposed.

The alluvial deposits in question are alluvial plains, alluvial fans, alluvium along river courses, talus, and to some extent dambos. These deposits consist of fine to coarse grained material, the coarser deposits being closest to the source of deposition, e.g. escarpments. The rest water levels in wells here are usually shallow (1-4 m.b.g.l.), and wells to about 20 metres of depth sometimes less should ensure a perennial supply of groundwater. The types of wells that should be constructed in alluvial deposits are ring wells, hand-drilled wells or power augered wells. The topography of the alluvial deposits is usually very smooth and, therefore, wells can be sited virtually everywhere across these deposits.

12.3.2 The Basement Complex

As stated in Chapter 7, groundwater in the Basement Complex is found mainly in the in-situ weathered rock zone over-lying the fresh rock. As the lower part of this saprolite is the most productive, groundwater abstraction should be based on wells drilled to a depth averaging 50 metres. Wells drilled across the African land surface will generally be somewhat deeper than those drilled on the post-African Surface because of the general difference in saprolite thickness.

To obtain reliable and sufficient groundwater from wells drilled in the Basement Complex, wells should be implemented as boreholes in the usual sense. The methods of drilling should be rotary or percussion drilling. Mud drilling or ODEX drilling in the overburden may be necessary in some places.

The water levels in properly sited wells will be shallow (3-6 m.b.g.l.) in most cases, and about 75% of the wells drilled will have yields sufficiently large for implementation with hand pumps.

The upper part of the saprolite is generally not recommended as an aquifer. The clay content is predominant and coarse material is rare, and the water bearing quality is consequently poor. The aquifer in question is a secondary or sometimes perched aquifer. The reliability of this aquifer as a source is doubtful as it is sensitive to draught periods.

Occasionally sandy layers in the upper weathered zone can be found, and in such cases sufficient yields may be present. However, to locate these interbedded sands is difficult and time consuming, and the reliability of these aquifers is still questionable.

If such formations should be exploited ring wells should be constructed. In this way there is a comparatively large amount of water in storage during the day, and the inflow should then be sufficient to refill the well during the night, otherwise it may frequently run dry.

In some areas the saprolite is very thin because of erosion. In these areas fractures must be found as they may be the only places where perennial groundwater can be found. However, the experience from the regions are that if the fractures are associated to Neogene faulting, saline juvenile groundwater may result making the fractures worthless for water supply. The areas where this type of groundwater is found are mainly close to the rift scarps, both above and below.

To obtain optimum performance of wells across the Basement Complex careful siting is necessary. Water levels are deepest (8-15 m) along the watersheds and shallow in the valleys and along the lower parts of the hillslopes (3-6 m). On the African land surface the success of drilling depends less on the well siting than is the case across the post-African land surface where watershed areas should generally be avoided in topographically pronounced terrains.

12.4 Iringa Region

12.4.1 Shallow Groundwater Resources

The main area where shallow groundwater occurs is the Ruaha Valley, especially in the northern part where large alluvial plains are found. Alluvial deposits are found elsewhere in the valley and alluvium and hill outwash are widespread along the numerous fault scarps in Iringa District. Due to the limited areal extent of these deposits they are not shown on the map but they can easily be located from the Quarter Degree Geological Maps. These alluvial deposits offer the most prospective groundwater resources and are easily developed by low-cost methods of drilling.

Across the Gondwana and post-Gondwana land surfaces shallow groundwater generally occurs in alluvial and outwash deposits in the valleys.

12.4.2 Deep Groundwater Resources

The deep groundwater resources in the region are found exclusively in the Basement Complex.

The most prospective areas are the post-African Surface in the Ruaha Valley and a belt of the African Surface about 25 km wide running through the central part of the region. As the Ruaha and Kilombero Valleys and the Livingstone Mountains are approached groundwater becomes more difficult to locate. Across the post-African land surface along the Ruaha Valley successful boreholes can be drilled in the valleys and on the lower reaches of the slopes. Rejuvenation of rivers has resulted in erosion of the saprolite which in places has become too thin to contain perennial groundwater. In such places fractures in the fresh rock may constitute the only groundwater source although this will generally be small. This is also the case in the scarp areas.

Groundwater across the Gondwana and post-Gondwana land surfaces is commonly restricted to valleys. Because of the deep valley incision (up to several hundred metres) groundwater levels across the plateaus remnants are deep and drilling is not recommended.

However, across the Gondwana and post-Gondwana Surfaces groundwater commonly occurs as springs which constitute reliable sources with good quality water.

12.5 Ruvuma Region

12.5.1 Shallow Groundwater Resources

Shallow groundwater is occurring in two main areas, the Lake Nyasa Shore and the Ruhuhu Depression.

Lake Nyasa Shore

Lake Nyasa is completely rimmed by a narrow belt of the Congo erosion surface, but inspection in the field and experiences from Mbeya Region indicate a good groundwater potential. Mass waste from the mountains interbedded with beach sands all along the shoreline have developed an aquifer system which is expected to have yields more than sufficient for wells equipped with hand pumps. Streams from the mountains above ensure a perennial replenishment of the aquifers. The retention time of groundwater is too short for major chemical alterations to take place, so the groundwater quality is expected to be good.

The Ruhuhu Depression

The Ruhuhu Depression is considered an ancient erosion valley infilled with Karroo sediments (Haldeman, 1956). The sediments are separated from the Precambrian rocks by post-Karroo fault-line scarps which have been rejuvenated. Quarternary erosion of the soft Karroo sediments has resulted in the largest continuous Congo erosion surface within the regions. In large areas the Karroo is eroded down to a very smooth land surface, and because of its position in the Trough, shallow groundwater generally is to be found. It is Being continuously replenished by streams flowing down the escarpments. The lithology in the area is largely unknown, but the yields are expected to be sufficient for hand-pump implementation.

The Basement Complex and The Eastern Karroo Basin

Geological mapping of Ruvuma is limited and preliminary so the maps do not offer any help in locating alluvial deposits across these formations. By comparison with the Iringa and Mbeya Regions alluvial deposits do exist in the Basement Complex but they must be located in the field.

Shallow groundwater does exist in the eastern Karroo Basin but apparently it is restricted to valleys and low-lying flat areas. Auger drilling in the Karroo has been partly successful but cannot be recommended in watershed areas.

12.5.2 Deep Groundwater

The Basement Complex

The Basement Complex of the western part of the Ruvuma Region is topographically very irregular. Deep drilling is recommended only in Central

Songea and in parts of the Mbinga District.

The Basement of the eastern and southern Tunduru District is much more levelled by erosion, and here deep drilling can be carried out for village water supplies in most places. Water levels will be shallow here and the water quality expected to be good, these areas having been apparently tectonically undisturbed during Neogene times.

The Eastern Karroo Basin

Deep drilling has proved successful in this area. All deep boreholes out of 12 drilled have had water, and the Karroo is considered to give sufficient yields for implementation with hand pumps. Due to an in some places irregular terrain water levels are deep in watershed areas (up to 25 m) and shallow (4-6 m) in the low-lying areas. Although the rainfall is low in the Tunduru District the permeability of the top soils is large, so a comparatively large portion of the rainfall will recharge the groundwater body resulting in perennial groundwater.

12.6 Mbeya Region

12.6.1 Shallow Groundwater Resources

The main areas where shallow groundwater occurs are the Kyela District at the northern end of Lake Nyasa and large alluvial fans bordering or overlying the Usangu Flats. Minor alluvial fans and talus are common along the foot of the Ufipa, Rukwa, and Usangu fault scarps, and are delineated on the Quarter Degree Geological Maps. These areas offer reliable sources of groundwater, and wells drilled here will have more than sufficient yields for implementaton with hand pumps. Wells drilled to 20 metres will generally be sufficient to ensure a perennial source but the drilling depth in the alluvial deposits in Kyela District should be at least 30 metres, and screening only of the lower 5-8 metres of the wells is recommended because of pollution hazards in this densely populated area.

Across the Basement Complex alluvial deposits exist but not to the same extent as in Iringa Region. Dambos are more frequent in Mbeya than in Iringa Region, especially in the north where very little tectonic disturbance has taken place. Water bearing interbedded sands in the dambos may be found occasionally but locating them prior to drilling will be difficult.

