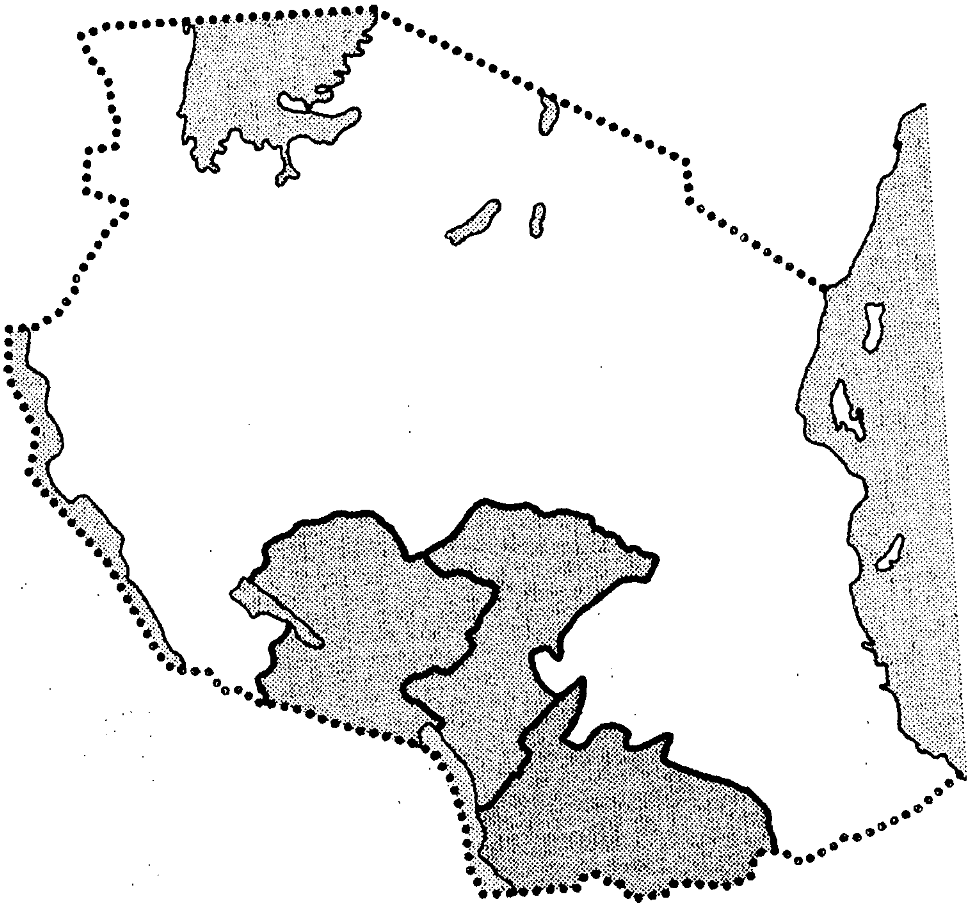
UNITED REPUBLIC OF TANZANIA

DANISH INTERNATIONAL DEVELOPMENT AGENCY • DANIDA

WATER MASTER PLANS FOR IRINGA, RUVUMA AND MBEYA REGIONS

HYDROLOGY

VOLUME 7



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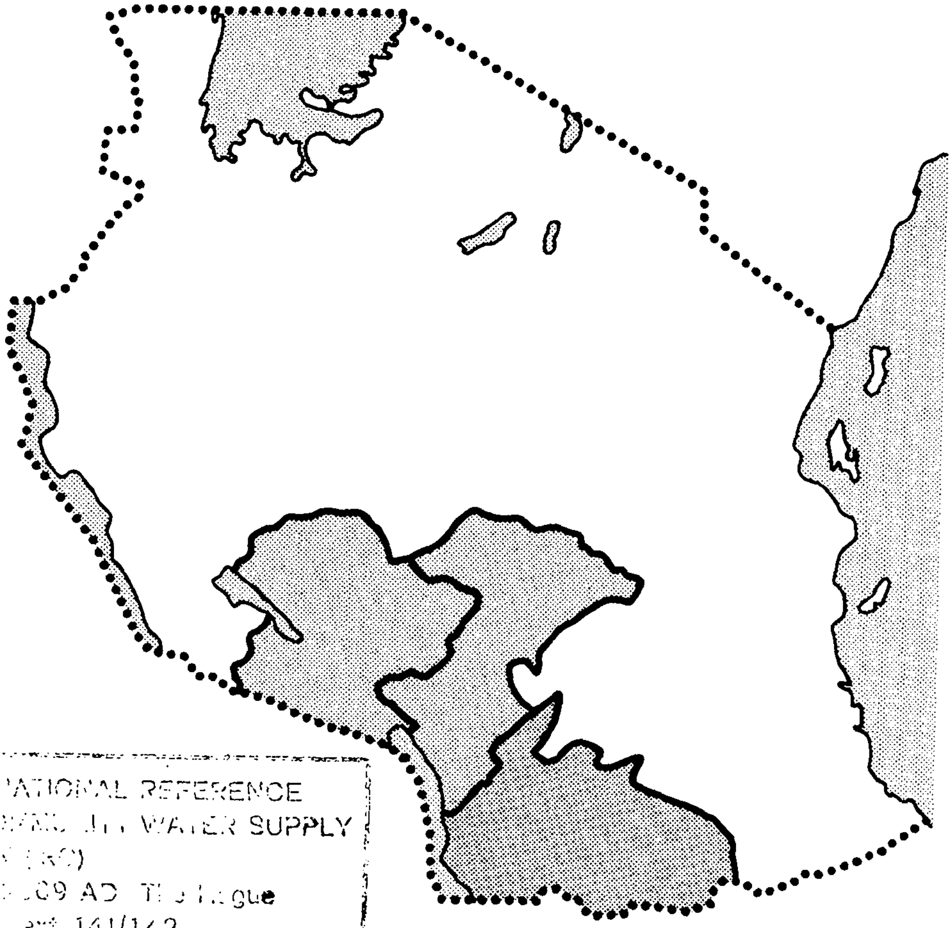

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GUIDE TO WATER MASTER PLANS FOR IRINGA,RUVUMA AND MBEYA

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

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1. INTRODUCTION

The present report describes the hydrological studies performed as part of the Water Master Plans for Iringa, Ruvuma and Mbeya Regions in Tanzania. Financed by the Danish International Development Agency (DANIDA), this study has been carried out in the period February 1980 to March 1982 Carl Bro - Cowiconsult - Kampsax-Krüger (CCKK), Consulting Engineers, in association with Danish Hydraulic Institute (DHI), for the Government of Tanzania, represented by the Ministry of Water, Energy and Minerals (MAJI).

The objective of the water master plans has been to provide the Government of Tanzania with firm recommendations for the development of the water resources of Iringa, Ruvuma and Mbeya Regions over the period 1981-1991, and a brief outline for an additional 10 years. Although the utilisation of water resources for all relevant purposes shall be considered, particular attention shall be given to the supply of water to villages for human and livestock use. Reliable low cost sources of quality acceptable to Tanzanian authorities shall be identified for every village within the regions.

Within these overall objectives the purpose of the hydrological studies described in this report has been to assess the availability of surface water resources for all human utilization, with particular emphasis on rural water supply, while providing an outline of the hydrology and water balance of the regions in a more general sense.

The work on the hydrological studies has focused primarily on the collection, processing and analysis of data from existing sources. A comprehensive and up-to-date hydrological data base has been established, not only for the purposes of the present study, but also for MAJI's future hydrological activities in the regions. The Consultants have inspected most of the hydro-meteorological gauging stations in the regions, and a comprehensive hydrological field measurement programme has been undertaken in 1980 including streamflow measurements at permanent gauging stations and spot measurements of streamflow in a large number of villages. Detailed hydrological studies have been carried out for selected representative catchment areas (index areas).

The hydrological data processing and computer analyses have been carried out at DHI, using the Northern European University Computer Centre (NEUCC).

Tanzanian counterparts have spent six months at DHI during this phase of the study, primarily for the purpose of training in hydrological computer modelling techniques. The counterparts have each been responsible for the detailed hydrological study and modelling of one index area, for which they have submitted separate reports to MAJI and DANIDA. Senior MAJI hydrologists have paid regular visits to Denmark in this period.

A general description of the hydrological studies is contained in the present report (Volume 7), the associated data volume (Volume 8), and a box containing maps (Box II). In addition to this the hydrological data base has been handed over to MAJI in the form of magnetic tapes and detailed computer printouts of their contents. Volume 7 is intended as a general text containing only key results and illustrative examples of analyses, presentations and results, while reference is made to Volume 8 for details. All figures and tables are numbered in consecutive order within each chapter, a "8" indicating that the respective figure or table is contained in Volume 8.

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 in Tanzania and in Denmark at regular intervals during the study period.

The present report has in draft form been presented to MAJI, DANIDA and the Water Master Plan Coordination Unit (WMPCU) in December 1981, and their comments have all been included in the present version.

2. PHYSIOGRAPHY

2.1 Topography

Mbeya, Iringa and Ruvuma 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 2.1).

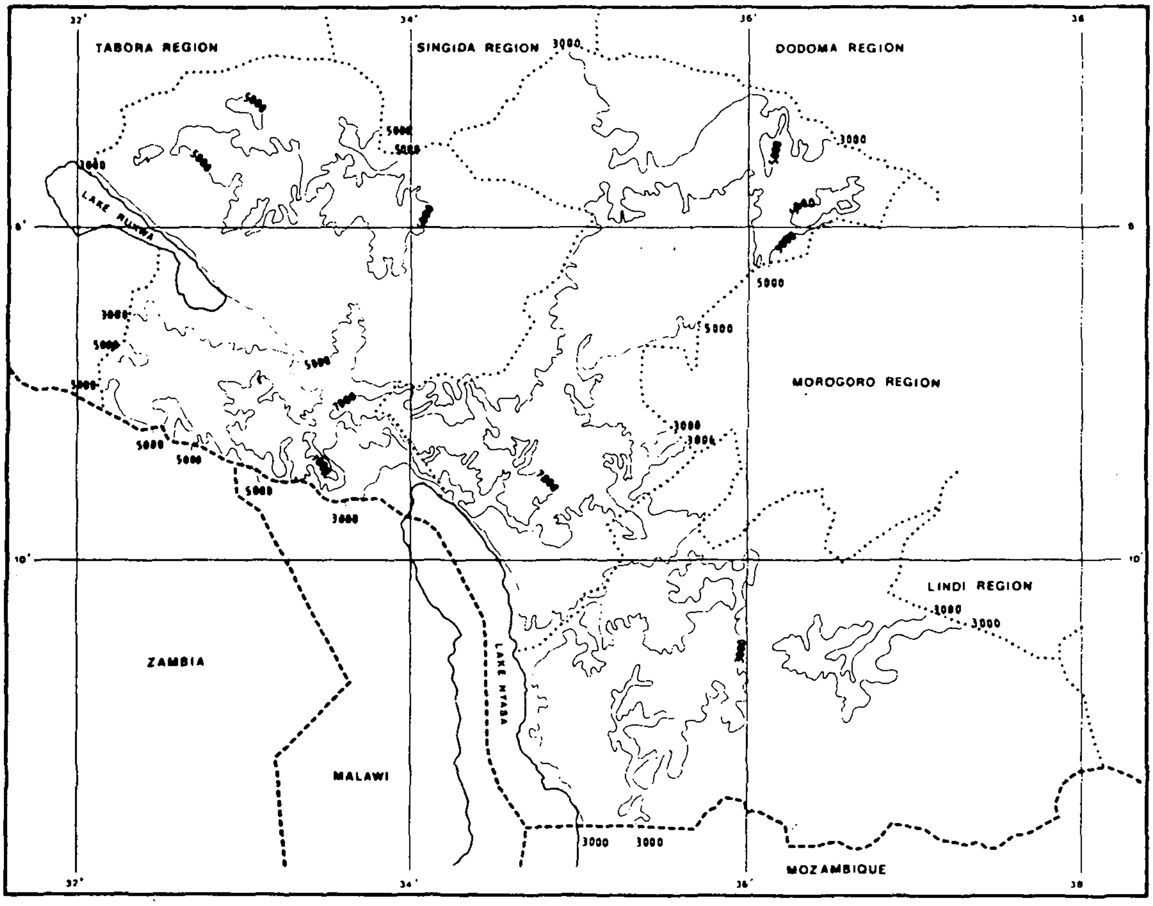

Fig. 2.1 - Main topographic features (altitudes in ft.)

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.

2.2 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.

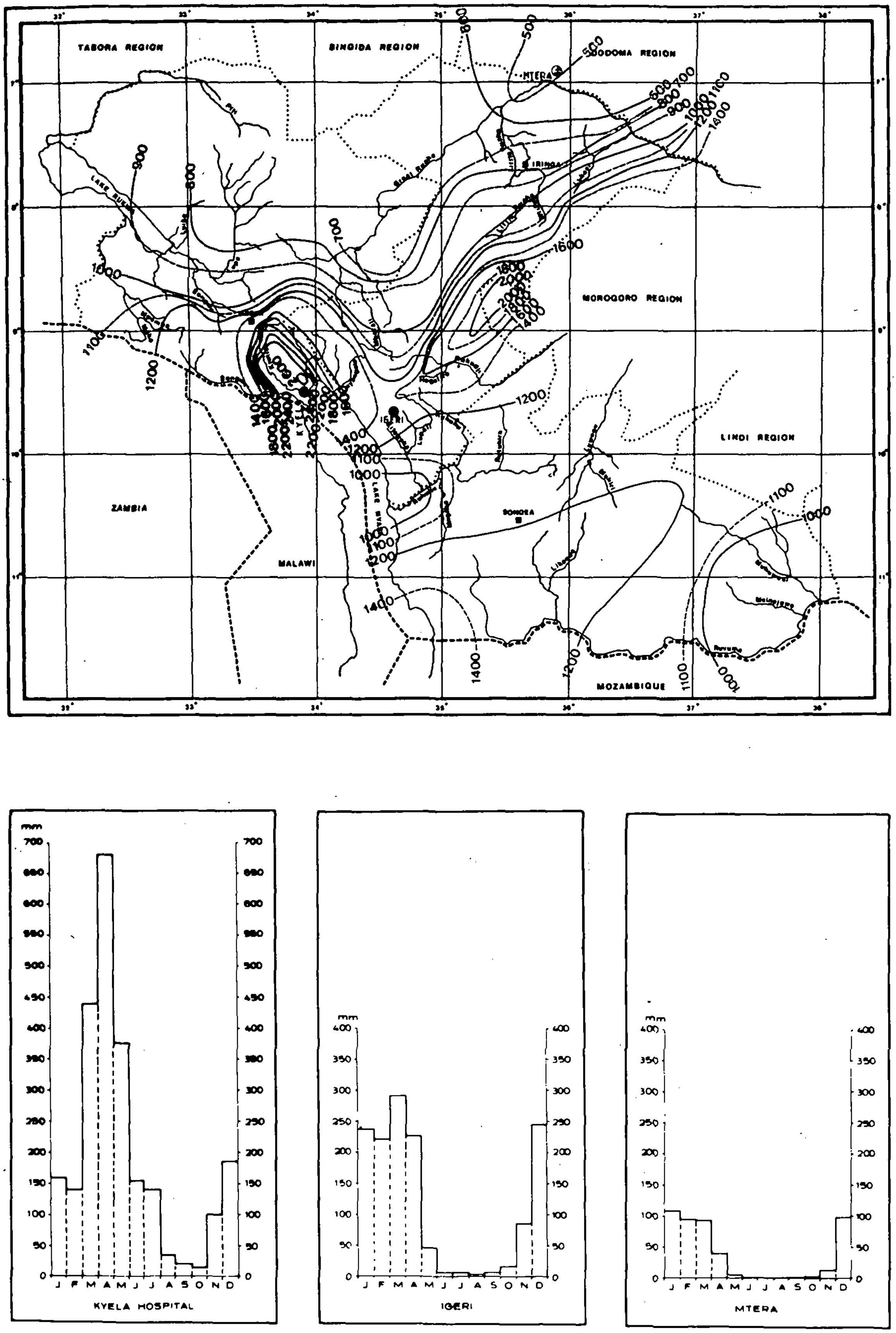

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Figure 2.2 - Mean annual rainfall and mean monthly rainfall variation at selected locations.

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.

The main climatic features of hydrological interest are illustrated in Figures 2.2, 2.3 and 2.4, 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 2.2, 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 2.3 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 2.3, 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.

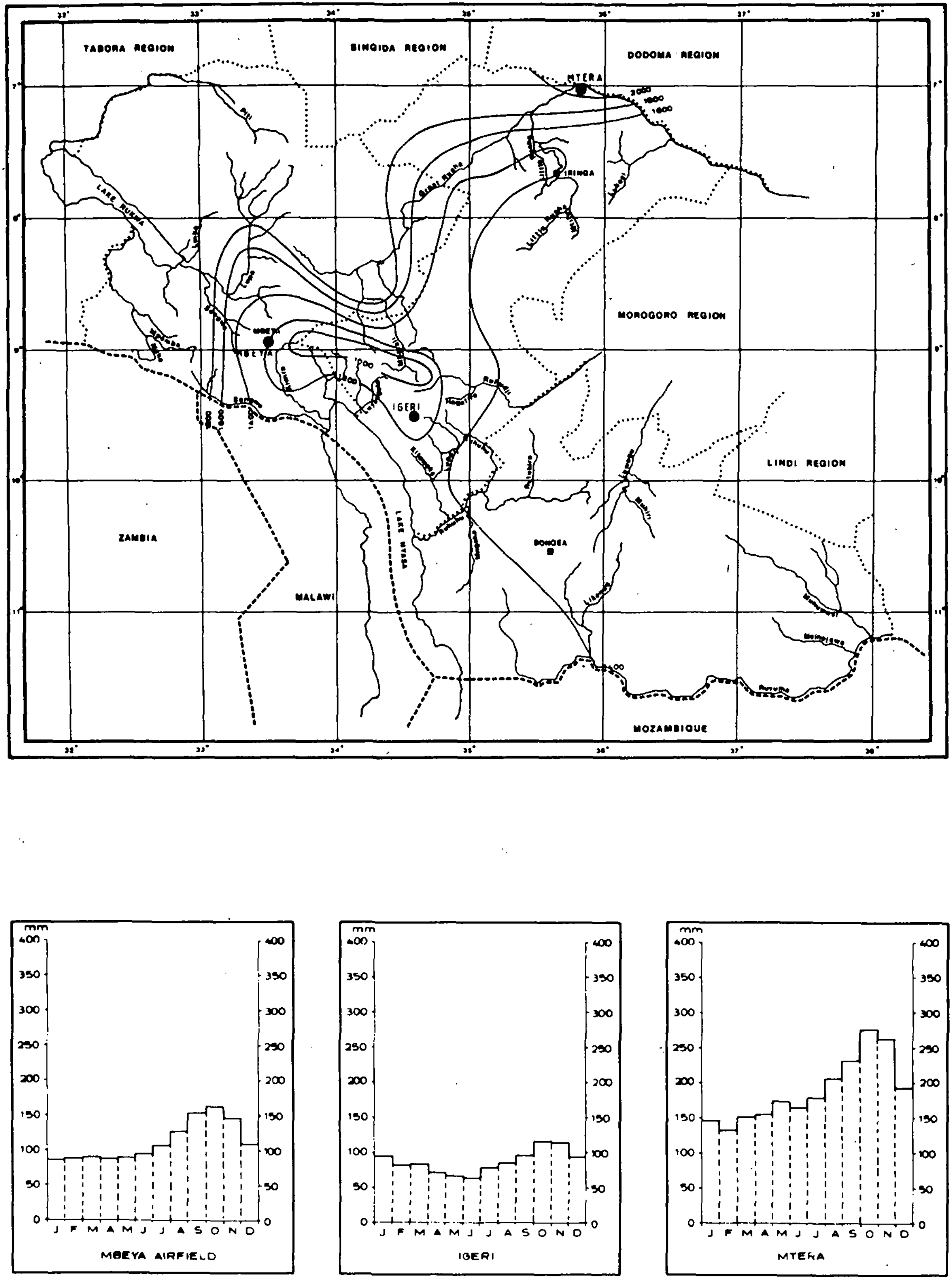


Figure 2.3 - Mean annual evapotranspiration, and mean monthly evapotranspiration at selected locations.

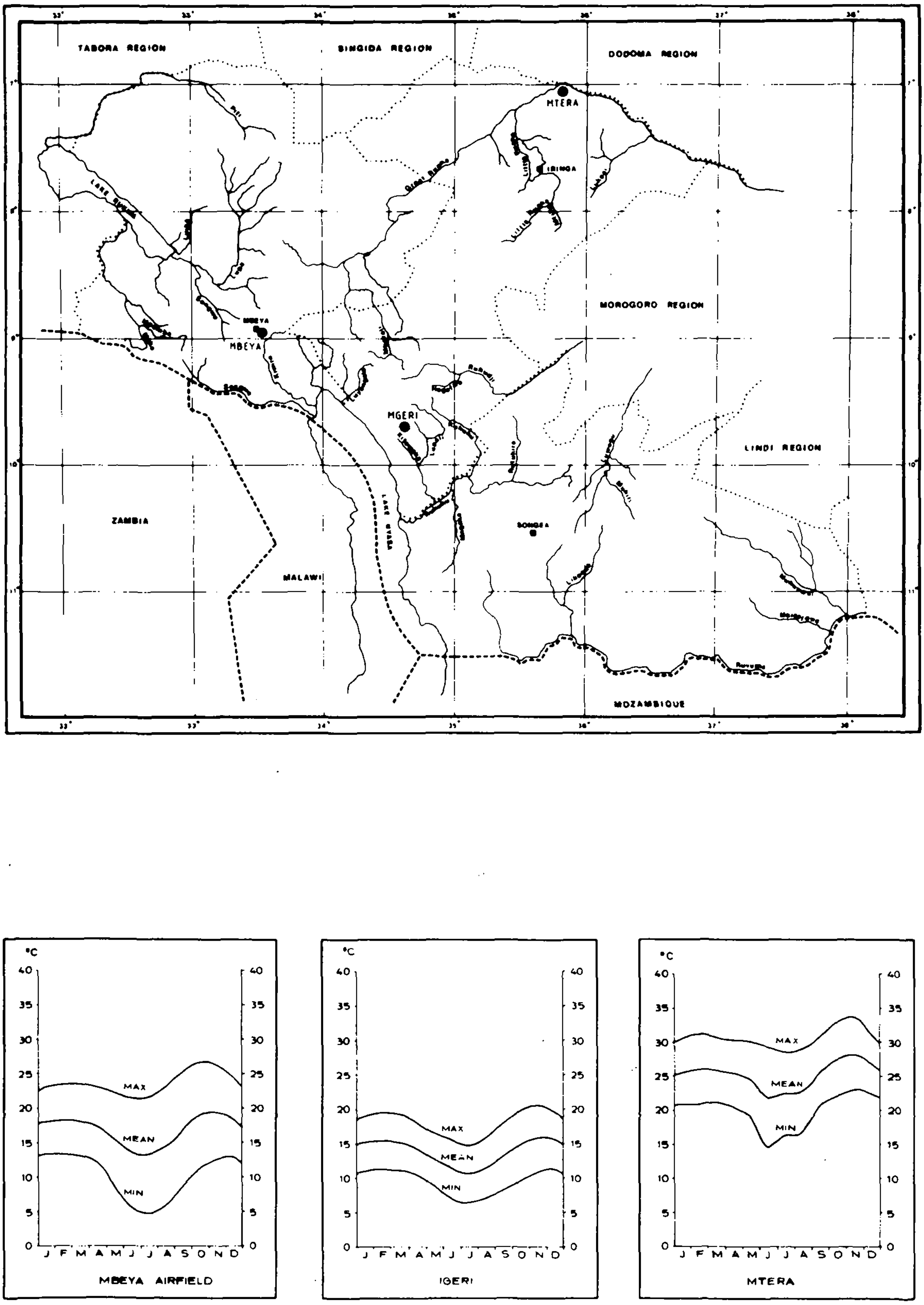


Figure 2.4 - Minimum, maximum and mean monthly temperature variation at selected locations.

Finally Figure 2.4 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.

2.3 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 2.5.

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.

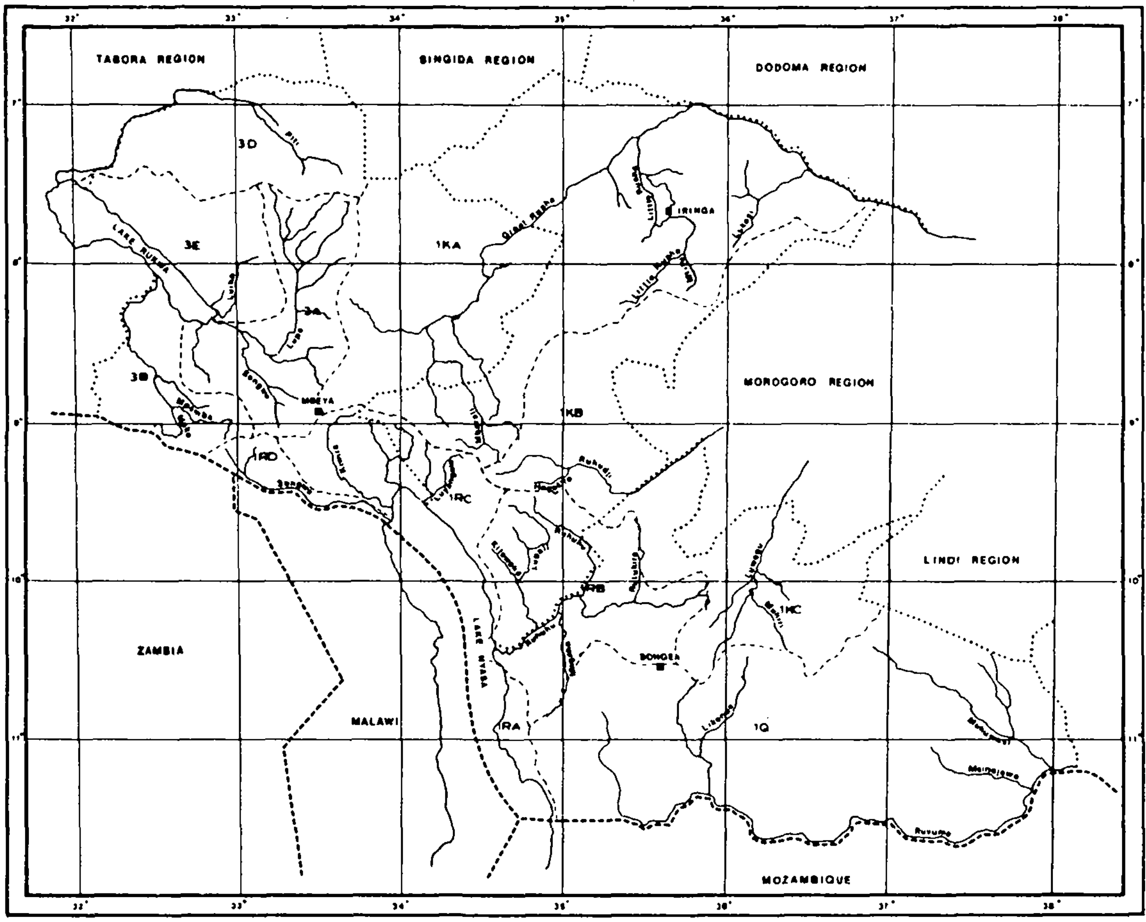


Figure 2.5 - Drainage map for Iringa, Ruvuma and Mbeya Regions.

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.

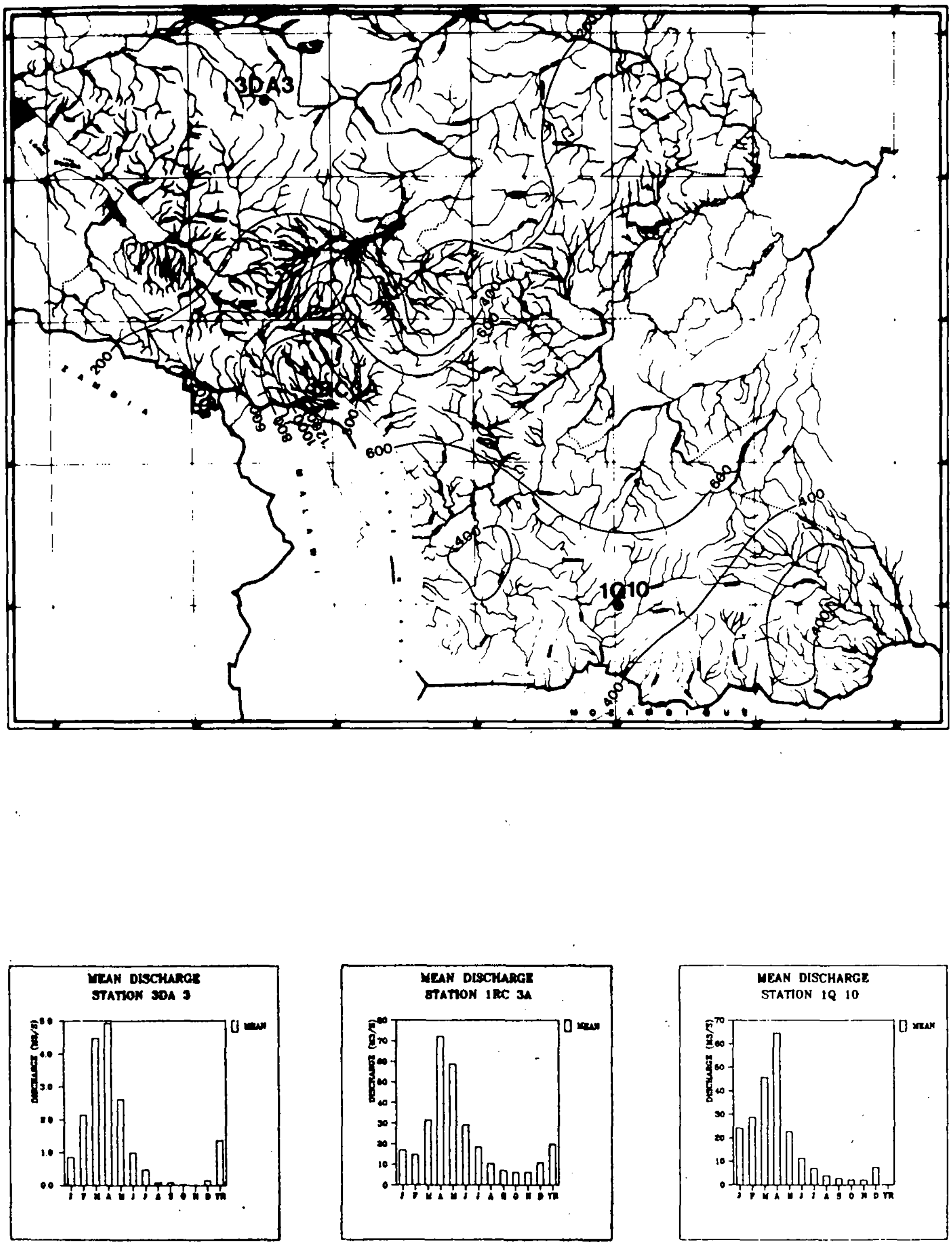


Figure 2.6 - Mean annual runoff, and mean monthly runoff at selected locations.

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 2.6.

2.4 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.

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 2.7:

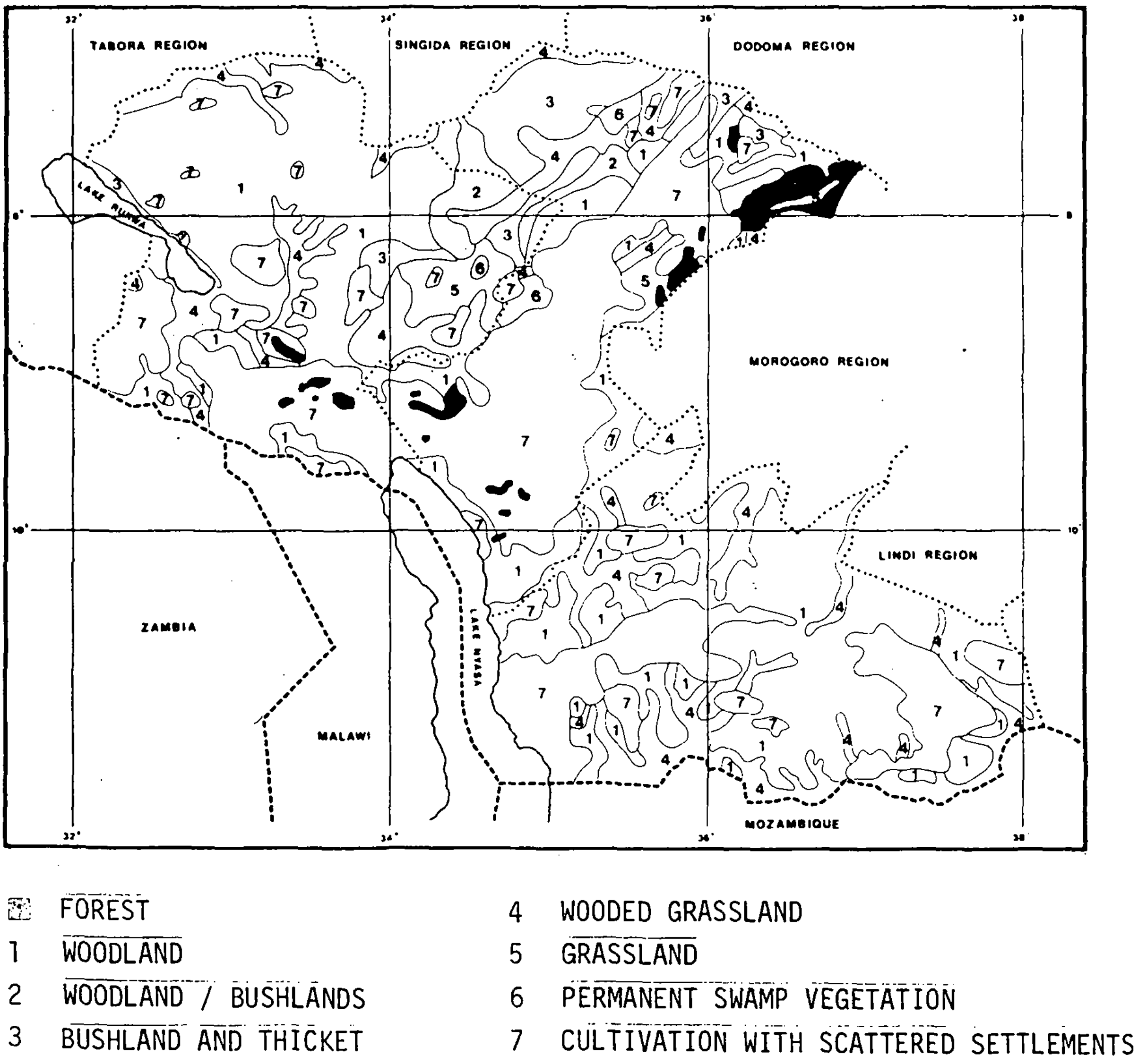


Figure 2.7 - Land use and vegetation.

2.5 Soils

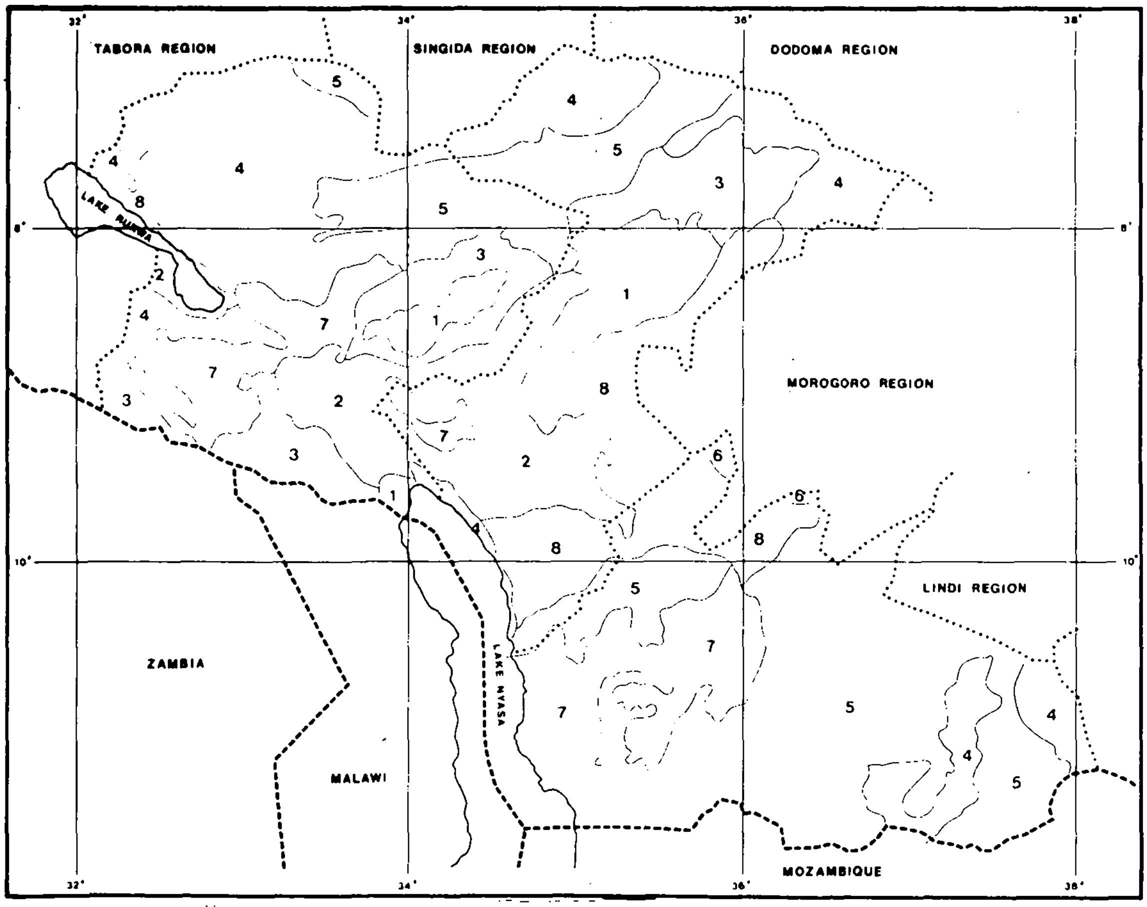
The soils of the three regions are generally well drained sands, clays, loams and mixtures of these. Only three areas are characterized by imperfect or poor drainage. These areas are the lake deposits of the Rukwa Trough, the Usangu Flats, and the flood plains north of Lake Nyasa in Kyela District.

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 2.8.



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

Figure 2.8 - Distribution of soils in Iringa, Ruvuma and Mbeya Regions.

3. RAINFALL

3.1 General

Rainfall is a factor of vital importance for living conditions in an area, primarily because of its direct influence on agricultural production and water supply. The length of the period in which rainfall exceeds potential evapotranspiration is decisive for the potential for crop production without irrigation, as well as for the formation of surface runoff and percolation to the groundwater required for reliable water supply.

Hence rainfall studies form an integral part of any investigation concerned with hydrology and water resources assessment, for which the quantity and time distribution of rainfall is of primary importance.

In the present study establishment of an updated and conveniently structured data-base for rainfall data has been given high priority as a necessary precondition for meaningful rainfall studies, in this as well as in the future studies by MAJI. Monthly rainfall values have been studied for the purposes of an overall analysis of rainfall occurrence in the regions, in time and space, while detailed analysis of daily rainfall has been carried out as part of the index area studies. Following a brief discussion of the general rainfall pattern, and a description of the data collection network and organisation, these studies are reported below. The index area studies are reported in Chapter 7.

3.1.1 Climate and rainfall pattern

For a tropical country Tanzania is rather dry. The reason for this is that the monsoon, winds which dominate the climate most of the year are relatively dry, while the main rainfall producing transition periods between the monsoons are very short. The three regions constituting the project area contain the full range of average Tanzanian rainfall, from more than 2600 mm per year in the area north of Lake Nyasa, to less than 500 mm in the Great Ruaha catchment in the northern part of Iringa region.

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.

As described in Chapter 2 the climate of the regions is dominated by the bi-annual passages of the inter-tropical convergence zone, and the prevailing monsoon winds between these passages. The rainfall pattern is determined partly by this climatic cycle, partly by the influence of topography upon the movement of the airmasses.

Referring to and following the general description of climate in Chapter 2, the rainfall pattern in the regions is explained by the prevailing climatic conditions in the four periods: December-February, March-May, June-September and October-November.

The north-east monsoon prevailing from December through February is rather dry. However, while this causes the northern parts of Tanzania to experience a dry season in this period, a combination of orographic lifting over the southern mountainous area, and convergence within the air stream results in considerable rainfall over the project area.

With the return to Tanzania of the inter-tropical convergence zone in March-May the wettest period in the regions sets in, heavy rainfall being produced as a result of large scale convergence and instability of the air mass. The main process causing the upward movement of air, and hence rainfall, is convection. This process is frequently related to local factors, with the result that rainfall is highly localized and has a high degree of spatial variability.

The south-east monsoon from June through September brings little moisture to the project area, and no or little rainfall occurs in this period. The reason for the dryness of this monsoon is that most of the air is of continental origin, and hence dry, while the air originating from the Indian Ocean has lost most of its moisture during the passage of Madagascar.

During October-November the inter-tropical convergence zone traverses Tanzania rather rapidly from north to south. It passes over the project area in November causing the rainy season to start, while October usually remains dry.

The annual rainfall extremes in the project area are due largely to topographical effects. The mountain ranges on both sides of Lake Nyasa cause local convergence, and hence high rainfall, at this location, while on the other end of the scale the very low rainfall in northern Iringa is due to the rainshadow effect prevailing on the leeward side of the Udzungwe Mountains.

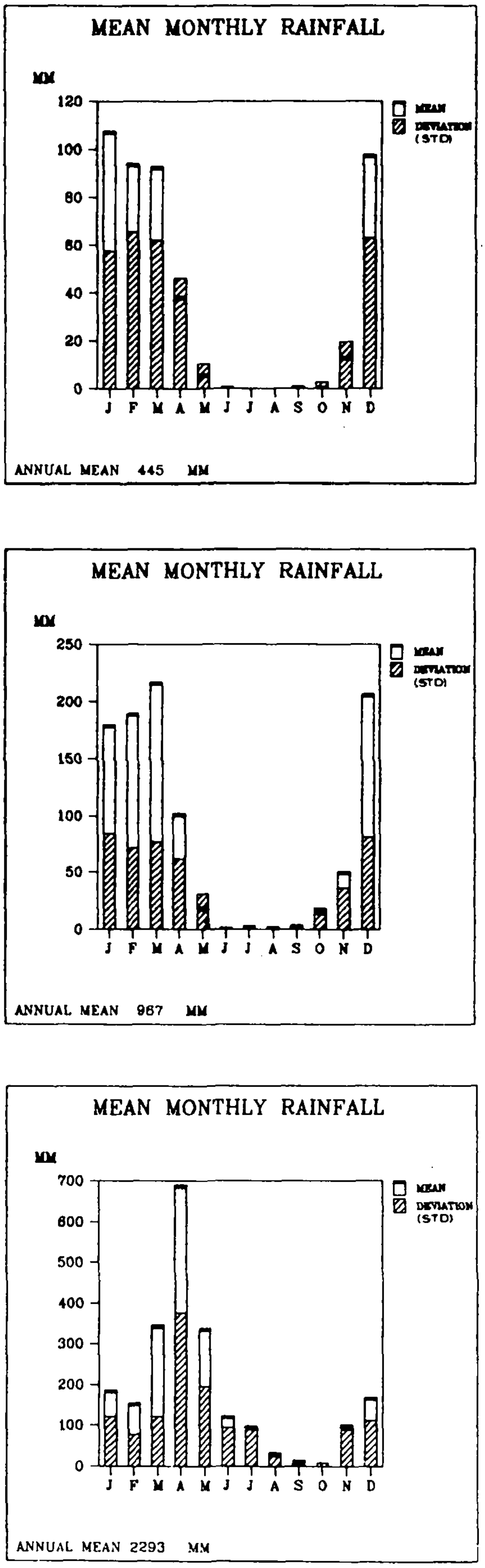


Figure 3.1 - Seasonal variations of rainfall in dry, medium and wet zone.

The seasonal variability is shown for a dry, a medium and a wet area in Figure 3.1, which clearly indicates a distinct rainy season in the study area from November through May. The figures show the mean monthly rainfall as well as the monthly standard deviations for representative locations. As indicated the standard deviations, may exceed the mean value, particularly in the dry months, because of the high variability in the rainfall from year to year. Hence actual annual rainfalls in the study area may vary from as low as 250 mm in Northern Iringa to 3100 mm in the area north of Lake Nyasa.

An isohyetal representation of mean annual rainfall is provided in Figure 3.17 and as a map in Drg. II-2 (cf. Section 3.6).

3.1.2 General gauging condition

The rainfall of the study area is gauged by an extensive network of stations with the Directorate of Meteorology, DOM, and MAJI as the main operating agencies. An assessment of network structure, density and operation has been made as described in Sections 3.2 and 3.3.

The process of gauging rainfall is encumbered with some degree of uncertainty due to numerous factors, of which the wind effect is probably the most important. Studies made in Denmark and other countries indicate that due to wind turbulence around the funnel of the raingauge, the rainfall measured is somewhat less the true amount. The degree of influence of the wind depends on a number of factors, such as gaugeheight above the ground surface, shape and type of the funnel, and exposure of the gauge. The studies made in Denmark on this topic indicate that the percentage measured varies between 80 and 100% of the true value.

With the comprehensive network forming the basis for the analysis of rainfall characteristics in this study, it has not been possible to include an inspection of every operating rainfall station, and consequently no attempt has been made to establish adjustment procedures for already existing rainfall measurements.

3.1.3 Objective of the rainfall study

The Consultants have planned and executed the study of rainfall with the following main objectives:

- Establishment of an updated and conveniently structured rainfall database as the necessary basis for the computerized analyses of rainfall characteristics during this study, as well as for the future use in MAJI's hydrological activities. (cf. Sections 3.2 and 3.5).

- Analysis and regionalization of the rainfall characteristics throughout the regions. (cf. Sections 3.4, 3.5 and 3.6).
- Preparation of reliable isohyetal maps of mean and minimum rainfall for the assessment of the water balance of the regions, particularly for runoff evaluation. (cf. Section 3.6).

3.1.4 Outline of general approach

Rainfall investigations during the present study has included:

- Collection and analysis of all available data from DOM, MAJI, the former East African Meteorological Department, (EAMD), and local stations.
- Updating of the rainfall data base to comprise daily data for all stations within or close to the index areas, and monthly totals for all remaining stations.
- Inspection and assessment of operating conditions, reliability and coverage for about 90 rainfall stations in the three regions.
- Establishment of new rainfall gauging stations in the index areas in order to supplement and strengthen the existing network.

The study has been carried out with close attention to publications on earlier studies of rainfall in the regions. (cf. Nieuwolt, 1972, and FAO, 1960).

3.2 Organisation, data collection and storage

3.2.1 Organisation

The central organisation responsible for collection of rainfall data in Tanzania is the Government agency, Directorate of Meteorology, DOM, organized as shown in Fig. 3.2[8]. Within DOM activities related to rainfall investigations are placed in the Climatology Division. Apart from being a collecting agency itself, DOM has since 1976 acted as the central registration unit for the other collecting agencies, MAJI and KILIMO. Until 1976 this was taken care of by EAMD.

Apart from the official network of gauges a number of stations have been established by individuals and private organisations, mainly farmers from large tea-, coffee- and wattle plantations. Some of these stations are currently reporting to DOM, but the majority of the private rainfall registrations are unfortunately being kept at the source and not reported. During the implementation of the field programme the consultants have come across several private long term records of daily rainfall, which seemed very reliable and had been carefully registered and filed. However, these sources were often found in areas with an already high density of reporting gauging stations, for which reason no attempt has been made to initiate a formal registration and collection of the data.

3.2.2 Data collection and reporting

The rainfall station network in the regions consists of stations established and operated by the three above mentioned agencies. No distinct reporting system from the resident observer to the central agency, DOM, has been set up, which implies that some stations report via MAJI and KILOMO, while others report both to the operating agency and to DOM. In both cases the daily observations are reported monthly, and copies are kept by the observers.

The subsequent handling of original data depends on the operating agency. The Climatology Division of DOM maintains a filing system of both daily values and monthly totals for all stations, whereas the system in MAJI and KILIMO is based on daily values only. An initial check of the data is performed before entry into the filing system.

3.2.3 Storage and processing of data

The station data files are currently being updated as the monthly reports reach DOM. Basic statistics such as monthly and annual means of rainfall and number of rainy days are computed and filed.

Until 1976 the former EAMD has been responsible for the computerized storage and processing of all rainfall data from the East African member countries. The data was stored on magnetic tape files, but since the end of 1976 no digital processing of Tanzanian rainfall data has taken place.

During the study period, the consultants have resumed this activity. The rainfall data-base has been redesigned (see below) and updated through 1979 on the basis of the following sources:

- Processed daily rainfall data from 279 stations covering the period 1926-1976, and stored on three magnetic tapes in EAMD.
- Daily rainfall from more than 40 stations within or close to the index areas, covering the period 1977 through 1979, and monthly totals from 180 stations, covering the period 1977 through 1979. These data were obtained from DOM's original files.

The transfer of the EAMD tape files to the consultants' disc-based storage system was somewhat complicated, mainly because three different storage methods had been applied for different periods of record by EAMD. Hence a new uniform data-base structure has been designed, as well as a comprehensive data manipulation procedure for the sorting and merging of all station records. The final storage of rainfall data has been made equivalent to MAJI's already existing data-base for hydro-data (cf. Chapter 5). Hence when the redesigned rainfall data-base is transferred back to Tanzania the extraction and presentation of rainfall data from the data-base can be executed using existing, but slightly modified MAJI-software. However, with respect to the future updating of station records new MAJI-programs must be prepared. Discussions on these aspects were held with MAJI senior hydrologist Mr. Mwalubandu during his visit to Danish Hydraulic Institute in August 1981. (cf. Chapter 5).

For the operation, updating and maintenance of the data-base during the study period an interactive software package was developed, based on principles similar to those described below in Chapter 5 for hydro-data. A short description of principal options of these programs has been included as annex 3-1. A sample output from this software giving a graphical representation of daily rainfall is shown in Figure 3.3.

A comprehensive computer print out of annual presentations of all station records applied in the present study, as well as an ICL magnetic tape holding the entire data-base as described above, accompany this report (cf. COMP-I).

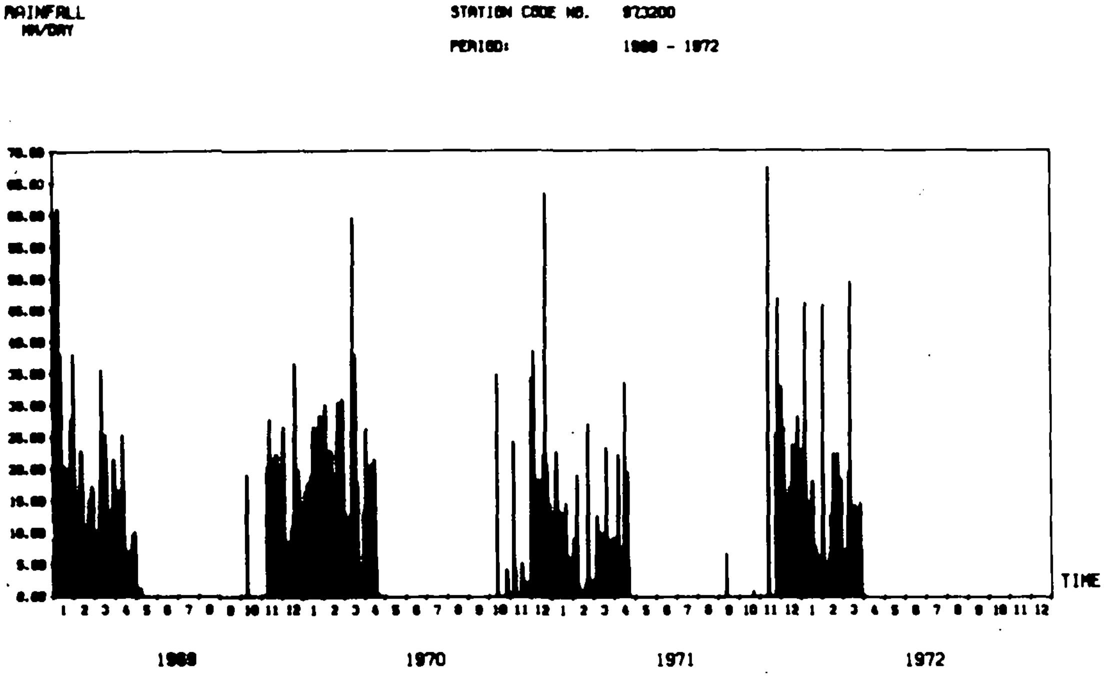


Figure 3.3 - Sample output from rainfall data-base.

3.3 Station network and instrumentation

3.3.1 Station network

The official rainfall station network within Iringa, Ruvuma and Mbeya regions consists of 289 gauging stations, of which 17 are fully equipped meteorological stations (cf. Chapter 4), while the rest are standard raingauges, at which daily rainfall is observed.

The majority of stations was established in the early 1950'es by EAMD, and only seven stations have been registered before this period. Figure 3.5 indicates the areal distribution of stations throughout the regions, while the rainfall station map (cf. Drg. II-1) contains detailed informations on instrumentation.

Grid reference system

A rigorous system for convenient identification of stations in such comprehensive networks is necessary for many reasons, the most important being to indicate the approximate geographical position of the gauge. Such a system was set up by EAMD. According to this system a rainfall station is identified by latitude and longitude and a serial number within the so-defined square as illustrated in Figure 3.4.

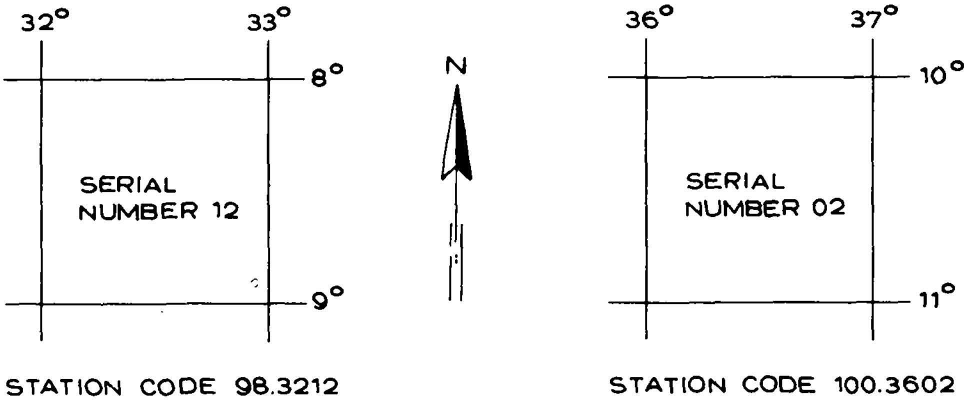
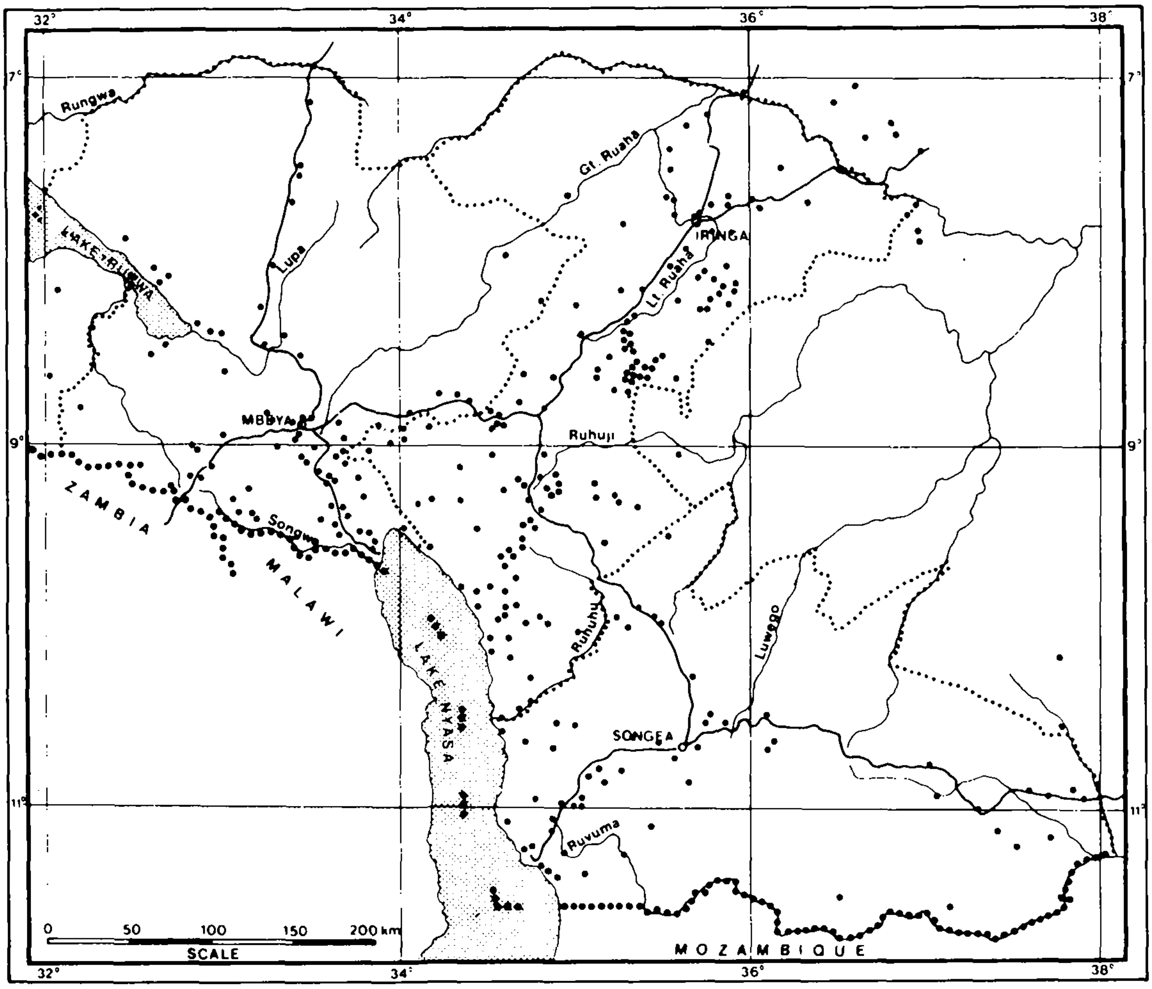


Figure 3.4 Grid reference system.



LEGEND

●●●●●●●●●●●●	INTERNATIONAL BOUNDARY
············	REGIONAL BOUNDARY
•	METEOROLOGICAL OR RAINFALL MEASURING STATION

Figure 3.5 - Rainfall station network density.

The first part of the code indicate the latitude north of the station ("9" followed by latitude, when less than 10° - and "0" inserted between first and last digit of latitude, when greater than 9°). The last part of the code, four digits, the first two digits indicate the eastern longitude, while the last two digits represent a serial number.

Network density

As it appear from Figure 3.5 the regions appear to have a reasonably dense network of rainfall stations. An analysis based on a regional scale and related to the population density has been made the results of which are presented in Table 3.1.

Region	Number of stations	Number per 1000 km^2	Population per km^2	Relative density
Iringa	111	2.0	19	50%
Ruvuma	50	1	9	30-40%
Mbeya	73	1.2	18	40-50%
All regions	234	1.3	15	40-50%

Table 3.1 Density of rainfall stations.

The analysis is based on estimates of the number of stations which are in operation today (cf. Section 3.4). The concept of relative density as defined by Langbein (1960) has been adopted, as illustrated in Figure 3.6, which is a representation of comparative areal densities of rainfall stations.

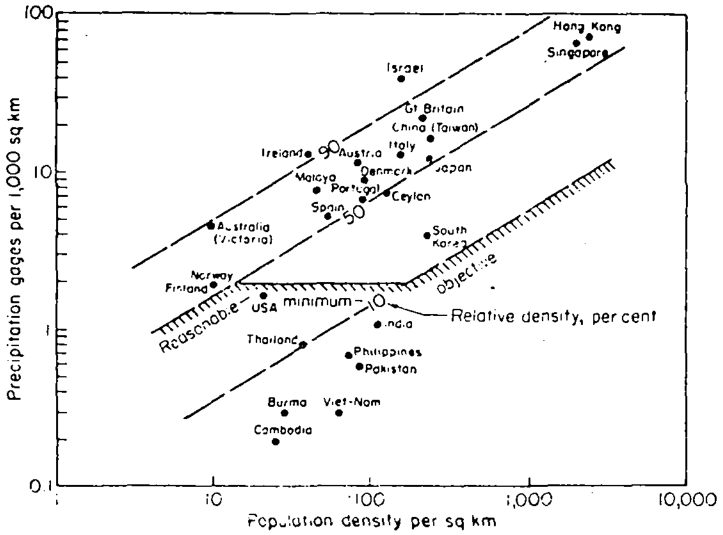


Figure 3.6 Comparative densities of national networks of rainfall stations. (From Langbein, 1960).

Compared to the 'reasonable minimum objective' in Figure 3.6 the station network can generally be considered adequate for Mbeya and Iringa regions, while additional stations need to be established in Ruvuma in order to strengthen the network.

However, these results, depend to a large extent upon the scale considered. A more detailed assessment of the station density has been made by relating the number of stations to the corresponding grid reference area, considering only that part of the reference area which falls within the regional boundaries. The number of stations per 1000 km^2 has been calculated for each grid, and the results are shown in Figure 3.7 and Table 3.2[8].

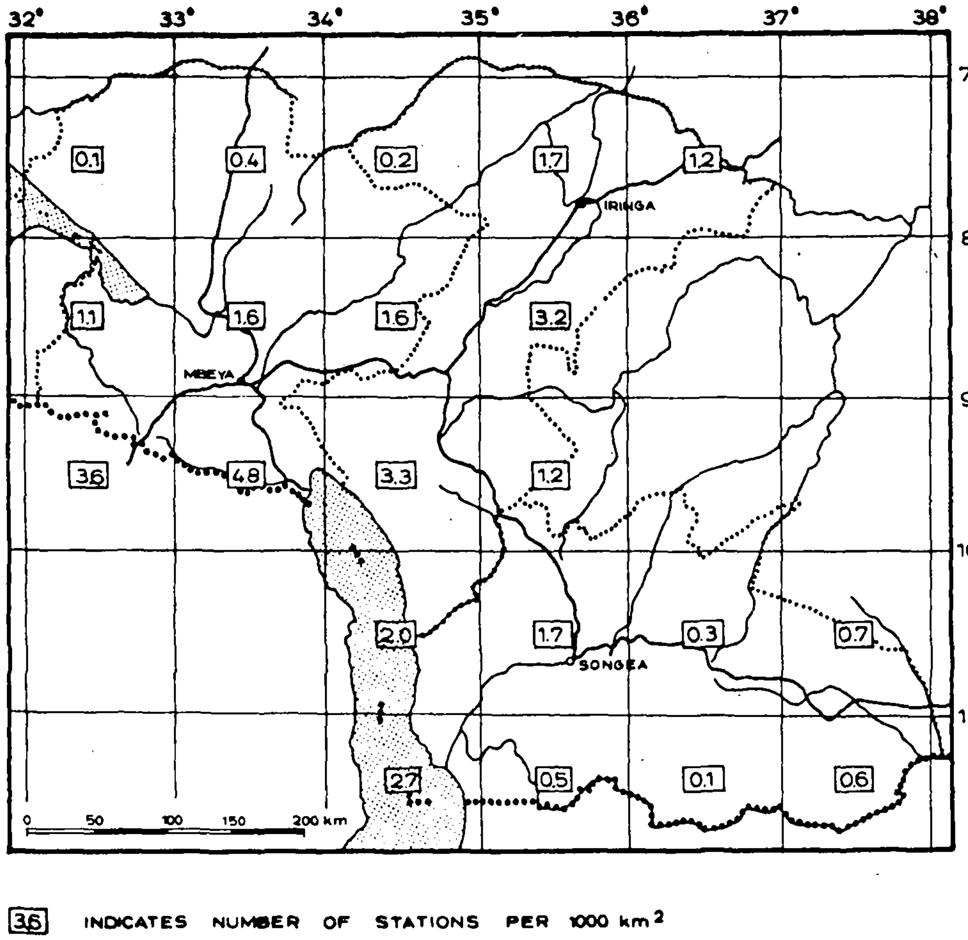


Figure 3.7 Rainfall station density related to grid reference area.

As stated by Langbein the absolute minimum objective is one station per 1000 km^2. As shown in Figure 3.7 only 13 out of 21 grid-squares meet this objective, northern Iringa, northern Mbeya and most of Ruvuma being inadequately covered. Hence priority in raingauge network improvement should be given to these poorly covered areas.

3.3.2 Instrumentation

As mentioned above the gauging installations typically belong to one of the following categories:

- Standard raingauge with a 5 inch funnel and a measuring glass graduated in mm. The standard set up of the gauge is 0.3 m above the ground surface, although a variation between 0.3 m and 2.0 m is frequently found for gauges of an earlier date. Rainfall is observed daily.
- Pluviographs of the tilting siphon type with a 5 inch funnel (cf. EAMD, 1976, for detailed description). These gauges are installed at the meteorological stations. Daily rainfall is also recorded on a standard raingauge.

