Hydrogeology of SOUTH AFAR AND ADJACENT AREAS, ETHIOPIA supported by interpretation of LANDSAT Imagery

by

Mezmure Haile Meskale

This thesis is submitted in partial fulfillment of the requirements of the Degree of Master of Science in Hydrogeology

Board of Examiners:

- *Prof.Dr. J.C. van Dam (Chairman), Technical University, Delft*
- *Prof.Dr.C. Voûte, ITC, Enschede*
- *Prof.Dr.Ir.S. Dijkstra, ITC, Delft*
- *Drs.D. Kovâcs (Supervisor), ITC, Enschede*
- *Drs. G.J. Krol (Director of Studies), ITC, Enschede*
- *Dr. A.M.J. Meijerink, ITC, Enschede*

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This thesis has its roots in the Hydrogeology Department of the Ethiopian Institute of the Geological Surveys (EIGS), from which a large part of the information has been obtained. From 1974 to 1987, my activities in the field and in the office - which play a major role in this thesis - were wholeheartedly shared by Shiferaw Kebede, Terefe Gizaw, Mullu Tesfa Belay and other enthusiastic colleagues at the EIGS.

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ABSTRACT

This study is intended to improve the fund of knowledge on the hydrogeology of South Afar and adjacent areas, by applying Landsat Remote Sensing techniques and extensive use of the computer.

Hydrogeological information obtained by the interpretation of various interrelated fields on the Landsat imagery were correlated and integrated with existing hydrogeological data; a hydrogeological map and report of South Afar and adjacent areas are presented.

The study is focussed on hydrogeological investigation of an almost closed basin. Apart from a surface water inflow into this basin by an inlet from the southern part, the only input into this basin is precipitation. Evapotranspiration is the only output considered. Groundwater inflow into the basin is assumed to be equal to groundwater outflow from the basin.

The study concentrates on various aspects of input and output relations and analyses different aspects, such as climate, hydrology, geology, geomorphology and vegetation.

Permeability parameters are treated, based on geological understanding of the area and statistical analysis of the lineaments.

Hydrological parameters have been quantified; different hydrographs are analysed and their relation to catchment characteristics compared.

Hydrometeorological factors are processed and analysed; the relation between hydrometeorological factors with geomorpholgy and vegetation is compared.

The water balance of eleven catchments, sub-basins and basins is calculated on a monthly and yearly basis.

Hydro-chemical data of 139 water samples have statistically been analysed.

Groundwater potentiality of the area is simplified and presented in a water resources map.

1 INTRODUCTION

1.1 Purpose and scope

The present study tries to decipher possible hydrogeological information from the interpretation of Landsat imagery. The main purpose of using Landsat imagery is to complete the gap where data is lacking or previous knowledge is insufficient. This study includes extraction of information from relevant sources, leading to a final hydrogeological map and subsequent report on the hydrogeology of South Afar and adjacent areas.

This study can be considered as a preliminary investigation which can be used as a stepping stone for future detailed work. It is hoped that future work on this area would benefit from the information so far obtained. Reasonable correlations are anticipated, when quantitative data, such as geophysical and borewell data, are added to this study.

1.2 Location, accessibility

The study area, which is about 175000 square kilometers, covers Southern Afar and adjacent escarpments and some parts of the Ethiopian and Ethio-Somalian Plateau.

It lies roughly between 8°00' and 12°00' N., and 38°00' and 44°00' E. (see location map, Fig. 1.)

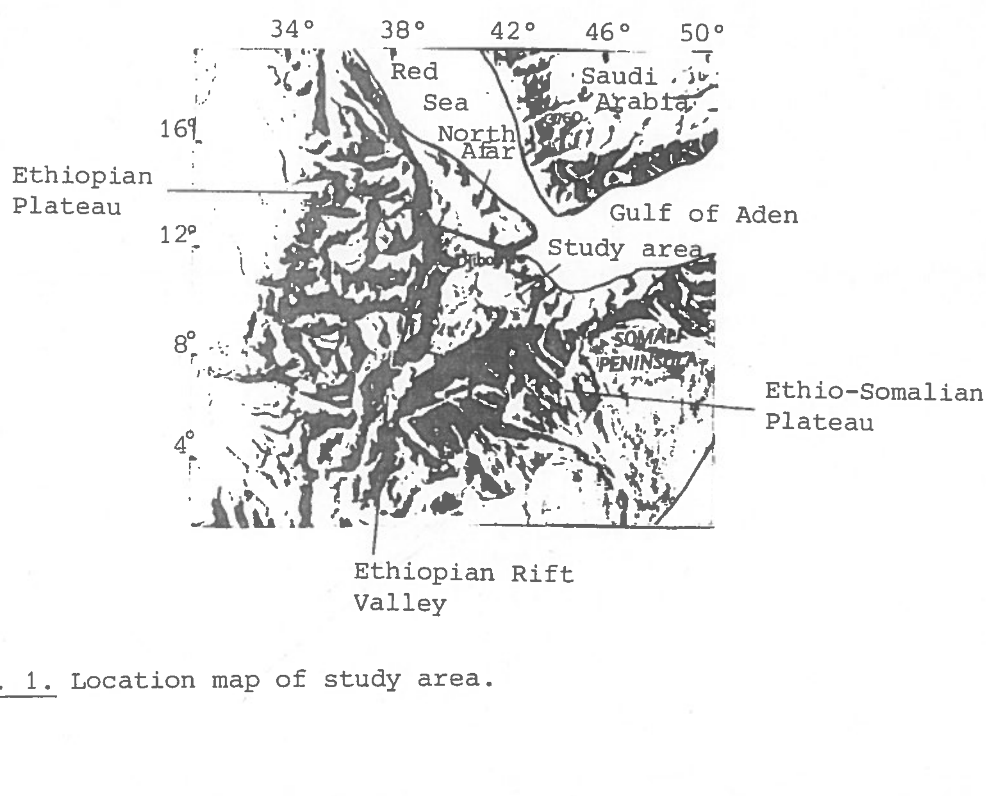


Fig. 1. Location map of study area.