Finally, shallow groundwater occurs in valleys cutting into the Gondwana and post-Gondwana land surfaces in the northern part of the region and surrounding the Mbozi Plateau.

12.6.2 Deep Groundwater Resources

The deep groundwater resources across the regions are found in the Basement Complex area, the Usangu Flats and the Rukwa Trough.

The Basement Complex

The most prospective areas for deep drilling across the Basement Complex are the African Surfaces on the Ufipa and Mbozi Plateaus, the northern part of the region in the corner between the Rukwa Trough and the Ruaha Valley, and the post-African land surface in the Ruaha Valley and in the Msangano Trough. These areas are well eroded and of topographically low relief as indicated by the common occurrence of dambos. Siting wells for village water supplies can be performed on geomorphological considerations alone.

Across the post-African land surfaces in the Chunya area, and bordering the Usangu Flats to the east, the rejuvenation of rivers has resulted in erosion of the saprolite which in some places os too thin to sustain a perennial groundwater source. In such places, fractures must be located as they will be the only groundwater source available.

The Gondwana and post-Gondwana land surfaces are heavily dissected in the south as these surfaces have been influenced by the rift faulting. The valleys are narrow and steep, and drilling for deep groundwater can be recommended in very few places only.

The Northern Gondwanaland is dissected by much more broad valleys of erosion, and here deep groundwater can more easily be located.

The Usangu Flats

Drilling across the Usangu Flats with the Auger Rig has shown that groundwater there is generally deep, and wells should be drilled to 40 metres. The water level usually seems to stand 20-25 m.b.g.l. except where occasionally perched aquifers are struck. Because of the extreme flatness of the area, well siting offers no problems. Until more drilling has been carried out and proved differently, groundwater can be assumed to be generally occurring, and well yields will be more than sufficient for an implementation with hand pumps. Geophysical surveys are not recommended prior to drilling as signal contrasts from the various layers are very low, and do not allow for strict interpretations.

The Rukwa Trough

The Rukwa Trough is by and large unexplored by drilling. On geological considerations and based on the fact that rivers lose water to the subsurface, groundwater exists. The three boreholes drilled in the trough indicate rest-water levels 8-10 m.b.g.l., so the water levels can be expected to be medium deep. The yields from the wells drilled were 2-12 m^3/hr which suggests that a groundwater solution is possible. Further drilling will probably confirm this viewpoint. However, the water quality may in some places (e.g. the area around Ivuna) cause problems.

12.7 Safe Yield Considerations

A general definition of the safe yield concept applicable to all groundwater situations is not possible. In one area the limiting factor defining the maximum amount of groundwater available for abstraction may be the streamflow from the area, which cannot be allowed to go below a certain level. In coastal areas, constraints may be imposed by salt water intrusion hazards.

The most widely used concept is that groundwater abstraction should not exceed groundwater recharge. This is expressed by the equation

$$G = P - E_a - Q - Q_{ss} - \Delta S, \text{ where}$$

G is safe yield, P rainfall, E_a actual evapotranspiration, Q runoff, Q_{ss} groundwater abstraction, inflow/outflow of groundwater across catchment divide, interbasin diversions, and ΔS is change in storage.

When groundwater abstraction starts, all terms in the equation except for P may change, especially in the case of large scale groundwater development. However, in rural areas, where groundwater development is usually small, the terms may be considered to be fairly constant, and an estimate of the possibility of groundwater mining hazards can be found by comparing the groundwater abstraction with the groundwater recharge.

Consider a rural population of 2,000,000 people distributed evenly in the regions with an area of approximately 175,000 km^2. With a per capita consumption of 25 l/day, the net groundwater recharge should be about 0.1 mm/year to balance the demand. If the population is concentrated in 1% of the area the necessary recharge should be 10 mm/year.

From the findings of the hydrology study, the groundwater recharge is generally 10 times this or more, and consequently it is unlikely, that the safe yield will be exceeded, even with the conservative assumption of serving the whole rural population from groundwater.

12.8 Yields of Wells across the Basement Complex

12.8.1 Tested Yields

The yield of wells based on available data in different geological strata within the study area has been discussed in detail in Chapter 7. It may be argued, that the amount of data presented is insufficient to make firm conclusions, and therefore data have been collected from Water Master Plans covering other regions in Tanzania. This has been done with two purposes:

- To check the reliability of data from the study area
- To establish a data base with enough information to make reasonably firm statistical conclusions.

This has been done for the Basement Complex only, as these rocks cover 68% of the study area and therefore constitute the major geologic unit. A similar analysis would be desirable for the Karroo sediments, but too little data is available.

Additional data on borehole yields have been collected from the Water Master Plans covering Mtwara, Lindi, Tabora, Shinyanga and the 3 Lake Regions, and from Coster (1960) whose data include wells drilled up to 1960.

In Figure 12.1 the relationship between average yields and drilling depths for 508 boreholes is shown. This figure describes the Basement Complex as a single hydrogeological unit, and no distinctions are made between types of rocks or geomorphological units.

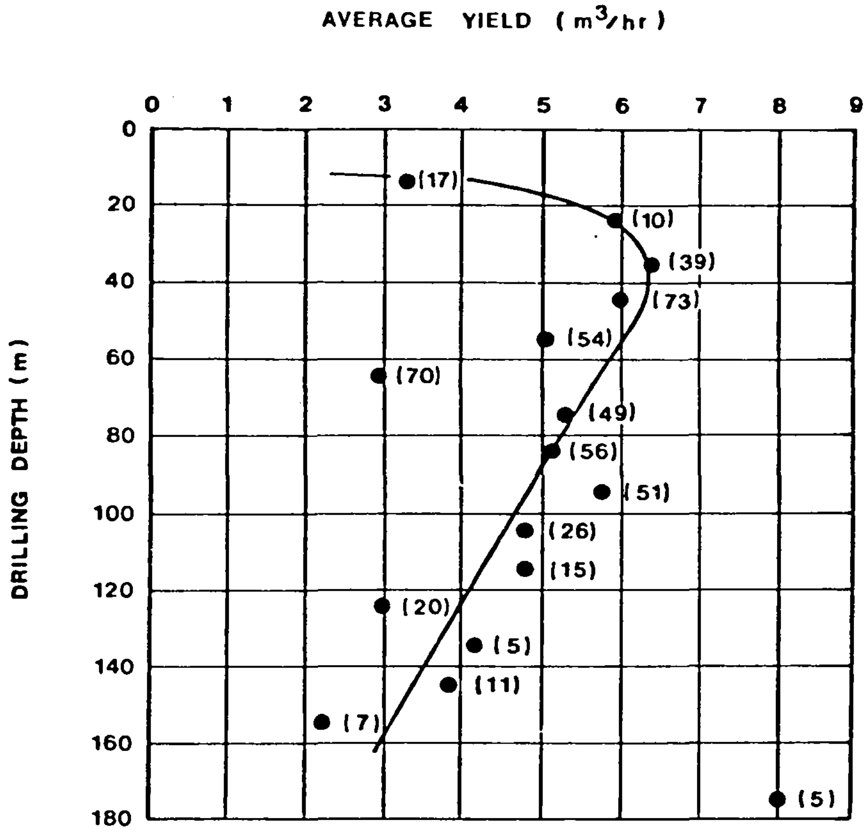


Figure 12.1 Average yield versus drilling depth from 508 wells across the Basement Complex of Tanzania. Numbers in brackets denote the number of wells averaged.

On comparing Figures 12.1 and 6.4 it may be concluded that the lower part of the saprolite generally is the main aquifer across the Basement Complex, and drilling below about 60 metres by when the saprolite is penetrated in 90% of the cases, will generally result in decreasing yields because bedrock is struck. Exceptionally, however, some boreholes completed in bedrock are known to be high yielding.

Considering the number of wells used to construct the depth-yield relationship, it may be stated that the maximum average yield from wells across the Basement Complex is 6-7 m^3/hr, and the best yielding wells are medium deep wells utilising the lower part of the saprolite.

