3. HYDROGEOLOGICAL INVESTIGATION

3. HYDROGEOLOGICAL INVESTIGATION

3.1 Topography and Vegetation

3.1.1 Satellite Images and Aero-photos

Satellite image and aero-photo interpretations are useful for understanding the topographical and geostructural features over a wide area in a short time. Because of this advantage, the satellite image and aero-photo interpretations were introduced in this Study as a means to prepare a hydrogeological map.

(1) Collected data

The kinds of data collected for this Study are listed in Table 3.1.1 and described below.

1) SPOT image data

The artificial satellite SPOT is mounted with HRV (High Resolution Visible Imaging Instrument) sensor and its resolution on land is about 10m in panchromatic mode and about 20m in multi-spectra mode. One scene of SPOT image covers an area of 60km x 60km in panchromatic mode. Fourteen (14) scenes of panchromatic prints with scale of 1:100,000 were obtained.

2) LANDSAT image data

The artificial satellite LANDSAT is mounted with two kinds of sensors, MSS (multi-spectral scanner) with 80m resolution on land and TM (thematic mapper) with 30m resolution on land. Both sensors cover an area of 180km x 180km in one scene. MSS is composed of 4 bands while TM consists of 7 bands. The choice of the type of image data to use depend on the purpose. For this Study, 12 scenes of MSS panchromatic photos (scale = 1:500,000) and TM data of good picture quality were obtained.

3) Aero-photos

Taken by France in 1949 to prepare the topographical map of Madagascar, the aero-photos obtained are in 1:40,000 to

1:45,000 scales.

The map covered by satellite images and aero-photos is shown in Fig. 3.1.1.

(2) Analytical method

1) Interpretation of satellite images and aero-photos

Using the LANDSAT and SPOT images in panchromatic mode, the drainage system, ridge system, photo-lineament and other elements were interpreted on a single photo.

The aero-photos were interpreted under the stereoscope on the areas where a satellite image was not clear and on the surrounding areas of the candidate villages.

The accuracy of the photo interpretation was improved by the ground-truth along the main routes in the Study Area.

The items listed in Table 3.1.2 were interpreted from the viewpoint of photo-geology.

2) Computer image analysis of LANDSAT TM data

The LANDSAT TM data is obtained in the form of CCT (computer compatible tape), which can be processed by the digital image analysis system to produce the desired images.

The flowchart of the analysis used in this Study is shown in Fig. 3.1.2.

The original LANDSAT data have various deformations. Geometric correction is made to the original data to convert the coordinates so that they may positionally coincide with topographic maps. To make the geometric correction to the LANDSAT data, it is necessary to determine the ground control points (GCP). Conspicuous points (like water fronts, rivers and roads) on both image and topographic maps are selected as the ground control points. Coordinate conversion is made to the ground control points which were selected by measuring the coordinates on both image and topographic maps. Given the topographic coordinates (x, y) and image coordinates (u, v), the conversion is made according to the following formula:

$$x = au_1 + bv_1 + c$$
$$y = au_2 + bv_2 + c$$

where a, b and c are unknown quantities to be estimated by the method of least squares from the coordinates of four (4) or more ground control points.

For this Study, land cover classification image and water content classification image are necessary in addition to the principal component image.

The geometric correction is then followed by the construction of false color image which is the color synthesis of three bands (Band 1, 2 and 4) out of seven bands of TM data. Color tones of false color image in this case are shown in Table 3.1.3.

Land cover classification image is constructed by classifying the false color image in accordance with the training fields (the areas, where land cover is already known, which are called trainers).

On the other hand, water content classification image is constructed by level slicing for Band 6 which is near-infrared and absorbed in water.

The principal component image is constructed by edge emphasis technique to clarify the boundaries of land use, geology, topography, and others.

Examples of the four (4) kinds of image mentioned above are shown in Figs. 3.1.3 to 3.1.6.

3.1.2 Topography

Fig.3.1.7 shows distribution of ground elevation, and Fig.3.1.8 shows topographical zone in the Study Area. Topography of the area is characterized by some massif extending in the NNE-SSW direction. Isalo massif (about 60km long) and Tangoormbohitr massif(about 60 km long) are located in the eastern margin of the Study Area. These massifs are separated by a wide valley of Ilakata river, a branch of Imalto river, even though, originally the two massifs formed a continuous mountain chain. A steep cliff continuously borders the edge of these mountains. Complicated deep valleys are developed between both massifs. Some mountains with flat top are distributed independently.

Only part of Isalo massif is contained in the Study Area, but it is the principal recharge area of Isahena and Malio rivers, which have its watershed located in the eastern part of the massif. On the other hand, watershed of Tangorombohitr is located in the western part of the massif, contributing only partially to recharge of Isahena and Malio river.

Lambosina massif extends over 100 km with very gentle slope. The western side of this massif is a very steep cliff, while the eastern side is a very long and gentle slope. This slope is the principal drainage basin of the right bank of Sakanavaka river. Two massifs sandwiching Sakondry river were originally formed by Lambosina massif as a continuous body, but it was eroded and divided by Fiherenana and Sakondry rivers.

Analavelona massif is 35 km in width and 100 km in length. Since the watershed is deviated to the west, the eastern slope is long. This side is the principal discharge basin of the right bank of Fiherenana river. The northern part of the massif includes Herea plateau, which is the principal drainage basin of Sakanavaka river.

Mikoboka massif is 25 km wide in its central part. This massif forms two branch chains in the northern part and sandwiches the valley of Sikily river, extending to the northern part of Mangoky river. The watershed of this massif(1,000 m -1,100 m in altitude) is deviated to the east, whereby the western slope is long, this side being the principal drainage basin of rivers flowing toward the coast.

There is a deep straight valley between the upper reaches of both Manombo and Sikily rivers. There is no valley between Mikoboka massif and Analavelona massif.

Between the western side of Mikoboka massif and the southern side of Analavelona massif, the Belomotra-Vineta plateau slopes gently to the south. This plateau extends almost 60 km south of Analavelona, crossing the Onilahy river. This plateau is basically flat, but includes very deep valleys in complicated pattern.

The western part of the mentioned plateau is a very wide continuous plain (Coastal plain), with an average elevation of less than 200 m, reaching to the coast line in the southern portion. There is a big delta in the northern margin, and a small delta by Fiherenana river in the southern margin, which is located in the coastal plain.
The width of this plain is around 70 km in the northern part, becoming gradually narrow toward the south. The above mentioned Belomotra -Vineta plateau faces directly the sea in the mouth of Onilahy river.
In the eastern side of an imaginary line from Lake Ihotry to the mouth of Manombo river, there are six fans from north to south along the western margin of Mikoboka mountain. This zone is divided by the river system into Lake Ihotry basin and Manombo river basin.

There are other basins in the Study Area. The basins formed in the middle reaches of Isahena, Sakanavaka and Fiherenana rivers, classified as poligon-shaped intramountain basins, are eroded by many branch rivers. The boundary between these basins and surrounding mountains is not clear. On the other hand, the basins formed in the lower reaches of Taheza and Sakondry rivers, classified as valley plain, are narrow and straight.

3.1.3 Vegetation

The vegetation of the catchment area is a very important factor for groundwater recharge. Cattle and sheep graze in the Study Area, and deforestation has rapidly advanced in the past 10 years to open up land for farming and grazing. The grazing land is burned every year, and therefore, there is no chance for reforestation. There are irrigation intake facilities which were damaged by cyclone flooding, on Mangoky river in January-February of 1972, and on Fiherenana river in December of 1966 and 1989. This problem suggests that deforestation greatly influences the river condition.

Fig. 3.1.9 shows the forest distribution as land cover classification map produced by Landsat TM data. According to this map, remaining forest area is found only in the western part of the Coastal plain, Belomotra-Vineta Plateau, the area from the western slope of Analavelona massif to Herea plataeu, and the area between the upper reaches of Fiherenana and Taheza rivers. The vegetation cover of two areas (Coastal plain and Belomotra -Vineta Plateau) is composed of bush which is considered to contribute little to groundwater recharge.

Table 3.1.1 List of satellite images and aero-photos

Kind of photo	Situation				
	Mode	Scale	Path	Row	Date
LANDSAT-1	MSS Panchro-matic	1:500,000	172	74	08 AUG '73
				75	08 AUG '73
				76	08 AUG '73
				77	15 JUN '73
			171	74	09 MAY '73
				75	09 MAY '73
				76	26 FEB '73
				77	26 FEB '73
			170	74	15 DEC '72
				75	11 SEP '73
				76	04 OCT '72
				77	02 JAN '73
LANDSAT-4	TM (Digital data)		160	75	27 FEB '85
			160	76	27 FEB '85
			161	75	17 JAN '85
			161	76	17 JAN '85
SPOT-1	Panchro-matic	1:100,000	163	394	06 MAR '86
				395	06 MAR '86
				396	24 APR '88
			164	397	27 JAN '88
			165	394	30 APR '88
				395	30 APR '88
				396	21 AUG '89
				397	21 AUG '89
			166	393	02 APR '89
				394	02 APR '89
				395	21 AUG '89
				396	21 AUG '89
			167	392	26 JUN '88
				394	06 SEP '89
AERO-PHOTOS	Panchro-matic	1:40,000-1:45,000	B:54-57 C:53-58 D:54-58 E:54,56,57 F:54-57 G:54-55 H:54 Total: 1,000 sheets		1949

Table 3.1.2 Methods and items of photo-interpretation

Kind of photos	Method	Item of photo-interpretation
LANDSAT	Mono-scopic	Photo-lineament, Drainage system, Ridge system, Basin, etc.
SPOT	Mono-scopic	Photo-lineament, Fracture trace Forms of fluvial origin, Drainage characteristics
Aero-photos	Stereo-scopic	Karst landscape features, Slope instability features, Aeolian features, Geological structure, Features resulting from bedrock structure, man-made features.

Table 3.1.3 Color tones of false color image

Objective	Color tone of image
Clouds	Pure white
Thick clouds	Pure white, with shadow
Thin clouds	White
Fog	Whitish
Forest	Red
Farmland, grassland	Pink (yellow brown)
Bare land	White
Humid land	Light blue
Streets	Light blue
Water (contaminated)	Light blue
Water (normal)	Dark blue
Shadow	Black