The type of installation at the individual stations has been indicated on the rainfall station map, cf. Drg. II-1.

3.3.3 Station reliability and coverage

The general impression from the field inspection of rainfall stations is that the operation and maintenance of the stations is fair. However, with respect to the monthly reporting of observations, as well as replacement of damaged equipment improved procedures need to be established (cf. Sections 3.4 and 3.7). During the field inspection programme the consultants have visited more than 90 gauging stations and made interviews with the resident observers. The result of these investigations are summarized in Table 3.3[8] in which all rainfall stations in the regions are listed along with the following information:

- station name and location (region)
- operational responsibility
- period of observation
- reliability as assessed during field inspection and review of records
- exposure of gauge
- number and average length of gaps in the records.

Generally the above conditions of reliability and exposure were found to be good. The majority of station locations has been carefully selected in order to ensure good measuring conditions, and review of available field books and data forms have in general indicated a thorough day to day operation routine. In particular local missions have shown to maintain an exemplary station operation.

3.3.4 Stations established during this study

In order to strengthen the permanent station network, and improve the information level from selected index catchments, the consultants have installed pluviographs on the following locations.

- Iringa region:
  Installation at Ngwazi Tea Estate.

- Mbeya region:
  Installations at station 99.3324 (Kiwira Primary School) and station 99.3326 (Mwalupindi Primary School).

- Ruvuma region:
  Installations at MAJI officies in Mbinga and at Mngaka discharge gauging station 1RB6.

The installations have all been supplemented by daily raingauges for calibration and 'back up' purposes, except in Mbeya (Kiwira) where daily raingauges were already in operation.

The stations have all been installed in late autumn 1980, the first data arriving at the regional offices in the beginning of 1981. The installations are intended to provide a general improvement of the hydrological data coverage in the selected index areas. Detailed hydrological studies have been carried out for these catchments (cf. Chapter 7), and these studies are expected to be continued by MAJI with the benefit of the additional data (rainfall and evaporation) now becomming available.

3.4 Data availability

The rainfall data-base has been described in Section 3.2 above. In total the data-base now contains data covering 3700 station years, of which 3245 years are on a daily basis, the remaining being monthly totals. These observations cover 289 stations throughout the regions.

Basic availability statistics, giving a first order assessment of the continuity and length of the rainfall records have been prepared, and the results are presented in Table 3.4. As indicated herein the analysis has been carried out for two groups of rainfall data, namely:

- Data available from EAMD, 1926-1976
- EAMD data plus data reported to DOM and processed by the consultants, 1926-1979.

Item	Period	
	1926-1976	1926-1979
No. of stations	279	289
No. of station years	3108	3700
Average no. of gaps per station	3	4
Average gap length (weeks)	23	30
No. of stations with complete and continuous record	15	7
Average record length (years)	11.1	12.8
Average degree of data availability	0.88	0.82

Table 3.4 Data availability statistics.

With respect to the data information covering the period 1926-1979 the following remarks must be considered in order to fully understand the present state of availability.

- The registration time, defined as the time lag between observation by gaugereader and registration at DOM, is for several stations in the order of years. Such stations have not reported observations since 1976/77, and consequently their data from this period must be considered (and registered in the data-base) as missing observations until further information is received from the observer.
- As mentioned earlier 180 stations have been updated using monthly rainfall amounts only. For months with missing data, the number of daily observations missing within the month has been set to 30.
- The average degree of data availability has been defined and calculated for each station as the ratio between total period of valid observations and total period of operation. The figure presented in Table 3.4 is an average for all stations.

The average data availability as shown in Table 3.4 must be considered satisfactory. Although the average gap length in the recorded data is estimated as high as 30 weeks for the present version of the data-base, a significant part of it is caused by the problem of delayed reports from observers. Hence the actual average should be found somewhere between 23 weeks, as valid in 1976, and 30 weeks. Furthermore it should be noted, that the above results represent averages of highly variable figures, some stations having nearly complete records, while others contain numerous gaps. Information on gaps for the individual stations is included in Table 3.3[8].

A comprehensive bar chart representation of available rainfall records with indication of gaps and their time of occurrence is shown in Figure 3.10[8].

Only seven stations with data before 1950 have been available. These are presented separately in Figure 3.10[8].

The variation in recording time is illustrated in Figures 3.8 and 3.9, using two different accounting procedures:

(a) Number of complete and continuous years of record

(b) Total number of years of record.

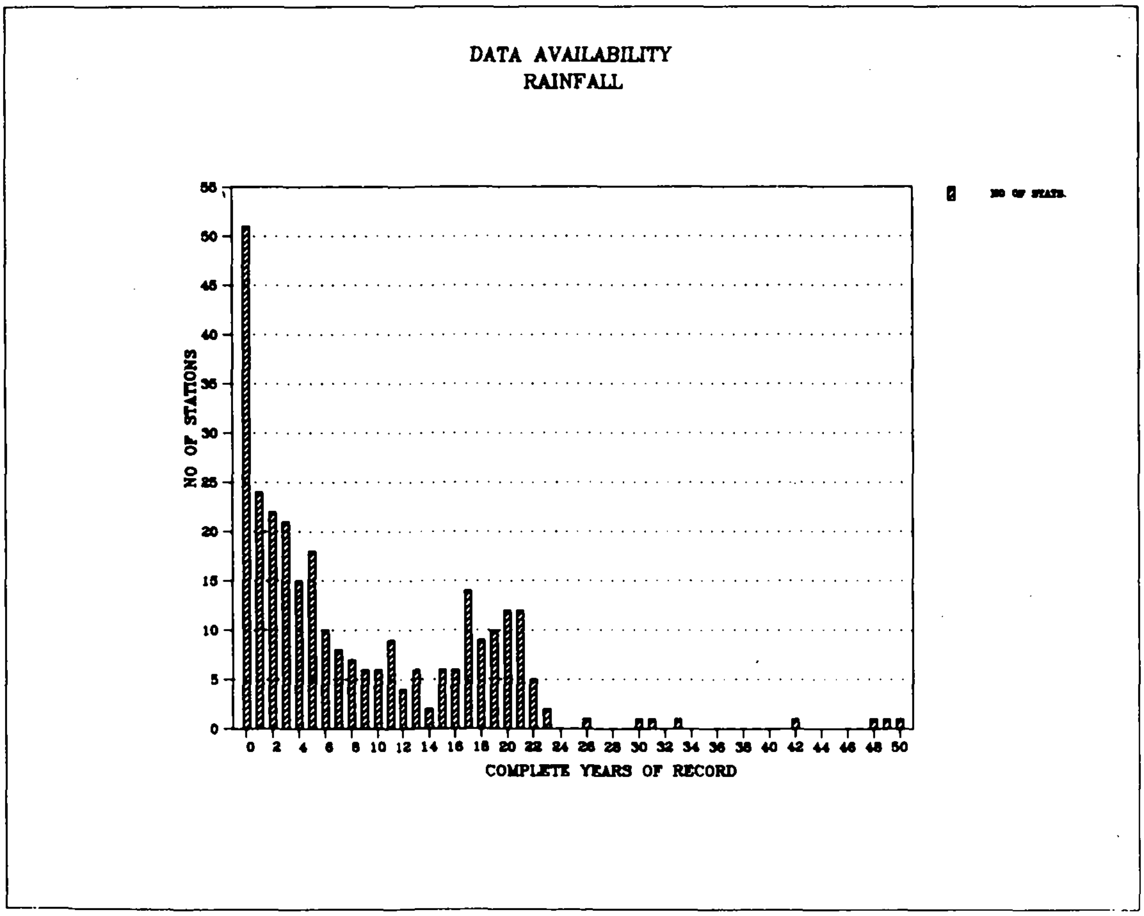


Figure 3.8 Data availability, complete and continuous years of record.

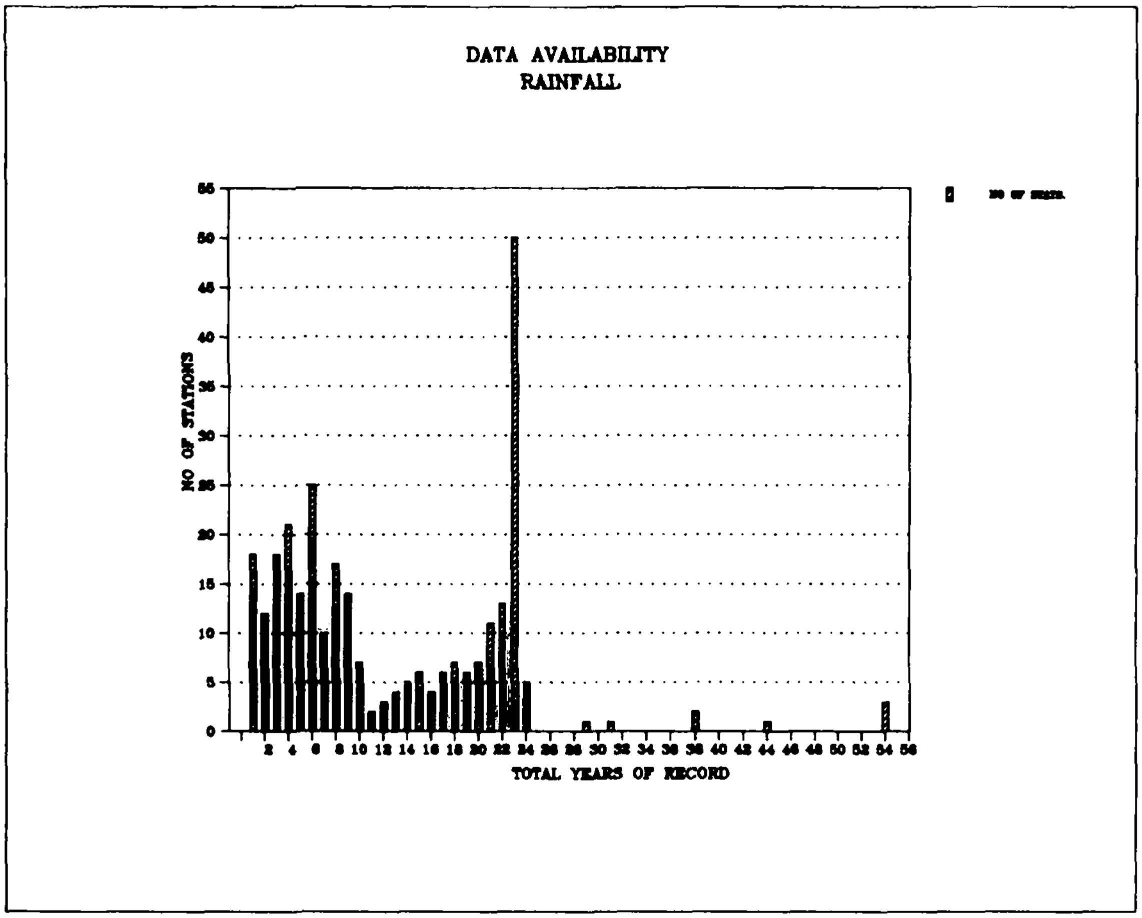


Figure 3.9 Data availability, total years of record.

From Figure 3.8 it is noted that 52 stations, corresponding to 18% og all stations, have zero gap free years of record. The peak at 23 years in Figure 3.9 indicate, that the digital processing of data from a substantial part of the network was initiated with data from 1957.

All analysis of rainfall data carried out during the present study have been based on available historical records, including stations which are no longer in operation.

The previously described problem of having extremely long reporting time for several stations makes it difficult to determine the number of stations, which are no longer in operation. However, no data have been registered since 1971 for more than 50 stations.

3.5 Station analysis

The analysis of rainfall data from all stations in the regions has been carried out with the main objective of arriving at useful descriptions and interpretations of regional rainfall characteristics. As part of the detailed hydrological studies of the three index areas analyses of spatial rainfall variability have been carried out as described in Chapter 7.

Hence the purpose of this section is to describe and illustrate tools and methods applied in the subsequent regionalization, (cf. Section 3.6).

3.5.1 Basic statistical analysis

For all 289 stations included on the data-base standard statistics, such as mean values, standard deviation and coefficient of variation have been calculated for

- Monthly and annual totals of rainfall
- Monthly and annual totals of rainy days. (On basis of daily data only).

Daily and monthly time series as well as mean values for the entire station lifetime have been processed and are presented in a separate computer print out, which accompanies this report. (cf. COMP-II). Sample results for station 98.3511 (Mkewe Estate) are shown in Table 3.5.

The calculations have been based on observed daily data without any filling of gaps. The asterisks in Table 3.5 indicate that a gap length of at least 1 day appears in that particular month, and consequently such monthly values are excluded from the analysis.

For each monthly statistic the number of years forming the basis for the calculation is listed. It is noted that the applied method may result in annual mean rainfalls which are different from the sum of monthly means. Station 98.3511 as shown in Table 3.5 is to a certain extent non-representative by having a very stable annual rainfall with a coefficient of variation (standard deviation divided by mean value) of only 0.15. The majority of stations in the regions are characterized by considerable fluctuations in annual rainfall, and hence large coefficients of variation, (cf. Section 3.1). In Figure 3.11 the monthly rainfall averages have been plotted for the same station, Mkewe Estate, illustrating the characteristic seasonal variation of rainfall in the regions. The pattern is basically

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                                        PRECIPITATION STATISTICS - TANZANIA

STATION CODE NO = 98.3511

YEAR                           JAN     FEB     MAR     APR     MAY     JUN     JUL     AUG     SEP     OKT     NOV     DEC         ANNUAL

1957  MONTHLY SUM (MM)       199.8   122.6   226.4   212.5     4.0     0.0     0.0     0.0     0.5    10.4    57.2   108.2          941.6
      NO OF RAINY DAYS          23      18      22      17       5       0       0       0       1       1       3      19            109

1958  MONTHLY SUM (MM)       214.2   185.6   281.6    67.5     1.0     0.0     0.0     0.0     0.0     0.0    23.2   175.9          949.0
      NO OF RAINY DAYS          18      13      25      10       1       0       0       0       0       0       3      19             89

1959  MONTHLY SUM (MM)       223.7   227.0   161.7   149.1    35.3     0.0     0.0     0.0     0.0     3.3    71.2   181.5         1059.8
      NO OF RAINY DAYS          20      16      24      14       3       0       0       0       0       3       8      23            113

1960  MONTHLY SUM (MM)       399.2   237.2   265.5    35.7    13.7     0.0     0.0     0.0     2.8     0.0    55.5    68.3         1077.9
      NO OF RAINY DAYS          21      25      24      13       4       0       0       0       1       0       3       8             99

1961  MONTHLY SUM (MM)       259.0   128.9   176.9    70.3   248.0     1.0     0.3     0.0     0.0    52.6    76.5   301.6         1315.1
      NO OF RAINY DAYS          24      21      23      12       5       1       1       0       0       3      12      26            128

1962  MONTHLY SUM (MM)       242.6   216.4   397.7    91.5     4.1     0.0     0.0     0.0     0.0    61.5    70.2   163.2         1249.4
      NO OF RAINY DAYS          21      27      27      13       2       0       0       0       0       6      11      19            126

1963  MONTHLY SUM (MM)       284.1   254.9   241.4    71.7    33.0     2.8     0.0     0.0     0.0    10.1   164.0   270.2         1332.2
      NO OF RAINY DAYS          26      18      23      12       1       1       0       0       0       3      13      23            120

1964  MONTHLY SUM (MM)       254.3   174.1   184.2    34.4     0.0     0.0     0.0     0.0     0.0     0.0    14.2   141.8          803.0
      NO OF RAINY DAYS          19      17      16       8       0       0       0       0       0       0       3      14             77

1965  MONTHLY SUM (MM)       137.1   173.9   205.7   107.1     0.0     0.0     0.0     0.0     0.0    76.2    32.1   284.7         1016.8
      NO OF RAINY DAYS          18      18      21      10       0       0       0       0       0       2       7      20             96

1966  MONTHLY SUM (MM)       190.2   157.5   279.0   100.1    13.8     0.0     0.0     0.0     0.0     9.4   141.8   220.7         1112.5
      NO OF RAINY DAYS          17      16      20      11       4       0       0       0       0       2       9      18             99

1967  MONTHLY SUM (MM)        81.1   235.0   179.0   219.5    70.1     0.0    14.7     0.0     7.1     0.0    92.5    72.2          971.2
      NO OF RAINY DAYS          10      14      23      18       6       0       3       0       1       0       7      15             97

1968  MONTHLY SUM (MM)       161.9   264.3   248.9   117.9    28.1    52.9     0.0     0.0    16.5    16.6    39.9   156.3         1103.3
      NO OF RAINY DAYS          15      26      21      15       5       2       0       0       2       2       4      15            107

1969  MONTHLY SUM (MM)       272.9   236.3   345.2   215.1     0.0     0.0     0.0     0.0     0.0     5.3    55.1   221.7         1351.6
      NO OF RAINY DAYS          24      20      18      11       0       0       0       0       0       1       5      13             92

1971  MONTHLY SUM (MM)      ******   111.8   191.9  ******  ******  ******  ******  ******  ******  ******  ******  ******         ******
      NO OF RAINY DAYS         ***      18      17     ***     ***     ***     ***     ***     ***     ***     ***     ***            ***

STATISTICS FOR THE ENTIRE PERIODE OF  14 YEARS

OBS NO                          13      14      14      13      13      13      13      13      13      13      13      13             13

AMOUNT OF PRECIPITATION (MM)

MEAN                         224.6   194.0   242.3   114.8    34.8     4.4     1.2     0.0     2.1    18.9    68.7   182.0         1098.7
STD                           77.9    51.2    67.6    65.4    67.5    14.6     4.1     0.0     4.8    26.4    43.6    75.7          170.2
STD/MEAN                      0.35    0.26    0.28    0.57    1.94    3.35    3.53     0.0    2.31    1.40    0.63    0.42           0.15



STATISTICS FOR THE ENTIRE PERIODE OF  14 YEARS

OBS NO                          13      14      14      13      13      13      13      13      13      13      13      13             13