In calculating the average yields, all wells with a reported yield, however small, have been included. The range of yields within each group is therefore large. 10-12 m^3/hr from a well is not uncommon, but high yields (>20 m^3/hr) are exceptional. The small yields reported are down to 0.4 m^3/hr.

Groundwater can be obtained from deep wells, utilising fractures, but yields are generally smaller, and the success rate of deep wells is smaller than that of medium deep wells. Additionally, the chance of striking water of deep-seated juvenile origin is great in parts of the study area, because of the frequent reactivation of pre-Cambrian faults during the Neogene.

It is not possible to determine exactly the success rate of the drilling campaigns in the areas from which the data of Figure 12.1 originate, because no information on the number of dry boreholes or why they were dry is readily available to the Consultants. It is expected that the success rate of a drilling programme aiming at medium deep wells will be 60-70%, assuming yields sufficient for hand pump implementation.

12.8.2 Specific Capacities

The specific capacity frequency analysis deals with the Basement Complex as a whole. There is no distinction between deep and medium deep wells, and, therefore, the specific capacity distribution should be considered in relation to the depth-yield relationship and the saprolite thickness distribution.

Specific capacites have been compiled from the same regions as above, and specific capacites from 143 boreholes are presented in Figure 12.2.

It appears from the data of the figure that the distribution is very close to the distribution obtained from the study area (Figures 7.13 and 7.21) indicating the uniformity of the hydraulic properties of the saprolite aquifer across the Basement Complex.

The minimum required specific capacities required for implementation with motor driven pumps or hand pumps can be found from the following considerations.

If 5 m^3/hr (1100 gallons/hr) is taken as the minimum acceptable yield from a borehole equipped with a motor driven pump, then, with a total head of 45 m (40 m of drawdown, rest water level 5 m b.g.l.) the minimum specific capacity required of the well is about 0.13 m^3/hr/m. From Figure 12.2 about 55% of the boreholes yielding water would be found suitable.

If a hand pump is installed, the yield should be about 1 m^3/hr (220 gallons/hr) or more. Allowing for a total head of 25 m (20 m of drawdown, rest water level 5 m b.g.l.) the minimum specific capacity required of the well is about 0.05 m^3/hr/m. From Figure 12.2, about 75% of the boreholes yielding water would be found suitable.

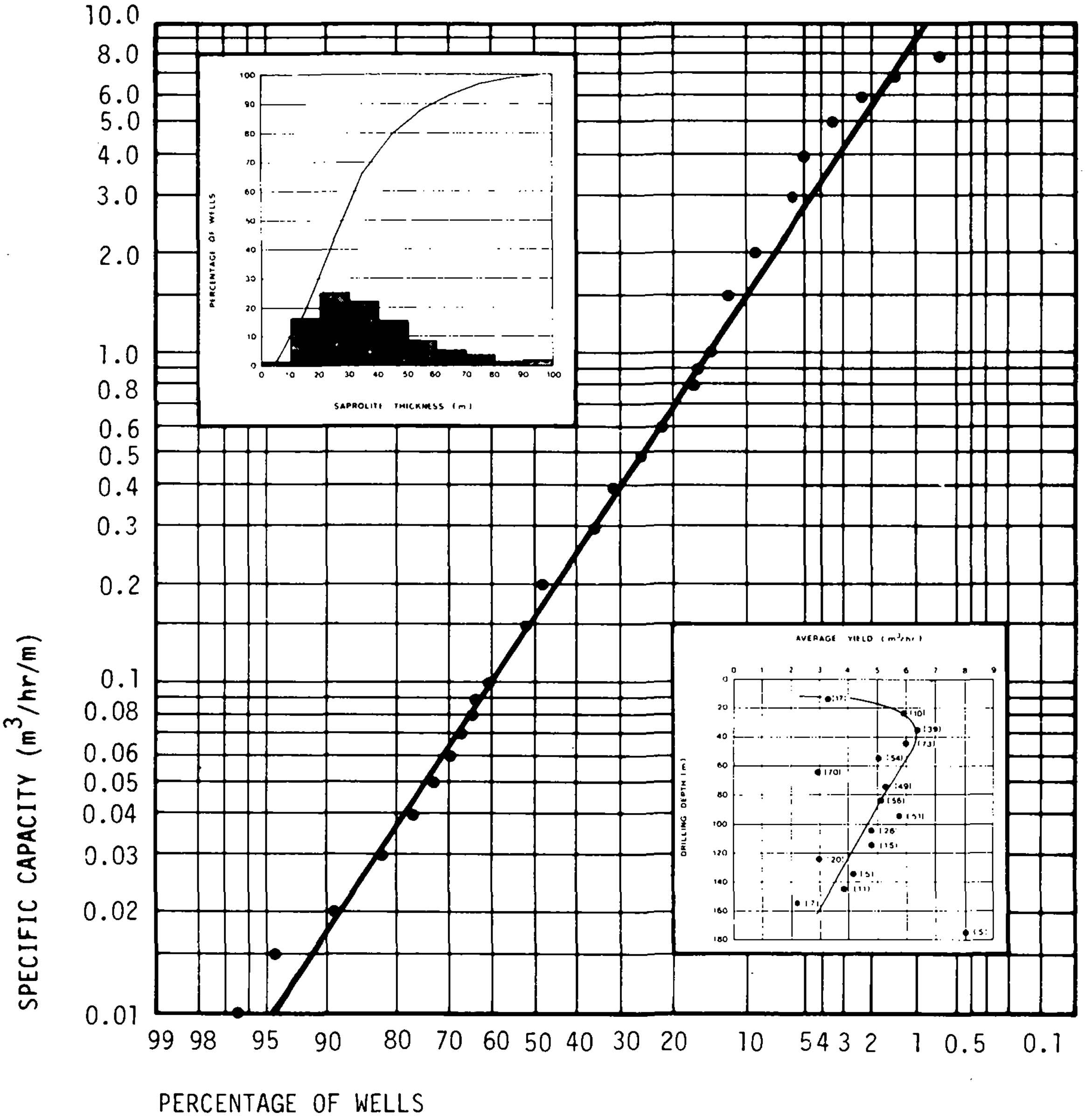


Figure 12.2 Specific capacity frequency distribution for wells drilled across the Basement Complex in Tanzania. Data from 143 wells.

12.8.3 Sustained Yield

The sustained yield or the long term yield is understood here to be a yield that can be obtained from a well without lowering the water level to a critical stage, or causing undesirable changes in the water quality. The critical level may be the top of screen or inflow face or the pump suction. According to Section 12.7 the safe yield concept does in general not influence the sustained yield.

The sustained yield calculations are, therefore, based on solely hydraulic properties. The sustained yield is calculated from the Theis formula, with a pumping period of 8 months (the dry period) and $r_w^2 S = 0.08$ m^2 and a range of yields. To facilitate the calculations, the graph shown in Figure 12.3 has been constructed. The general assumptions behind the Theis formula have been applied. Groundwater recharge has not been taken into consideration which makes the sustained yield estimate conservative.