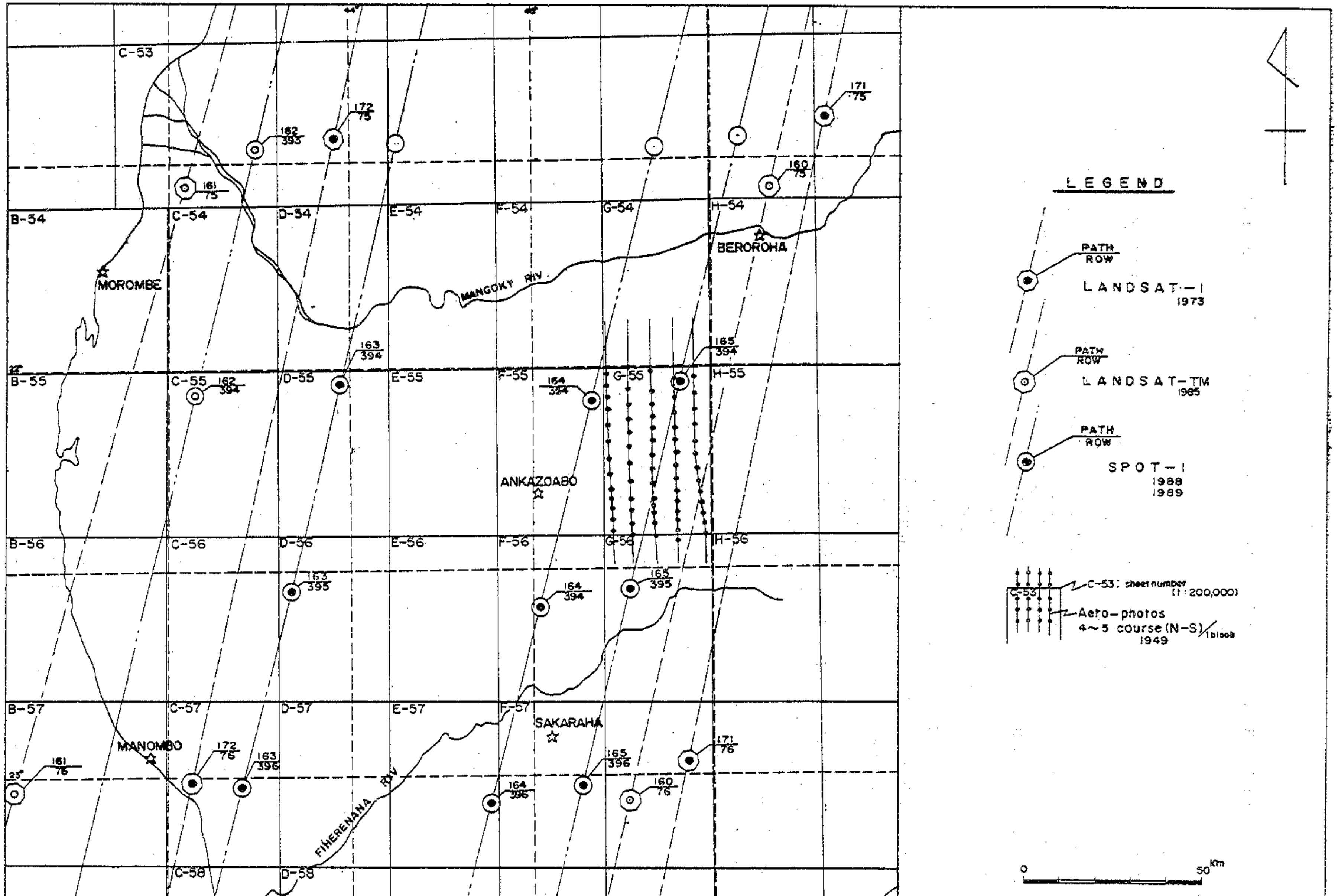


Fig. 3.1.1 Coverage Map of Satellite Image and Aero-Photos

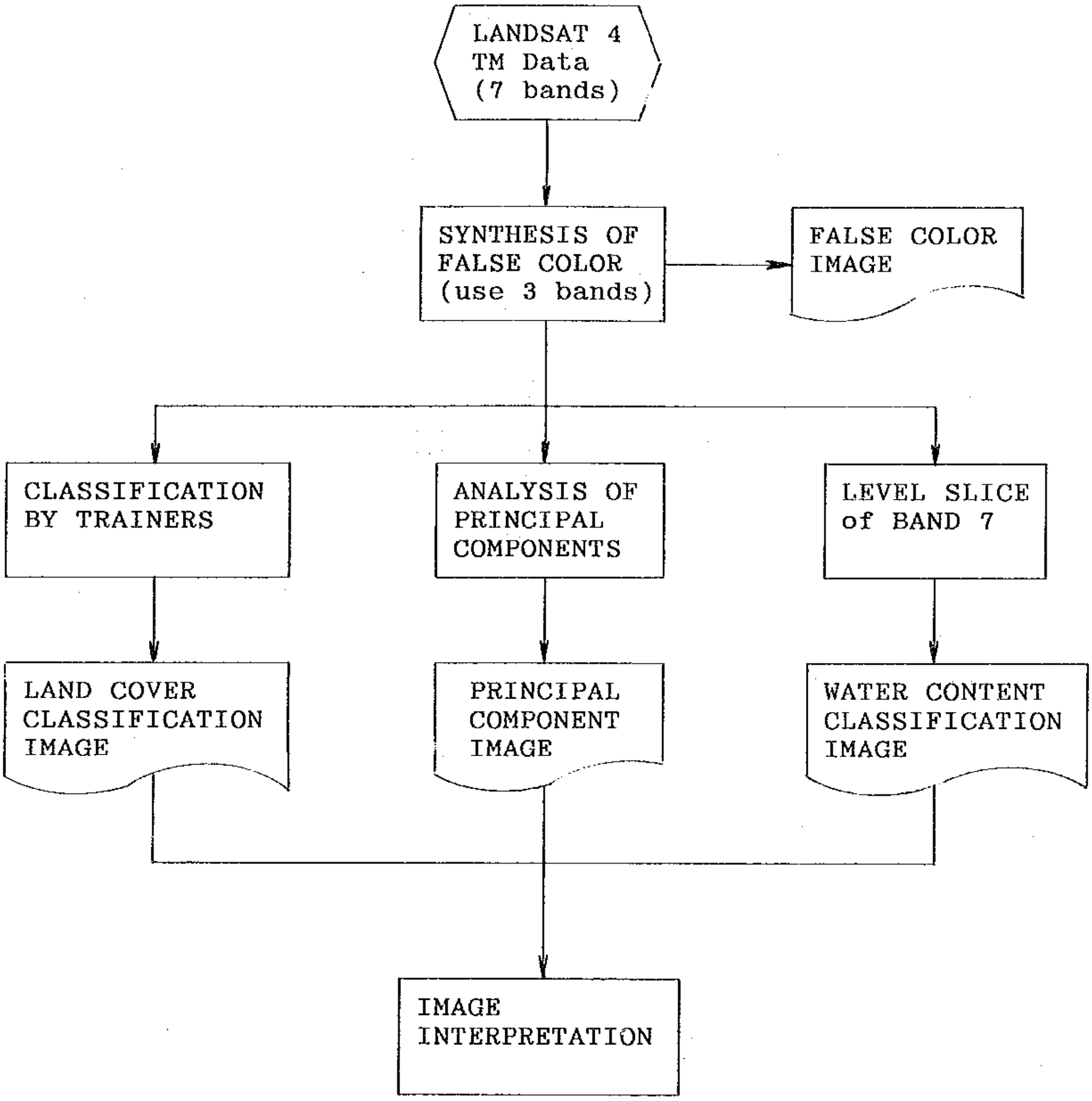


Fig. 3.1.2 Flowchart of LANDSAT TM Data Processing

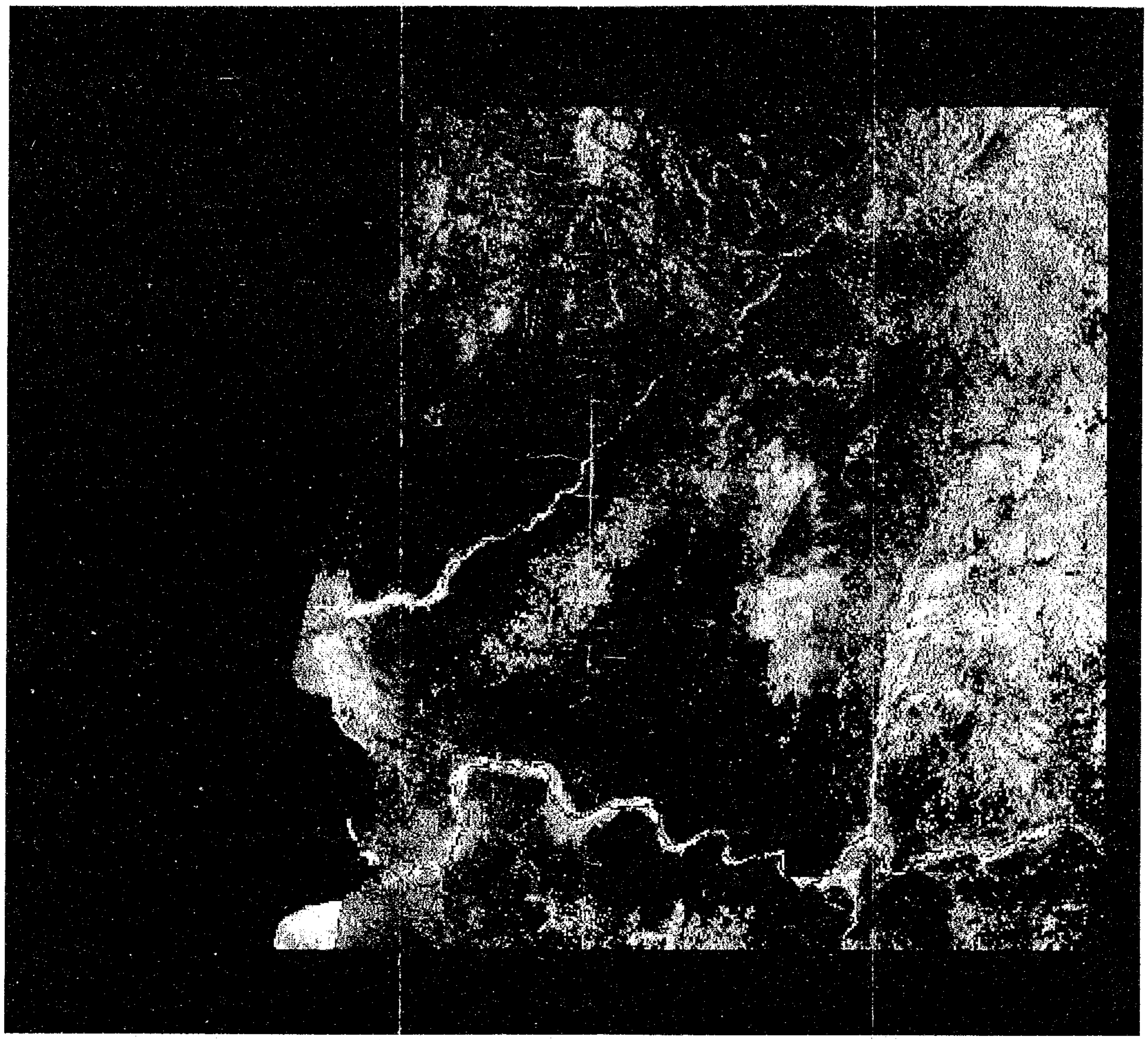


Fig. 3.1.3
False Color Image of
the Ceneral Part of TOLIARA Prefecture

Fig. 3.1.4
Principal Component Image of
the Central Part of TOLIARA Prefecture

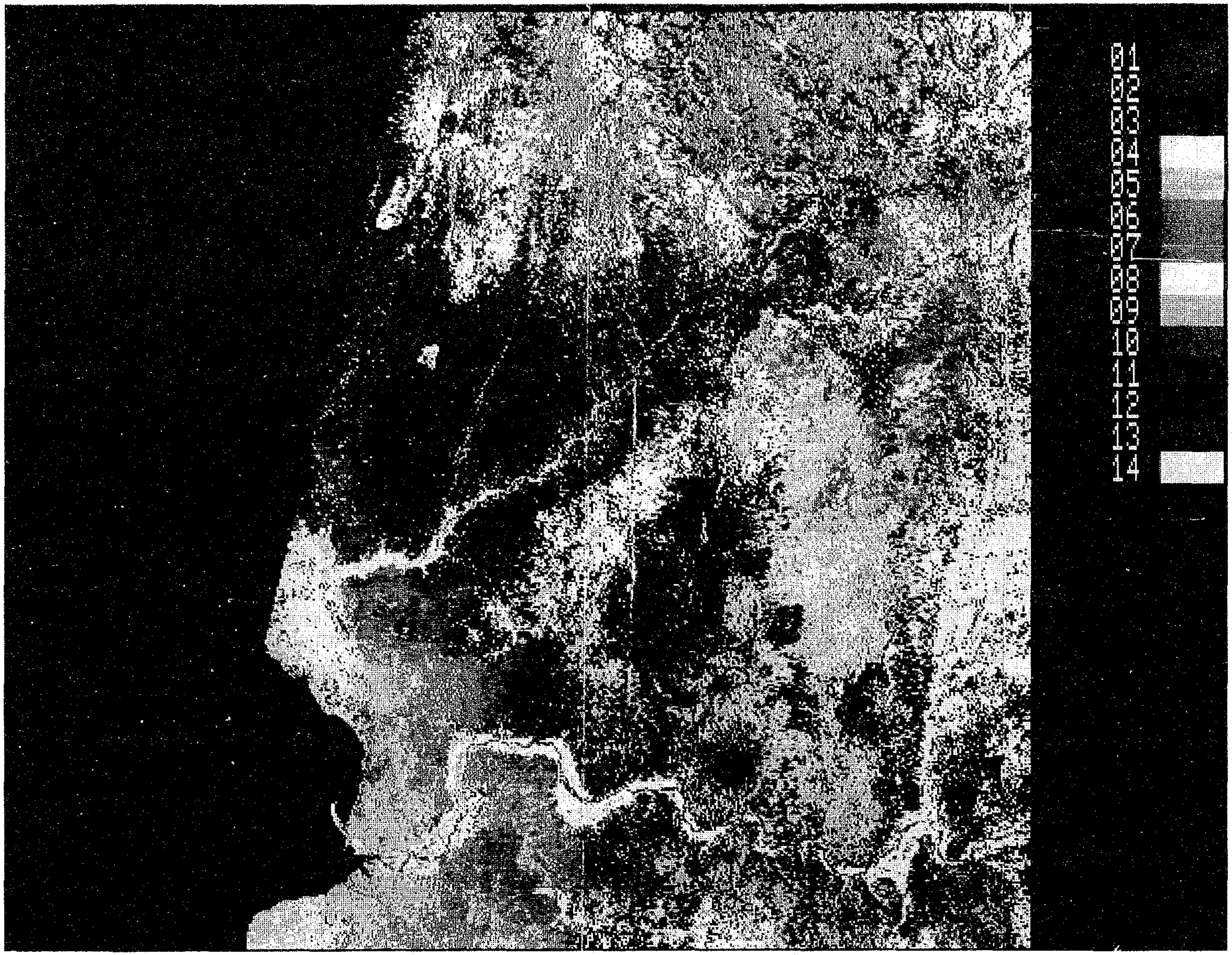


Fig. 3.1.5
Land Cover Classification Image of
the Central Part of TOLIARA Prefecture

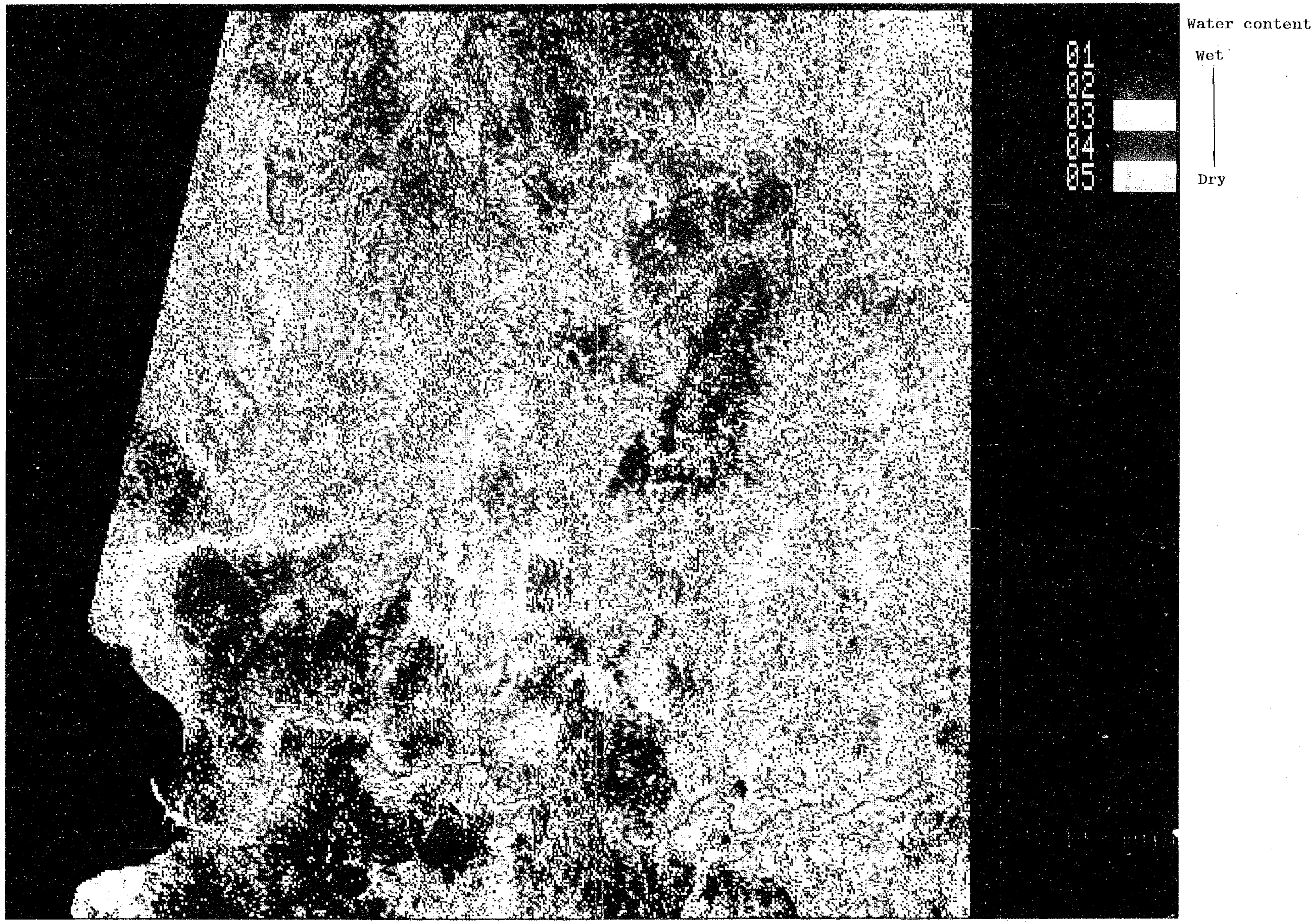


Fig. 3.1.6
Water Content Classification Image of the Central Part of TOLIARA Prefecture