It is accessible by a metalled road that runs from Addis Ababa through Nazret to Assab and Diredawa, another metalled road that runs from Addis Ababa to Asmara as well as by other, mostly dry-weather, roads.

1.3 Previous work

The geology of North and Central Afar has been studied by C.N.R.S. (Centre National de la Recherche Scientific)(France) and C.N.R. (Consiglio Nazional Delle Ricerche) (Italy). Several reports and articles have been published by a number of individual scientists of the groups mentioned above.

The geology of the northern part of the Ethiopian Rift and Diredawa area has been published by the Ethiopian Institute of the Geological Surveys (EIGS).

UN experts and Ethiopian staff of the Geothermal Division of the EIGS have studied groundwater potentiality of the area for geothermal purposes.

Some hydrogeological work on the Awash basin has been carried out by the Awash Valley Authority (Ethiopia).

The hydrogeology of Southwestern Afar and adjacent areas has been studied by the writer and his colleagues of the EIGS.

1.4 Present work and methodology

In the present study a geological map of 1:1 000 000 scale is prepared from Landsat imagery with the help of existing geological maps. Lineaments were digitized from which the permeability parameter is partly derived.

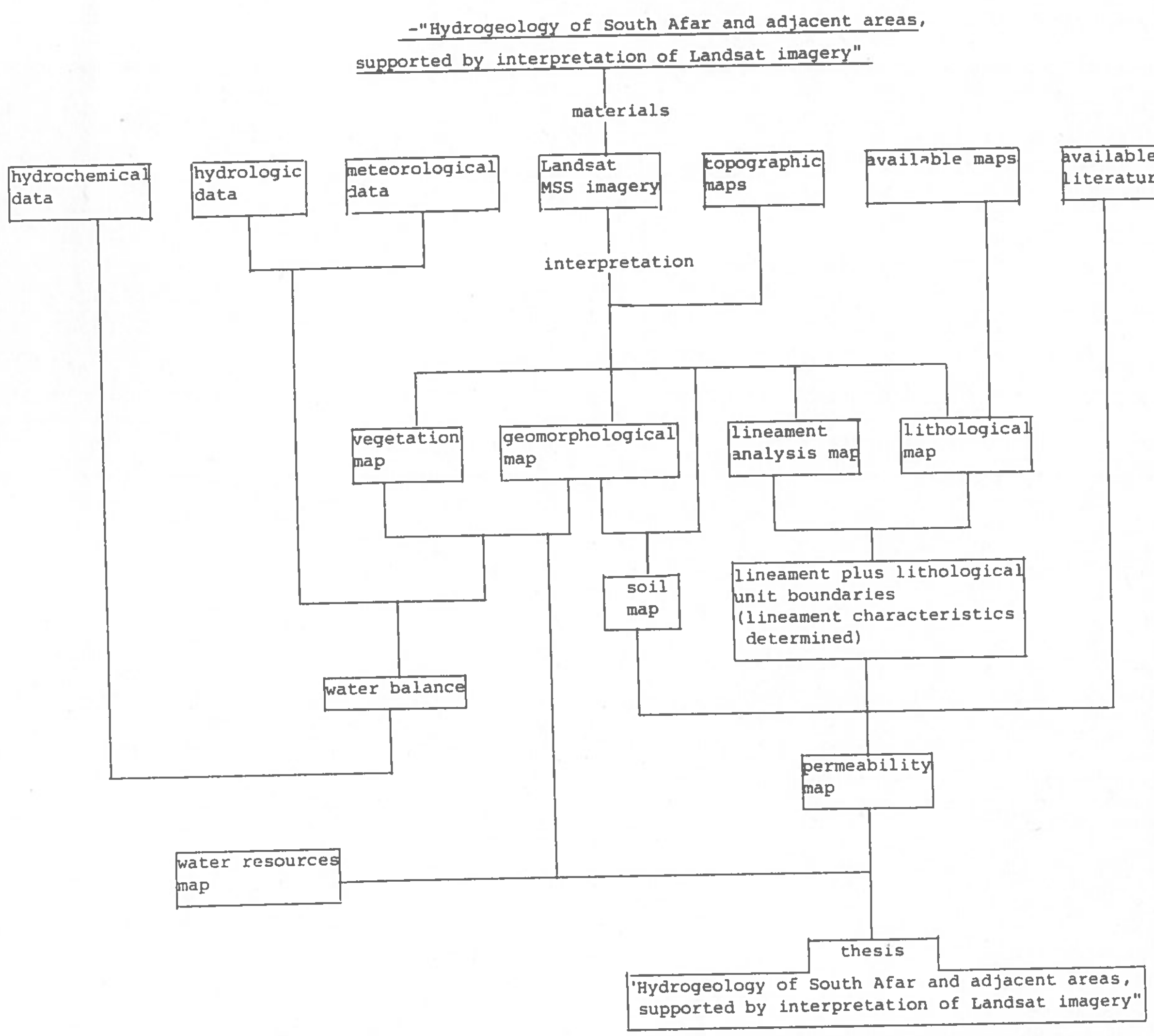
A hydrogeological map is prepared at 1:1 000 000 scale.