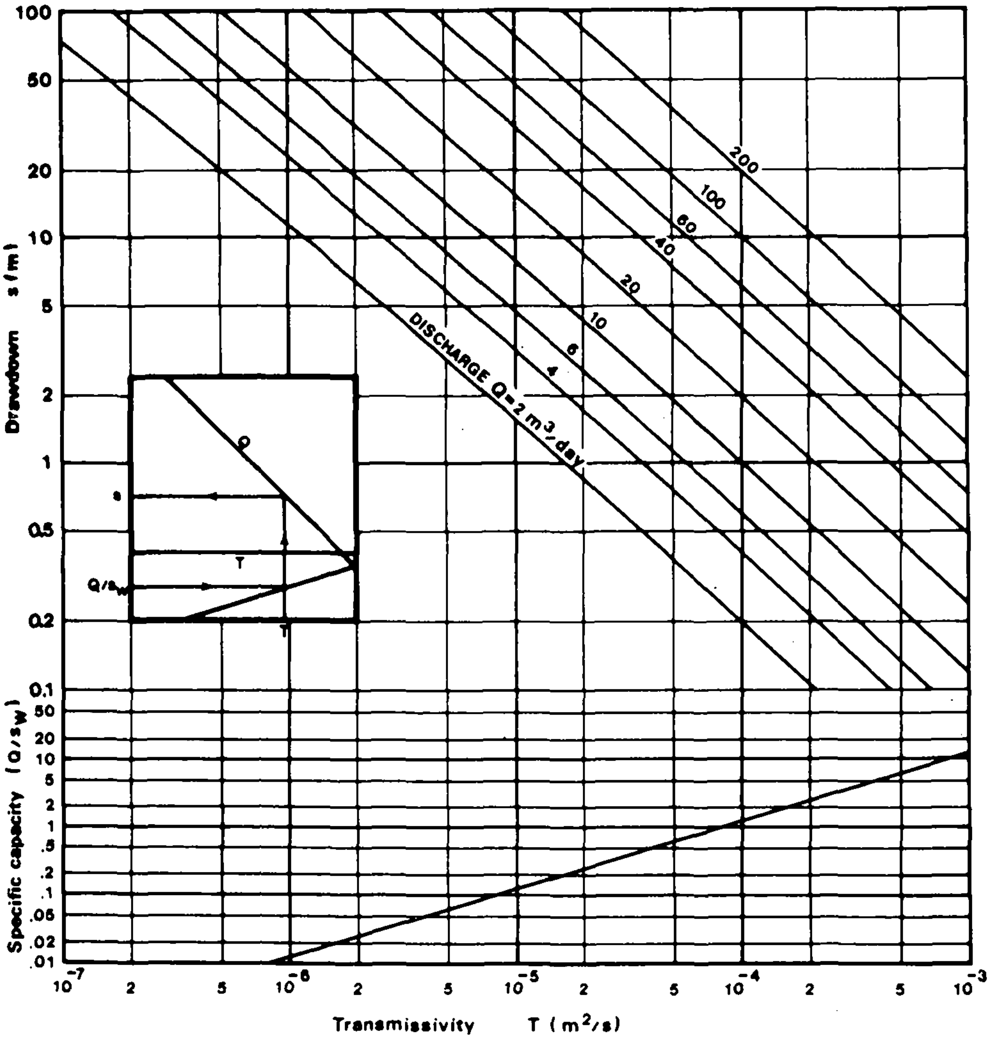


Figure 12.3 Calculation of sustained yield of wells across the Basement Complex.

The relationship between T and Q/s_w used in Figure 12.3 is obtained from the analysis of Chapter 7 (Figures 7.14 and 7.22). From a test T or Q/s_w is known. From the well construction the maximum drawdown is found and the sustained yield can be found from the graph.

As an example, take a well which has a tested specific capacity of 0.2 $m^3/hr/m$ ($T = 1.7 \times 10^{-5}\ m^2/s$). The maximum drawdown is 20 m (25 m from rest water level to top of screen, 5 m to allow for annual fluctuations and safety precautions). With these two figures as entries, the sustained yield is found to be 40 m^3/day. This yield should be larger than the actual demand from the well.

The graph can be used to calculate the drawdowns after 8 months of pumping, with a desired yield. With $Q = 20\ m^3/day$ and $T = 10^{-5}\ m^2/s$, the drawdown is 17 m. This figure is then compared to the drawdown available in the well.

12.9 Yield of Wells in Other Rocks

Data from the Karroo System of Ruvuma Region are too scarce to make similar calculations. From the experiences gained during the Consultants' drilling, however, it seems likely, that the Karroo sedimentary rocks have somewhat better water yielding properties when compared to the Basement Complex rocks. Therefore, until further data are available, Figure 12.3 may be used as a conservative estimate of the sustained yield of wells drilled in the Karroo.

Data from alluvial deposits and Lake beds are not as comprehensive as data from the Basement Complex, but they are considered sufficient to produce the graph shown in Figure 12.4, which is constructed on the same principles as the graph in Figure 12.3, and is used in the same way.

On comparing the two graphs, it is seen that the yields from the alluvial deposits are considerably larger. From Figure 7.31 more than 90% of wells having water have specific capacities larger than 0.1 $m^3/hr/m$, and virtually all wells in these deposits would have yields sufficient for a hand pump implementation. The drawdowns in those wells would on an average be about 10 times smaller when compared to the drawdowns that would occur with the same yield from a well drilled in the Basement Complex.

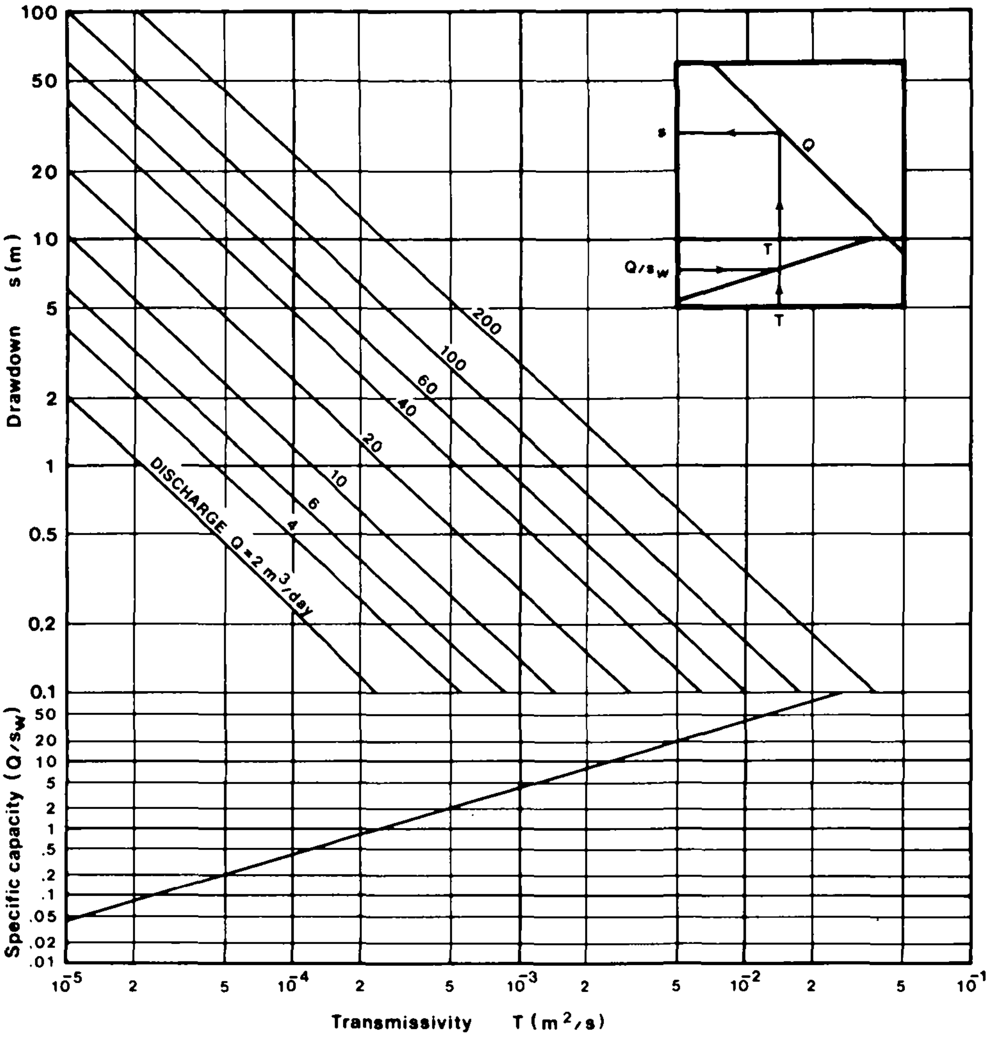


Figure 12.4 Calculation of sustained yield of wells drilled in alluvial deposits and Lake Beds.

13. RECOMMENDATIONS

13.1 Introduction

The recommendations given here will aim at two targets. One is the groundwater aspect of the implementation of the Water Master Plans, and the other is a proposal of investigations that should be currently carried out by the regional hydrogeologists in order to improve the assessment of the general hydrogeologic conditions in the regions.

Although these two targets are different in general, it seems difficult to distinguish between them as they have several factors in common. The results of an implementation drilling programme will have considerable bearing on the general hydrogeologic assessment, and the present knowledge of the hydrogeology of course controls the proposed guidelines for implementation drilling. Therefore, as new data are collected, these may result in need to modify the course of action proposed here, which is based on the study of data presently available.