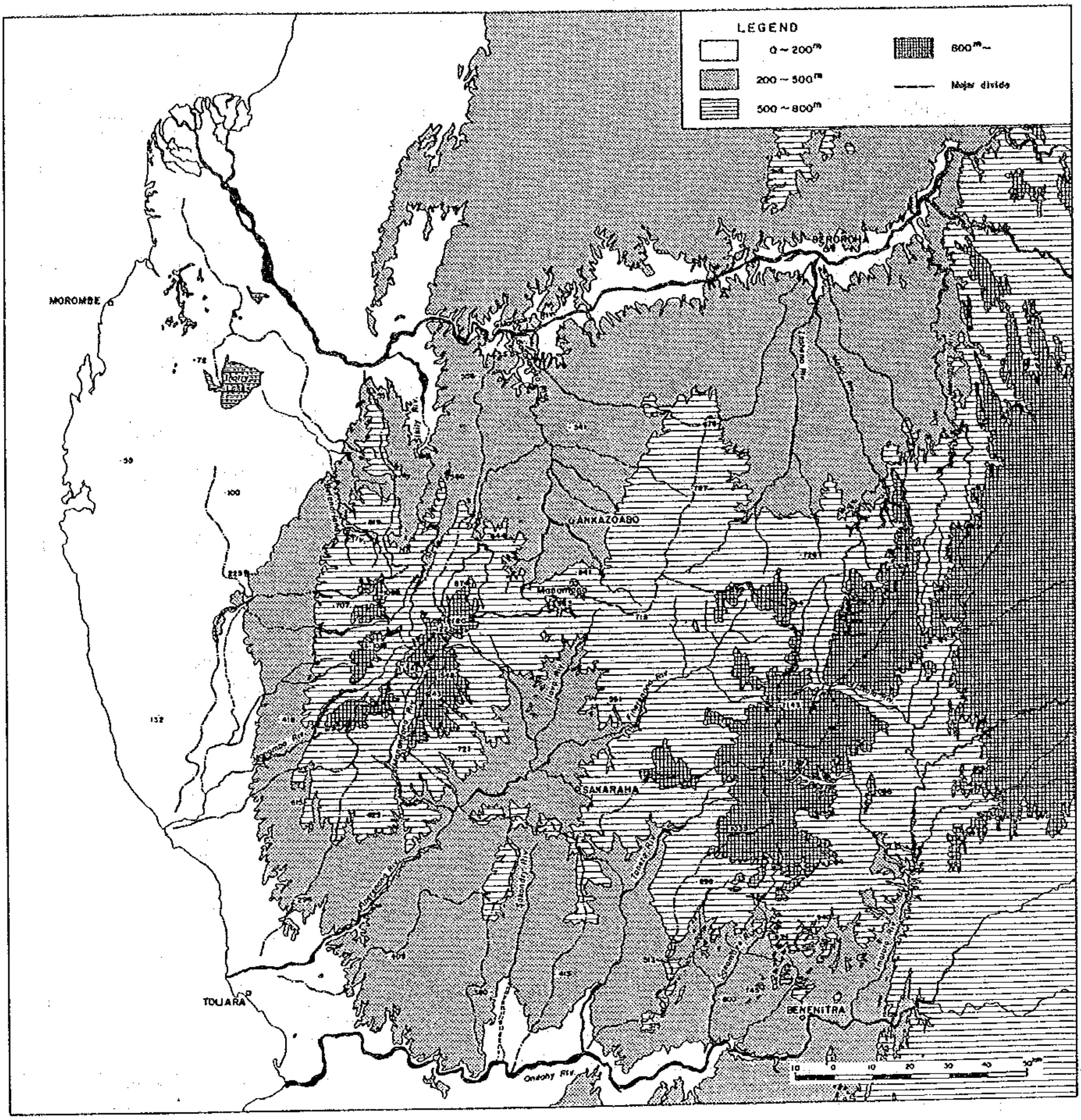


Fig. 3.1.7 Ground Elevation Map

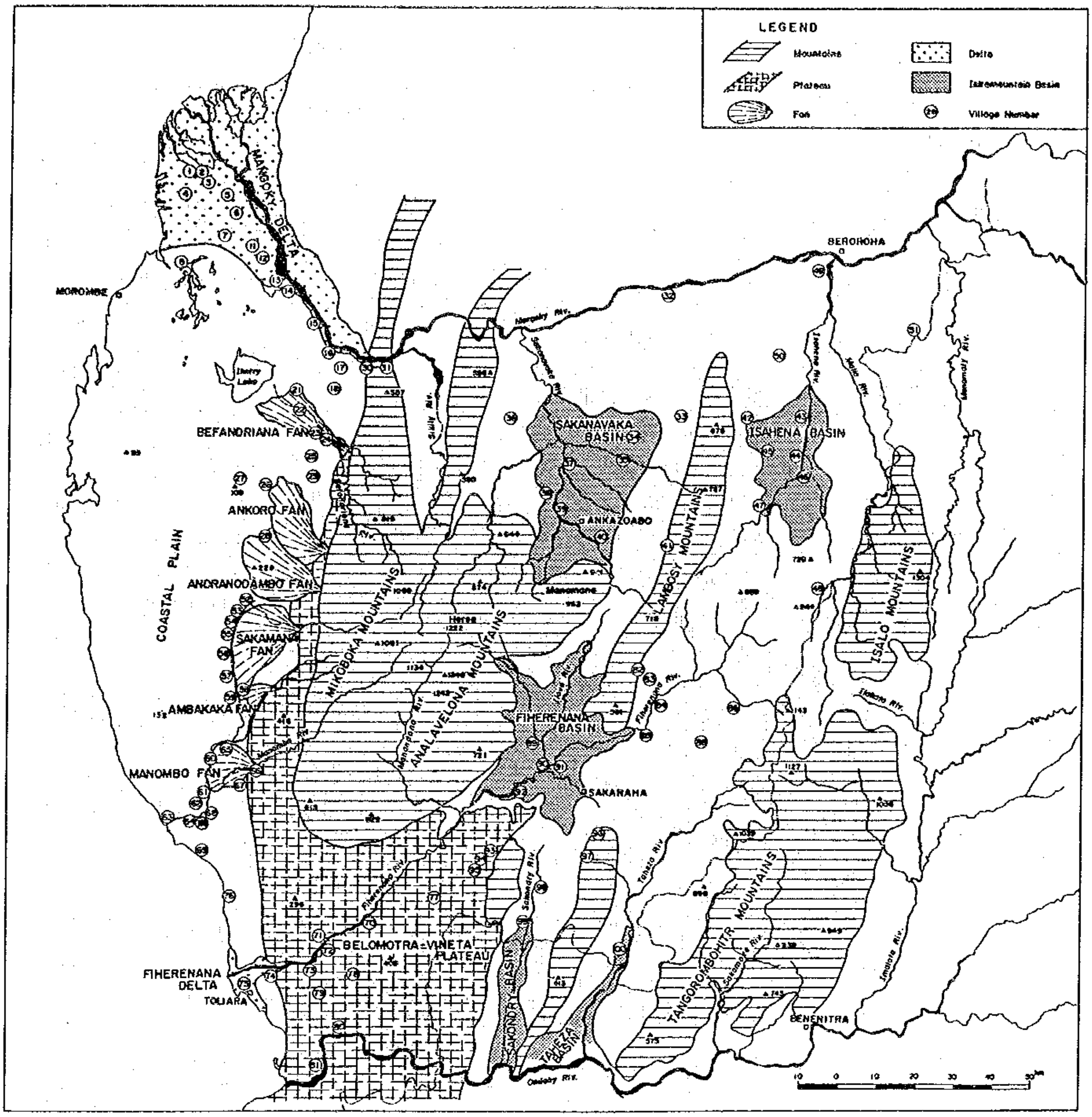


Fig. 3.1.8 Landform Classification Map

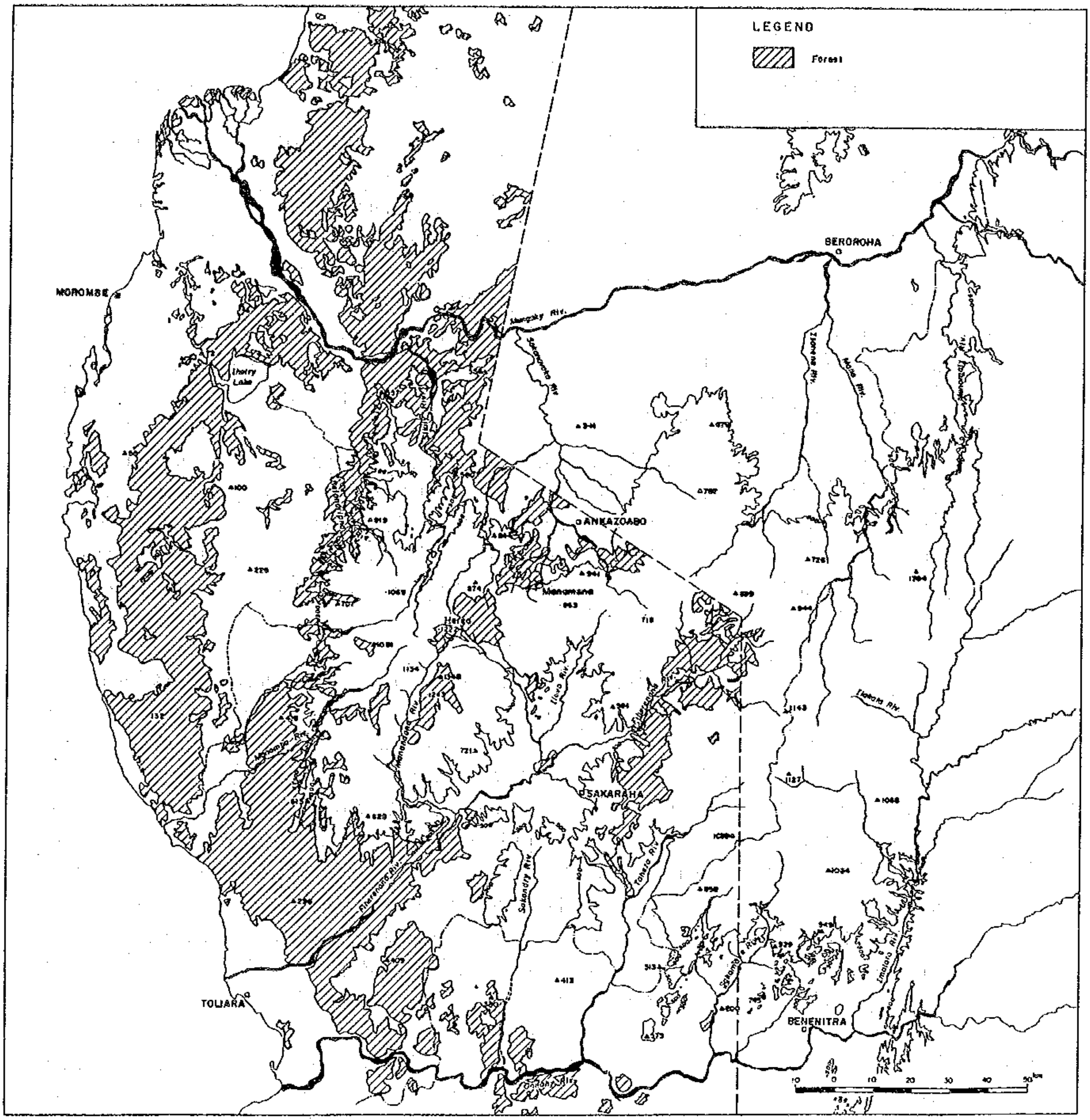


Fig. 3.1.9 Forest Distribution Interpreted on LANDSAT TM Data

3.2 Geology

3.2.1 Stratigraphy

The classification method of strata and age of each stratum underlying the Study Area varies somewhat depending on materials. Table 3.2.1 shows the classification of ages and the stratigraphy adopted in this report.

The Precambrian system is composed of hard metamorphic rocks and plutonic rocks exposed in a limited area at the eastern margin of the Study Area. The Sakoa and Sakamena Groups of the Carboniferous and Permian periods, respectively, are in unconformable or fault contact with the Precambrian system. Of the two groups, the Sakoa Group begins with basal tillite and is mainly composed of continental deposits, while the Sakamena Group is composed of continental deposits associated with lagoon sediments and marine deposits, indicating that the sedimentary environment changed during the sedimentation of the group.

Of the Jurassic system, the part composed mainly of continental deposits are collectively called Isalo Group and gradually changes into the underlying Sakamena Group. The Lower and Middle Isalo Groups consist mainly of arkose sandstone, which is low in solidity, and exhibit cross-bedding and conglomerate, but the Upper Isalo Group shows mixed facies of continental and marine origins. The marine Jurassic system shows the contemporaneous heterotopic facies of the Upper Isalo Group and composed mainly of limestone and calcareous sandstone, containing sandstone of continental origin at a considerable rate.

The Cretaceous system is divided into the Upper and Lower subsystems, and no large time gap is observed between the lower subsystem and the Jurassic system.The Lower Cretaceous system begins with limestone but is thin. The Upper Cretaceous system occupies the main part of the Cretaceous system and is composed of thick continental sandstone overlain by limestone. The Upper Cretaceous system is interbedded with several basalt beds. The thickest basalt bed reaches 100m or more and has a wide distribution of 100km in the north-south direction and 100km or more in the east-west direction. Since the strata directly above the basalt beds have undergone thermal metamorphism, the basalt beds are considered to be sheet intruded into the Upper Cretaceous system.

While the lower section of the Eocene series is composed mainly of limestone over the whole Study Area, the Middle and Upper Eocene series consist of marly limestone, marl, marly sandstone, sandstone, etc. Marine deposits are dominant in the southern part of the region, while continental deposits predominate in the northern part. In addition, basalt necks intruding into the Eocene series are everywhere on the coastal plain.

Although the Neogene system is limited in distribution and its accurate age is unknown, there are marine deposits resting unconformably upon the Eocene series, and continental deposits unconformably overlying the Isalo Group.

The Quaternary System is composed of alluvial-fan deposits, sand beds forming new and old sand-dunes, fluviatile deposits, etc. Of the deposits, the alluvial-fan deposits were expected to be distributed in the 6 alluvial fans identified from the topographical maps and satellite images, but no typical alluvial-fan deposit was found, except partially developed ones, as a result of this investigation.

Although the already existing geological maps classified sandy veneer rocks as members of the Quaternary system and showed their distributions, the rocks were regarded as surface soil and excluded from this hydrogeological map and stratigraphic table.

3.2.2 Geological Structure

In the past, petroleum prospecting was carried out in the Study Area and its periphery using gravity and airborne magnetic surveys, in addition to 10 petroleum exploration wells drilled to the depth of 1,000-4,000m. Fig. 3.2.1 shows cross sections prepared by partial modification of cross sections which had been drawn on the basis of the data obtained from the petroleum surveys and wells. The geological structure of this region assumed from the cross sections is summarized below.

The upper boundary of the Precambrian basement, widely ex

posed on the east side of the Isalo Mountain, steeply slopes westward and is overlain by Paleozoic and younger strata of 5,000-8,000m in total thickness. Since these strata generally dip westward at gentle dip angles, newer strata show up gradually toward the west. However, the zonal structure is disturbed by several fault systems.
The first system is composed of a group of north-south faults developed in echelon at the western margin of the Precambrian basement. Since the Carboniferous Sakoa and Permian-Triassic Sakamena Group occupy the west side of this group of faults only, it is considered that the main activity of the fault group took place early in the Paleozoic period.

The second fault system is the Ilovo Fault which longitudinally cuts the central part of the Study Area in the NNE-SSW direction. Since the fault not only bounds the western distribution of the Paleozoic and Lower Jurassic systems, but also displaces the Middle and Upper Jurassic systems of marine origin, it is considered that the main activity of the fault started during the Paleozoic period and continued to and after the Jurassic period.

The third fault system is a group of faults running in the NNE-SSW direction in both Analavelona and Mikoboka Mountain districts. Alternating westerly dipping and easterly dipping faults form horsts and grabens. Since this group of faults displaces the Eocene series and, at the same time, controls the arrangement of the basalt necks, it seems that the main faulting took place after the Eocene period caused by volcanic activities.

The fourth fault system is a group of faults running in the Tangorombohitr Mountain district in the NNE-SSW direction. This group of faults also forms horsts and grabens as the third fault system does, but the horsts are covered with the continental Neogene system. Therefore, it is considered that the main activity of this fault system took place after the Neogene period.

The fifth fault system is a group of faults (Toliara Fault) which bounds the western extension of the Belomotra-Vineta plateau. While the northern extension of the fault system from the Manombo River had to be estimated, it becomes clear from the interpretation of satellite images made during the course of this investigation that the fault system reaches the western margin of Lake Ihotry. The faults run in parallel with each other in the N-S to NNW-SSE direction and, since they cut Tertiary faults, they are considered to be the latest in the region.

3.2.3 Geological History

In order to logically estimate potential for groundwater development from the already existing materials, the palaeogeographical transition and geomorphic and structural history of target areas must be clarified. In addition, the subsurface facies and thickness distribution of the area must be properly estimated from the materials. Although, at present, the palaeogeographical transition and geomorphic and structural history of the region cannot be established clearly, their outlines are described below.

Since the Lower and Middle Paleozoic system do not exist in this region, it is considered that this region was a peneplain of metamorphic and plutonic rocks before the Sakoa Group was deposited.

Formed during the Carboniferous period was the group of faults which exists along the western side of the area currently consisting of the Precambrian system and the Ilovo Fault. A lake basin elongated in the north-south direction was formed between the group of faults and Ilovo Fault, and the Sakoa and Sakamena Groups were successively deposited. Since the latter contains marine deposits and lagoon sediment in addition to continental deposits, whereas the former is composed mainly of continental deposits, it is considered that the sedimentary environment frequently changed due to transgression and regression which took place when the Sakamena was deposited. However, it is also considered that the environmental changes were slow, since the Sakamena Group is mainly composed of relatively fine deposits. In addition, it is presumed from the thickness distribution of the Sakoa and Sakamena Group that the group of NNE-SSW faults was active in the Tangorombohitr Mountain district and formed horsts in the lake basin during the same period.

The zone between the group of faults running along the western boundary of the Precambrian system, and Ilovo Fault continuously subsided even in the Jurassic period, and thick continental deposits of the Lower and Middle Isalo Group were deposited. It is considered that the upheaving speed of the eastern mountain district increased and erosion became active in the district, since the continental deposits are composed mainly of coarse sediment. As the upheaving speed increased and erosion became active, the center of deposition of the sedimentary basin moved to the west side of the Ilovo Fault and the Upper Isalo Group was successively deposited. However, in the initial stage of the deposition of the Upper Isalo Group, the transgression took place from the west side and reef limestone was formed on the eastern margin of the sedimentary basin. Since the Lower and Middle Isalo Groups received little diagenesis, it is considered that the transgression did not advance further east of the Ilovo Fault.

During the period encompassing late Jurassic to the end of Cretaceous, mixed deposits of marine and continental origins and continental deposits repeatedly accumulated in the northern part, as the transgression and regression took place, in addition to the upheaval of the eastern mountain and movement of the central part of the sedimentary basin. The upheaval of the eastern mountain was weak and continuous deposition of neritic deposits took place mainly at and around the Belomotra-Vinetas District. When the Cretaceous system was deposited, large-scale basalt intrusion took place, and the continuous basalt sheet was formed extending over a large area of 100km in the north-south direction and 100km or more in the east-west direction.

Before the Eocene, the eastern mountain changed to the peneplain and uniformly shallow sea was formed on the west side, but during the middle and late Eocene, the northern part changed to land and a strong environmental change took place in the southern part. It is considered that such a change resulted from the activity of the group of NNE-SSW faults in the northern part and upheaval of the Analavelona and Mikoboka Mountains as horsts. The faulting activity was associated with small-scale basalt intrusion and effusions.

Because of the limited distribution of the Neogene system, estimation of the Tertiary palaeogeography is difficult, but it is considered that a lake having a length of 25km or more existed in the Tangorombohitr Mountain district, judging from the distribution of the continental Tertiary deposit.

In the Tangorombohitr Mountain District, the NNE-SSW fault system again became active after the Neogene system was deposited, and table mountains covered with continental deposits of Neogene period were formed as horsts. On the other hand, the Taheza basin was formed as graben. The Sakondry basin was also controlled by the faults which became active during this period.

Following the activity of the NNE-SSW fault system, the Toliara Fault became active and the western margin of the Belomotra-Vineta plateau was cut off. In addition, downward erosion of the Mangoky, Fiherenana, and Onilahy Rivers was reactivated and cut deep gorges in the mountains and plateaus, resulting in the formation of a group of alluvial fans by transported earth and sand on the western side of the Mikoboka Mountain.

Table 3.2.1 Stratigraphic Classification

Geological Time				1/1,000,000 Madagascar (1965)	1/500,000 MORONDAVA (1969)	1/500,000 AMPANIHY (1970)	1/250,000 This Map (1991)
Quaternary	Alluvium			a, d	a, d^1	a, d^1	a / d
Quaternary	Pleistocene			ac, d^1	ac, d^a	ac,cc,d^2,d^3	f / d
Tertiary	Neogene	Pliocene		n*	P*	N^*	N / N^*
Tertiary	Neogene	Miocene		m	m	m / N^*	N / N^*
Tertiary	Paleogene	Oligocene					
Tertiary	Paleogene	Eocene	Ludian	e	e^2	e^3	Em+u
Tertiary	Paleogene	Eocene	Ledian	e	e^2	e^3	Em+u
Tertiary	Paleogene	Eocene	Lutetian	e	e^1	e^2	El
Tertiary	Paleogene	Eocene	Ypresian	e	e^1	e^2	El
Tertiary	Paleogene	Paleocene				e^1	
Mesozoic	Cretaceous	Upper	Maestrichtian	C^2	C^{9-8}	C^{9-8}	Cu
Mesozoic	Cretaceous	Upper	Campanian	C^2	C^{9-8}	C^{9-8}	Cu
Mesozoic	Cretaceous	Upper	Santonian	C^2	C^7	C^{7-3}	Cu
Mesozoic	Cretaceous	Upper	Coniacian	C^2	C^7	C^{7-3}	Cu
Mesozoic	Cretaceous	Upper	Turonian	C^1	C^{6-3}	C^{7-3}	Cm+ℓ
Mesozoic	Cretaceous	Upper	Cenomanian	C^1	C^{6-3}	C^{7-3}	Cm+ℓ
Mesozoic	Cretaceous	Lower	Albian	C^1	C^{6-3}	C^{7-3}	Cm+ℓ
Mesozoic	Cretaceous	Lower	Aptian	C^1	C^1		Cm+ℓ
Mesozoic	Cretaceous	Lower	Neocomian		Cv		
Mesozoic	Jurassic	Upper	Tithonian	J^3	J^{8-5}	J^8	Ju
Mesozoic	Jurassic	Upper	Kimmeridgian	J^3	J^{8-5}	J^8	Ju
Mesozoic	Jurassic	Upper	Oxfordian	J^3 / I_{III}^{Δ}	J^{4-2}	J^4	Ju / $I_{III}^{*\Delta}$ (Isalo Group)
Mesozoic	Jurassic	Middle	Callovian	J^2 / I_{III}^{Δ}	J^1	J_I^1	Jm / $I_{III}^{*\Delta}$ (Isalo Group)
Mesozoic	Jurassic	Middle	Bathonian	J^2 / I_{III}^*	J_{I-II} / I_{III}	J_{I-IV} / I_{III}^*	Jm / $I_{III}^{*\Delta}$ (Isalo Group)
Mesozoic	Jurassic	Middle	Bajocian	J^2 / I_{III}^*	J_{III-IV} / I_{III}	J_{I-IV} / I_{III}^*	Jm / $I_{III}^{*\Delta}$ (Isalo Group)
Mesozoic	Jurassic	Lower	Aalenian	(J^1) / I_{II}^*	I_{II}	I_{II}	I_{II}^* (Isalo Group)
Mesozoic	Jurassic	Lower	Lias	(J^1) / I_{II}^*, I_I^*	I_{II}, I_I	I_{II}, I_I	I_{II}^*, I_I^* (Isalo Group)
Mesozoic	Triassic			I_I^*	I_I	I_I	I_I^* (Isalo Group)
Mesozoic / Paleozoic	Triassic / Permian			K^2	(Sakamena G.) K^6~K^4	(Sakamena G.) K^4, K^3	PJu
Paleozoic	Carbaniferous			K^{1*}	(Sakoa G.) K^1~K^3	(Sakoa G.) K^2, K^1	PJℓ
Igneous rock (Basalt)	Post Eocene			β^2	β^3	β^3	β^2
Igneous rock (Basalt)	Pre Eocene			β^1	β^1, β^2	β^1, β^2	β^1

* Continental facies sediments
△ Mixed facies sediments

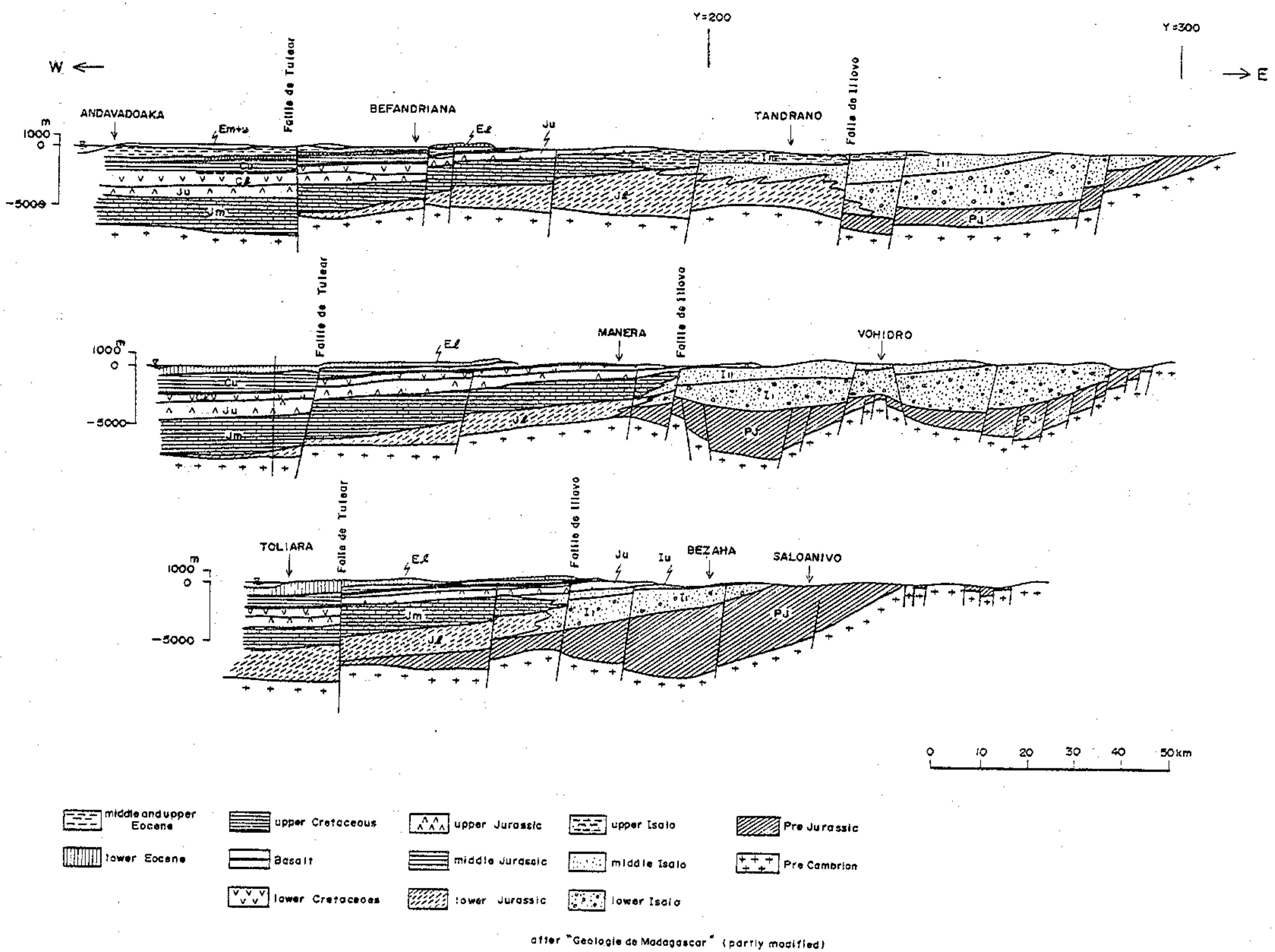


Fig. 3.2.1 Regional Geological Cross Sections

3.3 Climatic Features

3.3.1 Existing Stations

The required meteorological data of the Study Area were obtained in Antananarivo from the Directorate of Meteorology. The locations and details of the meteorological stations operated by this Directorate are shown in Fig. 3.3.1 and Table 3.3.1.