NO OF RAINY DAYS

MEAN                          19.7    19.4    21.7    12.6     2.8     0.3     0.3     0.0     0.4     1.8     6.8    17.8          104.0
STD                            4.3     4.1     3.1     2.8     2.2     0.6     0.9     0.0     0.7     1.7     3.6     4.8           15.0
STD/MEAN                      0.22    0.21    0.14    0.23    0.80    2.05    2.78     0.0    1.69    0.98    0.54    0.27           0.14
```

Table 3.5 - Sample statistics for station 98.3511.

unimodal with one rainy season from November to May, but a minor drop in rainfall is experienced in February (cf. Section 3.1). The heaviest rainfalls occur in March and April as a result of convergence associated with the inter-tropical convergence zone.

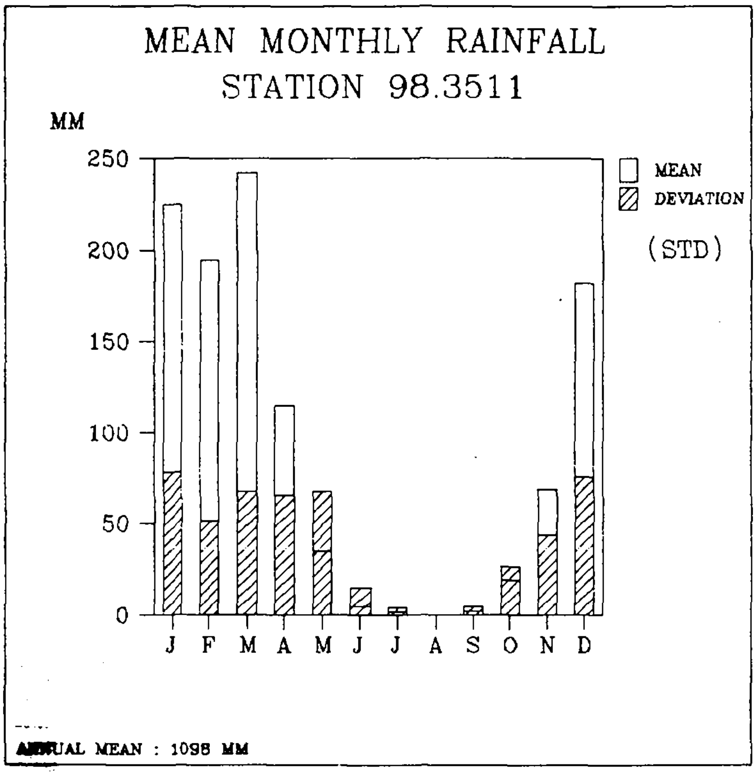


Figure 3.11 Representative seasonal variation, Mkewe Estate.

The mean monthly rainfall and associated standard deviations have been plotted for all stations with continuous records greater than 15 years Cf. Figure 3.19^{8}.

3.5.2 Analysis of trend

Analysis of trend in annual rainfall has been performed for seven selected reliable long term stations, listed in Table 3.6. The analyses have been performed using two different methods:

- Regression analysis; statistical test, (t-test) for zero slope of regression line.
- Visual inspection of plots of centered ten-year moving average values.

The Figures 3.12, 3.13 and 3.14 show results from the moving average analyses for stations 98.3300, 99.3302 and 101.3700 respectively. Only station 98.3300, Mbeya Bomani, indicates a slight increase in rainfall during the last 10-15 years, whereas no significant trend can be detected for the rest of the stations analysed. Other hydrological studies carried out in

Tanzania confirm this assessment of overall stationality in the rainfall pattern of the country (NEDECO, 1974, Finnwater, 1977). This stationality is very important for the present study by implying that general conclusions may be drawn on the basis of available historic records.

Station code	Station name	Region	Period	No. of complete years
98.3300	Mbeya Boma	Mbeya	1926-1973	42
98.3301	Mbeya Airport	Mbeya	1957-1979	23
98.3509	Kilima Tea Company	Iringa	1957-1976	20
99.3302	Rungwe Tea Estate	Mbeya	1926-1979	48
99.3413	Luponde Farm	Iringa	1958-1979	22
100.3401	Litembo Mission	Ruvuma	1957-1975	19
101.3700	Tunduru Bomani	Ruvuma	1926-1979	50

Table 3.6 Stations for which analysis of trend have been performed.

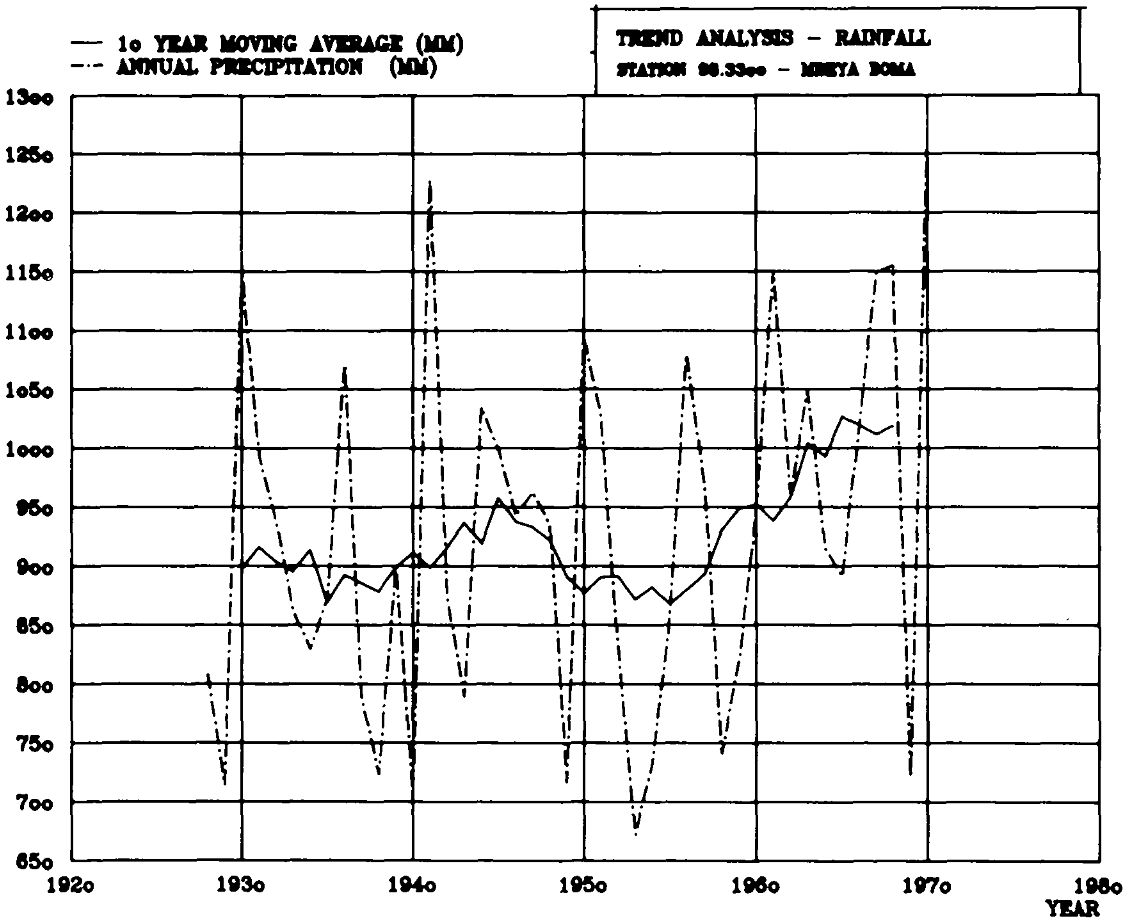


Figure 3.12 Trend analysis for station 98.3300, Mbeya Bomani

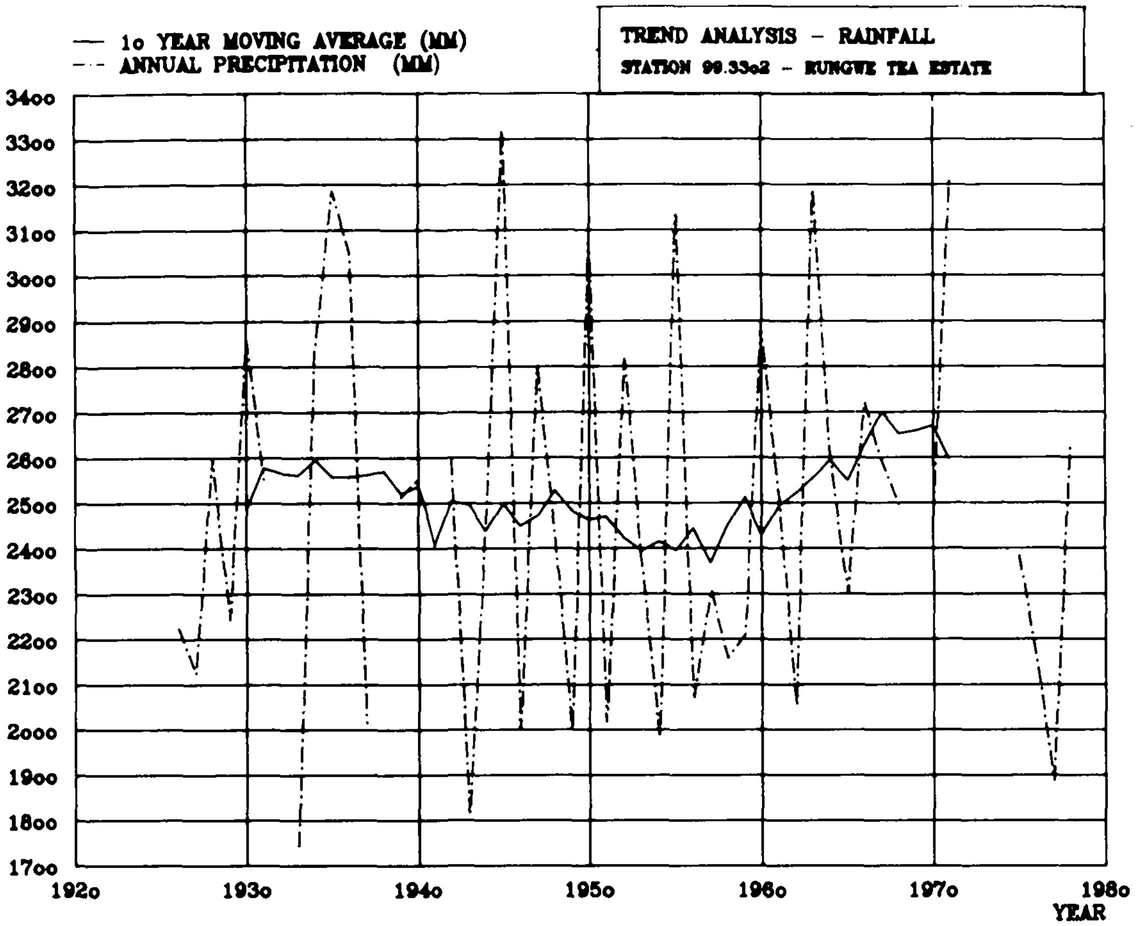


Figure 3.13 - Trend analysis for station 99.3302 - Rungwe Tea Estate.

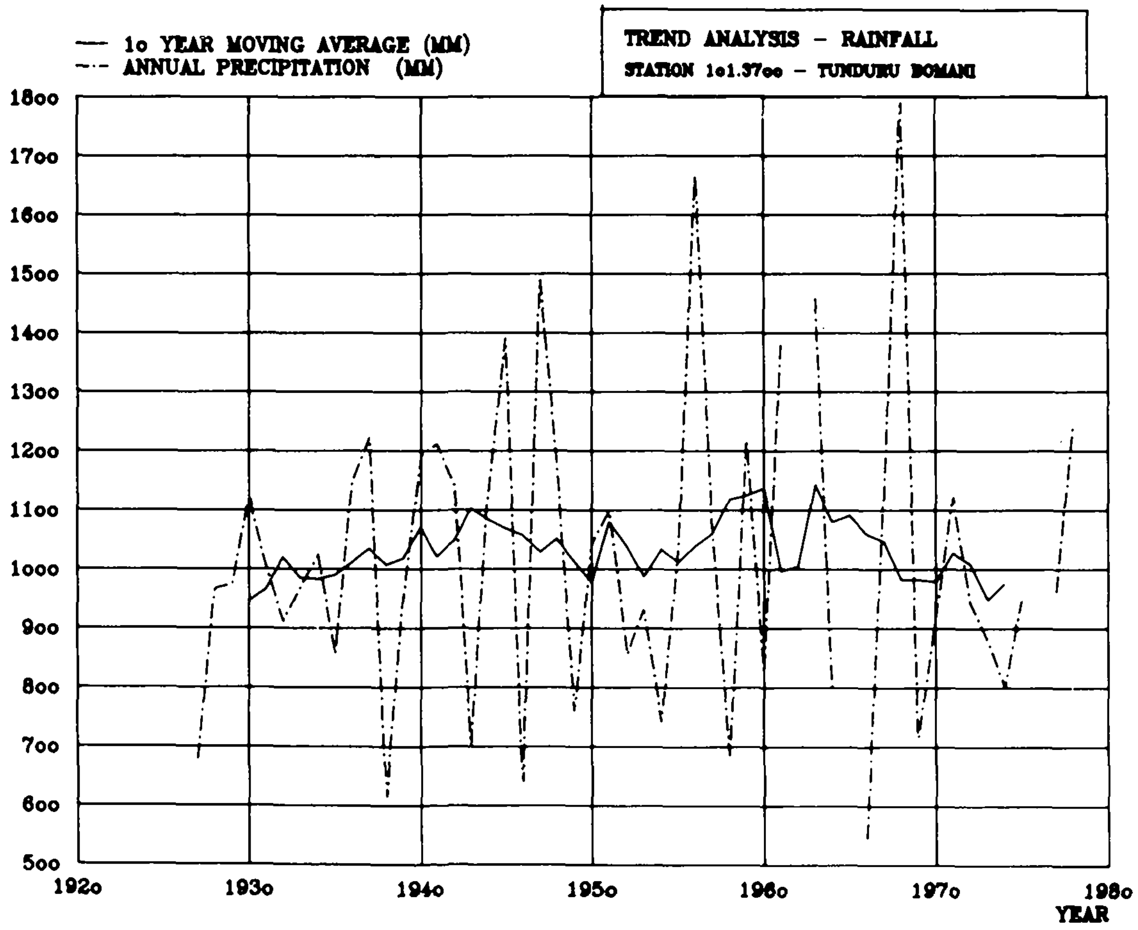


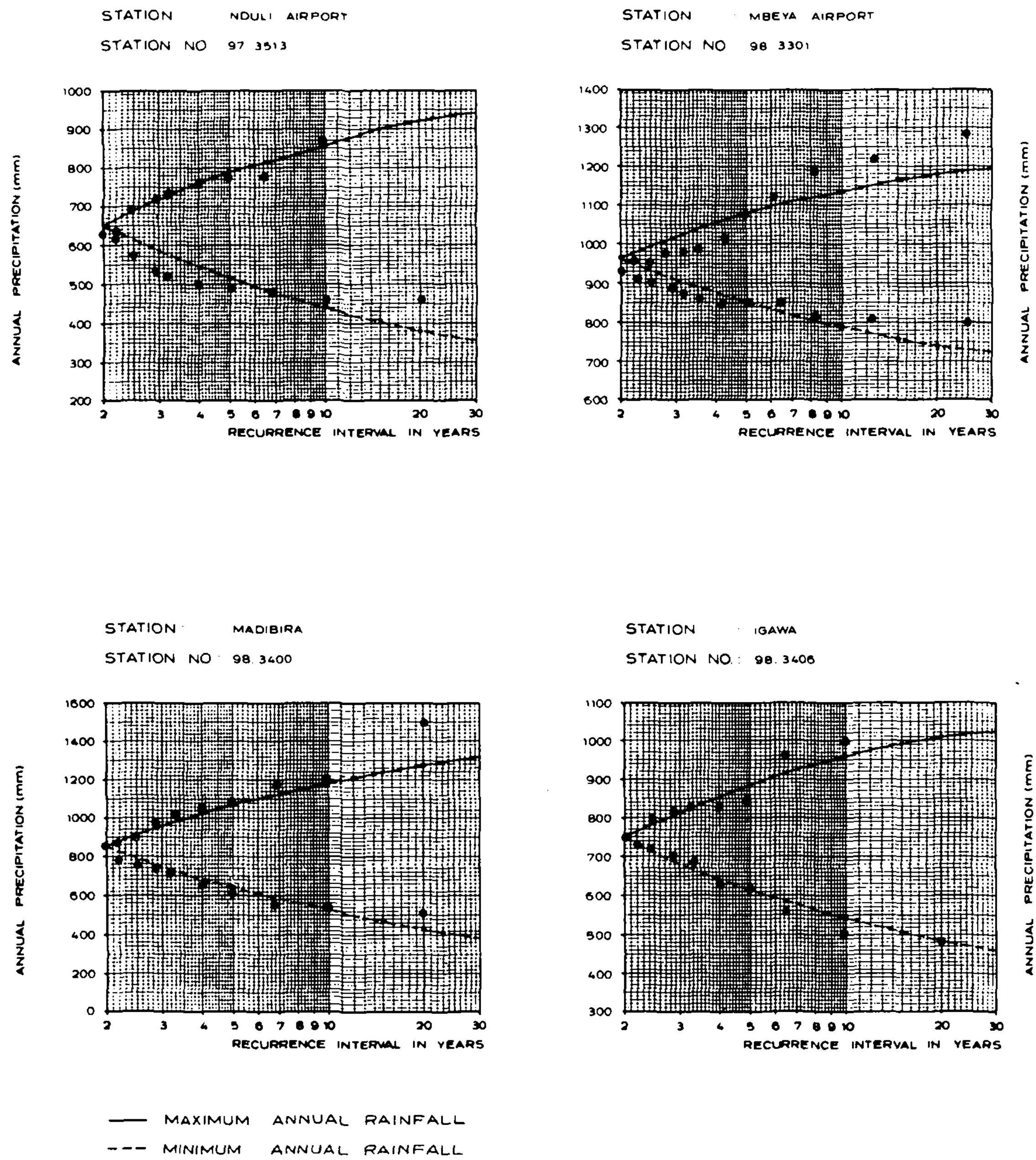
Figure 3.14 - Trend analysis for station 101.3700 - Tunduru Bomani

3.5.3 Frequency analysis of annual rainfall

As mentioned above the main part of the study area experiences substantial inter-annual variations in rainfall amounts. Rainfall is the single most important factor affecting runoff, and hence the availability of surface water resources. Assessment of reliable surface water yields is consequently closely linked to the evaluation of extreme rainfall.

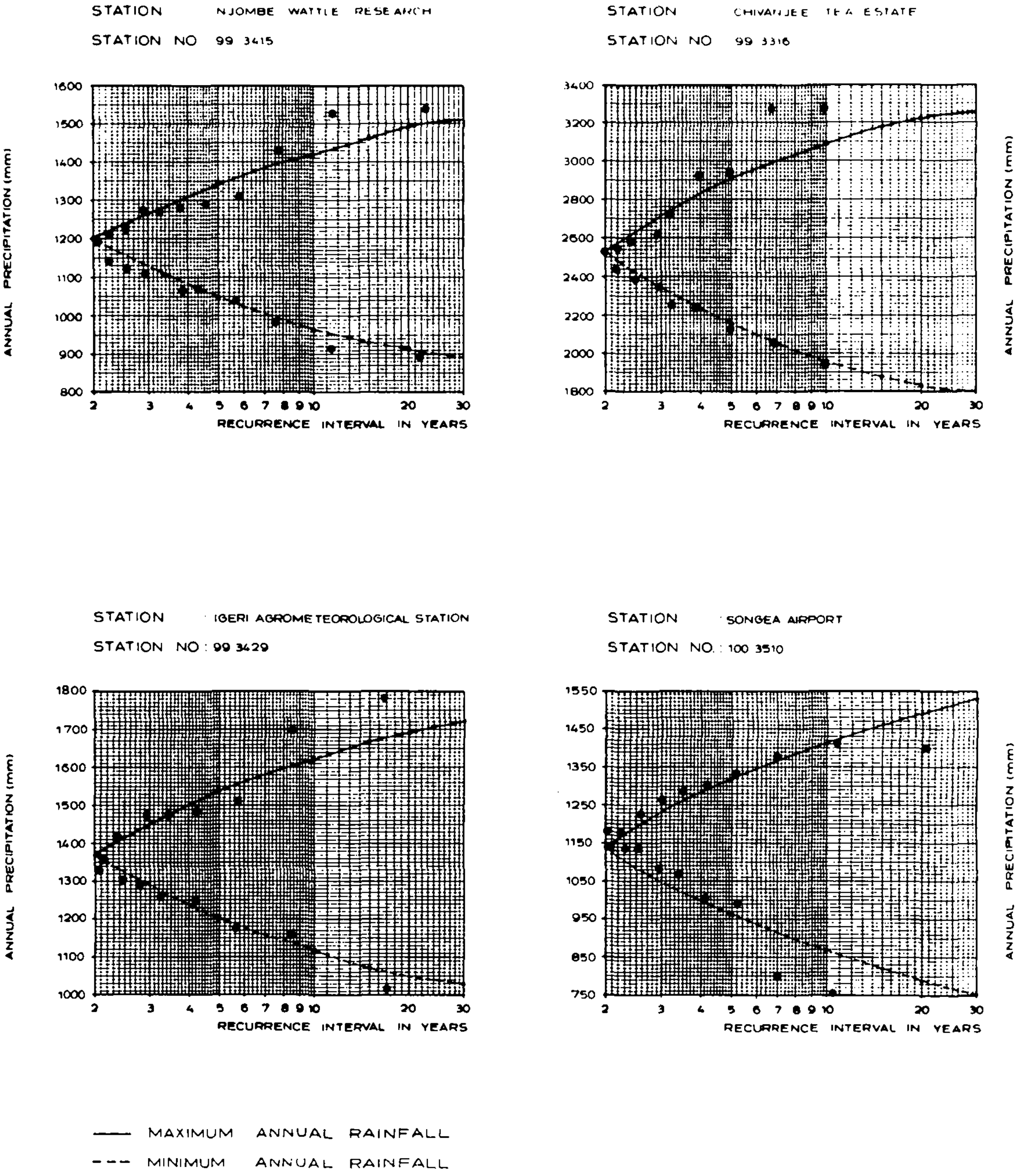
Frequency analyses have been performed with the purpose of determining extreme rainfall events, particularly the 10 year minimum annual rainfall. The analyses have been carried out for all stations with complete record lenghts greater than 10 years (102 stations). Statistical tests for different distributions of annual values have been carried out showing that the annual rainfall approximates a normal distribution on an average level of significance around 30%, varying between 5% and 95% for these stations. (Although a sample size of 10 to 15 will produce a rather weak statistical test, the event results as predicted by the normal distribution agree closely with those predicted through conventional ranking and plotting procedures). Hence based on the normal distribution the 10 year minimum events have been determined. The results are assessed in detail in Section 3.6.

For all long term meteorological stations the maximum and minimum annual rainfall have been determined for recurrence intervals of 2, 5, 10, 15, 20 and 30 years, using the same method as described above. The results are shown in Table 3.7[8] and 3.8[8] and plotted in Figures 3.15 and 3.16, which clearly show the inter-annual variability of rainfall. Similar variation patterns have been detected for stations in the neighbouring regions Mtwara and Lindi (cf. Finnwater, 1977).



—— Maximum annual rainfall, --- Minimum annual rainfall.

Figure 3.15 - Frequency analysis of annual rainfall. For distribution function and parameters see Table 3.11[8]



—— Maximum annual rainfall, --- Minimum annual rainfall.
Table 3.16 - Frequency analysis of annual rainfall. For distribution function and parameters see Table 3.11[8]

3.5.4 Rainfall intensity

Rainfall intensity measurements have been carried out at all meteorological stations in the regions for several years. The registrations (pluviograph charts) have been filed at Maji, Ubungo, but so far little processing has taken place. Processing, control and analysis of this vast amount of charts has not been possible within the scope and resources of the present study, and reference is made to existing sources for information on short duration rainfall intensities. EAMD has published an analysis of short duration rainfall intensities (cf. EAMD, 1974), comprising 8 stations from whole of Tanzania. However, the Mbeya Bomani meteorological station is the only station analysed within the three regions. The maximum recorded rainfall over a period of 34 years for six selected durations is indicated in Table 3.9 below.

	Duration					
	15 min.	30 min.	1 hour	3 hours	6 hours	24 hours
Maximum rainfall (mm)	38	49	55	62	82	97

Table 3.9 Maximum recorded rainfall at Mbeya Bomani (after EAMD, 1974)

A frequency analysis of maximum daily rainfall for two selected stations (a "wet" and "dry" station) has been carried out. The time series of annual maximum daily rainfall have shown good approximations to the Gumbel extreme value distribution, and on basis of this the events corresponding to a 2, 5, 10, 20, and 50 years return period have been estimated. The results are listed in Table 3.10.

Station	Events (mm/day) for return period (years)				
	2	5	10	20	50
Wet area Station 99.3302 Tukuyu, Mbeya	140	210	260	310	370
Dry area Station 97.3511 Mtera, Iringa	50	70	85	95	115

Table 3.10 Frequency analysis of maximum daily rainfall.

The results give an indication of the variation in maximum daily rainfall in the regions. The medium zone station Mbeya Bomani shown in Table 3.9 has a maximum recorded daily rainfallof 97 mm in 34 years, which is close to the dry area 30 year event. This indicates that especially the daily rainfall in wet areas deviates from the average event picture. However, it must be noted that the above analysis has been based upon maximum daily rainfall figures extracted from records originally processed by EAMD, and that thorough control of the reliability of these figures has not been possible. Although the above estimates are believed to give a fair indication of the expected range, further studies should be made prior to drawing firm conclusions on maximum daily rainfall.

3.6 Regonalization

The results obtained from the station analyses have been regionalised through preparation of isohyetal maps. Such maps are useful for the general classification of wet and dry areas. The maps have been prepared for mean annual rainfall and 10 year minimum annual rainfall respectively. (Cf. Drg. II-2, Drg. II-3, Figures 3.17 and 3.18).

The determination of isohyets has been based mainly on stations with more than 10 years of complete record, excluding stations of poor reliability.

Detailed local knowledge of stations have been utilized in the definition of isohyetes in class-boundary areas. No attempt has been made to extrapolate values or extend isohyets into areas of poor and insufficient station coverage. Thus in the northern parts of Mbeya as well as in Eastern Ruvuma the isohyetal pattern is not very well defined.

3.6.1 Mean annual rainfall

The mean annual rainfall ranges from 500 mm in northern Iringa to 2600 mm in southern Mbeya. The orographic effect as described in Section 3.1 is clearly evidenced in the areas north of lake Nyasa. Almost following the contours of the mountain ranges surrounding the center of this area, the variation in mean annual rainfall is as high as 1200 mm within a distance of only 40 km. The rainshadow effect created by the mountainous eastern boundary areas of Iringa also results in considerable gradients in mean annual rainfall in the north-western direction.

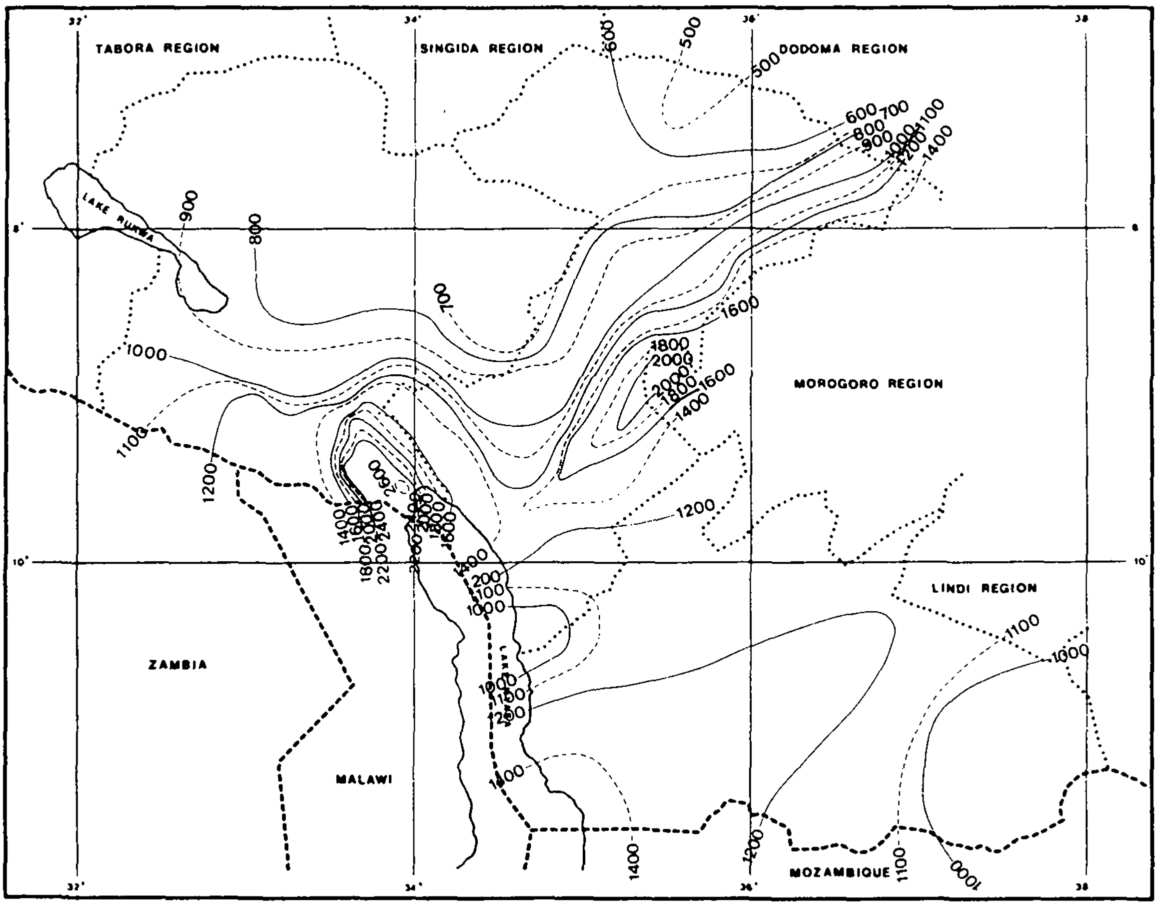


Figure 3.17 - Mean annual rainfall.

3.6.2 10 year minimum annual rainfall

The concept of the 10 year minimum annual rainfall represents the most likely amount to be exceeded in 9 out of 10 years. As for the mean annual rainfall the mapping of isohyets has been based on point estimates for the 10 year events. Hence for estimates of the minimum areal rainfall for local catchments the results based on frequency analysis of the weighted rainfall would most probably be higher than the estimate obtained from the isohyetal map. However, for many purposes, this 10 year minimum rainfall representation is applicable and very useful. For the assessment of potential agricultural production, water supply possibilities and irrigation requirements, the 10 year minimum estimate of available rainfall resources is valuable information.

The map prepared on the basis of data available for this study shows a variation between 250 mm and 1750 mm, which is about 30-50% lower than the corresponding mean annual rainfall.

A very good agreement with earlier published maps (cf. Niewolt, 1971) based on data available up to 1971 has been found for both the mean annual and 10 year minimum rainfall maps. This implies that the last 10 years of rainfall has not contributed to any considerable changes in the average picture, a conclusion compatible with the trend analysis findings as described in Section 3.5.

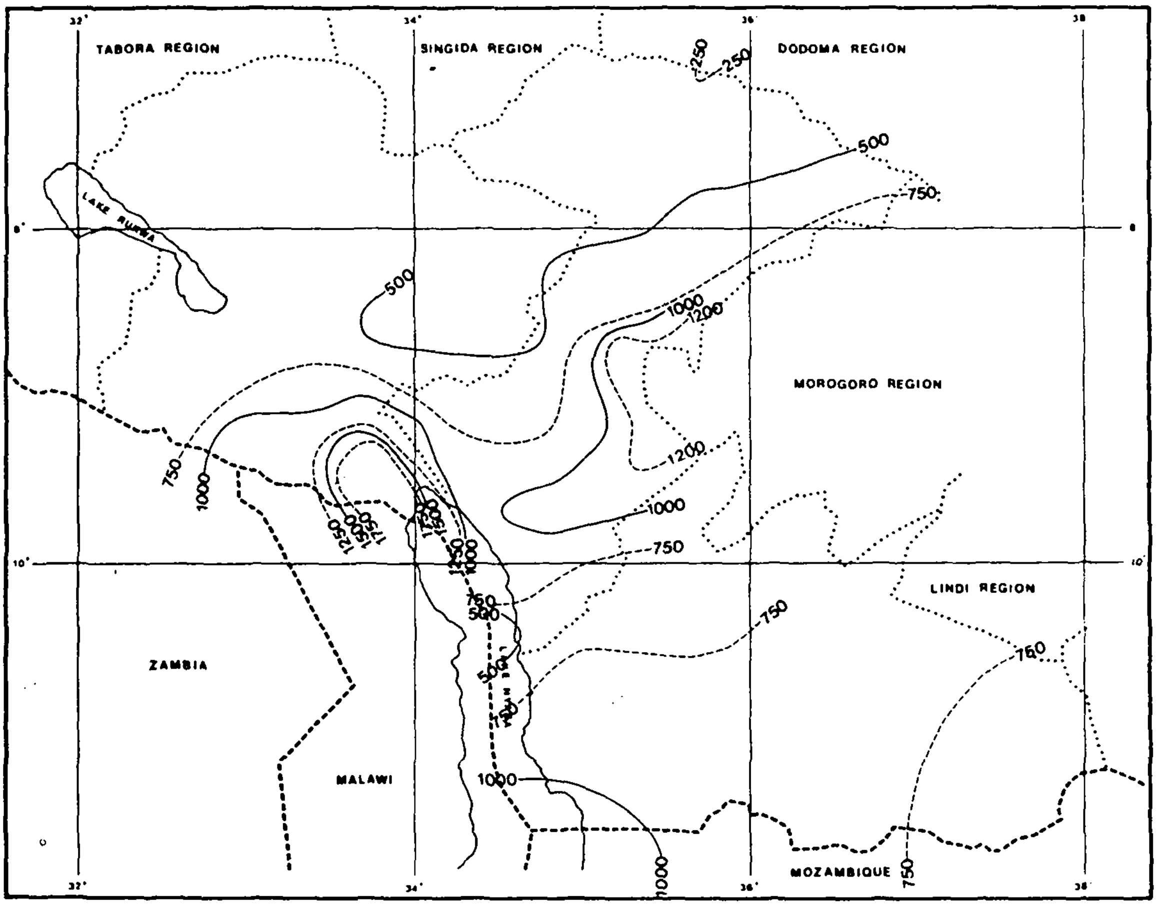


Figure 3.18 - 10 year minimum rainfall.

3.7 Recommendations

In order to maintain and improve the present rainfall registering network as well as the collection, storage and analysis of rainfall data, the following recommendations are stressed:

Gauging network and procedures

(a) Station density should be increased in poorly covered areas such as northern Mbeya, north-eastern Iringa, and eastern Ruvuma (cf. Figure 3.5 and Figure 3.7).

(b) More frequent station inspections are required in order to ensure:

- repair and replacement of damaged equipment
- general control of the state of operation
- feed-back to the observer, improving his motivation by showing interest in and appreciation of his work.
- enforcement of monthly station reporting directly to DOM.

Private sources of rainfall measurements should be approached and requested to report to DOM. These measurements could, because of their high reliability, be used as a check, of the reliability of the surrounding rainfall stations. The rainfall data base created as part of the present study should be completed by collection, control and storage of remaining rainfall data from private sources.

Reporting procedures to DOM should be unified, whether from Maji, Kilimo, private sources or others.

Data processing

(a) The enture rainfall data base now kept in Nairobi should be transferred to DOM, and the activities previously performed by EAMD should be resumed at DOM, i.e.

- central computerized data storage (data base)
- standard processing and basic statistical analysis
- regular punlication of data

(b) Further checking and correction of historical data series is required.

(c) In connection with Maji hydrological planning activities, e.g. hydrological modelling studies, Maji could assist DOM by checking and processing rainfall data using standard DOM procedures, and reentering the checked and processed data into the DOM data base.

(d) Systematic control, processing and storage of rainfall intensity records should be initiated.

4. EVAPORATION

4.1 General

Evapotranspiration is the process by which water is transferred from land or bodies of water to the atmosphere. Since a major part of the rainfall is returned to the atmosphere through this process, it is obvious that evapotranspiration represents a very important element of the hydrologic cycle.

The evaporation/transpiration processes are essential elements in studies of crop water requirements and irrigation projects, in water resources planning and management programs, in reservoir planning for hydropower, water supply or irrigation purposes, in water supply studies, in catchment water balance studies etc. The evaporation/transpiration processes are accordingly important elements in the present study.

The processes of evaporation and transpiration are affected by several climatic and environmental factors, which will be briefly described below. The local rate of evaporation depends on the availability of water and energy, and on a number of other factors: the nature of the surface, vegetation, humidity, wind etc. The energy supply is primarily from shortwave solar radiation and it varies on a global scale with latitude and season, and on a local scale with weather conditions, exposure of the surface and its reflective properties (albedo). Since the incoming solar radiation has a marked diurnal variation, the evaporation rate will also show a diurnal variation more or less in phase with the radiation, somewhat depending on the other components of the energy budget. These other components are the longwave net radiation, sensible heat flow and the heat stored in the soil or water body. The above mentioned components constitute the vertical energy balance budget at the soil surface, water surface or at a reference level in a crop stand. In this vertical energy budget a component due to advection is not included. However, this component may increase the supply of energy considerably, especially under arid conditions. For the transport of water vapour away from the evaporating surfaces, wind and its turbulence play the most important role. The various energy fluxes affecting the evaporation/transpiration processes are illustrated in Figure 4.1.

In the present evapotranspiration study recordings from evaporation pans and available Penman estimates have been utilized. The estimates from the two methods have been compared in order to establish pan coefficients for the pan recordings. Under most conditions evaporation pans do not represent natural conditions very closely, and adjustment of the recordings is required.

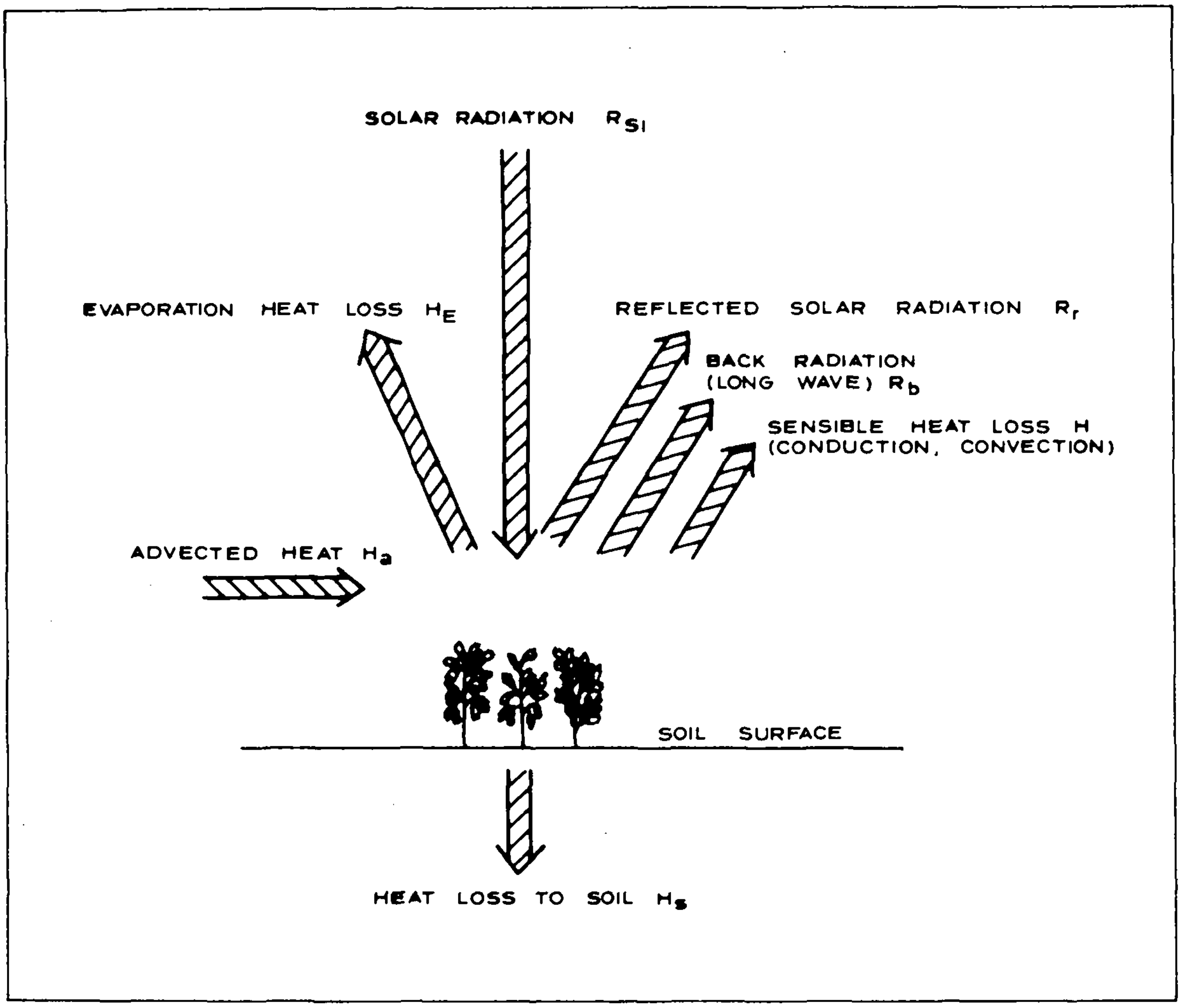


Figure 4.1 Illustration of energy budget applied at the soil surface. $(R_{si} + H_a - R_r - R_b - H - H_E - H_S = 0)$

It is generally agreed whenever reliable climatological observations are available, the Penman equation, which incorporates these climatological factors, will provide the best estimate of the true evaporation potential. Consequently the approach in this study has been to rely on the Penman figures as being the most reliable estimates of the evaporation potentials, and adjust the pan measurements accordingly. In connection with the comparison study between the two estimation methods a few supplementary Penman calculations have been carried out. Generally, however, little processing of climatological data from the study area has been performed.

The present evaporation study has been undertaken in order to provide information about this very important component of the overall hydrologic cycle. The general evaporation pattern in the three regions is investigated and illustrated in various ways, and an isoline-map of the annual potential evapotranspiration has been prepared. Further, the evaporation study has provided input to the hydrological modelling work for the establishment of the overall water balance in the area.

4.1.1 Basic terms

The basic terms and definitions of evaporation concepts as used in this study are primarily based on the guidelines given by FAO (1977) and FAO (1979). Since some confusion exists in the definitions, the interrelationships and the estimation methods of the basic evaporation quantities a summary of the concepts, as interpreted in this study, is given below.

(a) Evaporation from a free-water surface (E_0)

E_0 is the rate of water transfer from a free-water surface to the atmosphere under given environmental conditions. The factors controlling E_0 are well known, but their evaluation is difficult because of their interdependency. Basicly E_0 is determined by the difference in vapour pressure between the surface of the water body and the air, which in turn depends on temperatures of the water and air, and the turbulent exchange between the surface and the surroundings. In the following potential evaporation will refer to evaporation from a free-water surface (E_0).

(b) Soil evaporation (E_S)

The atmospheric conditions which affect evaporation from a free-water surface also affect that from soils. However, the opportunity for evaporation varies very strongly for soils depending on the water availability. During storm periods, when the soil may be highly saturated, the soil evaporation will be very close to the potential evaporation from a free-water surface. At the other extreme at very low moisture contents the soil evaporation will tend towards zero.

(c) Transpiration (E_T)

The process of evaporation of water which has passed through the plants is called transpiration. Transpiration is basically a process by which water is evaporated from the airspaces (stomata) in plant leaves, and it is therefore controlled essentially by the same climatic factors that determine evaporation. However, the transpiration process is affected by various physical and physiological factors as well, which imply that the transpiration rate normally is different from the evaporation rate from a free-water surface. Very important for the transpiration process is the soil moisture availability for the plant roots, since this condition greatly affects the stomatal behaviour. Compared to a free-water surface more solar energy is reflected from a vegetated surface, and consequently less energy is available for the evaporation purpose. On the other hand the surface roughness of a vegetated surface is greater than the surface roughness of a free-water surface, which enhances the sensible heat exchange with the ambient air. The taller crop, the more effective is the exchange.

(d) Potential/actual evapotranspiration (E_p and E_a)

When considering a vegetated surface where soil evaporation and transpiration occur simultaneously, there is no easy way to distinguish between the two processes. Therefore, the term evapotranspiration is used to describe the total process of water transfer into the atmosphere from vegetated land surfaces. This leads to the concept of potential evapotranspiration (E_p), which usually is defined as the total water loss to the atmosphere from an extended surface of short green crop, actively growing, completely shading the ground and well supplied with water. In this common definition the height of the crop is only mentioned implicitly, although it is known that the height of the crop influences the evapotranspiration (see the definition below of reference crop evapotranspiration in which the crop height is explicitly considered).

Under most circumstances the evapotranspiration from a vegetated area is lower than the potential level, because the crop is not always well supplied with water. The total evapotranspiration which occurs in this situation is termed the actual evapotranspiration (E_a).

Under ideal conditions (i.e. without any advection contributions) potential evapotranspiration cannot exceed free water evaporation under the same weather condition, but this assumption may be invalid under certain non-ideal circumstances. In the definition of E_p the term "an extended cropsurface" was used, indicating no boundary effects. However, all fields are to some extent influenced by their surroundings, and this influence is likely to be most important in arid regions where the spatial variability in moisture availability as a result of irrigation is greatest. Because of these "oasis" or advection effects a well-watered crop, which is tall or aerodynamically rough, can consume more energy and evaporate more water than a free-water surface. Although important, no considerations to oasis effects have been given in this study.

(e) Reference crop evapotranspiration (E_{cr})

The definition of this term is given in FAO (1977): "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". In the concept of potential evapotranspiration a shorter crop height is presumably implied, and consequently E_p is generally a little less than the reference crop evapotranspiration as defined above. However, the difference between these two terms is believed to be small, and for practical purposes they can be considered equal. This assumption has been made for the purposes of this study. Reference crop evapotranspiration is used as basis for the calculations of crop water requirements.

It should be mentioned that other definitions of reference crop evapotranspiration exist in literature. In Jensen (1973) alfalfa with 30-50 cm of top growth is used as the reference crop.

(f) Crop water requirements

In FAO (1977) crop water requirement is defined as "the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields under non-restricting soil water conditions including soil water and fertility and achieving full production potential under the giving growing environment".

The crop water requirement is calculated by multiplying the reference crop evapotranspiration by a so-called crop coefficient, which will vary with the actual crop and its stage of growth.

4.1.2 Methods for estimating potential evaporation/evapotranspiration

Several methods exist for estimating potential evaporation and potential evapotranspiration. Here only two methods will be discussed: evaporation pan and the Penman formula. These two are selected because the evaporation pan is the most widely used instrument for direct measurements of open water evaporation, while the Penman formula generally provides the most reliable estimates. Further, these two methods have traditionally (and currently) been used in Tanzania.

Pan evaporimeter

The most widely used method for estimating the potential free-surface evaporation is by means of evaporation pans. The type of pans used most frequently in Tanzania is a variant of the U.S. National Weather Service Class A pan. Contrary to the standard Class A pans the pans are here painted black on the inner side and covered by a protective wire mesh. The evaporation pans can only approximate natural conditions. As a consequence of the small mass of water in the pan, considerable fluctuations in water temperature occur as a result of variations in air temperature and solar radiation. Hence, the pan is not thermodynamically and aerodynamically similar to free water bodies, and generally the pan measurements are greater than the true potential evaporation.

The ratio of annual free-surface evaporation to annual pan evaporation, usually termed the pan coefficient, averages very nearly 0.70 for the majority of the reliable class A pans. Generally the range of the pan coefficient for this type of pan is from 0.60 to 0.90, very much dependent of the pan surroundings and the general climatic conditions (cf. FAO, 1977). As described above the type of pans installed in Tanzania deviate from the standard Class A pan the former being black painted on the inner side and covered by a protective wire mesh. These two measures affect the pan coefficient in opposite directions. The black interior will tend to increase energy absorption and thus increase pan evaporation (reducing pan coefficient). On the other hand the wire mesh tends to reduce the pan evaporation. Which of the two measures have the strongest influence is difficult to tell. Most likely the wire mesh will have the most significant effect.

The pan coefficient is fairly consistent from year to year, while monthly ratios of free-surface evaporation to pan evaporation shows considerable variation. Monthly pan evaporations corrected by the use of the annual pan coefficient should be used with caution, since such estimates may be seriously in error. From a study at Lake Hefner, Oklahoma, U.S.A., the monthly ratios of lake evaporation to pan evaporation varied between 0.13 and 1.31.

Estimation of potential evapotranspiration, alternatively reference crop evapotranspiration as defined by FAO (1977), from pan measurements will require the use of a different pan coefficient, since the albedo from vegetated areas and soils are higher compared to a free-water surface. As a result, potential evapotranspiration is generally somewhat less than free-water surface evaporation. Usually this difference has a magnitude of 10-20% and the pan coefficient should be adjusted accordingly, (i.e. 0.6 rather than 0.7).

For practical purposes, however, most investigators have assumed that potential evapotranspiration is roughly equivalent to free-surface evaporation as determined from a Class A pan. Theoretically this is not correct for the reasons mentioned above. Firstly errors in estimating free-surface evaporation from pan records are such that a further adjustment for potential evapotranspiration would be of questionable value. Secondly the potential evapotranspiration from certain crops exceeds the potential evapotranspiration for grass, and consequently the average potential evapotranspiration from a catchment with mixed vegetation types may approach the free-surface evaporation. Estimated free-surface evaporation from pan records may, therefore, be assumed to be a good indicator of potential evapotranspiration from a catchment with a varied crop pattern. In this study potential evapotranspiration (E_p) from a grass vegetation has been used as the reference potential evapotranspiration. This quantity has also been used in the hydrologic modelling studies, although the potential evaporation (E_0) might have been a better indicator of the average potential evapotranspiration from a catchment with a varied crop pattern. However, as long as the potential evaporation quantities are used consistently in a modelling study, the choice of the reference potential evapotranspiration has no influence on the components in the water balance, but will only affect the calibration of the parameters describing the maximum water content in the individual storages (cf. Chapter 7).

It is emphasized that the potential evapotranspiration figures (E_p) appearing in this study must be increased by 20% to obtain the evaporation from a free water surface (E_0). This is imperative when using these results for the design of reservoirs.

Penman formula

It has been agreed among agriculturalists and hydrologists for several years, that although evaporation pans are easy to operate and maintain, the reliability of the records and the definition of pan coefficients can be questionable .

Penman based estimate of potential evaporation is generally regarded as the most suitable evaluation of open water evaporation. This was also the conclusion of an earlier study on evaporation in Tanzania (Woodhead, 1968).

The Penman equation requires information about vapour pressure, net radiation, wind speed and temperature. Often some of these parameters are not measured and must be assessed from other information by using empirical formulae. As an example net radiation may be estimated from the number of sunshine hours and an albedo coefficient.

The version of the Penman formula used in this study, and to some extent in the two former (Woodhead, 1968 and Brown and Coheme, 1969), is recommended in FAO (1979) and shown in Figure 4.2.

The two formulae in Figure 4.2 differ from one another in the estimate adopted for the albedo which is assumed to be 25% for a vegetation cover, and 5% for a free water surface. Another difference appears in the aerodynamic term or wind-function, in which the greater roughness of a vegetation covered surface in comparison to a water surface, is taken into account by assigning a larger constant factor to the wind speed term.

The major contributor to evaporation is the term representing incoming solar radiation, but unfortunately radiation measurements are often deficient and not too reliable in Tanzania. However, several studies have suggested, that solar insolation can be assessed through measurements of sunshine hours. This correlation technique is and has been widely used in studies in Tanzania. The other necessary climatological parameters for the Penman calculations are normally measured more regularly. Otherwise, certain approximations can be justified, since the accuracy of these parameters is less crucial than the predominant radiation term.

All Penman estimates shown here, as well as in the two former Tanzania studies, are evaluated in terms of average values, over a several-year period, for each of the basic variables for each month of the year. In Woodhead (1968) the estimates based on average climatic values were compared to the corresponding average monthly and annual estimates derived from calculations for individual months and years. The monthly and annual values obtained from the two procedures were in close agreement, the annual values being within two per cent. These findings justify the calculation of average evaporation values from long term mean values of the climatic variables.

Furthermore, in East Africa potential evaporation at a location does not change very much from year to year, because it is largely dependent on the solar insolation, which outside the atmosphere is nearly constant. The variability in Penman estimates from East Africa have been studied by Woodhead (1968) and Brown and Coheme (1969) indicating a relative variability for annual values in the range 3-6%. For individual months, however, the relative

Potential evapotranspiration

$$E_T = \frac{\frac{p_0}{p} \cdot \frac{\Delta}{\gamma} \left[0.75 R_A (a + b \frac{n}{N}) - \sigma T_K^4 (0.56 - 0.079 \sqrt{e_d})(0.10 + 0.90 \frac{n}{N} \right] + 0.26 (e_a - e_d)(1.00 + 0.54 U)}{\frac{p_0}{p} \cdot \frac{\Delta}{\gamma} + 1.00}$$

Evaporation of a free-water surface

$$E_0 = \frac{\frac{p_0}{p} \cdot \frac{\Delta}{\gamma} \left[0.95 R_A (a + b \frac{n}{N}) - \sigma T_K^4 (0.56 - 0.079 \sqrt{e_d})(0.10 + 0.90 \frac{n}{N}) \right] + 0.26 (e_a - e_d)(0.50 + 0.54 U)}{\frac{p_0}{p} \cdot \frac{\Delta}{\gamma} + 1.00}$$

Explanation of the units used in the formula

The terms intervening in the formulae are defined hereunder and expressed in the following units:

E_T = estimation of the potential evapotranspiration for a given period, expressed in mm;

E_o = estimation of the evaporation from a free-water surface for a given period, expressed in mm;

p_o = mean atmospheric pressure expressed in milibars at sea level;

p = mean atmospheric pressure expressed in milibars as a function of altitude, for the station where the estimate is calculated;

Δ = rate of change with temperature of the saturation vapour pressure expressed in milibars per degree ^oC;

γ = the psychrometric coefficient for the psychrometer with forced ventilation = 0.66;

0.75 and 0.95: factors expressing the reduction in the incoming short wave radiation on the evaporating surfaces and corresponding respectively to an albedo of 0.25 and 0.05;

R_A = short wave radiation received at the limit of the atmosphere expressed in mm of evaporable water (1 mm = 59 calories) and taking for the solar constant the value of 2.00 $cal.cm^{-2}.min^{-1}$;

a & b = coefficients for the estimation of total radiation from the sunshine duration (a = 0.29, b = 0.42)

n = sunshine duration for the period considered in hours and tenths;

N = sunshine duration astronomically possible for the given period;

σT_K^4 = blackbody radiation expressed in mm of evaporable water for the prevailing air temperature;

e_a = saturation vapour pressure expressed in milibars;

e_d = vapour pressure for the period under consideration expressed in milibars;

T^o_C = air temperature measured in the meteorological shelter and expressed in degrees Celsius;

T^o_K = air temperature expressed in degrees Kelvin where $T^o_K = T^o_C + 273$;

$U_{m/s}$ = mean wind speed at an elevation of 2 m for the given period and expressed in m/sec.

Figure 4.2 Penman equation (FAO, 1979).

variability is considerably larger, typically between 6% and 16%. Further, in Woodhead (1968) under the assumption of normal distributions, monthly and yearly confidence levels have been evaluated, which also indicate a rather small variation. Consequently it is a fair approximation to consider annual and even monthly potential evaporation as constant from year to year and apply these quantities in water balance calculations. Easy calculation of the potential evapotranspiration after Penman is shown in Annex 4-1, FAO (1979).

4.2 Direct measurements

Direct evaporation measurements by pans, rather than measurements of climatic variables for indirect evaporation estimates, is the most widely used method in Tanzania. Although direct measurements are very difficult to make with a satisfactory degree of accuracy, because evaporation pans do no represent natural conditions very closely, they do provide a fair indication of the potential evaporation pattern.

During the present study the consultants have collected all available information on pan measurements in the study area. The majority of the evaporation pans are operated by government agencies, who collect the data on a routine basis. Besides some pans have been installed in tea estates for crop monitoring and prediction of yields. The most widely used evaporation pan in the area is a Class A type, which is modified according to recommendations from the former East African Meteorological Department, i.e. painted black inside, and covered by a wire mesh. The other kinds of pans installed in the area are of the sunken type, the records from which have been considered too unreliable for inclusion in the present study.

Consequently only records from modified Class A pans (standard Tanzanian pans) are used in the analyses.

4.2.1 Organisation, data collection and storage

The government agencies responsible for the operation of evaporation pans in the study are Directorate of Meteorology (DOM) and MAJI. Supplementary pans installed by the consultants are now under the responsibility of MAJI. All these pans are of the modified Class A type. The operational responsibility of the evaporation pans in the three regions is indicated in Table 4.1[8]. All collected data from pans operated by DOM and MAJI are stored on special charts from where the data have been copied. For the MAJI stations copies of these charts are also stored at the regional offices.

4.2.2 Network and instrumentation

Pan evaporation records have been processed from eight locations in Mbeya region, three locations in Iringa region and three locations in Ruvuma region. The locations of the pans appear from Table 4.1[8] and Figure 4.3. In connection with the present investigation the consultants have installed six evaporation pans in the regions. The stations have been established in the three index areas (two in each) with the purpose of extending the station network in these representative areas, and they are now part of the permanent network under the responsibility of MAJI. Five of these were installed in late 1980, and the sixth (Sao Hill) in March 1981.

The Msembe meteorological station (including the evaporation pan) has been moved during the study period, because it was not properly maintained and operated. The new location is near the hydrological gauging station 1KA59. The Mtera meteorological station has also been relocated during this period due to the finalisation of the dam construction at Mtera.

The pans mentioned above, including the newly installed, are all a variant of the U.S. National Weather Service Class A pan. This pan is circular, four feet in diameter and ten inches deep. The bottom, supported on a wooden frame, is raised six inches above the ground surface. The datum level is indicated by the top of a hook mounted within a stilling well. Following the guidelines from the former East Africal Meteorological Department the interior of the pan is painted black in order to absorb as much of the incoming short wave radiation as possible. The exterior is supposed to be painted with aluminium paint to reduce the radiation loss. (The traditional Class A pan is painted inside and outside with aluminium paint). Further, the Tanzanian pans are covered by a wire mesh with a mesh size of approximately one square inch.

The evaporative loss is measured daily at 9:00 a.m. by bringing the water level in the pan to datum. If the rainfall depth in the last 24 hours has been less than the evaporation depth, water must be added, and if the rainfall depth has been greater, water must be taken out. A cup of standard volume is used to measure the water amounts. During heavy rainfall water may be lost by splashing, or the amount of rain may be large enough to cause the pan to overflow. In this case unknown amount of water is lost which will lead to an overestimate of the evaporation.

At the three tea estates, Lugoda, Matugutu and Ifupira a sunken pan type has

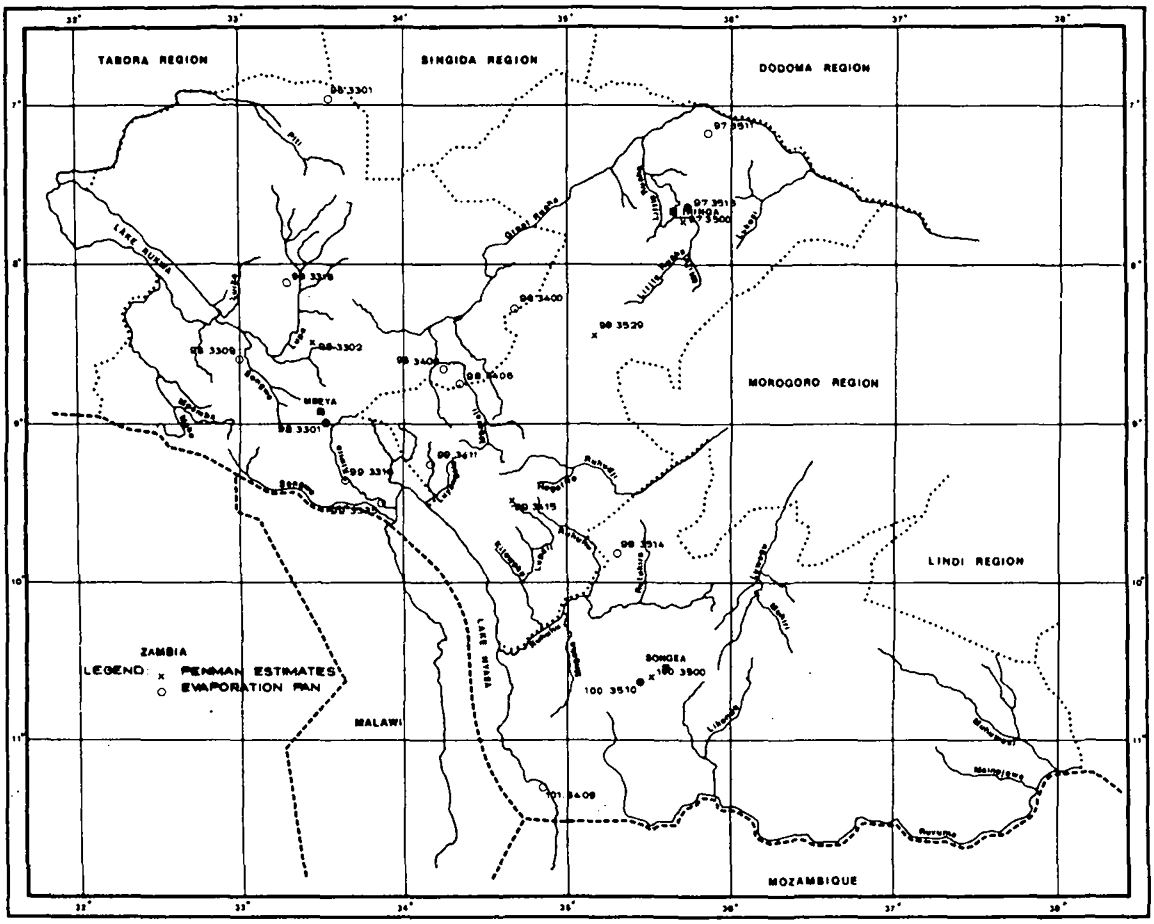


Figure 4.3 - Evaporation station network.

been operated in the dry seasons since the mid-1970'es. Because of the different pan type (including different pan coefficients), and because the records from these pans appear unreliable, they have not been used in the present study.

4.2.3 Data availability

The standard Tanzanian "Class A" pans which have been operated in the study area are listed in Table 4.1[8]. In the table are also indicated the period of the records, the collecting agency, the general impression of reliability, altitude of station, and observed pan evaporation multiplied by the pan factor 0.70.

The annual values appear to be fairly variable. Apart from a few extreme values, the annual amounts range from about 1300 mm to 1900 mm, with an average of roughly 1500 mm. The maximum value is found in Mtera, in northern Iringa, namely 2230 mm, which is to be expected with the prevailing climatic conditions in this arid area. Also Galula is situated in an semi-arid to arid region (near lake Rukwa) with a relatively low yearly rainfall amount, and consequently the evaporation potential is expected to be fairly high. Chivanjee and Bulongwa represent the other end of the scale. These stations are both situated on high plateus (near Tukuyu and in the Kipengere range respectively) in areas with high rainfall, relative low temperatures and consequently low potential evaporation. The annual pan evaporation found in Lupatingatinga is considered to be inconsistant with the general evaporation pattern. This station is situated in the northern semi-arid part of the Mbeya region and would therefore be expected to have a much higher evaporation value, at least at the level of Galula.

Monthly values from all the pan evaporation stations are shown in Tables 4.2[8]-4.16[8], and in Table 4.17[8] mean monthly and annual values are listed. A few stations have records back to the beginning of the 1960'es, and some have been operated from the late 1960'es. However, the majority of the pan evaporation stations have records only from the 1970'es.

The majority of the evaporation pans have been inspected by the consultants. The standard of maintenance and operation of the pans is quite variable. A number of the pans are well maintained, while others leave a lot to be desired. The records have been reviewed by the consultants, and the most obvious errors and inconsistencies have been corrected or deleted from the records. However, it has not been possible to perform this correction procedure in a very consistent manner, and there are still figures which may be somewhat unrealistic. This fact, together with the numerous gaps in the records imply that the general quality of the pan evaporation records must be considered rather low. The availability of pan evaporation is detailed in Figure 4.4

Considering the general data quality, combined with the uncertainties involved in the assessment of pan coefficients, the potential evaporation estimates based on pan evaporation records must be applied with caution, and can not be considered as more than approximate compared to the true potential evaporation values.

4.3 Indirect estimates

As an alternative to direct measurements potential evaporation rates can be estimated indirectly on the basis of climatological variables. Perhaps the most widely used method for computing the evaporation potential from climatological factors is the Penman equation, which is based on a combination of aerodynamic and energy balance equations, (cf. Figure 4.2).

In the study area the necessary climatological data for Penman calculations are supplied from standard meteorological stations which are equipped with:

- raingauge (daily observations)
- pluviograph
- evaporation pan
- Gunn-Bellani radiation integrator
- Cambell-Stoke sunshine recorder
- Cup anemometer
- Stevenson screen containing a min/max thermometer, a dry/wet bulb psycrometer and a thermograph.

The locations of climatological stations in the three regions are indicated in Figure 4.3.

The climatological stations in the regions have all been inspected by the consultants, and their records have been reviewed. The generel impression from this inspection programme has been that improved procedures for station operation and maintenance, including station inspection by the responsible agency, are required for several stations if reliable and readily accessible climatological data shall result. For the present study thorough control and processing of climatological data for indirect evaporation estimates has not been possible within the time and resources available.

Consequently Penman estimates from only three representative stations have been made on the basis on mean monthly climatological data. Otherwise the evaporation study has been based on pan evaporation data, and already available Penman estimates from Woodhead (1968) and FAO (1969, and unpublished).

4.3.1 Summary of Penman calculations

Woodhead (1968)

In Woodhead's study Penman calculations are published from 64 locations in East Africa, of which 17 are from the present project area. The Penman version which has been applied deviates from the FAO-version described earlier, in the sense that other constants and a different data preparation procedure have been applied. Woodhead has incorporated his own coefficients for radiation estimates from cloud observations, and wherever possible he has used direct measurements of global radiation, mostly obtained from Gunn-Bellani distillation radiation integrators. However, this instrument is generally considered very difficult to calibrate and maintain, and if not operated properly erroneous measurements will result. Further corrections have been made for altitude and latitude (according to Glover and McCulloch, 1963), and another wind term expression is used. Finally the estimates are based on a mean dew point temperature, taken as a the average of the measurements at 9 a.m. and 3 a.m., whereas the FAO estimates and the estimates made by the consultants rely on the 9 a.m. values only. Altogether these circumstances imply that the Woodhead estimates can be expected to deviate from the estimates based on the Penman version suggested by FAO (1979).

For consistency, and since the FAO estimates are considered to be more reliable, the Woodhead estimates have been used neither in the comparison with the pan records, nor for the iso-map preparation.

The Woodhead calculations for locations inside the project area is presented in Table 4.18[8].

FAO studies

The early FAO study, Brown and Coheme (1968), provides information on Penman estimates (potential evapotranspiration) from 36 locations in East Africa, of which four are inside the project area. However, the figures listed are all obtained from Woodhead and do not contain any new information.

However, later Penman estimates have been prepared by the FAO (unpublished). These are all performed in accordance with the procedure described in FAO (1979) and are considered to be reasonably reliable. A summary is given in Table 4.19[8].

Penman calculations by the consultants

In connection with the comparison study of Penman estimates and pan measurements, three locations (one in each of the three regions) have been subject to a closer analysis. Penman estimates of mean monthly and annual potential evaporation (E_0) and potential evapotranspiration (E_p) have been made by the consultants for these three stations. The resulting mean annual potential evapotranspiration values are shown in Table 4.20[8], and more detailed results are listed in Tables 4.22[8], 4.23[8] and 4.24[8]. The calculations are based on mean monthly climatic data over the indicated periods. The climatic data, which have been used, have been corrected for the most obvious errors and inconsistencies. However, a thorough data processing and control has not been undertaken. Further, no attempt has been made to calculate the yearly variability for which reference is made to Woodhead (1968), (cf. Section 4.1).

In Table 4.21 below a summary is shown of Penman estimates for mean annual potential evapotranspiration from the three locations mentioned above, as calculated by Woodhead, FAO and the consultants:

	Penman estimates (in mm)		
Location	Woodhead	FAO	Consultants
Mbeya Airfield	1370 (1955-64)	1252 (30 years)	1426 (1963-78)
Songea Airfield	1377 (1955-64)	1381 (5 years)	1277 (1955-77)
Nduli	1575 (1960-62)	1817 (2 years)	1325 (1970-79)

Table 4.21 Comparison of Penman estimates for mean annual potential evapotranspiration. The time periods are indicated in the brackets.

Discrepancies are obvious when comparing the estimates by Woodhead, FAO and consultants. Firstly the time periods are not identical. However, assuming that there is no significant trend in the basic climatologic data, this can not explain these deviations. This is supported by the fact the yearly variation in annual potential evapotranspiration in the East African areas is found to be fairly small (cf. Woodhead (1968) and Brown and Coheme (1969)). Another explanation is that different versions of the Penman equations have been used, as explained above. However, it is believed that the main cause for these discrepancies is the uncertainties in the basic climatological data applied in the three studies.

4.3.2 Comparison study of Penman and pan estimates

Penman estimates of potential evapotranspiration have been compared to the direct methods (pan recordings) in order to establish the necessary pan coefficients. Corrections of the pan recordings by applying appropriate factors should make direct and indirect estimates comparable.

For the comparison study three meteorological stations have been selected one in each region. From these stations both climatological data for the Penman calculations and pan recordings are available. Further the selected stations are the ones with the longest and most consistent records available.

The stations included in the comparative study are: Mbeya Airfield (Mbeya), Nduli (Iringa) and Songea Airfield (Ruvuma).

The data material used in this section is shown in the Tables 4.22[8], 4.23[8] and 4.24[8]. Indicated in the tables are also the sources of the Penman computations or pan measurements, together with the periods of records used. For the Penman computations both the free-water surface evaporation (E_0) and the potential evapotranspiration (E_T) are shown on a monthly basis, corresponding to what could be termed a "climatological mean month". The two computation methods differ from one another in the figure adopted for the albedo, and in the aerodynamic description as described earlier. The difference between the two estimates is usually about 20%, and this figure is adopted as a standard conversion factor between the two terms if both are not calculated. The values derived through the use of this factor are marked with an asterisk in the tables. Pan measurements as they appear in the tables are all uncorrected (i.e. original observations).

Mbeya Airfield (Mbeya)

Which 30 year period is covered by the FAO calculations is not known, but it most likely includes the other periods used in the comparison. The Woodhead and the consultants' estimates are in good agreement despite the different time periods and the difference in calculation method, whereas the FAO figures are much lower. Although FAO covers a much longer period this is not immediately expected to cause this difference, considering the generally small year-to-year variability in potential evaporation. However, different measurement and maintenance practices may explain this difference. For these reasons the consultants' Penman estimates have been adopted as the most reliable. The covered period coincides in this case reasonably closely with the pan measurement period. Assuming that Penman estimates represent the most reliable evaluation of the atmospheric evaporation potential, the pan recordings should be corrected by the monthly factors indicated in the table. The monthly pan factors seem to be fairly constant over the year, although with a tendency to attain smaller values in the dry season. However, keeping the uncertainties in pan operation in mind, it will be of questionable value to apply monthly correction factors, and consequently one constant applicable throughout the year must be considered most appropriate. In this case, the correction factors to be used for obtaining potential evapotranspiration and potential evaporation would be 0.76 and 0.95 respectively. These figures seem to be somewhat higher than normal for the standard Class A pans, for which a factor of 0.70 is generally used to obtain potential evaporation. However, local surroundings and atmospheric conditions may have a pronounced influence on the correction factors and the obtained values are by no means out of range (see e.g. FAO (1977)). As explained in Section 4.1 the black painting of the interior of the pans and the wire mesh cover imply, that the pan coefficient for the Tanzanian pans may deviate from the coefficient for a standard Class A pan.

Nduli (Iringa)

The FAO and Woodhead calculation are most likely from the same period and based on the same data, but even then the figures deviate considerably. Because of this serious discrepancy which probably is caused by differences in the constants involved in the Penman calculations, the estimates by the consultants have again been considered to be the most reliable. Also in this case the covered period coincides reasonably closely with the pan measurement period. The pan coefficients for potential evapotranspiration and potential evaporation are in this case 0.66 and 0.81, which are lower than for the Mbeya station. The monthly values are again fairly constant throughout the year with a tendency for lower values in the dry season.

Songea Airfield (Ruvuma)

The Penman estimates for this location appear to be more consistent than for the two previous stations. The pan coefficients for potential evapotranspiration and potential evaporation are calculated as 0.70 and 0.89 respectively.

The pan coefficient varies somewhat over the year as it appears from Figure 4.24[8], where the seasonal variation at the three stations included in the comparison study are shown.

It appears that lower values are prevailing in the dry season and higher in the rainy season which could lead one to apply seasonally varying coefficients, e.g. one coefficient in the dry season and another one in the rainy season. However, since several uncertainties are involved in the operation of evaporation pans and further, since the basis of the present comparison analysis is rather sparse and uncertain, application of pan coefficients which vary both seasonally and locally does not seem to be justified in the present study. Furthermore, application of one general coefficient is the most usual approach adopted, when adjusting pan measurements. Hence, on the basis of the above comparison analysis, it is recommended to adopt a general pan coefficient to be used throughout the three regions.

The results of the comparison analysis is summarized below. The potential evapotranspiration from a grass vegetation is used as the reference evaporation, and hence only the pan coefficient describing the relation between potential evapotranspiration and pan measurements is shown in Table 4.25.

Location	Pan Coefficient: $K_{pan} = \frac{\text{potential evapotranspiration } (E_p)}{\text{recorded pan evaporation}}$
Mbeya Airfield (Mbeya)	0.76
Nduli (Iringa)	0.66
Songea Airfield (Ruvuma)	0.70
Average for Mbeya, Iringa and Ruvuma regions	0.70

Table 4.25 Summary of comparison between Penman estimates and pan measurements.

Based on the above comparison study it is recommended to apply the average pan coefficient $K_{pan} = 0.70$ for the adjustment of all monthly pan measurements in the regions. It is emphasized, however, that the adjusted monthly values will be associated with a considerable degree of uncertainty, whereas the annual values represent a fair approximation to the true potential evapotranspiration rate.

The monthly pan evaporation figures presented in Tables 4.2^8-4.16^8 are all adjusted by a pan coefficient of 0.70. In the design and operation of reservoirs these values should not be applied directly, the evaporation from a free-water surface being larger than the potential evapotranspiration. In order to obtain a measure for the evaporation from a free-water surface the values should be increased by 20% (cf. Section 4.1 and Tables 4.22^8, 4.23^8 and 4.24^8).

4.4 Pan evaporation analysis

4.4.1 General

Three stations have been selected for a closer analysis: Mtera in northern Iringa and Igawa and Mbarali in the Mbeya region. These are the stations with the longest and most reliable periods of record.

Annual histograms of mean monthly rainfall and mean monthly pan evaporation over the years of record are shown in Figure 4.5 and Figures 4.6^8- 4.8^8.

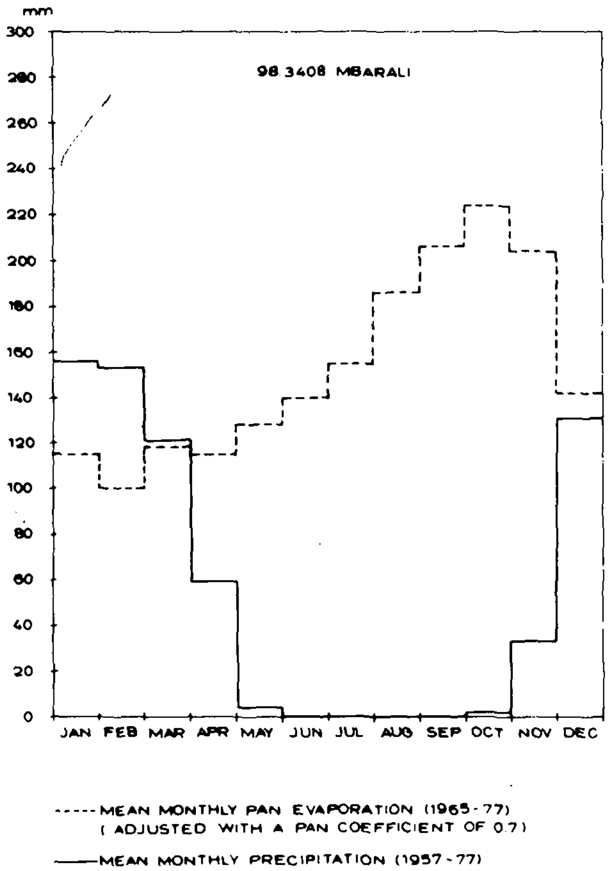


Figure 4.5 Seasonal variation of mean monthly rainfall and mean monthly pan evaporation.

The three stations experience a similar variation both in rainfall and evaporation pattern. Distinct seasons are recognized, the rainy season from November through May, and the dry season from June through October. Potential evapotranspiration generally increases during the dry season, reaching a maximum just before the rainy season starts. However, the seasonal variation is much less pronounced compared to the rainfall variation.

Comparison between long-term monthly averages of rainfall and potential evapotranspiration can provide some information about the water availability for crop growth and the need for irrigation. The rainfall in most of the study area is concentrated during a relatively short season, whereas the seasonal variation of potential evapotranspiration is moderate. These patterns imply that a few months will have a surplus of water, while most of the months will have a deficit. Generally, on an annual basis, the total deficit exceeds the total surplus.

The amount of water available for crop growth is not equivalent to the rainfall supply. If the rainfall intensity is greater than the infiltration capacity of the soil, some of the rainfall will runoff in the surface, and will not be available for the crop transpiration. On the other hand, some of the rainfall from the months of surplus will be stored in the crop root zone and become available for transpiration during the dry season when there is a deficit of water.

For an actively growing crop having attained full ground cover the potential evapotranspiration will correspond roughly to the potential water requirements for achieving full production potential. If the actual water supply to the crop is less than the potential evapotranspiration, crop production will be reduced. The water supply can be provided from either rainfall, supplementary, or the available water in the root zone. In periods with little rainfall (e.g. Figure 4.5) the crop will have to make use of the available water in the root zone. However, the root zone has limited storage capacity (depending on soil type and depth of root zone), and only part of the water is readily available for the crop. Consequently, a reduction in crop production will usually result in dry areas where no supplementary irrigation water is provided.

Crop water requirements do not always correspond to the potential evapotranspiration, but vary with the stage of the crop growth cycle and the general density of the crop cover. Accordingly, irrigation demand is not equivalent to the rainfall deficit in the dry season, and only a comparison between the seasonal variation of rainfall and potential evapotranspiration can provide some indications of the irrigation requirements. For a more comprehensive study of the climatic factors in relation to agriculture reference is made to Nieuwolt (1973).

4.4.2 Yearly variability

The histograms, discussed above, indicate a more steady variation in the evaporation pattern relative to that of the rainfall. This indication is clearly confirmed from the analysis discussed below.

In Figure 4.9 and Figures 4.10^8-4.12^8 the annual pan evaporations (adjusted with a pan coefficient of 0.7) for all station years are shown as histograms.

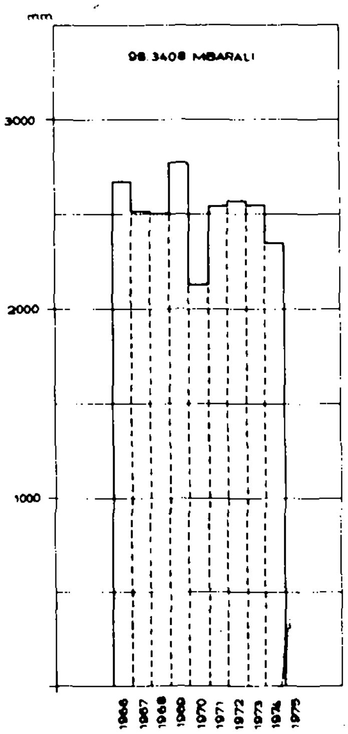


Figure 4.9 Annual pan evaporation (adjusted with a pan coefficient of 0.7).

Table 4.26 (in more detail in Table 4.27^8) shows the coefficients of variation (standard deviation divided by mean value) on monthly and yearly basis for both rainfall and pan evaporation.

Location	Annual coefficient of variation		Monthly range of coefficient of variation	
	Rainfall	Pan evaporation	Rainfall	Pan evaporation
Mtera	27%	6%	0-424%	6-20%
Igawa	22%	10%	0-469%	8-20%
Mbarali	18%	4%	33-447%	5-22%

Table 4.26 Annual coefficients of variation for rainfall and pan evaporation

For pan evaporation the interannual relative variability is between 4% and 10%, against 18% and 27% for rainfall. For the individual months relative variability is larger with an average of about 13%, higher values occur in the rainy season and lower in the dry season. Monthly rainfall variabilities are considerably higher.

Relative variability of Penman estimates is described earlier in this chapter. These figures are of about the same magnitude as for the pan evaporations, although a little less.

The greater variability of rainfall compared to evaporation is illustrated in another way in Figure 4.13 and Figures 4.14^8-4.16^8.

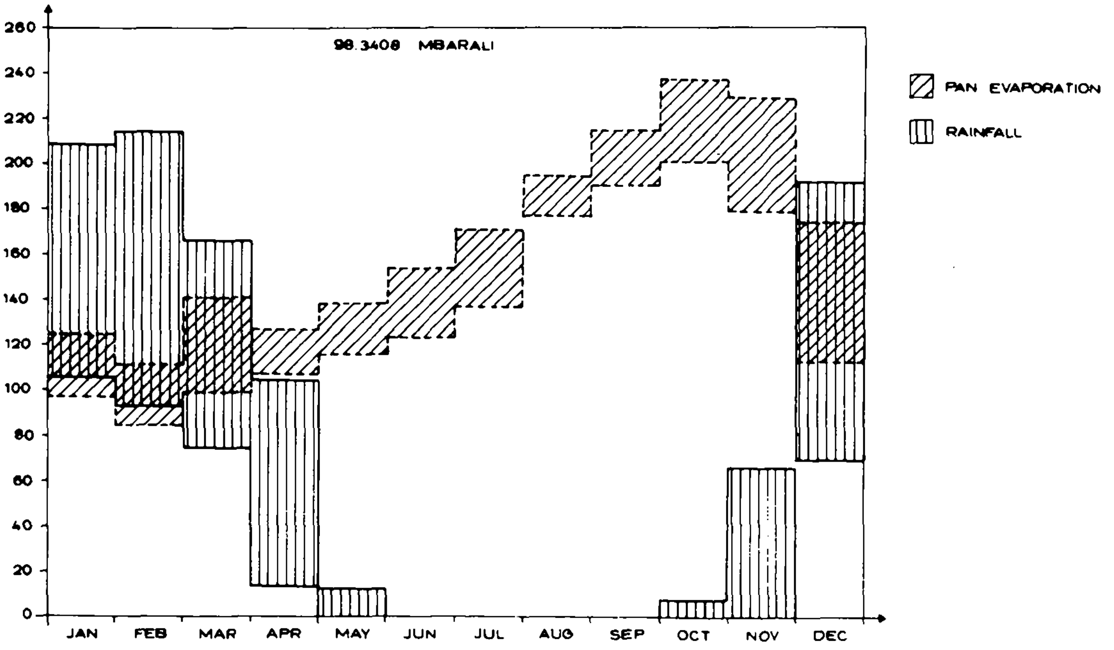


Figure 4.13 Variability of monthly pan evaporation and monthly rainfall.

A range of variability is indicated for each month in the way that the monthly standard variations are added to and subtracted from the monthly mean values of rainfall and evaporation. Under the assumption that the monthly values follow a normal distribution, (a reasonable assumption according to Woodhead, 1968), 68% of the probability mass is contained inside this band. From the figures it is clearly seen that the range of variation for evaporation is much smaller than that of rainfall.

In conclusion these analyses confirm that for water balance calculations it will be permissible to consider annual and even monthly potential evaporation values as constants.

4.4.3 Variation with elevation

In Figure 4.14 mean annual potential evapotranspiration obtained from the various stations is depicted against altitude.

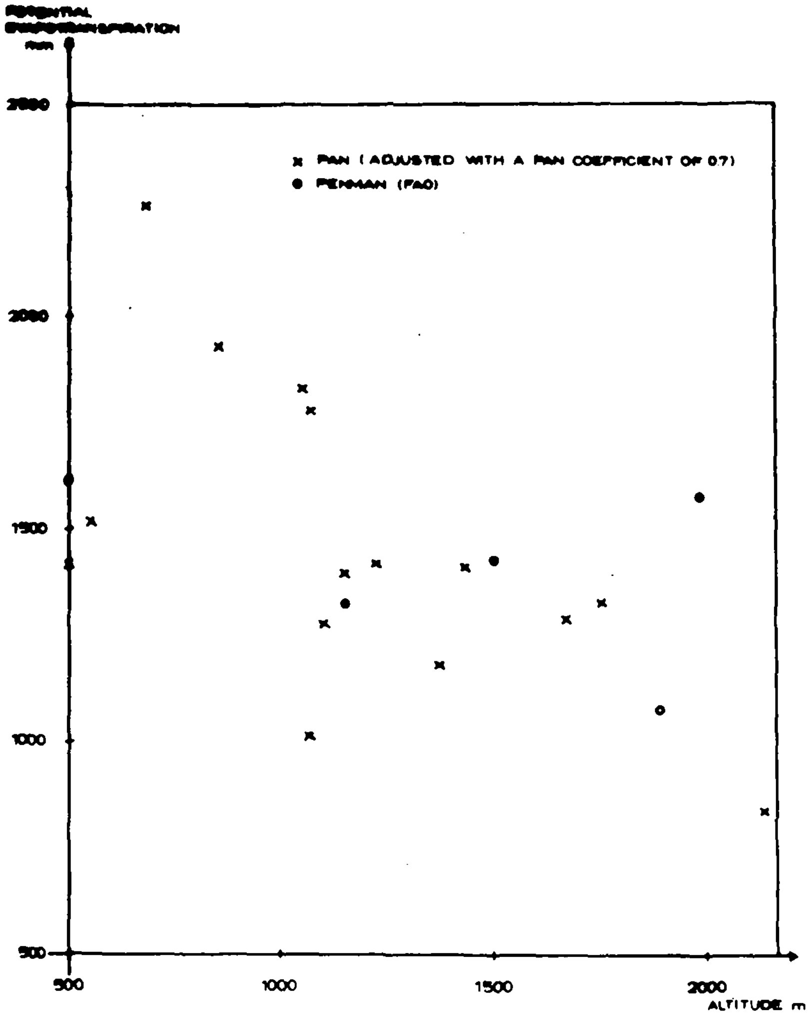


Figure 4.17 Mean annual potential evapotranspiration versus altitude.

A slight tendency of decreasing potential evapotranspiration with increasing altitude is noticed. However, it is not possible on basis of the available information to establish an unambiguous relation between the two factors. Various physical factors influence the evaporation rates in opposite directions with increasing altitude. A general higher solar radiation intensity at higher elevation provides an increased energy supply. Also, the decrease in temperature with altitude decreases the long wave back radiation, resulting in a net gain of energy. On the other hand, if the vapour content in the air was to be unaffected, the vapour deficit would decrease, and so would the evaporation. In fact an increase in humidity with altitude can be expected due to the decrease of the condensation level. This will tend to increase the cloud cover, and both circumstances will contribute to reducing the evaporation. Other factors, which are not mentioned here, also influence the evaporation potential, and all these factors combined with regional differences, produce the dispersed picture seen in Figure 4.17.

4.4.4 Correlation between stations

Two closely situated stations, Igawa and Mbarali, have been selected for a correlation analysis. The two pan evaporation stations are located within a distance of approximately 20 km and should therefore be expected to show some correlation. The correlation analyses have been carried out on a monthly basis to retain the seasonal variability.

For each month of the year corresponding values from the two stations have been plotted in diagrams (Figures 4.18[8]-4.19[8]), and the relevant regression coefficients have been calculated. Further, statistical tests have been performed in order to reveal any correlation between the stations. The results are shown in Table 4.28[8]. Generally very low correlation coefficients have been found for all months, and all tests on the regression coefficients failed for the selected level of significance (5%). Particularly low correlation coefficients are found in the months March through July. Consequently the regression coefficient can not be considered significantly different from zero, and the evaporation pattern at the two locations can only be interpreted as being uncorrelated. This is surprising when considering the small distance between the two stations.

The correlation between Igawa and Mtera has also been investigated. (Table 4.29[8] and Figures 4.20[8]-4.21[8]). These stations are very far from each other, (approximately 500 km), and consequently no significant correlation is to be expected, particularly in view of the arid climatic conditions in the area of Mtera. The correlation coefficients for these stations are of about the same magnitudes, i.e. generally very low, as for the two closely situated stations.