13.2 Geological and Geomorphological Investigations

While general geological mapping is available for the whole of Tanzania, some areas within the study regions have not been mapped in detail. These areas are especially the very northern parts of Iringa and Mbeya Regions, and the Tunduru Karroo Basin in Ruvuma Region.

The northern areas of Iringa and Mbeya Regions belong to the Basement Complex and geomorphologically they form part of the African land surface. They are thinly populated and accordingly the water demand is low.

Because the geomorphology of the area is known, the hydrogeologic conditions can be reasonably well assessed from the experiences obtained from similar geomorphological areas in other parts of the regions.

The Tunduru Karroo Basin is largely unexplored. The only available information on the lithology of the sedimentary series of the Karroo System is obtained from the Consultants' drilling campaign. The approximate boundaries of the Karroo have been established from the aeromagnitic maps and landsat imageries.

From a water resources point of view, regional geological mapping is now required to establish the lithology of the different sedimentary strata together with a physical description of the sedimentation of the basin. With this information available a more firm basis is established from which the Karroo Basin can be subdivided hydrogeologically and well sites be chosen.

The Geomorphological Map (Drawing II-9) has been mainly prepared to explain the hydrogeology of the Basement Complex. Although the map may seem to be a generalisation, the hydrogeologic conditions across each erosion surface are so uniform that the Geomorphological Map combined with the Groundwater Development Potential Map (Drawing II-13) offers sufficient background for an assessment of the groundwater prospects across the Basement Complex. A more detailed Geomorphological Map may prove necessary for other purposes (agriculture or irrigation f.inst.) but is not required for the purpose of implementation or future systematic hydrogeologic research.

13. Drilling

The recommendations on drilling are aimed at groundwater development for rural water supply only. Drilling for research purposes is not dealt with, but some boreholes of course may have scientific interest.

13.3.1 Siting Boreholes

The Basement Complex

Across the Basement Complex, boreholes cannot be sited successfully in an area without prior assessment of its geomorphology. The degree of planation of the land surface is of ultimate importance for the occurrence and reliability of groundwater. Inspection of the landforms around a village situated on a mature pediplain immediately indicates the best drilling sites in terms of depth to the rest water level. The saprolite thickness, and the yield can be predicted as a probability.

Choice of geomorphologically equally good sites can be based on a seismic or geoelectric survey, of which the latter should be preferred as it is easier and faster to perform. If required the saprolite thickness can be approximately determined and the most promising sites chosen by such geophysical methods.

It should also be taken into consideration that a geophysical survey does not predict the yield of a borehole. The yield of a borehole is determined by the statistical laws irrespective of the siting procedure, and therefore boreholes on mature pediplains are most easily sited from geomorphological considerations alone.

In areas of pronounced topographical relief and in scarp areas, the saprolite may be an aquifer only in the low-lying areas or along the lower reaches of hills. Here boreholes can be sited from geomorphological considerations alone.

Where the saprolite is missing or is very thin, fractures must be utilised. They can be located best from aerial photographs, and a geophysical survey may be advantageously carried out to locate hidden discontinuities in the bedrock surface. In the study regions, such areas are usually influenced by Neogene faulting, and care must be taken to avoid fractures that are expected to conduct juvenile water.

The Karroo System

The experiences on the Karroo Formations, although presently limited, indicate that the rest water levels form a smooth regional surface and in a damped way reflect the topography. This means that the groundwater is shallow in low-lying areas and medium deep to deep in elevated areas. Siting of boreholes should, therefore, be based on the topographical expression of an area. Geophysical surveys carried out in the central part of the basins have shown, that it is possible in some cases to obtain an estimate of the position of the groundwater table and such investigations may be helpful to site boreholes. However, the results of the geophysical surveys confirm what can be concluded solely by inspecting the landforms, and such surveys are, therefore, not considered necessary to locate successful boreholes.

Along the edges of the Karroo basins and sub-basins, the geophysical surveys indicate the thickness of the Karroo beds and the depth to the underlying pre-Karroo land surface. This information is useful because if water is not struck in the Karroo itself, the saprolite of the underlying Basement rock has to be penetrated to obtain water.

Lake Beds

Although not thoroughly explored, the Lake Beds of the Usangu Flats and the Rukwa Trough are believed to possess water bearing qualities more than sufficient for a hand pump implementation.

As the topography across the Lake Beds is very level, there are no topographical indications to distinguish between borehole sites. Geophysical surveys carried out indicate a limited use of these to detect aquifers because of the small variation in response from the Lake Beds. It is possible, however, that a systematic and intensive geoelectric survey may provide useful results in identifying and delineating buried channel aquifers, and it is suggested that such a survey be carried out by the regional hydrogeologist in the near future, before an implementation starts, to test the validity of this application.

On hydrogeological considerations, groundwater should occur everywhere, and siting the boreholes within village areas without a prior investigation should result in successful boreholes.

Alluvial Deposits

The hydrogeologic conditions across alluvial deposits are largely as above. Geophysical surveys probably will yield useful results, but considering the comparatively large yields that are obtained from boreholes in alluvium, a geophysical survey is not necessary to ensure results, and boreholes can be sited in the village areas where convenient.

13.3.2 Drilling Methods

Basement Complex

Drilling in weathered or hard rock is most efficiently carried out by using down-the-hole air hammers. Occasionally the upper 5-10 metres of the weathered mantle may require mud drilling or the use of Odex equipment.

Heavy rigs (Schramm T64 and similar) are not suitable for drilling in rural areas with poor road conditions. Rigs weighing about half as much (10-12 tons) with the same performance should be selected for future work.

Percussion or cable tool rigs have a low productivity in relation to the rotary rigs, but are much lighter and simpler to maintain in working order, and further, they are cheaper in operation. It may prove beneficial to consider the use of such rigs.

The Karroo System

The deep holes drilled in the Karroo by the Consultants were all drilled using down-the-hole air hammers, but the experience gained showed that mud or ODEX drilling would be preferred for the first 50-60 metres of drilling when constructing production boreholes in some areas.

Where the Karroo rocks have been eroded to a very level surface with shallow depth to groundwater, power augering may be used. It should be noted, however, that for general auger drilling in any type of sediment, the rigs should be equipped with a high pressure water flushing device for cleaning the holes.

Percussion rigs can be advantageously used in the Karroo formations.

Lake Beds

In these soft, unconsolidated sediments power augering and hand drilling should technically and economically be preferred, but the expected drilling depth of 40 metres excludes this possibility.

Mud or ODEX drilling will prove efficient, but the best choice is a cable tool rig, which also has a larger degree of freedom to be moved from site to site.

Alluvial Deposits

Across the alluvial deposits the water levels are shallow (1-4 m b.g.l.) and hand drilling or power augering should be preferred. Digging of wells lined with concrete rings will also prove successful in many areas.

Other more advanced methods of drilling can be applied, but are not recommended for economical reasons.

In all these areas the need to provide large quantities of water for mud drilling can add considerably to the logistical problems and the cost of drilling. Such drilling should, therefore, be avoided.

13.3.3 Borehole Construction

Boreholes drilled for production in the various groundwater domains should be constructed in one of the following ways:

The Basement Complex:

- Plain surface steel casing and open hole. This method requires a close geological control in setting the casing to prevent too many fines and clay to enter the borehole.
- UPVC plain and slotted pipe. Gravel pack where deemed necessary.

The Karroo System:

- UPVC plain and slotted pipe. Gravel pack where deemed necessary.

Lake Beds:

- UPVC plain and slotted pipe. Gravel pack.

Alluvial Deposits:

- UPVC plain and slotted pipe. Gravel pack.
- Concrete rings. Gravel pack.

Appropriate measures should be taken to ensure that spoil water is led away from the well and polluted water is prevented from infiltrating in the immediate vicinity of the well. This can be done by means of a concrete construction according to usual standards (DHV, 1978).

Borehole logging can in general be considered useful in placing screens.

If wells are constructed for the purpose of rural water supply and meant to be implemented with a hand pump, logging is still useful, but not necessary.