These stations are categorized into three classes, depending on the meteorological elements being observed (e.g., temperature, humidity, etc.).

Class	Meteorological Element(s)
A	Temperature, Relative Humidity, Evaporation, Wind Speed, Sunshine Hour, Rainfall
B	Temperature, Relative Humidity, Rainfall
C	Rainfall

Androka, Toliara and Morombe Stations are located in the coastal plain of the Study Area, with elevations of less than 10m above the sea level. The other stations are situated in the hilly or mountainous areas, with elevations varying from 100m to 800m above sea level. Among these stations, Ranohira Station has the highest elevation. Most of these stations are located in big villages or in town centers.

Although these stations are distributed over the whole Study Area, the insufficiency of their numbers (coverage) will create some constraints in characterizing the local climatic condition of the Study Area.

3.3.2 Climatic Elements

Table 3.3.2 and Fig. 3.3.2 show the monthly mean values of climatic elements like temperature, relative humidity, sunshine hours, wind velocity and evaporation.

(1) Temperature

The mean annual temperature in the coastal area is about 24°C, while it is about 22°C in the mountainous area. At Ranohira Station, the highest monthly mean value of the daily maximum temperature is about 29-30°C occurring from October to February, and the lowest monthly mean value of the daily minimum temperature is about 10°C which prevails in June and July. At Toliara Station, the highest monthly mean value of the daily maximum temperature is about 31-32°C prevailing from December to February, and the lowest monthly mean value of the daily minimum temperature is about 14°C which prevails from June to August. The difference between the daily maximum and minimum temperatures is bigger in the mountainous area than in the coastal plain. The Study Area is under the winter temperature regime from June to August, and under the summer temperature regime from October to February.

(2) Relative Humidity (RH)

The monthly mean RH value is higher in the coastal plain than in the mountainous area. The months with the lowest and highest mean RH are August (68%) and January (75%), respectively, at Toliara Station, while they are May (lowest at 71%) and February (highest at 79%) at Morombe Station. At the stations in the mountainous area, the lowest mean RH is concentrated in September, while the highest mean RH is distributed over the rainy months.

(3) Evaporation

Three stations (Toliara, Ranohira and Morombe) have been measuring evaporation by Piche evaporimeter. As shown in Table 3.3.2, the variability (the difference between the highest and the lowest values) of evaporation is bigger in the mountainous area than in the coastal plain.

(4) Wind Velocity

Wind velocity is being measured at three stations, namely, Toliara, Ranohira and Morombe. The monthly mean wind speed is highest in October and lowest in May. It is higher in the coastal plain than in the mountainous area.

(5) Sunshine Hours

Average daily sunshine duration varies from 8 to 10 hours throughout the year at Toliara, Morombe and Ranohira. Compared with Toliara and Ranohira, it is shorter at Morombe by about two hours from November to March and by about one hour from April to October.

3.3.3 Rainfall

The Study Area is located in the driest region of Madagascar. Fig. 3.3.3 shows the monthly mean rainfall distribution at stations where records were collected for the 1950-1988 period. In the coastal area, the rainfall pattern is characterized by one short rainy season and a long dry season, while in the mountainous area the rainfall pattern is typified by a fairly long rainy season and a long dry season. The coastal area has a three-month rainy season from December to February, each month with more than 75mm, while the mountainous area has a five-month rainy season from November to March, with more than 100mm per month.

As shown in Fig. 3.3.3, the coastal area has a mean annual total rainfall ranging from 383mm in Toliara to 418mm in Morombe, while the mountainous area has it varying from 633mm in Bezaha to 973mm in Ranohira. Thus, the annual isohyets are decreasing from east to west of the Study Area, as shown in Fig. 3.3.1.

Only a limited area of about a few square kilometers was observed to be covered by the rainfall field during the conduct of the first field survey. Rainfall comes accompanied by lightning and thunder, lasting under thirty minutes. This kind of rainfall occurs during the transition period of the dry to the wet season in November. In December, however, clouds cover a much larger area and rainfall duration is much more extended, thus marking the onset of the rainy season.

In the rainy season, rain making disturbances are more frequent with abundant cumulus clouds, producing heavy downpours and thunderstorms. Most rainfalls occur in the afternoon and early evening. Night rains are also frequent. Rainfall periods are rather short, lasting for a few days and alternating with periods of clear sky.

Rainfall records show that intensities as well as individual storm totals can be considerable in the coastal plain. Table 3.3.3 shows the annual rainfall and the first, second and third ranked maximum daily rainfall at different stations. Toliara with a mean annual total of only 380mm has recorded more than 100mm in one day: 187.5mm on 20 December 1974, 143.2mm on 28 December 1975, 125.4mm on 28 February 1977, and 110.7mm on 28 November 1979. This feature is also shown at Morombe but not at the stations in the mountainous area. This tendency is not peculiar of dry climates, and it is influenced by cyclones in the wet season.

Fig. 3.3.4 shows the annual rainfall from 1950 to 1988 (39 years) at the Toliara, Sakaraha and Ranohira stations. In this period, the records show neither increasing nor decreasing tendency in annual rainfall. Fig. 3.3.5 displays the coefficient of variability of annual rainfall at these stations. The annual rainfall is more variable (exceeding 50%) at Morombe and Toliara in the coastal plain than at Ranohira in the mountainous area.

Fig 3.3.6 shows the relationship between the annual rainfall and the altitude of the stations. From this figure, it can be roughly assumed that rainfall increases with elevation. This is a rough assumption because rainfall varies with many local factors such as topography, wind regime, etc.

By this assumption, an annual rainfall of more than 800mm (considered around 1000mm from this figure) is estimated for mountainous area like Mikoboka, Analavelona, Belomotra Vineta and Tangorombohitr Isalo.

Fig. 3.3.1 shows the annual isohyets which indicate that rainfall decreases from the northeastern to southwestern portion of the Study Area. Compared with the coastal plain, the mountainous area has a bigger amount of rainfall, the difference being accounted for by the unequal rainfall amounts in the two areas during the rainy season.

3.3.4 Evaporation and Evapotranspiration

Daily evaporation has been measured at three stations, namely, Toliara, Morombe and Ranohira by Piche evaporimeters. No Class A evaporation pan was installed in the Study Area. Basically, Piche evaporimeter is not designed to make actual measurement of evaporation and is not recommended for hydrological analysis in arid zones.

Evapotranspiration is usually estimated by empirical formulas. Using the 1969-1988 climatic records from the said three stations, evapotranspiration was calculated by the Thornthwaite and modified Penman methods to compare and check the adaptability of the different procedures. Fig. 3.3.7 shows the monthly evaporation at Toliara station as measured by Piche evaporimeter and the monthly potential evapotranspiration as calculated by using modified Penman and Thornthwaite methods. The potential evapotranspirations estimated by the modified Penman method resemble those by the Thornthwaite method (highest in January, lowest in June) but differ from Piche evaporation. This may demonstrate the limitations of the Piche evaporimeter as mentioned above. The modified Penman method is adaptable in most cases but requires data which are available only at Toliara, Morombe and Ranohira stations.

Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Toliara													
(a)	171	148	147	114	83	58	59	67	81	110	132	162	1332
(b)	158	136	139	112	97	84	90	114	123	146	150	153	1500
Morombe													
(a)	165	142	145	116	85	59	61	56	69	113	138	163	1310
(b)	145	121	122	109	98	83	93	104	119	149	141	201	1486
Ranohira													
(a)	135	114	116	94	77	64	72	96	124	145	145	137	1319
(b)	129	110	108	85	63	43	45	55	76	104	118	127	1064

* (a) Thornthwaite
(b) Modified Penman (FAO Irrigation and Drainage Paper No.24)

3.3.5 Climatic Type

From the hydrological viewpoint, Koppen's classification probably gives the most comprehensive account of the variety of climatological regimes in the tropics. Based on the above rainfall and temperature characteristics of the Study Area, two (2) climatic types under this classification are applicable to the Study Area, which are described as follows.

- Savanna climate (Aw) which has a mean annual temperature of above 18°C all year round. Rainfall is a function of temperature, and at 20°C and 25°C, annual rainfall that should be available are at least 600mm and 700mm, respectively. The mountainous area belongs to this type.

- Steppe climate (Bs), where at mean annual temperature of 25, 20 and 15°C, maximum annual rainfall is 700, 600 and 500mm, respectively. The climate in the coastal area is characterized by this type.

According to Balek (1983), "The savanna climate is under the influence of trade winds and has its dry period sharply bounded in time. The rainfall occurs in the summer, and the temperature amplitude is higher. The duration of the dry season is at least two months. The variability of diurnal temperature is considerable. Often the hottest period precedes the time of the highest sun. Thus, September, October and November are usually warmer than December and January which are the rainy months in the southern hemisphere. The annual rainfall is typically between 1000

and 1500mm, however, an even lower amount is common. The rain comes mainly in the form of convective showers. A return of ITCZ (intertropical convergence zone) toward the equator brings an anticyclonic drought in winter, thus the farther the region is from the equator, the longer is the dry season. The summer rain peak comes after the sun has reached its zenith.
The steppe (or semi-arid) climate cannot be defined in terms of temperature, unless rainfall is taken into account. The limits of annual rainfall are given as between 250-500mm, others between 375-600mm. The semi-arid regions have a short period of heavy rain, most frequently at the time of high sun (summer). The rainfall distribution is similar to that in the wet and dry climate except that the dry season is longer and total precipitation less."

Reference: Balek, J. (1983): Hydrology and Water Resources in Tropical Regions, Elsevier, New York, pp 62-65.

3.3.6 Rainfall Monitoring

To generate rainfall data for the Study Area, three automatic rainfall recorders were installed in the following villages or stations.

Station	Altitude(m)	Remarks
Maninday	625	candidate village No.88
Andranolava	525	candidate village No.83
Tanambao	114	near candidate village No.66

Monthly rainfalls measured at these stations are summarized below and, are compared with those measured during the same period at Sakaraha and Ankaraobato stations by the Directorate of Meteorology. The amount of overlapping data is still inadequate for sound correlation analysis.

unit:mm

Station	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
Maninday	-	-	28	0	0	0	0	0	2	36	0
Andranolava	-	-	-	(24)	23	3	0	0	5	35	0
Tanambao	119	146	87	7	32	14	20	6	10	19	0

Table 3.3.1 List of Meteorological Stations

	Station	Latitude	Longitude	Altitude	Period	Class
1.	Toliara	23° 23'S	43° 44'E	9	'69-'88	A
2.	Morombe	21° 45'S	43° 22'E	5	'69-'88	A
3.	Ranohira	22° 33'S	45° 24'E	823	'69-'88	A
4.	Sakaraha Forest	22° 55'S	44° 32'E	470	'69-'87	B
5.	Ankazoabo Sud	22° 27'S	44° 32'E	428	'69-'88	B
6.	Beroroha	21° 40'S	45° 10'E	180	'69-'75	B
7.	Betsioky Sud	23° 43'S	44° 23'E	263	'69-'88	B
8.	Androka	25° 01'S	44° 05'E	4	'69-'83	B
9.	Bezaha	23° 30'S	44° 31'E	100	'69-'84	B
10.	Benenitra	23° 26'S	45° 05'E	220	'69-'76	C
11.	Sakaraha Village	22° 55'S	44° 32'E	460	'69-'88	C

Where,
Monitoring Items is as follows
A class -- Temperature, Relative Humidity, Evaporation, Mean Wind Velocity, Sunshine Hour, Rainfall
B class -- Temperature, Relative Humidity, Rainfall
C class -- Rainfall

Table 3.3.2 General Climatic Condition (1)

General Climate in Toliara Station, 1969-1988

ITEM		UNIT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TEM.	MAX.	C	32.52	32.47	32.23	30.75	28.92	27	26.93	27.7	28.58	29.35	30.41	31.38
	MIN.		23.03	23.21	22.12	20.07	17.16	14.95	14.52	14.8	16.31	18.63	20.39	22.26
	MEAN		27.78	27.84	27.17	25.41	23.04	20.97	20.72	21.25	22.44	23.99	25.4	26.82
HUM.	7:00	%	92.1	92.5	91.8	92.5	92.5	91.9	91.8	91	91	91	90.85	91.85
	12:00		57.1	56.4	54.6	52.1	48	46	44.8	43.2	47.1	52.1	55.7	57.05
	17:00		76.1	76.7	75.4	75.3	74.2	72.3	71.9	70.5	73.2	74.6	75.6	76.2
	MEAN		75.1	75.2	73.93	73.3	71.56	70.06	69.5	68.23	70.43	72.56	74.05	75.03
SUN		h/d	10.21	9.71	9.68	9.58	9.53	9.51	9.62	10.25	10.16	10.17	10.64	9.77
WIND		km/h	12	12	12	11	11	11	11	13	13	14	13	12
EVAP		mm/d	5.3	5	5.1	4.9	4.7	5	5	5.6	5.4	5.2	5.4	5.1

General Climate in Ranohira Station, 1969-1988

ITEM		UNIT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Tem	MAX.		29.73	29.51	29.27	28.6	26.52	24.4	24.47	25.93	28.82	30.16	30.52	29.72
	MIN.		19.02	19.08	18.04	16.03	13.17	10.71	10.56	11.13	13.16	15.64	17.48	18.56
	MEAN		24.37	24.3	23.66	22.31	19.85	17.56	17.51	18.53	20.99	22.9	24	24.14
HUM.	7:00	%	94.1	94.9	94.7	95.8	95.3	95.4	94.6	93.3	90.3	90.1	91.1	92.4
	12:00		49.3	50.7	48.3	42.9	38.2	36.5	33.4	30.3	26.6	32.5	38.2	46.7
	17:00		75.1	77	75.6	73.1	70.8	70.4	68.4	64.4	58.6	61.7	66.2	73.4
	MEAN		72.83	74.2	72.86	70.6	68.1	67.43	65.46	62.66	58.5	61.43	65.16	70.83
SUN		h/d	9.54	8.85	9.57	9.56	9.73	9.63	9.61	10.25	10.16	10.14	10.75	9.56
WIND		km/h	9.5	9.7	9.1	7.9	6.9	7.1	7.5	9.3	10.4	10.8	9.9	9.4
EVAP		mm/d	3.8	3.6	3.6	3.9	3.9	3.8	4.3	5.3	6.5	6.4	5.8	4.2

General Climate in Morombe Station, 1969-1988

ITEM		UNIT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	MAX.		31.67	31.45	31.6	30.66	29.29	27.52	27.39	26.24	27.15	29.7	29.83	31.26
	MIN.		23.01	23.07	22.04	20.31	17.12	14.42	14.25	13.61	15.22	18.65	21.64	22.5
	MEAN		27.34	27.26	26.84	25.52	23.2	20.97	20.82	19.93	21.19	24.17	25.74	26.88
HUM.	7:00	%	92.3	95.7	95.3	93.7	94	94.8	95.7	96.5	95.5	94	92	92.3
	12:00		60.3	60.3	59	52.3	43.6	46	44.3	43	54	51.7	59	60.3
	17:00		78	81.5	80.3	78.3	75.4	75	76.5	78.5	80.5	77	75.5	78
	MEAN		76.86	79.16	78.2	74.76	71	72.43	72.83	73.33	75.5	73.73	76.33	50.86
SUN		h/d	7.85	7.65	7.99	8.69	8.79	8.61	8.61	9.46	9.52	9.22	8.84	7.74
WIND		km/h	13.5	13.2	11.6	11	10.5	11.2	12.8	13.8	16	16.2	14.1	13.1
EVAP		mm/d	4.5	4	4.1	4.2	4.2	4.1	4.4	4.7	4.8	5.1	5.3	4.5

Table 3.3.2 General Climatic Condition (2)

Monthly Rainfall, 1969-1988

Unit: mm

Station	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
(1)Morombe	98	118	54	24	11	5	1	2	1	12	12	79	418
(2)Betsioky Sud	166	122	74	27	13	7	6	3	10	32	72	152	685
(3)Toliara	81	75	38	18	13	14	5	4	8	11	26	91	383
(4)Ankazoabo	194	106	75	7	11	1	6	0	7	27	45	166	647
(5)Ranohira	208	180	130	34	15	2	4	6	13	63	106	212	973
(6)Sakaraha	205	144	99	40	14	8	7	11	6	35	65	190	822

Table 3.3.3 Daily Rainfall

1st, 2nd and 3rd Max. Daily Rainfall

Morombe — Unit: mm

Year	Annual	1st	2nd	3rd
1969	515	106	59	55
70	171	47	22	19
71	-	119	112	80
72	345	45	35	29
73	-	187	117	117
74	802	95	90	90
75	334	62	57	33
76	461	77	60	58
77	526	90	80	61
78	521	83	73	49
79	158	45	26	14
80	-	40	11	25
81	-	38	24	11
82	-	59	57	45
83	-	24	19	10
84	-	54	38	30
85	-	14	9	8
86	-	137	83	73
87	-	72	55	32
88	-	47	36	33

Ankazoabo-Sud — Unit: mm

Year	Annual	1st	2nd	3rd
1969	-	-	-	-
70	-	-	-	-
71	-	-	-	-
72	-	-	-	-
73	-	101	69	46
74	-	83	67	46
75	-	54	49	40
76	-	17	15	9
77	-	22	22	11
78	-	30	10	7
79	-	57	36	18
80	-	64	55	44
81	-	105	92	46
82	-	67	-	-
83	-	-	-	-
84	-	-	-	-
85	-	-	-	-
86	-	-	-	-
87	-	-	-	-
88	-	-	-	-