The apparently very low correlation between stations is surprising in view of the little variation in monthly evaporation from year to year. The little variation from year to year is a consequence of little variation in the driving climatological parameters, i.e. primarily the solar radiation, and these factors would also be expected to behave relatively uniform over an area. In particular this should be true for the sunny and rather cloud-free dry season, whereas the spatial variation in the wet season will be more pronounced because of the high spatial variability in the rainfall pattern (cf. Chapter 3). Examination of the evaporation records reveals that the variation between stations in the monthly figures has a pronounced erratic behaviour, indicating that the evaporation pans are under considerable influence of local conditions. These include advection effects, i.e. dry winds, high humidity deficits, blowing across the pan areas, but also measurement errors due to deficient operation and maintenance procedures play an important role. It is believed that these circumstances explain the disparity between the small variation in monthly evaporation values from year to year, and the apparent lack of correlation between stations.

The apparent lack of correlation between even closely situated stations as depicted in the Figures 4.18[8]-4.19[8] is for these reasons believed not to fully reflect reality. Some degree of correlation is believed to be present, although it is not possible on basis of the available pan evaporation records to reveal it. Since the basic climatological parameters are not influenced by advection effects to the same degree as the pan behaviour is, comparison of monthly Penman estimates between stations may show a larger degree of correlation.

The assumption of some spatial correlation, justifies transfer of monthly potential evapotranspiration values from gauged to ungauged locations, as has been done in the index area studies. The level of the transferred values may not be in complete accordance with the general level in the actual areas, but the general seasonal variation is believed to be described satisfactorily, even when transferring potential evapotranspiration over relatively large distances. For the modelling studies it is not crucial if the level of the transferred values deviates slightly from the true value, as long as the seasonal variation is described properly, (cf. Chapter 7).

4.5 Actual evapotranspiration

The water budget method can be used to estimate actual evapotranspiration from a catchment. This method is based on the simple mass balance equation:

$$E_a = P-Q-Q_{ss} \pm \Delta S$$

in which

E_a - actual evapotranspiration
P - rainfall
Q - runoff
Q_{ss} - deep seepage, inflow/outflow of groundwater across catchment divide, interbasin diversions
ΔS - change in storage

When considering longer time periods (e.g. one year, preferably more) the change in storage may be relatively small, and if the Q_{ss}-term can be considered insignificant, the actual catchment evapotranspiration can be estimated as the difference between catchment areal rainfall and runoff.

From the modelling study in the three index areas the various components of the water balance have been determined on a daily basis over a period of several years (cf. Chapter 7). For each of the index areas three cases of yearly rainfall events have been selected representing the average, a maximum and minimum rainfall situation. The two extreme situations correspond roughly to 10-year events. The annual water balance components for all cases are listed in Table 4.30.

The runoff values shown in the table are the simulated values, so that this component is consistent with the other components of the water balance. Looking at the change in the storage it is noticed that this value can attain fairly large values, even for a time period of one year. The three catchments mentioned represent different hydrological regimes. Although the hydrogeological conditions and soil types are fairly similar, vegetation and especially climatological conditions are quite different. The hydrological regime can be described in a rather crude way by the potential surplus/deficit, i.e. rainfall minus potential evapotranspiration. Although the catchments do not cover the complete range of hydrological regimes in the regions (cf. Chapter 7), they do represent catchments with a potential surplus of rainfall, with potential evapotranspiration of the same order as rainfall, and with a potential deficit of rainfall.

Quantity	Lt. Ruaha (at 1KA32A)			Mngaka (at 1RB6)			Kiwira (at 1RC5A)		
	max.	mean	min.	max.	mean	min.	max.	mean	min.
Rainfall (P) mm	1229	955	858	1510	1186	975	2102	1652	1519
Potential evapotranspiration mm	1581	1581	1581	1277	1277	1277	1426	1426	1426
Potential surplus(+)/deficit(-)(P-E_p) mm	-352	-626	-723	233	-91	-302	676	226	93
Actual evapotranspiration (E_a) mm	790	716	744	851	786	740	1010	869	958
Runoff (Q) mm	445	222	55	691	407	270	932	789	528
Change in storage (S) mm	-6	17	59	-32	-7	-35	164	5	45
E_a/E_p	0.50	0.45	0.47	0.67	0.62	0.58	0.71	0.61	0.67

Table 4.30 Annual components of the water balance for the three index areas for three rainfall situations.

Looking at the ratios of actual evapotranspiration to potential evapotranspiration it is recognized that these ratios are fairly constant for the wetter regimes (i.e. Kiwira) and for the regimes with no pronounced deficit (i.e. Mngaka). The variation of the ratio is in the range 0.58-0.71. For the catchment with potential rainfall deficit (i.e. Lt. Ruaha) the ratio is also fairly constant, in range 0.45-0.50.

For detailed studies of the water balance application of a hydrological model is preferable. However, as a first approximation the ratio of actual evapotranspiration to potential evapotranspiration can be applied. In the study area for catchments with no pronounced potential rainfall deficit the ratio can be estimated as being in the range 0.60-0.65, whereas the ratio for catchments with rainfall deficit is estimated to lie in the range 0.45-0.50. It should be emphasized, however, that even though a region may have an appreciable potential rainfall surplus on a yearly basis it is not necessarily an indication of an abundant water supply for agricultural production all year round. With seasonally varying rainfall, crops may experience water stress in the dry season, and consequently the actual evapotranspiration rate will be below the potential level. This fact is clearly demonstrated in the present study area in which dry season production without irrigation is possible only in the wetter areas.

4.6 Regionalization

Pan measurements, adjusted by a pan coefficient of 0.70, and available Penman estimates has formed the basis for the preparation of an iso-line map showing the mean annual potential evapotranspiration (Figure 4.22). Isolines are shown from 1000 mm up to 2000 mm with intervals of 200 mm. Measurements and estimates of potential evapotranspiration are few and scattered across the regions, particularly so in Ruvuma and northern Mbeya, which makes the delineation of the isolines very uncertain. In the preparation of the map the general knowledge of catchment characteristics, obtained from the field reconnaissance, has been utilized. Hence, the isoline map must be considered approximate.

The maximum value (2260 mm) of mean annual evapotranspiration has been found in Mtera in northern Iringa and the minimum value (840 mm) in Bulongwa in Iringa north of Lake Nyasa. All other estimates lie within this range. An area with relatively low potential evapotranspiration values is found north of Lake Nyasa. From there a general increase occurs in all directions, with a maximum in the arid region in northern Iringa. In Ruvuma region, the measurements are sparse. However, it is believed that the variation in potential evapotranspiration is small because of the moderate variations in altitude. The isoline which is indicated here, may therefore be considered representative for this region. Also in northern Mbeya measurements are few. A rather constant potential evapotranspiration is expected here when considering the physical characteristics. The general level is supposed to be about 1800 mm on an annual basis.

Comparison with topography (altitude) is discussed in Section 4.4. A tendency for decreasing potential evapotranspiration with altitude has been revealed, but no unambiguous relation between the two parameters could be established, because many physical factors influence evapotranspiration in opposite directions.

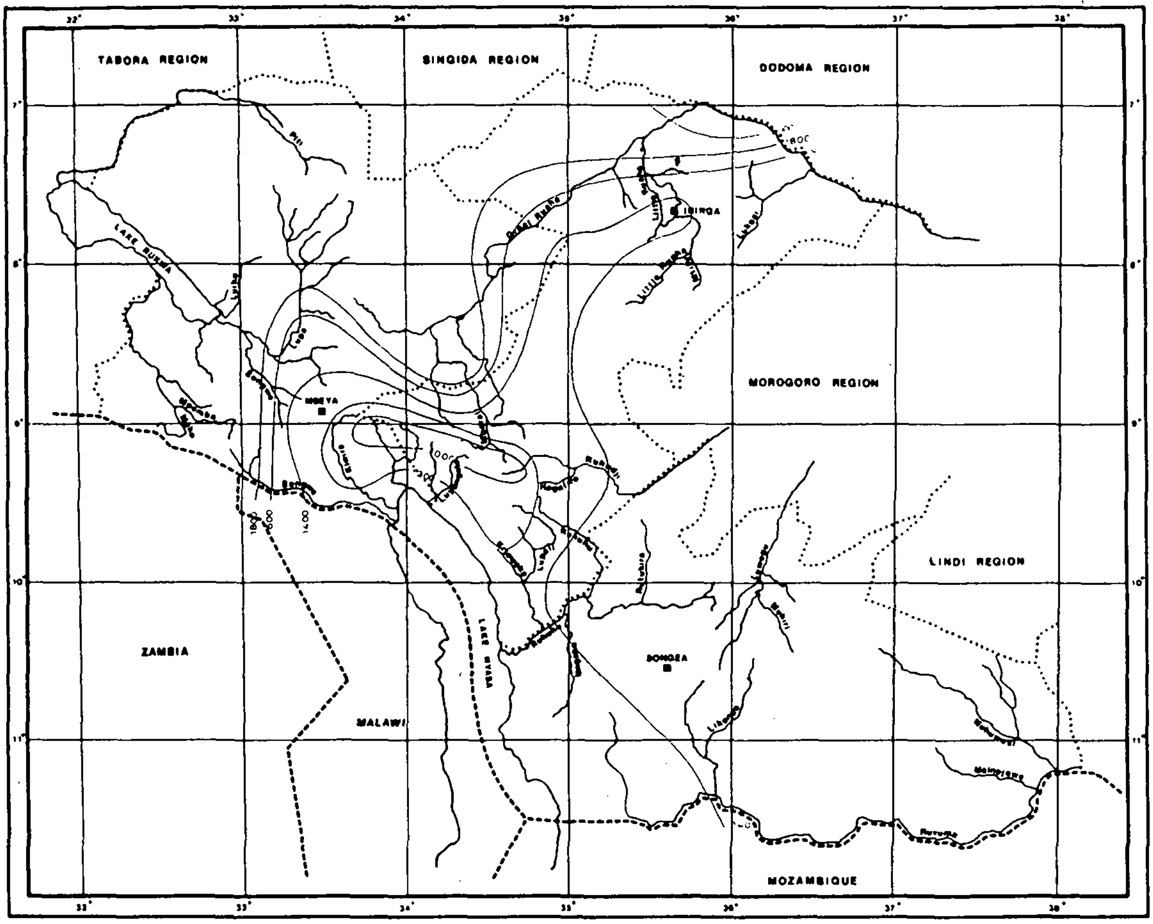


Figure 4.22 - Isoline map of potential evapotranspiration.

When comparing the potential evapotranspiration and rainfall patterns no obvious correlation is found. However, there is a tendency to high potential evapotranspiration values in areas deficient in rainfall, and vice versa. The conditions in the Mtera area and in the Chivanjee area north-west of Lake Nyasa are clear examples of this tendency.

In Woodhead (1968) a map showing the variation in potential evaporation for the whole of Tanzania is presented. A section of this map, covering the project area, is shown in Figure 4.23[8]. When comparing Woodhead's map with the one prepared in this study, it must be remembered that the maps illustrate two different evaporation concepts, the difference between these being roughly 20%. Although there are some deviations between the maps, they do show the same tendencies, i.e. low values north of Lake Nyasa and increasing values in all directions from there. The local differences between the two maps, demonstrate the uncertainties involved in the determination of the evaporation potential.

In conclusion, large areas are poorly covered by evapotranspiration data and there is an obvious need for additional evaporation information. Further, to obtain a more reliable data base, improved procedures for station operation and maintenance, both for evaporation pans and climatological stations, are required.

4.7 Recommendations

Additional data and information is required in order to provide a proper description of evaporation conditions in the regions.

At the moment the regions under study are very sparsely gauged. The following recommendations are stressed.

Pan evaporimeter network and procedures.

(a) Increased station density should be given high priority.

(b) More frequent station inspections are required in order to ensure:

- repair and replacement of damaged equipment
- general control of the state of operation
- feed-back to observer, improving his motivation by showing interest in and appreciation of his work
- enforcement of monthly station reporting
- improved observation procedures, particularly during periods of high rainfall when pan overflows often result in wrong measurements.

Processing of pan evaporation data.

Careful review of historical pan data not analysed as part of this study is required, particularly with respect to

- checking and correction of errors
- improving the filing and storage procedures

Climatological station operation.

In order to calculate potential evapotranspiration by the Penman or similar formulae reliable climatological data are required. Before considering any expansion of the climatological station network (e.g. eastern Ruvuma, or northern Mbeya and Iringa regions) there is an urgent need to improve station operation. As above, more frequent station inspections are required in order to ensure:

- repair and replacement of damaged equipment, and necessary supplies for its operation (e.g. ink, destilled water, recorder charts etc.)
- general control of the state of operation
- feed-back to observer, improving his motivation by showing interest in and appreciation of his work
- enforcement of monthly station reporting

5. RUNOFF - BASIC INFORMATION

5.1 General

The land phase of the hydrological cycle starts with atmospheric moisture travelling towards the land surface in the form of rain, hail, snow or condensation. A portion of this moisture, the interception loss, is retained by the vegetation. The remainder reaches the ground, and either infiltrates into the topsoil, or runs off on the surface (overland flow). Some of the water is returned to the atmosphere by evaporation from vegetation-, soil- and water surfaces, or by transpiration from the vegetation. Some is returned to the sea, directly through surface runoff and river flow, or indirectly by reaching the river system through the soil. The latter process may occur as interflow laterally through the upper soil horizons, or as baseflow through the groundwater aquifers. The remainder returns to the sea directly from the aquifers in the coastal zone. (See Figure 5.1).

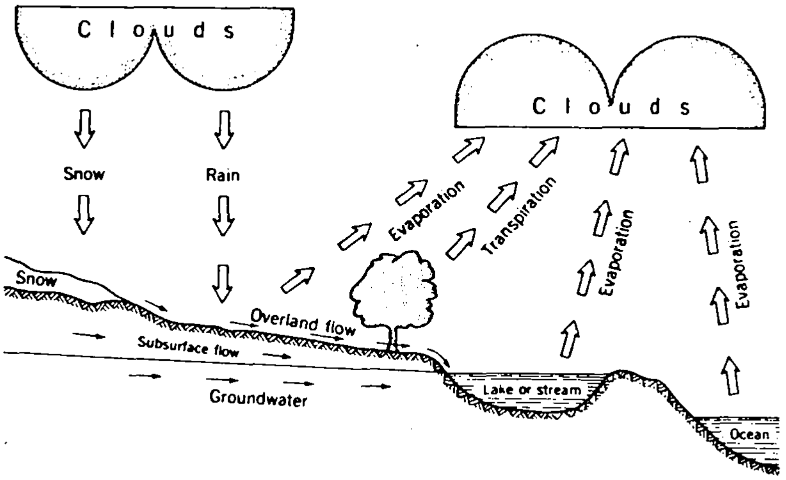


Figure 5.1 The hydrological cycle.

The rainfall - and evapotranspiration processes are described in the preceding chapters. The runoff processes are the subject of this and the following chapter.

The processes of surface runoff are of great importance to the human population. Water is drawn from small streams and big rivers for a variety of human needs: domestic water supply, animal watering, irrigation, hydropower, industrial use etc. Too much runoff can cause disasters when major floods occur, and too little of it lead to water shortages. Hence careful control and planning of surface water resources is crucial if optimal benefits are to be derived from this natural resource.

Mbeya, Iringa and Ruvuma regions are no exception to this rule. Most of the villages in the regions, including almost all the traditional villages, are situated near a natural watercourse (stream or river) from which they draw water. Drawing from such a source is often the cheapest and most convenient way of providing safe water supply for individual villages, or groups of villages conveniently located for gravity distribution schemes. Consequently an important aspect of the present study has been to investigate the surface water potential by collecting, processing and analysing runoff data from the regions.

Whereas the water master planning effort has had as its objective to investigate availability of and demand for water resources for all human purposes, emphasis has been put on the immediate goal of providing village water supply for domestic use and animal watering. For this purpose the most critical aspect of the runoff investigation has been the determination of safe minimum yield, or the amount of runoff to be relied upon towards the end of the dry season in dry years. Hence the hydrological studies have focussed to a large extent on the low flow situations, and a considerable effort has been made to obtain hydrological information in the dry season of 1980. This information has been gathered through an intensive field programme, and by including stream gaugings and hydrological questions in the village inventory programme (cf. Sections 5.5 and 5.6). Map showing all stream gaugings (cf. Drg. II-7 and Table 5.27[8]).

However, runoff has been studied also in a more general context for the purpose of determining the general water balance of the regions, and providing the hydrological information required for the irrigation - and hydropower investigations. Detailed hydrological studies have been carried out on three index areas (representative catchments), including mathematical modelling and analysis of the rainfall - runoff processes.

5.1.1 Determination of runoff

Runoff occurs in many different forms, most of which are not subject to measurements. An indirect determination of runoff can be made when it occurs in the form of streamflow in a well defined channel. In this case the discharge (flow) of the stream can be determined by measuring flow velocities and -areas (cf. Section 5.3 below). The measured discharges are then related to the stages (or water levels) at the time of measurements, and a stage-discharge relationship (rating curve) for the site is determined. A discharge record for the site is established by observing water levels continuously, and converting these to discharges by means of the rating curve.

In Tanzania, as in most other countries, water level observations are made once or several times daily by resident observers, who read staff gauges in centimeters (previously inches) at the site. At some locations automatic water level recorders are installed in which the water level variation is recorded on charts. So far very little use has been made of the records from automatic recorders in the three regions, and the runoff investigations in the present study are based entirely on manually observed water levels (cf. Section 5.5).

In the conversion of observed water levels into discharge considerable uncertainties are introduced. Rating curves are rarely well defined throughout the entire range of water level- and discharge variation, and extrapolation is often required, particularly at very low and at very high water levels. Furthermore, due to changing bed configuration at the site, rating curves may change over time, in which case frequent discharge measurements are required in order to continuously update the rating curve. These and other considerations relating to the reliability of discharge determinations are discussed further below.

5.1.2 Previous studies

Hydrological studies addressing runoff conditions in the three regions have been undertaken earlier by the Food and Agriculture Organisation of the United Nations (FAO) in the period 1954-59, and by the Norwegian Agency for International Development (NORAD) in the period 1974-79.

The FAO study involved comprehensive hydrological investigations of the Rufiji River Basin, including the establishment of a large number of discharge gauging stations on the Rufiji River and its tributaries. Most of the stations with national code number 1KA.. were established during this study.

The Hydrometeorological Survey of Western Tanzania (often called the Western Tanzania Project, or WTP) by NORAD covered the five regions: Kigoma, Tabora, Mbeya, Rukwa and Ruvuma. During this project a large number of hydrometeorological stations were established and rated (i.e. rating curve determined), and many existing stations were checked and their data controlled and, where necessary, corrected. Hydrographs for WTP stations were prepared for the project period.

The WTP also provided for training of MAJI personnel, and provision of hydrometeorological instruments. As part of the project an excellent set of manuals: "Manuals on Procedures in Operational Hydrology" were prepared, which cover establishment and operation of stream gauging stations, discharge measurements, stage-discharge relations and sediment transport analysis. These manuals have been helpful for the present study.

The location of the WTP stations appear from the map of hydrological gauging stations, cf. Drg. II-4.

5.1.3 Approach to runoff studies

The main elements of the runoff investigation undertaken as part of the present study have been:

- Control and updating of the hydrological data-base
- Selection and in-depth analysis of priority stations
- Selection and in-depth study of index areas
- Spotgaugings and interviews as part of village survey
- Hydrological field programme

These elements are all described in detail in subsequent chapters, and only a brief outline of the overall approach shall be given here.

A comprehensive, up-to-date and thoroughly checked data-base is an absolute prerequisite for meaningful hydrological studies, not only for the present water master plan, but also, and probably even more importantly, for the future hydrological work by MAJI. Collection, processing and control of data from all MAJI stations in the regions have consequently been given first priority in the present study, and the hydrological team - Tanzanian as well as Danish hydrologists - have spent the major portion of their time on this activity (cf. Sections 5.2 - 5.6).

Within the time and manpower resources available for the present study in-depth analysis of all discharge gauging stations in the regions (total 1047 station years) has not been possible. It was therefore decided to select a limited number (19) of representative stations for in-depth analysis while up-dating and analysing the remaining stations at a slightly lower level of ambition. Criteria for the selection of the 19 so-called priority stations have been:

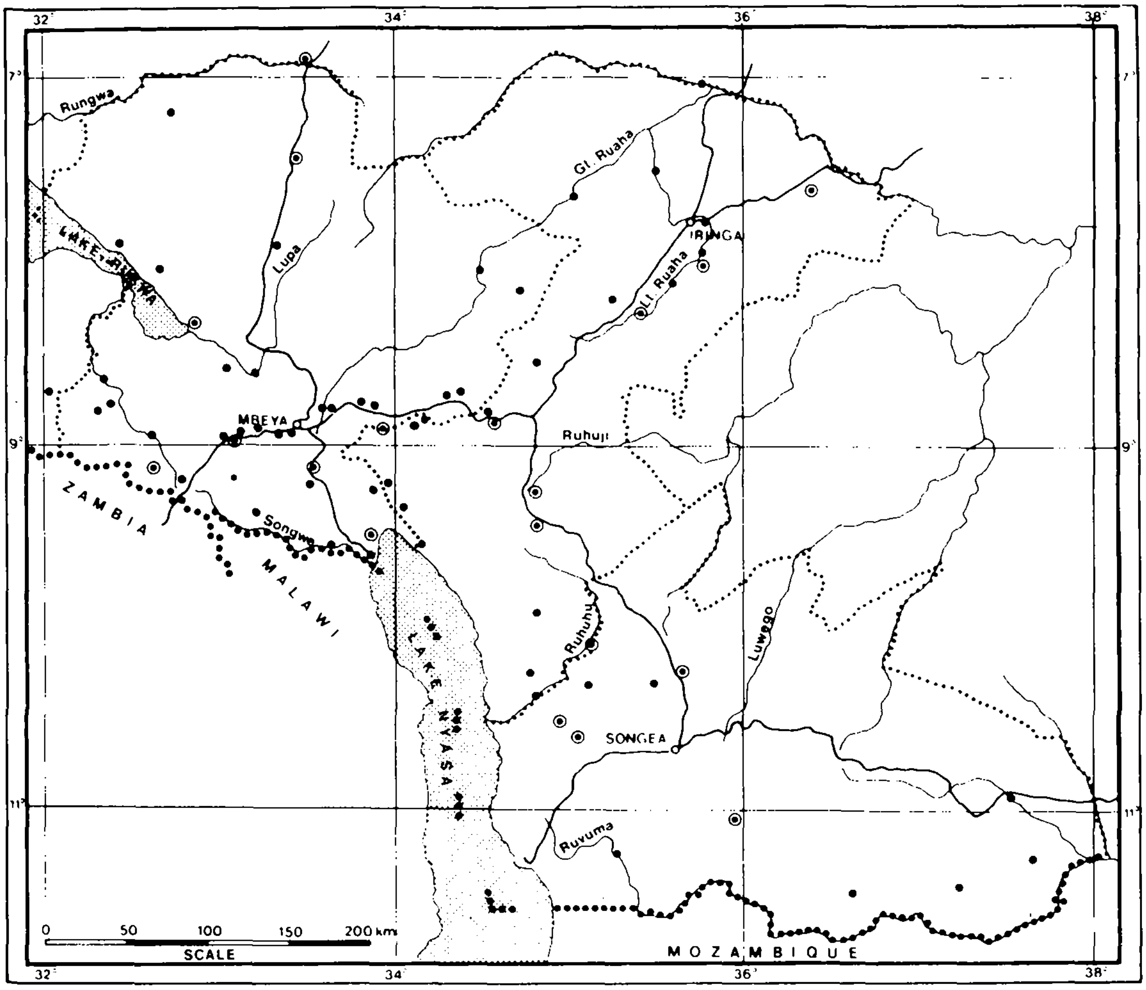
- Stations shall represent a cross section of characteristic hydrological conditions and regimes in the three regions.
- Stations shall represent a reasonable range of catchment sizes, bearing in mind the emphasis on rural water supply
- Station density shall be highest in the most populated areas
- A reasonable number of stations shall cover catchments in or near which rainfall stations with long records are located (water balance studies)
- Stations with long records shall be preferred
- Stations with stable rating (i.e. constant and hence relatively reliable rating curve) shall be preferred

Locations of the selected priority stations appear from the station map (cf. Drg. II-4 and from Figure 5.2).

Following an initial selection on the basis of available material the potential priority stations were inspected and their records reviewed. A few changes in the list were made as a result of this investigation, and a final selection made. The final list of priority stations was approved by MAJI before further studies were undertaken.

Detailed studies of runoff characteristics, based on an analysis of the general hydrology and water balance of characteristic hydrological regimes in the regions, have been carried out as part of the index area studies. These studies which have focussed on three representative catchments (one in each region) are reported in some detail in chapter 7, as well as in the reports to MAJI and DANIDA from the two counterpart hydrologists who spent six months at Danish Hydraulic Institute (DHI) as DANIDA stipendiates.

A very important element of the hydrological studies has been the unique opportunity of obtaining first hand hydrological information in a large number of villages scattered throughout the regions. As described



LEGEND

●●●●●●●●●●●●	INTERNATIONAL BOUNDARY
············	REGIONAL BOUNDARY
◉	PRIORITY HYDROLOGICAL GAUGING STATION
●	HYDROLOGICAL GAUGING STATION

Figure 5.2 - Density of Hydrological stations.

in Chapter 6 the spotgaugings and interviews on stream characteristics have been particularly valuable for the low flow studies.

Finally the hydrological gauging programme undertaken during the present study has provided additional discharge measurements for the improvement of poorly defined rating curves at selected stations (cf Section 5.3). The field measurements have been carried out by MAJI hydro-teams, under the planning and supervision of the consultants' hydrologists and their counterparts.

5.2 Organisation, Data Collection and Storage

5.2.1 MAJI organisation

The organisation of MAJI is shown in Figures 5.3^8-5.5^8.

The office of the Chief Hydrologist is located in MAJI-Ubungo in Dar-es-Salaam. This office plans, coordinates and controls the work of the regional offices of MAJI, each of which has a hydro-section responsible for hydrological investigations, and the operation and maintenance of hydro-meteorological stations.

Each year a programme for discharge- and sediment measurements at selected stations in the regions is prepared by the Chief Hydrologist. Due to limited resources, particularly with regard to transport, this programme covers only a limited number of stations, generally those for which ratings are shifting or otherwise problematic. This work is carried out by special hydro-teams under the supervision of the regional hydro-sections. These sections also make sure that most of the MAJI hydro-meteorological stations are inspected every year, and repaired if damages have been inflicted during the flood season.

Other responsibilities of the hydro-sections include training of gauge-readers and hydro-technicians, checking and filing of water level observations, computation of discharges from field measurements, provision of required hydrological data and information for the preparation of water supply schemes, and handling of water right affairs. Requests for diversion of surface water for water supply, irrigation or industrial purposes are directed through the hydro-section which reviews applications and grants permissions after investigating the availability of water for the requested purpose.

5.2.2 Data collection, processing and storage

Observers at the hydrological gauging stations forward water level data to the hydro-section where the data is checked and copied on to special forms. The hydro-section files the data forms, and forwards copies to MAJI-Ubungo. Here the data is copied onto special computer coding forms, and subsequently punched and read into the computer for final storage on magnetic tapes.

In addition to the manually observed water levels, some stations have been equipped with automatic water level recorders, and the charts from these are sent to MAJI-Ubungo via the regional offices, after checking and corrections have been carried out, cf. Section 5.5.

Comprehensive files for each station containing station history, inspection reports, water level data forms, discharge measurements and computations etc. are kept in the hydro-sections of the regional MAJI offices.

The data storage system at MAJI-Ubungo consists of three sets of magnetic tapes: water level tapes, tapes containing rating curves for each station, and tapes containing discharges computed on the basis of the water levels and rating curves.

A set of computer programs are used which

- Update the water level information
- Update the rating curve information
- Compute and update discharge information

The water level tape contains up to three daily water level observations.

The rating curve tape contains stage-discharge relations in the form of formulas or tables, depending on the characteristics of the station. The periods of validity for each rating curve is also included (e.g. stations with shifting rating have several rating curves, each valid for a certain period of record).

Discharges are computed by multiplying the instantaneous water levels as stored on the tape by a conversion factor obtained by interpolation in the rating table, or directly from the rating curve formula, using the rating curve which is valid in the period of the water level observation. Mean daily discharge is then computed by arithmetic averaging and stored, and only the maximum and minimum instantaneous discharge value for the month is stored.

Mean daily discharges, and mean, maximum and minimum discharges for each month (together with date of occurrence) are published for all stations in the Hydrological Yearbooks.

MAJI-Ubungo has access to the main computer of the Ministry of Finance, which is an ICL 1900 machine. The input medium has until 1981 been punchcards, but change-over to a terminal system is now being considered. Because of heavy usage by the Ministry of Finance and other ministries MAJI's access to the computer is limited to a few nights every month. These conditions have created a severe bottleneck in the processing and storage of hydrological data, with the result that MAJI is far behind in the updating of almost all of the hydrological gauging stations in the country.

For this reason it was necessary to include the updating of hydrological data from Mbeya, Iringa and Ruvuma regions as an important part of the water master planning study.

MAJI's computer capabilities have been improved somewhat in 1980-81 by the provision of a desk top computer (HP 9845) from the Government of Ireland, along with training of two MAJI staff members in its use. However, this computer is intended primarily for the digitalization and processing of data from automatic water level recorders, and it does not have an adequate capacity for handling the primary hydrological database. Thus, until MAJI gets its own computer, whether by acquiring a new system or expanding the HP 9845-system, it must continue to rely on the ICL-computer of the Ministry of Finance.

5.2.3 Approach to data processing and storage

As mentioned in Section 5.1 and further explained above, control and updating of the hydrological data-base of the regions has been given first priority in the present study, in order to ensure that this and later hydrological studies in the regions be based on a comprehensive and reliable data-base.

The main elements of this activity have been:

- Thorough inspection of all gauging stations
- Critical review of station records, particularly those of the priority stations
- Control and updating of the hydrological data-base. (Up to 31 December 1980 for the 19 priority stations; and up to 31 December 1979 for all other stations in the regions)

A primary objective of this work has been to ensure full compatibility with current MAJI standards and procedures, particularly in the computer storage, processing and presentation of data. This has been emphasized for two main reasons. Firstly because standardisation of hydrological procedures is important for the coordination of studies and plans prepared on a regional basis; secondly because adherence to current MAJI standards enables the results of the present study to be utilized directly by MAJI in future hydrological activities involving the three regions. Extensive efforts by Danish and Tanzanian hydrologists have been devoted to the tedious work of going through original files, checking and correcting rating curves for the priority stations, and checking to the extent possible all historical water level- and discharge data in the data-base for the regions.

A documentation of all modifications and revisions made to existing data has been prepared for each station in the form of a log-book with detailed comments for each station (Annex 5-1).

After inspecting the stations, (cf. Section 5.3) the files and filing systems in the three regional offices have been reviewed and rearranged in a cooperative effort between the Danish hydrologists and their counterparts (who in two of the regions were heads of hydro-sections). Data not yet processed have been collected, checked and computerized.

Updating of the data-base has been performed in Denmark. Having reviewed and discussed with MAJI the data processing programs mentioned above, software has been developed which performs exactly the same operations, but tailored to the IBM 3033 computer at Northern European University Computer Center (NEUCC) at which a large part of the computer work for the present study has been carried out. Hence an interactive computer processing system has been developed for easy review, editing, updating and presentation of data from the data-base. This system is described a little further in Annex 5-2, Volume 8, and examples of output from the system are shown in Section 5.6 below. The data-base itself was copied onto IBM tapes at NEUCC in the beginning of the present study, the updated base being transferred back to the ICL system towards the end of the study.

Close liaison with MAJI has been maintained throughout the hydrological computer work. Thus the Chief Hydrologist, Mr. W. Balaile, has followed the work during several visits to the institute in the study period, and the senior MAJI hydrologists, Mr. J. Kobalyende and Mr. J. Mwalubandu, have spent time in Copenhagen in order to follow the work and ensure compatibility with MAJI stadards. The two hydrologist counterparts, Mr. I. E. Mwakalinga and Mr. W. Mwaruvanda have spent six months in Copenhagen participating in the data processing and analysis, while receiving training in computer work and hydrological modelling (cf. Chapter 7).

5.3 Station network. Instrumentation and methods

5.3.1 Station network

Hydrological gauging stations were established in the three regions in the 1950'es, most of them by the Water Department and Irrigation Division (WD&ID, later MAJI), some by the FAO during the Rufiji River basin study, and some by the Public Works Department. In the 1970'es additional stations in remote areas were established as part of the Western Tanzania Project (cf. Section 5.1).

The station network is shown in Figure 5.2 and in Drg. II-4. As it appears from this map the regions have a reasonably dense network of gauging stations, except for the eastern part of Ruvuma. The station density is summarized in Table 5.1 below:

Region	Number of stations	Number per 1000 km^2	Population per km^2	Relative density
Mbeya	41	0.68	18	70-80%
Iringa	18	0.32	19	60%
Ruvuma				
Total	15	0.25	9	50%
Western part	11	0.41	11	60-70%
Eastern part	4	0.12	7	35-40%

Table 5.1 Station Density.

The concept of relative station density as defined by Langbein (1960) has been listed in the table, the results of which should be interpolated according to Figure 5.6 below which indicate comparative areal densities of streamflow gauging stations. Compared to the "reasonable minimum objective" stated by Langbein only eastern Ruvuma is inadequately gauged. the rest of the area falling well above the reasonable minimum objective.

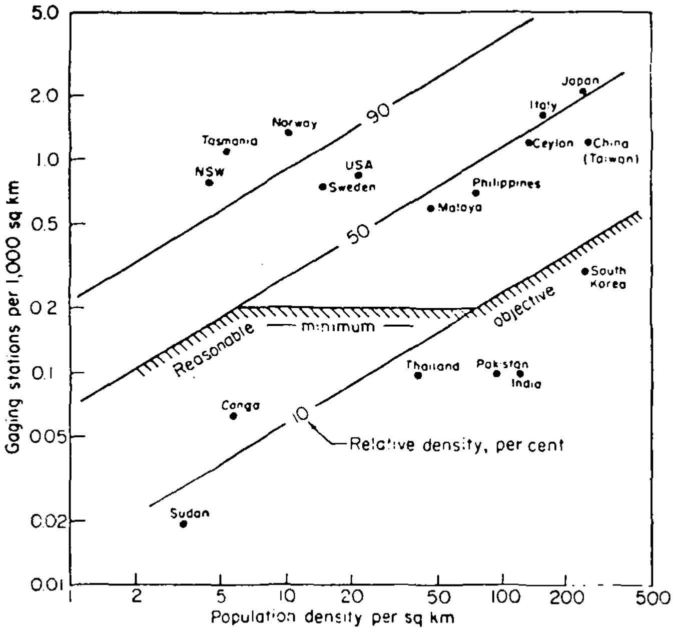


Figure 5.6 Comparative areal densities of streamflow gauging stations (from Langbein, 1960).

It must be emphasized, however, that these are "average" considerations, which do not take the distribution of gauging stations into account. Hence, although the general average may be considered adequate, certain areas are still poorly covered, e.g. the Lake Nyasa drainage basin in southern Iringa. Improvement of the permanent gauging network should therefore initially focus on such poorly covered areas.

The gauging stations in the three regions have been established for different purposes. The FAO stations were located from a river basin study point of view, MAJI stations have been located with the objective of obtaining representative information for water development purposes, mainly water supply and irrigation, while most of the WTP stations have been located from a hydropower potential point of view. However, by and large the station network covers a reasonable range of catchment sizes and hydrological regimes.

Local stations have been established for special projects. These are not included in the above considerations.

A comprehensive list of hydrological gauging stations is included in Table 5.2[8]. Several numbering systems have been and are being used for the hydrological gauging stations. The basic system is MAJI's national code numbering system in which the station code numbers indicate in which main catchment the station is located (e.g. Indian Ocean, Atlantic Ocean etc.), the main river systems to which it drains (e.g. Great Ruaha, Rufiji etc.), and how many times the station has been relocated. This coding system is described in Table 5.3[8].

In the computerized data-base MAJI has assigned consecutive code numbers to all the national stations for easier identification in this system.

Finally, the WTP stations have their own numbering system. (cf. Drg. II-4).

5.3.2 Station instrumentation and operation

Most of the gauging stations are operated as streamflow gauging stations, i.e. with daily water level observations and more or less regular discharge measurements for rating curve definition. A few stations have only water level observations.

Water level observations at staff gauges are usually performed twice daily (at 06 and 18 hrs) in the dry season (little fluctuation), and two or three times daily in the wet season.

Four types of stations exist:

(a) Standard vertical staff gauges in meter-sections, graduated in centimeters

(b) Staff gauges as in (a), supplemented with automatic water level recorder (type Ott X).
Discharge measurements from nearby bridge or by wading.

(c) Staff gauges as in (a). Cableway for discharge measurements.

(d) Installation as in (c), supplemented with automatic water level recorder

The variuous types listed here are indicated in Table 5.2[8] Reference is made to the WTP reports and manuals for a detailed description of station instrumentation, installation and operation (particularly automatic water level recorders).

As indicated earlier stations are operated by resident gauge readers who report to the regional hydro-section (water level observations, charts from automatic recorders) Hydro-teams visit the stations at irregular intervals, checking the equipment and the gauge readers records, making repairs etc.

5.3.3 Discharge measurements

Ideally every gauging station should have its rating checked, and if necessary revised every year. However, primarily because of lack of transport only a few stations are gauged every year, while most other stations are subject to very irregular rating controls. Most discharge measurements are carried out in the wet season, for which reason very few stations have reliable rating curves in the low flow regime. (Dry season).

Sites for discharge measurements are generally carefully selected, and in most cases reasonably straight stream reaches upstream of stable control sites are being used (cf. Section 5.6). Measurements are usually carried out from bridges or cableways, and only rarely from boats or by wading. Current meters of the type Ott (C31 and C2) are used.

Discharge is measured following the commonly used standard procedures of the United States Geological Survey (USGS procedures). The stream cross section is divided into a number of sub-sections for which the mean velocities are found by measuring flow velocities in 0.2D and 0.8D (two point method), or in 0.6D (one-point method), where D is the water depth. Discharge is determined by summation of the products of mean velocity and area for each sub-section. Inaccurate measurements may result from this method at low stages for which the assumption of a regular logarithmic velocity profile does not hold very well because of the irregularity of the often very rocky streambeds in the regions.

Region: Iringa

River Name: Mtitu

Station Name: Mtitu at Mtitu

National Station Code: 1 KA 22

Code No.: 10

Latitude: 7° 58' 50"

Longitude: 35° 46' 50"

Altitude: 1680 m

Catchment Area: 445 km^2

Established: 1957.05.26

Observation Frequency: Twice daily

Period of Discharge Measurements: 1957.06.08 - to date

Range of Water Level: 0.44 - 3.43 m

Range of Discharge Measurements: 1.4 - 13.7 m^3/sec.

No. of Valid Discharge Measurements: 152

Range of Computed Discharges: 1.1 - 37.7 m^3/sec.

No. of Curves: One

Type: Formula

Curve Stability: Good

Extrapolation:

Description of Control: Rock bar across the channel

Control Stability: Stable

Description and Location of Installations: 0-2 m standard vertical staff gauges attached to angle iron on right bank 70 m from bridge. Portable traveller just upstream bridge. Old gauges 0'-7'.

Table 5.4 - Hydrological station description.

STATION NUMBER 1KA 22

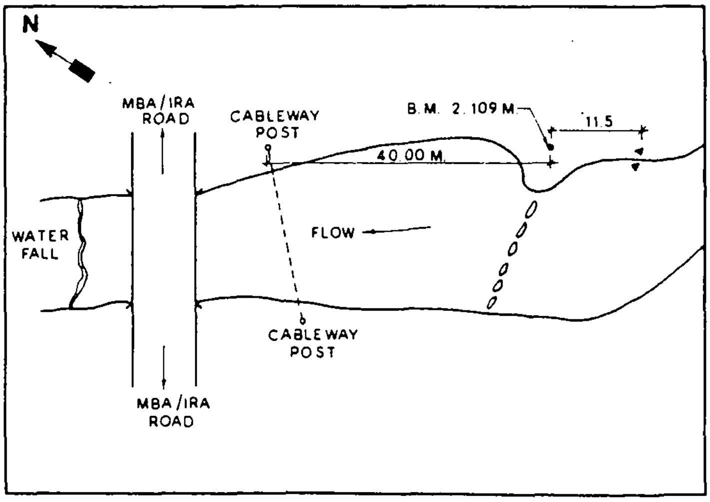


Figure 5.7 - Hydrological station sketch.

Discharge computations are usually made in the office of the regional hydro-sections, and not on the spot. The latter would be preferable because it would enable the hydro-teams to immediately plot the results on the rating curve and investigate possible reasons for large deviations (whether caused by measurement errors or other circumstances).

5.3.4 Station inspections

As it appears from the station list in Table 5.2[8] most of the gauging stations in the regions were inspected by the consultants and their counterparts. As an integral part of this programme the consultants assisted and supervised the hydro-teams working in the regions.

The procedure followed during station inspections included checking of the equipment, levelling of the staff gauges (priority stations only) and, if necessary, clearance of the control. The location of the station on the stream was checked to ascertain that it has been optimally located, and a station sketch was prepared. The gauge reader was interviewed and his records reviewed. Station inspection reports were prepared for each station and submitted to the regional MAJI offices. A sample station description, location map and sketch is shown in Table 5.4 and Figure 5.7 above.

Descriptions and sketches for all 19 priority stations are contained in Volume 8, Tables 5.4[8]-5.22[8] and Figures 5.8[8]-5.26[8] respectively.

The reliability, referring here to station siting, installed equipment and the resident observer, of the gauging stations in the regions is generally quite good (see Table 5.2[8]), in spite of problems associated with maintenance and operation. Most of these problems are related to the lack of material and transport, which results in too infrequent station inspections and lack of materials for necessary repairs. 90% of the priority station staff gauges levelled were correct, the remaining 10% requiring only minor adjustments (2-5 cm).

The problems on the operation side are caused primarily by gauge reader changes, and also in many cases an apparent lack of dedication to their jobs. Gaps in the records may occur for these reasons.

The hydro-teams, however, are very capable and dedicated, and achieve good results with the resources available to them. The reliability of their discharge measurements is generally quite good.

5.3.5 Supplementary instrumentation

New streamflow gauging stations have not been established as part of the present project.

A number of automatic water level recorders (four recorders of the type Ott R 20) were supplied to MAJI from DANIDA as part of the water master planning study, but it was agreed not to install them. As a general MAJI policy hydrological gauging stations are established either for the purposes of special investigations (local stations), or as part of the permanent gauging network (permanent stations). As installation of the latter type is very demanding in terms of manpower, material and transportation resources, and no immediate purposes for installation of the former type were identified, MAJI preferred to save these recorders for later use.

5.4 Data availability

Apart from eastern Ruvuma and a few isolated areas elsewhere in the regions, the streamflow gauging network provides a reasonable general coverage of the three regions. (cf. Section 5.3).

The histograms in Figures 5.27 and 5.28 below illustrate the availability of water level - and discharge data respectively, showing that more than 50% of the gauging stations have more than 15 years of record.

The difference between the availability of water level and discharge data is caused by periods of missing rating curves (cf. Section 5.6), including two stations in eastern Ruwuma (1Q4 and 1Q7) which have no reliable rating. A total of 74 permanent stationsin the regions have a total of 1047 station years.

The records contain a number of gaps. The average number of gaps per station is 13, with an average gap length of about 6.2 weeks, amounting to 11% of the total record length. As indicated earlier these gaps are due primarily to gauge readers being absent without replacement. Considering the size of the area, the inaccessibility of many of the stations and the general lack of transport facilities this figure is not unexpectedly high. It should here be stressed that the consultants have made no attempts to fill out any of the above mentioned gaps. However, the record could be markedly improved by paying more attention to station operation and regular station inspection.

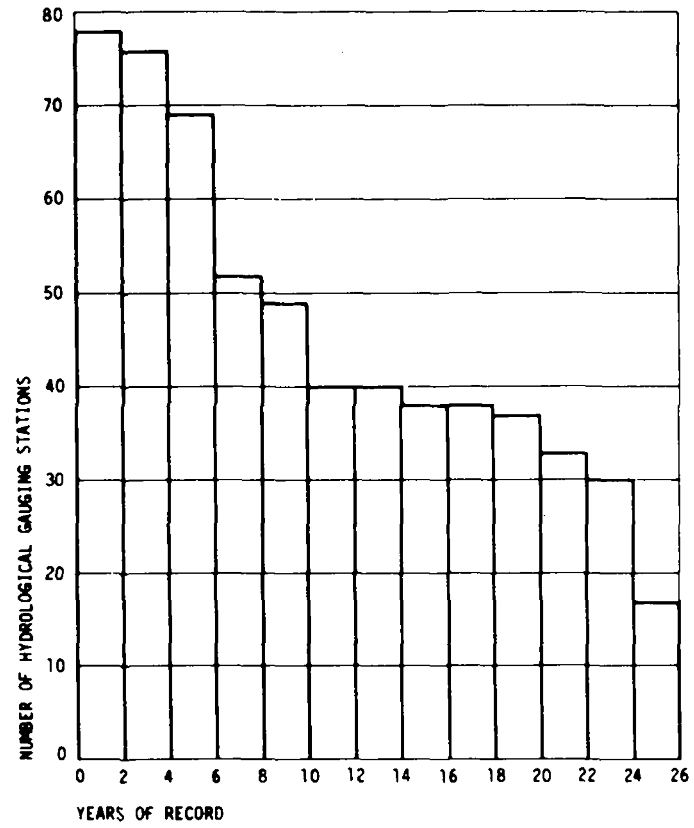


Figure 5.27 - Histogram - water level data availability. Distribution of record length.

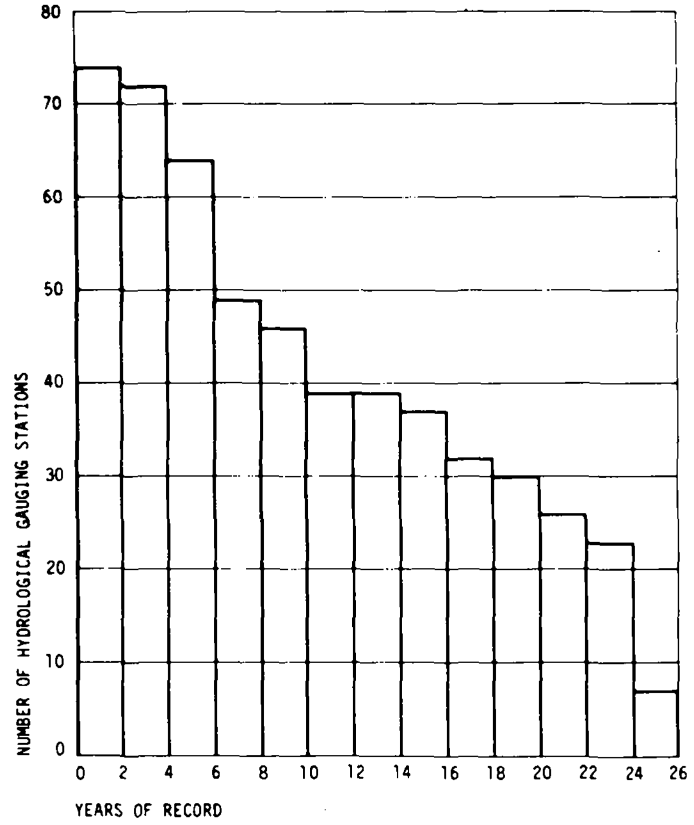


Figure 5.28 - Histogram - discharge data availability. Distribution of record length.

The availability of water level- and discharge data is detailed in the bar charts **Figures** 5.29[8] and 5.52[8] (cf. Sections 5.5 and 5.6).

5.5 Water Levels

Water level measurements are performed manually by observers reading staff gauges, or automatically by the operation of automatic water level recorders. The hydrological data-base in MAJI-Ubungo, which has been the focus of the present study, is based entirely on the former type of water level information, while continuous water level records from automatic recorders have been used very little.

5.5.1 Continuous water level records

Twenty of the 76 permanent hydrological gauging stations in the three regions are equipped with an automatic water level recorder (cf. Drg. II-4). These stations are also equipped with staff gauges which serve the dual purpose of providing a manually observed record for the station as back-up for the automatic one, and providing the reference levels for the automatic recorder.

The typical recording gauge installation is described in detail in the WTP reports, which also contain an excellent discussion of the problems associated with its operation. Most of the automatic water level recorders now operating in Mbeya and Ruvuma were installed by WTP.

Continuous recording of the water level variations is useful primarily in the wet season when rapid discharge fluctuations cannot be "captured" by manual observations three times daily (and of course never during the night). Occasional absence of the gauge reader does not lead to gaps in the records, most automatic water level recorders being set to run more or less unattended for at least one week.

However, in Tanzania as in many other countries the virtues of the automatic water level recording are often compromised by a number of disadvantages which in the end lead to disuse of the recorder and reliance on the simpler manual water level observations. Some of the main problems associated with automatic water level recording in the regions are

- Siltation of the intake
- Inadequate station operation

- Infrequent station inspection
- Complicated and time consuming data processing

Because of these and other problems practically none of the charts from the automatic recorders have been processed (except for those treated during the WTP period). Analysis of some of the charts have indicated that thorough checking and correction will be required, errors in time and amplitudes of the charts being quite common.

With the aquisition of the HP9845 mini-computer an effort will now be launched in MAJI-Ubungo to process the many continuous water level records stored there. (cf. Section 5.1).

The quality and volume of non-processed continuous water level records taken into account, it was decided not to spend time on these records during the present study, which consequently is based entirely on the manually observed water levels constituting MAJI's present hydrological data-base. The only adverse consequence of this approach is a lack of refinement in the analysis of peak flow events, particularly flash floods. However, as indicated in the introduction to this Chapter, emphasis in the present study is on the prediction of low flows and overall water balances, for the purposes of which an approach based on manual water level observations must be considered satisfactory.

5.5.2 Manual water level observations

The route from water level observation at the staff gauge to final storage or magnetic tape in MAJI-Ubungo is lengthy, and involves many steps in which errors can be introduced. (cf. Section 5.2). Careful inspection and checking procedures have been set up and practised by MAJI for many years which reduce the occurrence of errors, but obviously no system is perfect, and errors do find their way into the data-base. A detailed logbook with one page for each station is contained in Annex 5-1, in which most of the errors identified during this study are listed along with extensions made to original data series. Examples of typical errors in the water level data are:

- Field book errors for low water levels (e.g. "0.8" instead of "0.08", "0.05" instead of "- 0.05" at stations with high zero-levels)

- Errors in copying from original observations to water level forms in regional offices (e.g. one-meter errors, double-copying of same line)
- Errors in transfer of data onto coding form
- Punching errors
- Lack of unit identification, especially problematic in historical records
- Wrong card sequence when reading-in data to the computer

5.5.3 Checking and updating of water level data

The availability of manually observed water level data is shown in Figure 5.29[8] in which each gauging station is represented by a bar indicating the period of record. The figure also indicates the periods which have been updated during the present study, amounting to a total of 275 station-years.

Thorough control involving review and scrutiny of raw water level data and original station files has been made for all priority station records from their beginning to 31 December 1980 (a total of 282 station-years). For non-priority stations such scrutiny has been applied only to the period of updating, i.e. from the last date of computerized data storage to 31 December 1979 (a total of 836 station-years) (see Figure 5.29[8]).

Remaining historical data have been checked by visual printout- and hydrograph review and study of monthly averages and statistics, but further checking by review of raw data and original station files is required. if all errors are to be corrected for these years.

An essential input to the data control and correction process has been provided by the counterparts, whose personal knowledge of local conditions and most of the gauging stations have been of valuable assistance.

The procedure for updating water level data tapes in the present study has been to copy data directly from the gauge readers' forms onto coding forms, thereby eliminating at least one step in the usual procedure, and thus at least one potential source of error. After thorough checking in the regional offices the coding forms have been sent to DHI for punching and storage in the data-base.

As mentioned above a set of interactive programs have been developed for the water level data processing at DHI. These programs have been developed with the purpose of easy handling, storage, retrieval and display of data, yet following exactly the same general updating procedures as used by MAJI-Ubungo.

Water levels are stored in the data-base as instantaneous values. An ICL magnetic tape in the original format, and a printout of the data-base showing all mean water levels for all stations in the three regions accompany this report in a separate box. A sample printout for one station for one year is shown as Table 5.23 below. (Station 1KA22 - Mtitu at Mtitu - is used for this as well as for all the following illustrative examples of data-base and analysis output).

Visual checking of water level has been based on a combination of discharge hydrograph review (cf. Section 5.6) and study of mean daily water levels (sample output in Annex 5-2). As a last resort the printout of instantaneous values has been used.

While it has been possible to correct all errors found in priority station records and records for the updated periods of non-priority stations, some errors in the historical records of non-priority stations have been identified without any possibility of correction, because raw data have not been available. Such errors are flagged in the data-base (replaced by 99.99) for later correction by MAJI.

5.6 Station ratings and discharges

5.6.1 Determination of rating curve and discharge

As explained in Section 5.1 above, stream discharges are determined from manual water level observations, converted to discharge by means of the rating curve (stage-discharge relation) for the gauging station. It is also indicated that considerable uncertainty is introduced in this process due to the difficulties associated with the definition of the rating curve.

No extensive discussion elaborating on these difficulties shall be made here. NORAD discusses rating curves, and the problems associated with their determination in western Tanzania, in one of the earlier mentioned "Manuals on Procedures in Operational Hydrology", based partly on experience from Ruvuma and Mbeya regions. As a summary of different hydraulic conditions affecting rating curves NORAD mentions:

NATIONAL STATION CODE 1KA22
STATION CODE NO 10

STAGE OBSERVATIONS (M OR FT)
YEAR 1979

RIVER: MTITU R.
LOCATION: MTITU
REGION: IRINGA

DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.37	0.77	0.81	1.03	1.04	0.90	0.71	0.66	0.65	0.58	0.53	0.73
2	0.78	0.99	0.76	1.01	0.95	1.05	0.71	0.64	0.64	0.58	0.53	0.77
3	0.72	1.12	0.72	0.99	0.92	1.06	0.72	0.65	0.64	0.57	0.53	0.74
4	0.76	0.98	0.67	0.99	0.91	1.04	0.72	0.67	0.62	0.57	0.53	0.70
5	0.66	0.93	0.80	0.99	0.93	0.98	0.72	0.67	0.65	0.57	0.53	0.67
6	0.67	0.88	0.75	1.03	0.93	0.95	0.72	0.67	0.66	0.57	0.53	0.66
7	0.70	0.96	0.73	1.03	0.94	0.89	0.72	0.67	0.67	0.57	0.51	0.58
8	0.73	0.81	0.72	1.03	0.93	0.85	0.74	0.66	0.68	0.57	0.51	0.58
9	0.76	0.96	0.82	1.05	0.90	0.82	0.76	0.66	0.68	0.57	0.53	0.56
10	0.88	0.82	0.91	1.03	0.87	0.79	0.75	0.67	0.64	0.57	0.53	0.55
11	0.75	0.75	0.91	1.00	0.86	0.79	0.75	0.66	0.62	0.58	0.56	0.35
12	0.79	0.71	0.89	1.00	0.85	0.77	0.74	0.66	0.62	0.58	0.58	0.54
13	0.80	0.72	0.89	0.99	0.83	0.76	0.74	0.66	0.62	0.58	0.61	0.68
14	0.80	0.78	0.92	0.98	0.81	0.76	0.74	0.67	0.62	0.57	0.61	0.69
15	0.81	0.75	1.03	0.98	0.81	0.76	0.73	0.67	0.62	0.56	0.56	0.83
16	0.78	0.78	1.07	0.98	0.80	0.75	0.73	0.67	0.62	0.56	0.55	0.79
17	0.75	0.79	0.99	0.95	0.79	0.75	0.72	0.67	0.62	0.57	0.55	0.77
18	0.72	0.80	0.92	0.95	0.79	0.75	0.71	0.68	0.62	0.58	0.55	0.87
19	0.73	0.90	0.87	0.93	0.78	0.75	0.71	0.68	0.61	0.58	0.54	0.87
20	0.78	0.85	0.83	0.92	0.77	0.75	0.71	0.68	0.60	0.58	0.54	0.87
21	0.77	0.83	0.99	0.91	0.77	0.75	0.71	0.68	0.60	0.56	0.53	0.88
22	0.75	0.78	1.04	0.92	0.78	0.75	0.70	0.68	0.60	0.57	0.53	0.87
23	0.74	0.87	1.18	0.96	0.84	0.75	0.70	0.68	0.58	0.57	0.53	0.85
24	0.73	0.93	1.09	1.02	0.83	0.74	0.69	0.67	0.58	0.56	0.53	0.84
25	0.77	0.94	1.15	1.12	0.83	0.73	0.69	0.66	0.58	0.56	0.54	0.86
26	0.80	0.91	1.25	1.09	0.87	0.73	0.68	0.66	0.58	0.55	0.54	0.86
27	0.76	0.90	1.14	1.15	0.86	0.73	0.69	0.66	0.58	0.55	0.55	0.82
28	0.76	0.86	1.04	1.12	0.86	0.72	0.68	0.66	0.58	0.55	0.57	0.81
29	0.93	*****	1.04	1.05	0.85	0.71	0.68	0.65	0.58	0.54	0.58	0.81
30	0.82	*****	1.24	1.01	0.83	0.71	0.68	0.65	0.58	0.54	0.70	1.10
31	0.90	*****	1.21	*****	0.83	*****	0.68	0.66	*****	0.54	*****	0.89

DATE:
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NATIONAL STATION CODE 1KA22
STATION CODE NO 10

STAGE OBSERVATIONS (M OR FT)
YEAR 1980

RIVER: MTITU R.
LOCATION: MTITU
REGION: IRINGA

DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.77	0.97	0.80	0.75	0.83	0.70	0.64	0.65	0.64	0.67	0.62	0.51
2	0.87	1.09	0.79	0.75	0.85	0.69	0.64	0.64	0.63	0.69	0.59	0.68
3	0.92	1.06	0.81	0.75	0.86	0.69	0.66	0.64	0.61	0.67	0.57	0.65
4	0.81	1.01	0.84	0.74	0.90	0.68	0.65	0.63	0.60	0.64	0.57	0.73
5	0.77	0.99	0.84	0.73	0.92	0.67	0.65	0.62	0.60	0.63	0.56	0.74
6	0.74	0.97	0.84	0.70	0.93	0.67	0.66	0.62	0.59	0.61	0.54	0.75
7	0.74	0.92	0.96	0.69	0.93	0.67	0.65	0.62	0.58	0.59	0.53	0.77
8	0.75	0.88	0.87	0.68	0.90	0.66	0.65	0.63	0.59	0.57	0.53	0.85
9	0.76	0.89	0.87	0.64	0.84	0.65	0.64	0.63	0.60	0.58	0.55	0.92
10	0.77	0.76	0.84	0.79	0.84	0.66	0.64	0.63	0.59	0.55	0.71	0.87
11	0.77	0.74	0.82	0.76	0.83	0.68	0.63	0.64	0.60	0.56	0.68	0.81
12	0.75	0.71	0.98	0.82	0.80	0.67	0.63	0.64	0.59	0.56	0.67	0.72
13	0.74	0.69	0.93	0.88	0.78	0.66	0.63	0.63	0.60	0.57	0.64	0.63
14	0.84	0.68	1.03	1.00	0.79	0.65	0.63	0.64	0.59	0.57	0.58	0.78
15	0.93	0.67	0.97	0.89	0.78	0.65	0.64	0.64	0.59	0.57	0.56	0.69
16	0.86	0.67	0.92	0.97	0.78	0.65	0.64	0.64	0.58	0.59	0.68	0.73
17	0.97	0.72	0.87	1.02	0.77	0.63	0.64	0.63	0.58	0.56	0.66	0.74
18	0.80	0.74	0.89	1.01	0.76	0.63	0.65	0.63	0.57	0.54	0.66	0.75
19	1.06	0.75	0.88	1.06	0.76	0.64	0.65	0.62	0.55	0.53	0.62	0.77
20	1.01	0.71	0.86	1.12	0.75	0.64	0.65	0.62	0.55	0.52	0.60	0.82
21	0.99	0.71	0.80	1.06	0.75	0.63	0.65	0.62	0.56	0.53	0.58	0.72
22	0.96	0.68	0.90	0.99	0.74	0.63	0.65	0.65	0.57	0.53	0.55	0.71
23	0.93	0.67	0.88	0.92	0.74	0.63	0.66	0.65	0.56	0.53	0.53	0.70
24	0.93	0.72	0.77	0.87	0.74	0.63	0.66	0.64	0.56	0.52	0.53	0.74
25	0.93	0.65	0.75	0.83	0.74	0.63	0.67	0.63	0.56	0.52	0.52	0.83
26	0.98	0.64	0.74	0.81	0.73	0.63	0.67	0.62	0.56	0.52	0.51	0.81
27	1.10	0.63	0.75	0.78	0.73	0.62	0.67	0.62	0.57	0.54	0.51	0.77
28	0.96	0.79	0.75	0.76	0.73	0.63	0.65	0.61	0.57	0.62	0.51	0.75
29	1.03	0.73	0.73	0.75	0.72	0.63	0.65	0.61	0.57	0.64	0.50	0.74
30	1.14	*****	0.73	0.76	0.71	0.63	0.65	0.64	0.73	0.67	0.50	0.76
31	1.20	*****	0.72	*****	0.70	*****	0.65	0.64	*****	0.67	*****	0.86

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Table [illegible] 1KA22 (sample)

- Permanent control
- Scour and fill in an unstable channel
- Growth and decay of aquatic vegetation
- Variable backwater in uniform channels
- Variable backwater submerging a low water control
- Rapidly changing discharge
- Overflow and ponding in areas adjoining the stream channel

In the inspection of gauging stations and review of rating curves in the three regions it was found that suitable locations have been selected for most stations, the majority of which have stable controls (i.e. reasonably well defined, permanent stage-discharge relations). These are generally stations located in rocky streambeds, as opposed to stations with so-called channel control (shifting control) at which the stage-discharge relationship changes with time as a result of changing bed configuration at the site. (Aggradation and/or degradation of the streambed). At the latter stations rating curves will often have to be defined on the basis of highly scattered points, and the period of validity for any curve defined through a set of points may be rather short. However, due to the limited resources available for discharge gauging programmes, rating curve validity must often be extended beyond the justifiable period, thereby introducing errors into the discharge determination.

Another problem associated with inadequate discharge gauging is the generally rather poor coverage for the very high as well as the very low discharges. Thus determination of extreme discharges is often based upon extrapolation of rating curves which are well defined only in the range of medium discharges. Many gauging stations in the regions experience overflow at high water levels resulting in a very uncertain determination of flood discharge anyway.

A solution to the problem of shifting control in sandy streambeds which has been applied to some of the gauging stations in Mbeya and Iringa regions (e.g. 1KA50A and 1KA56),is the establishment of artificial controls in the form of concrete weirs or concrete slabs under bridges.

Since 1970 all the stage-discharge relationships for gauging stations in the three regions have been defined and stored in analytical form.

$$Q = G(H-H_0)^N \qquad (5\text{-}1)$$

in which Q and H are discharge and stage respectively, while G, H_0 and N are constants. This formula defines a straight line on double-logarithmic paper with Q and $H-H_0$ along the two axes. Prior to 1970, and still for some stations in other parts of Tanzania, stage-discharge relationships are defined and stored in table form (rating tables).

H_0 in equation (5-1) is the point of zero flow, i.e. that stage at which no flow occurs. This level, which can be approximately determined by levelling in the field, is only rarely equivalent to the zero-level of the staff gauge. However, for almost all the rating curves in MAJI's data-base this information is unavailable, and accordingly H_0 is set at zero.

A final remark on rating curves in the three regions concerns their sensitivity. The exponent N in equation (5-1) is generally in the range 1.5-4 but values as high as 22 occur in some of the rating curves, (e.g. 1KA10A). Obviously the determination of discharge from water levels at stations with such rating curves are extremely sensitive to the value of H, and a small error in the water level observation will result in a considerable error in the discharge. This may be particularly critical in low flow situations at stations where the control site can be partly blocked by branches, weeds etc. resulting in local backwater effects. One station (1KA56) was rejected as priority station for this reason.

5.6.2 Checking and extension of rating curves

In runoff studies the rating curves for the hydrological gauging stations involved represent the most critical link in the chain. Water levels can be observed reliably and rather accurately, and almost all of the uncertainty in the discharge determination is introduced through the rating curve. For this reason a considerable effort has been made in the present study to review and correct rating curves for gauging stations in the regions, and all stage-discharge plots for all stations in the regions have therefore been carefully checked for their entire record length. In most of the cases the historical rating curves and tables were found to be satisfactory, while in some cases these rating curves, and hence the historical discharges computed on the basis of these curves had to be revised.

As part of this checking process the theoretical point of zero flow (H_0) has been computed and included in the revised rating curve. Whenever practical this point has been determined by levelling in the field.

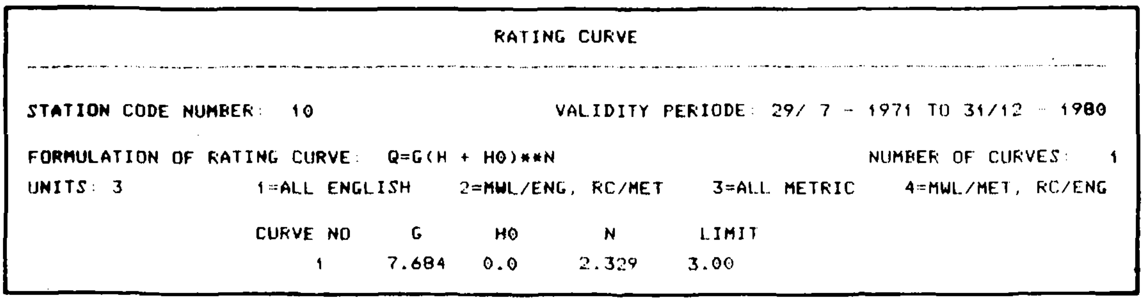
As outlined above an intensive discharge measurement programme has been undertaken in 1980 with emphasis on improvement of priority station rating curves in the low flow regime. Continued improvement of low flow ratings has been carried out in 1981.

For all stations in the regions the latest discharge measurements have been plotted on the latest rating curve in order to check if its validity could be extended up to the present time, illustrated in Figures 5.55^{8}.5.73^{8} for priority stations. In most cases this was found justifiable while in some cases a new curve had to be defined. In these cases it was often found appropriate to extend the new rating curve backwards in time as well.

A total of **951** station-years of **records** have been **examined** of which 691 station-years were found satisfactory, while some 260 station-years have been either revised or extended. All revisions and extensions of rating curves have been approved by MAJI-Ubungo prior to their inclusion in the data-base and subsequent use for discharge computations.

The bar chart in Figure 5.31^{8} shows the availability of rating curves for all permanent stations in the regions, together with an indication of periods for which rating curves have been revised or extended in this study. The log-book in Annex 5-1 details the changes made for each station.

A computer program has been developed and used for the updating, storage and retrieval of rating curves. A sample output from this program showing the rating curve for station 1KA22 (the station for which water levels are shown in Table 5.23) is shown in Figure 5.30 below.