If the same wells are planned to have a motor driven pump installed at a later stage, screens should be placed in an optimal way according to the results of logging. This of course has considerable bearing on the cost of drilling. The wells must in many cases be drilled deeper (especially in alluvial deposits and Lake Beds) because they have to serve two purposes, and the actual construction of the wells become more expensive. In addition to this the success rate of drilling decreases because the limiting yield is defined at a higher level.

13.4 Groundwater Implementation

13.4.1 Choice of Pumps

In choosing a pump for groundwater abstraction from boreholes, several factors have to be taken into consideration. The sociological factors are dealt with elsewhere, here only technical and economical aspects are considered.

The factors are:

- Initial price
- Running cost
- Availability of fuel
- Durability of pump system
- Maintenance
- Availability of spare parts
- Accessability of village.

There are two types of pumps or pump systems to be considered, hand pumps and motor driven pumps (including pumps driven by solar power or wind power).

On inspecting the factors above the hand pump appears to be the most favourable choice for rural areas.

The initial price and the running costs are the lowest, and fuel problems do not exist. The durability is as good as for any of the other systems. Maintenance is simple in relation to the other systems and cheaper. The number of spare parts that should be in stock is small, and actual repair work of pumps is simpler.

If central stores are established, pumps can be replaced when broken and repaired at the central store.

The accessability of the village, especially during the rainy season, offers less problems if the village is served by hand pumps. A standard village may be served by either 8-10 wells with hand pumps or 1-2 wells with a motor driven pump. Communication is not likely to be critical if one or two hand pumps break down. There will still be sufficient pumps in operation to ensure a supply. If the motor driven system breaks down, which it inevitably does at some stage for a shorter or longer period, then the village is without any supply at all.

It is therefore recommended that boreholes in rural areas are implemented with hand pumps. Only in cases of larger communities which can overcome technical and logistic problems by themselves motor driven pumps can be recommended, provided the necessary economic basis is present.

13.4.2 Implementation of Wells Drilled by the Consultants

Some of the boreholes drilled by the Consultants can be immediately implemented with hand pumps and used for village water supply. Other wells are recommended to be used for routine monitoring of groundwater levels (Section 13.5). The list of boreholes given below contains the deep boreholes as well as the shallower augered holes. It is felt that it is too early now to give firm recommendations, as villagers as well as MAJI have to be consulted before any final decision should be taken.

BH No.	CCKK No.	Village	District	Region	Sustained yield (m^3/day)
19/81*	MS 10	Kikusya	Kyela	Mbeya	200
22/81*	MS 13	Itenya	-	-	170
24/81	MS 15	Kabanga	-	-	40
29/81*	MS 16	Tenende	-	-	400
30/81	MS 17	Ipinda	-	-	400
73/81	MS 18	Ndobe	-	-	150
2/81*	ID 1	Nzihi	Iringa	Iringa	80
3/81	ID 2	Nzihi	-	-	6
55/81	IS 1	Ndolezi	Mufindi	-	80
181/81	IS 14	Mapogoro	Iringa	-	45
255/81	RD 3	Mtukano	Songea	Ruvuma	30
256/81	RD 4	Ndenyende	Tunduru	-	180
258/81	RD 6	Nandembo	-	-	400
262/81	RD 10	Namiungo	-	-	40

Table 13.1 List of boreholes suitable for hand pump implementation, * indicates that the water was not clean upon completion of pumping test.

Boreholes with insufficient yield, unacceptable water quality or situated too far from villages are not included. Other boreholes have been excluded from the list because the drawdown possibilities have been to small. These are mainly auger holes (e.g. the holes across Usangu Flats).

Testing of the auger holes in Ruvuma was tried, but due to clogging of screens it was not possible to complete the tests. These holes are recommended for routine monitoring, but may be turned into production holes if they are cleaned using high pressure water jetting.

13.5 Long Term Monitoring of Boreholes and Springs

The purpose of the long term monitoring of groundwater levels in boreholes and of discharges of springs is to establish a relationship between the rainfall and the groundwater recharge. Records of groundwater level variations and discharge variations of springs are very useful in assessing the general hydrogeologic conditions of an area and they will be of great value for hydrologic modelling in the future.

13.5.1 Borehole Monitoring

In choosing the boreholes for the long term water level monitoring it was imperative that they be spread geographically and represent different geological and geomorphological environments. The boreholes chosen are situated across the African and post-African land surfaces, the Karroo sediments, the alluvial deposits and Lake Beds.

In future, water levels should be measured once every month by means of the electric dippers provided. The automatic water level recorders should be installed as shown in Table 13.2.

The results of the measurements should be plotted currently on linear paper, and a water level file should be opened for each borehole.

13.5.2 Spring Monitoring

As no detailed spring survey has been carried out by the hydrogeologists it is not possible at this stage to point out the exact location of springs to be monitored.

The criteria for choosing the springs should be geographical, geological and geomorphological. The discharge measurement is easy if capped springs are chosen.

The springs should all be gravity springs. Juvenile springs of deep-seated origin are of little interest from a water supply point of view.

BH.No.	CCKK No.	Village	District	Region
276/81	MD 1	Vwawa	Mbozi	Mbeya
77/81	MD 2	Mpemba	-	-
76/81**	MD 3	Chiwanda	-	-
113/80	MS 1	Nkhangamo	-	-
23/81*	MS 14	Katumbwa Songwe	Kyela	-
208/81	MS 20	Luhanga	Mbeya	-
209/81**	MS 22	Ukwaheri	-	-
205/81	MS 24	Ihowelo	-	-
4/81**	ID 3	Mloa	Iringa	Iringa
56/81*	IS 2	Ndolezi	Mufindi	-
58/81	IS 4	Mloa	Iringa	-
60/81	IS 6	Mloa	-	-
178/81*	IS 11	Idodi	-	-
253/81**	RD 1	Hanga River	Songea	Songea
254/81	RD 2	Gumbiro	-	-
263/81*	RD 11	Maji Maji	Tunduru	-
264/81*	RS 1	Hanga River	Songea	-
265/81	RS 2	-	-	-
269/81	RS 6	-	-	-
270/81	RS 7	-	-	-
271/81*	RS 8	Azimio	Tunduru	-
272/81	RS 9	-	-	-
273/81	RS 10	-	-	-

Table 13.2 Boreholes proposed for long term monitoring of water levels.
* Automatic water level recorder
** Automatic water level recorder with barograph

Discharges should be recorded once every month and plotted on a linear scale, and a file should be opened for each spring.

It is recommended, that springs are monitored in the following areas (Table 13.3).

MBEYA REGION		
Geomorphological Unit	Location	No. of Springs
Gondwana/post-Gondwana	Bundali Hills	3
	Mbeya Range	3
	Umalila Mts.	3
African	Mbozi Plateau	3
	Ufipa Plateau	3
Rungwe Volcanics	High and low altitudes	6
Scarp Areas	Songwe Valley	2
	Usangu Escarpment	2
IRINGA REGION		
Gondwana/post-Gondwana	Poroto Mts.	3
	Gofio Plateau	3
	Livingstone Mts.	3
	Makete District	6
	North Iringa District	3
	Mufindi District	3
African	Central area along G.N. Road	6
Scarp Areas	Along the Ruaha Valley in North Iringa District	3
RUVUMA REGION		
Gondwana/post-Gondwana	Livingstone Mts.	3
African	Around Songea	3
Karroo	Ruhuhu Trough	3
	Tunduru District	3

Table 13.3 Proposed number and location of springs for ideal long term discharge monitoring.

14. SUMMARY AND CONCLUSIONS

14.1 Geology and Structure

14.1.1 Geology

The rocks found in the regions can be divided by their geological age into three main groups (Drawing II-8):

- pre-Cambrian rocks
- Karroo sediments
- Neogene deposits.

The pre-Cambrian rocks are collectively referred to as the Basement Complex, and they occupy 68% of the study area. They are, therefore, the most important geologic unit. 97% of the Basement Complex rocks are psammitic metamorphic rocks or acidic plutonic rocks covering a large range of gneisses, granites and migmatites, which when weathered usually form good aquifers. The remaining Basement rocks are pelitic basic and ultrabasic plutonic rocks, and basic and intermediate extrusives, all of which have poor water bearing qualities in their weathered form.