Betsioky-Sud — Unit: mm

Year	Annual	1st	2nd	3rd
1969	792	106	90	51
70	425	82	46	37
71	755	98	91	87
72	746	73	48	47
73	834	65	62	46
74	857	80	66	43
75	957	93	76	74
76	525	32	30	28
77	728	109	51	50
78	614	60	31	31
79	591	59	51	46
80	731	109	72	65
81	721	93	92	58
82	752	80	58	58
83	411	63	37	34
84	685	70	56	56
85	740	91	79	49
86	805	112	66	66
87	497	62	56	50
88	542	60	55	51

Ranohira — Unit: mm

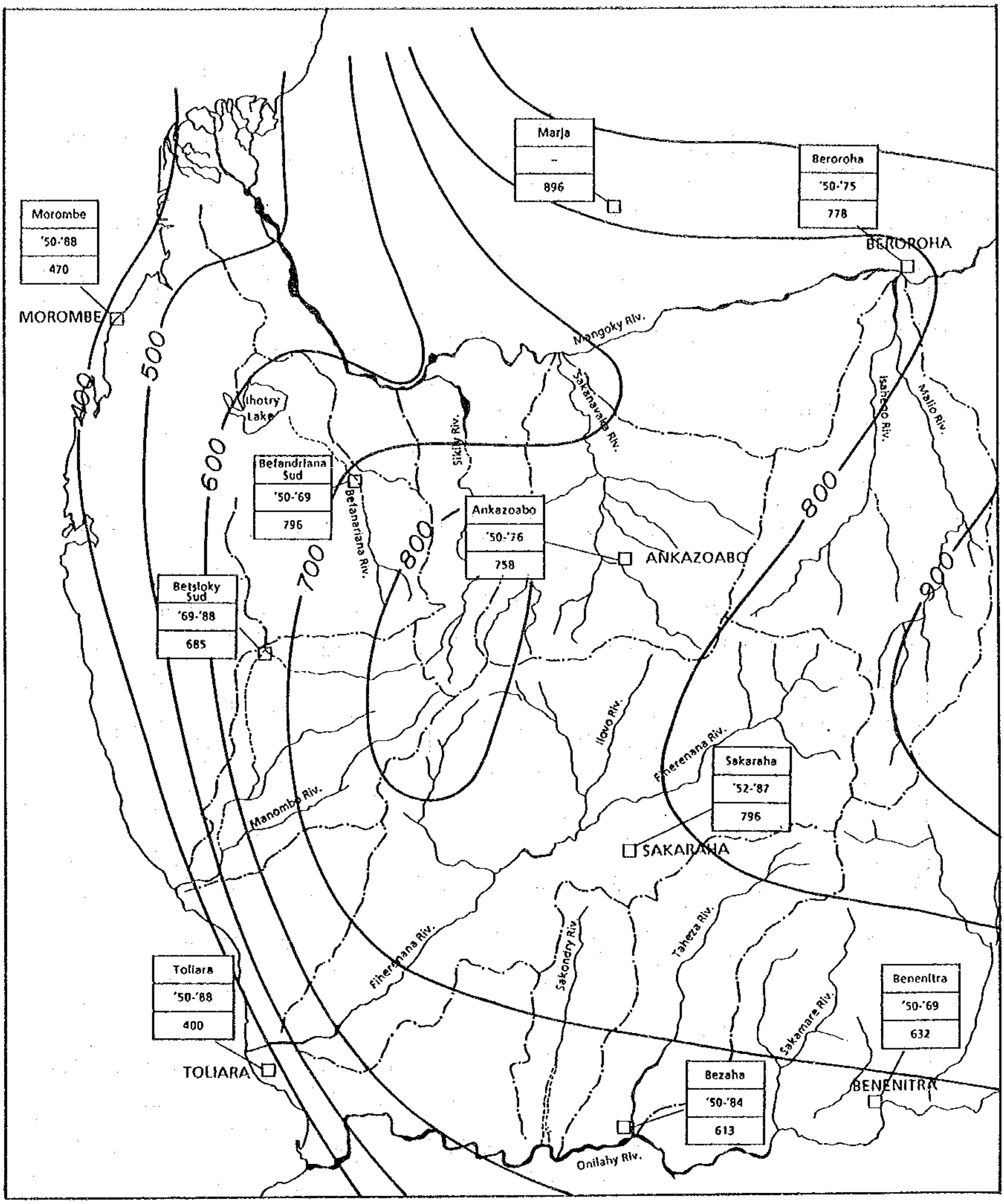
Year	Annual	1st	2nd	3rd
1969	1111	58	53	52
70	820	80	66	42
71	1337	155	149	65
72	1167	78	70	65
73	1056	89	78	57
74	1151	78	72	61
75	1076	78	66	63
76	745	47	43	31
77	827	98	59	35
78	790	70	54	47
79	853	65	61	60
80	884	83	56	54
81	1166	90	78	53
82	1505	87	84	66
83	767	52	45	41
84	1313	95	72	52
85	591	86	47	23
86	988	59	47	39
87	772	97	66	38
88	532	50	32	27

Toliara — Unit: mm

Year	Annual	1st	2nd	3rd
1969	304	45	33	33
70	166	30	26	24
71	461	45	34	30
72	414	53	38	30
73	456	57	44	34
74	685	188	92	44
75	464	143	45	65
76	370	45	43	36
77	572	125	53	51
78	355	52	31	29
79	281	111	29	26
80	286	81	41	21
81	393	57	55	37
82	534	48	47	37
83	212	39	36	28
84	423	45	35	30
85	248	71	44	21
86	272	37	27	20
87	394	79	54	26
88	379	36	34	34

Sakaraha — Unit: mm

Year	Annual	1st	2nd	3rd
1969	925	68	67	66
70	778	117	58	58
71	1371	105	105	71
72	989	98	74	50
73	973	63	59	48
74	1287	106	76	69
75	640	68	63	50
76	774	65	46	36
77	719	84	50	33
78	634	93	72	51
79	789	94	71	57
80	518	70	44	43
81	-	71	50	14
82	-	13	10	5
83	-	51	48	44
84	-	40	40	35
85	-	53	43	41
86	652	75	64	60
87	-	99	68	57
88	-	74	60	42



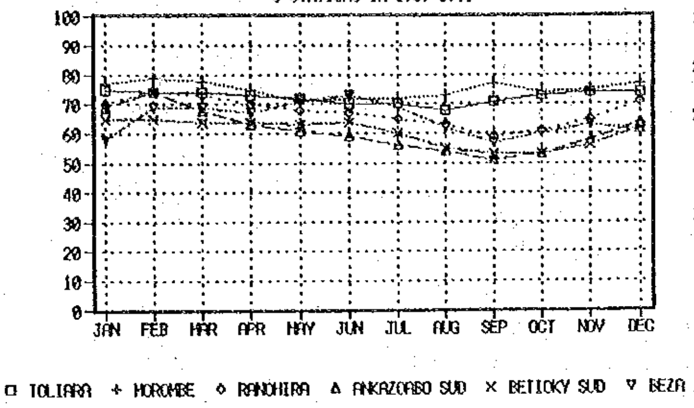
LEGEND

- Station
- Collected record
- Average of annual rainfall
- Rainfall contour line (mm/year)
- Catchment area
- River

Fig. 3.3.1 Location of Meteorological Stations and Annual Isohyet

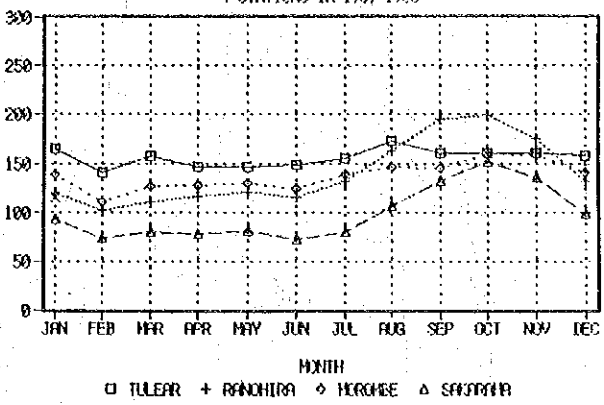
Monthly Mean Relative Humidity

6 STATIONS IN 1969-1988



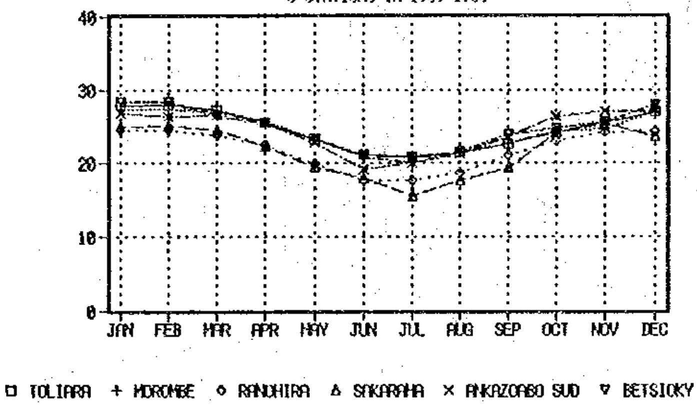
Monthly Mean Evaporation

4 STATIONS IN 1969-1988



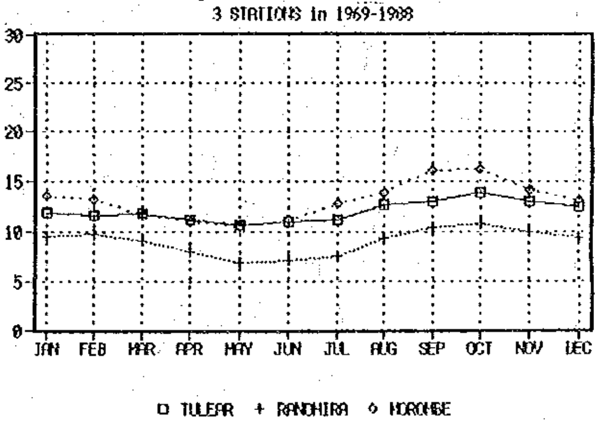
Monthly Mean Temperature

6 STATIONS IN 1969-1988



Monthly Mean Wind Velocity

3 STATIONS in 1969-1988



Monthly Mean Sunshine Hour

3 STATIONS in 1969-1988

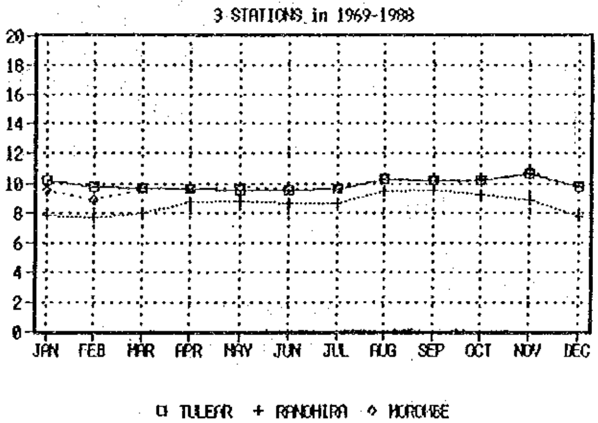
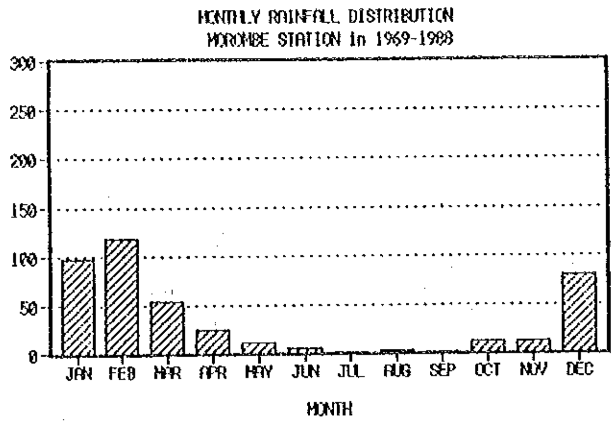
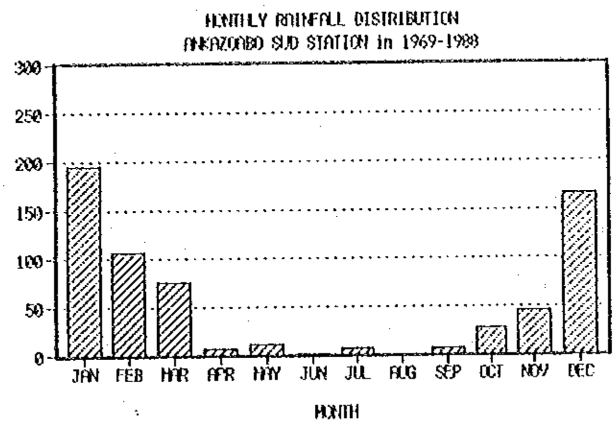
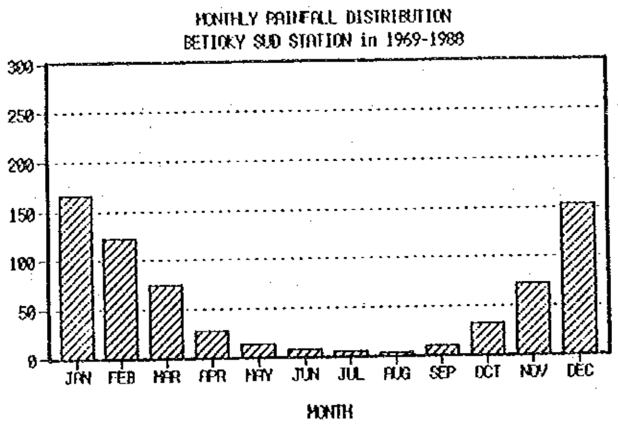
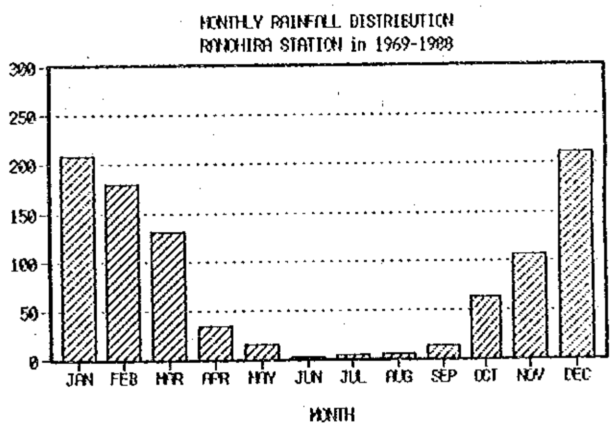


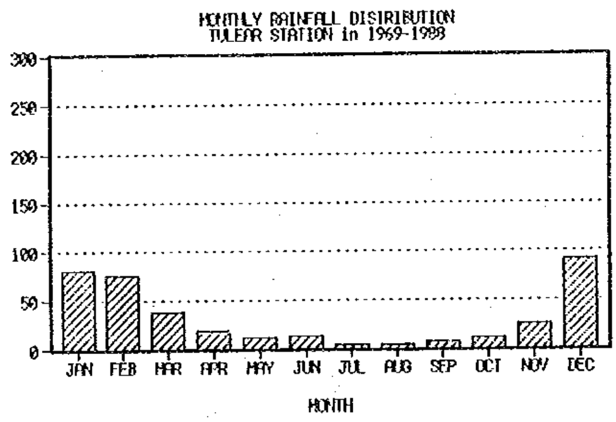
Fig. 3.3.2 General Climatic Characteristics