```
                                    RATING CURVE
--------------------------------------------------------------------------------------------

STATION CODE NUMBER:  10                          VALIDITY PERIODE: 29/ 7 - 1971 TO 31/12 - 1980

FORMULATION OF RATING CURVE:  Q=G(H + H0)**N                              NUMBER OF CURVES:   1
UNITS: 3            1=ALL ENGLISH    2=MWL/ENG, RC/MET    3=ALL METRIC    4=MWL/MET, RC/ENG

                    CURVE NO     G      H0        N       LIMIT
                        1      7.684   0.0      2.329     3.00
```

Figure 5.30 Rating curve, station 1KA22.

Computer printouts and an ICL magnetic tape containing all rating curves for all stations in the regions accompany this report in a separate box.

5.6.3 Checking and updating of discharge data

Having checked, corrected and updated water levels and rating curves, and stored this information in the data-base, discharges have been updated and stored subsequently. As for water level- and rating curve revision and updating, a computer program has been developed at DHI in which discharges are computed, stored and presented in the same way as in the corresponding MAJI software.

A sample output from this program is shown in Table 5.24 below, the corresponding discharge hydrograph being shown in Figure 5.32. The discharge hydrograph shown in this table and figure results from conversion of the water levels in Table 5.23 using the rating curve in Figure 5.30 (station 1KA22). The discharge tables have been prepared in the same format as those presented in MAJI's Hydrological Yearbooks.

Hydrographs for all priority stations for their entire periods of records are contained in Volume 8, Figures 5.33^8-5.51^8.

The final checking of data in the hydrological data-base has been carried out primarily on the basis of thorough examination of the discharge records and subsequently by tracing errors to the water level data-base. Visual inspection of hydrographs has been the most important element in this checking process, and on the basis of this experience it is strongly recommended that MAJI be provided with adequate plotting facilities for routinely preparation of hydrographs.

The availability of discharge data in the data-base is detailed in the bar chart in Figure 5.52^8.

Discharge tables in the form of Table 5.24 for all stations for their entire period of record are contained in the computer printouts which accompany this report. The discharge data-base on ICL magnetic tapes in the original MAJI format has also been handed over to MAJI.

NATIONAL STATION CODE 1KA22
STATION CODE NO. 10

RIVER: MTITU R.
LOCATION: MTITU
REGION: IRINGA

DISCHARGE IN M3/S
YEAR 1980

DATE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
1	4.26	7.33	4.55	3.87	4.91	3.34	2.71	2.81	2.66	3.02	2.47	1.60	
2	5.55	6.29	4.43	3.93	5.26	3.23	2.71	2.71	2.57	3.23	2.20	3.13	
3	4.34	8.91	4.03	3.93	5.49	3.19	2.91	2.71	2.38	3.02	2.07	2.81	
4	4.70	7.86	5.12	3.81	6.01	3.07	2.81	2.61	2.33	2.71	2.07	3.69	
5	4.18	7.53	5.11	3.63	6.32	3.02	2.81	2.52	2.29	2.57	1.99	3.81	
6	3.81	7.07	5.04	3.34	6.48	3.02	2.91	2.52	2.24	2.43	1.82	3.87	
7	3.81	6.25	6.99	3.18	6.49	3.02	2.81	2.52	2.16	2.24	1.75	4.18	
8	3.93	5.63	5.55	3.07	6.01	2.91	2.81	2.61	2.24	2.07	1.71	5.20	
9	4.05	5.90	5.56	5.04	5.12	2.81	2.71	2.61	2.33	1.90	1.91	6.33	
10	4.18	3.99	5.05	4.44	5.04	2.92	2.71	2.61	2.24	1.90	3.47	5.48	
11	4.16	3.75	4.84	3.99	4.60	3.12	2.61	2.71	2.29	1.99	3.12	4.63	
12	3.93	3.46	7.29	4.85	4.56	3.02	2.61	2.71	2.24	1.99	3.02	3.81	
13	3.81	3.23	6.49	5.66	4.30	2.91	2.61	2.61	2.33	2.07	2.71	2.57	
14	5.11	3.12	8.15	7.68	4.37	2.81	2.61	2.66	2.24	2.07	2.16	4.24	
15	6.50	3.02	7.15	5.85	4.30	2.81	2.71	2.71	2.24	2.07	1.99	3.24	
16	6.98	2.97	6.33	7.07	4.24	2.81	2.71	2.66	2.16	2.24	3.12	3.69	
17	7.18	3.57	5.46	7.95	4.18	2.61	2.71	2.61	2.16	1.99	2.91	3.76	
18	5.20	3.81	5.78	7.77	4.05	2.61	2.76	2.61	2.03	1.82	2.86	3.87	
19	8.71	3.93	5.63	8.81	3.99	2.71	2.81	2.52	1.90	1.75	2.47	4.18	
20	7.77	3.53	5.33	9.90	3.93	2.71	2.81	2.52	1.90	1.67	2.29	4.77	
21	7.50	3.40	4.57	8.80	3.93	2.61	2.81	2.47	1.95	1.75	2.11	3.57	
22	6.90	3.07	6.15	7.42	3.81	2.61	2.81	2.81	2.03	1.78	1.90	3.46	
23	6.40	3.02	5.71	6.25	3.75	2.61	2.91	2.76	1.99	1.75	1.75	3.34	
24	6.40	3.58	4.18	5.55	3.81	2.61	2.91	2.71	1.99	1.67	1.71	3.75	
25	6.49	2.81	3.93	4.97	3.81	2.61	3.02	2.57	1.99	1.67	1.63	4.97	
26	7.24	2.71	3.81	4.63	3.69	2.61	3.02	2.52	1.95	1.67	1.60	4.71	
27	7.08	2.57	3.87	4.24	3.69	2.52	3.02	2.52	2.07	1.79	1.60	4.11	
28	6.90	4.38	3.87	3.99	3.63	2.61	2.81	2.43	2.07	2.52	1.56	3.93	
29	8.23	•••••••	3.69	3.87	3.51	2.61	2.81	2.43	2.07	2.71	1.52	3.81	
30	10.32	•••••••	3.69	3.99	3.46	2.61	2.81	2.66	3.63	3.02	1.52	4.05	
31	7.55	•••••••	3.57	•••••••	3.34	•••••••	2.81	2.71	•••••••	3.02	•••••••	5.42	
VOL (MCM)	15.93	11.19	13.96	13.95	12.11	7.31	7.48	7.01	5.76	5.88	5.62	10.69	ANNUAL: 116.88
MEAN	5.95	4.46	5.21	5.39	4.52	2.82	2.79	2.62	2.22	2.20	2.17	3.99	
MAX	10.42	9.39	8.80	10.00	6.48	3.34	3.02	2.81	3.69	3.23	3.93	6.65	
DATE	30	2	14	20	6	1	25	1	30	2	10	9	
MIN	1.95	2.52	3.57	3.02	3.34	2.52	2.61	2.43	1.90	1.67	1.52	1.52	
DATE	18	27	31	6	31	27	11	21	19	20	28	1	

Table 5.24 - Discharges, hydrological station 1KA22.

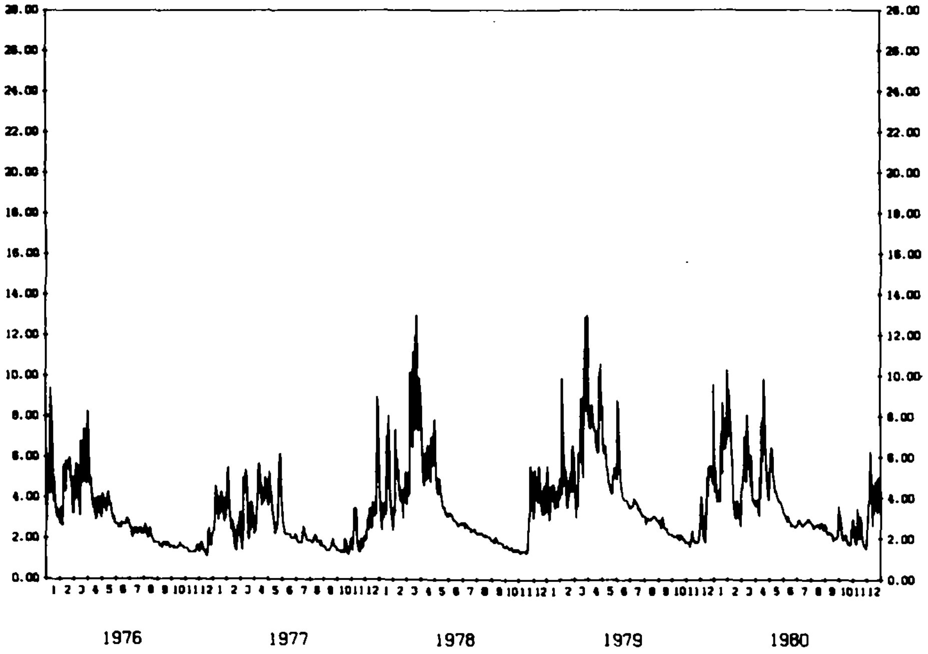


Figure 5.32 - Hydrograph, hydrological station 1KA22.

5.7 Sediment transport

5.7.1 Sediment production

Every stream carries some suspended sediment, while moving larger solids along the stream bed as bed load. These sediments are produced from the catchment as a result of soil erosion coused by surface runoff.

The sediment transport characteristics of a stream are important primarily for reservoir planning and design, the sediment production of the catchment upstream of the reservoir determining its rate of sedimentation, and thus the lifetime of the reservoir. For water supply planning the concentration of sediment in the water is an important water quality parameter, and for irrigation planning sediment carrying characteristics have an impact on channel design (channel siltation).

Many factors control the soil erosion, and hence the sedimentation production, in a given catchment. The geomorphology of the study area id described by using the erosion cycle consept in Volume 9 of this report, to which reference is made for a discussion of the geological factors controlling the land-form development and soil erosion. Rainfall characteristics, and type and extent of vegetation cover are other important factors. Hence, cultivation practices and forest management influence soil erosion significantly, an adequate plant cover being essential for the retention of the top soil in the presence of overland flow.

The general impression of the state of soil erosion in the regions is that denudation of the steep slopes in the cultivated areas is a serious problem.

The early rain is often in the form of heavy showers of great intensity, and it occurs at a time when fields are generally devoid of vegetation having been prepared for planting in anticipation of the rain. This is the time when much serious erosion takes place, and much soil is carried away to the rivers. Severe signs of sheet erosion is often seen at that time of the year. Later when the crops have been established and new grass has covered the uncultivated land, erosion comes to an end for the season, and the sediment load in streams and rivers drop off dramatically.

In many areas the original top soil has been eroded away, and unless protective measures are taken, the agricultural production potential of many of these areas may be in jeopardy. Another unfortunate consequence of soil erosion is greater fluctuation in streamflow. The reduced storage capacity of the soil cover leads to more rapid runoff, and hence increased flooding severity, while less water seeps into the streams during the dry season.

Few studies on sediment transport have been carried out in the regions. Sweco in their report on the Mtera Dam (Sweco, 1975) made some studies on the sediment transport of the Great Ruaha, including analyses of grain size distribution, but these studies are not very representative for the majority of the study area for which the sediment transport of smaller streams is of primary interest.

5.7.2 Determination of sediment transport

The sediment transport of a stream can be determined directly by actually measuring the suspended load and the bed load, or indirectly by measuring the suspended load only, estimating the total load (suspended load + bed load) on the basis of that. No satisfactory equipment and procedure exist for routine bed load measurements, and the latter procedure is therefore generally preferred. This is true for the three regions under study as well, in which MAJI has performed a total of 1257 suspended load measurements in the period 1956-76 (848 in Iringa, 287 in Mbeya and 122 in Ruvuma). No bed load measurements, and no grain size distribution analyses have been made. During the present study the sediment sampling programme was restarted at some of the priority stations (e.g. 1KA37A), but laboratory analyses of these samples at MAJI-Ubungo have not yet been completed.

Sediment samples are collected using depth integrated sediment samplers of the type DH-48 or D-49, both carrying one litre bottles. The samplers are designed to minimise distortion of the streamlines of flow so as to collect a representative sample of the sediment-laden water. A number of samples (usually three) are taken in a cross-section. Samples are analysed at MAJI-Ubungo, where they are filtered, dried and weighed.

The relation between suspended sediment load Q_s (in tons per day) and discharge Q (in m^3/s) is generally represented by a logarithmic plot which may be expressed mathematically by an equation of the form

$$Q_s = k\,Q^n \qquad (5\text{-}2)$$

where k and n are constants. The so-called sediment-rating curve expressed by this equation, may be used to estimate suspended sediment transport from the continuous record of streamflow, in the same manner as discharge is estimated from the continuous water lwvel record by use of a stage discharge relation. Total load may be stimated either by use of theoretical formulae, or by simply adding a certain percentage (often 10-20%) to the suspended transport to allow for the bed load contribution.

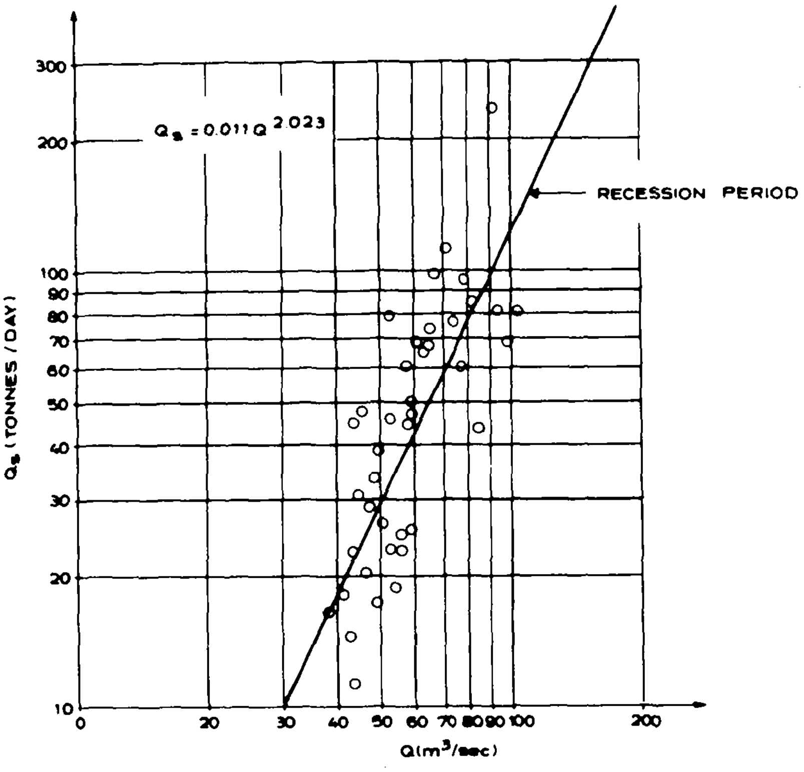
It is emphasised, however, that sediment rating curves are much less accurate than the corresponding streamflow rating curves. Not only are sediment rating curves usually defined by drawing a straight line through a set of highly scattered points (e.g. Figure 5.53 below), but at least two curves are required to account for the very different sediment production characteristics of the early and late wet season. As explained above, sediment concentrations are much higher during the early stage of the rainy season than during the later streamflow recession period.

An excellent discussion of sediment transport measurement and analysis is contained in the earlier mentioned "Manuals on Procedures in Operational Hydrology" prepared by NORAD during the Western Tanzania Project.

5.7.3 Available sediment data

A list of available sediment sampling results is presented in Table 5.25[8], and sediment rating curves stored in MAJI's data base are shown in Table 5.26[8].

In addition, the sediment plot and rating curve for station 1RB2 (Ruhuhu at Masigira) is shown in Figure 5.53 below.



Period of measurements, March to May 1976.

Validity interval 38 $m^3/s < Q < 105 m^3/s$.

Range of computed discharges 14 m^3/s - 201 m^3/s.

Figure 5.53 - Suspended sediment rating curve.

All these sediment rating curves must be considered very inaccurate. The main reasons for this are:

- Curves are generally defined on the basis of recession period measurements only (falling stage - low concentrations - short period).
- Sediment sampling has covered only a small range of discharges (e.g. 38-104 m^3/s range, out of the possible 15-201 m^3/s range for 1RB2 in Figure 5.53).
- Uncertainties in sediment measurements.

Suspended sediment transport generally varying with a power greater than 1 in equation 5-2, and the lack of samples during the highest flows, when most of the sediment transport occurs, severely restricts the usefulness of the available samples. A number of problems makes the sampling procedure extremely difficult to perform to satisfaction. These include i.a.:

- The lowering and rising velocity of the sampler must be the same.
- The weight of the lead sinker needed at high flow velocities makes it difficult to handle.
- The sampling flask should never be filled to more than 3/4 full.

This, combined with the lack of rising stage samples, has led the consultants not to attempt to compute sediment transport, and hence, sediment production from the catchments, on the basis of the presently available information. This decision has been made in full agreement with senior Maji hydrologists.

The sediment rating curves in Table 5.26[8] have been plotted as shown in Figure 5.54, indicating also the geomorphological zone of the stations. It appears from this plot that no distrinct relation between shape and magnitude of sediment rating curves and geomorphological zones can be identified on the basis of the available data. The figure also shows that generally very low suspended sediment transport rates are found during the streamflow recession periods. However, as indicated above, this does not necessarily imply that the total sediment production is low, as soil erosion occurs primarily during the early rains.

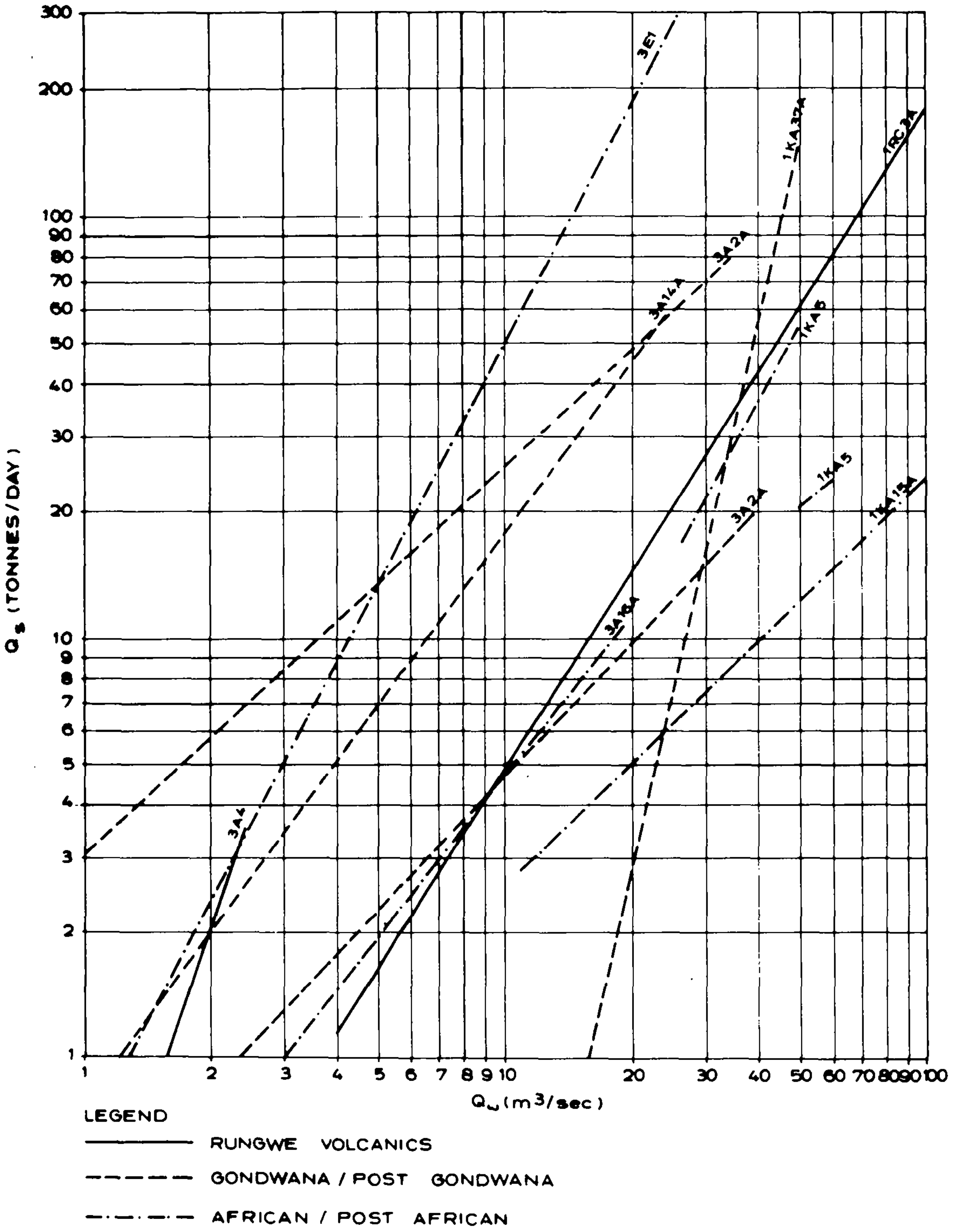


Figure 5.54 - Sediment rating curves for different geomorphological groupings.

5.8 Recommendations

In connection with the planning and implementation of group and local water supply schemes, it is strongly recommended that detailed hydrological investigations be carried out in order to obtain the maximum amount of knowledge about the hydrology in the area concerned, thus providing the best possible basis for the design and operation of the supply scheme.

The existing network of hydrostations is adequate in almost all parts of the regions, and establishment of additional stations should primarily take place in connection with well defined projects. New permanent stations should be established primarily as part of a general network improvement, and thus in accordance with a well defined network improvement program.

The following recommendations are stressed:

Data processing.

(a) Elimination of the bottleneck in Maji's data processing, storage and retrieval system by providing adequate computer facilities at Maji Ubungo itself is urgent and should be given top priority.

(b) Historical water level- and discharge series contain a great number of errors, which should be eliminated through careful checking of original observations, regional office records and records stored at Maji Ubungo.

In fact it is strongly recommended to initiate a systematic control procedure for all hydro-stations corresponding to the one undertaken for priority stations in the present study.

(c) Water rights should be reviewed critically, and rights not properly utilized should be withdrawn.

(d) It should be attempted to publish hydro-data annually, thereby ensuring frequent and better control of data.

(e) Sediment samples and data should be processed and analysed at the regional offices and data stored both at regional offices and at Maji Ubungo.

(f) The on-going effort to process and store automatically recorded water levels (with Irish assistance) should continue to have high priority.

Gauging network and procedures.

(a) More frequent station inspections are required in order to ensure:

- repair and replacement of damaged equipment, particularly during the flood season when staff gauges may be damaged,
- annual ratings in both seasons for all stations,
- general control of the state of operation.

(b) Computed discharge values should be plotted on the rating curve immediately after the measurement has been made. This provides a first control of the reliability of the measurement, and if truly off the curve it will give an indication of possible problems with the stability of the rating curve.

(c) Sediment ratings should be made routinely as part of the discharge measurement programme. Sediment data for the early rainy season (rising limb of hydrograph) are almost totally lacking and should be given high priority.

6. RUNOFF ANALYSIS

6.1 General

Surface runoff as it appears in the form of flow in streams and rivers in the three regions is the hydrological variable of primary interest in the present study, and consequently the one most thoroughly investigated. Inventory of reliable surface water resources, primarily for water supply purposes, but also for other potential uses such as irrigation and hydropower production, has been the main objective of the present hydrological studies. However, runoff in streams and rivers is the end result of a series of hydrological processes, the understanding of which requires studies of rainfall, evaporation and subsurface water storages and flows. For this reason investigations of these other elements of the hydrological cycle have been made, as reported in Chapters 3, 4 and 7.

In recognition of the importance of drawing conclusions on the basis of complete and reliable runoff data, a significant part of the time and resources available for the present study has been devoted to processing, control and storage of basic runoff data in the comprehensive data-base. These activities are described in Chapter 5.

The final runoff series resulting from these data processing activities contain much information on important aspects of water resources planning and management. In order to extract some specific information for presentation in a general overview form several runoff analyses have been performed. Analyses of runoff data have been carried out for selected stations, as well as on a regional scale. The main station analyses and their objectives have been the following:

- Analyses of streamflow hydrographs. Particular emphasis has been put on the analysis of the recession constants of the baseflow part of the hydrographs in order to support the further low flow analyses.
- Analyses of possible trends and periodic fluctuations of annual runoff volumes. The results of these analyses have been important because of the fact that not all hydrological stations have data for the same period.
- Duration curves containing information on the seasonal variation of runoff. Such curves are particularly applicable for reservoir planning and hydropower investigations.

- Low flow and flood flow frequency analyses. Information on the frequency of the low flows is crucial for surface water evaluations for water supply planning. The frequency of the flood flows are important in the evaluation of design criteria for hydraulic structures located in or close to the rivers, as well as for the assessment of flood problems in certain areas.
- Monthly statistics, annual statistics and correlation analyses for the general evaluation of the regimes.
- Illustrative example of a simple reservoir analysis.

Evidently most of these are standard hydrological analyses. In addition to giving a general picture of the characteristic hydrological regimes in the regions, the streamflow analyses presented below illustrate some of the commomly used techniques of time series analysis. These techniques form the basis on which to develop stochastic hydrological models for generation of synthetic streamflow series with the same statistical characteristics as the historical series.

As detailed runoff analyses require relatively long records, and because the reliability of these records is very important for the further generalization, most of the analyses have been carried out for the priority stations only. These are 19 hydrological gauging stations representing a characteristic cross-section of the prevailing hydrological regime in the study area. (cf. Chapter 5 in which the priority station approach and the criteria for their selection is described). However, in some of the analyses other selection criteria have been applied.

The general approach to the present reporting of the station runoff analysis is to show all the results in tables and figures in the hydrological data volume (Volume 8), while for the purposes of illustration showing results for the two priority stations 1KA22 and 1KA23A in this volume (Volume 7).

Station 1KA22 is located at the perennial Mtitu river at Mtitu south of Iringa town. The catchment area is 445 km^2, located in the African geomorphological zone in a relatively wet climate. Station 1KA23A is located at the ephemeral Huhuni river at Iyayi west of Makambako in the western part of Iringa region. The catchment area is 803 km^2, located in the African geomorphological zone in a relatively dry climate.

The main regional analyses and their objectives have been the following:

- Preparation of a map showing the mean annual specific runoff (mm/year) in the three regions in order to give a general overview of the different hydrological regimes.
- Preparation of a map showing the 10-year minimum specific runoff ($l/s/km^2$) in the three regions to be applied directly in the water supply planning.
- Analyses of the relationships between geomorphological zones, rainfall and runoff characteristics, in order to investigate the possibility of assessing runoff characteristics in ungauged areas on the basis of information on rainfall and geomorphology.

Station runoff analyses are reported in Section 6.2, while the regionalization studies are reported in Section 6.3 below.

6.2 Station analyses

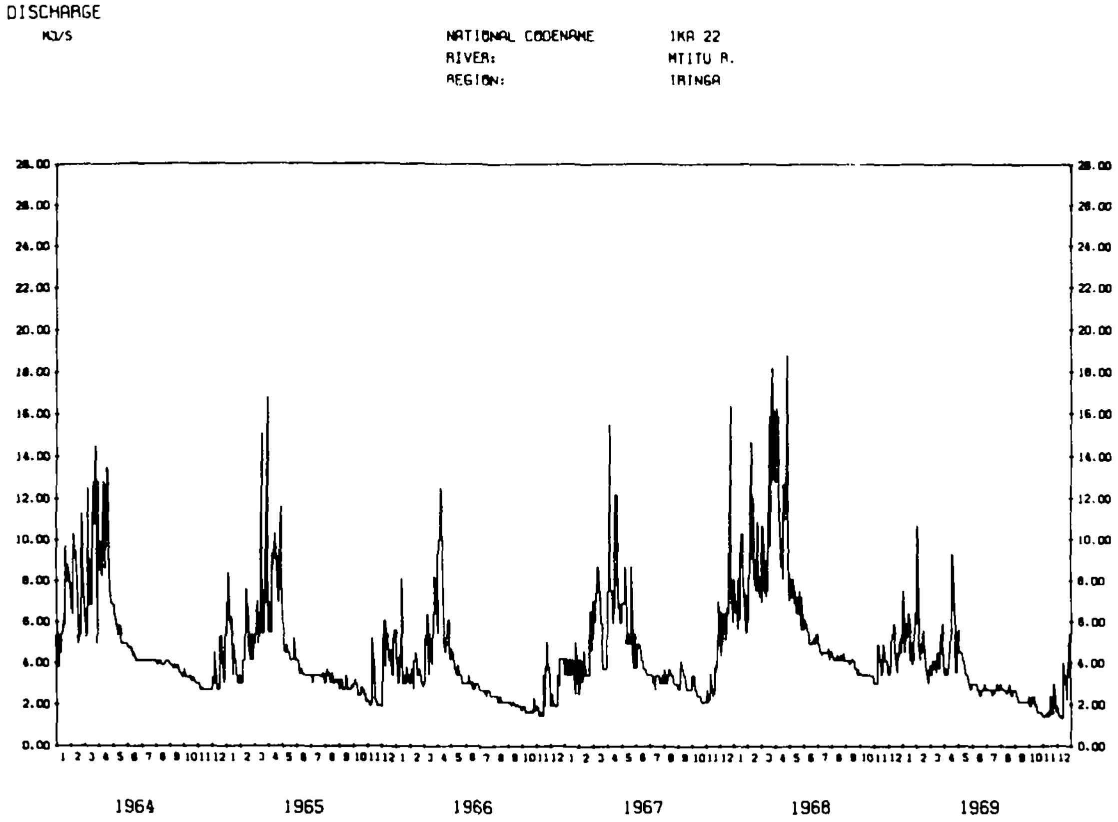
6.2.1 Streamflow hydrographs

A streamflow hydrograph is a continuous plot of the discharge versus the time. As discussed in Chapter 5 the runoff data in the data-base are daily mean discharge values.

In Figure 6.1 the hydrographs for the two stations 1KA22 and 1KA23A are shown for same years, while the hydrographs for all priority stations are shown in Figures 5.32^8-5.51^8. From the hydrographs many of the runoff characteristics can easily be extracted qualitatively. From Figure 6.1, for instance, it is seen that 1KA22 has a relatively moderate discharge variation with a considerable baseflow component, while 1KA23A is characterized by a much more flashy behaviour with very little baseflow to prevent it from running dry in the dry season.

As discussed in Chapter 5 a visual inspection of the plotted hydrographs has constituted an important part of the control of the runoff data in the data-base.

As also discussed in Chapter 5 the hydrographs are often separated into the three streamflow components: overland flow, interflow and baseflow. As the time scale of the overland- and interflow components are of the order of days or weeks, while the time scale of the baseflow component is of the order of months or years, it is evident that the baseflow component is the only one left in the late dry season . For this reason baseflow analyses are very important for low flow studies.



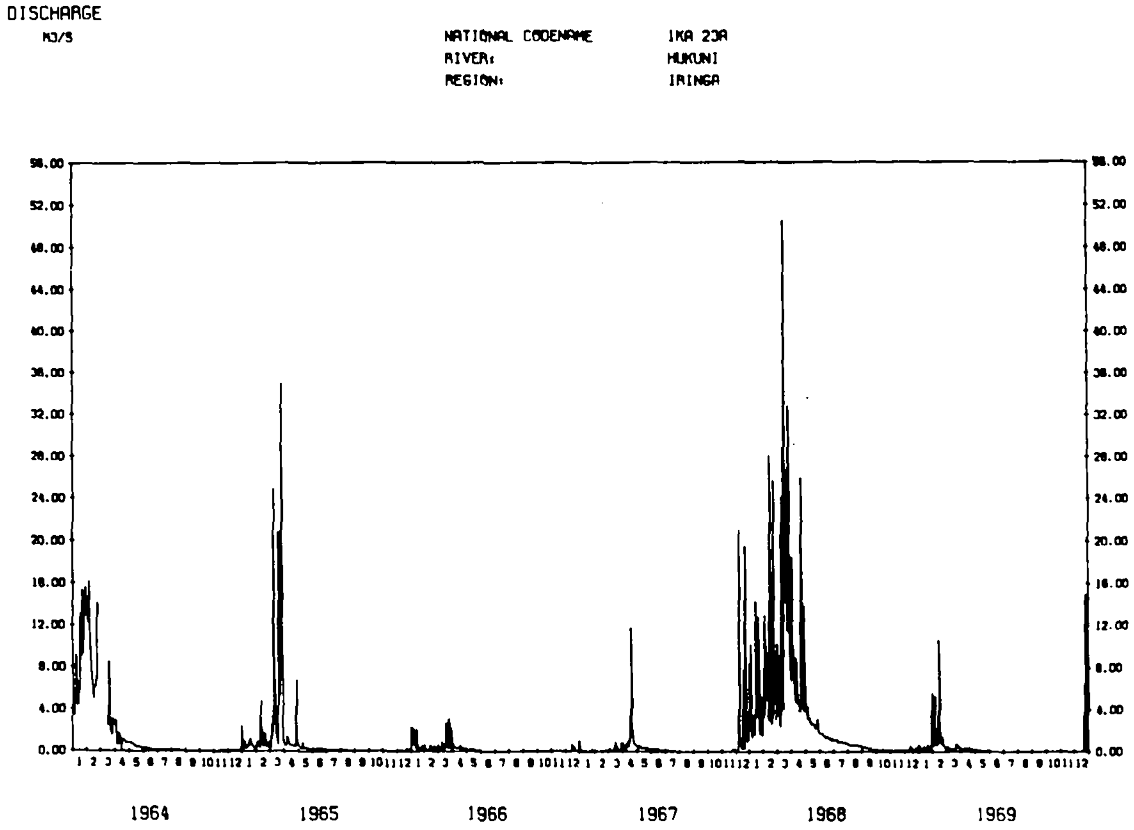


Figure 6.1 - Hydrographs for the stations 1KA22 and 1KA23A.

Often the recession part of the baseflow (i.e. the recession part of the hydrograph in the dry season) can be described by an exponential decay function, see Figure 6.23[8].

$$Q_t = Q_o \, e^{-kt} \qquad (6\text{-}1)$$

where

Q_t = the streamflow at time t

Q_o = the streamflow at time 0

k = the recession constant [day^{-1}]

t = the time [days]

As part of the hydrological field programme, dry season flows in otherwise ungauged streams have been "spotgauged" during the village visits. In order to utilize the information from these spotgaugings in the evaluation of minimum runoff (cf. Subsection 6.3.2) the recession behaviour of the gauged streams has been analysed and subsequently applied in the low flow studies.

The recession constants for all priority stations with at least five years of data have been calculated for the months August-November. In Table 6.1[8] the average recession constants and their range of variation (from year to year, and from month to month) are shown.

For perennial streams the recession constants range from 0.002 day^{-1} to about 0.010 day^{-1}. Generally large catchments tend to have slightly lower recession constants than small catchments. On the safe side it is recommended that a recession constant of about 0.010 day^{-1} is used in low flow evaluations for perennial streams, except in the Rungwe area where recession constants of about 0.005 day^{-1} should be used. In areas where streams occasionally run dry the recession constants vary between 0.010 day^{-1} and 0.050 day^{-1}. A (safe) average value of 0.035 day^{-1} is recommended for such streams. In areas where streams run dry frequently the recession constants are generally larger than 0.040 day^{-1}.

6.2.2 Duration curves

Flow duration curves, showing the percent of time in which the flow exceeds a given value, have been determined for priority stations with records of at least ten years length without gaps. The duration curves have been generated from mean monthly specific runoff values.

The duration curves are shown in Figure 6.2^{8}. The duration curves for the stations 1KA22 and 1KA23A are also shown in Figure 6.3.

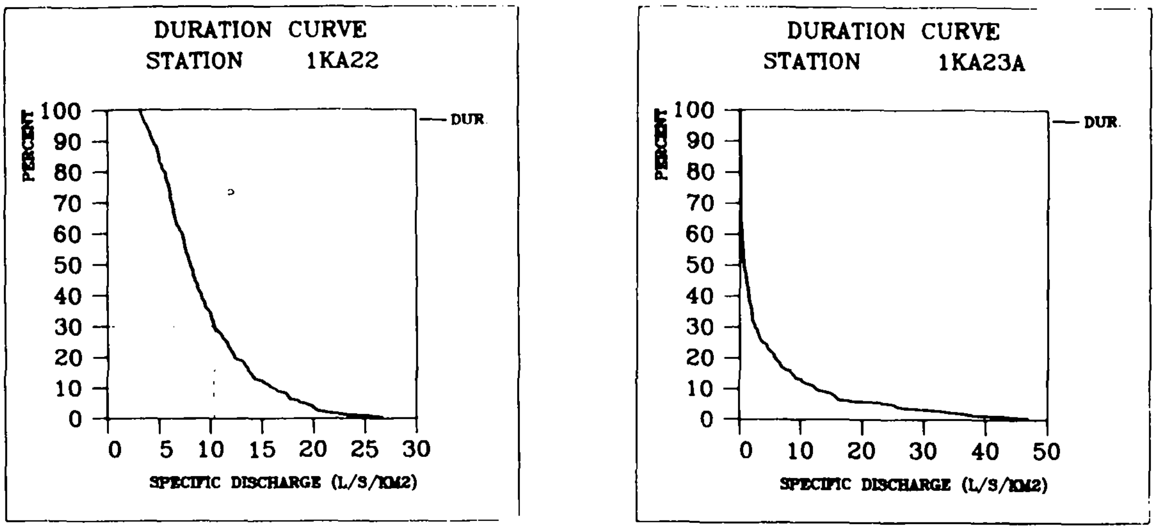


Figure 6.3 Flow duration curves for the stations 1KA22 and 1KA23A. (Example: In 30% of the time a specific discharge of appr. 10 $l/s/km^2$ is exceeded at 1KA22).

The distinction between a perennial stream (1KA22) and a non-perennial (ephemeral) stream (1KA23A) is evident. The minimum observed monthly runoff at 1KA22 is seen to be about 3.5 $l/s/km^2$ (read at 100%), while the maximum observed monthly runoff is about 27 $l/s/km^2$ (read at 0%). The duration curve of 1KA23A is typical for a flashy stream, which frequently dries out, but at other times carries large amounts of water.

In general duration curves are useful in analysing the behaviour of hydrological catchments, i.e., predicting the availability and variability of streamflow. Typically, streams with a high baseflow component show the least seasonal variability and the highest dry season yields.

Among other things duration curves provide valuable information for the design of dams for water supply, irrigation or hydropower generation.

The 75% and the 25% fractiles from the duration curves have been used in the regionalization analyses below (cf. Section 6.3).

6.2.3 Extreme flow analysis

In hydrology frequency analysis procedures are used for interpreting historical time series in terms of future events (droughts, floods) and their probability of occurrence.

Frequency analysis of streamflow data is commonly applied in the determination of design events for water supply systems and other water utilization schemes such as for instance, the determination of the daily or monthly minimum flow to be exceeded in 9 out of 10 years (10-year minimum flow).

Using DHI's standard extreme value analysis software the following analyses have been carried out on data from the runoff data-base:

- Selection and ranking of extreme events, e.g. daily minimum values of low flow for each year.
- Run tests of the extreme value series for independency.
- Estimation of probability distribution function parameters, using the method of moments or the method of least squares.
- Testing of fit between observations and the theoretical probability distribution function, using the chi-square test.
- Estimation of the extreme events and the corresponding confidence limits.

The theoretical probability distribution functions which have been applied for the present extreme value analyses are the Weibull distribution for the low flows, and the Gumbel distribution for the high flows, as discussed below. The Weibull and the Gumbel distributions are commonly used as they usually fit well, and have also in our analyses shown to represent the best fit. Also under certain, not very restrictive assumptions regarding the flow distribution the methods can be shown to be the theoretical probability distribution functions for minimum events, given a lower flow limit, and for maximum events (no limits).

Extreme low flows

The extreme value type III distribution is commonly used in hydrology as the distribution for extreme low flows. The type III distribution for minimum values is also known as the Weibull distribution. For all low flow calculations presented in this study the 3-parameter Weibull distribution discussed by Kite (1977) has been used.

The cumulative probability distribution function for the 3-parameter Weibull distribution is given below.

$$P(x) = e^{-\left(\frac{x-\gamma}{\beta-\gamma}\right)^{\alpha}} \qquad (6\text{-}2)$$

Where

x = the extreme low flow event
α = a scale parameter
β = a characteristic drought flow
γ = the lower limit of x

Extreme high flows

The extreme value type I distribution has been used in this study to analyse extreme high flow series. The type I distribution is also known as the Gumbel distribution.

The cumulative probability distribution function for the Gumbel distribution is given below.

$$P(\alpha) = e^{-e^{-\alpha(x-\beta)}} \qquad (6\text{-}3)$$

Where

x = the extreme high flow event
α = a concentration parameter
β = a meassure of central tendency

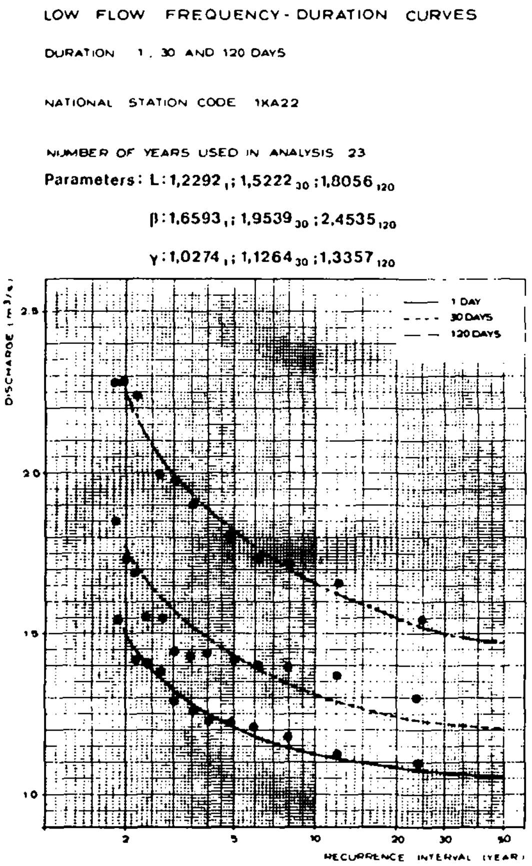
The following analyses have been carried out:

- For low flows the 1-day minimum, 30-day minimum and 120-day minimum (calculated on moving averages series) have been analysed. Ephemeral streams such as the Huhuni at 1KA23A have not been included.
- For high flows the maximum recorded instant flows have been analysed. As water levels have been observed only one to three times per day the maximum recorded instant flows analysed in this study are smaller than the true peak flows but larger than the mean daily maximum flows.

Low flow analyses have been carried out for all stations with more than 10 years of data (plus a few stations with shorter records), while only priority stations with more than 10 years of data have been subject to high flow analyses. Only results from the priority stations are shown here.

At all the stations run tests for independency and chi-square tests for probability distribution have been positive at a 5% level of significance.

Low flow frequency-duration curves are plotted on semi-logarithmic paper in the Figure 6.4^8. The curves for 1KA22 are also shown in Figure 6.4 (left).

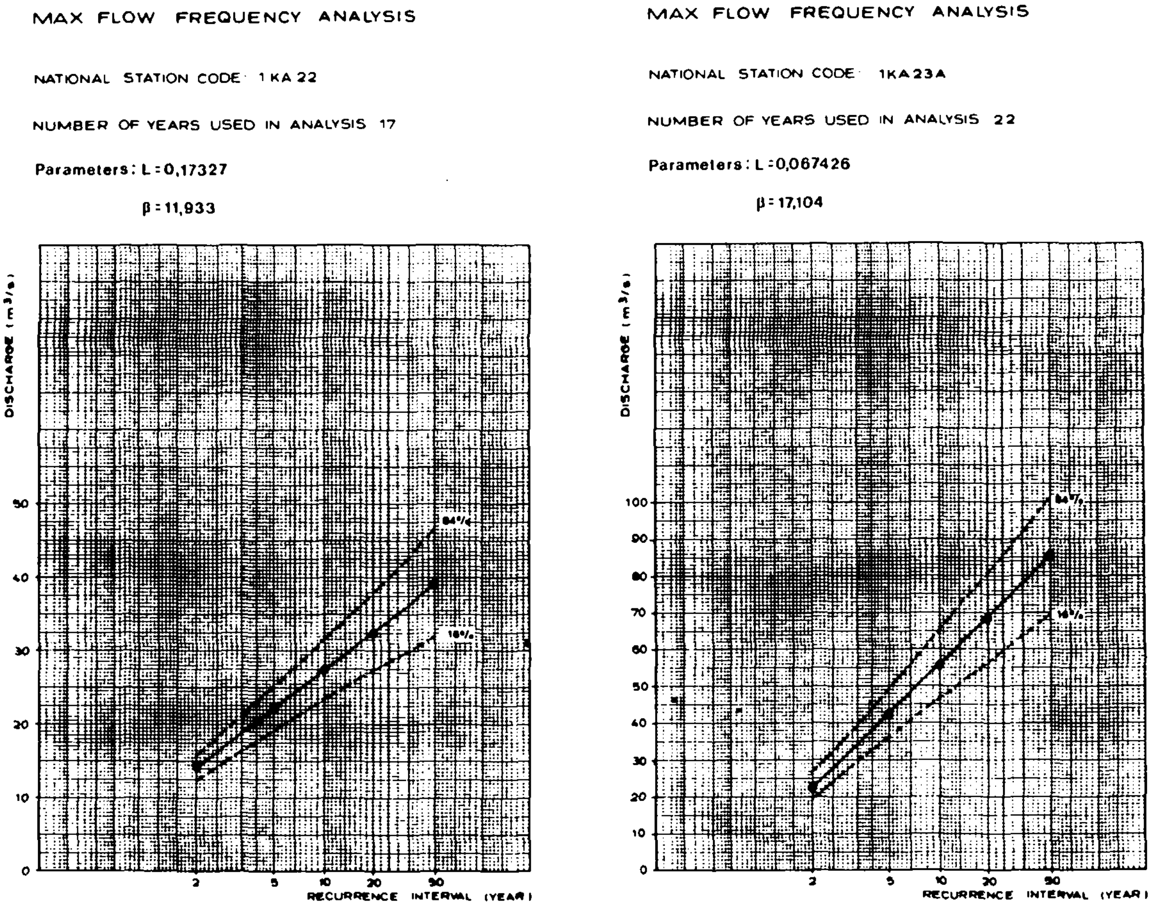


DURATION DAYS	RETURN PERIOD YEARS	EVENT M^3/SEC.	STANDARD DEVIATION M^3/SEC.
1	2	1.49	.12
	5	1.21	.07
	10	1.13	.10
	20	1.08	.13
	50	1.05	.17

Figure 6.4 Low flow frequency duration curves on semi-logarithmic paper (left) and 1-day minimum flow together with confidence limits (right) for the station 1KA22.

To show the uncertainty associated with the extreme value estimates the standard deviations of these estimates are included in the Table 6.2^8-6.10^8. As the extreme events are approximately normal distributed confidence limits can be found directly from the events and the associated standard deviations. Thus, the 16% and the 84% confidence limits, for example, are defined by subtracting and adding one standard deviation, to the estimated "mean" extreme value respectively. For station 1KA22 the frequency event for the 1-day minimum flow is shown in Figure 6.4 (right). As an example it is seen from this figure that the 50 year 1-day minimum flow has been estimated at 1.05 m^3/s. However, from the confidence limits it is seen that there is 16% probability that the 50-year daily minimum flow will be smaller than 0.88 m^3/s, and 16% probability (100%-84%) that it will be larger than 1.22 m^3/s.

The maximum frequency curves plotted on Gumbel probability paper with the 16% and the 84% confidence limits are shown in Figure 6.5[8]. For the stations 1KA22 and 1KA23A the curves are also shown in Figure 6.6.


MAX FLOW FREQUENCY ANALYSIS

NATIONAL STATION CODE 1 KA 22

NUMBER OF YEARS USED IN ANALYSIS 17

Parameters: L = 0,17327

β = 11,933

MAX FLOW FREQUENCY ANALYSIS

NATIONAL STATION CODE 1KA23A

NUMBER OF YEARS USED IN ANALYSIS 22

Parameters: L = 0,067426

β = 17,104

Figure 6.6 Gumbel maximum flow analysis for stations 1KA22 and 1KA23A.

The uncertainties discussed above only account for the statistical uncertainties. Further the observations are found from discrete instantaneous measurements (1-3 per day), which leads to a minor underestimation of the maximum flows.

6.2.4 Monthly and annual runoff statistics

The following common statistics have been calculated for all stations from monthly and annual runoff series.

- Mean
- Standard deviation
- Coefficient of skewness
- 25%, 50% and 75% fractiles (only for stations with at least 5-years data).

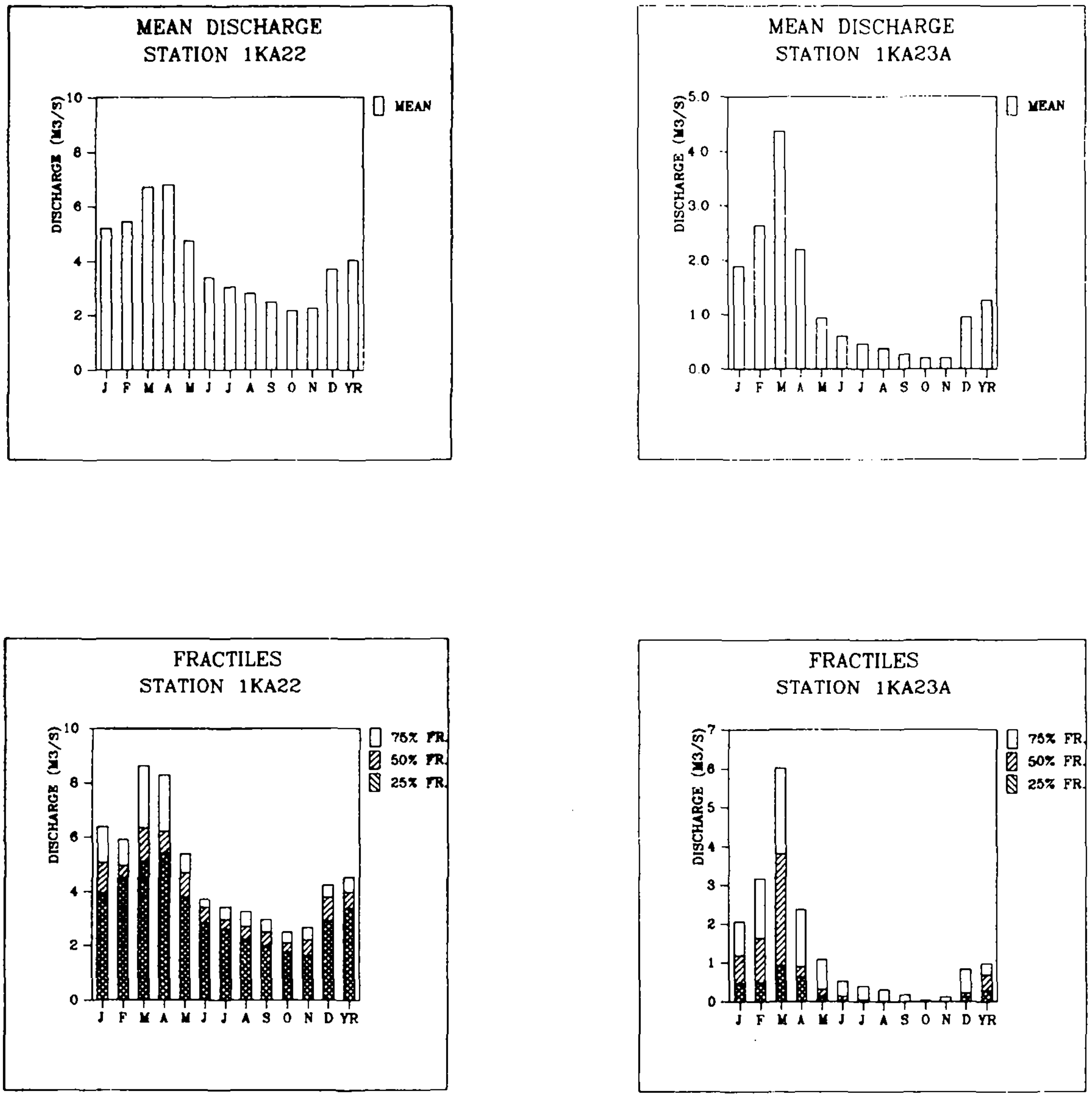


Figure 6.8 - Means, 25%, 50% and 75% fractiles of monthly flow series at the stations 1KA22 and 1KA23A.

The mean and the fractile values are plotted in Figure 6.7^{8}. The plots are also shown for the stations 1KA22 and 1KA23A in Figure 6.8. These figures provide a good illustration of the flow regime, both with respect to the variability from year to year, and the variability within the year. Hence it is seen that the mean monthly discharges at station 1KA23A vary between 0.2 m^3/s (October) and 4.4 m^3/s (March), while for March the mean discharge is below 0.9 m^3/s in 25% of the years and above 6.0 m^3/s in another 25% of the years.

Generally, it is noticed that the variability at 1KA23A is much larger than at 1KA22. Also, the difference in low flow behaviour at the two stations is evident from the figure. Station 1KA22 has relatively large low flows, indicating a considerable baseflow component, while the ephemeral Huhuni River at station 1KA23A has very small low flows. Thus the 50% fractile at 1KA23A is zero for the months August-November, indicating that the river dries up during an average of four months at least every other year.

It has been attempted to utilize the coefficient of skewness in the regionalization studies discussed below. This coefficient is a measure of the asymmetry of the distribution of monthly flows. It is noted, for example, that the mean monthly discharge in April at 1KA23A equals the 75% fractile, indicating that in some years very large flows have occurred during this month.

6.2.5 Autocorrelation analyses

The autocorrelation studies discussed in this subsection are standard analyses for hydrological time series. These studies have been carried out primarily for the sake of completeness in the analyses of priority station records, but also because the autocorrelations provide an interesting, although not very surprising, illustration of the different flow regimes. Furthermore, autocorrelation analyses as those presented below represent a necessary first step for the selection and application of stochastic streamflow generation models.

The analyses have been carried out for all priority stations with a continuous record (without gaps) of at least ten years.

The autocorrelation is defined as the serial correlation between a time series and the same series at a later point in time. This time difference is termed the time lag.

If the time series is compated to itself (zero time lag) the correlation is of course +1.0. At any other time lag the correlation varies between -1.0 and 1.0. By determining the correlation for a number of time lags (here monthly steps up to a time lag of 24 months) the autocorrelogram can be constructed. Hence the autocorrelogram reflects the persistence and the time scale of the runoff process.

In Figure 6.9[8] the autocorrelograms are shown together with the seasonal variation of the lag-1 autocorrelation coefficient. These figures are also shown for the stations 1KA22 and 1KA23A in Figure 6.10.

From the figure it is noticed that the seasonal lag-1 autocorrelation coefficients generally are largest in the dry season, when the baseflow recession dominates the hydrograph, and smallest in the transition periods between the dry and the wet season. (e.g. zero autocorrelation for station 1KA23A between November and December monthly flows).

Autocorrelograms are shown for the original discharge series (raw data), as well as for a standardised series. The discharge series has been standardised by subtracting the monthly mean from the monthly flow and dividing this difference by the monthly standard deviation.

The raw data autocorrelograms show large positive correlation at 12 and 24 months time lag, as would be expected because of the annual cycle in hydrological events. The lag-12 and lag-24 correlations are relatively small for station 1KA23A due to the large variability of the flow regime at that station. This is also apparent from Figure 6.8.

From the correlograms for the standardised series it is noticed that the standardisation has removed the annual periodicity. Thus the standardised correlograms can be interpreted in terms of persistence and time scale of the runoff process. Examination of the correlograms for the stations 1KA22 and 1KA23A shows a larger time scale (i.e. larger persistence) at 1KA22 than at 1KA23A, which is in good agreement with the baseflow component being much more dominant for the perennial Mtitu River at 1KA22 than for the ephemeral Huhuni River at 1KA23A.

However, the interpretation of the autocorrelograms is "disturbed" by frequent zero-flows in some rivers (e.g. 1KA23A). Large month to month correlations can be due either to an almost 100% baseflow with a large time scale, or to zero-flows in consecutive months.

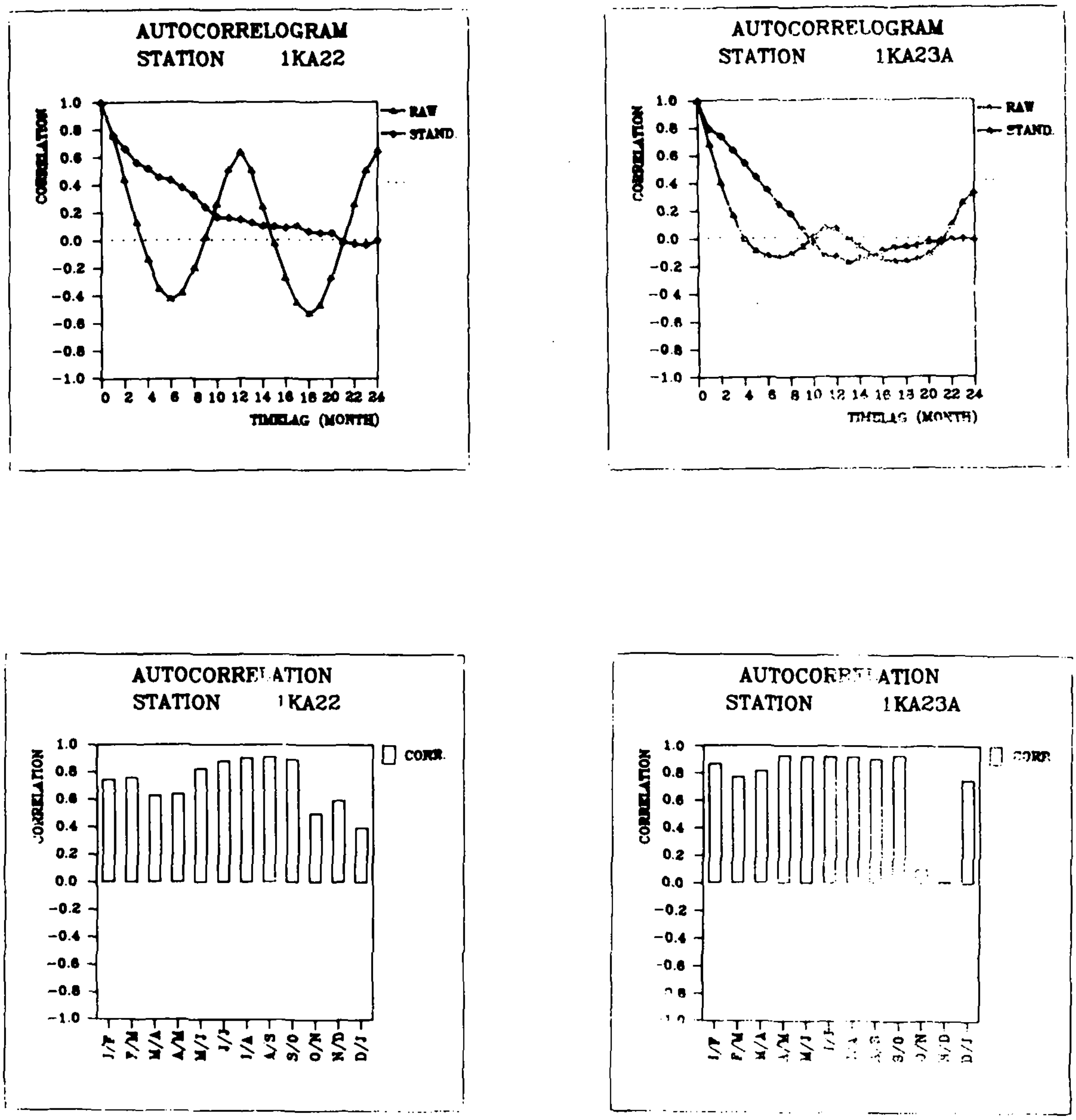


Figure 6.10 - Autocorrelograms for raw and standardised data, as well as the seasonal variation of lag-1 autocorrelation coefficient of the raw data, for the stations 1KA22 and 1KA23A.

6.2.6 Trend analyses

Some of the runoff analyses included in this chapter have been based on relatively few years of data, whereas for most analyses between 10 and 30 years of data have been available.

When dealing with fairly short data series trend and long periodic fluctuations (several years) represent possible sources of error. If different data series do not originate from the same period of time, comparisons of statistics, estimated from the data series (e.g. mean annual runoff, 10-year minimum runoff) will yield unbiased results only if there is no trend or no long periodic fluctuations in the data series.

In Chapter 3 it has been concluded that there are no significant trends or long periodic fluctuations in the rainfall data series. The evapotranspiration studies in Chapter 4 have shown no indication of trend, but the data available for these studies has not permitted a rigorous trend - or periodicity analysis. Consequently, assuming at least almost stationary evapotranspiration conditions, no trend or long periodic fluctuations would be expected in the runoff series either. In order to test this hypothesis the analyses shown in Figure 6.11 have been carried out. The curve of the accumulated discharge (mass curve) is seen to be almost rectilinear, indicating no trend and no significant fluctuations. Annual discharge has been plottet versus time and a linear regression analysis has been carried out yielding a very small correlation coefficient. A t-test has shown that a hypothesis of no trend in the data series can be accepted easily.

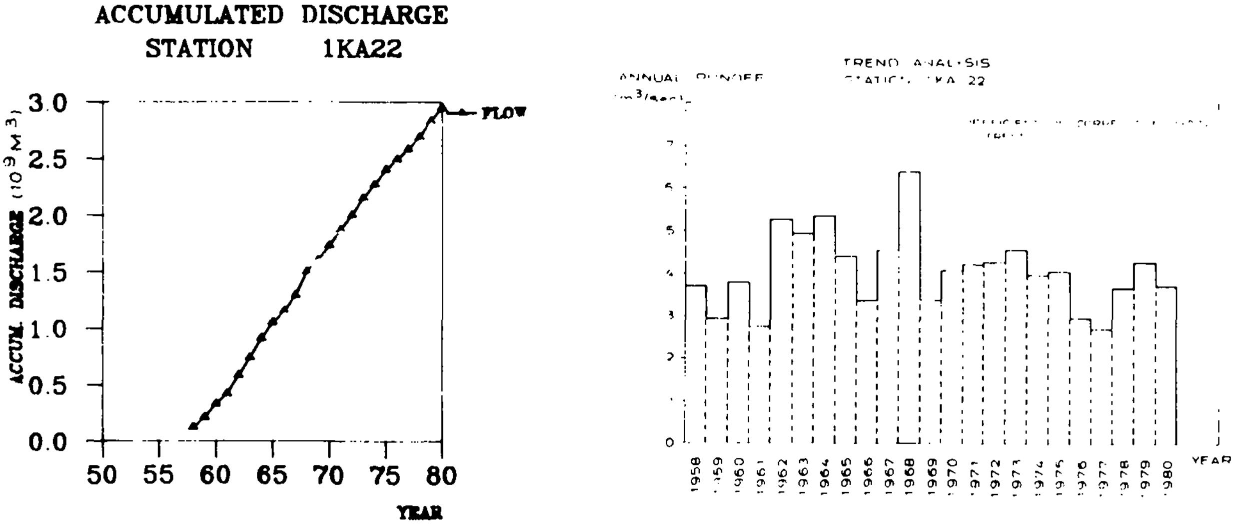


Figure 6.11 Accumulated and annual discharges versus the time for station 1KA22.

Consequently, runoff has been analysed under the assumption of no trend and no long periodic fluctuations in the data series.

6.2.7 Reservoir analysis

For many water resources projects, such as hydropower plants, irrigation and water supply schemes, the question of having sufficient reservoir capacity is a central problem. Hence, an example for one of the priority stations has been included in order to illustrate methods for determining the required storage capacity as a function of required draft under different design conditions.

The reservoir water balance components are illustrated in Figure 6.12.

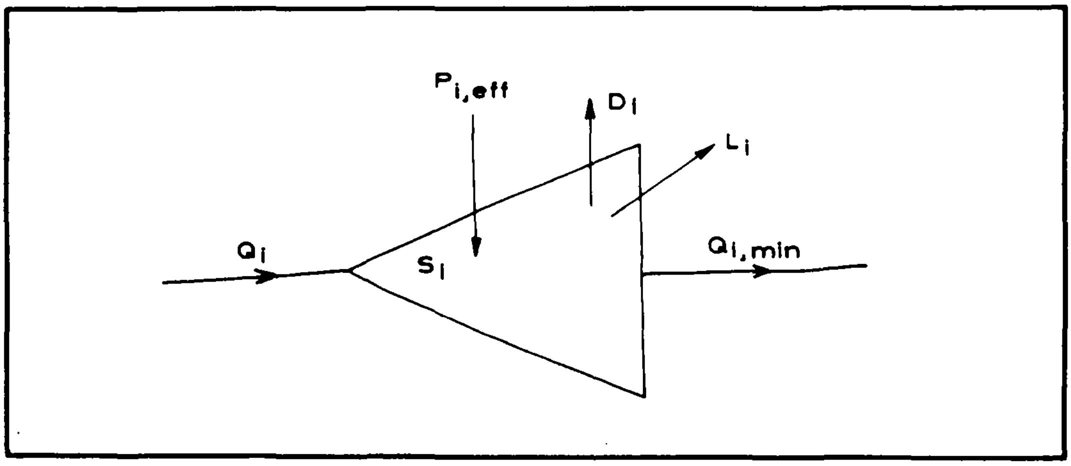


Figure 6.12 Reservoir water balance components.

The mass balance equation for this system reads

$$S_i = S_{i-1} + Q_i - D_i + P_{i,eff} - L_i - Q_{i,min} \qquad (6\text{-}4)$$

where

i = time

S_i = reservoir storage at time i

S_{i-1} = reservoir storage at time i-1

Q_i = reservoir inflow

$P_{i,eff}$ = the effective rainfall over the reservoir area (i.e. rainfall minus evaporation)

D_i = draft from reservoir

L_i = reservoir spill, where $\begin{cases} L_i = 0 \text{ for } S_i < S_{max} \\ L_i = Q_i - D_i + P_{i,eff} - Q_{i,min} \text{ for } S_i = S_{max} \end{cases}$

S_{max} = maximum storage capacity

$Q_{i,min}$ = minimum discharge required downstream of reservoir.

In reservoir simulations the minimum discharge required downstream can normally be included as part of the draft term. In the case study reported below, the effective rainfall (rainfall - evaporation) is neglected, while the draft term is considered constant over time. A spill term is inevitable because few reservoirs can be economically designed to contain the entire wet season inflow.

The reservoir equation, modified as explained above, has been applied to estimate the required storage capacity of a hypothetical reservoir by running a so-called deficit analysis, in which the required capacity is found as the largest reservoir drawdown that would be encountered in a reservoir of unlimited depth which satisfies the draft D. Figure 6.13 illustrate the principle of this approach.

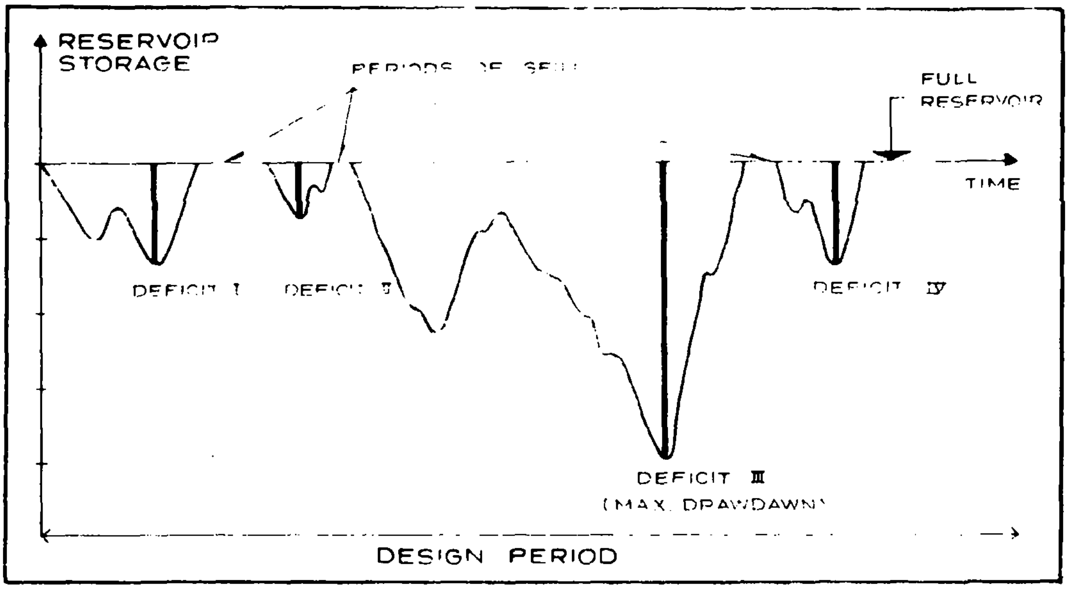


Figure 6.13 The principle of a deficit reservoir analysis.

The Hagafiro River at the gauging station 1KB19, where the catchment area is about 150 km^2, has been selected for a case study. Daily mean discharge data for the period 1961-79 have been used to simulate the reservoir behaviour for a number of different drafts D, all less than the average inflow of the 19 year record. From all the drawdowns encountered during the 19 year simulation period the 5 and the 20 year return periods of reservoir failure have been determined. These results are shown in Figure 6.14.

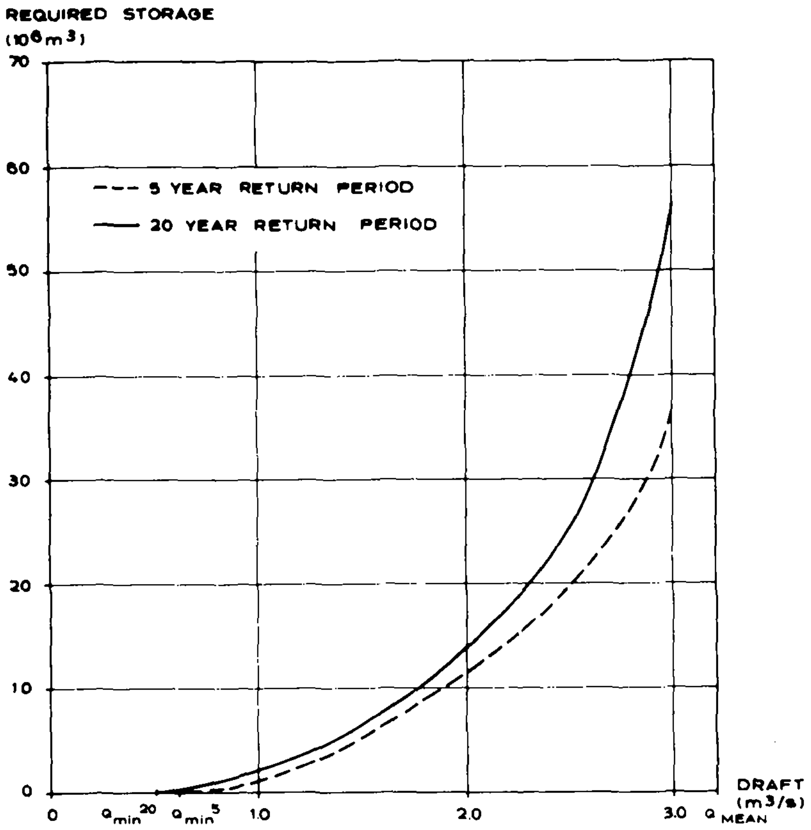


Figure 6.14 Necessary reservoir capacity as a function of draft and return period based on runoff data from 1KB19 Hagafiro River.

From the figure it is seen that the necessary reservoir capacity corresponding to a draft of 2.5 m^3/s is 20 million m^3, if a 5-year return period of reservoir failure is accepted, and 25 million m^3 for a 20-year event as the design criteria.

In order to fully utilize the information in the historical runoff series for the reservoir analyses,time series analyses are often carried out by means of stochastic streamflow generation models. By this approach synthetic streamflow series which preserve the statistical characteristics of the original historical record (e.g. mean, variance, skewness, correlation structure, distribution) are generated in order to enable the evaluation of the uncertainties associated with the curves shown in Figure 6.14. As the present analysis for 1KB19 has been carried out with the sole purpose of illustrating the principles of reservoir analysis , no stochastic model has been applied in this case. However, it should be mentioned that most of the runoff analyses performed in the previous subsection (e.g. correlation studies) are important elements of the statistical time series analyses on which a stochastic model has to be based.

6.3 Regionalisation

The primary objective of the hydrological part of the water master planning study is to provide a basin-wide inventory of surface water resources, enabling the water supply, irrigation and hydropower planners to assess the surface water availability at any location. However, exploitable surface water occurs in numerous streams throughout the regions, and only a small fraction of these streams are gauged, and then only at a single location. Hence the hydrologist must extrapolate these findings from gauged to ungauged locations, and preferably present this extrapolation in such a form that the water resources planners can get an immediate indication of the surface water potential at any point in the regions.

This process of extrapolation and basin-wide representation of runoff conditions is termed regionalisation. In the present study regionalisation efforts have been directed towards preparation of maps showing mean annual runoff and some measure of the minimum runoff. The seasonal variation in mean annual runoff is adequately illustrated in the mean monthly runoff diagrams in Figure 6.8.

In the regionalisation study all available runoff information has been used, i.e.

- Runoff data from existing hydrological stations.
- Spotgaugings, i.e. single discharge measurements at numerous locations as part of the village inventory programme.
- Information on rainfall and evapotranspiration.
- Results and conclusions from the detailed index area studies.