A geomorphological map, soil map and vegetation map are also prepared from Landsat.

A water resource map is made by superposing all the information obtained from Landsat and integrating the result with data previously obtained from the field.

Available hydrogeological data are processed, and statistically analysed, with the help of the computer.

The methodology and procedure followed in completing the study is presented in a simplified form in the following flow-chart.


-"Hydrogeology of South Afar and adjacent areas,
supported by interpretation of Landsat imagery"
materials
hydrochemical data
hydrologic data
meteorological data
Landsat MSS imagery
topographic maps
available maps
available literature
interpretation
vegetation map
geomorphological map
lineament analysis map
lithological map
soil map
lineament plus lithological unit boundaries (lineament characteristics determined)
water balance
permeability map
water resources map
thesis
'Hydrogeology of South Afar and adjacent areas, supported by interpretation of Landsat imagery"

2. GENERAL BACKGROUND

The Ethiopian Highlands are characterized by high runoff and high sediment-load transport, whereby Ethiopia looses a lot of water and sediment to adjacent countries. On the other hand, the Ethiopian Rift valley and the Afar region gain surface waters and sediments, which are discharged from adjacent highland areas.

The area north of Lake Abbe is called North Afar (Danakil Depression). The area between Awash railway station and Lake Abbe, where one of the greatest rivers in Ethiopia (Awash river) terminates, is hereby referred to as South Afar.

The study area includes closed basins within the major basin; the 'Middle Awash' and 'Lower Awash' are parts of the major basin.

A number of perennial, seasonal and intermittent streams flow from either sides of the Escarpment Highlands bordering the Afar. They disappear into the alluvial sediments of the Depression, or join the Awash river.

Although most parts of the Depression suffer from dry weather and high evaporation rates, a number of lakes and marshy areas still exist. A number of hot springs, fumaroles and geysers are associated with volcanic activity and tectonism.

The geology of the Afar floor consists mostly of Upper Miocene to recent volcanic rocks, which are mostly basic. The Depression areas are covered by alluvial sediments. The Escarpment areas consist of 'Plateau Basalts'; the Eastern Plateau consists of Precambrian metamorphic rocks with Mesozoic sedimentary cover.

Despite the fact that groundwater recharge takes place in some favourable areas, like the alluvial fans and foot-hill areas, the present supply of water is far too little to satisfy the requirements of the population.

Water shortage is more accute in the lowland regions than in the highland parts.

The southern Afar region is inhabited by the Afar tribe in the west and the Issa tribe in the east.

Due to scarcity of water, the nomadic population in the lowlands consume unclean water from the rivers, or water of low quality from hand-dug wells located by tribal memory. During severe drought periods, the groundwater levels are lowered beyond the reach of the nomads. Because of the claiming of water points, like hot springs, tribal conflicts have always resulted in the past.

3 SATELLITE REMOTE SENSING TECHNIQUE

Some of the vantage points of satellite remote sensing are as follows:-

- -large area coverage
- -high geometric accuracy
- -easy synoptic view
- -uniformity in greytone and colour across a frame
- -possibility of acquiring images under the same temporal and spatial position.

Taking advantage of the above, attempts are made to adapt technological innovations to increase the level of understanding of the hydrogeology of the study area.

The purpose of using this technique in the present study is to acquire more information concerning the hydrogeology of the area, which, otherwise,would need more field checking in order to complete the work.

It will be clear from ongoing discussions that information gathered from Landsat is used to interpolate and extend the survey to areas not yet visited.

The acquisition of information from remote sensing for the purpose of the present study is geared towards evaluation of distinct hydrogeological characteristics as regards various interrelated features, such as lithology, structure-including lineament-analysis, soil, vegetation, geomorphology and soil moisture. The information obtained is integrated and combined with such information as had been already acquired from the field. It should be emphasized that the information gathered from remote sensing can only be considered as one of the several data sources which supplement, but not replace, other methods of data acquisition.

The materials used for this purpose are:1 : 1 000 000 scale, black and white imagery with bands 4,5,7,as well as false colour composites of the same bands. All of the imagery except one is cloud-free and represents dry periods of January - June 1973, 1976, NASA ERTS, and 1979 NASA LANDSAT.

Reduced colour prints prepared from the false colour composites are incorporated within the thesis.

3.1 Multi spectral sensing

Information from electromagnetic radiations can be obtained from passive-type sensors, carried by spacecraft.
The multi spectral scanner (MSS) is one of the primary sensor systems which record the solar radiation reflected from the earth's surface. It consists of a 4-band scanner. The energy reflected from the earth's surface is received by a scanning mirror and reflected through the optical system, where it is spectrally dispersed. The energy in specific wavelength bands is measured by detectors behind this optical system. The signals from the detectors are amplified and are then simultaneously recorded on magnetic tape or transmitted directly to the ground. The products from the MSS system can be stored digitally on computer-compatible tapes (cct), or can be reproduced in the form of images.