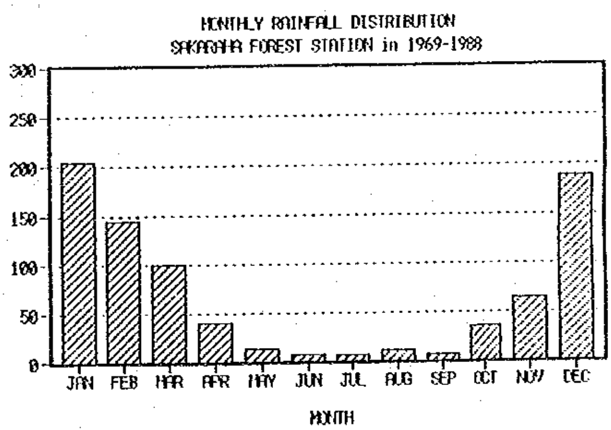












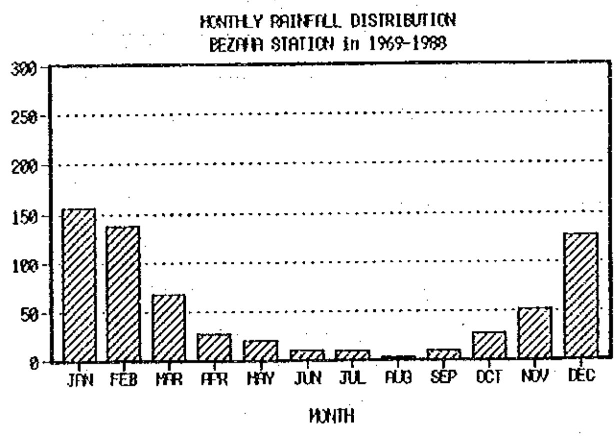


Fig. 3.3.3 Distribution of Monthly Mean Rainfall

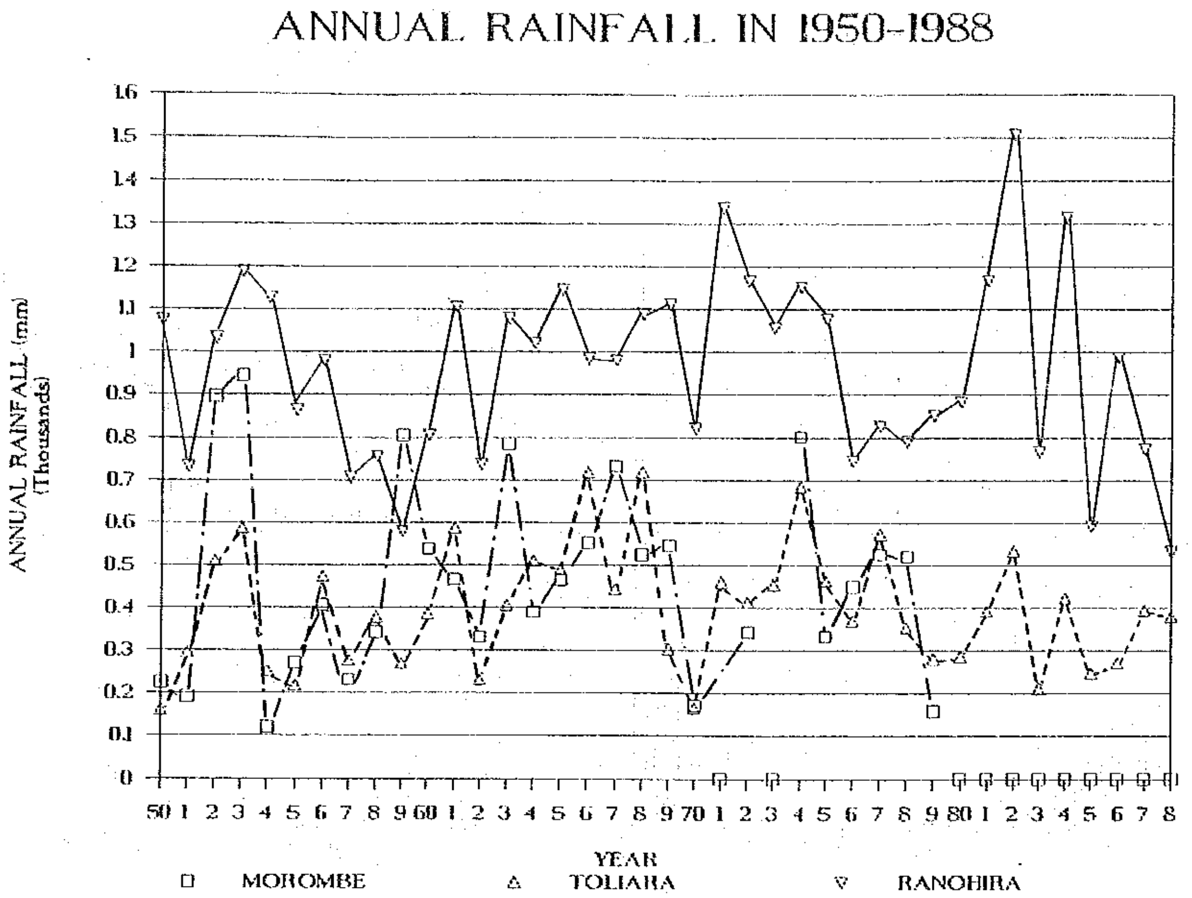


Fig. 3.3.4 Annual Rainfall in 1950-1988

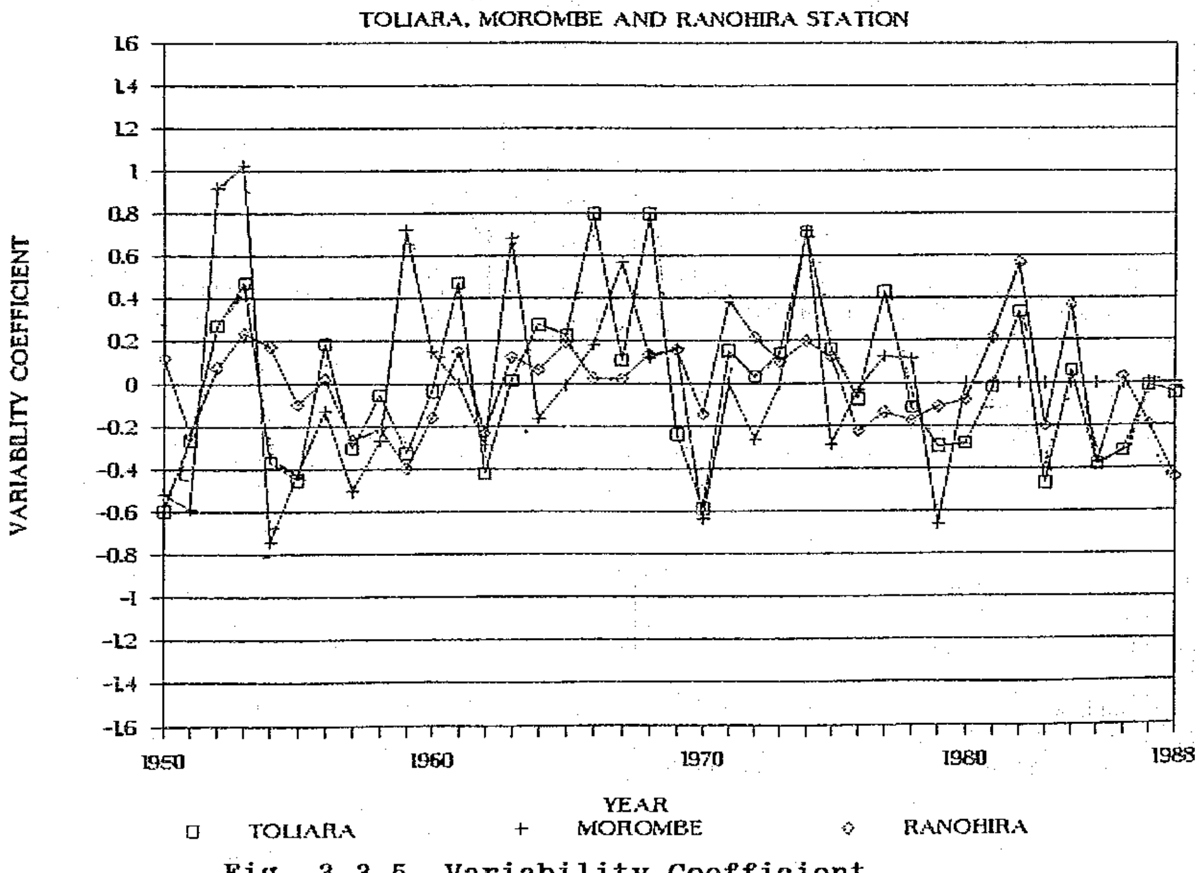


Fig. 3.3.5 Variability Coefficient

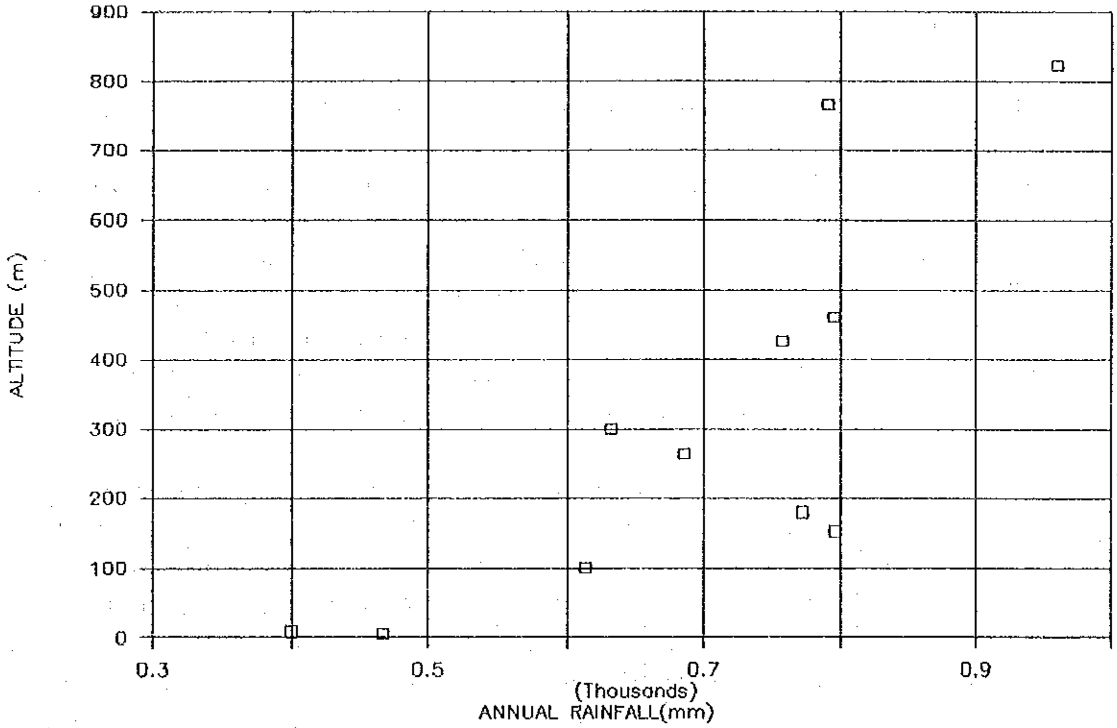


Fig. 3.3.6 Altitude-Annual Rainfall Curve

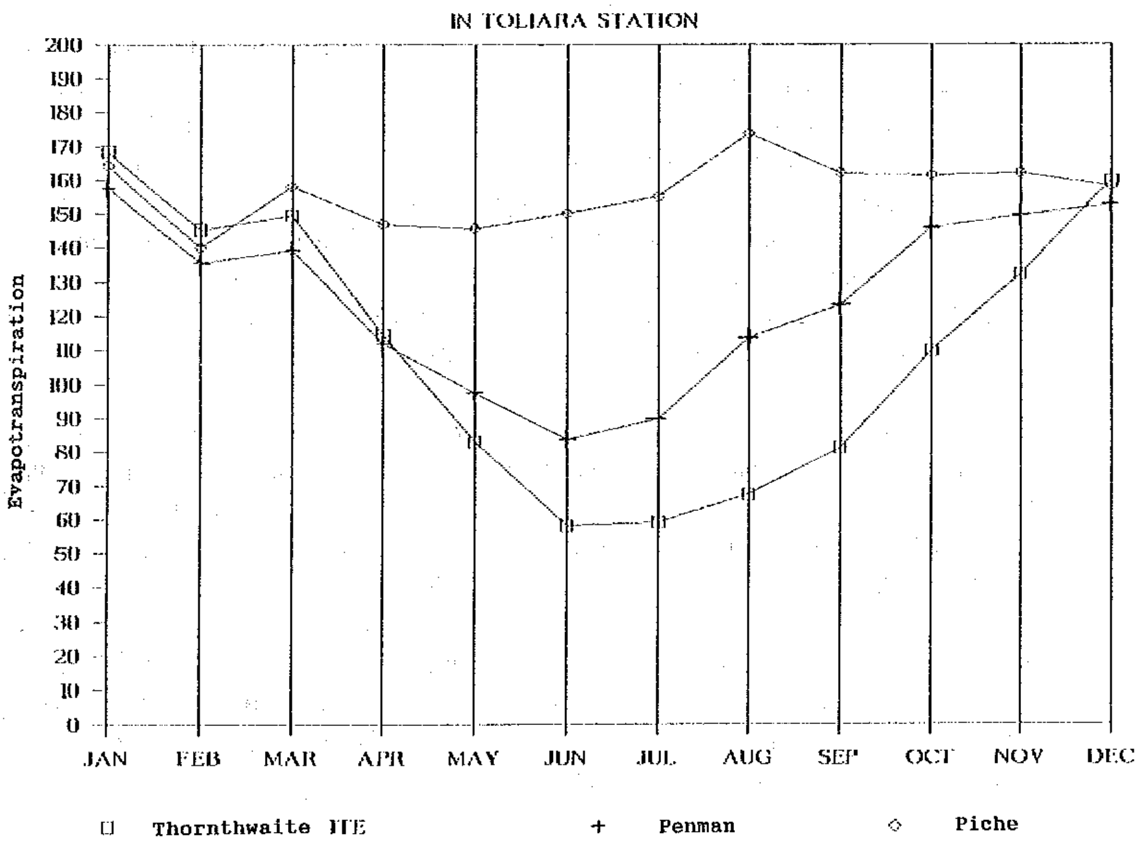


Fig. 3.3.7 Comparison of Evapotranspiration

3.4 Streamflow

3.4.1 General Condition and Discharge Records

As shown in Fig. 3.4.1, two big rivers exist in the Study Area--the Mangoky River and Onilahy River, both flowing from east to west. The Mangoky River serves as the northern boundary of the Study Area, while the Onilahy River serves as its southern limit. Catchment area for Mangoky River at Bevoay Gaging Station is around 54,000km^2; for Onilahy River at Tongobory Gaging Station, about 29,000km^2.

Between Mangoky and Onilahy Rivers are the Manombo River, the Fiherenana River and many seasonal rivers. The Manombo River originates from the Mikoboka Mountains, with a catchment area of 380km^2 above Andoharano Village. The catchment area of Fiherenana River covers the Analavelona Mountains on the north, and the catchment area's eastern edge lies almost at the center of the area between Sakaraha and Ranohira. Many small seasonal rivers existing in the coastal area originate from the Mikoboka Mountains.

The required hydrological data of the Study Area were obtained in Antananarivo from the Directorate of Meteorology, Organization de Recherche' Scientifique de Territoires d'Outremer (ORSTOM) and MIEM. The locations of the streamflow gaging stations are shown in Fig. 3.4.1. The discharge observations were being performed well in most of these stations before they were closed in the sixties. ORSTOM reopened some of them in 1983. Fig.3.4.2 shows the collected discharge records (1960-1983).

Among the rivers with gaging stations, some of the gage height records were converted into discharge data. Table 3.4.1 presents the monthly discharge records at nine stations, and Fig. 3.4.3 shows the hydrographs at five different locations along the river.

Bevoay Station is located at the intake facility for the Lower Mangoky River Development Project (Samangoky) of the Ministry of Agriculture. Other stations exist in the upper reaches and along the tributaries.

The amount of discharge varies seasonally, i.e., from wet to dry seasons, especially in the downstream. For example, Banian Station has a maximum discharge of almost 1,300 m^3/sec in December and a minimum discharge of about 50 m^3/sec in September. Other stations exhibit the same characteristics: maximum discharge occurring in December-February, the minimum occurring in September. This pattern clearly reflects the seasonal distribution of rainfall.

3.4.2 Field Inspections and Discharge Measurements

Field inspections of rivers in the Study Area were conducted along the main national roads, Routes 7, 9 and 10, as well as along the Sakaraha-Ankazoabo Road in October-December 1989 (end of dry season/onset of rainy season) and in February-March 1990 (rainy season).

Erosion problems in the Study Area are quite serious. Large volumes of sediments are deposited in the downstreams and along the courses of the rivers as well, thus raising the level of river beds. The silt and sand carried by the rivers are brought forth by the erosional processes in the drainage basins. Also, deforestation has aggravated this problem. As observed during the field survey of the Study Area, trees in large numbers were being felled or burned down in the upper river basins to open up new agricultural fields and to increase sources of fuels.

In the coastal area, water flow was observed in Mangoky and Onilahy Rivers even in the middle of October which is near the end of the dry season. No flow was observed in Fiherenana, Manombo and other seasonal rivers along Route 9 in the same period. However, some amount of flow could be observed in the upstreams of the Manombo and Fiherenana Rivers. The absence of flow in these two rivers in the coastal plain is jointly accounted for by the lack of rainfall, the irrigation diversions and the recharge to groundwater in the upstreams.

(1) Spot Measurements

In June-July and September-October 1990, spot measurements were performed in order to understand the general flow conditions in the following rivers.

- Sakanavaka River (Mangoky River System)
- Malio River (Mangoky River System)
- Isahera River (Mangoky River System)
- Sakondry River (Onilahy River System)
- Taheza River (Onilahy River System)
- Fiherenana River
- Manombo River

The results of spot measurements are presented in Table 3.4.2 and are outlined as follows.

(a) Mangoky River System

- Sakanavaka River

Measurement points are located along the road from Tandrano to Ankazoabo and are shown in Fig 3.4.4.

All tributaries had a scant flow of water and the stream-flow estimates are:

Ifantaka River	--- 0.2 m^3/sec
Rozaki River	--- 0.01 m^3/sec
Mangitraki River	--- 0.2 m^3/sec
no name	--- 0.16 m^3/sec
no name	--- 0.08 m^3/sec
no name	--- 0.03 m^3/sec
Sakanavaka River at Ankazoabo	--- 2.0 m^3/sec

- Malio and Isahena Rivers

Measurement points are shown in Fig 3.4.4 and results are presented below.

unit:m^3/sec

	July	Sept
Malio	12.26	
Isahena	4.57	

(b) Onilahy River System

- Sakondry and Taheza Rivers

Spot measurements of the Sakondry River flow were performed at the bridge on the Andranavory-Bezaha road in June and September 1990.

For the Taheza River, observation was made above the barrage which is located upstream of Ankiliarivo village. This barrage is now being rehabilitated as part of the irrigation project funded by the European Development Community.

Large paddy fields are located along this river because of its continuous flow all year round.

Measurement points of Sakondry and Taheza Rivers are shown in Fig 3.4.4 and the results are:

unit: m^3/sec

River	June	Sept
Sakondry	-	0.80
Taheza	14.95	15.42

(c) Fiherenana River

Monthly discharge measurements were conducted at two points and the results are discussed in (2) of this subsection.

(d) Manombo River and Amboboka Springs

The Manombo River flows throughout the year in its upper reaches. However, and since most of the water is being diverted by the barrage at the Andoharano village, no flow can be observed even during the rainy season at the bridge on Route 9. The results of monthly discharge measurement at this diversion point are discussed in the next paragraph.

Amboboka village is located around 7 km east of Ankililioka village and 10 km north of Manombo River. The five springs existing in this village discharge into a swamp located west of the springs. Two small barrages were constructed to control the water from this swamp. Three main canals divert water from both barrages to irrigate the paddy fields between Ankililioka and Tranoratsy along Route 9.

Discharge measurements for these springs were performed at the measurement points shown in Fig 3.4.4. Results are as shown below.

unit:m^3/sec

Measurement point	June	Sept	Remarks
Spring flow 1	0.408	-	biggest spring
Barrage 1	2.16	-	one of 2 barrages
Canal 1	1.018	0.85	to Ankililioka
Canal 2	-	0.08	to Ankililioka
Canal 3	-	0.06	
Canal 4	-	-	
Canal 5	1.065	1.41	to Ankaraobato

Total amount of discharge derived for the five springs is 3.1 m^3/sec as estimated from the discharge at Barrage 1 and canals 1 and 2 . Villagers observed that there is no decrease of this flow even during the dry season.

Results of the electric conductivity (EC) measurements done in September 1990 are as follows.

Measurement point	EC (S/cm^2)
Manombo River	370
Amboboka Spring	443
Canal 1	488
Canal 2	529
Canal 5	485
Barrage 2	471

These results show that Manombo River is recharged by groundwater during the dry season. The hydrogeological structure of both places is discussed in Section 4. The all year round flow in these places is ascribed to the location of the fault.

(2) Monthly Discharge Measurements

To generate data for the water balance analysis, monthly discharge measurements were conducted for the Manombo and Fiherenana Rivers.

(a) Fiherenana River

Monthly discharge measurements for Fiherenana river were conducted at the following two points.

- upstream: at the bridge along the Sakaraha-Ankazoabo Road (the nearest village is Antaralava)

- downstream: at the intake facility in Behompy

Results of the monthly discharge measurements are shown below.

Date	Discharge (m^3/sec) Antaralava	Behompy
17 Oct '89	7.64	2.0
27 Nov '89	14.86	-
29 Dec '89	16.15	-
24 Jan '90	25.06	-
23 Feb '90	49.20	53.82
09 Mar '90	36.42	-
15 Apr '90		19.13
23 May '90	15.30	3.20
18 Jun '90	9.36	9.42
29 Aug '90	7.25	4.72
17 Sep '90		3.15

To check the rainy season behavior of streamflow between

Antaralava and Behompy, a measurement of discharge at Behompy was done on 23 February 1990 and the result was 56.36m^3/sec. However, this flow decreased suddenly just downstreams of Behompy, and only a wet channel bed could be observed a few hundred meters above the irrigation intake at Ambolonkira. In this case, the water table might have fallen downstream because of the highly permeable channel bed which is composed of sand sediments and calcareous stones, resulting in groundwater recharge through influent seepage. Flow reappeared below the Ambolonkira intake and increased gradually, but never regained the upstream discharge. At this river section, the water table might have risen again above the channel bed, and effluent seepage might have occurred, causing the reemergence of the streamflow.