- Hydrogeological information.
- Information on soils and vegetation.
- Local knowledge.

It has been a matter of hydrological judgement to combine all this information in the regionalisation process.

Evidently the uncertainty of the runoff estimates as obtained in the regionalisation study is considerable, especially in ungauged areas. However, it is emphasized that the purpose of the regionalisation study is to provide a broad outline of required runoff characteristics, and hence a first estimate of surface water potential. More detailed studies will be required at specific locations where surface water utilization schemes are planned, particularly if the water demand for such schemes are in the same order of magnitude as the predicted surface water availability.

6.3.1 Mean annual runoff

A map, cf. Figure 6.15 and Drg. II-5, has been prepared showing the mean annual runoff for the three regions. This map is required because

- The mean annual runoff is an important variable in the general hydrological description of the three regions.
- The mean annual runoff gives a theoretical upper limit of the water that can be drawn from a catchment (for water supply, irrigation, hydropower or other purposes) if the necessary reservoir capacity is provided.

The main basis for the preparation of the mean annual runoff map shown in Figure 6.15 has been the runoff data from the hydrological gauging stations. The mean annual runoff has been calculated for all sufficiently reliable stations with more than 4 years of record (about 80% of all stations). For the rest of the area interpolations have been made considering average rainfall and evapotranspiration pattern, topography and geomorphology, and general information on local conditions.

From the mean annual runoff map it is evident that there is a considerable runoff variation within the three regions. Generally the variability shows the same regional pattern as the mean annual rainfall, cf. Figure 3.17.

The largest runoff amounts, in the range 800 mm/year to more than 1200 mm/year, occur north of Lake Nyasa in Mbeya region. From there the runoff in Mbeya region is decreasing gradually towards the north, where almost all the rivers are ephemeral, the mean annual runoff being below 200 mm/year.

In Iringa region the mean annual runoff is varying from more than 600 mm/year in the southern part to less than 200 mm/year in the northern part.

In Ruvuma region the mean annual runoff varies from 400-600 mm/year in the western part of the region to about 200 mm/year in the eastern part.

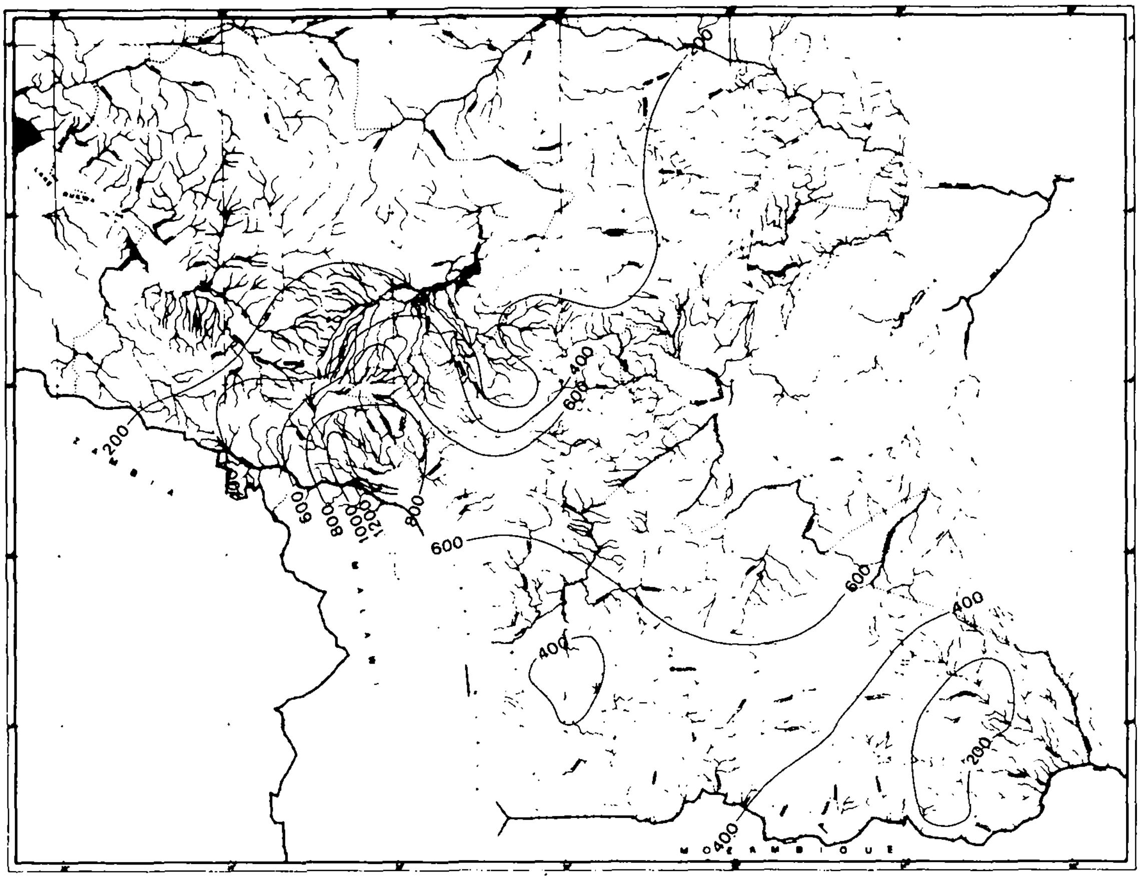


Figure 6.15 Map of mean annual runoff.

6.3.2 Minimum runoff

For rural water supply planning the minimum runoff is an important variable in evaluating the possibilities of abstracting water directly from streams for domestic water supply and animal watering purposes.

In the present hydrological study the 10 year minimum runoff has been adopted as an appropriate indicator of minimum flow conditions. The 10-year minimum runoff in the three regions as illustrated in the map in Figure 6.16 and in Drg. II-6, has been estimated by the following approach

(a) For each of the hydrological stations with a sufficiently long record the 10-year minimum runoff has been estimated from a standard frequency analysis based on the recorded annual minima and the Weibull probability distribution, cf. Subsection 6.2.3 above.

(b) The recession constants of the hydrographs in the low flow period have been estimated for a number of hydrological stations, cf. Subsection 6.2.1. An important finding in this analysis has been that the recession constants are almost constant from year to year. When comparing recession constants from large and small catchments it has generally been found that the smaller the catchment, the larger the recession constant. Generally for perennial streams in small catchments recession constants less than 0.015 day^{-1} have been found, while recession constant larger than 0.015 day^{-1} are characteristic for non-perennial streams.

(c) Numerous spotgaugings have been performed during 1980 at locations other than the hydrological gauging stations. As most of the spotgaugings have been carried out in the dry season the results have been applicable estimating the minimum runoff at these locations. The 10-year minimum flow at the location of the spotgauging has been estimated by first estimating the 1980 low flow at the location, and subsequently transform this to a 10-year minimum value, as explained in the following.

(d) For the spotgaugings at locations, close to a hydrological station with 1980 flow data, the recession constant k (day^{-1}), for the gauging station and the time t (days), defined as the time from the date of the spotgauging to the date of the 1980 minimum flow event at the gauging station, have been determined. The 1980 minimum flow at the location of the spotgauging has been estimated as

$$q_{1980}^{\min} = q_o e^{-tk} \qquad (6\text{-}5)$$

where

$q_{1980}^{\min}$ = the 1980 minimum flow at the location of the spotgauging $[\text{l/s/km}^2]$

q_o = the result of the spotgauging $[\text{l/s/km}^2]$

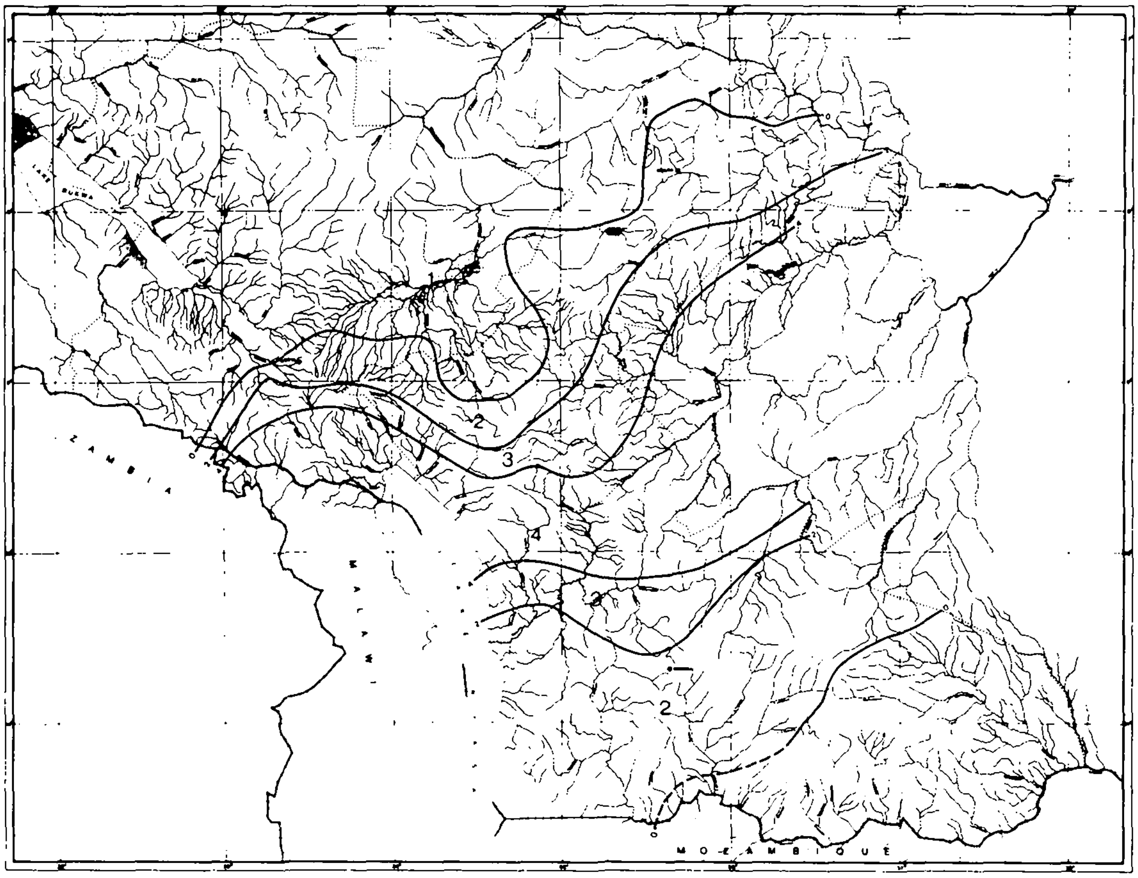


Figure 6.16 - 10-year minimum runoff. (1 = Dry, 2 = 80% of streams has a 10-year minimum runoff in the interval 0-2 l/s/km^2, 3 = 80% of streams has a 10-year minimum flow in the interval 2-4 l/s/km^2, 4 = 80% of streams has a 10-year minimum flow above 4 l/s/km^2).

(e) For spotgaugings a considerable distance from any hydrological gauging stations the approach (d) has been applied, but with k- and t-values based on a number of 1980 hydrographs for surrounding stations.

(f) For the spotgaugings close to a hydrological station without 1980 flow data, the minimum 1980 flow for the hydrological station had to be estimated prior to proceeding by approach (d). 1980 minimum flows for such stations have been estimated from the 1980 rainfall and the 10-year minimum runoff and - rainfall as follows:

$$\frac{Q^{min}_{1980}}{Q^{min}_{T=10}} = \frac{P_{1980}}{P^{min}_{T=10}} \qquad (6\text{-}6)$$

where

Q^{min}_{1980} = the desired minimum runoff at the gauging station in 1980 [l/s/km^2].

$Q^{min}_{T=10}$ = 10-year minimum runoff at the gauging station [l/s/km^2].

P_{1980} = total rainfall in 1980 [mm/year].

$P^{min}_{T=10}$ = 10-year minimum rainfall estimated from Figure 3.18 [mm/year].

The t-value has been estimated from surrounding stations.

(g) In order to estimate the 10-year minimum flow from the spot-gauged locations the following relationship has been used:

$$\frac{q^{min}_{T=10}}{Q^{min}_{T=10}} = \frac{q^{min}_{1980}}{Q^{min}_{1980}} \qquad (6\text{-}7)$$

where

q = runoff at the location of the spotgauging [l/s/km^2].

Q = runoff at the nearest gauging station(s) [l/s/km^2].

(h) Some of the questions contained in the village inventory questionnaires were designed to support the hydrologists' low flow evaluations, such as: "Do the streams run dry ?", "If so, in which month do they run dry ?" etc. The answers to these questions, together with the information from field inspections and the Tanzanian counterparts' local knowledge have formed the main basis for the hydrological judgements to be made in order to interpret and regionalise the results from the above analyses.

Low flow conditions in the regions are characterised by considerable spatial variability, local geological, topographical and land cover conditions playing a major role for the low flow at a specific location. Hence, as emphasised also in the remarks to the mean annual runoff map above, the 10-year minimum runoff map shown in Figure 6.16 must be applied with caution, particularly at locations where water demands are comparable to the indicated minimum flow.

The general regional pattern of the 10-year minimum runoff is seen to resemble the regional pattern of the mean annual runoff, cf. Figure 6.15 and hence also to some extent the mean annual isohyetal pattern.

From the map it is noticed that there are two broad areas in the three regions with zero 10-year minimum flow, i.e. areas where streams are non-perennial. The largest area is the northern part of Mbeya and Iringa regions where rainfall is low and potential evaporation high. The other area is the eastern part of the Ruvuma region where rainfall is relatively low, and baseflow conditions are poor because of the impermeable rocks and a thin layer of soil characterising the formations in eastern Ruvuma.

Furthermore it is noticed that in the central part of the regions, i.e. in the southern parts of Mbeya and Iringa and in the north-western part of Ruvuma, the surface water potential is quite good with 10-year minimum flows larger than 2 $l/s/km^2$.

6.3.3 Other regional considerations

In order to identify broad regional relationships to support the regionalisation efforts it has been attempted to relate the following regional characteristics and hydrological variables:

- Geographical location.
- Geomorphology.
- Mean annual rainfall.

to the following runoff variables:

- Mean annual runoff.
- 25% fractile of runoff from the duration curve, cf. Subsection 6.2.2.
- 75% fractile of runoff from duration curve.
- 10-year minimum runoff.
- Annual runoff statistics, such as the coefficient of variation and the coefficient of skewness.

The purpose of these attempts has been to support the estimates of mean annual runoff and 10-year minimum runoff, as well as to obtain regional information on other runoff variables. In the following only those relationships which have given promising results are discussed.

In Figure 6.17 the relationship between mean annual rainfall and mean annual runoff is shown for selected stations listed in Table 6.11[8]. The stations which have been selected for this purpose are the ones with reliable data and sufficiently long records. The same relationship for a larger number of stations is shown in Figure 6.18[8] and in Table 6.12[8]. In these figures the geomorphological zones to which the respective catchments belong are indicated.

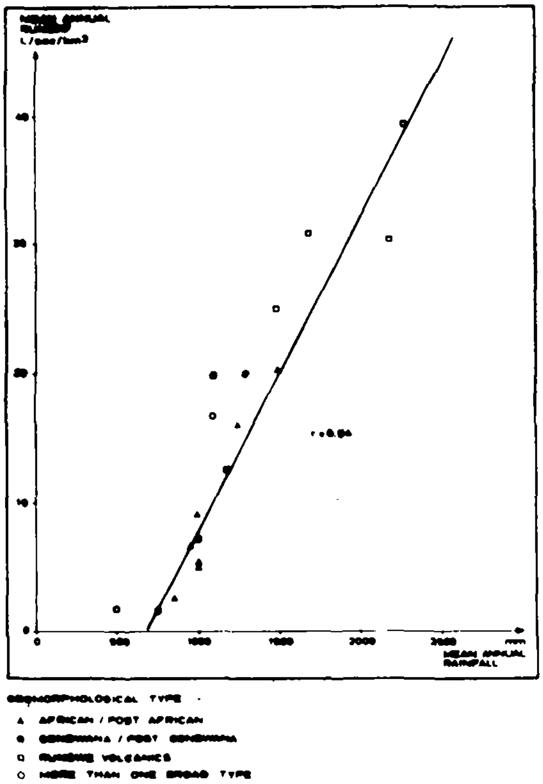


Figure 6.17 Mean annual runoff plotted against mean annual rainfall for selected catchments.

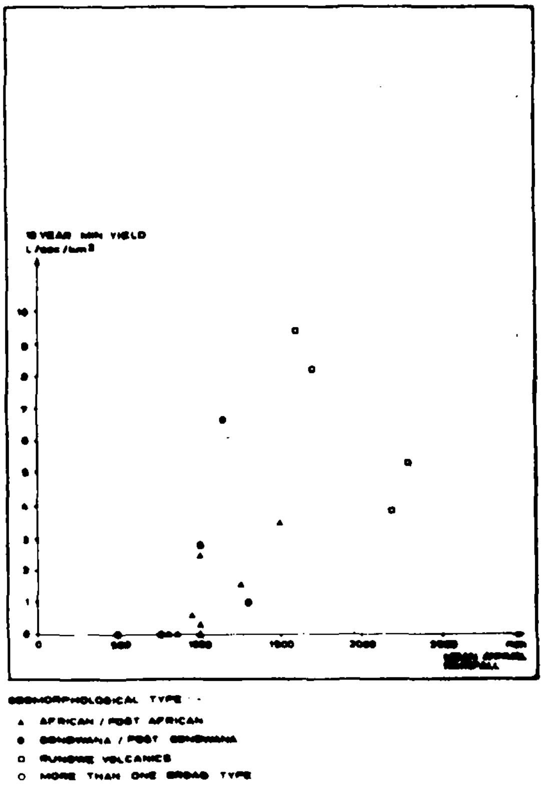


Figure 6.19 10-year minimum runoff plotted against mean annual rainfall for selected catchments.

In Figure 6.17 the linear regression line between mean annual rainfall and mean annual runoff is shown. This regression analysis has indicated a surprisingly high correlation ($r = 0.94$) between the mean annual rainfall and the mean annual runoff. Furthermore the correlation does not show a marked dependence on the geomorphological zones of the catchments. From Figure 6.18[8] the same conclusion can be drawn, although the correlation in this case is a little weaker. It is consequently concluded that mean annual rainfall is a good index for mean annual runoff, a finding which to some extent has supported the regionalisation of mean annual runoff (cf. Subsection 6.3.1).

In Figure 6.19, the 10-year minimum runoff is plotted against the mean annual rainfall, the geomorphological zones being indicated on the plot. Evidently there is no general relationship between the 10-year minimum flow and the mean annual rainfall. There is a tendency for the Rungwe-catchments to have the largest minimum flows, but this may as well be due to the large rainfall in these catchments, as to the difference in the geomorphological zones. In the same way, it is not possible to make any clear distinction here between the behaviour of the African-catchments and the Gondwana-catchments.

In the Figures 6.20, 6.21 and 6.22 the 25% fractile of the monthly flows Q_{25}, the 75% fractile Q_{75}, and the ratio Q_{75}/Q_{25} respectively are plotted against the mean annual rainfall. As in Figure 6.17 and Figure 6.19 it is not possible from these correlations to draw conclusions concerning a behaviour of different geomorphological zones. The particular hydrological effects of a geomorphological zone may, however, have been masked by inhomogenities in the catchment. The rainfall seems to be a quite good indicator of runoff characteristics. The Q_{25} in Figure 6.20 may be interpreted as pure baseflow in the middle of the dry season. The dependence of hydrological characteristics on the geomorphological zones in the catchment should, however, be studied more closely when more data become available as the physical conditions of which geomorphology is an indicator must have a hydrological effect.

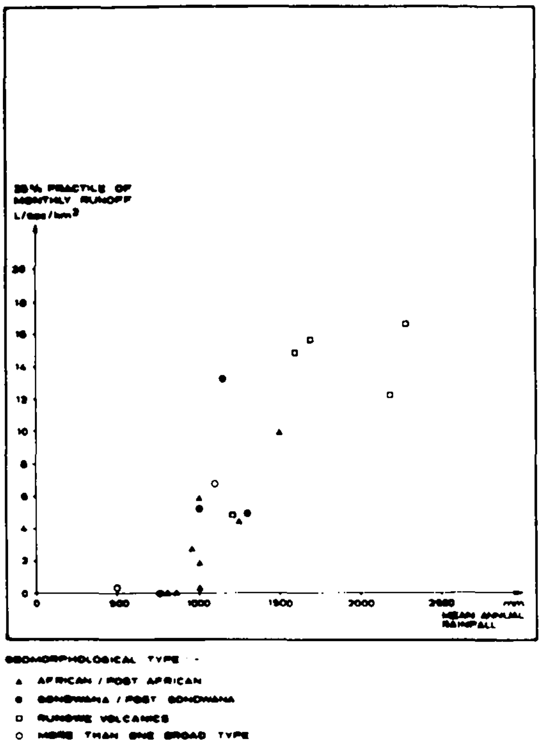


Figure 6.20 - 25% fractile of the monthly flows, Q_{25}, plotted against mean annual rainfall for selected catchments.

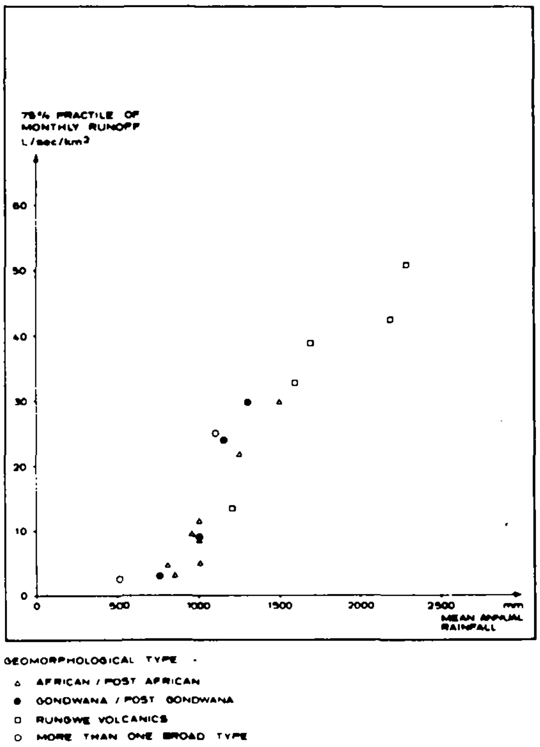


Figure 6.21 - 75% fractile of the monthly flows, Q_{75}, plotted against mean annual rainfall for selected catchments.

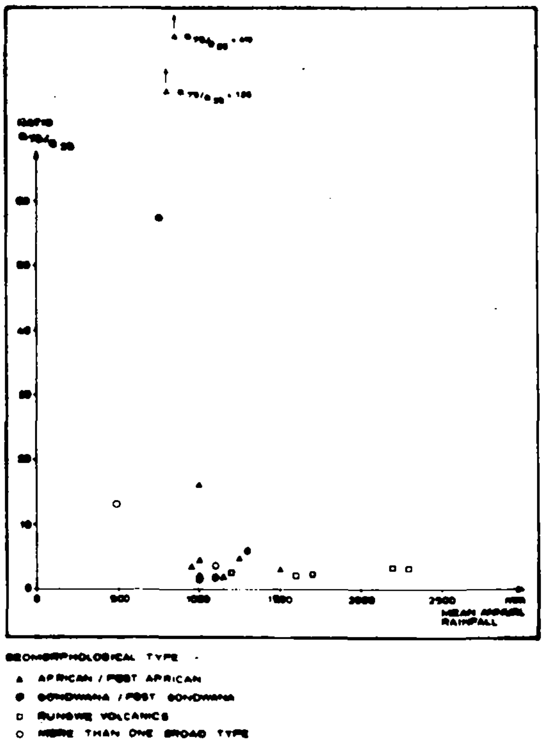


Figure 6.22 - The ratio between the 75% and the 25% fractiles of the monthly flows, Q_{75}/Q_{25}, plotted against mean annual rainfall for selected catchments.

6.4 Recommendations

A number of standard data representations and analyses have been presented in this chapter which should be routinely performed by Maji on the continously checked and updated data in the data base at Maji Ubungo.

A particularly useful data representation is the hydrograph plot. Hopefully Maji will be provided with computer facilities of its own very soon (cf. Section 5.8) and one of the first tasks following the data base and -processing set-up and organization should be to arrange for routinely plotting and publication of hydrographs. (Assuming that plotting hardware and software will be part of a future computer installation at Maji Ubungo).

Most of the standard analyses presented here require computer processing, but some (like e.g. the extreme value analyses) can be performed manually and as such be carried out in the regional offices as well.

It is recommended that a range of standard software for hydrological data processing and analysis be transferred to Maji and installed at the (hopefully) coming computer facility at Ubungo. Training of Maji staff should be provided for as part of the software transfer and installation.

7. INDEX AREA STUDIES

7.1 Introduction

7.1.1 Purpose of the index area studies

As a supplement to the hydrological analyses based on all available data in the three regions, and to the more detailed analyses from selected stations (priority discharge stations, long term precipitation and evapotranspiration records), in-depth hydrological studies have been performed on three representative catchments (index areas).

The principal objectives of the index area studies have been the following:

- To perform detailed analyses of well gauged catchments, located in different hydrological regimes
- To obtain general hydrological conclusions to be extrapolated to other catchments which have been subject to less detailed investigations.

7.1.2 Approach to index area studies

In the selection of index catchments the following criteria have been applied:

- A maximum of three index areas can be considered within the scope of the present study.
- The catchments shall represent a reasonable cross-section of the characteristic hydrological and hydrogeological regimes prevailing in the three regions.
- The catchments shall represent a range of catchment series of particular relevance for the rural water supply studies.
- Catchments with a high reliability of streamflow - and rainfall data shall be given priority.
- Catchments with long simultaneous records of streamflow and rainfall records shall be given priority.

On the basis of these criteria the following three catchments were selected as index areas:

- The Kiwira catchment upstream of the discharge station 1RC5A, located in Mbeya region.

- The Lt. Ruaha catchment upstream of the discharge station 1KA32A, located in Iringa region.
- The Mngaka catchment upstream of the discharge station 1RB6, located in Ruvuma region.

The locations of the catchments are shown in Figure 7.1.

Although the catchments represent a wide variety of series, slopes, vegetation, mean annual rainfall and potential evapotranspiration it has not been possible to cover all the different kinds of hydrological regimes in the three regions. The streams of the three index areas are perennial, while there are several non-perennial streams in the semi-desert areas in the northern part of Mbeya and Iringa, e.g. 3DA3 and 3D4, where the mean areal rainfall is less than 800 mm/year. Non-perennial streams also dominate the formations in the eastern part of Ruvuma, e.g. 1Q8, where the soil cover is very thin. As evident from the stream flow hydrographs, cf. Chapter 5, the non-perennial streams are generally much more flashy than the perennial streams, i.e. quickly responding to rainfall events, and without significant baseflow components. Unfortunately, it has not been possible to identify a non-perennial stream as an index catchment because very few reliable, long term rainfall stations are located in these areas.

The areas of the three index catchments are 220 km^2, 760 km^2 and 690 km^2, respectively. From a rural water supply point of view it would have been desirable to include also a smaller index catchment. However, only five gauged catchments have areas smaller than 100 km^2, (1KA16, 1KA45, 1KA51A, 3A7A and 3B8), and in these catchments either the discharge data were of insufficient reliability for the index area studies, or no useable representative rainfall data were available.

Thorough field inspection programmes were carried out in each of the index areas:

- 6-10 discharge measurements have been performed, predominantly in the low flow period.
- At the discharge gauging stations the cross sections of the rivers have been checked, and the rating curve carefully analysed.
- Almost all of the rainfall stations were inspected, and their data reliability evaluated.
- Field excursions were made throughout the catchment in order to assess

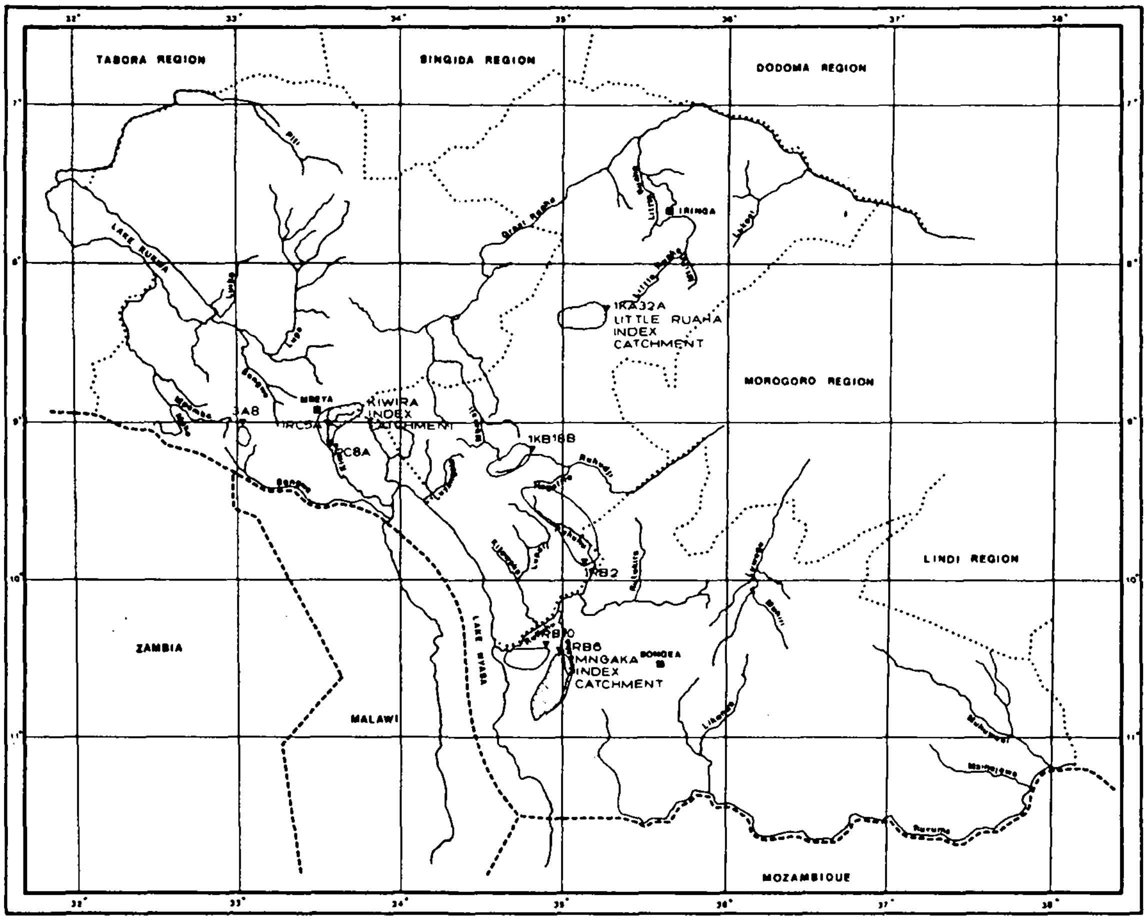


Figure 7.1 - Location of the three index catchments, the Ruhudji catchment (1KB18B) and the four catchments on which NAM simulations with the "standard" parameter set have been carried out.

features of importance for the hydrological studies (soils, vegetation, topography etc.)

- Supplementary daily rain gauges, pluviographs and evaporation pans were established in the catchments.

The principal elements of the index area studies have been detailed studies of spatial rainfall variability and mathematical modelling of the rainfall-runoff processes. The main purpose of the modelling studies has been to investigate the water balance and the general hydrological behaviour of the catchments, including actual evapotranspiration, soil moisture variation, groundwater recharge and the distribution of runoff in overland flow, interflow and baseflow components.

The usefulness of mathematical hydrological modelling techniques in the regions has been illustrated by extending the short streamflow record of Mngaka by using the longer records of rainfall over the catchment, and the possibility of transferring model parameters to ungauged catchments has been investigated with quite encouraging results.

7.2 Catchment descriptions

7.2.1 The Kiwira catchment

The Kiwira catchment at the discharge gauging station 1RC5A at Kiwira village is located in the Rungwe district in Mbeya region. The catchment area of 220 km^2 is shown in Figure 7.2.

Geology

The Rungwe district is a volcanic, mountainous area, located in the geomorphological zone called the Rungwe Volcanics (cf. Volume 9 of this report). The volcanic rocks and the alkaline basalts are covered by a thick layer of volcanic ash. Outcrops of basalts can be seen a few places.

Topography

The catchment is located between the Rungwe mountain to the south, the Mporoto mountain ridge to the north and the Kipingere ranges to the east. It is a steep catchment falling from 2960 m to 1360 m above sea level over a distance of about 30 km, measured from the topmost point of the stream to the outlet of the catchment at the gauging station. The average slope is about 5%. However, the main part of the basin is made up of a plateau

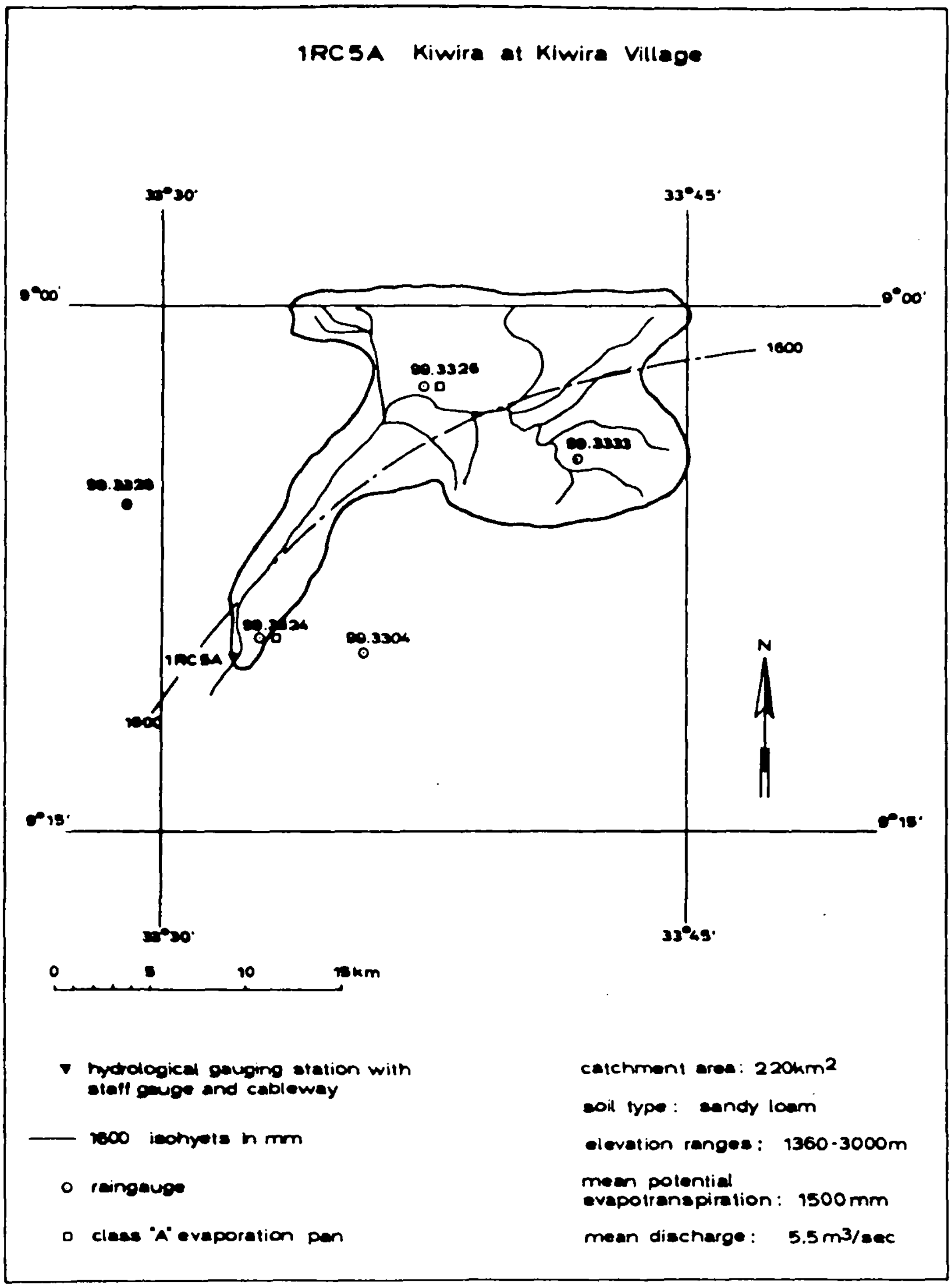


Figure 7.2 Map of the Kiwira index catchment.

between the three mountainous formations. The elevation of this plateau is 1600-2300 m above sea level.

Soils

The soils are loam and sandy loam of volcanic origin. The drainage and the water storage properties are good. The density of the drainage system is low, which is an indication of the good drainage properties of the soils. The good moisture storage properties are indicated by the agricultural production in the area. For instance both maize and tomatoes, planted at the end of the rainy season, grow very well in the dry season without irrigation.

Climate and hydrology

The mean annual rainfall is about 1600 mm varying from below 1400 mm in dry years to more than 2000 mm in wet years. The mean annual potential evapotranspiration is about 1500 mm (cf. Chapter 4) with a relatively small variation from year to year. The mean annual runoff is about 800 mm, varying from below 600 mm in dry years to more than 900 mm in wet years. The Kiwira river at the gauging station is perennial.

Mean annual rainfall exceeding mean annual potential evapotranspiration shows that the catchment is situated in a surplus area, but with two pronounced seasons there is considerable variation within the year. The rainy season starts in November and ends in May, while the dry season covers the rest of the year.

Typical rainfall,potential evaporation and runoff patterns appear from the hydrological model results shown in Figure 7.11 below.

Vegetation

An evergreen tropical mountainous forest covers about one third of the catchment. A relatively small part of the catchment is covered by planted forest of cedars. The forest area covers about half of the catchment, while the rest is covered by grass and agricultural crops like bananas, maize, potatoes, pyrethrum and vegetables.

7.2.2 The Lt. Ruaha catchment

The Lt. Ruaha catchment at the discharge gauging station 1KA32A at Makalala is located in the Iringa region. The catchment area of 760 km^2 is shown in Figure 7.3.

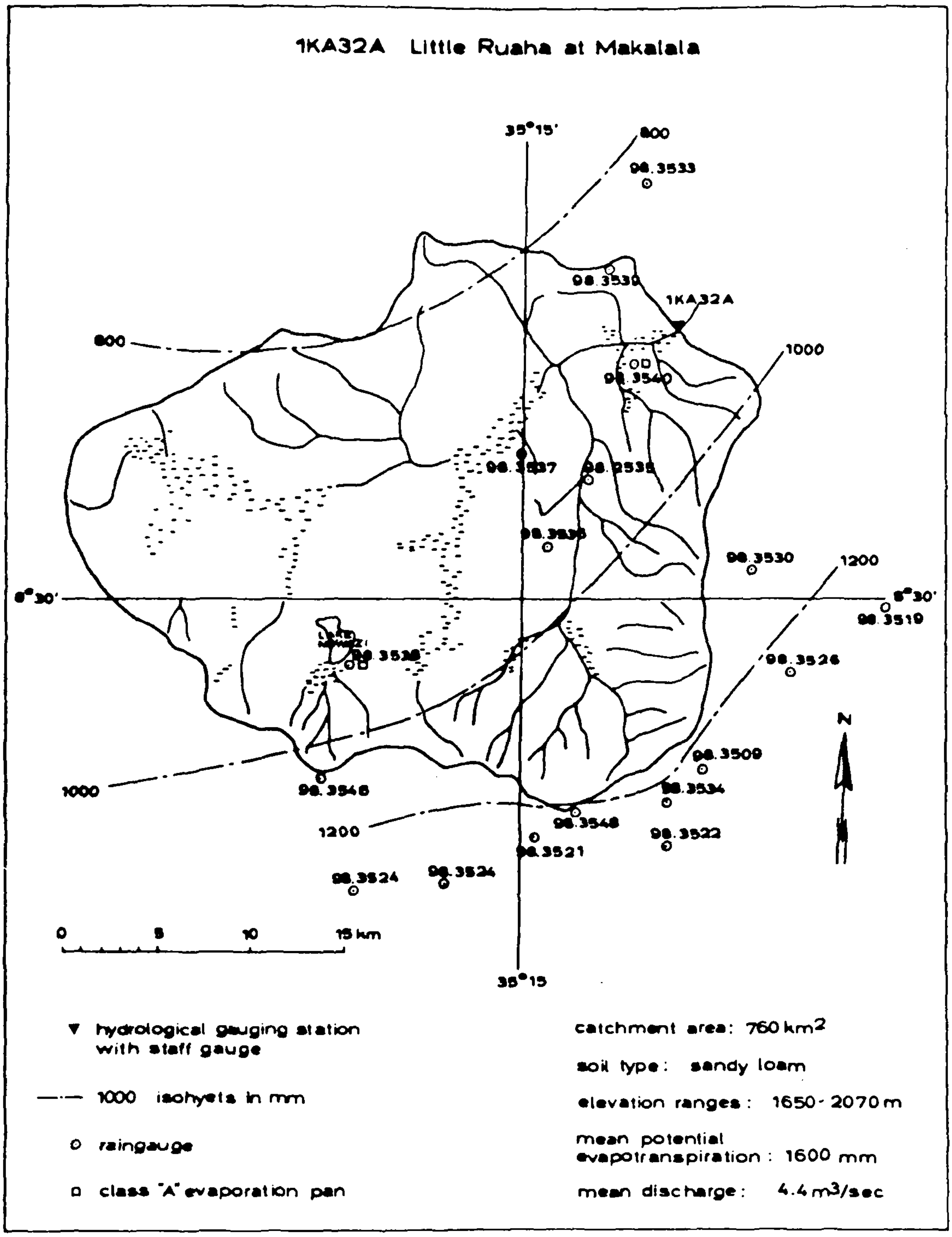


Figure 7.3 Map of the Lt. Ruaha index catchment.

Geology

The catchment is located on the African erosion surface (cf. Volume 9). The weathered rocks are covered by a thick layer (20-40 m) of lateritic soil.

Topography

The catchment is located south of the Sao Hill and north of the Mufundi escarpment, which at the highest points reaches about 2000 m above sea level. The catchment is relatively flat with the lowest point about 1650 m above sea level. The average slope is about 1%. The drainage system is not very dense.

Soil

The catchment is essentially covered with sandy soils of good drainage and water storage properties. However, in the river valleys more clayey and silt-clayey soils are found, and swamps dominate the central and western portion of the catchment.

Climate and Hydrology

The mean annual rainfall is about 1000 mm varying from below 900 mm in dry years to above 1200 mm in wet years. The variability of the mean annual rainfall is relatively high within the catchment, varying from about 1200 mm in the southern hills to about 800 mm in the northern part of the catchment.

The mean annual potential evapotranspiration, is about 1600 mm with a relatively small variation from year to year.

The mean annual runoff is about 200 mm varying from below 100 mm in dry years to above 400 mm in wet years. The Lt. Ruaha river is perennial at the gauging station.

The mean annual potential evapotranspiration exceeding mean annual rainfall shows that the catchment is located in a deficit area. There is a considerable surplus in the rainy season from November to May and a correspondingly high deficit in the rest of the year. Typical rainfall, potential evapotranspiration and runoff patterns appear from the hydrological model results shown in Figure 7.14 below.

The distinction between the rainy and the dry season is most pronounced in the northern part of the catchment, while in the southern hills it usually rains a little in the dry period.

Vegetation

The natural vegetation of the catchment is grassland in the northern part and wooded grassland in the southern part. A portion of the catchment is forested with pine trees. About 15% of the area is covered by swamps with aquatic vegetaion. The rest of the area, about 60%, is covered by agricultural crops, mostly tea and maize.

7.2.3 The Mngaka catchment

The Mngaka catchment at the discharge gauging station 1RB6 is located in the Ruvuma region. The catchment area of 690 km^2 is shown in Figure 7.4.

Geology

The catchment is located in three geomorphological regions, Gondwana in the southern part of the catchment, Congo in the northern part and African in between (cf. Volume 9). Weathered rocks are covered by a thick layer of sandy loam.

Topography

The area is very hilly, especially in the southern mountainous part. The elevation ranges from 1900 m above sea level in the south to 800 m at the outlet of the catchment in the north, which implicates a mean slope of about 2%. However, the slope is more than 10% in the southernmost portion, and 1.5-2% in the central part of the catchment. The drainage system is relatively dense.

Soils

The catchment area is covered by sandy loam with good drainage and water storage properties.

Climate and hydrology

The mean annual rainfall is about 1200 mm varying from below 1000 mm in dry years to above 1500 mm in wet years. Mean annual rainfall varies from about 1300 mm in the south-east to about 1000 mm in the north-west.

The mean annual potential evapotranspiration is about 1300 mm with a relatively small variation from year to year.

The mean annual runoff is about 400 mm varying from below 300 mm in dry years to above 600 mm in wet years. The Mngaka river is perennial at the gauging station.

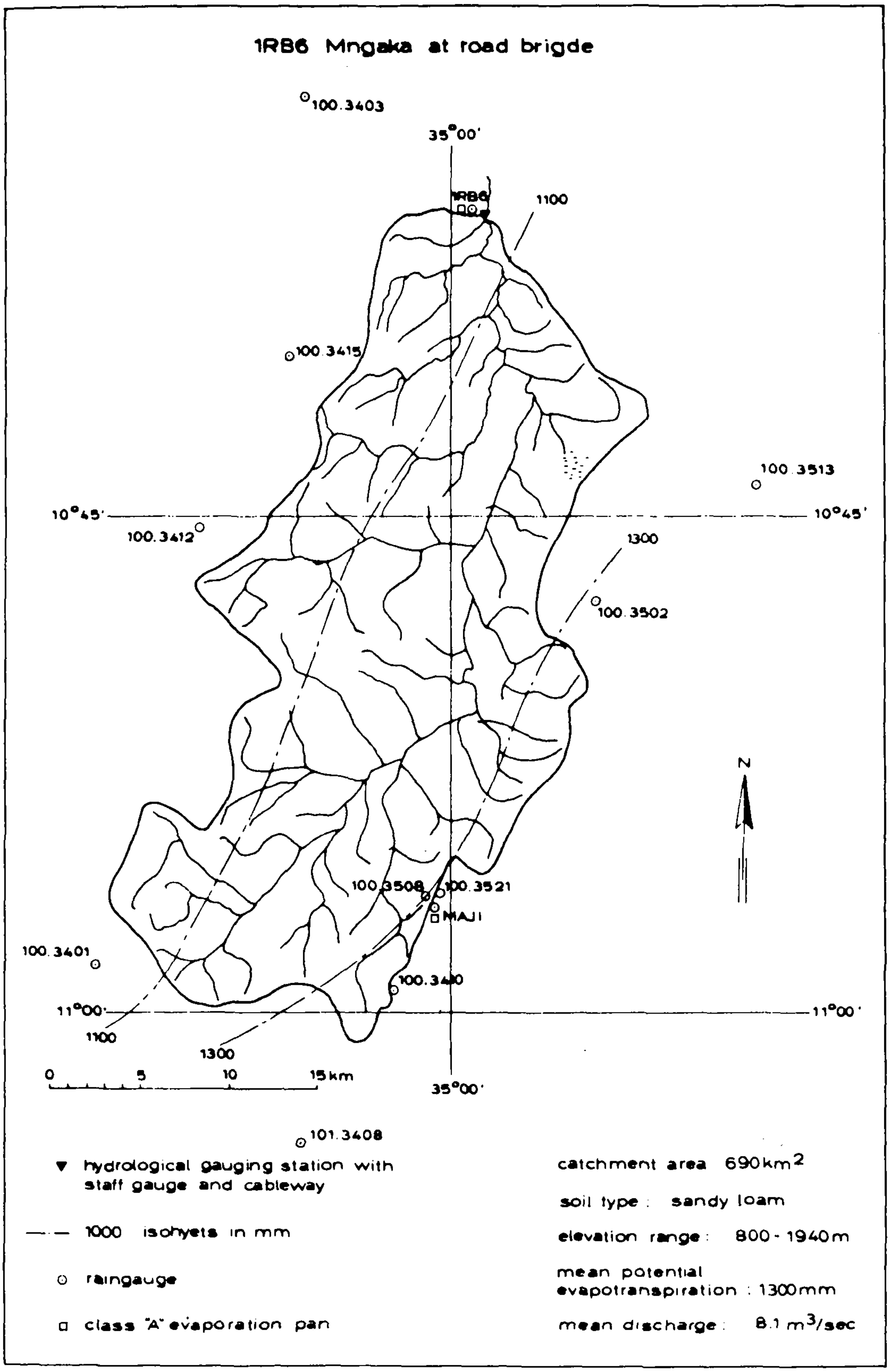


Figure 7.4 Map of the Mngaka index catchment.

Although the mean annual rainfall is of the same size as the mean potential evapotranspiration there is a large seasonal variability, particularly for rainfall. Typical rainfall, potential evapotranspiration and runoff patterns appear from the hydrological model results shown in Figure 7.18 below.

The two pronounced seasons are the rainy season from November to May and the dry season the rest of the year.

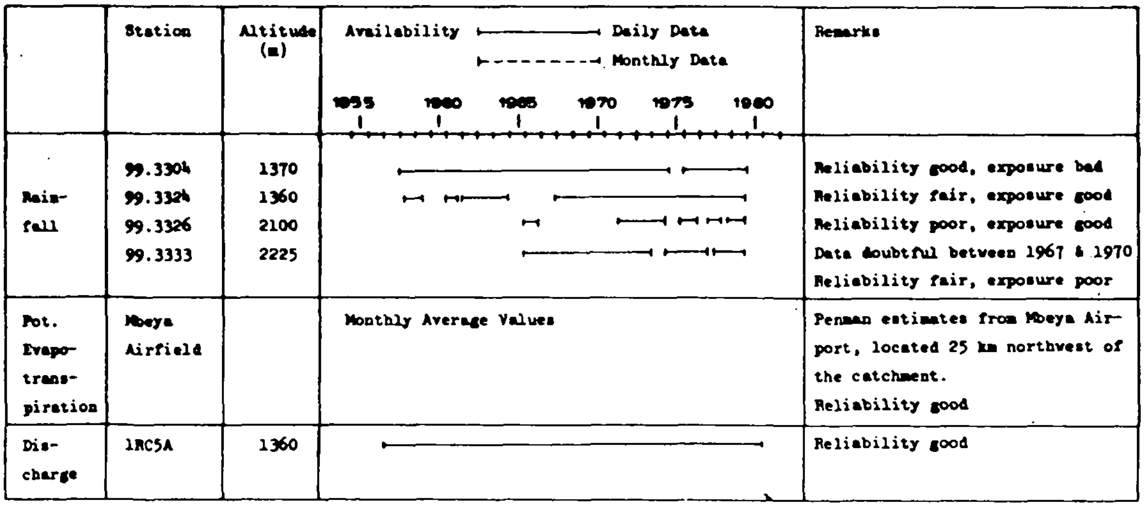
Vegetation

Almost the entire northern part of the catchment is covered by miombo woodland, with hardly any cultivation. The southern part of the catchment is well cultivated with maize, bananas, wheat, vegetables, pyrethrum and a little coffee.

7.3 Data base and preparation of data

7.3.1 The Kiwira catchment

The data availability is illustrated in Figure 7.5.



	Station	Altitude (m)	Availability ⊢——⊣ Daily Data ⊢- - - -⊣ Monthly Data 1955 1960 1965 1970 1975 1980	Remarks
Rain-fall	99.3304	1370		Reliability good, exposure bad
	99.3324	1360		Reliability fair, exposure good
	99.3326	2100		Reliability poor, exposure good
	99.3333	2225		Data doubtful between 1967 & 1970 Reliability fair, exposure poor
Pot. Evapo-trans-piration	Mbeya Airfield		Monthly Average Values	Penman estimates from Mbeya Airport, located 25 km northwest of the catchment. Reliability good
Dis-charge	1RC5A	1360		Reliability good

Figure 7.5 Data availability in the Kiwira catchment.

The locations of the rainfall- and discharge gauging stations are shown in Figure 7.2.

Rainfall

It is seen that the most reliable rainfall station, 99.3304, is located outside the catchment in an area with an average annual rainfall which is 10-20% larger than that of the Kiwira catchment itself.

It is also noticed that the records from the two rainfall stations located in the upper plateau of the catchment, 99.3326 and 99.3333, contain several gaps. These gaps must be filled in order to obtain a continuous record of mean areal daily rainfall to be used in the rainfall-runoff modelling studies.

The structure of the rainfall pattern has been studied by investigating the correlation between the annual rainfall of the four rainfall stations. From these results, shown in Table 7.1, it is seen that the correlation between the annual rainfalls is relatively small. (A correlation coefficient of more than 0.85-0.90 signifies a high degree of correlation). Because of the relatively small number of years available for the analysis, and because the correlation coefficients are based on different sequences of years, firm conclusions can not be drawn on the basis of this material. However, it should be noticed that there is no significant correlation between the stations 99.3326 and 99.3333, between 99.3324 and 99.3304 or between 99.3324 and 99.3333. It must be expected that correlation coefficient based on monthly or daily rainfalls are even smaller than those based on annual rainfall.

Station Station	99.3304	99.3324	99.3326	99.3333
99.3304	1.0 (21)	-0.29 (14)	0.65 (6)	0.70 (11)
99.3324		1.0 (15)	0.71 (5)	-0.23 (10)
99.3326			1.0 (6)	0.10 (5)
99.3333				1.0 (12)

Table 7.1 Correlation coefficients between annual rainfall values for stations in or close to the Kiwira catchment. The values in () are the number of values (years) on which the correlation coefficients are based.

The high spatial variability of rainfall indicated by the above analysis is probably caused by convective cells dominating the rainfall pattern. However, observation uncertainties also contribute to reducing correlation coefficients.

The three stations within the catchment, 99.3324, 99.3326 and 99.3333, have been used in the establishment of a record of daily mean areal rainfall for the period 1966-1979. In periods when data have been available from all 3 stations the weight factors 0.11, 0.43 and 0.46, derived from the Thiessen polygonal method, have been applied. In periods where data from one or two of the stations have not been available, an indirect gap-filling technique has been applied by adjusting the weights of the other stations in such periods. The weight coefficients are shown in Figure 7.6[8].

It is noted that the rainfall station 99.3304 has not been included in the determination of mean areal rainfall for the catchment.

Potential evapotranspiration

As discussed in Chapter 4 the reliability of the Penman estimates of potential evapotranspiration is generally regarded to be higher than the reliability of pan evaporation measurements. For this reason the index area studies have been based on Penman estimates of potential evapotranspiration.

Furthermore, as discussed in Chapter 4, the year to year variability of potential evapotranspiration is relatively small (typical standard deviations of about 5% of the mean annual values) compared to the variability of the annual rainfall. The annual variation, furthermore, is of local significance such that a transfer of an annual variation from a long range station outside the catchment to superimpose on a mean annual E_p within the catchment is not possible.

The nearest meteorological station with data on potential evapotranspiration is located at the Mbeya Airport, cf. Chapter 4. The Penman estimates from that station, shown in Table 7.9 below, have been used directly.

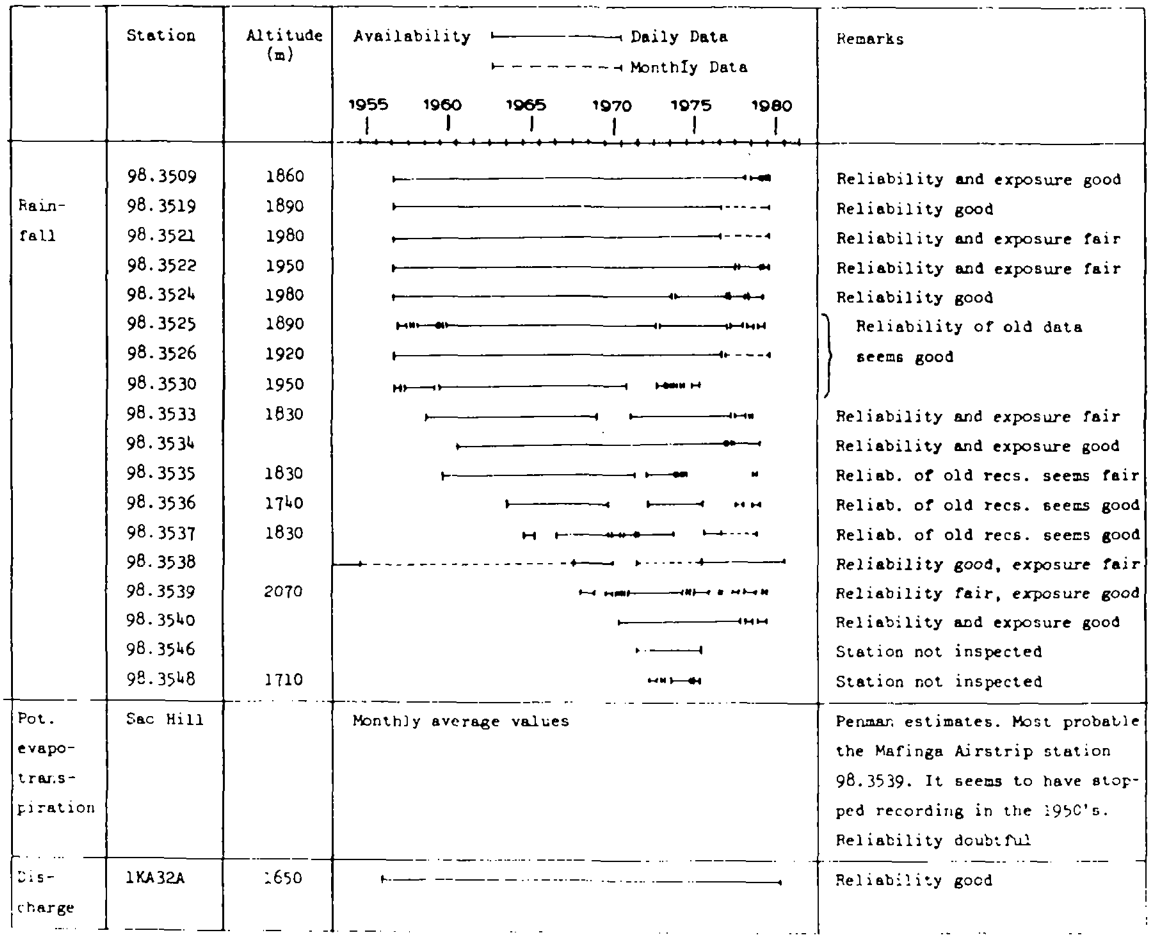
As only average monthly values have been available, the same potential evapotranspiration values have been applied in every year of the model simulations. The small variation in mean annual potential evapotranspiration justifies this approach.

Discharge

As discussed in Chapter 5 the rating curve, water level- and discharge data from 1RC5A have been subject to careful review, and the discharge data can therefore be considered quite reliable.

7.3.2 The Lt. Ruaha catchment

The data availability is shown in Figure 7.7. The locations of the rainfall- and discharge gauging stations can be seen in Figure 7.3.



	Station	Altitude (m)	Availability	Remarks
Rainfall	98.3509	1860		Reliability and exposure good
	98.3519	1890		Reliability good
	98.3521	1980		Reliability and exposure fair
	98.3522	1950		Reliability and exposure fair
	98.3524	1980		Reliability good
	98.3525	1890		Reliability of old data seems good
	98.3526	1920		
	98.3530	1950		
	98.3533	1830		Reliability and exposure fair
	98.3534			Reliability and exposure good
	98.3535	1830		Reliab. of old recs. seems fair
	98.3536	1740		Reliab. of old recs. seems good
	98.3537	1830		Reliab. of old recs. seems good
	98.3538			Reliability good, exposure fair
	98.3539	2070		Reliability fair, exposure good
	98.3540			Reliability and exposure good
	98.3546			Station not inspected
	98.3548	1710		Station not inspected
Pot. evapotranspiration	Sac Hill		Monthly average values	Penman estimates. Most probable the Mafinga Airstrip station 98.3539. It seems to have stopped recording in the 1950's. Reliability doubtful
Discharge	1KA32A	1650		Reliability good

Figure 7.7 Data availability in the Lt. Ruaha catchment.

Rainfall

It is seen that most of the stations are located in the hilly area south of the catchment. Among those stations are the ones with the most reliable data and the longest continuous records.

Furthermore, it is seen that there are no rainfall stations in the north-western part of the catchment.

The six rainfall stations located centrally in the catchment, 98.3535-98.3540, are seen to contain numerous gaps, and generally they are not considered very reliable.

As a consequence hereof, and because the rainfall pattern and amounts change considerably from south to north, it must be concluded that the available rainfall information is not quite satisfactory for the purpose of rainfall-runoff modelling studies.

A correlation analysis on annual rainfall similar to the one described for the Kiwira catchment has been performed for the five rainfall stations selected for the determination of mean areal rainfall. The results are shown in Table 7.2[8].

It is noticed that the correlations between the three stations located in the central part of the catchment, 99.3535, 99.3538 and 99.3540, are not very high, indicating either a poor reliability of the data, a high spatial variability of the rainfall, or both. In any case this leads to considerable uncertainty in the determination of the mean areal rainfall. As indicated above the high spatial variability is believed to be caused primarily by the convective rainfall pattern in the regions.

An indirect way of gapfilling similar to the one applied for the Kiwira catchment has been carried out in connection with the determination of mean areal rainfall. The applied weight coefficients are shown in Table 7.3[8].

Potential evapotranspiration

The available potential evapotranspiration data from stations located within the catchment consist of one year of pan evaporation data, and Penman estimates of monthly averages from a station at Sao Hill. For reasons discussed above in connection with Kiwira catchment it has been decided to use the Penman estimates in the hydrological modelling studies. The estimates are shown in Table 7.10 below.

Discharge

As discussed in Chapter 5 the rating curve, water level- and discharge data from 1KA32A have been subject to careful review, and the discharge data can therefore be considered quite reliable.

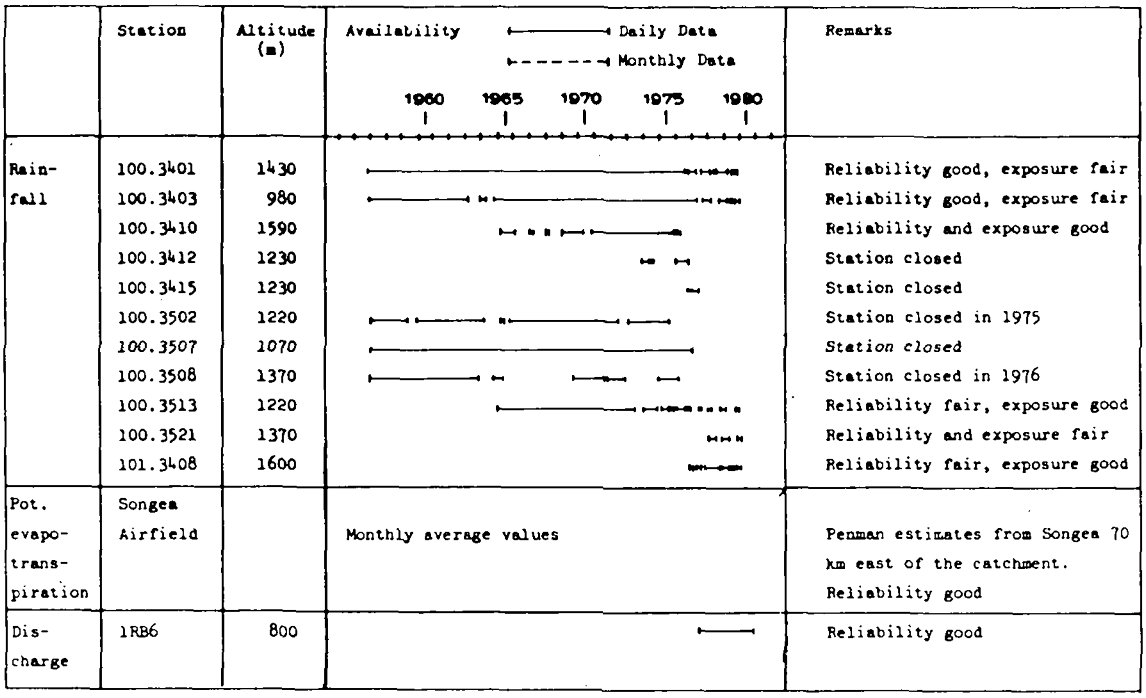
7.3.3 The Mngaka catchment

The data availability is shown in Figure 7.8. The locations of the rainfall and discharge gauging stations are shown in Figure 7.4.

Rainfall

As it appears from Figure 7.4 there is a good distribution of rainfall stations within or close to the catchment.

In order to analyse the areal rainfall pattern a correlation analysis on annual rainfall data similar to the one described for the Kiwira catchment has been carried out. The results are shown in Table 7.4[8].



	Station	Altitude (m)	Remarks
Rain-fall	100.3401	1430	Reliability good, exposure fair
	100.3403	980	Reliability good, exposure fair
	100.3410	1590	Reliability and exposure good
	100.3412	1230	Station closed
	100.3415	1230	Station closed
	100.3502	1220	Station closed in 1975
	100.3507	*1070*	*Station closed*
	100.3508	1370	Station closed in 1976
	100.3513	1220	Reliability fair, exposure good
	100.3521	1370	Reliability and exposure fair
	101.3408	1600	Reliability fair, exposure good
Pot. evapo-transpiration	Songea Airfield		Monthly average values; Penman estimates from Songea 70 km east of the catchment. Reliability good
Dis-charge	1RB6	800	Reliability good

Figure 7.8 - Data availability in the Mngaka catchment.

From Table 7.4[8] it appears that there is no regular correlation pattern, such as, for instance, inverse relationship between inter-station correlations and the distances between the stations concerned. Part of the reason for that may be that the analysis is based on a small number of years (values), and that consequently, because of the significant variation in rainfall from the year to year, the particular time period on which the correlation analysis is based may play a significant role.

The relationship between the mean annual rainfall and the altitude of the rainfall stations is plotted in Figure 7.9[8], in which also a linear regression line for this relationship is established. The analysis indicates a' reasonably well defined relationship between the altitude and the mean annual rainfall in this area.

As one of the main objectives of the rainfall-runoff modelling studies of the Mngaka catchment has been to extend the streamflow series back to 1957, it has been necessary to establish a mean areal rainfall record for the 1957-79 period. This record had to be based on the same stations in the calibration period 1977-79 as in the extension period 1957-77. For this reason only the two stations 100.3401 and 100.3403 have been included in the determination of mean areal rainfall. Each station has been given a 50% weight. In periods with gaps for one of the stations the other station was given the weight 1.0.

Potential evapotranspiration

No stations with a long-term record of potential evapotranspiration are located within the catchment. For reasons discussed above in connection with the other index catchments it has been decided to use Penman estimates of monthly averages in the hydrological modelling studies. The nearest and most reliable meteorological station in the region is the station at Songea Airfield, the values from which are shown in Table 7.11 below.

Discharge

As discussed in Chapter 5 the rating curve, water level- and discharge data from 1RB6 have been subject to careful review, and the discharge data can therefore be considered quite reliable.

7.3.4 Supplementary data

During the present study the consultants have installed supplementary hydro-meteorological stations in the three index areas for the purposes of:

- Hydrological training and research
- Collection of representative data for the continuation of detailed hydrological investigations in the three index areas.

Due to the limited time available no use has been made of the supplementary data in the present study.

Equipment

In each of the three catchments two pluviographs and two evaporation pans have been installed, as well as an standard (daily) rain gauge in the Lt. Ruaha catchment. The pluviographs are Hellmann recording raingauges of the siphon type with a 31 days recording mechanisms and a six inch funnel (cf. Chapter 3). The evaporation pans are standard Tanzania "Class A" pans, (black inside and covered by a wire mesh) placed six inches above the ground on a wooden grid. (cf. Chapter 4).

Station set-up

The stations have been placed near an existing hydrological gauging station or daily rainfall station. The locations are shown in the Figures 7.2, 7.3 and 7.4.

Unfortunately, the equipment was not available for installation until late autumn 1980, at which time it was installed simultaneously in the three index areas.

Inspection and gauge reading

The equipment is inspected daily by the gauge reader at the nearby, existing station. The gauge readers have been instructed to record the data, change paper in the recorder and maintain the equipment. At some of the stations several visits were required before the equipment was handled properly, and for these stations no reliable data has been available until the beginning of 1981.

Data

It takes time to train a gauge reader properly, and for this reason data from the newly installed stations must be considered at best moderately reliable. Moreover, with only a few months of data available at the end of the field programme it was decided not to use the data from the supplementary stations directly in the hydrological modelling studies.

However, it is hoped that as the readers get aquainted with the equipment, the records will become of good quality, and as such useful for later use by MAJI primarily in further hydrological investigations of the index areas, but also as supplement to the routine data collection programme in the regions.

7.4 Hydrological modelling

7.4.1 Purpose of modelling

For each of the three index areas intensive mathematical modelling studies have been carried out.

The objectives of these modelling studies have been the following:

- To obtain a better understanding of the hydrological processes and regimes of the three index catchments.
- To obtain hydrological information which is not directly available as measured data, such as time variation (seasonal and annual) of actual evapotranspiration, soil moisture content in the root zone and groundwater recharge.
- To support the hydrological regionalisation and water balance analysis by extrapolation and transformation of the detailed physical (hydrological) knowledge from the index areas to other areas in the regions.
- To investigate the applicability and potentials of hydrological model studies in Iringa, Mbeya and Ruvuma regions.
- To give the two Tanzanian counterparts, who as DANIDA stipendiates stayed six months at Danish Hydraulic Institute (May through October 1981), practical training and practical experience in hydrological modelling.

The specific objectives of the modelling of the three index areas have been primarily:

- Kiwira and Lt. Ruaha: Water balance studies.
- Mngaka: Water balance studies and streamflow extension.
- All catchments: Investigation of the possibility of simulating streamflow from ungauged catchments for periods for which adequate rainfall- (and potential evaporation) records are available.

7.4.2 Hydrological modelling approach

The application of mathematical models in hydrology has increased considerably during the last decade. Today hydrological computer based models are routinely used for the solution of practical problems.

A mathematical hydrological model is simply a set of linked mathematical statements describing in a simplified quantitative form the behaviour of the hydrological cycle (or a part of it).

Numerous hydrological models of different types exist. For the purposes of this study a so-called conceptual rainfall-runoff model with moderat input data requirements has been considered appropriate.

The NAM model meets these requirements, and has been selected for application in this study.

For a more detailed discussion of hydrological modelling in general, and of the NAM model in particular, reference is made to the reports made by the two Tanzanian counterparts, Mr. I.E. Mwakalinga and Mr. W. Mwaruvanda, during their stay in Denmark. However, a short description of the NAM model is given below in order to better understand the subsequent description of the index area studies.

The NAM model. A short description

NAM is an abbreviation of the Danish: "Nedbør-Afstrømnings-Model", meaning precipitation-runoff-model. This model has been developed by the Hydrological Section of the Institute of Hydrodynamics and Hydraulic Engineering at the Technical University of Denmark.

NAM simulates the rainfall-runoff process in rural catchments. It operates by accounting continuously for the moisture content in four different and mutually interrelated storages representing physical elements in the catchment. (See Figure 7.10).

The model operates on the basis of daily values of precipitation and temperature together with mean monthly values of potential evapotranspiration. On this basis it produces,as a main result,mean daily values of streamflow. as well as information on other elements of the land phase of the hydrological cycle, such as, for example, the temporal variation of the soil moisture content.

Moisture intercepted on the vegetation, as well as water trapped in depressions and in the uppermost cultivated part of the ground is represented as surface storage. U^* (see Figure 7.10) denotes an upper limit of the amount of water in surface storage.

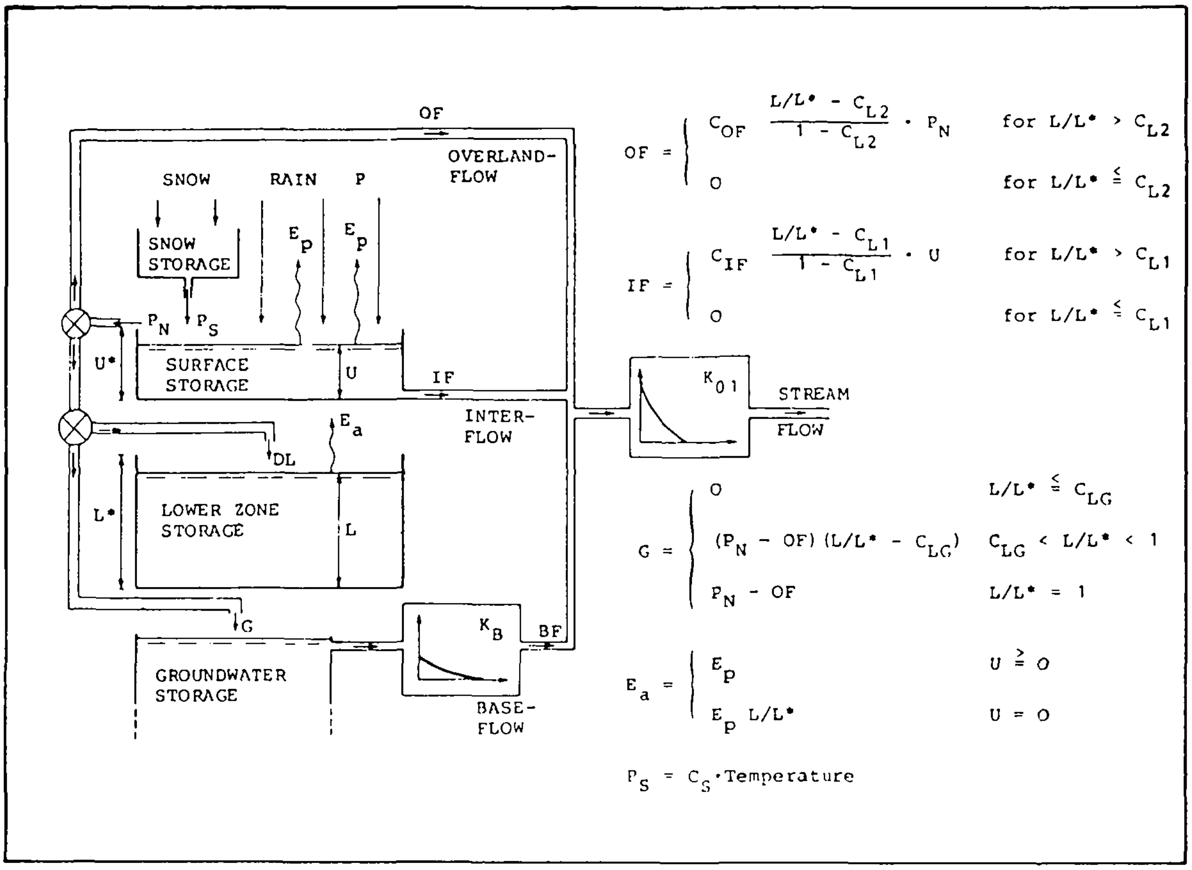


Figure 7.10 Structure of the NAM model.

The soil moisture in the root zone is represented as lower zone storage. L* denotes an upper limit of the amount of water in this storage.