3.1a Electromagnetic spectrum

Every object emits, absorbs, diffuses, transmits and reflects natural electromagnetic energy. The electromagnetic spectrum is a continuum of rays, ranging from short rays, like cosmic rays and gamma rays, to long waves, like radar waves and radio waves. Although the electromagnetic energy is broken down into various spectral regions, no distinct boundary actually exists between these regions.
The multi spectral scanners operate in the optical wavelength region. The major portion of their reflective wavelengths are:-

- ultra violet (290 - 400 nm)
- visible region (400 - 700 nm)
- infrared region (700 - 3000 nm)

Transfer of radiation takes place through about 872 kms of vaccuum, where no absorption or any other disturbance takes place, and through about 40 kms. of the earth's atmosphere, where considerable disturbance arises due to its turbid medium, composed of a heterogeneous mixture of gases and particles, where absorption, scattering, emission and refraction takes place. Certain spectral regions, however, are insignificantly affected by interference. These portions of electromagnetic spectrum, where little or no absorption takes place, are called transmission windows or atmospheric windows.

The main atmospheric windows occur at:-

- 400 - 1000 nm (visible and near infrared)
-3500 - 5500 nm (middle infrared)
-8000 -14000 nm (far infrared)

Highest transmission of energy through the atmosphere is provided by these windows.

3.1b Reflectance characteristics of objects

Reflectance of different objects can be found as a function of wavelength, which can be measured by spectro-radiometer. The values obtained, however, can only be used so as to compare and contrast different objects from the point of view of their reflectance characteristics.
The properties of objects are affected by their varying spatial and physical conditions.
The earth's surface can be grouped into:-

- rock and soil
- vegetation
- water surfaces
- man-made features

An understanding of basic properties of electromagnetic spectrum with spectral characteristics of different objects is essential for correct interpretation of data obtained from remote sensing.
Figure 2. below, shows spectral characteristics of common objects.

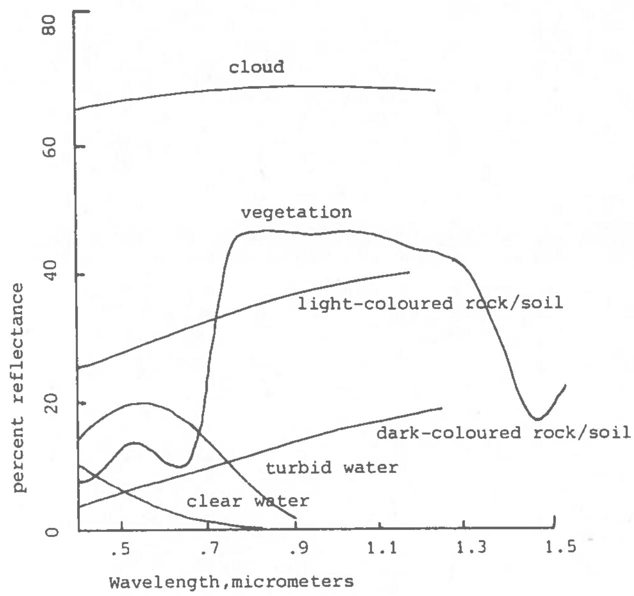


Fig. 2. Spectral characteristics of common objects

3.1c Interpretation of features from Landsat imagery

The interpretation of images depends upon the scale, brightness (or tone), texture, contrast ratio and spatial resolution.

From black and white images, variations in greytone for the same object are compared from one band to the other and the observed signature compared with spectral reflectance curves of known objects. (see fig. 2.)

In this way it has been possible to distinguish the major cover types. For example, due to inverse relation of reflectance peaks of vegetation and water, vegetation appears relatively lighter in band 7 than in band 5, whereas water appears relatively lighter in band 5 than in band 7.

Some lithological units, like the recent basalts, can readily be recognized by their dark grey tone, whereas distinction within the basic and acidic varieties is almost impossible without the use of other maps.

It should be noted that objects that are easily detectable may not be easily recognizable. The composite effect of bed rock and associated soil and vegetation cover may sometimes lead to 'telegeologic' units.

Colour print (Plate 1.) shows the combined effect of rock/soil, vegetation and moisture content.

Plate 1.
Colour print shows limestone areas which are at places covered by wet soil and vegetation;
Eastern escarpment and plateau.

4. GEOMORPHOLOGY

The geomorphology of the area is also mapped from landsat imagery (see Fig. 3) with a view to establishing the factors affecting hydrogeological parameters, such as runoff and infiltration.
The area attains topographically contrasted regions which influence climate and vegetation, resulting in various physico-chemical processes operating at different rates. The geomorphology of the area is governed by land forms as a function of the structure process and stage (see Plate 2).