The continental deposits of the Karroo System occur predominantly in Ruvuma Region, where they occupy the Ruhuhu Trough and large parts of Tunduru District (the Tunduru Basin). They cover 21% of the study regions (61% of Ruvuma Region). The Karroo sediments were laid down on mainly pre-Cambrian crystalline rocks, which have been exposed to weathering in pre-Karroo times. The thickness of the Karroo Beds are believed to be up to 3000 metres in the Ruhuhu Trough and Tunduru Basin. Karroo rocks probably occur at depth in the Rukwa Trough and below the Lake Beds of the Usangu Flats. Lithologically the Karroo rocks are mudstones, siltstones, sandstones, conglomerates, varved clays, carbonaceous shales and coals.

The Neogene sedimentary deposits of hydrogeological importance within the study area are alluvial and colluvial deposits and Lake Beds.

Alluvium and colluvium occur in connection with escarpments where rivers dispose of their sediment load as they flow across the topographically level terrain below the scarp. Due to the large proportion of eroded plateaus of little topographical relief, the alluvial deposits have a limited areal extent. Only in the northern part of the Ruaha Valley and in Kyela District have larger alluvial plains been observed.

Lake Beds are found in the Rukwa Trough and across the Usangu Flats. Lithologically they are fine sands, silts and clays. Their thickness is estimated to be up to 200 metres at the most.

The occurrence of the Neogene extrusive rocks of the Rungwe Volcanic Province is limited to mainly Rungwe District in Mbeya Region. The rocks are usually divided into the Older and Younger Extrusives. The Older Extrusives are lavas in the trachyte to phonolitic range and basalts. The younger Extrusives are mainly basalts and phonolitic trachytes, associated with widespread pumice and ash.

14.1.2 Structure

The structural setting of the study area is dominated by the pre-Cambrian orogenic episodes and subsequent rift faulting, which has taken place since the late pre-Cambrian. These mountain building episodes have been separated by periods of erosion, uplift and sedimentation. The faults that can be observed in the pre-Cambrian rocks are mainly parallel to the trends of the fold belts. Movements along these faults have taken place during several periods since the Bukoban (Table 5.2), in the late-Cretaceous, Tertiary and Quarternary. The present linear topographic expression of the faults was established during the Pleistocene. (The eastern and western Rift Valleys, Figure 5.1).

14.2 Geomorphology

Iringa, Ruvuma and Mbeya regions are characterised by high plateaus. They are a result of erosion which has taken place during the past 150 million years, since the late Jurassic. These plateaus are known as erosion surfaces established during different geological periods. They are (Drawing II-9):

- The Gondwana and post-Gondwana Surfaces. They form the crests of the present water sheds at 2000-3000 m.a.s.l. They are preserved mainly as plateau remnants, dissected by later erosion cycles.
- The African Surface, a very smooth and mechanically stable land surface covering the major part of the study regions.
- The post-African Surface, a more undulating and mechanically unstable surface, less developed than the African Surface.

- The Coastal Plain and Congo Surfaces with limited areal extent within the regions. They are found as narrow belts along rivers and Lake shores.

The aggradational surfaces, established by deposition of material during the Neogene, are areally limited, but of local hydrogeological importance. They are mainly:

- The Rukwa Trough
- The Usangu Flats
- The Rungwe Volcanics

A geomorphological classification provides a link between the geology and the hydrogeology of the Basement Complex. It is used as a framework in describing the hydrogeology of the study area, especially the Basement Complex.

14.3 Groundwater Occurrences

The groundwater occurrences and development potential in the regions are shown on Drawing II-13, Groundwater Development Potential.

14.3.1 The Basement Complex

Once a land surface has become mechanically stable, deep chemical weathering takes place by circulating groundwater. This process establishes a weathered zone or saprolite zone above the parent rock. As time is the most important factor in producing the in-situ weathered profile (Chapter 5) the profile is thicker and more developed on older rather than younger pediplains.

The aquifer across the pediplains is predominantly the lower part of the saprolite.

Generally, therefore, across the Basement Complex the groundwater occurrences can be classified according to the geomorphological history of a given area.

The mature African Surface posesses the best potential for aquifer development. Groundwater is generally occurring everywhere. Aquifers will be artesian with rest water levels 2-8 m below ground level.

As the topography becomes more rolling (post-Gondwana and post-African Surfaces) perennial groundwater is found along the lower reaches of hills and in valleys. Rest water levels are shallow in the low-lying, deep in the more elevated areas.

Across the highly dissected plateaus of the Gondwana Surface, groundwater is restricted to valleys. Groundwater levels may be deep. In the scarp areas and in areas where rejuvenation of erosion has resulted in a thin or removal of the saprolite cover, fracture and fissure zones must be struck by drilling to locate a reliable groundwater source.

The yields of wells across the Basement Complex follow a log-normal distribution. Average yields from successful boreholes are 3-7 m^3/hr. (Chapter 7 and 12). An estimated 75% of boreholes striking water would have yields sufficient for hand pumps and an estimated 55% would have yields sufficient for motor-driven pumps.

14.3.2 The Karroo Basins

Information on the hydrogeology of the Karroo is based mainly on the Consultants' drilling results. The aquifers are found to be predominantly confined. Groundwater levels reflect the topography, they are deep (up to 25 m below ground) in upland areas and shallow (2-4 m below ground) in depressions. Perennial groundwater generally occurs everywhere.

The yields of wells drilled in the Karroo rocks may, according to the results of drilling, expected to be higher than in the Basement Complex rocks.

14.3.3 Neogene Deposits

Lake Beds

Drilling in the Rukwa Trough and across the Usangu Flats has shown that perennial groundwater may be expected to exist in these deposits. The specific capacities of wells are considerably higher than in general across the Basement Complex, and more than 90% of wells having water will have yields sufficient for hand pump implementation. However, water levels are expected to be deep, about 10 m in the Rukwa Trough and up to 25 metres below ground level across the Usangu Flats.

Alluvial Deposits

Drilling in these has shown that they are the most prospective groundwater sources within the regions. Yields are generally high, up to 10 m^3/hr allowing for 10 m drawdown. Water levels are shallow, less than 4 below ground and wells can be sited in or around villages.

The Rungwe Volcanics

In these rocks drilling for groundwater is not recommended, as topography is very rugged and groundwater quality unpredictable. Springs offer much better groundwater prospects.

14.3.4 Springs

Springs have been found to constitute the major mode of groundwater drainage over

- the Gondwana and post-Gondwana Surfaces
- the African Surface
- the Karroo Basins
- the Rungwe Volcanics.

The yield of springs are generally 0.5-1 l/s, but yields over 100 l/s have been recorded. Where found, they are reliable groundwater sources which should be considered the prime target of groundwater implementation.

14.4 Groundwater Chemistry

Groundwater chemical analyses are shown on Drawing II-11, and described in more detail in Chapter 9.

14.4.1 The Basement Complex

Although local variations occur, the groundwater quality within the Basement Complex generally meet the requirements of the standards set for drinking water. Iron, manganese and fluoride contents will mostly lie within accepted limits. Exceptions are areas influenced by Neogene tectonics. Boreholes drilled in such areas may contain juvenile water, often with a high content of chloride and sometimes fluoride.

These areas are found following the fault-lines defining the Rift Valleys and associated fault-lines.

14.4.2 The Karroo Basins

In these sedimentary continental deposits groundwater is chiefly potable. All samples analysed have indicated water qualitites suitable for human consumptions.

14.4.3 Neogene Deposits

Lake Beds

The groundwater quality in the Lake Bed sediments has been found to be highly variable. Potable groundwater has been found, but groundwater has also been observed to be locally influenced by juvenile water originating from fracture zones below the Lake Beds. Across the Usangu Flats this is demonstrated by high fluoride contents in places. In the Rukwa Trough this has resulted in high salinities locally.

Alluvial deposits

In these deposits the groundwater quality is generally acceptable, but the iron content may locally be high, and juvenile water has been found near Neogene faults.