On 17 October 1989, at the end of the dry season, 7.64m^3/sec was measured at Antaralava and 2.0m^3/sec was measured at Behompy. No flow was observed downstream of Behompy.

(b) Manombo River

Monthly discharge measurements for Manombo river were conducted at the Andoharano barrage with irrigation intake facility, and results are as presented below.

Date	Discharge (m^3/sec)
29 Nov '89	3.30
28 Dec '89	5.07
26 Feb '90	4.49
10 Mar '90	3.28
19 May '90	3.90
20 Jun '90	2.10
31 Aug '90	1.50
20 Sep '90	1.28

Measurement in January 1990 was not performed because Andoharano was not accessible due to the rain damaged road.

The staff gage which was installed above the barrage in December 1989 was missing after a flood discharge of about 200-240m^3/sec passed through that river section. This flood also destroyed the mid-section of the barrage. The whole streamflow is presently concentrated at this destroyed portion, leaving the irrigation intake canal without water.

3.4.3 Daily Discharge and Runoff Coefficient

(1) Daily Discharge

In order to assess the runoff and base flow characteristics of the Study Area, daily discharge records were collected from the following three stations.

- Bevoay (1955/56-1967/68)
- Betroka (1968/69)
- Behompy (1983)

Figs. 3.4.5 (1)-(4) show the daily specific discharges (converted by dividing each discharge by the catchment area, i.e., from m^3/sec to l/sec/km^2) at these stations.

Fig. 3.4.5 (1) shows the records at Bevoay station for the 1964-65 and 1968-69 periods.

River discharge during the rainy season (including the transition period from dry to wet seasons) is normally affected by rainfall. The maximum discharge varies from 30 l/sec/km2 to 350 l/sec/km2; the minimum discharge, which is considered as base flow from groundwater, is almost 2-3 l/sec.

Fig. 3.4.5 (2) shows the discharge at Bevoay (Mangoky River) and Betroka (Onilahy River) stations. Flood patterns between these stations are somewhat different, but the amount of base flow of 1-4 l/sec/km2 in April-October can be considered as being the same.

Figs. 3.4.6 (1) and (2) show the duration curves at Betroka and Behompy stations. These results are summarized as follows.

Behompy	Day	Discharge (l/sec/km^2)
	95	10.39
	185	3.72
	275	2.18
	355	1.22

Betroka	Day	Discharge (l/sec/km^2) 1967/68	1968/69
	95	4.99	9.59
	185	2.42	3.55
	275	1.54	1.58
	355	0.67	0.67

These curves for Betroka show that the 275-day discharge and 355-day discharge are almost stable and are affected only by groundwater (base flow).

(2) Runoff Coefficient

Based on the discharge records and the estimated areal rainfall, the runoff coefficient is roughly calculated as follows.

- Behompy

Annual runoff = 17978 (m^3/sec) x 86400
= 1.553 x 10^9 (m^3)

Areal Rainfall

	(1981/82)	Weight
Toliara Station	573 mm	25 %
Sakaraha Station	1118 mm	50 %
Ranohira Station	1799 mm	25 %

Annual Rainfall = 573 x 0.25 + 1118 x 0.5 + 1799 x 0.5
= 1152 mm

Annual Runoff
Coefficient $= 1.553 \times 10^9$ (m^3) / 1152 (mm) x 6755 (km^2)
= 20 %

- Betroka

Annual runoff = 3935 (m^3/sec) x 86400
= 0.340×10^9 (m^3)

Areal Rainfall

	(1967/68)	Weight
Iakora Station	791 mm	100%

Annual Runoff
Coefficient $= 0.340 \times 10^9$ (m^3) / 791 (mm) x 2345 (km^2)
= 18 %

Table 3.4.1 Monthly Discharge Records

(1) MONTHLY DISCHARGE

Unit: m3/sec

Station	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Malakialina	83.6	376.7	644.5	399.0	367.0	154.8	85.1	77.8	59.7	56.9	45.9	38.8	83.6	376.7
Tsitondroina	42.3	214.0	256.1	193.2	185.3	69.0	29.6	27.2	20.5	19.6	15.5	14.1	42.3	214.0
Bevoay	186	523	1430	1394	887.1	365.4	176.1	139.2	139.3	122.9	104.0	106.2	186.1	522.7
Ihosy	6.8	33.9	50.1	36.6	22.2	12.8	7.0	5.1	4.6	5.0	4.5	4.0	6.8	33.9
Ankaramena	5.5	21.6	28.4	27.0	16.0	6.3	3.6	2.7	2.8	2.9	2.2	2.4	5.5	21.6
Vandrove	91.3	467	1700	681.0	1833	618.0	215.0	155.0	135.0	111.0	119.0	145.0	91.3	467.0
Behompy	24.9	52.4	113.0	125.0	107.0	52.2	32.6	21.8	14.0	14.7	8.4	11.5	24.9	52.4
Mahamena	-	-	-	-	-	39.1	38.9	39.3	35.8	31.9	36.9	39.1	-	-
Betroka	10.5	17.5	45.5	49.0	29.3	15.1	9.1	7.1	5.0	3.8	2.5	2.4	10.5	17.5

(2) SPECIFIC DISCHARGE

Unit:l/sec/km2

Station	C.A.(km2)	period	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Malakialina	11715	'53-'63	55.0	34.1	31.3	13.2	7.3	6.6	5.1	4.9	3.9	3.3	7.1	32.2
Tsitondroina	6510	'53-'68	39.3	29.7	28.5	10.6	4.6	4.2	3.1	3.0	2.4	2.2	6.5	32.9
Bevoay	53810	'60-'83	26.6	25.9	16.5	6.8	3.3	2.6	2.6	2.3	1.9	2.0	3.5	9.7
Ihosy	1500	'54-'68	33.4	24.4	14.8	8.5	4.6	3.4	3.1	3.3	3.0	2.7	4.5	22.6
Ankaramena	610	'62-'69	46.6	44.3	26.2	10.3	5.9	4.4	4.6	4.8	3.6	3.9	9.0	35.4
Vandrove	52764	'66-'67	32.2	12.9	34.7	11.7	4.1	2.9	2.6	2.1	2.3	2.7	1.7	8.9
Behompy	6755	'81-'82	16.7	18.5	15.8	7.7	4.8	3.2	2.1	2.2	1.2	1.7	3.7	7.8
Mahamena	25625	'81-'82	-	-	-	1.5	1.5	1.5	1.4	1.2	1.4	1.5	-	-
Betroka	2345	'67-'69	19.4	20.9	12.5	6.4	3.9	3.0	2.1	1.6	1.0	1.0	4.5	7.5

Table 3.4.2 RESULTS OF SPOT MEASUREMENTS

RIVER SYSTEM	RIVER	CATCHMENT AREA	JUN/JUL m3/sec	JUN/JUL l/sec/km2	SEP/OCT m3/sec	SEP/OCT l/sec/km2
1. MANGOKY RIV. SYSTEM	(1) SAKANAVAKA RIV.					
	(a) MANGITRAKI	81	-	-	0.20	2.47
	(b) SOMORY	137	-	-	0.16	1.17
	(c) SAKANAVAKA (ANKAZOABO)	332	-	-	2.00	6.02
	(2) MALIO RIV.	2046	12.26	5.99	12.74	6.23
	(3) ISAHENA RIV.	1870	4.75	2.54	2.39	1.28
2. ONILAHY RIV. SYSTEM	(1) SAKONDRY	727	-		0.80	1.10
	(2) TAHEZA	1600	14.95	9.34	15.42	9.64
3. FIHERENANA RIV.SYSTEM	(3) FIHERENANA RIV.					
	(a) ANTARALAVA	2157	9.36	4.34	6.81	3.16
	(b) BEHOMPY	6755	9.42	1.39	3.15	0.47
4. MANOMBO RIV.SYSTEM	(4) MANOMBO RIV.	508	2.10	4.13	1.28	2.52

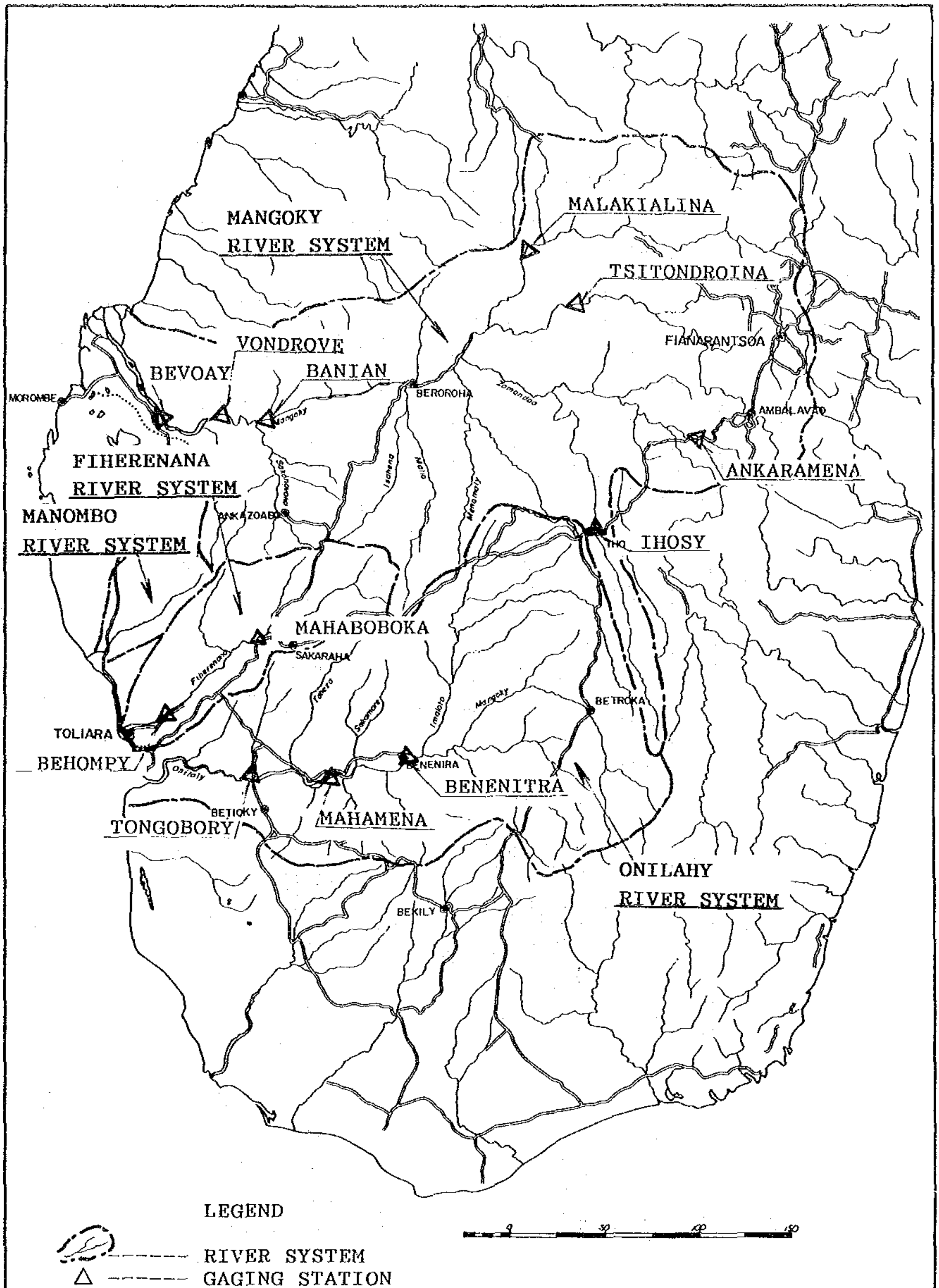


Fig. 3.4.1 River Systems and Locations of Gauging Stations

River System	River	Station	Catchment Area(km2)	LONGITUDE	LATITUDE	ALTITUDE (m)	1955	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
Mangoky	Ihosy	Ihosy	1500	22 23'	46 06'	96.28	A	A	A	A	A	A	A	A	A	A	A	A	A	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mananan-tanan	Tsiton-droina	6510	21 19'	46 00'	95.69	A	A	A	A	A	A	A	A	A	A	A	A	A	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mangoky	Bevoay	53810	21 50	43 52'	39.25	-	-	-	-	-	-	A	-	-	-	A	A	A	A	A	-	-	-	-	-	-	-	-	-	-	-	A	A	A	-	-
	Mangoky	Betroka	2345	*		*	-	-	-	-	-	-	C	-	-	-	-	-	-	A	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mangoky	Banian	50000	*	71 42'	71.42	C	C	C	C	C	C	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mangoky	Vondrove	52762	21 19'		62.78	-	C	C	C	C	C	C	-	-	-	-	-	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Matsiatra	Malakialina	11715		62 78'	92.94	A	A	A	A	A	A	A	A	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Zomandao	Ankaramena	610	21 57'	46 39'	95.65	C	C	C	C	C	C	C	A	A	A	A	A	A	A	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Onilahy	Onilahy	Benenitra	*	23 27'	45 06'	97.72	C	C	C	C	C	C	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Onilahy	Tongobory	*	23 30'	44 18'	97.73	C	C	C	C	C	C	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	A	-	-
	Onilahy	Mahamena	25625	23 36'	44 42'	*	-	-	-	-	-	-	-	-	-	-	-	-	-	A	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fiherenana	Fiherenana	Sakaraha	*	22 54'	44 32'	*	-	-	-	-	-	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Fiherenana	Mahaboboka	3812	22 48'	44 27'	96.68	-	C	C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Fiherenana	Behompy	6755	23 15'	43 50'	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	A	-	-

A ---- Daily Discharge
B ---- Monthly Discharge
C ---- Daily Water Level
D ---- Monthly Water Level
- ---- No Record

Fig. 3.4.2 Collected Discharge Records

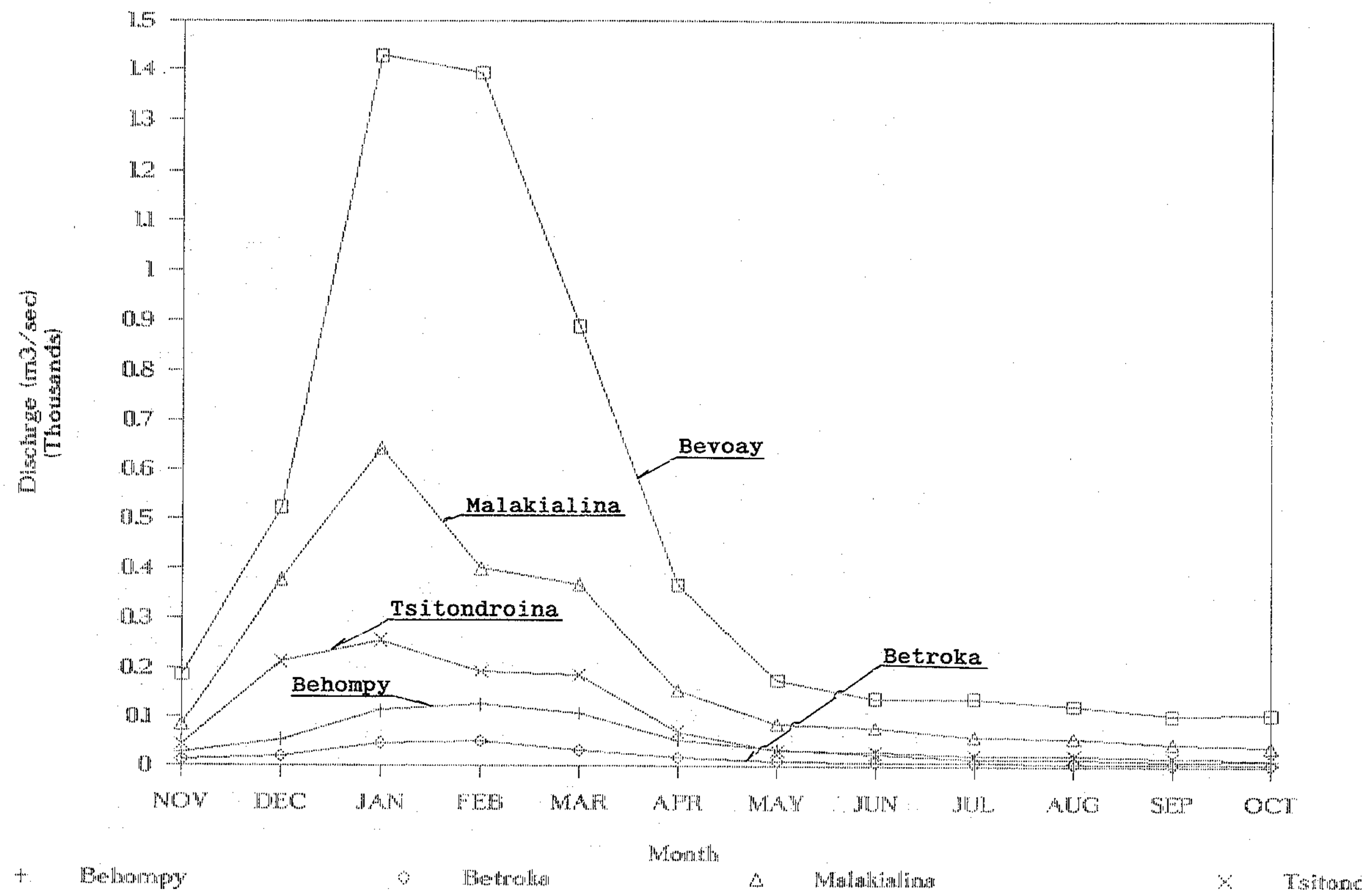
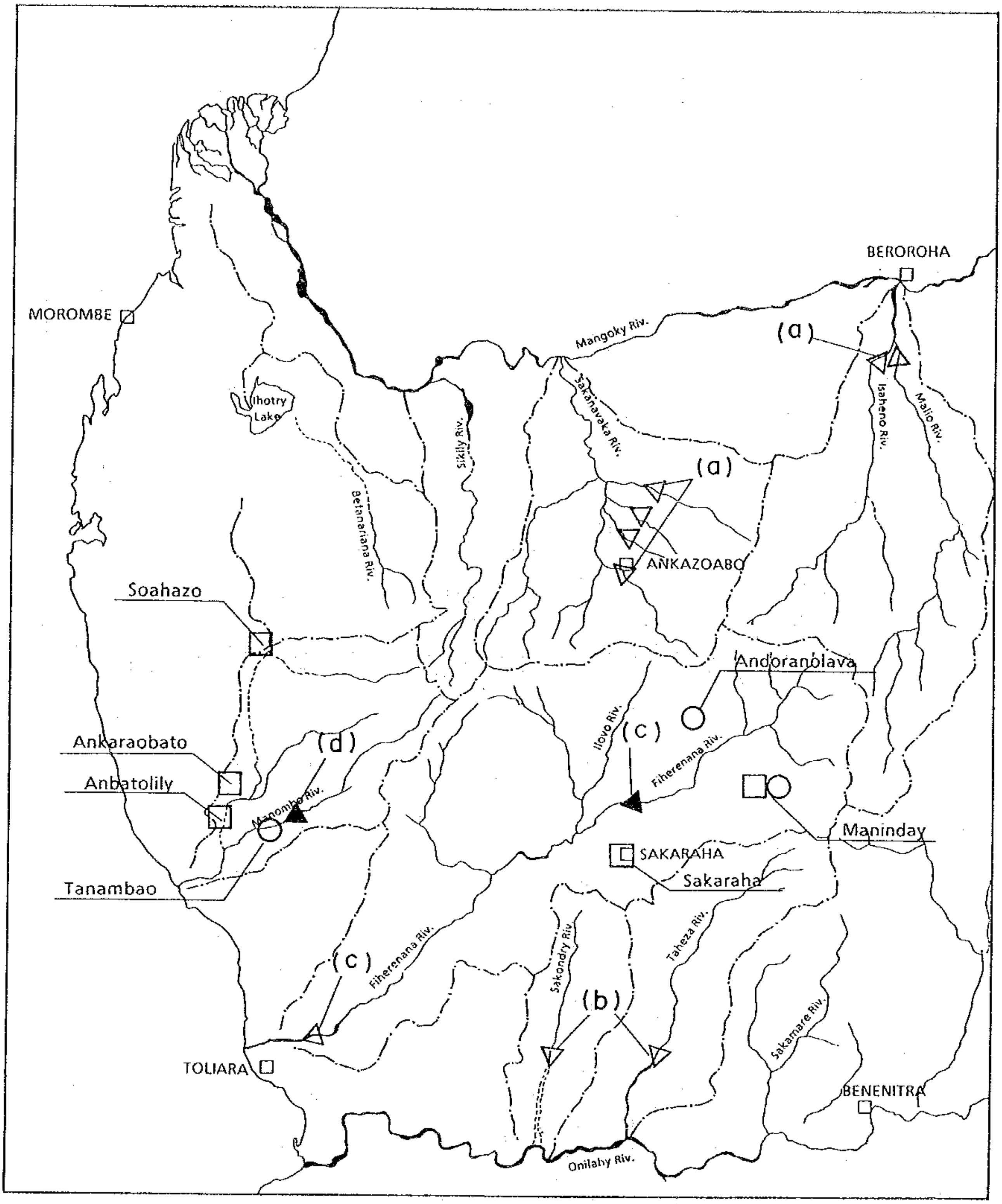