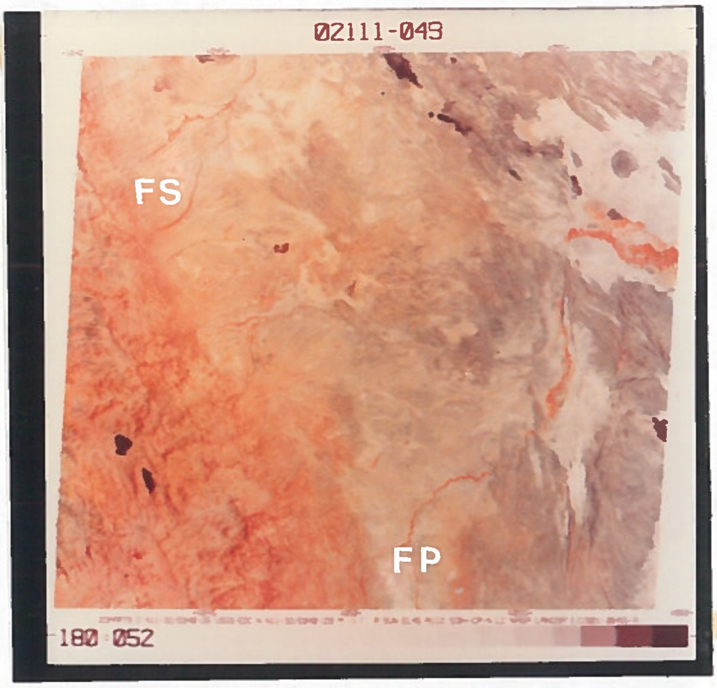


Plate 2. Colour print shows an example of some of the geomorphological units, Western Escarpment, east of Lake Hayk.

The major land units of structural/denudational origin and their significance from the point of view of hydrogeology are summarized as in the following:

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GEOMORPHOLOGICAL MAP OF SOUTH AFAR & ADJACENT AREAS

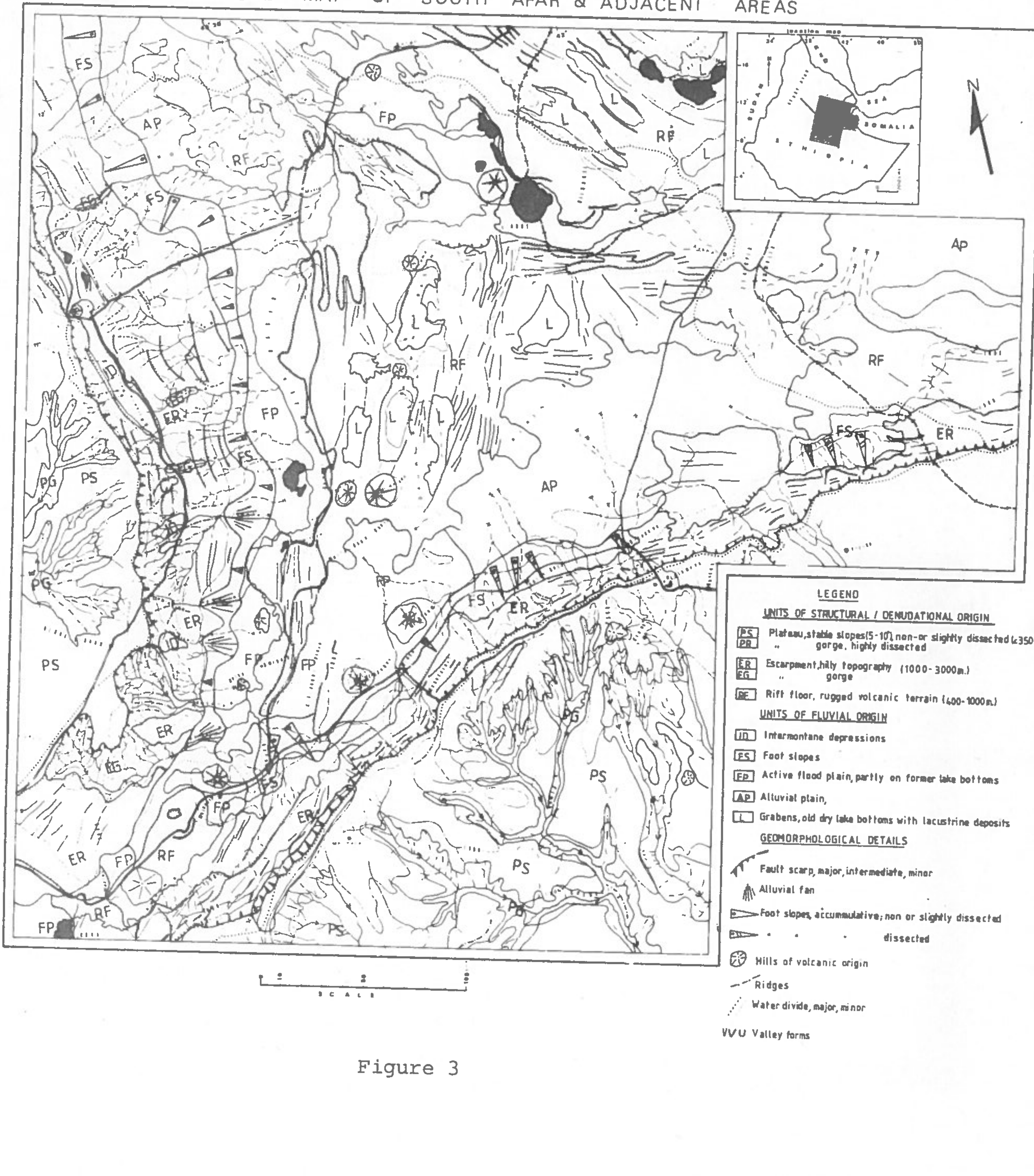

Figure 3

Units of structural/ denudational origin	process	hydrogeological significance
-1) Plateau, relatively stable, non or slightly dissected	high rainfall intense weathering	high infiltration
-2) Plateau gorges, highly dissected	high erosion rates	high runoff
-3) Escarpment, hilly and rugged topography	moderate erosion rates, moderate weathering	moderate runoff, moderate infiltration
-4) Escarpment gorges, highly dissected	high erosion	high runoff
-5) Rift floor, rugged volcanic terrain, highly faulted	slight weathering	high infiltration