The Rungwe Volcanics

In these rocks the groundwater quality is unpredictable. Numerous Neogene faults are responsible for a large content of dissolved solids and in places gases in the groundwater. This seems not to have affected the quality of spring water, which is generally good, except for the juvenile hot springs.

14.4.4 Springs

Except for the juvenile springs, spring water is reported to have more than acceptable quality and is probably the best drinking water found in the regions, regardless the geologic environment.

14.5 Geophysical Investigations

Geoelectric and seismic surveys have been found useful in determining the saprolite thickness across the Basement Complex. After empirical corrections, the results of these investigations have been found to be in accordance with borehole strata logs, and they confirm the geomorphological features found across the Basement Complex.

Geophysical surveys have also proven useful in defining the boundaries of the Karroo Basins in Ruvuma Region.

Down-the-hole logging is an effective tool in determining lithological contacts in rapidly changing layers such as the Karroo sediments. Logging is less suited to define the contact between weathered and fresh rock, as their composition of basic minerals is the same, and the contact is seldom distinct.

14.6 Drilling Programme

Drilling was carried out using two rigs, 1 MAJI Schramm T64 Rig (Rig 45) and 1 MAJI CME Auger Rig (Rig 53). A total of 70 holes were drilled in the regions, 20 of which were deep holes drilled by Rig 45 and 50 were shallow holes drilled by Rig 53.

14.6.1 Results of Drilling

Drilling in the Basement Complex, which was comparatively well known beforehand, gave no essentially new knowledge, but confirmed the interpretation of the hydrogeologic conditions based on the existing data.

Drilling in the Karroo, Lake Beds and alluvial deposits, however, have given useful results in drawing the preliminary conclusions outlined in Section 14.3 above.

14.6.2 Recommendation for future drilling

Methods of drilling

The Schramm T64 Rig has been found to be too heavy in relation to the road conditions in Tanzania. For rotary drilling in hard rocks lighter rigs should be preferred. Percussion rigs may, although they have slower penetration rate, prove to be more efficient rigs to operate, because they are less heavy and require less sophisticated maintenance.

Auger drilling has proved successful in unconsolidated deposits and, equipped with cleaning and jetting equipment, would be an efficient method of drilling, although the drilling depth is limited to about 30 metres.

Hand drilling is recommended in alluvial deposits. The yields of aquifers here are usually high enough to provide the base for groundwater abstraction from hand drilled tube wells. In many places hand dug ring wells can be successfully used.

Siting Wells

Across the well pedimented plateaus of the Basement Complex geomorphological interpretation should be used to site wells. Geophysical surveys may be useful but are not considered necessary, because the weathering and consequently the groundwater conditions are revealed by the geomorphological characteristics in these areas.

In the Karroo Basins, groundwater conditions are largely given by the topography. Therefore, geomorphological interpretations would be sufficient to site wells. Along the edges of Basins, however, geoelectric soundings can be advantageously used to determine the depth to the pre-Karroo land surface, and consequently determine the main type of strata to be expected.

Across Lake Beds and alluvial deposits, the surface is so level and groundwater conditions so uniform, that no investigations are required before drilling, except for field reconnaissance.

Implementation of Wells

Because of the advantages of hand pumps in relation to motor driven pumps (cf. Chapter 13) wells should be equipped with hand pumps, whether deep or shallow. Many of these wells will be suitable for motor driven pumps, should this prove beneficial in the future.

Shallow well drilling programme

Wells utilising shallow groundwater resources can be successfully drilled in several areas. They are:

- Alluvial plains in the Ruaha Valley and in Kyela District at the northern end of Lake Nyasa.
- Alluvial fans along escarpments, notably in the Rukwa Trough and bordering the Usanga Flats. Local fans are found elsewhere in association with major faults.
- The colluvial deposits along escarpments.
- The Karroo sediments of the Congo Surface in the Ruhuhu Trough.
- Local alluvial tracts in river valleys across Basement Complex plateaus.

- Alluvial deposits in valleys dissecting the Gondwana plateaus.

These wells should be auger wells, hand drilled tube wells to 20 m or dug ring wells to 10 m. An estimated 90% or more of wells striking water will have sufficient yields for hand pump implementation.

Wells equipped with hand pumps and utilising medium deep or deep groundwater resources can be successfully drilled in parts of the remaining area. These are:

- The topographically level areas on the African and post-African Surfaces, where the saprolite cover is preserved. Drilling depths would on an average be 50 m and 40 m respectively.
- The Karroo Basins. Drilling depths cannot be estimated accurately, but probably in the range 50-100 m.
- The Usangu Flats and Rukwa Trough. Drilling depths would on an average be 40 m.
  Across the Basement Complex an estimated 75% of wells striking water will have sufficient yields for hand pump implementation. This figure would be somewhat higher for the Karroo. Across the Lake Beds of the Usangu Flats and the Rukwa Trough the estimate is 90% or more.

In scarp areas, areas with rejuvenated erosion and topographically irregular terrains, general guidelines cannot be given. The saprolite aquifer is not present and the presence of reliable groundwater will depend on fracture and fissure zones, some of which conduct poor quality groundwater.

14.7 Future Hydrogeologic Data Collection

It is recommended, that selected springs and boreholes are monitored regularly in the future to establish a base for evaluating hydrogeologic conditions on a regional basis. Boreholes drilled by the Consultants covering the main hydrogeological domains have been selected (cf. Chapter 13). Also a number of springs have been proposed as a part of the monitoring programme. Further, regional geological mapping is suggested to be carried out in areas where this has not yet been done.

Literature :

Abu-Zied, M.A. and H.V. Scott: "Nonsteady flow for wells with decreasing discharge". Proc. A.S.C.E. Journ. Hyd. Div. 1963.

Andersen, L.J.: "Cyclogram technique for geological mapping of borehole data". Geological Survey of Denmark, III Series No. 41. 1973.

Carrol, D.: "Rock Weathering". New York. 1970.

Coster, F.M.: "Underground Water in Tanganyika". Dep. of Water Development. Dar-es-Salaam. 1960.

DHV Consulting Engineers: "Shallow Wells". The Netherlands. 1979.

Flint, R.F. and B.J. Skinner: "Physical Geology". New York. 1974.

Gillman, C.: "The Geography and hydrology of the Tanganyika Territory part of the Ruvuma Basin". Dar-es-Salaam. 1943.

Graff Petersen, P.: "Physical Geology". Copenhagen (in Danish). 1960.

Hadwen, P.: "The Groundwater resources of the Greater Ndola area". Dep. of Water Affairs, Hydrogeology Branch. Lusaka. 1972.

Haldeman, E.G.: "A Note on Structural Features and Erosion in Eastern and Southern Tanganyika". First Meeting, East-Central Regional Committee for Geology. Dar-es-Salaam. 1956.

Hantush, M.S.: "Drawdown around Wells of Variable Discharge". Journ. Geoph. Res. Vol. 69. No. 20. 1964.

Harkin, D.H., A.C.M. McKinlay and J. Spence: "The Karroo System of Tanganyika". Geol. Survey Division, Report No. DAH 11. Dodoma. (No Year).

Heath, C.R. and F.V. Trainer: "Introduction to Groundwater Hydrology". New York. 1968.

Holmes, A.: "Principles of Physical Geology". Thomas Nelson, London. 1978.

Johnson, E.E. Inc.: "Groundwater and Wells". Johnson Division, Univ. Oil Products Company. Minnesota. 1966.

King, L.C.: "Morphology of the Earth". London. 1962.

Monkhouse, F.J. and J. Small: "A Dictionary of the Natural Environment". Edward Arnold. London. 1970.

Pallister, J.W.: " The Rift System in Tanzania". Unesco Seminar on the East African Rift System. University of Nairobi. 1965.

Piper, A.M.: "A Graphic Procedure in the Geochemical Interpretation of Water Analyses". U.S.G.S., Ground Water Note 12. 1953.

Saggerson, E.P.: Geology. In Morgan, W.T.W. (Ed) : "East Africa, its people and resources". Oxford. 1969.

Stockley, G.M.: "The Geology of the Ruhuhu Coal Fields". Quart. Journ. Geol. Soc., Vol. 88. London. 1932.

Walton, W.C.: "Groundwater resource evaluation". New York. 1970.