The amount of water U in surface storage is continuously diminished by evaporative consumption as well as by horizontal leakage (interflow). When it is full, some of the excess water from the surface storage enters the stream as overland flow, whereas the remainder is diverted as infiltration.

Moisture in the lower zone storage is subject to consumptive loss from transpiration, and the moisture content controls that part of the infiltrating water which enters the groundwater storage.

Groundwater storage is continuously drained to the stream as base flow. If desired it is further possible to separate the baseflow into two components, originating from for instance upper and lower groundwater reservoirs with different time constants for outflows. Thus two groundwater storages have been used in the Kiwira catchment; while only one has been used in the Lt. Ruaha and the Mngaka catchments.

Corresponding to the action of simple linear reservoirs, the outflows from the various types of storages in the form of overland flow, interflow and base flow are routed to the stream according to different exponential lags or distribution functions for the particular type of flow considered. By adding up the different kinds of contributing flows,a continuous streamflow hydrograph is obtained.

Applicability of the NAM model

As is evident from Figure 7.10 the NAM model is an example of a simple, yet powerful instrument for the prediction of runoff from rural catchments. It is well suited for the extension of streamflow records in situations where such records are short but long series of precipitation (and evaporation)data are available. It is generally recognized that, for this purpose, conceptually simple models with relatively few parameters (eleven in the NAM model) do almost as well as the very complex and time consuming catchment models. However, it is also well suited for water balance studies, where information on the amounts and the temporal variation of e.g. recharge and actual evapotranspiration is required.

Model simplicity is very important for applications in countries where computer resources are limited. Simple models are easy to understand and describe, modest in computer requirements, and cheap and easy to run. Thus, in the hydrological modelling field the NAM model is a piece of "appropriate technology" to be applied in development projects. Local hydrologists can be easily trained in the use of the model, which upon the completion of the project can be transferred to the recipient country.

The NAM model is a well proven engineering tool that has been successfully applied to a number of catchments in different climatic regions of the World. In addition to numerous applications in Denmark, it has been applied for water supply studies in Borneo and Sri Lanka, for irrigation studies in Thailand, for hydropower studies in Greenland and Tanzania (Kifunga hydropower project near Njombe), and it is currently being used for flood studies in India.

Approach in the present study

In the present study the snow routine has been omitted so that the only requirements to the input data are daily values of mean areal rainfall and monthly values of mean areal potential evapotranspiration. For the calibration and test periods daily streamflow values are also needed.

For the Kiwira and the Lt. Ruaha catchments where the length of the streamflow records are about 20 years, corresponding to the longest rainfall records in the catchments, the following approach was applied:

- A four-year period,has been selected for calibration of the model, i.e. for estimation of the model parameters.
- The rest of the period with both rainfall and streamflow data, has been used for testing the model, i.e. streamflow has been simulated by use of the model parameters estimated in the calibration period. This kind of test on streamflow data from periods other than the calibration period is usually called a split sample test.
- The simulation results and the model parameters have been evaluated for the purpose of hydrological interpretations and conclusions with respect to the general water balance of the catchments.

For the Mngaka catchment, for which only a few years of streamflow data are available, the following approach has been taken:

- The model has been calibrated for the period of available streamflow data.
- The short streamflow record has been extended by simulating streamflow for rainfall data from a 20-year period for which no streamflow data has been available.
- The simulations and the model parameters have been evaluated for the purpose of hydrological interpretations and conclusions.

Method of calibration

Calibration of rainfall-runoff models can be performed either by trial and error, adjusting the parameters subjectively, or by some numerical optimization method. Previous experience with a numerical algorithm for the NAM model, supported by the general experience from other institutions during the last five years, have shown that numerical parameter estimation methods often lead to physically unrealistic parameter values. Furthermore, the trial and error method is the only possible approach allowing a distinction between calibration objectives, such as giving priority to accurate prediction of low flows for water supply planning purposes. For these reasons the trial and error calibration method has been applied in this study.

The criteria which are usually applied as calibration objectives, are the following:

- Good general behaviour of the simulated hydrograph compared to the observed hydrograph, e.g. good description of the seasonal variations.

- Water balance agreement, i.e. agreement between average simulated streamflow and average observed streamflow.
- Good simulations of low flows.
- Good simulations of high flows.

Assignment of priorities to the above four calibration objectives depends on the objective of the modelling studies. For the present study, in which emphasis is put on the water supply aspects, high priority is given to good simulation of low flows. In another study recently completed by DHI in the same area, the objective has been to extend a four year streamflow series at Ruhudji river near Njombe, Iringa, for estimation of flood discharge and determination of a flow duration curve for reservoir design. In that study a higher priority was given to the calibration objectives of water balance agreement and good simulation of high flows.

Often some numerical criteria are a supplement to the above qualitative objectives. In the present study two numerical indices have been calculated for each year of simulation, namely the correlation coefficient between the observed and simulated streamflows, and the so-called "model efficiency", which is a standardised measure of the sum of squared deviations between the observed and the simulated values. However, the numerical criteria depend greatly on the variances in the series of recorded streamflows. It is therefore meaningless to use the numerical measures when comparing the goodness of simulations from different catchments. Additionally, it is not recommended to use the indices for comparing simulations from the same catchment from different time periods, as the variance in the recorded streamflow series changes from one time period to another. Consequently, the numerical indices have only been used as secondary criteria to the above four objectives in the calibration process.

7.4.3 Calibration and tests of the NAM model

Kiwira catchment

The calibration run for the 1972-75 period is shown in Figure 7.11, in which comparisons between simulated and recorded streamflows are shown, together with the input data, (daily rainfall and monthly potential evapotranspiration).

Verification runs (tests) for the periods 1968-71 and 1976-79 are shown in the Figures 7.12^{8} and 7.13^{8}.

It is seen that the agreement between the recorded and simulated discharges is generally good, both in the calibration run and in the test runs.

Particularly the recession part of the hydrographs in the dry periods are simulated well. On the other hand there are some minor disagreements in November-December and in April-May in the transition periods between the dry and the rainy seasons. This is believed to be caused primarily by uncertainties in the main areal rainfall data. Furthermore, it is noticed that the agreements between simulated and observed streamflows is equally good in the calibration and verification periods. This is a good indication of model validity.

Lt. Ruaha catchment

The calibration run for the 1968-71 period is shown in Figure 7.14, while verification runs for the periods 1960-63, 1964-67 and 1972-75 are shown in the Figures 7.15[8], 7.16[8] and 7.17[8].

It is seen that the agreement between the recorded and simulated discharges is generally fair. For some years with medium or low rainfall the agreement is good (e.g. 1960 and 1966), while for other years, especially for years with large rainfall (e.g. 1963 and 1965), the simulated discharges are much larger than the recorded ones.

Mngaka catchment

The calibration run for the 1977-79 period is shown in Figure 7.18.

In run 1, which is the ordinary calibration run, there is a major discrepancy in 1978. This discrepancy is probably caused by the rainfall events on 21.01.78 and on 07.03.78, indicated by arrows in the figure. On these dates station 100.3401 recorded about 150 mm, while no other stations in the area reported any rainfall. By ignoring the rainfall on these dates the simulation, shown as run 2, in Figure 7.18, has resulted.

In run 2 the general agreement between the simulated and recorded streamflow is seen to be very good, for the rising as well as for the recession part of the hydrograph.

Evaluation of the quality of the model performance

In a deterministic simulation of the land phase of the hydrological cycle, as performed with the NAM model there are four fundamental sources of errors:

(a) Random and systematic errors in the input data to the model, e.g. rainfall and potential evapotranspiration.

(b) Random and systematic errors in the discharge records used for comparison with the simulated output.

(c) Inappropriate model structure.

(d) Non-optimal parameter values.

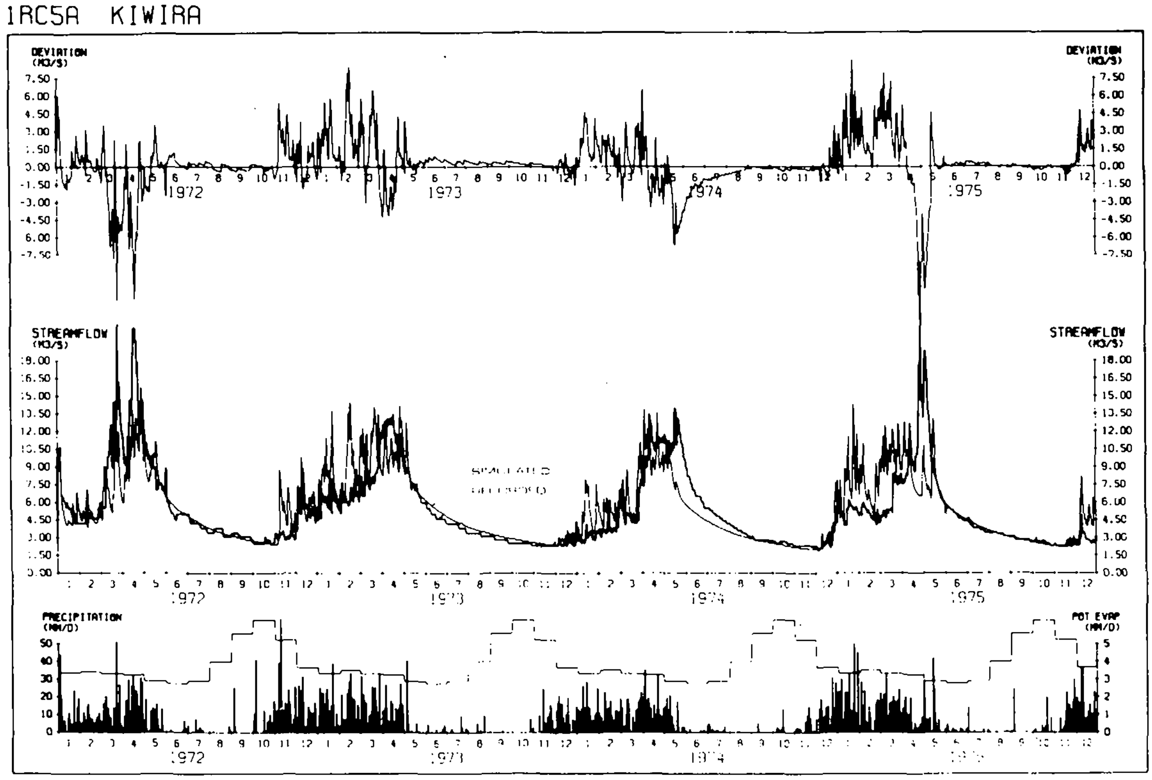


Figure 7.11 - Calibration run, Kiwira catchment at 1RC5A.

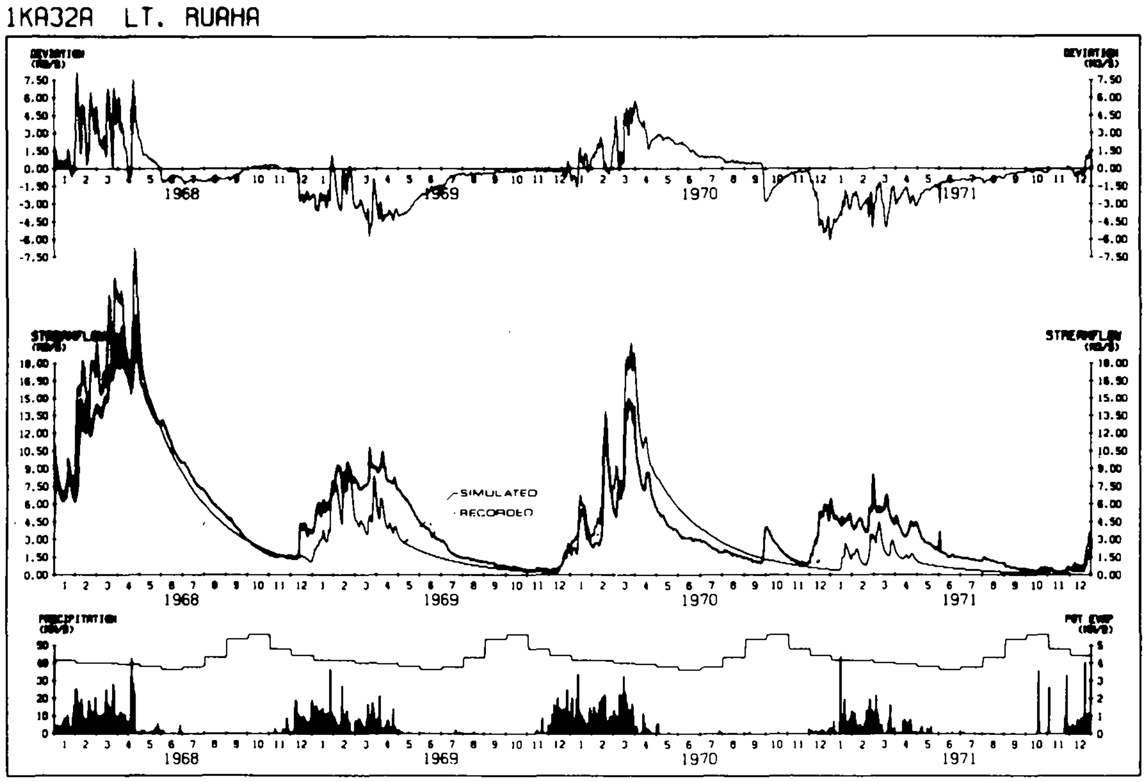
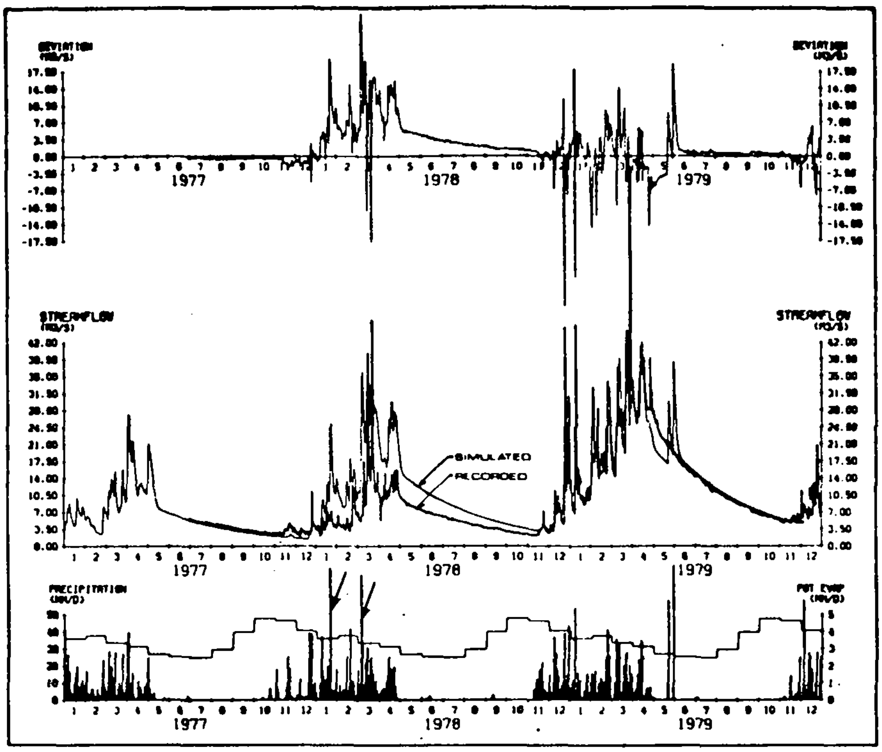


Figure 7.14 - Calibration run, Lt. Ruaha catchment at 1KA32A.

RUN 1: Ordinary run.

1RB6 MNGAKA



RUN 2: Simulation with zero rainfall at the two days indicated by arrows in run 1 (21.01.78 and 07.03.78).

1RB6 MNGAKA

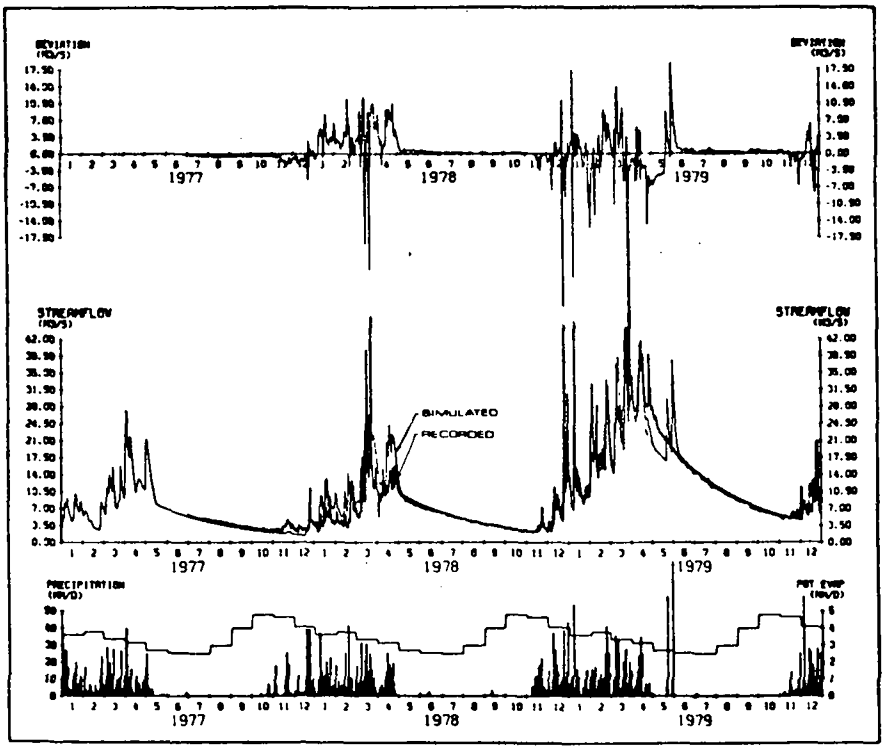


Figure 7.18 - Calibration runs, Mngaka catchment at 1RB6.

Of these errors only (d) can be reduced by calibration. Hence, to evaluate the performance of the model, it is necessary to judge how much of the deviation between the simulated and recorded streamflows are due to the errors (a) and (b), and how much is caused by an inappropriate model structure(c).

In order to make this judgement the Kiwira catchment has been simulated with a different rainfall input, but with the same model parameters as used previously. As alternative rainfall input data from station 99.3304 have been used. This station is located outside the catchment area, but is considered more reliable than the three stations located within the catchment, and is applied in the simulations shown in Figures 7.11, 7.12[8] 7.13[8]. As 99.3304 is located in an area with a larger mean annual rainfall than that of the Kiwira catchment area, the rainfall data from 99.3304 have been reduced by the factor 0.85 before application in the NAM simulations.

The results of the simulations for the period 1968-71 are shown in Figure 7.19[8]. It is noticed that the quality of the simulation with data from 99.3304 is just as good (in the year 1970 even better) as the quality of the simulations with data from the stations within the catchment, cf. Figure 7.12[8]. As 99.3304 is located outside the area, rainfall from this station cannot be more representative for the Kiwira catchment than the areal rainfall obtained by using the three stations within the area itself. Consequently it could be concluded that the reason for the better simulations with the 99.3304 data is that the reliability of the data from 99.3304 is much better than that of the other three stations.

For the Lt. Ruaha catchment the relation between the annual mean areal rainfall and the annual recorded runoff is shown in Table 7.5[8]. From this table it is evident why the NAM model has difficulties simulating correct streamflows in wet years. It is seen, for example, that 1963 (1600 mm rainfall) yields a smaller recorded runoff than 1968 (1020 mm rainfall). Such extremes indicate inconsistency in the data, and leads to the conclusion that the main reason for the poor simulation results in the Lt. Ruaha catchment is the poor reliability of the rainfall data.

Finally the sensitivity to two days' rainfall values in the Mngaka simulations (runs 1 and 2 in Figure 7.18) provides yet another illustration of the great importance of reliable input data to the model.

These results confirm the general experience that the main problems in hydrological modelling are related to the sufficiency and reliability of input data, rather than to the model structure and parameter identification.

7.4.4 Physical interpretation of the model simulations

Simulations for a two year period with plots of the various streamflow components, as well as the relative water contents in the surface and lower zone storage (cf. Figure 7.10), are shown for the three index catchments in Figures 7.20, 7.21 and 7.22.

The parameter values obtained for the three index catchments are shown in Table 7.6. Parameter values for the Ruhudji catchment at 1KB18B, as obtained in the earlier mentioned study of the Kifunga hydropower project near Njombe in Iringa, are also indicated in the table.

It is seen that the baseflow component constitutes the major part (about 80%) of the streamflow in all three catchments. In order to adequately represent the action of a non-linear groundwater reservoir the baseflow component in the Kiwira catchment has been divided into two parts with different time constants. The relatively large baseflow components agree very well with the fact that the three index catchments are characterized by highly permeable soils, implying that a rather high recharge rate should be expected.

The overland flow constitutes only a very small fraction of the total streamflow. It should probably be interpreted as runoff from river-near areas and swamps, where the phreatic surfaces (groundwater tables) are very close to the ground surface in the rainy season.

Like overland flow, interflow is seen to be active only in the rainy season, and it also constitutes only a small part of the total runoff.

From the plots of relative storage contents it is noticed that the surface storage, U, (vegetation, surface depressions) is emptied in a couple of days without rainfall, thus remaining empty throughout the dry season. The lower zone storage, L, which represents the soil water storage, is seen to be filled in the rainy season and depleted to about 5% relative soil moisture content in the dry season in the Kiwira and Mngaka catchments. In the Lt. Ruaha catchment the lower zone storage very rarely fills up in the rainy season, and it is always completely emptied in the dry season.

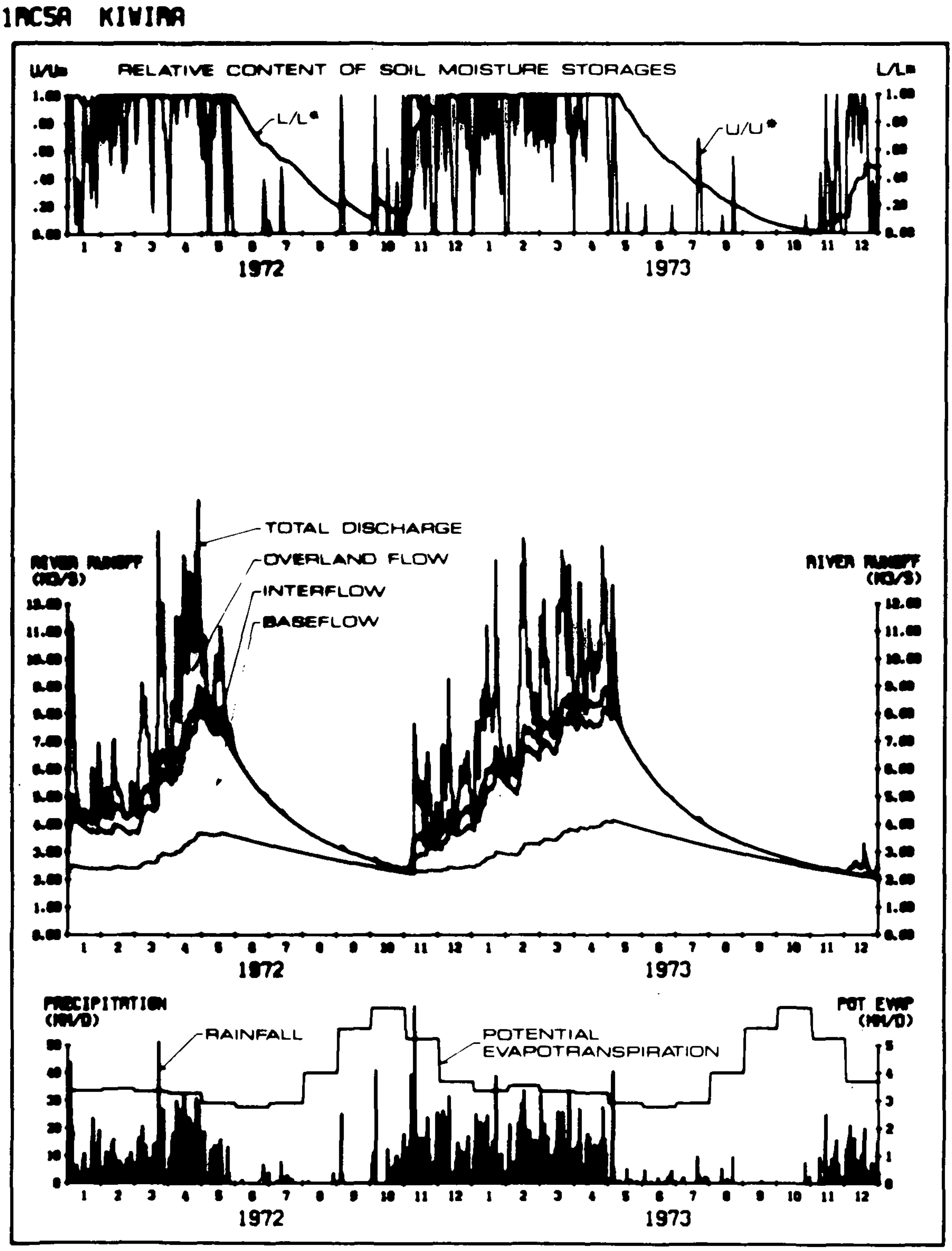


Figure 7.20 - Meteorological input, streamflow components and relative soil moisture content, Kiwira catch at 1RC5A.

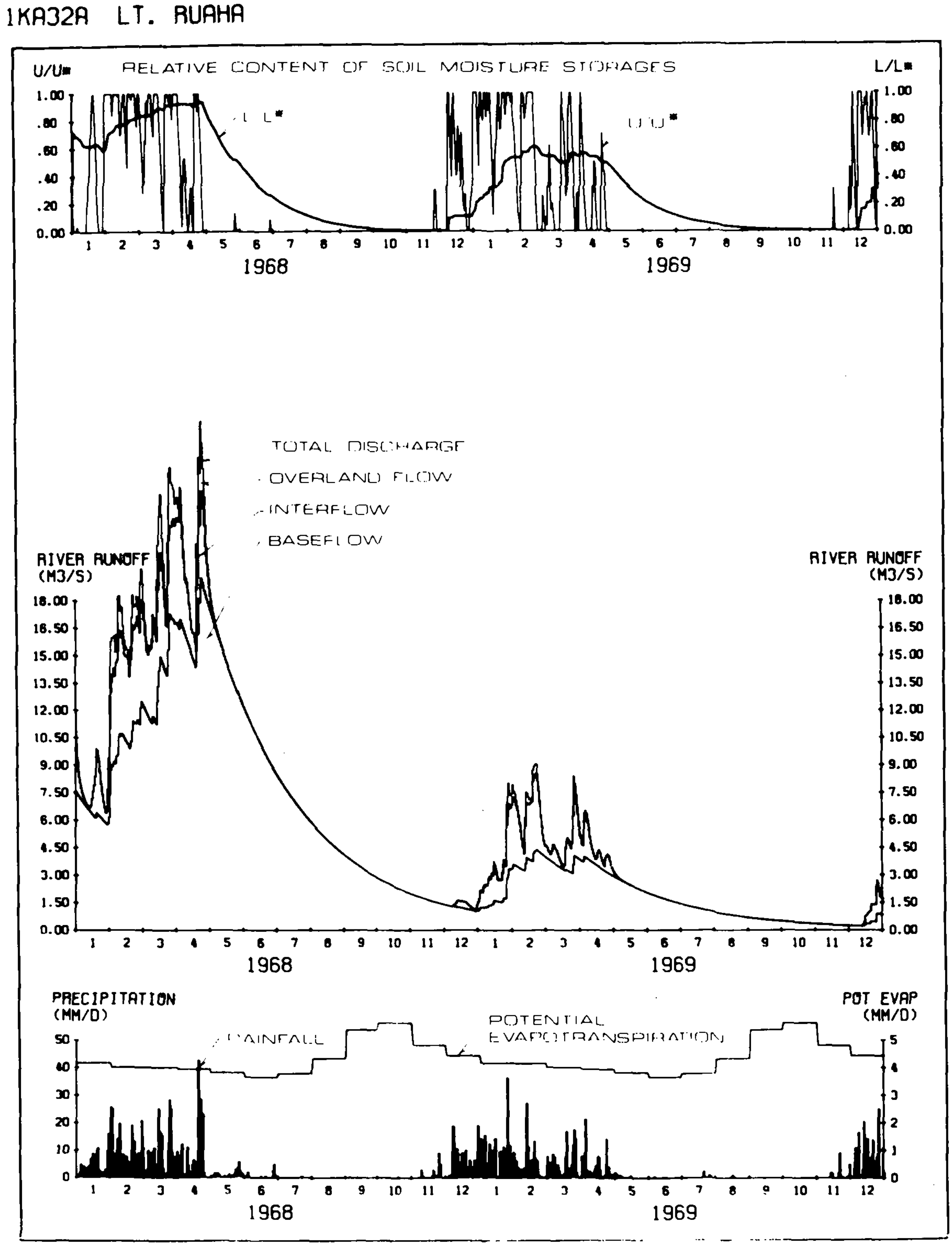


Figure 7.21 - Meteorological input, streamflow components and relative soil moisture content, Lt. Ruaha catchment at 1KA32A.

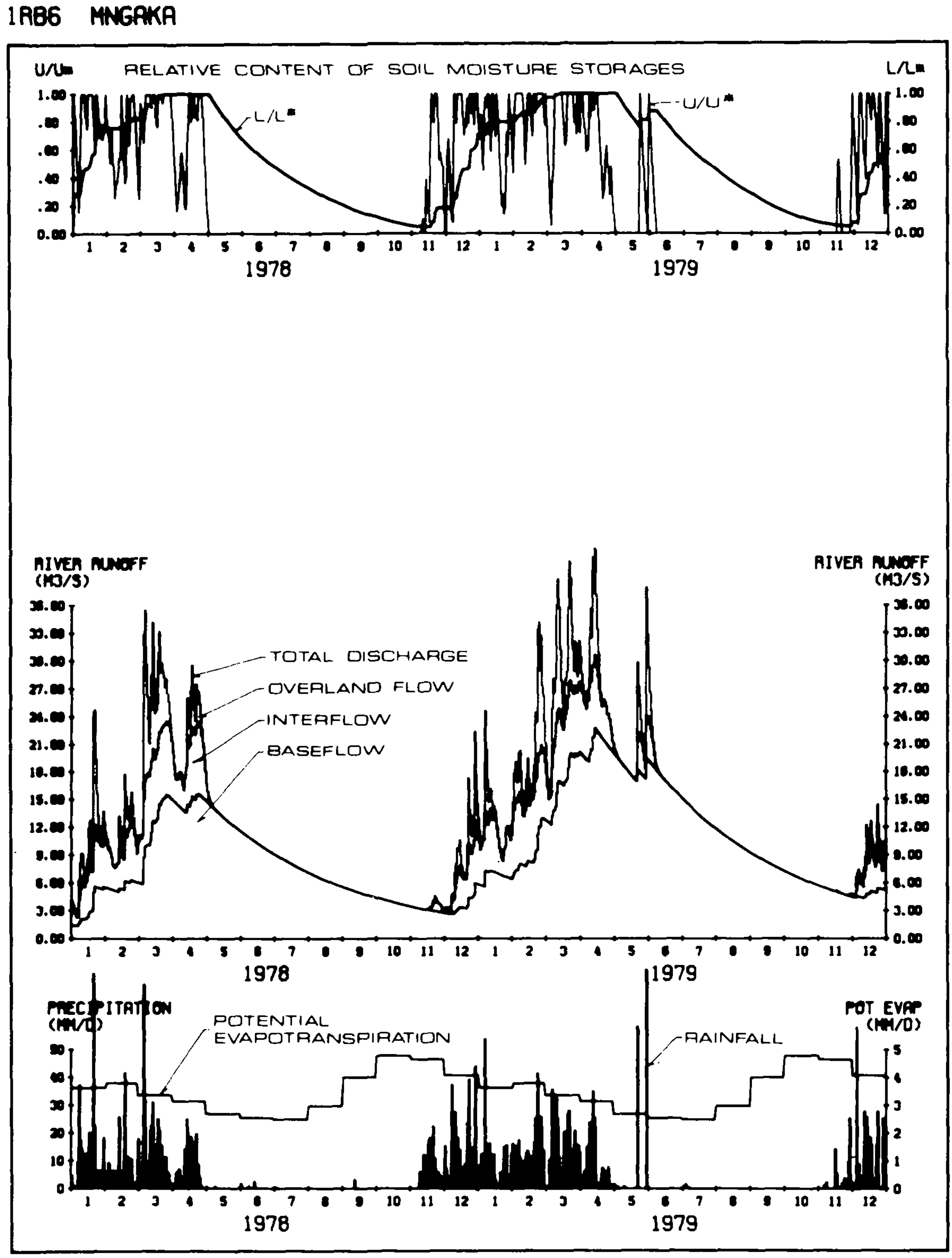


Figure 7.22 - Meteorological input, streamflow components and relative soil moisture content, Mngaka catchment at 1RB6.

		1RC5A Kiwira	1KA32A Lt. Ruaha	1RB6 Mngaka	1KB18B Ruhudji	"Standard" cf Subsection 7.4.5
x)	U* (mm)	10	15	20	15	15
x)	L* (mm)	130	175	200	150	175
x)	C_{OF}	0.15	0.05	0.10	0.15	0.10
	C_{L2}	0.25	0.10	0	0	0.20
	C_{IF}	0.03	0.05	0.05	0.03	0.05
	C_{L1}	0	0	0	0	0
	C_{LG}	0.30	0	0.10	0.50	0.10
	C_{BF}	0.65	0	0	0	0
	K_{OI}(days)	2	$3\frac{1}{3}$	2	$2\frac{1}{2}$	3
x)	K_{BF_u}(days)	50	83	125	111	100
x)	K_{BF_l}(days)	300	-	-	-	-
	$\overline{P}$(mm/year)	1680	970	1190	1130	
	$\overline{E}_p$ (mm/year)	1430	1580	1280	1080	
	$\overline{E}_a$(mm/year)	900	740	780	660	
	$\overline{Q}$ (mm/year)	780	230	410	470	
	Recharge (mm/year)	630	190	290	350	
	Elevation ranges (m)	1400-3000	1600-2000	800-1800	1800-2200	
	Soils	Volcanic sandy loam	Sandy soil	Sandy loam	Sandy loam	
	Vegetation	Rainforest and agricultural crops	Grassland and wooded grassland	Woodland and agricultural crops	Highland forest	
	Geomorphology	Rungwe volcanics	African	Mixed	African	

x) Most important parameters.

Table 7.6 NAM parameter values for calibrated catchments and proposed standard values.

Physically the lower zone storage includes that part of the soil moisture in the root zone which is available for transpiration via the vegetation. Thus the model simulations can be interpreted to show that the soil moisture content reaches the wilting point towards the end of the dry season in the Lt. Ruaha catchment, while in Kiwira and Mngaka catchments there is still a small amount of water available for transpiration at the end of the dry period. This interpretation is in good agreement with the agricultural experience from the three areas.

However, in making physical interpretations of the parameters of the NAM model it must be remembered that the model is of the lumped type, which implies that the parameter values represent averages for the entire catchment.

Furthermore, it should be pointed out that systematic errors in the input data may to some extent be compensated for by changes in the model parameters. If for instance the estimate of the potential evapotranspiration is too high this can be compensated by a smaller L*-value. The effect of a smaller lower zone storage capacity is that the E_a/E_p ratio will be diminished so that the actual evapotranspiration, and hence the simulated streamflow, on the average will be simulated quite well. Similarly systematic underestimation of rainfall (e.g. due to wind effects) can be compensated by a smaller L*-value, and hence a corresponding underestimation of the actual evapotranspiration. Consequently, if errors are systematic and relatively small (5-10%) they can usually be compensated for without reduction in the quality of the streamflow simulations. However, in such cases the L*-value does not reflect the average root zone capacity to be expected from physical considerations. In extremely dry and wet years simulations with such "biased" parameter values may yield poor simulations.

Comparison of the obtained model parameter L* to the actual root zone capacities which it is supposed to reflect, indicates that the L*-value in some cases may be biased due to systematic errors in the input data. As an example, consideration of soil and vegetation characteristics of the Kiwira catchment lead to the following conclusion:

(a) The Kiwira soil types, loam and sandy loam, point to an available soil moisture content for plant transpiration (i.e. field capacity minus wilting point) between 100 mm and 120 mm per meter root depth.

(b) About two thirds of the catchment is covered by forest with a root zone depth of probably at least 2 m. The vegetation in the rest of the area is grass and agricultural crops like maize, potatoes, bananas etc. As the agricultural crops are sown towards the end of the rainy season, and apparently grow quite well without irrigation in the dry season, the average root zone depth in these areas must be considerable, probably between 1 and 2 metres.

(c) Consequently, the average root zone capacity can be estimated to about 200 mm which is higher than the L*-value of 130 mm.

Similar considerations and conclusions can be made for the Ruhudji catchment, while the Lt. Ruaha and the Mngaka catchments appear to have unbiased L*-values.

7.4.5 Practical application of hydrological modelling

Extension of streamflow records

A typical application of a rainfall-runoff model is the extension of streamflow records from catchments with only few years of rainfall data. The test results from the Kiwira catchment have shown that with reliable rainfall data such an extension, based on a calibration period of only a few years, is permissible.

The purpose of streamflow extension is to obtain additional information on the runoff regime. Such information may be required for various purposes, such as reservoir design, low flow analyses or flood studies. An example of application of a streamflow series extended by use of the NAM model is the previously mentioned hydrological investigations in connection with design of the Kifunga Hydropower Plant at Ruhudji river near Njombe, Iringa, (DHI, 1981).

In the present study the streamflow series at the Mngaka catchment has been extended back to 1957. Some streamflow statistics for the original series (3½ years) and for the extended series (24 years) are shown in Table 7.7.

	Original record 01.07.77-31.12.80	Extended record 01.01.57-31.12.80
Mean Annual runoff (mm/year)	470	460
Daily minimum runoff (m^3/s)	2.0	1.0
Daily maximum runoff (m^3/s)	71.5	71.5

Table 7.7 Streamflow statistics for the Mngaka catchment.

From the table it is seen that the mean annual runoff in the original record happened to be very close to the mean runoff of the 24 year extended record. Hence, the estimate of mean annual runoff has not changed considerably; but it is now estimated with a much greater degree of certainty. The minimum flow during the 24 year period, however, is only half of the minimum flow experienced during the 3½ year with recorded data, whereas the recorded daily maximum flow in this period has in fact turned out to be the highest in the entire 24 year record. If only data from the original 3½ year period were to be considered the 71.5 m^3/s would have been evaluated as a 3-4 year event, i.e. probability of occurrence once every 3-4 years. With the additional information from the simulated 20½ year period the 71.5 m^3/s must be considered a 25 year event.

Prediction of runoff from ungauged catchments

The NAM-model is a conceptual, lumped hydrological model, the parameters of which are semi-empirical coefficients which can be given a general physical interpretation. Hence L* can be interpreted as a measure of the average root zone capacity of the catchment, but it is obviously not subject to direct field measurement. With this structure the NAM-model requires at least some years of calibration for parameter identification, and in principle the resulting parameters are valid only for the specific catchment on which they have been determined.

However, experience with the NAM-model has indicated that it is fairly robust, and that in many cases it may be applied successfully to ungauged catchment of similar characteristics (soils, geology, vegetation etc.) and hydrological regime as the one on which it has been calibrated. Obviously the streamflows generated from rainfall and potential evapotranspiration in such cases must be considered as first estimates, subject to later verification, but such preliminary assessments of flow regimes are often required in feasibility - or preliminary design studies.

The NAM-model has earlier been applied for simulation of streamflow from ungauged catchments, e.g. in connection with a pump irrigation and flood protection project in the Mekong Basin in north-eastern Thailand (1979-80) and in a feasibility study for water supply in Sabah, Malaysia (1979-80). In both projects NAM has been calibrated on neighbouring catchments and the parameter values transferred. Both projects have since been followed up by installation of streamflow gauges and supplementary investigation programmes for the final design phase.

From inspection of the parameter values for the three index catchments and the Ruhudji catchment , listed in Table 7.6, it is noticed that the variability in parameter values is relatively small. If generally the variability in parameter sets from one catchment to another is as little as is the case for these catchments, it should be possible to produce reasonably good streamflow simulations from ungauged catchments in the area.

In order to test this hypothesis simulated streamflows have been compared to recorded streamflows from the four catchments listed in Table 7.8^{8}. The locations of these four catchments are shown in Figure 7.1 above. In all the simulations the parameter set denoted "standard" in Table 7.6 has been used. The results of this test of ungauged catchment simulations are shown in the Figures 7.23^{8}-7.26^{8}.

It should be mentioned that no special rainfall or evaporation analyses have been performed on these test catchments. The four catchments have been selected from the simple criterion that concurrent records of rainfall and streamflow were available.

The 1RC8A Kiwira catchment is located in the Rungwe district in Mbeya region, the index catchment 1RC5A being a subcatchment of 1RC8A. As previously in the Kiwira simulations (cf. Figure 7.19^{8}) rainfall input from the station 99.3304, scaled down to 85%, has been used. In the test simulation shown in Figure 7.23^{8} the average water balance is good. However, low flows are simulated on the low side due to a too fast baseflow recession in the model, and the simulated peak flows are too small. As regards the peak flows, however, the rating curve at 1RC8A may be questionable, so that in reality the disagreement is not as pronounced as indicated in Figure 7.23[8].

The 3A8 Myovisi catchment is located west of Mbeya town. The test simulation shown in Figure 7.24[8] is again surprisingly good. The average water balance is simulated well. There are some discrepancies in 1972 and 1973, while the years 1974 and 1975 are very good indeed, with respect to both high flows and low flows. Only the recession part of the hydrographs might have been simulated a little better.

The 1RB2 Ruhuhu catchment is located north of Songea in the Ruvuma region. The test simulation shown in Figure 7.25[8] can be characterized as encouraging. The average water balance is simulated well. The simulated high flows are too high, and low flows are also in this case simulated on the low side due to a too fast baseflow recession. Hadthe baseflow time constant been estimated correctly, the simulation would have been considerably better.

Finally, the 1RB10 Mwinamaji catchment is located northwest of the Mngaka index catchment in Ruvuma region. As rainfall input the Mngaka areas rainfall, reduced by a factor 0.85, has been applied. The test simulation shown in Figure 7.26[8] is the poorest of the four test simulations with respect to water balance agreement. The simulated annual streamflows are about 30% larger than the recorded ones. However, apart from the major water balance error the simulation is fair. The shape of the hydrograph resembles the observed one, and the time constant of the baseflow recession agrees well with that of the recorded hydrographs.

Altogether the four test simulations are very encouraging with respect to the feasibility of applying the NAM-model to ungauged catchments in parts of the three regions Mbeya, Iringa and Ruvuma. Two major problems are associated with such a streamflow simulation from ungauged catchments:

(a) Simulation of the annual water balance.

Water balance was simulated quite well in three of the four test catchments. In order to avoid water balance problems it is crucial to make a thorough analysis of the rainfall and evaporation input to the model. However, as discussed above, possible biases in the meteorological input can to some extent be compensated in a calibration by working with physically unrealistic (biased) parameter values.

(b) Prediction of the baseflow recession constant.

As the recession is relatively regular during the dry period a good estimate of the baseflow recession constant in an ungauged catchment can be obtained from a few spotgaugings at different times during the recession period. Such estimates may improve the baseflow component of a model when applying it to an otherwise ungauged catchment.

In conclusion, reasonably good streamflow simulations from ungauged catchments in a large part of the three regions should be possible, particularly if the baseflow recession constants can be estimated beforehand from a few spotgaugings. However, the standard parameters shown in Table 7.6 can only be expected to be valid in catchments with soil and hydrogeological characteristics within the general range of the index catchments, i.e. relatively thick layers of soils with good drainage and water retention properties, and such hydrogeologic conditions that the baseflow component represents a major streamflow component. As discussed in Section 7.1 such soil- and hydrogeological conditions are found in the major part of the three regions, with the exception of the northern part of Mbeya and Iringa and the eastern part of Ruvuma.

7.4.6 Water balances

The NAM-model provides a simplified description of the entire land phase of the hydrological cycle, and by utilizing all the simulation results (rather than just the streamflow simulations), it is possible to obtain rough estimates of the different elements of the water balance and their time distribution. Thus for each of the three index catchments monthly values of the meteorological inputs (rainfall and potential evapotranspiration) and simulated values of actual evapotranspiration, recharge and streamflows are shown in the Tables 7.9, 7.10 and 7.11 for a medium year, a wet year and a dry year. The wet and the dry years have been selected as approximate 10 year events. As regards the uncertainty of the estimates in the three tables the monthly totals themselves should be used with some caution, whereas the seasonal and annual patterns are believed to be simulated well.

From the three tables the following characteristics of the water balances of the index catchments are noticed:

- The annual actual evapotranspiration, E_a, shows only little variation from dry to wet years. Actually E_a is more dependent on the seasonal distribution of rainfall, than on the total amounts.

- The ratio E_a/E_p varies from approximately one in the wet season to close to zero towards the end of the dry season, as can be envisaged from the plots of the soil moisture contents in the Figures 7.20-7.22. However, a difference between the Kiwira catchment, located in a wet zone, and the Lt. Ruaha catchment, located in a dry zone, is evident. In the Kiwira catchment the lowest monthly E_a/E_p ratio is 0.10, and it is rarely below 0.20. In the Lt. Ruaha catchment the lowest monthly E_a/E_p ratio is zero, and it always drops below 0.05. As could be expected the E_a/E_p ratios for the Mngaka catchments are in between those of the other two catchments. These findings agree well not only with the different rainfall regimes, but also with the difference in natural vegetation of the three catchments: rainforest in Kiwira, woodland in Mngaka, and wooded grassland in Lt. Ruaha.

- For each of the three catchments the seasonal and annual variation of the recharge is considerably higher than the variation of the other elements in the water balance. It is common for the three catchments that no recharge at all occurs during the dry season. The internal parameters arrived at will depend to some extent on corrections made or not made on the rainfall and to some extent also on the particular calibration objectives. Thus some of the water balance components i.e. recharge, could be affected.

- Generally the variation from year to year of recharge and discharge are larger in the dry zone (lt. Ruaha) than in the wet zone (Kiwira). The discharge in Lt. Ruaha, for example, varies almost by a factor ten between a dry and a wet year, while the corresponding variation in Kiwira is less than a factor two.

1RC5A Kiwira index catchment

Month	Rainfall P	Pot. Evap. E_p	Act. Evap. E_a	Recharge G	Sim. Discharge Q
1977 dry year (all values in mm)					
1	189	104	104	28	41
2	183	99	94	52	43
3	190	103	103	65	60
4	255	98	98	131	86
5	59	90	85	7	58
6	4	83	49	0	39
7	13	90	36	0	32
8	16	124	32	0	27
9	21	168	30	0	22
10	129	197	58	2	21
11	314	157	155	80	56
12	147	114	114	23	44
Year	1520	1427	958	388	529
1971 medium year (all values in mm)					
1	47	104	96	0	37
2	416	99	98	219	96
3	383	103	103	229	134
4	148	98	97	47	110
5	123	90	87	39	90
6	2	83	55	0	60
7	3	90	32	0	49
8	0	124	19	0	40
9	8	168	16	0	33
10	71	197	52	0	30
11	343	157	103	108	58
12	108	114	110	5	50
Year	1652	1427	869	648	789
1979 wet year (all values in mm)					
1	397	104	104	239	115
2	169	99	99	67	84
3	351	103	103	192	122
4	320	98	98	182	139
5	87	90	84	39	109
6	44	83	64	2	72
7	7	90	41	0	57
8	12	124	33	0	46
9	22	168	32	0	38
10	134	197	98	0	35
11	208	157	139	9	36
12	350	114	114	151	79
Year	2101	1427	1009	881	932

Table 7.9 Monthly totals of the different water balance elements for the Kiwira index catchments in a dry year, a medium year and a wet year.

IKA32 Lt. Ruaha index catchment

Month	Rainfall P	Pot. Evap. E_p	Act. Evap. E_a	Recharge G	Sim. Discharge Q
1977 dry year (all values in mm)					
1	179	129	127	8	5
2	93	116	101	2	6
3	152	124	116	14	13
4	91	118	90	7	11
5	39	118	61	0	5
6	0	109	17	0	3
7	0	117	8	0	2
8	5	134	9	0	2
9	1	161	3	0	1
10	9	174	10	0	1
11	121	144	99	2	2
12	165	137	102	12	4
Year	855	1581	743	45	55
1960 medium year (all values in mm)					
1	252	129	119	52	21
2	196	116	114	43	26
3	194	124	123	48	47
4	131	118	114	26	45
5	36	118	83	0	27
6	15	109	41	0	18
7	0	117	23	0	13
8	0	134	9	0	9
9	0	161	4	0	6
10	0	174	2	0	4
11	0	144	0	0	3
12	131	137	83	4	3
Year	955	1581	716	173	222
1962 wet year (all values in mm)					
1	286	129	129	103	57
2	268	116	116	105	64
3	235	124	124	103	97
4	150	118	116	26	74
5	25	118	89	0	49
6	0	109	38	0	32
7	4	117	23	0	23
8	4	134	13	0	16
9	0	161	4	0	11
10	10	174	11	0	8
11	41	144	38	0	5
12	206	137	89	28	11
Year	1229	1581	790	365	447

Table 7.10 Monthly totals of the different water balance elements for the Lt. Ruaha index catchment in a dry year, a medium year and a wet year.

1RB6 Mngaka index catchment

Month	Rainfall P	Pot. Evap. E_p	Act. Evap. E_a	Recharge G	Sim. Discharge Q
1969 dry year (all values in mm)					
1	167	112	111	11	19
2	191	106	102	34	26
3	228	104	104	60	50
4	200	94	94	58	60
5	1	83	68	0	31
6	0	76	41	0	21
7	0	77	28	0	17
8	0	92	22	0	14
9	0	120	17	0	10
10	0	148	11	0	8
11	46	139	41	1	6
12	144	126	101	1	8
Year	977	1277	740	164	270
1975 medium year (all values in mm)					
1	233	112	112	31	27
2	205	106	101	44	28
3	301	104	104	126	78
4	246	94	94	98	80
5	13	83	75	0	53
6	1	76	48	0	37
7	2	77	34	0	30
8	1	92	27	0	23
9	2	120	22	0	18
10	4	148	16	0	14
11	30	130	35	0	11
12	148	126	118	0	11
Year	1186	1277	786	299	407
1979 wet year (all values in mm)					
1	191	112	112	35	49
2	319	106	106	134	71
3	324	104	104	170	109
4	190	94	94	85	109
5	140	83	77	60	80
6	0	76	62	0	71
7	4	77	44	0	52
8	0	92	34	0	41
9	0	120	26	0	31
10	0	148	16	0	25
11	66	139	51	0	19
12	276	126	126	31	34
Year	1510	1277	852	515	691

Table 7.11 Monthly totals of the different water balance elements for the Mngaka index catchment in a dry year, a medium year and a wet year.

7.5 Recommendations

By selecting representative catchments (index areas) covering a cross section of hydrological conditions in the study area, establishing additional instrumentation in these catchments, and performing detailed hydrological studies on their data, a beginning has been made for representative hydrological investigations which Maji should continue in the future. Hence, it is recommended that

- Maji continues the operation of the newly established stations in the index areas, including data control, processing and storage
- Maji follows-up on the hydrological modelling studies of these areas as new data becomes available
- Maji considers installations of additional equipment in the index areas, focussing future research, development and staff training activities concerned with the hydrology of the south-western highlands in these areas.

The present study has demonstrated the usefulness of a simple rainfall-runoff model (the NAM model) for streamflow extension, water balance studies and prediction of runoff from ungauged areas in the major part of the three regions under study. Two highly qualified Maji hydrologists have received extensive training in the use of the model. Thus the NAM model could become a very useful tool for Maji in future investigations in south-western Tanzania, as well as in many other parts of the country.

Consequently it is strongly recommended that the NAM model be installed and tested at a computer installation which hopefully will be acquired for Maji-Ubungo (cf. Section 5.8 above). This and other hydrological models should be routinely used in future water resources investigations, whether for water supply, hydropower, irrigation or other purposes.

8. WATER BALANCES

8.1 General

The objectives of the water balance studies have been the following:

- To identify the various components of the general water balance on a regional basis, and to analyse time and spatial variations.
- To interrelate the various components and discuss characteristic relationships.
- To identify existing water appropriations, and relate these to surface water resources potential.

The water balance equation is a very important hydrological concept, which can be applied for any system over any time period to account for the hydrological components. The equation simply states that the difference between the inflow to and outflow from the system must balance the change in storage within the system, all values having the unit of volume per unit time.

The water balance equation can be applied for any area, however, it is usually applied on catchment scale, for which it reads:

$$P = E_a + Q + Q_{ss} + \Delta S$$

in which

P - rainfall
E_a - actual evapotranspiration
Q - runoff
Q_{ss} - deep seepage, exchange of groundwater across catchment divide, interbasin diversions (e.g. abstracted groundwater).
ΔS - change in storage over the considered time period.

The terms P and E_a can be measured with various degrees of accuracy. In practice it is usually an impossible task to measure ΔS since that requires the measurement of changes in water storages both above and below the ground surface. However, when considering longer periods (e.g. one year or more) it may be a good approximation to assume that the ΔS-term is negligible. The Q_{SS}-term may also be difficult to assess. Groundwater abstractions which are exported to other catchments are relatively easily obtained. However, it is almost impossible to measure the flow of groundwater across the catchment divide. In cases where the catchment and groundwater divides are almost coinciding this component will be negligible, otherwise it may have to be estimated.

Supposing that a long period of time is considered during which the change in storage can be assumed insignificant, and further assuming that the various factors included in the Q_{SS}-term can be neglected, the original water balance equation reduces to

$$E_a = P - Q$$

Hence, under these assumptions it may be possible to estimate the actual catchment evapotranspiration as the difference between areal rainfall and runoff. Although the reduced equation represents a rather crude approximation it is widely used as a guide in water resources planning.

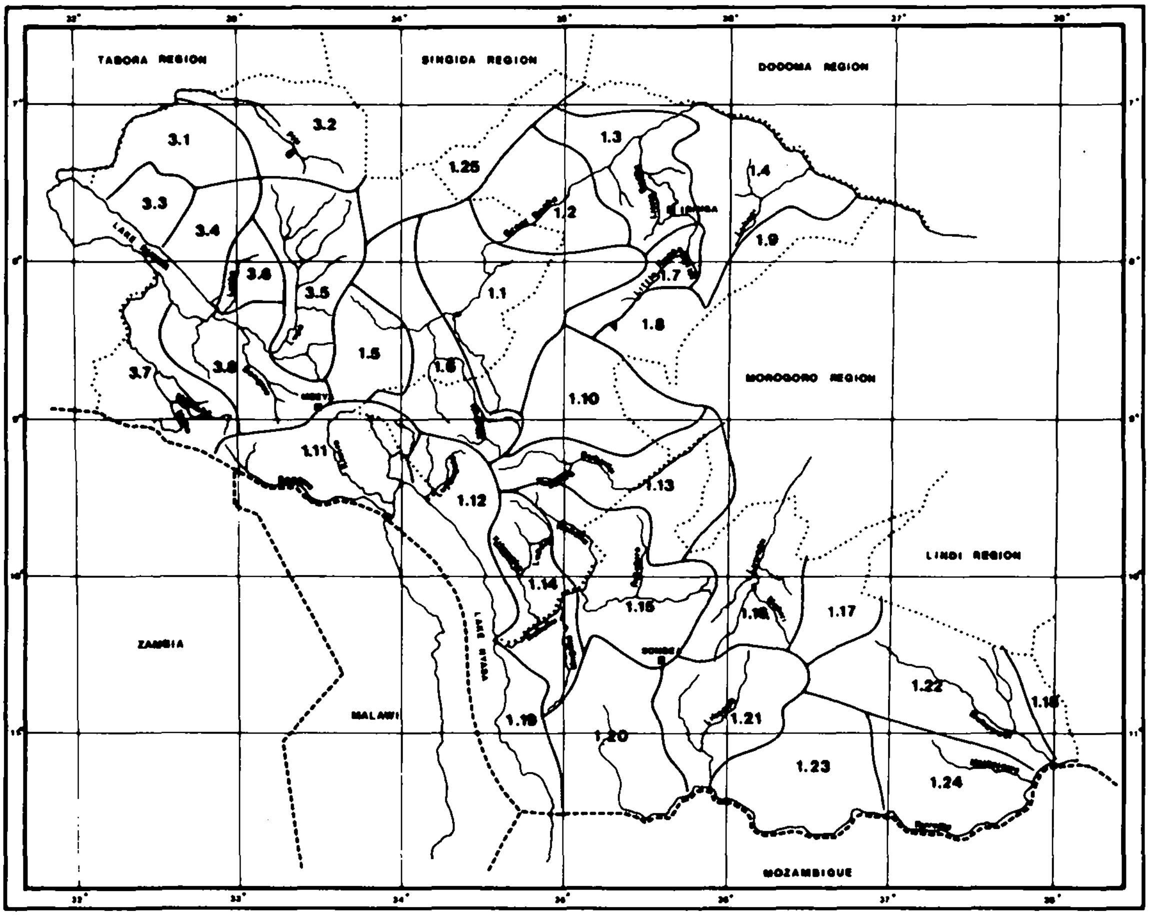
Alternatively, mathematical models may be applied for establishing the water balance components for catchments or subdomains. This procedure is often preferable since the unmeasurable variables may be simulated in this way and information about the amounts and the time variation of the individual water balance elements are easily obtained.

8.2 Annual water balances

In this chapter the elements of the water balance are discussed on a mean annual basis, and various characteristic relationships are established. Since one of the primary objectives of the present study is to provide basin-wide hydrological information, the elements of the mean annual water balance are established on a regional basis utilizing the results from the regionalisation described in the previous chapters.

For the purpose of water balance studies the study area has been divided into 33 drainage units or main catchments in order to systematize the regionalisation process and eliminate the effects of local variations. The main catchments are shown on Figure 8.1 and a number has been assigned to each of then, where the first digit of which indicates whether drainage takes place to the Indian Ocean or to Lake Rukwa.

The catchment characteristics in terms of area, mean annual runoff, 10-year daily minimum runoff, mean annual rainfall and mean annual potential evapotranspiration are shown in Table 8.1.



1.__ INDIAN OCEAN DRAINAGE BASIN

3.__ LAKE RUKWA DRAINAGE BASIN

Figure 8.1 - Main drainage basins.

Catchment No.	Area Km^2	Mean annual runoff $\bar{Q}$ (mm)	10-year minimum runoff $1/sec/Km^2$	 mm/year	Mean annual rainfall $\bar{P}$ (mm)	Mean annual potential evapotranspiration $\bar{E}_p$ (mm)	$\bar{E}_a$ $\bar{P} - \bar{Q}$ (mm)	$\bar{P} - \bar{E}_p$ (mm)	$\bar{E}_a/\bar{E}_p$	$\bar{Q}/\bar{P}$
1.1	10,900	<200	0	0	700	1,600	>500	-900	>0.31	<0.29
1.2	7,500	<200	0	0	650	1,600	>450	-950	>0.28	<0.31
1.3	5,200	200	1	32	700	1,700	500	-1,000	0.29	0.29
1.4	9,900	250	1	32	800	1,600	550	-800	0.34	0.31
1.5	2,200	500	1	32	1,050	1,300	550	-250	0.42	0.48
1.6	7,100	400	1	32	950	1,400	550	-450	0.39	0.42
1.7	2,600	350	2	63	1,100	1,500	750	-400	0.50	0.32
1.8	1,600	500	3	95	1,500	1,400	1,000	100	0.71	0.33
1.9	1,450	400	3	95	1,300	1,400	900	-100	0.64	0.31
1.10	4,700	600	4	126	1,500	1,400	900	100	0.64	0.40
1.11	5,800	800	8	252	1,900	1,200	1,100	700	0.92	0.42
1.12	4,000	600	4	126	1,400	1,200	800	200	0.67	0.43
1.13	3,150	600	4	126	1,400	1,200	800	200	0.67	0.43
1.14	5,500	450	2	63	1,100	1,300	650	-200	0.50	0.41
1.15	8,300	600	4	126	1,250	1,500	650	-250	0.43	0.48
1.16	6,750	600	2	63	1,200	1,500	600	-300	0.40	0.50
1.17	4,250	500	1	32	1,200	1,500	700	-300	0.47	0.42
1.18	1,350	300	0	0	1,000	1,500	**700**	-500	**0.46**	0.30
1.19	2,000	450	1	32	1,300	1,300	850	0	0.65	0.35
1.20	7,600	400	1	32	1,300	1,300	900	0	0.69	0.31
1.21	6,600	500	1	32	1,300	1,400	800	-100	0.57	0.38
1.22	9,600	250	0	0	950	1,500	**700**	**-550**	**0.46**	0.26
1.23	6,850	400	0	0	1,150	1,400	750	**-250**	0.54	0.26
1.24	4,400	200	0	0	950	1,500	750	**-550**	0.50	0.21
1.25	5,800	<200	0	0	650	1,900	>450	-1,250	>0.24	<0.31
3.1	5,300	<200	0	0	850	1,900	>650	-1,050	>0.34	<0.24
3.2	6,600	<200	0	0	800	1,900	>600	-1,100	>0.32	<0.25
3.3	2,200	<200	0	0	900	1,900	>700	-1,000	>0.37	<0.22
3.4	2,800	<200	0	0	900	1,900	>700	-1,000	>0.37	<0.22
3.5	6,500	<200	0	0	900	1,600	>700	-700	>0.44	<0.22
3.6	2,000	<200	0	0	900	1,800	>700	-900	>0.39	<0.22
3.7	5,700	<200	0	0	1,050	1,900	>850	-850	>0.45	<0.19
3.8	4,000	200	0	0	1,000	1,700	800	-700	0.47	0.20

Table 8.1 - Catchment characteristics on mean annual basis.

The values listed in this table are average catchment values obtained by including all available data from the hydrological stations inside the catchments. The catchment values have been calculated as simple averages of the mean annual station values without giving weights to the areas represented by the individual stations. In some catchments in the arid zones the coverage of runoff stations is rather sparse, and it has not been possible to provide reasonable figures for the mean annual runoff values. In these cases the runoff has been tabulated as being anything less than 200 mm/year, implying that the actual evapotranspiration and the various ratios cannot be given more definite values. On basis of the measured quantities described above, the following quantities have been derived: the mean annual actual evapotranspiration obtained as the difference between rainfall and runoff, the potential water surplus/deficit, the ratio of actual evapotranspiration to potential evapotranspiration and the runoff coefficient defined as the ratio of runoff to rainfall. Various figures have been prepared to illustrate the regional variation of these quantities.

8.2.1 Actual Evapotranspiration

An iso-line map for the actual evapotranspiration is shown in Figure 8.2. The figure illustrates the areal variation of the water lost from the catchments by the combined processes of transpiration and evaporation. The actual evapotranspiration is always less than or equal to the potential evapotranspiration, which occurs only when an adequate water supply is available to a fully vegetated surface. When the water supply from rainfall or irrigation is insufficient the plants will draw water from the soil moisture storage, but this storage has a limited capacity, and with increasing moisture stress the actual evapotranspiration will fall below the potential value. It eventually reduces to zero if the permanent wilting point is reached.