Units of fluvial origin	process	hydrogeological significance
-1) Intermontane depressions	active fluvial processes	high infiltration
-2) Foot slopes	active fluvial and gravitational processes	high infiltration
-3) Active flood plains on former lake bottoms	active fluvial processes on former lake environment	moderate infiltration
-4) Alluvial plains	active wind deposition and slight sheet wash deposition	moderate infiltration
-5) Grabens, old dry lake bottoms	active wind deposition on former lacustrine deposits	moderate infiltration

5 VEGETATION

A vegetation map is prepared from false colour composites (4,5,7 bands). The main purpose in preparing this map is to delineate areas with different density and type of vegetation cover, which may indirectly indicate availability of water. (See fig. 4.)
As the type, density and height of vegetation affects the rate of transpiration, the vegetation map furnished herewith is used in order to delineate areas where the rate of evapotranspiration is most affected by vegetation.
Areas with high vegetation cover appear lighter on band 7 as compared to bands 4 and 5. This situation can be seen in colours from the false colour composites, whereby intense red colour indicates thickly vegetated areas; light red indicates sparse vegetation and a yellowish colour may be due to grass cover (see Plate 3.)

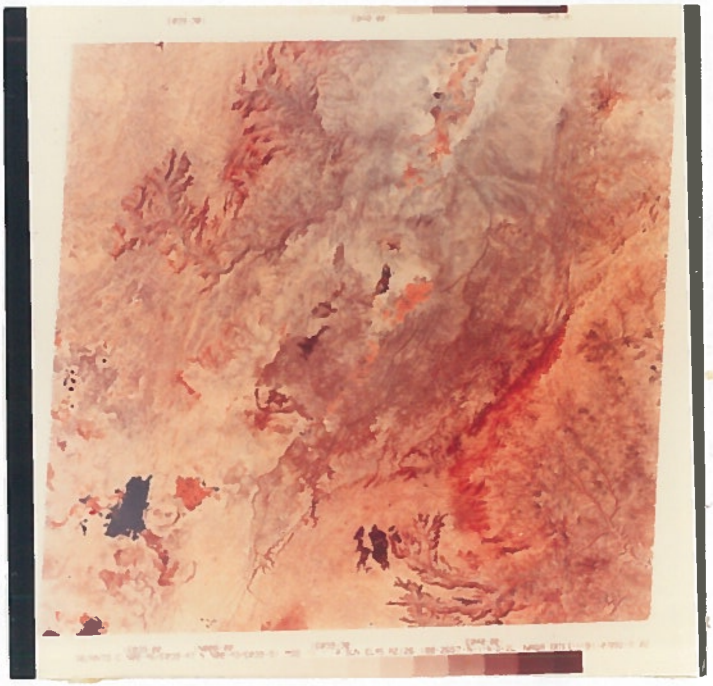

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Plate 3. Colour print shows vegetation in red; clear water in dark blue, and turbid water in light blue; Ethiopian Rift, Middle Awash.

The contrasting morpholigical set up of the area has produced contrasting climatic and edaphic conditions, affecting the principal habit forms of the natural vegetation, which are dependent on altitude