Fig. 3.4.3 Monthly Discharge Records



LEGEND

□ — Groundwater Level (by Recorder)

○ — Rainfall (by Recorder)

◀ — Monthly Discharge Measurement

◁ — Seasonal Discharge Measurement

Fig. 3.4.4 Location of Monitoring System

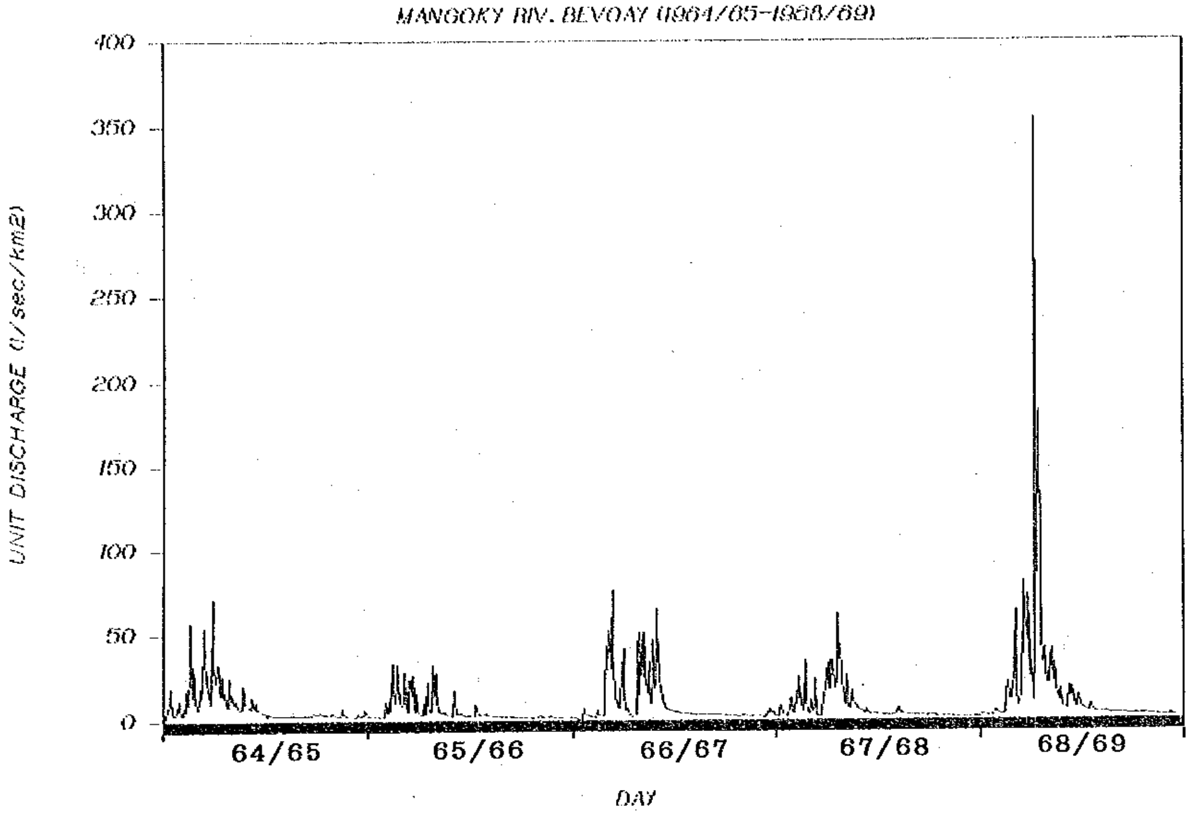


Fig. 3.4.5 Daily Discharge (1)

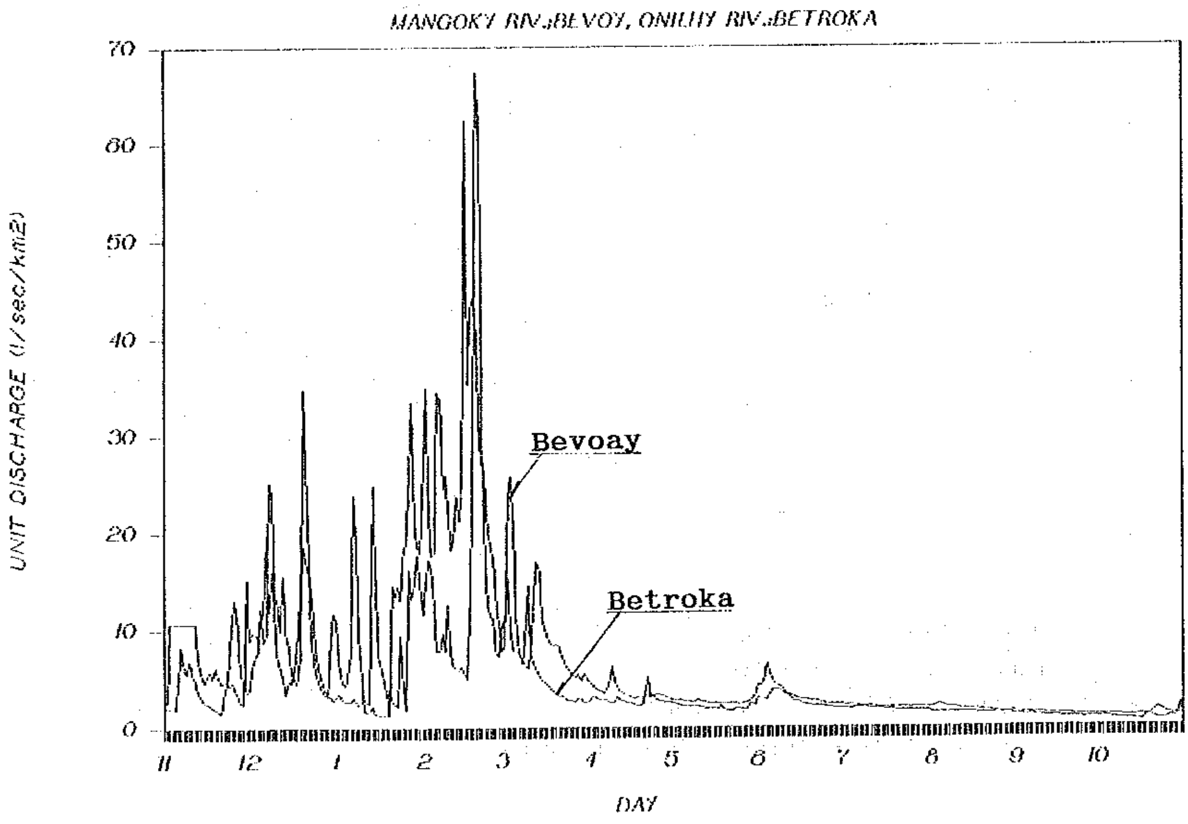


Fig. 3.4.5 Daily Discharge (2)

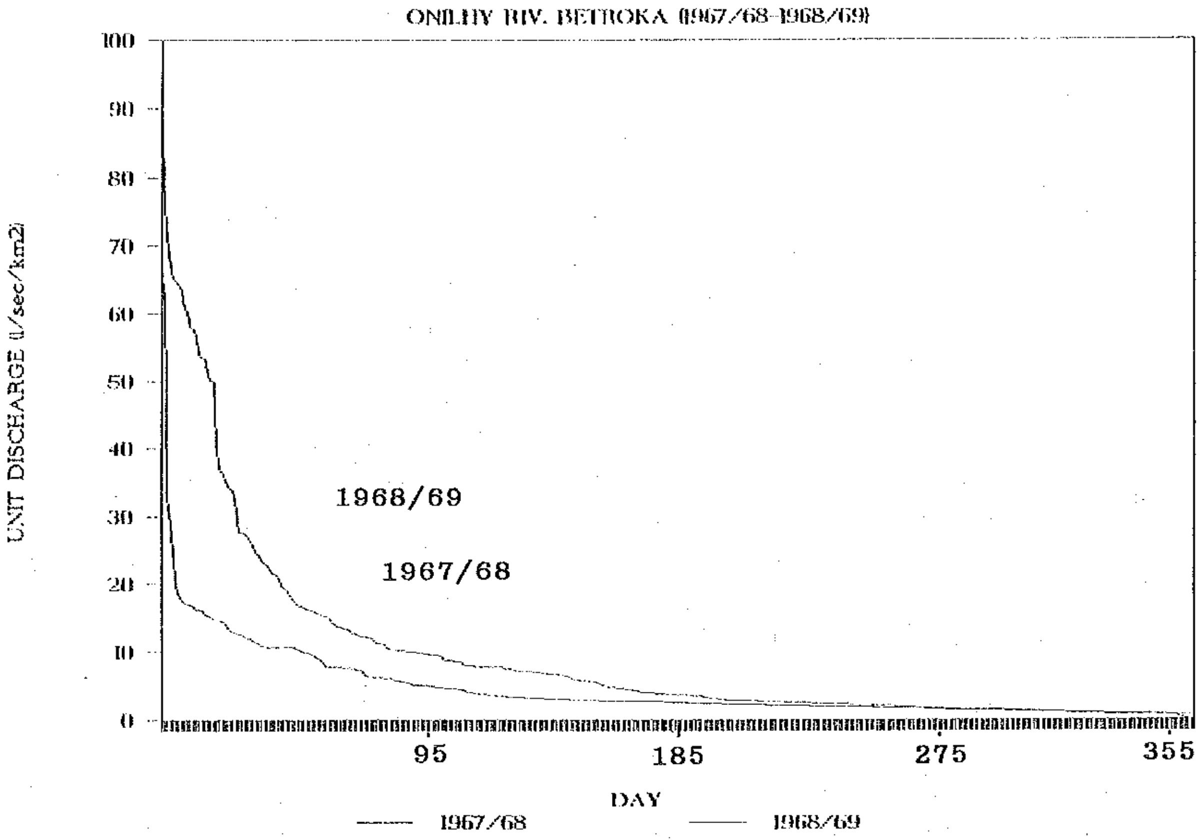


Fig. 3.4.6 Duration Curve (1)

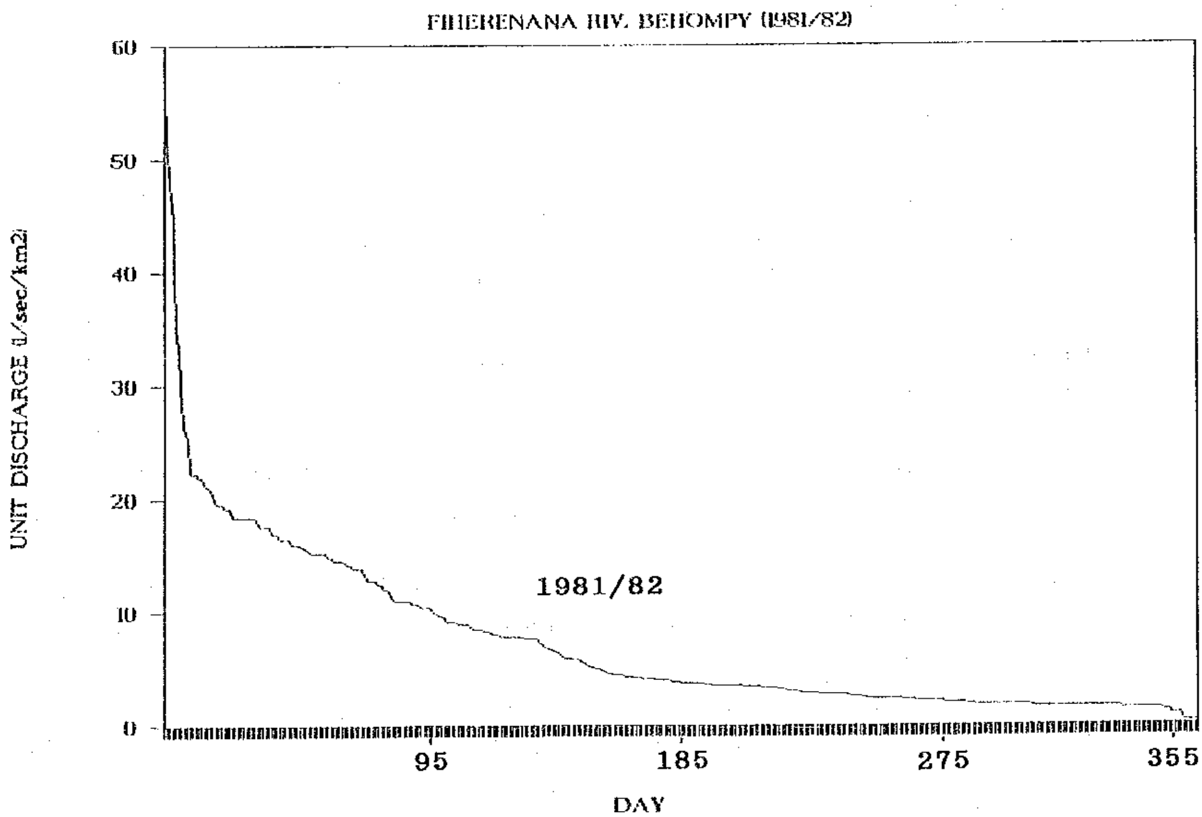


Fig. 3.4.6 Duration Curve (2)

3.5 Existing Wells and Groundwater Levelling

3.5.1 Inventory of Existing Wells

Well inventory involves the collection of all available data on existing wells including location, depth and construction details, lithologic and electric logs of the borehole, pump installation, yield and total production, static and pumping water levels, quality of water, and results of pumping test carried out in the well.

A well inventory is an indispensable activity of this Study. It is the source of much of the basic hydrologic data, and it is also the best reference for the selection of wells for observation of water level and water quality, as well as for carrying out pumping tests and other kinds of subsurface geophysical surveys.

(1) Field Inspection of Existing Wells

Well information of the Study Area were collected from MIEM in Antananarivo and Toliara. In 1989, the MIEM Hydrogeological Section in Antananarivo collected the necessary information from existing reports and arranged them in the following form:

- well location was plotted on the topographical map (1:100,000), and
- information like depth, groundwater level, casing diameter, water quality, etc. on each well were recorded on a piece of index card.

However, important data like drilling log and results of pumping test were missing.

Verification and updating of the well information collected from MIEM were done during the first field survey.

All boreholes and some dug wells, which were constructed by U.S. AID, the Government of France, MIEM and by the village people themselves, were visited during the survey to determine the precise location of each well. Also, gaps in the data were filled-in whenever possible, especially for the key parameters of yield and production, quality of water, static and pumping water levels and groundwater usage. For supplementary data collection, inventory was taken of some wells existing in candidate villages but not registered in MIEM records.

All inventory data for each well, including a sketch map of the site, were recorded on a well inventory form which was designed to facilitate automatic data processing.

Well data collected during the field survey were registered in the proposed hydrogeological database management system. The Hydrogeological Section of MIEM in Antananarivo shall create a special sub-section with the responsibility to manage this database system.

(2) Results of Well Inventory

Dug wells (shallow/deep) are used to tap groundwater in areas where the static water level is rather high. Shallow boreholes are also available in these areas. Deep boreholes are usually utilized in areas where groundwater is restricted to the confined aquifer.

More than 200 well sites were visited to check the wells' existing conditions; however, some wells could no longer be found, and the locations of some other wells did not match the records. A total of 114 wells were finally located and checked in the field, 56 of which boreholes and the rest dug wells.

Fig. 3.5.1 shows the locations of these wells on the map of the Study Area, and Table 3.5.1 lists their present states.
In order to understand well locations, all wells are given code number by their prefecture and type.
Well code is composed of 4 digits as explained below.

* * * *
a b c d

a: Prefecture

Toliara I	----1
Toliara II	----2
Sakaraha	----3
Ankazoabo	----4
Morombe	----5
Beroroha	----6

b c d: well No.

New borehole incl. JICA project	---- 000-499
New dug well	---- 500-699
Existing borehole	---- 700-799
Existing dug well	---- 800-999

Most borehole data, e.g., well depth, date of completion and static water level in Table 3.5.1 were taken from existing reports. In case of dug wells, all data were collected by actual measurements and by interviewing local residents.

The map shows that most wells are located along the main national roads like Routes 7 and 9. Boreholes are found throughout the coastal plain and were mostly drilled along Route 9, while dug wells are distributed throughout the Study Area.

Results of the well inventory can be outlined as follows.

Most boreholes were completed between 1965 and 1970, and only 10 out of 56 boreholes are still working. Twenty one (21) of the 46 remaining boreholes were completely damaged and mostly filled-in with sand. Most of the 25 wells (of the 46 boreholes) with damaged handpumps were either abandoned or filled-in. (Wells were sometimes abandoned mainly because of the 'salty' taste of water.) According to the village people, these wells lasted only for about 10 years, basically because of mechanical and generator failures.

As shown in Table 3.5.1, most boreholes are 15 to 30m deep