Hence, the actual evapotranspiration is essentially determined by three factors: the climatologically determined upper limit for the evapotranspiration, i.e. the potential evapotranspiration, the water supply from rainfall, and the water holding capacity of root zone. The latter determines the amount of water which can be stored in the root zone, thus enabling a surplus of rainfall during one period to compensate for a deficit during the following period. When comparing the regional variation of actual evapotranspiration to the variation of rainfall and potential

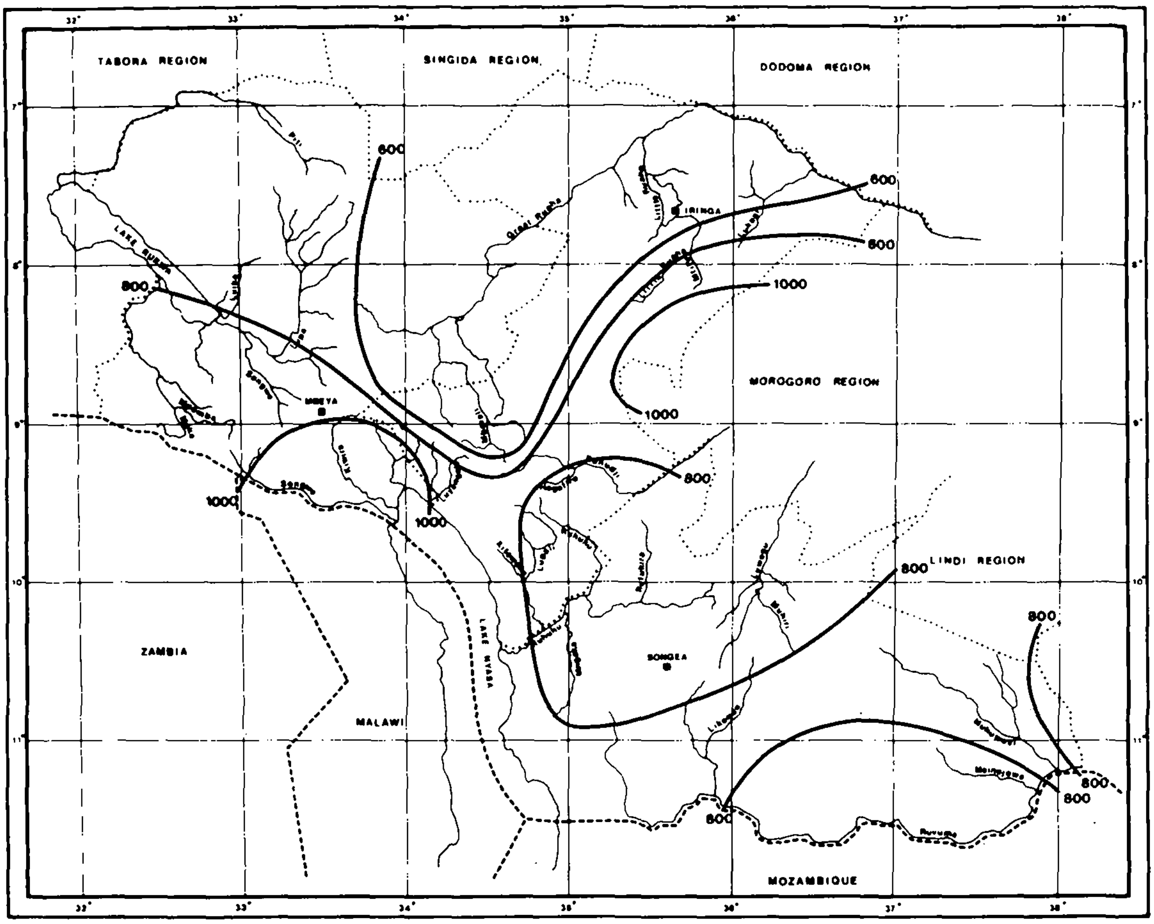


Figure 8.2 - Mean annual actual evapotranspiration (E_a) in mm.

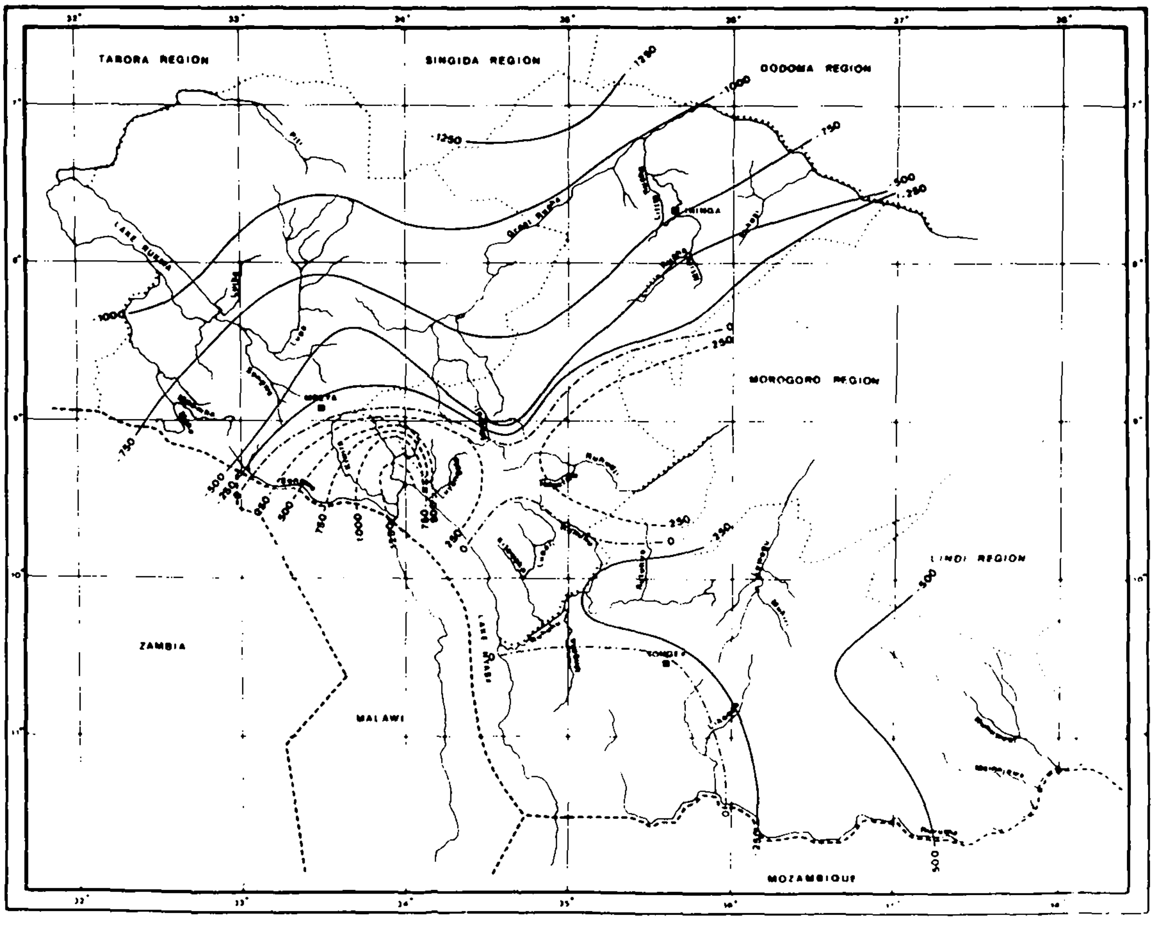


Figure 8.3 - Mean annual surplus and deficit ($P - E_p$) in mm.

evapotranspiration (cf. Chapters 3 and 4) it is evident that rainfall is a much more important factor in determining the actual evapotranspiration than is the potential evapotranspiration. However, when this comparison is made on basis of annual mean values the correlation will not be very high, because the seasonal distribution of the rainfall is important. If a high annual rainfall is concentrated during a few months the crops will experience water stress and hence reduction in actual evapotranspiration outside the rainy season.

8.2.2. Surplus - Deficit.

A standard representation of the hydrological conditions is the comparison between rainfall and potential evapotranspiration to determine whether an area has a water surplus or a deficit. The regional variation of mean annual surplus and deficit, obtained as the difference between rainfall and potential evapotranspiration, is shown in Figure 8.3. As it appears from the figure a fairly large range of variation is found in the study area, from a surplus of 1250 mm/year to a deficit of 1250 mm/year. The general variation reflects the rainfall variation rather closely, and also to some extent the variation in potential evapotranspiration. The largest surplus is found north of Lake Nyasa, and the largest deficits in the Northern Iringa. However, a large surplus on a yearly basis does not necessarily ensure a reliable water supply all year round, because the rainfall may be concentrated over a short period, thus leaving a long period with a considerable lack of water and a resulting reduction in crop production. Seasonal water balances have been prepared for the index areas for which the necessary detailed hydrologic modelling studies have been carried out (cf. Section 8.3)

8.2.3 Ratios of elements of the water balance

The regional variation of the ratio between mean annual values of actual and potential evapotranspiration is depicted in Figure 8.4. The same tendencies appear from this figure as for the previous ones: the highest values are found in areas with heavy rainfall, and the lowest values in the more arid areas. The seasonal variation of the rainfall is the important factor.

Finally, the variation of the runoff-rainfall ratio is shown in Figure 8.5. Also in this case the regional variation in mean yearly rainfall pattern is reflected rather well.

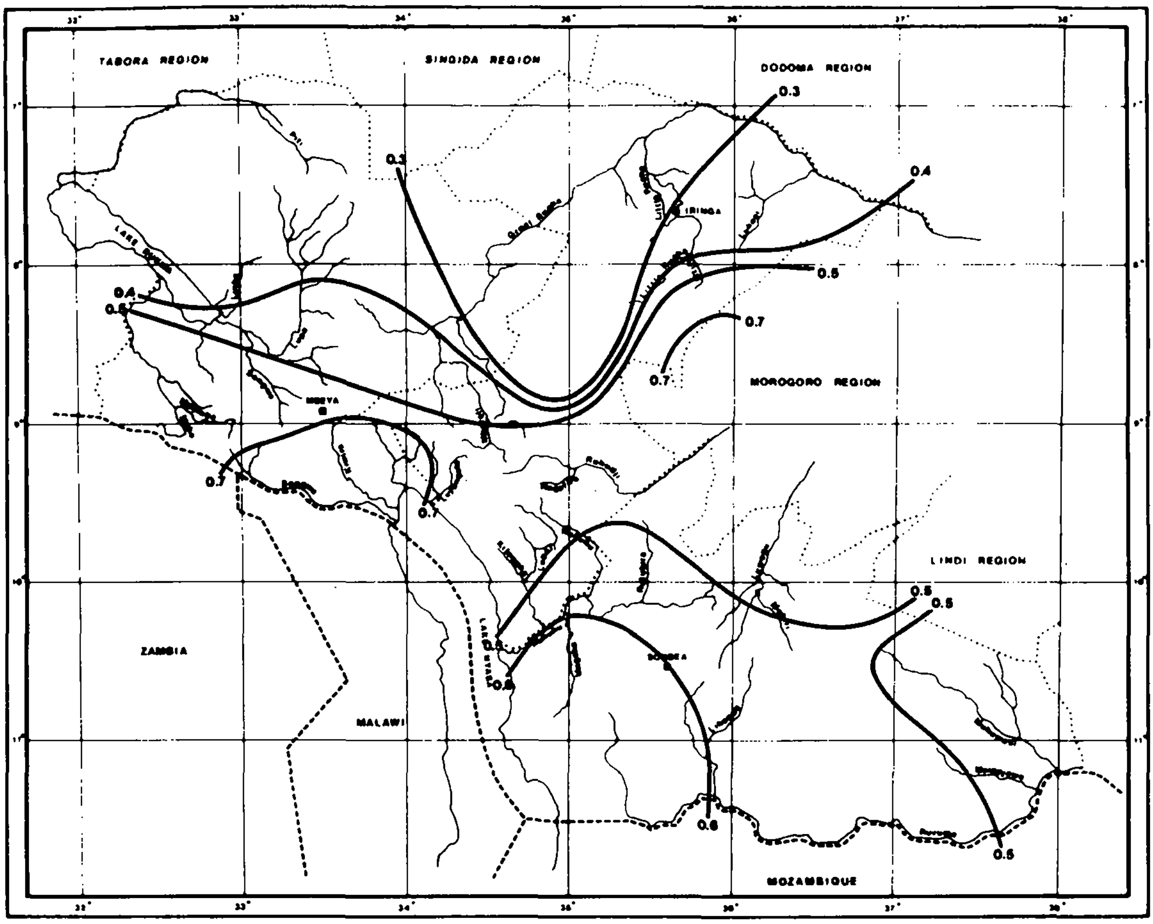


Figure 8.4 - Variation in ratio between mean annual actual evapotranspiration and potential evapotranspiration (E_a/E_p).

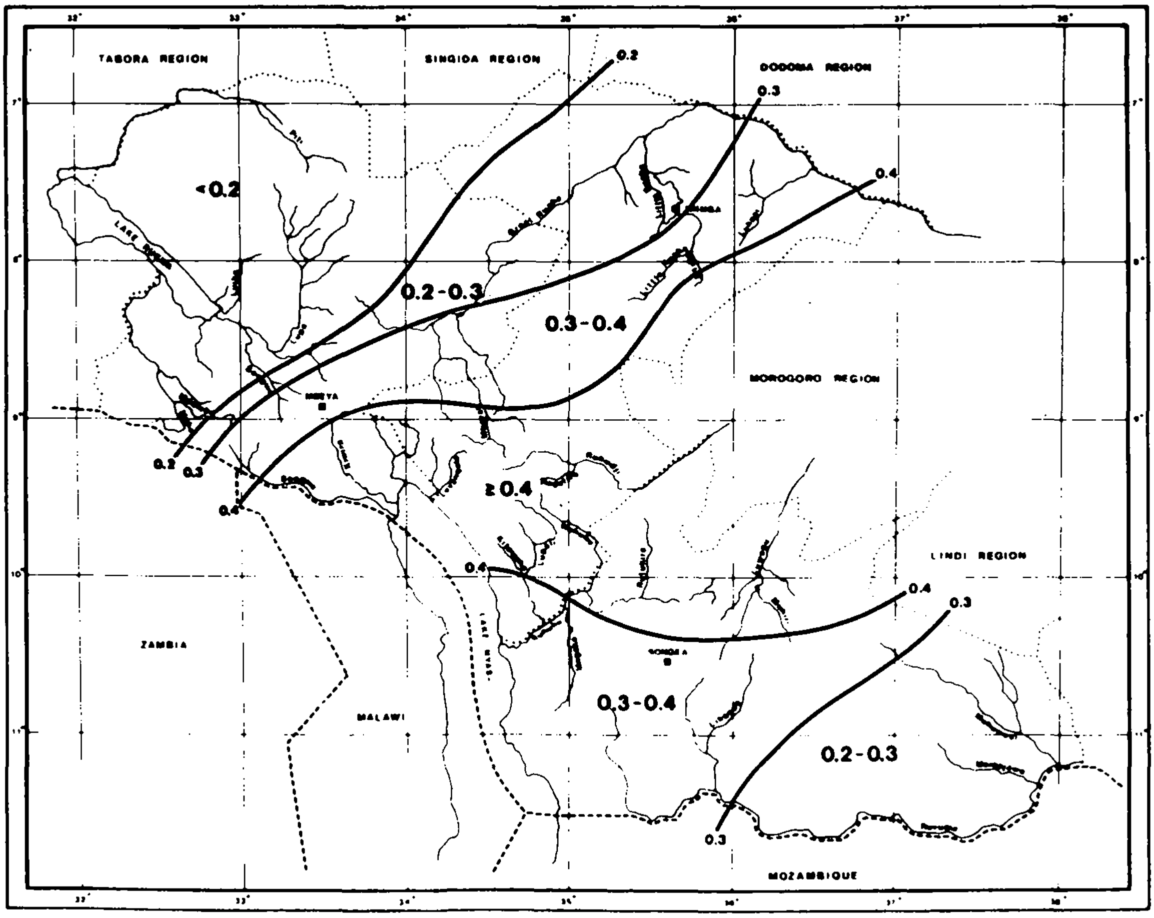


Figure 8.5 - Variation in runoff-rainfall ratio ($\overline{Q}/\overline{P}$).

It is emphasized that all the figures described above have been prepared on the basis of mean annual values. Since especially the rainfall exhibits a high seasonal and yearly variation all figures shown on the maps represent gross averages of highly variable quantities.

8.2.4 Regional balances

The three elements of the simplified water balance, i.e. rainfall, actual evapotranspiration and runoff, have been integrated over Northern and Southern Mbeya (dividing latitude $8^{o}30'$), Iringa and Ruvuma. The results are shown in Figure 8.6. The mean annual runoff which represent the absolute upper limit of available water for various water supply purposes (provided necessary reservoir capacity) displays the greatest variation. The extremes are found in Mbeya region, varying from less than 200 mm/year to 430 mm/year. The figures depicted in Figure 8.6 have been converted to gross regional volumes and are given in Table 8.2.

Region	Rainfall mill. m^3/year	Runoff mill. m^3/year	Actual evapotranspiration mill. m^3/year
Northern Mbeya	32,000	8,000	24,000
Southern Mbeya	22,000	8,000	14,000
Iringa	54,000	19,000	35,000
Ruvuma	69,000	24,000	45,000

Table 8.2 - Regional annual gross figures for rainfall, runoff and actual evapotranspiration.

8.3 Index area water balances

The structure of the NAM-model and its application to the three index areas has been described in detail in Chapter 7. Some of the results from these modelling studies are presented below.

The NAM-model provides a simplified description of the land phase of the hydrological cycle, and since it simulates various flows in the system, e.g. recharge and actual evapotranspiration, and accounts for the water content in both the soil moisture zone and the groundwater zone, the model is well suited for water balance studies. When applying the general water balance equation, a long period (one year or more) must be considered in order to eliminate one of the unknowns in the equation, namely the water storage in the system. By setting up a model like the NAM-model on a catchment, information on the temporal variation of the elements in the water balance is automatically obtained. This is made possible primarily by the inclusion of descriptions of the evapotranspiration and deep percolation processes which rely on the moisture availability in the soil moisture zone.

For each of the three index catchments monthly values of meteorological inputs (rainfall and potential evapotranspiration) and simulated values of actual evapotranspiration, recharge and streamflow are shown in the Tables 8.3[8], 8.4[8] and 8.5[8] for a medium year, a wet year and a dry year. The wet and the dry years have been selected as approximate 10-year events. As regards the interpretation of the estimates in the three tables the monthly totals should be considered as rather approximate, whereas the seasonal and annual patterns are believed to be simulated rather closely. The three catchments represent broad classes of wet, medium and dry hydrological regimes inside the study area, one index area located in each of the three regions. Some of results listed in the tables are also shown on graphical form. The Figures 8.7, 8.8 and 8.9 illustrate the seasonal variation of the water balance components for medium years of the three catchments. Figure 8.10 depicts the water balance variation for the wettest condition of all the cases being considered namely a wet year in Kiwira catchment, and Figure 8.11 shows the driest condition (dry year in Lt. Ruaha catchment). As apposed to the discussion above, which is based entirely on mean annual values, the simulation results presented here cover both seasonal and yearly variations of the elements in the water balance.

The following characteristics of the seasonal water balances for the index catchments are observed: The annual actual evapotranspiration E_a shows little variation from dry to wet years. In fact E_a is more dependent on the seasonal distribution of rainfall than on the total amounts.

The general pattern is that during the rainy season rainfall is abundant and gives rise to a large water surplus, which secures an actual evapotranspiration at the potential level. During the dry season where none or only an insignificant amount of rainfall occurs, any actual evapotranspiration

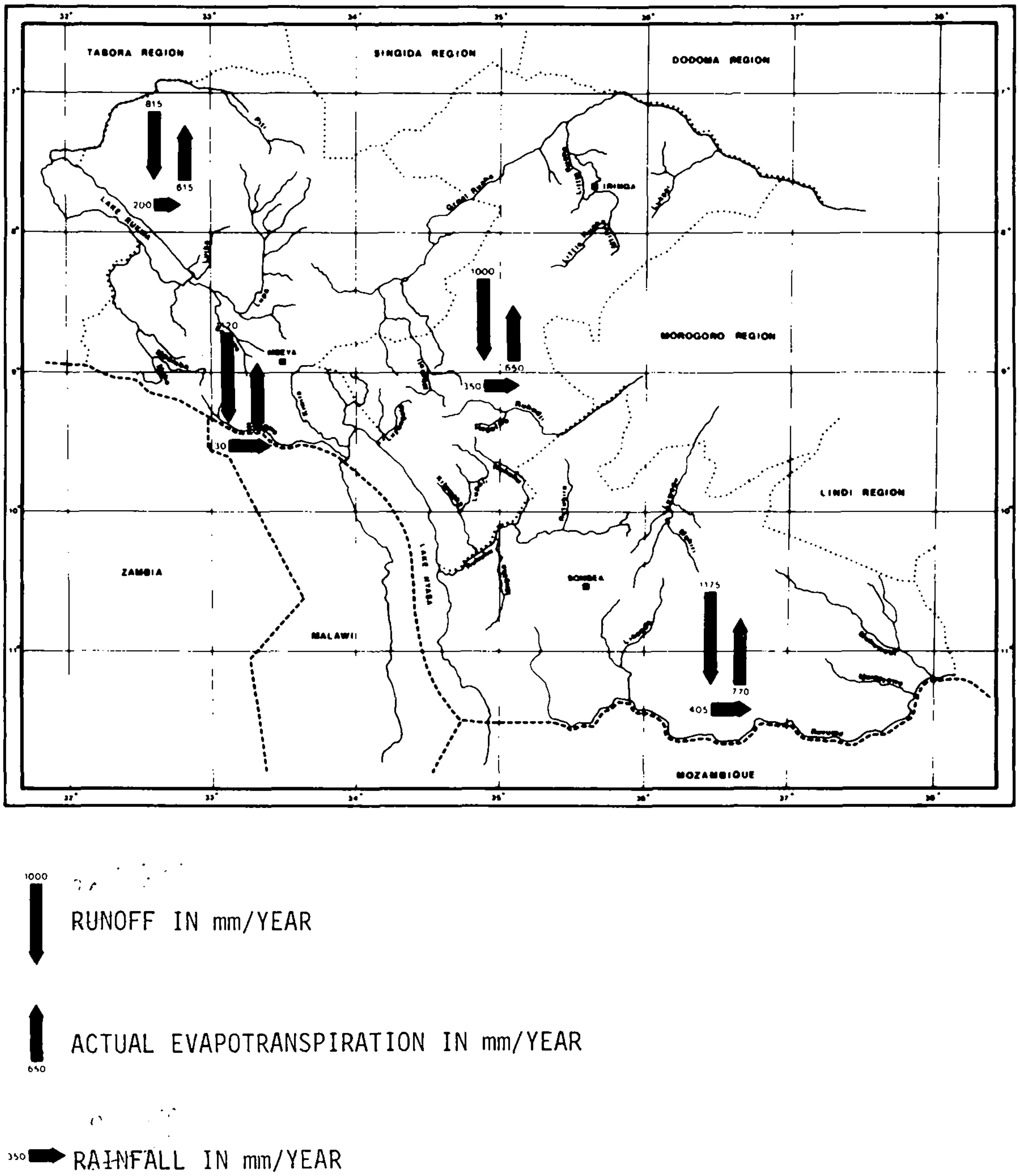


Figure 8.6 - Gross water balance components.

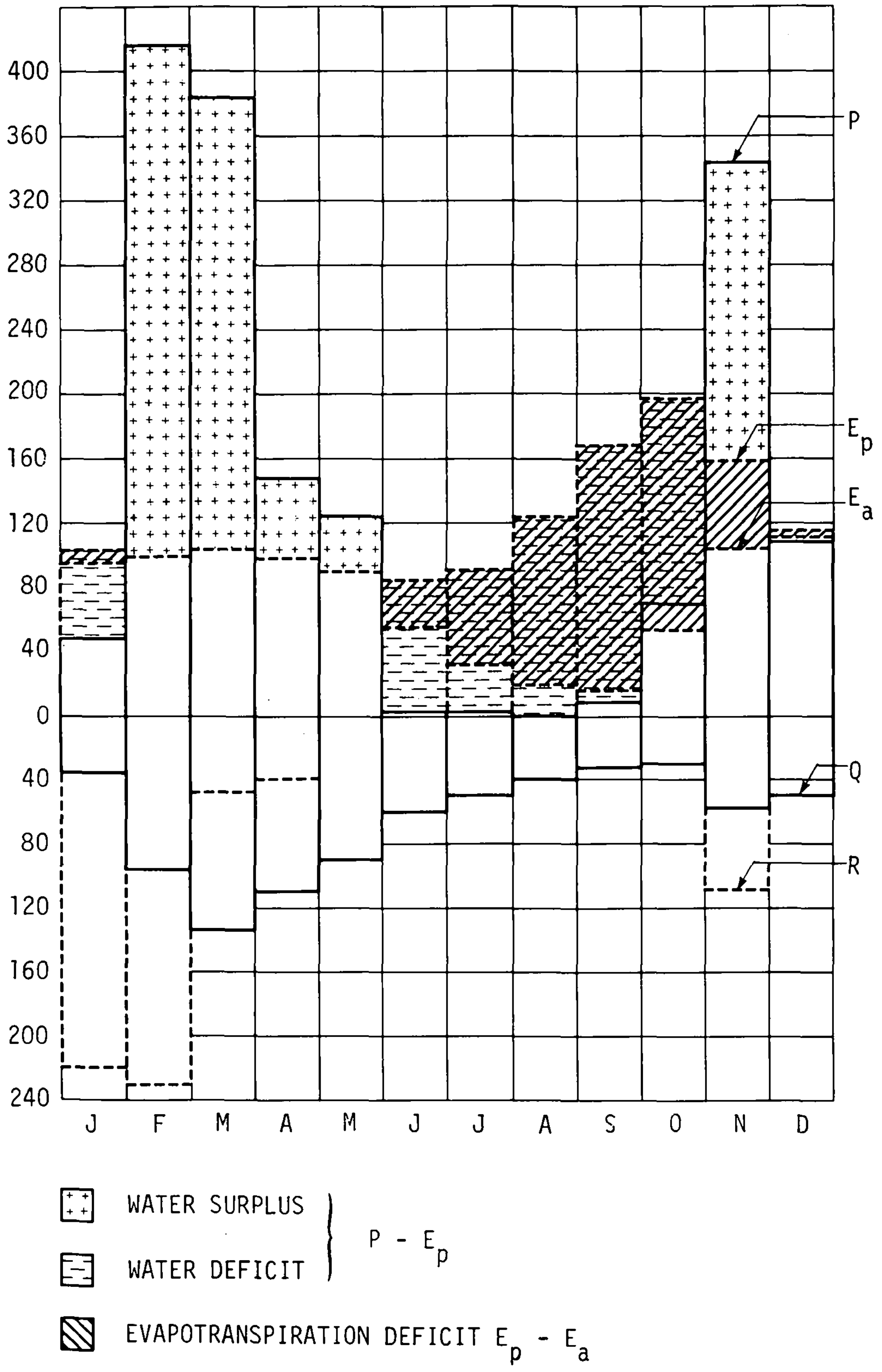


Figure 8.7 - Seasonal variation in water balance components. Kiwira index catchment (medium year).

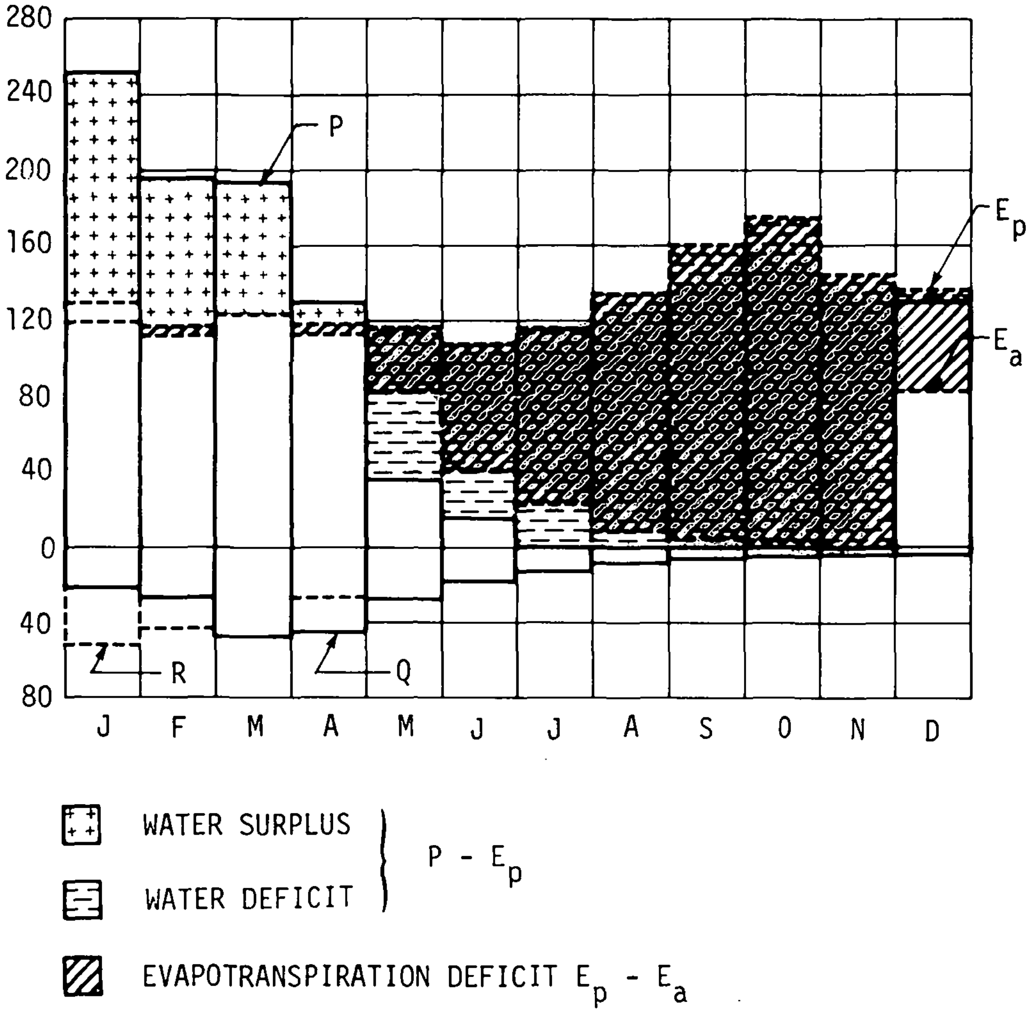


Figure 8.8 - Seasonal variation in water balance components, Lt. Ruaha index catchment (medium year).

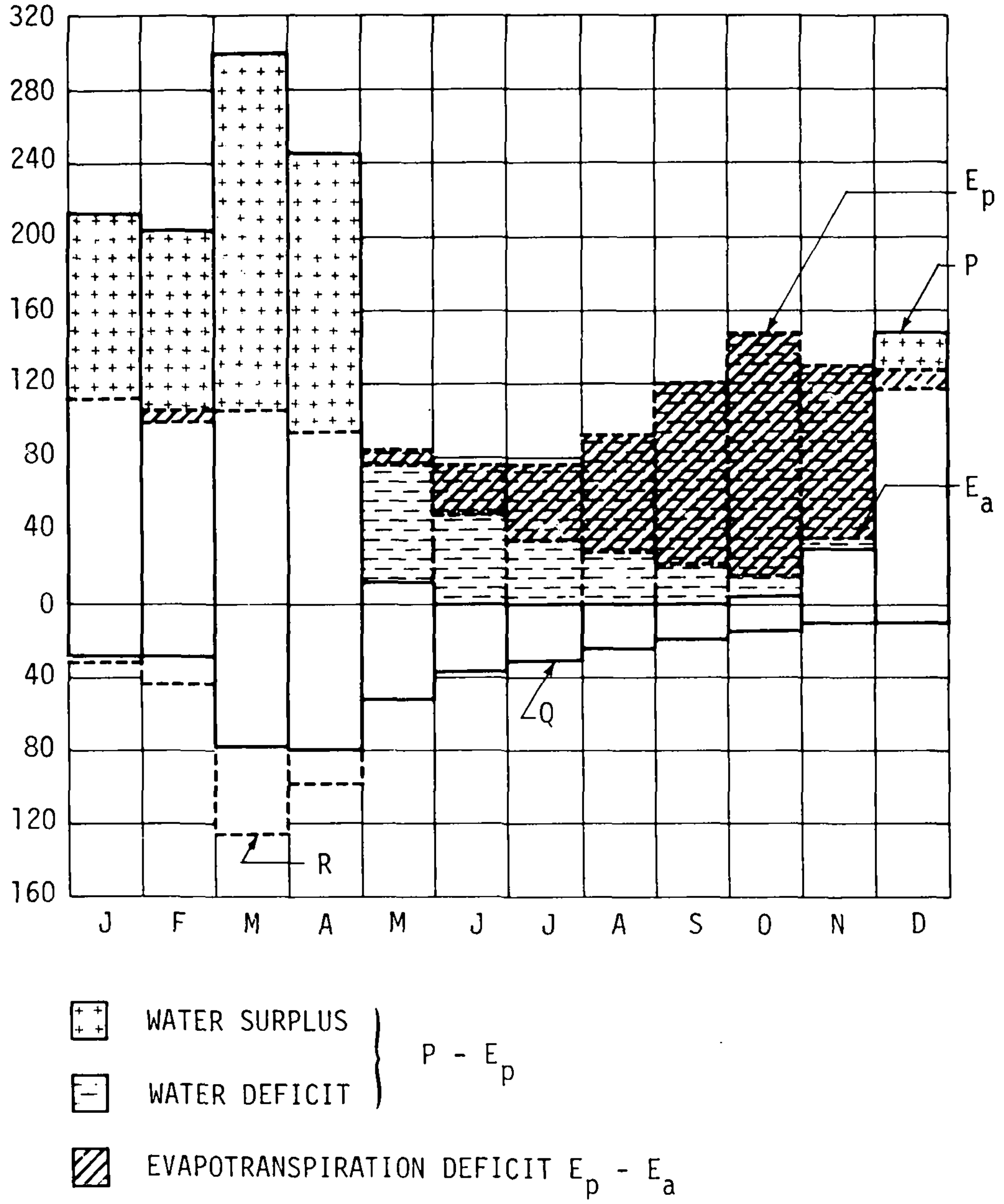


Figure 8.9 - Seasonal variation in water balance components, Mngaka index catchment (medium year).

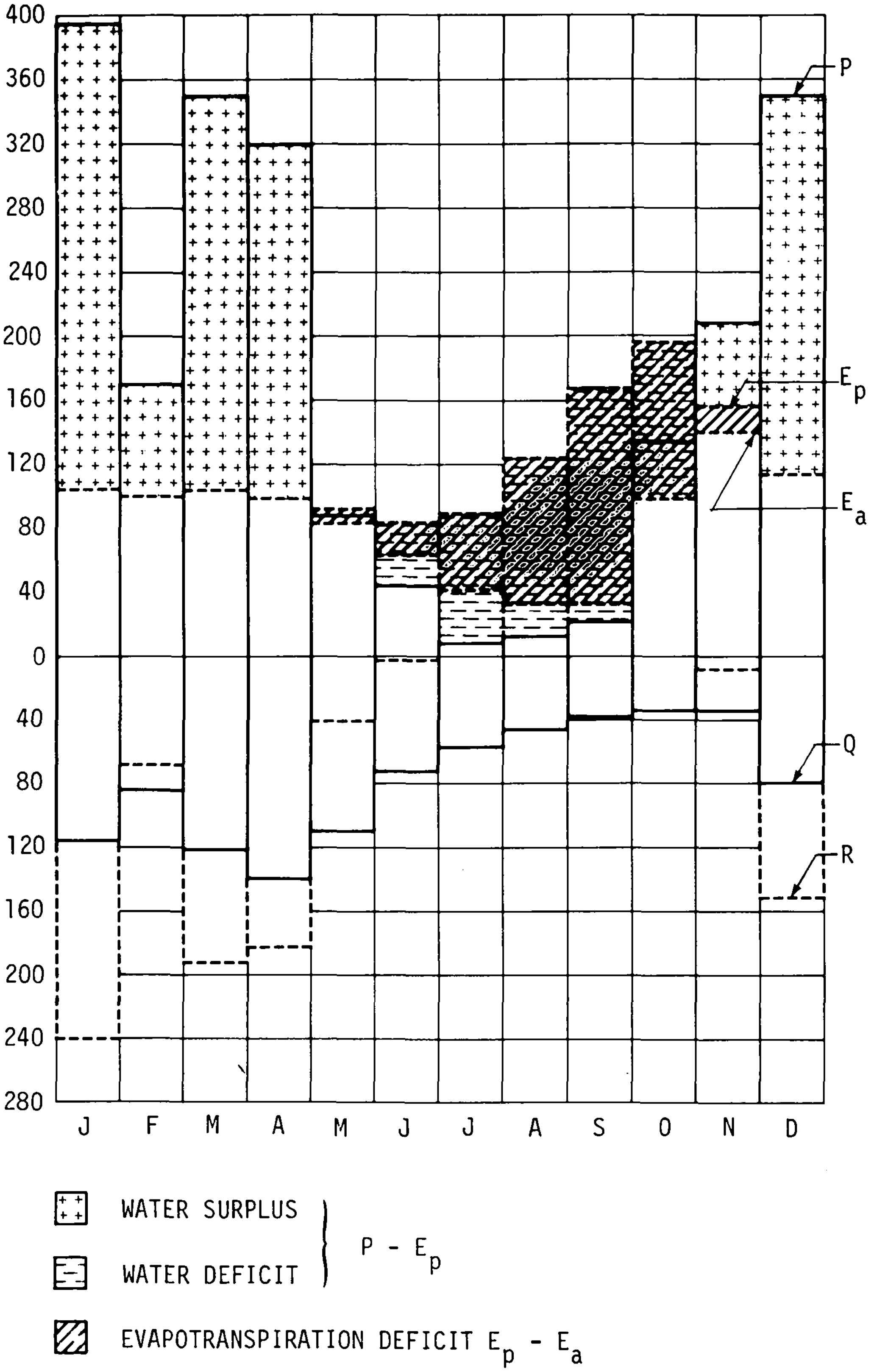


Figure 8.10 - Seasonal variation in water balance components. Kiwira index catchment (wet year).

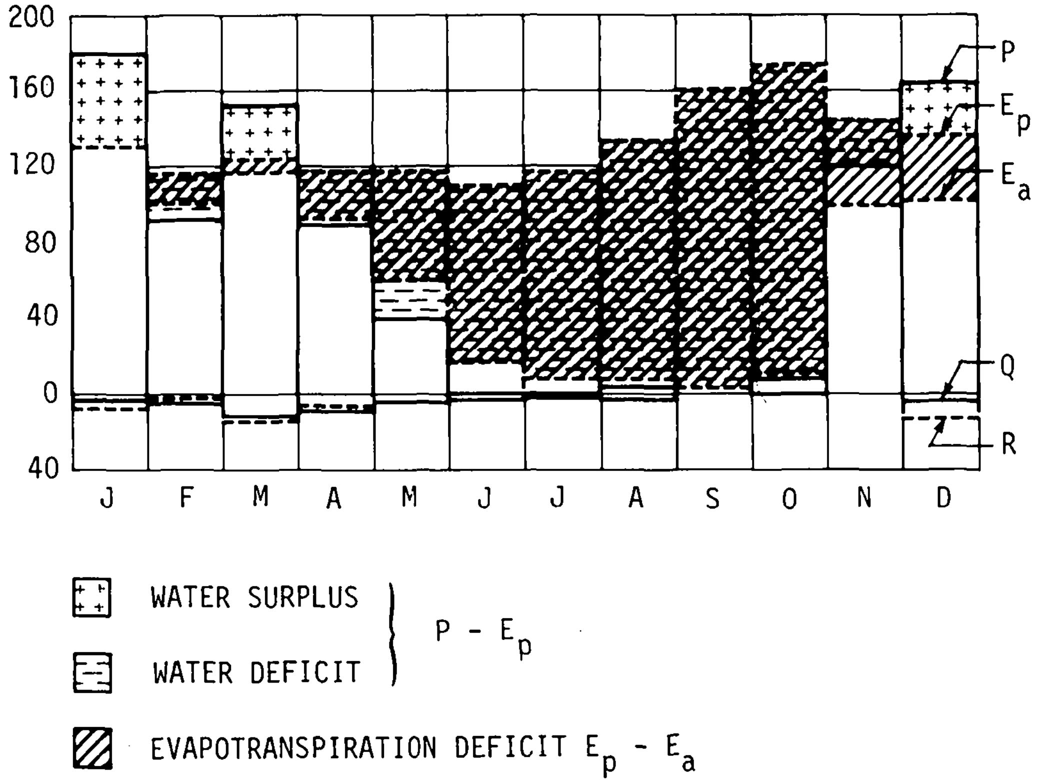


Figure 8.11 - Seasonal variations in water balance components. Lt. Ruaha index catchment (dry year).

has to be extracted from the available moisture in the root zone. However, the moisture content is often so low towards the end of the dry season that only a limited actual evapotranspiration can be maintained. Rains during the dry season have the greatest influence on the annual amount of actual evapotranspiration. If the rainy season lasts longer, the late rainfall may provide water for a higher evapotranspiration, and may even increase the moisture content in the root zone. Similarly an earlier beginning of the rainy season tend to increase the annual evapotranspiration. However, these natural variations in rainfall still lead to a variation in annual evapotranspiration within a rather narrow range.

For the range of hydrological conditions discussed here, the Kiwira catchment always has an annual water surplus, and the Lt. Ruaha always an annual water deficit, while the Mngaka catchment experiences more neutral surplus deficits, cf. Table 8.6^8. Obviously the surpluses appear during the rainy months, and the deficits during the months deficient in rainfall.

When the water supply from rainfall is insufficient to sustain the evapotranspiration requirements, the plants are supported from the available water in the root zone. However, it is only at the beginning of the period of deficit that the evapotranspiration is close to the potential level. When about half of the water holding capacity of the soil has been used, the actual evapotranspiration reduces below the potential level, and it eventually tend to zero when the permanent wilting point is reached later in the season. The largest deficits in evapotranspiration occur in the Lt. Ruaha catchment. This is due both to the difference in climatological conditions (rainfall and potential evapotranspiration), and to the difference in natural vegetation and soil conditions, which determine the moisture holding capacity of the root zone. The natural vegetation in the three catchments are rainforest in Kiwira, woodland in Mngaka, and wooded grassland in Lt. Ruaha.

The difference between potential and actual evapotranspiration, shaded in the figures, is indicative for the irrigation requirements in the sense that the plants have to increase the transpiration by this amount in order to attain full production potential. It is noted that months with only a small surplus may not secure optimal evapotranspiration conditions, since the rainfall may be unevenly distributed within the month.

A characteristic measure for the reduction in evapotranspiration is the ratio E_a/E_p. This quantity varies between 0 and 1 over the season as explained above. The annual values are given in Table 8.6^8. In the dry zone the ratio varies between 0.45 and 0.50, whereas the variation in the wetter zones is in the range 0.60 - 0.70.

The highest variability, both seasonal and yearly, is found for the recharge component. Recharge occurs only in the months with a large water surplus and is consequently concentrated over relatively few months, depending on the prevailing climatic conditions. As discussed in the modelling studies (cf. Chapter 7) the streamflow in all three catchments is dominated by baseflow, which in turn is supplied from the recharge. The rather high recharge rates are due to the highly permeable soils in the catchments. Comparison between the time variation of recharge and discharge shows that the groundwater reservoir reacts rather slowly to a recharge impulse. This observation is supported by the modelling studies in which the time constants for the groundwater storages in the three catchments have been estimated to about 100 days. However, since the discharge as illustrated in the figures contains all flow components (overland-, inter- and baseflow), comparison between recharge and discharge as done above is only approximate.

The discharge also displays a high degree of annual variability. The variability of this component is greatest in the dry zone, where it varies by a factor of almost ten between a dry and a wet year, while the corresponding variation in the wet Kiwira catchment is less than a factor two. The recharge has a similar variation. As evident from the figures the discharge exhibits a steady recession in periods without recharge.

Towards the end of the dry period the ground water storage may be depleted to such an extent that the outflow from it almost ceases. Obviously this phenomenon is most predominant in the dry areas.

Comparison of the hydrological characteristics of the index areas to average characteristics of the regions to which they belong show some discrepancies, as evident from Table 8.6^8 Mngaka index catchment for the medium case is fairly similar to catchment no. 1.14 and Ruvuma region in general in terms of water balance behaviour. However, the Lt. Ruaha catchment, and especially Kiwira catchment, deviate consisiderably from the average regional characteristics. These deviations are due primarily to the large climatological variability inside the study area which implies that averages over large areas tend to obscure a considerably range of variability. Hence comparisons of detailed water balances at the catchment acale to average regional characteristics have limited relevance.

8.4 Water appropriation

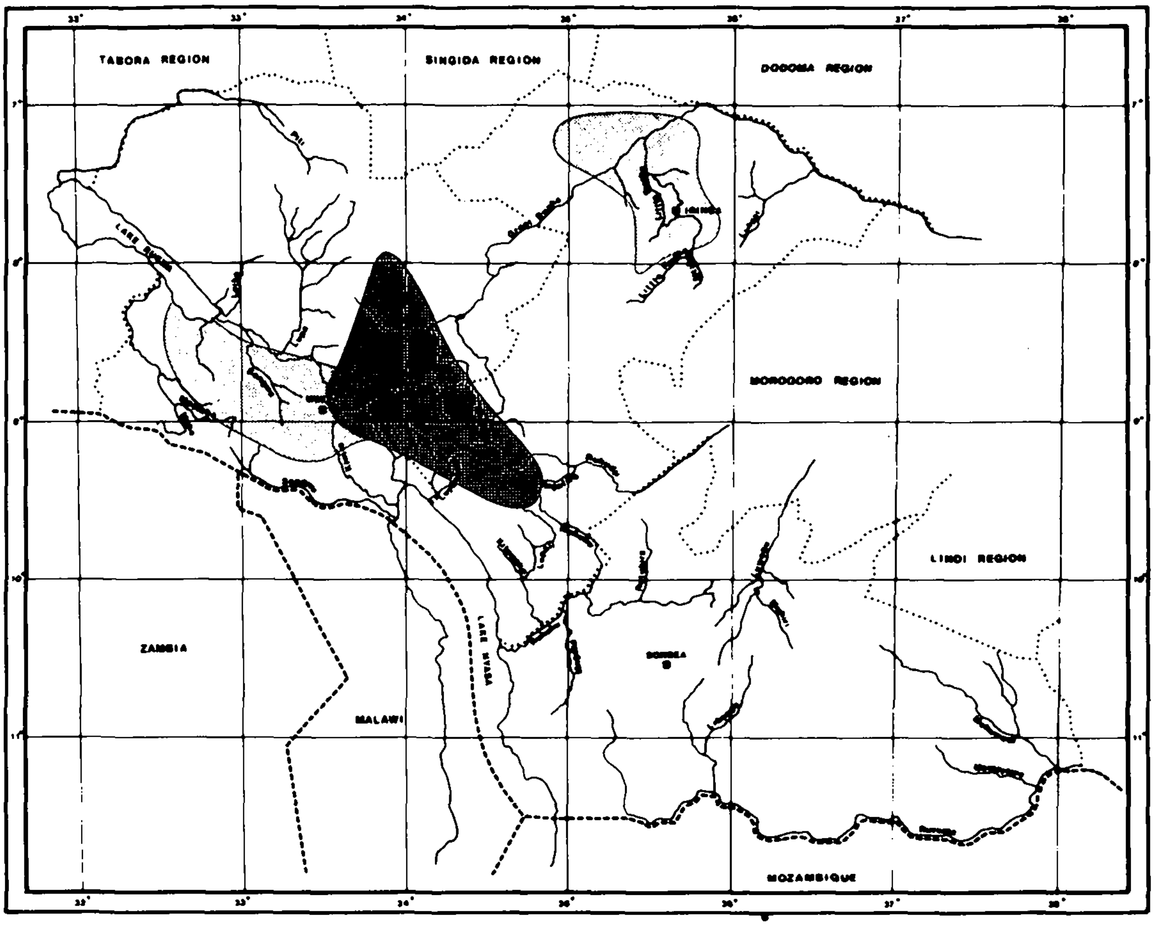
The system of appropriation of right to draw water has principally been managed by the Regional Water Engineers Office from considerations of water availability and previous appropriations. In practice nearly all applicants have been approved. However, with the increasing number of applicants and the at places rather limited water resources available, it seems urgent to establish some sort of management system or appropriation rules in order to handle the often conflicting interests of water allocations for domestic supply, irrigation, hydropower, etc.

As part of the present study a complete inventory of present water appropriations in the three regions has been prepared, as presented in Table 8.7[8]. In this table the following information is provided: amount of water appropriated for the individual water rights, purpose of water appropriation, source of water abstraction, and grantee. The water right information has been tabulated on a regional basis.

The appropriated river diversions as listed in Table 8.7[8] must be related to the available surface water resources. Where no regulation measures of the rivers have been carried out, minimum runoff situations will be decisive for the amount of water which can be appropriated. In the present study the 10-year minimum runoff has been adopted as an appropriate indicator of minimum flow conditions. This variable has been investigated in detail in Chapter 6 and a map has been prepared showing the regional variation of the minimum runoff (Figure 6.16). In the context of the present study it has therefore been natural to relate the degree of present water appropriation to this variable.

For each of the main catchments shown in Figure 8.1 the total issue of water rights have been compiled. These values are listed in Table 8.8 together with 10-year minimum and mean flows. The degree of appropriation for the individual catchments have been calculated as defined above, and for comparison the total water appropriation has further been related to the mean flow. These ratios are also shown in Table 8.8.

The regional variation of the degree of water appropriation is shown in Figure 8.12. From this Figure it appears that surface water resources are quite heavily appropriated during low flow periods in the agricultional



A : TOTAL APPROPRIATION

Q_{min} : 10 YEAR MINIMUM FLOW

▓ $A/Q_{min} \geq 1$

░ $A/Q_{min} = 0.5 - 1.0$

□ $A/Q_{min} = 0 - 0.5$

Figure 8.12 - Regional variation of the degree of water appropriation.

areas of Southern Mbeya and Iringa regions, and to some extent also around the town of Iringa. Water is little or only moderately appropriated in Ruvuma and the remaining parts of Mbeya and Iringa regions.

Catchment No.	Total appropriation l/s/km² W	10-year minimum flow l/s/km² Q_{min}	Mean flow l/s/km² $\bar{Q}$	Degree of appropriation	
				W/Q_{min}	$W/\bar{Q}$
1.1	0,004	0,0	6,3	x	0,0006
1.2	0,14	0,0	6,3	x	0,02
1.3	0,28	0,5	6,3	0,6	0,04
1.4	0,02	0,5	7,9	0,04	0,002
1.5	0,64	0,5	12,6	1,3	0,05
1.6	1,49	1,0	12,6	1,5	0,12
1.7	0,208	2,0	9,5	0,1	0,02
1.8	0.89	3,0	11,1	0,3	0,08
1.10	0.00	4,0	12,6	0,0	0,0
1.11	0,10	8,0	22,1	0,01	0,004
1.12	0,53	4,0	18,9	0,1	0,03
1.13	0,47	4,0	19,0	0,1	0,02
1.15, 1.16	0.008	3,0	17,4	0,003	0,0
1.20	0.01	2,2	12,6	0,005	0,0
1.21	0,008	2,2	17,4	0,004	0,0
1.22, 1.24	0,001	0,0	12,6	x	0,0
3.3,3.4,3.5 and 3.6	0,0007	0,0	6,3	x	0,0
3.7	0,028	0,3	6,3	0,09	0,004
3,8	0,53	1,0	9,5	0,5	0,06

x: Rivers in catchment of ephemeral nature - may therefore not flow in the dry season.

Table 8.8 - Water appropriation on catchment basis for Iringa, Ruvuma and Mbeya regions. Catchment numbers refer to Figure 8.1.

8.5 Recommendations

For detailed water balance studies on a rather short-term basis, as e.g. mounthly intervals, application of simple concepthal models containing a soil moisture accounting procedure (e.g. NAM) is strongly recommended. These models provide a nearly optimal use of readily available hydrological data (i.e. daily observations of rainfall and discharge and monthly values of potential evapotranspiration), and they simulate the amounts and the temporal variation of hardly measurable quantities such as actual evapotranspiration, recharge and water storage in the catchment. The NAM and similar models are engineering tools which are superior to the standard procedures used in water balance studies such as water surplus/deficit representations. Such representations serve illustrative purposes only, and can not be used operationally.

The rapidly increasing population and the growing need for irrigation for improved plant production requires a proper management of the available water resources. It is consequently recommended that the present water right holdings be critically reviewed in order to ensure that water rights which are not presently being beneficially utilized do not impair optimal planning and management of the available surface water resources.

9. SUMMARY AND CONCLUSIONS

9.1 General

The hydrological studies undertaken as part of the present Water Master Plan for Iringa, Ruvuma and Mbeya Regions have had as their primary objective to assess the availability of surface water resources for human utilisation, with particular emphasis on rural water supply. A secondary objective has been to study the hydrology of the regions in a more general context in order to determine their overall water balance. As an important part of this activity detailed modelling studies of the hydrological processes from rainfall to runoff have been carried out for three selected representative catchments (index areas) in the regions.

The hydrological study has involved extensive field work, including a comprehensive field measurement programme in 1980, and inspection of a large number of hydro-meteorological gauging stations. A computerised data base including rainfall and runoff data for all stations in the regions has been established and updated, based partly on existing data stored in Dar es Salaam and Nairobi, partly on data collected during the study period. In total, rainfall records from 289 stations with a total record length of 3,700 station years and runoff records from 74 stations with a total record length of 1,047 station years have been included in the study.

Full time participation of Tanzanian hydrologists has ensured incorporation of local methods and knowledge in the procedures and conclusions of the study. In addition, the Consultants have had the unique opportunity of obtaining hydrologic information from the detailed inventory of the 1,509 villages in the area, which has been of particular importance for the low flow studies.

By participating in the hydrological computer work at the Danish Hydraulic Institute (DHI) for a period of six months the Tanzanian hydrologists have received extensive on-the -job training, particularly in hydrological modelling techniques.

9.2 General hydrology

The project area, generally known as the Southern Tanzanian Highlands, is characterised by the mountains of southern Mbeya and Iringa, the relatively flat, high plains of northern Mbeya and Iringa and the undulating hills covering most of Ruvuma. This topography has a profound impact on the hydrology of the regions by giving rise to high rainfall, and hence high runoff and abundant surface water availability in the mountainous areas, while contributing to lower the rainfall and runoff in the flatter northern and eastern parts of the project area. Thus the general pattern of mean annual rainfall and runoff (cf. Figures 2.2 and 2.6) shows a remarkable dependence upon the topographical features.

The reason for this impact of topography upon the rainfall regime is the combined effect of local convergence and orographic lifting of airmasses, primarily during the northeast monsoon period from December through February, but also during subsequent inter-monsoon period from March through May. The southeast monsoon from June through September brings little moisture to the project area, in which rains usually start in November during the passage of the inter- tropical convergence zone from north to south.

The surface runoff in the regions occurs within five major drainage basins. The Indian Ocean drainage basin covers Iringa, Ruvuma and more than half of Mbeya, while the remaining part of Mbeya drains to the internal Lake Rukwa drainage basin. Drainage to the Indian Ocean takes place through the Rufiji River tributaries, the Great Ruaha, the Luwegu and the Ruhudji/Kilombero Rivers as well as the Ruvuma River and the Lake Nyasa drainage system (cf. Figure 2.5).

9.3 Rainfall

Rainfall conditions in the regions have been studied with the objective of verifying and refining existing regional rainfall maps, while at the same time providing data for the hydrological studies, particularly for the low flow assessment for water supply and the detailed hydrological studies of the three index areas.

An important objective in itself has been the establishment and updating of a unified data base comprising rainfall data from the period 1926-1976 currently available only at the former East African Meteorological Department in Nairobi, as well as more recent data collected from various sources in Tanzania. This data base has been designed to confirm current MAJI computer processing standards.

The rainfall study has involved inspection of a large number of rain gauges and establishment of additional daily rain gauges and self-recording pluviographs in the index areas. Rainfall data have been collected, checked and stored in the data base so as to form the basis for statistical analyses and preparation of isohyetal maps for mean and minimum annual rainfall. The statistical analyses have included basic statistics, frequency and trend analyses. More detailed studies of local rainfall patterns have been limited to the index areas.

In general, a reasonably dense network of rain gauges exists in the populated areas, while the sparsely populated northern and eastern parts of the project area are inadequately covered (cf. Figure 3.7). A total of 289 stations with 3,700 stations years of data is now contained in the data base, and the average degree of data availability (ratio of total period of valid observations to total period of station operation) is 82%. Although there is a scope for improvement of the operation and maintenance of many rainfall stations the reliability of rainfall data is generally quite good.

The rainfall studies confirm the general pattern outlined above, as can be seen from the isohyetal maps in Figures 2.2 and 3.17. Mean annual rainfall varies from less than 500 mm in northern Iringa, to more than 2,600 mm in southern Mbeya. Individual annual rainfall amounts vary from less than 250 mm to more than 3,100 mm. The seasonal rainfall variation is basically unimodal, rains occuring in the period from November through May, while the period June to October is generally dry (cf. Figure 2.2). Rainfall amounts may vary considerably from year to year. Hence frequency analyses of annual rainfall amounts at various locations show that rainfall in wet years may be 50-60% higher than in dry years (cf. Figures 3.15 and 3.16), and the 10-year minimum annual rainfall as shown in the isohyetal map in Figure 3.18 is about 30-50% lower than the corresponding mean annual rainfall.

Detailed studies of local rainfall patterns indicate a generally very high spatial variability, hence confirming the convectional nature of rainfall in the Southern Highlands. Heavy localised rainstorms occur, which in the wet areas may produce up to several hundred millimetres of rain in a day.

Analysis of trends for selected reliable long term stations confirm the general view that ho significant change in the rainfall regime of the Southern Highlands has taken place over the past 50 years. A similar conclusion has been reached with respect to runoff conditions, and this implies that general hydrological conslusions may be drawn on the basis of the historical records available for the present study.

9.4 Evaporation

Studies of evapotranspiration, defined as the combined process of evaporation and transpiration from crops and natural vegetation have been essential for the detailed hydrological index area studies, as well as for the determination of overall water balances. A primary objective of these investigations has been to determine the spatial and seasonal variability of the potential evapotranspiration, which represents an upper limit for the rate of water loss from a vegetated surface to the atmoshere. However, because of the lack of adequate water in the soil for the plants during the dry season the actual evapotranspiration is always less than the potential rate, and consequently, from a water balance point of view, studies of actual evapotranspiration have been equally important.

The evapotranspiration study has involved inspection of all climatological stations and evaporation pans in the project area. All available pan evaporation data have been collected and analysed, and some of the available climatological data have been collected and used for indirect determination of potential evapotranspiration using the Penman formula. A comprehensive comparison study between all available direct (evaporation pans) and indirect (Penman) estimates of potential evapotranspiration has been undertaken.

The areal coverage of climatological and pan evaporation stationsis anadequate for detailed evapotranspiration mapping, particularly in northern Mbeya and Iringa and eastern Ruvuma. In addition the quality of data from these stations are generally rather poor, primarily because of station operation and maintenance problems. The results of the present evapotranspiration study are consequently subject to considerable uncertainty.

Having arrived at an average pan coefficient of 0.7 for converting pan evaporation measurements to potential evapotranspiration an isoline map of annual potential evapotranspiration has been prepared (cf. Figures 2.3

and 4.22). Evaporation rates from free water surfaces are approcimately 20% higher than the potential evapotranspiration rates indicated in this map. Whereas potential evapotranspiration, as opposed to rainfall, varies only little from year to year, the spatial variability is considerable, ranging from more than 2,200 mm per year in the dry and warm northern Iringa, to less than 850 mm per year in the cool and wet highlands of southern Mbeya and Iringa. Potential evapotranspiration generally increases during the dry season, reaching a maximum in October just before the rainy season sets in. Compared to the variation in rainfall the seasonal variation of potential evapotranspiration is rather small (cf. Figure 2.3).

Actual evapotranspiration ahs been estimated from mathematical modelling studies of the index areas, and also as the difference between rainfall and runoff from general water balance considerations. The ratio between actual and potential evapotranspiration varies in the range 0.40-0.65, increasing from dry to wet areas. Approximate isoline maps of this ratio, and of the annual evapotranspiration rate, have been prepared (cf. Figures 8.4 and 8.2).

9.5 Runoff

The main objective of the runoff studies has been to make an inventory of surface water resources for village water supply planning. For this purpose low flow conditions have been of primary interest, in the generalisation of regional runoff characteristics, as well as in the assessment of minimum yields for specific surface water supply schemes. In addition, as part of the general hydrological study, runoff conditions have been investigated in great detail, by compiling and analysing all available water level and stream flow data, and conducting detailed rainfall runoff studies in the ghree index areas.

The runoff studies have had three basic components: Collection, control and processing of basic tata, detailed analyses of the resulting data material, including regionalisation of the results, and the index area studies. All 74 permanent streamflow stations in the project area, with a total of more than 1,000 years of daily streamflow data (based on twice or thrice daily water level observations), have been included in the investigations. 19 of these (280 station-years) representing a characteristic cross-section of hydrological conditions in the ghree regions, have been selected as so-called priority stations for very detailed data evaluation and analysis.

In order to verify and improve the existing data material almost all the streamflow gauging stations in the regions have been inspected. A comprehensive programme of streamflow measurements has been undertaken during the dry season of 1980, particularly for the purpose of improving the rating curves (water level - streamflow relationships) in the critical low flow regime. This programme has been implemented by MAJI's hydro-teams, under the Consultants' planning and supervision. A large number of spot measurements of streamflow have been carried out in connection with the general village inventory to support the low flow evaluation.

A major and very important activity has been the control and up-dating of MAJI's hydrological data base for the ghree regions. A central hydrological data base for the entire country containing water levels, rating curve and streamflows on magnetic tapes is maintained by MAJI-Ubungo using the computer of the Ministry of Finance. However, primarily because of the lack of computer facilities in MAJI itself, and the very limited access to the central computer, MAJI has great difficulties coping with the large amount of data from all over the country. The result has been considerable delays in the hydrological data processing, storage and control. In order to assist MAJI in this respect, and provide a reliable and up-to-date data base for the present study, the Consultants have designed and operated on their home office computer a data base and data processing system fully compatible with MAJI's own system. Using this system all records in the existing data base have been checked, and where necessary corrected, and all streamflow stations in the data have been updated through 31st December 1979 (31st December 1980 for priority stations). Senior MAJI hydrologists and counterparts have participated actively in this work in Tanzania and Denmark.

In general, a reasonably dense network of streamflow gauging stations covers the project area, particularly after the completion of the Norwegian financed Hydrometeorological Survey of Western Tanzania. However, in certain areas, such as eastern Ruvuma and the Lake Nyasa drainage area, station coverage is still inadequate. The reliability of water level and streamflow data is generally acceptable, but satisfactory operation and maintenance is still a problem for many stations. Only little information is available on sediment transport, and the available data covers only the streamflow recession period when sediment loads are low.

The surface runoff pattern corresponds rather closely to the general unimodal rainfall pattern. Streams start rising in November-December, experience maximum flow in March-April, and have their recession period from May to October-November. In the warm and dry northern parts of Iringa and Mbeya, with average annual rainfall below 500-800 mm, streams run dry every year, and the southwestern highlands, where average annual rainfall is in the range 1,200-1,600 mm, streams are perennial, and mean annual runoff exceeds 10 $l/s/km^2$. Between these extremes, in areas like eastern Ruvuma, western Mbeya and Mufindi receiving 800-1,200 mm of rianfall annually streams are perennial or intermittent (only occasionally dry) and mean annual runoff is in the range 2-10 $l/s/km^2$.

In fact, the correlation between average annual rainfall and runoff is remarkably high, apparantly more or less irrespective of the geomorphological chracteristics. However, no clear dependence on rainfall can be detected for minimum runoff conditions (cf. Figures 6.17 and 6.19).

As an important result of the present study isoline maps of mean annual runoff and 10-year minimum instant runoff have been prepared (cf. Figures 6.15 and 6.16). While based primarily on the analysis of available streamflow data, information from the spot gauging programme, interviews with the local population, hydrogeological considerations and consideration of rainfall and evapotranspiration regimes have been incorporated in the preparation of these maps.

The runoff maps are the result of regionalisation of runoff characteristics obtained by statistical analysis of the basic streamflow data. A number of such standard analyses have been performed, some for all the streamflow stations in the data base, others for the priority stations only. These analyses have included calculations and graphical presentation of basic streamflow statistics, preparation of flow duration curves, plotting and analysis of streamflow hydrographs, including detailed analysis of recession constants, trend analyses for selected long-ter, stations, high and low flow extreme value analyses, using Gumbel and Weibull distributions respectively, auto-correlation analyses, including preparation of auto-correlograms, and a sample reservoir capacity-draft analysis using a simple reservoir design computer programme.

When comparing these analyses for different locations in the regions a general picture of the variability of the characteristic hydrological regimes in the project area emerge, in which dry and wet areas show distinctly different characteristics. However, although more than 80% of the runoff appears in the form of baseflow (i.e. entering the streams by way of the groundwater aquifer system), in dry as well as in wet areas, runoff characteristics seem to bear little direct relation to the broad geomorphological zones identified in the hydrogeological study.

9.6 Index area studies

The primary objective of the detailed hydrological studies in selected representative catchments has been to investigate water balances in different hydrological regions. Another objective of these studies has been to provide the necessary hydrological background and instrumentation for continued representative studies in the regions, drawing partly on expertise developed during the training of hydrologist counterparts in hydrological computer modelling.

In order to meet these objectives within the scope of the hydrological studeies three index areas have been selected, the Kiwira River in Mbeya, the Little Ruaha River in Iringa and the Mngaka River In Ruvuma (cf. Rigure 7.1). These areas have been selected with a view to represent dry and wet conditions and a range of catchment sizes of particular relevance for rural water supply studies, while requiring reasonably long and reliable data records.

The index area investigation have included inspection of all gauging installations in the catchments, through data control and processing, including detailed studies of rainfall patterns and spatial correlation between stations, and mathematical modelling of the hydrological processes in the catchments. Additional hydro-meteorological instrumentation, including automatic rainfall recorders and evaporation pans, ahs been established in the ghree index areas, primarily for the purpose of collecting supplementary data for future investigations.

The mathematical modelling studies have been carried out using the so-called NAM-model, a hydrological computer simulation model, originally developed at the Technical University of Denmark. The model describes the land phase of the hydrological cycle by accounting, on a daily basis, for the water content in surface water, soil and groundwater storage, thus computing daily values of actual evapotranspiration, infiltration, recharge to the groundwater storage and the various runoff components: overland flow, interflow and baseflow. The required input to the model is daily rainfall and mean monthly potential evapotranspirations.

The results of the modelling studies have been very encouraging. Good agreement between observed and simulated runoff for the three catchments has been obtained, and on this basis it has been possible to extend the rather short streamflow record for Mngaka River using longer records of rainfall. The model predictions of soil moisture levels correspond well with agricultural experience in the three catchments, soil moisture being fully depleted in the dry Lt. Ruaha catchment, while being depleted only partly in the wetter Mngaka and Kiwira catchments.

Probably the most important and encouraging result from the modelling studies has been that model parameters vary little between the catchments, implying that the NAM-model with a standard set of parameters can be applied to obtain at least approximate prediction of runoff from rainfall in the major part of the project area. This hypothesis has been tested with positive results on four additional catchments in the regions, and is further supported by a recent hydrological modelling study using the NAM-model at Kifunga near Njombe.

With the above evidence of the ability of the NAM-model to account for the hydrological processes, the model computation of non-measurable quantities such as actual evapotranspiration, groundwater recharge, baseflow etc. have been utilised to support the determination of overall water balances. Thus the interpretation of the model results has contributed significantly to the general understanding of the hydrology of the project area.

9.7 Water balances

The results of the rainfall, evaporation, runoff and index area studies described above has been summarised in the form of maps showing average annual values of characteristic water balance quantities, such as actual evapotranspiration, average runoff coefficient, ratio of actual to potential evapotranspiration and water surplus/deficits defined as the difference between rainfall and potential evapotranspiration (cf. Figures 8.2-8.6).

Gross figures in mm per year for rainfall, actual evapotranspiration and runoff on a regional basis are also presented (cf. Table 8.2).

It is emphasised that the water balance representations have been included for illustative purposes only, and that hydrological information for operational use must be found in the more detailed sections of the report and the associated data volume. Overall water balances have been prepared on an annual basis only, referring to the more detailed index area water balances for an indication of the seasonal variation in various hydrological regimes.

Finally an investigation of existing water right issues have been made, indicating that during low flow periods surface water resources are quite heavily appropriated in the populated agricultural areas of southern Mbeya and Iringa, and to some extent also in the area around Iringa Town (cf. Figure 8.12).

10. RECOMMENDATIONS

As part of the present Water Master Plan study hydrological investigations have provided an inventory of available surface water resources. This inventory has been based primarily on existing hydrological data, supplemented by discharge measurements in 1980, and has resulted in regional runoff maps, as well as specific low flow estimates at a number of locations in the regions. Rural water supply schemes can in many cases be designed and implemented safely on the basis of this information, particularly in areas where surface water resources are perennial, and planned water supply schemes require little water. However, in other cases it will be necessary to make additional hydrological measurements and investigations in order to ensure that potential surface water sources do indeed satisfy design requirements, both with respect to quantity and quality.

It is strongly recommended, therefore, that supplementary (temporary) hydrological gauging stations be established soon at locations where such additional hydrological investigations may be required.

With respect to the network of permanent hydrological gauging stations it is concluded that coverage is adequate in almost all parts of the regions, and that new stations should be established primarily as part of a general network improvement programme. The raingauge network, however, needs strengthening in the poorly covered northern and south-eastern parts of the project area, while the network of pan evaporation stations requires a thorough general improvement. An effective programme of sediment sampling needs to be initiated.

For all types of hydro-meteorological gauging stations, and not least for the climatological stations in the regions, more frequent station inspections are required in order to properly support and encourage the observers, and thus ensure regular and reliable reporting of data to the central agencies. Poor infra-structure and inadequate transport possibilities represent a major constraint in this regard.

Upon receipt of data reports from the various hydro-meteorological stations expedient control, processing, storage and publication of data is a primary responsibility of the central agencies, such as Maji and the Department of Meteorology (DOM). This task is currently not being performed to the required standard, with the result that data are published with long delays, and not always properly controlled.

A major constraint in this regard is the lack of computer facilities at Maji Ubungo. Maji has a number of well trained and experienced hydrologists, who, given adequate computer facilities, could maintain an up-to-date, high quality data base to support the investigations required for water resources management, whether for water supply, irrigation or other purposes. The Water Master Plan Coordination Unit, located at Maji Ubungo, has as one of its' important responsibilities the task to organize a large volume of information in a data bank, which also requires computer facilities. For these reasons alone acquisition of a medium-size computer system to be installed at Maji Ubungo is strongly recommended.

However, Maji's needs and capabilities in computer analysis go beyond data base management. Maji has experienced staff competent at hydrological data analysis by the use of computers, including mathematical modelling of hydrological processes. As part of the present study Maji hydrologists have been trained in the use of the Danish hydrological catchment model, the so-called NAM-model which has proven to be a useful tool for hydrological investigations in the three regions concerned, and probably also for many other parts of Tanzania. Consequently it is strongly recommended that the NAM-model, together with other hydrological software, be installed and tested at a computer installation at Maji Ubungo, hence enabling Maji hydrologists to put their knowledge to practical and beneficial use for the solution of future water resource problems.

Finally it is recommended that the water right system be critically reviewed, and that rights not properly utilized be withdrawn.

In addition to the general recommendations given in this chapter, sections are included at the end of each chapter which contain more specific recommendation, and elaborate on the above, particularly with respect to gauging network and procedures.

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