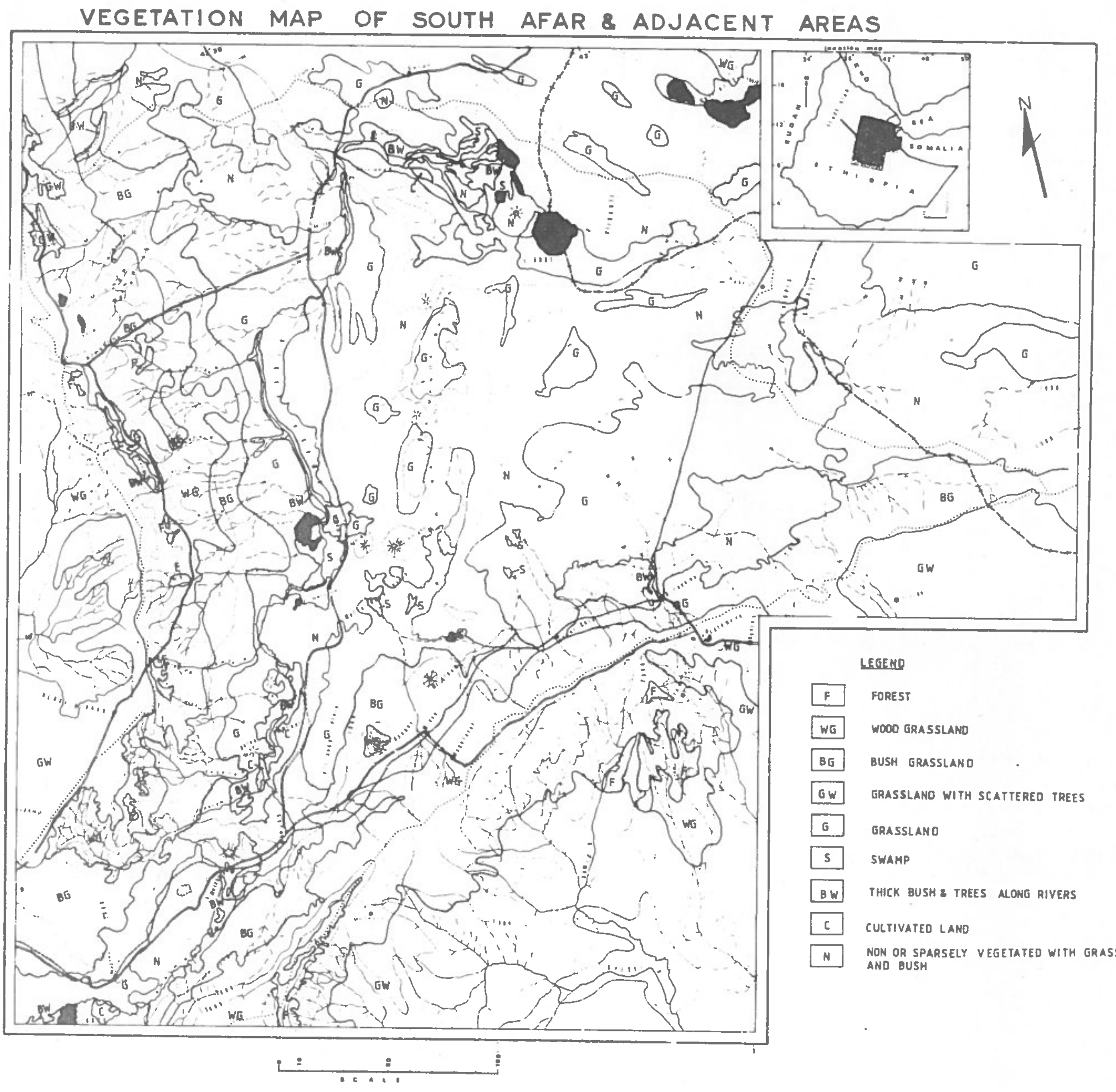

VEGETATION MAP OF SOUTH AFAR & ADJACENT AREAS
SUDAN
SEA
SOMALIA
ETHIOPIA
N
LEGEND
F FOREST
WG WOOD GRASSLAND
BG BUSH GRASSLAND
GW GRASSLAND WITH SCATTERED TREES
G GRASSLAND
S SWAMP
BW THICK BUSH & TREES ALONG RIVERS
C CULTIVATED LAND
N NON OR SPARSELY VEGETATED WITH GRASS AND BUSH
SCALE

Figure 4

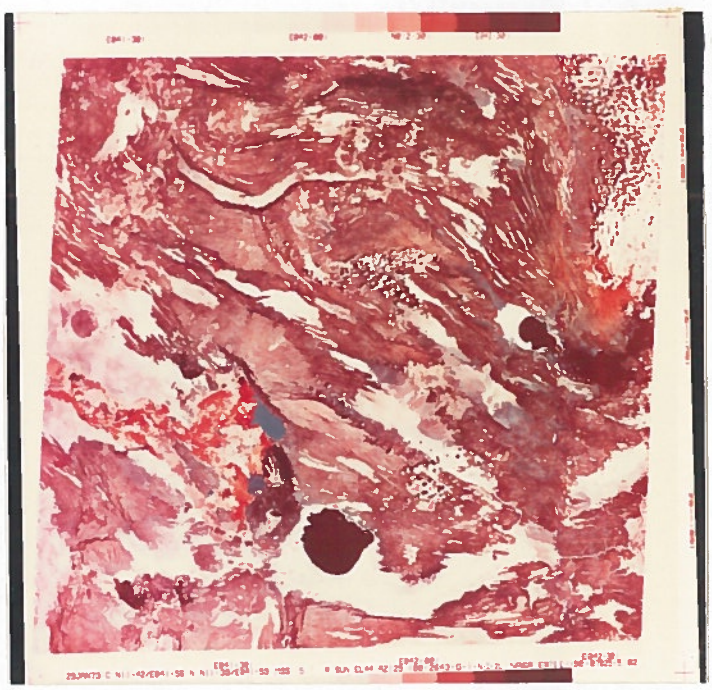
and temperature zones.
In general, the highland areas are occupied by forest, where the high density of vegetation is related to concentration of springs.
The lowland areas are characterized by semi-arid savannah, where the soil is usually deficient in moisture content.
The existence of marshes and lakes in the arid regions of the lowlands usually indicates groundwater recharge, which balances loss due to evapotranspiration; marshy areas along rivers and lakes are also common.

6 GEOLOGY

6.1 General geological background

The geology and structural set-up of the area reflects tectonic setting of the Egypt-Sudan-Ethiopia segment, the Horn of Africa segment, and the Arabian segment in terms of their positions in the pattern of plate movement.

In the Afar region, the three important tectonic structures (the Red Sea, the Gulf of Aden and East African rifts) converge. The main Ethiopian rift, which funnels out into the Afar, continues north-northeast towards lake Abbe, where it is dominated by northwest (Red Sea) and eastwest (Gulf of Aden) trends.(see Plate 4.)



1190-07025

Plate 4. Colour print shows lake Abbe area, where the three tectonic trends meet.

The main structural units and the corresponding main lithological units are given below:

1) The Western Escarpment and Plateau are dominated by Oligocene to Miocene basalts, locally with tuffs and rhyolites. Grabens, like Robit and Cheffa are well marked features of the Western Escarpment.

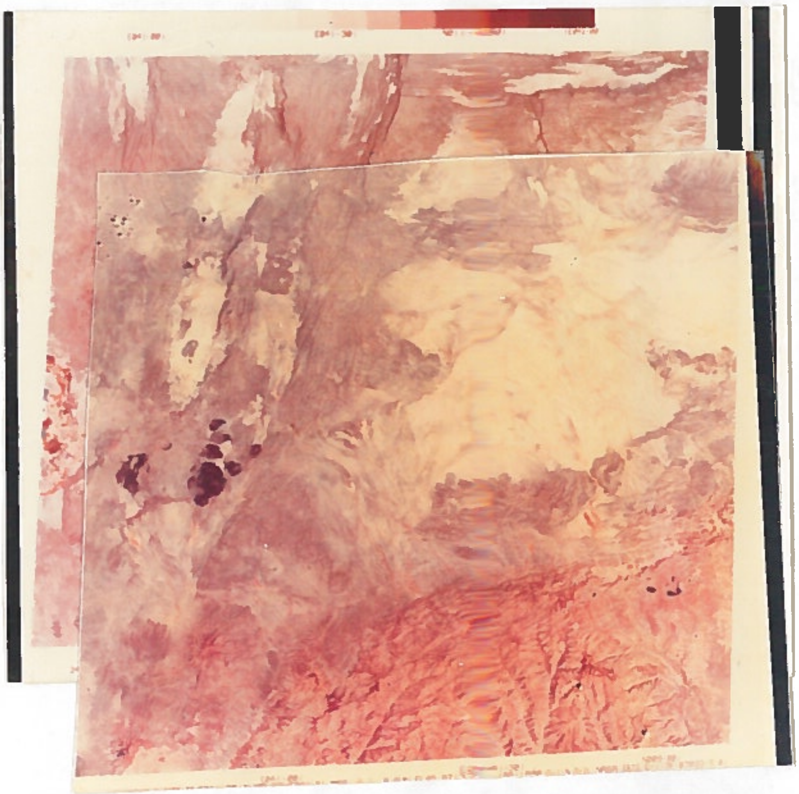
2) The Eastern Escarpment is composed of Oligocene to Miocene silicics and basalts, whereas the Plateau area consists of Mesozoic sedi-

ments that are unconformably overlain by the Precambrian metamorphic rocks.

3) The Aysha Horst, southeast of lake Abbe, consists of Precambrian metamorphic rocks, granite and granodiorite intrusions, that are unconformably overlain by Mesozoic sediments.

4) Depressions boardering the escarptments are filled by Plio-Pleistocene alluvium and lacustrine sediments, Upper Pleistocene flood sheet conglomerates and Holocene lacustrine, alluvial and outwash plain sediments.

5) The central, relatively uplifted part consists of rocks, mainly of the Upper Tertiary basalts with occasional Pleistocene-Holocene eruptions. (see Plate 5)



1136-04833

Plate 5. Colour print shows Dahwi and Manda Grabens within the central and relativelh uplifted parts.

The central volcanoes like Ayelu,Abida are aligned in the northeast-southwest direction, along the axial zone of the main Ethiopian Rift. These young volcanoes continue to the south into the main Ethiopian

Rift, where they still occupy the position of the axial zone.

6) The axial Grabens (10-15 kms wide), like Dahwi and Manda, lie within the central relatively uplifted part. They are boardered by steep normal faults and are filled by an unknown thickness of lacustrine and eolian sediments. These Grabens express the extension of the Ethiopian Rift trend into the Southern Afar.

7) Grabens trending northwest-southeast start from lake Abbe area, where Tendaho Graben forms one of the seven Grabens that exist towards the Red Sea (along Dessie-Assb road). (see Plate 4.)

6.2 Lineaments

Lineaments, especially within the Afar region, may represent tectonic trends. The lineaments were traced from band 7, black and white Landsat imagery (see fig. 5). The lineaments were then grouped according to their 'structural' significance.

The lineaments from each group were digitized and represented in directional classes of 2 and 5 degree intervals. Frequency- and length-histograms were also prepared in order to have a better view of the situation (see fig.6 to fig.11).

The direction of the peak concentrations of the lineaments of the groups considered is given below:-

1) The Aysha Horst - 85 to 90 and 280 to 285 degrees
2) Eastern Escarpment, Afar border - 275 to 280 and 80 to 85 degrees
3) Eastern Escarpment, Ethiopian Rift border - 45 to 55 degrees
4) The "Main Ethiopian Rift" - 15 to 40 degrees
5) Ethiopian Rift, south of Lake Abbe - 10 to 35 degrees
6) The Gulf of Aden Rift - 275 to 285 and 85 to 90 degrees
7) The Red Sea Rift - 305 to 330 degrees
8) Central and South Afar - 275 to 285, 310 to 330, 10 to 35 and 85 to 90 degrees
9) Western Escarpment, Ethiopian Rift border - 25 to 45 degrees
10) Western Escarpment, Afar border - 330 to 355 degrees
11) All lineaments, excepting the Plateaux cluster into four main groups: 270 to 285, 305 to 335, 10 to 35 and 80 to 85 degrees

The lineaments traced in the Plateaux area are subtle lineaments which may not have any structural significance.

MAP SHOWING LINEAR FEATURES INTERPRETED FROM LANDSAT, SOUTH AFAR & ADJACENT AREAS

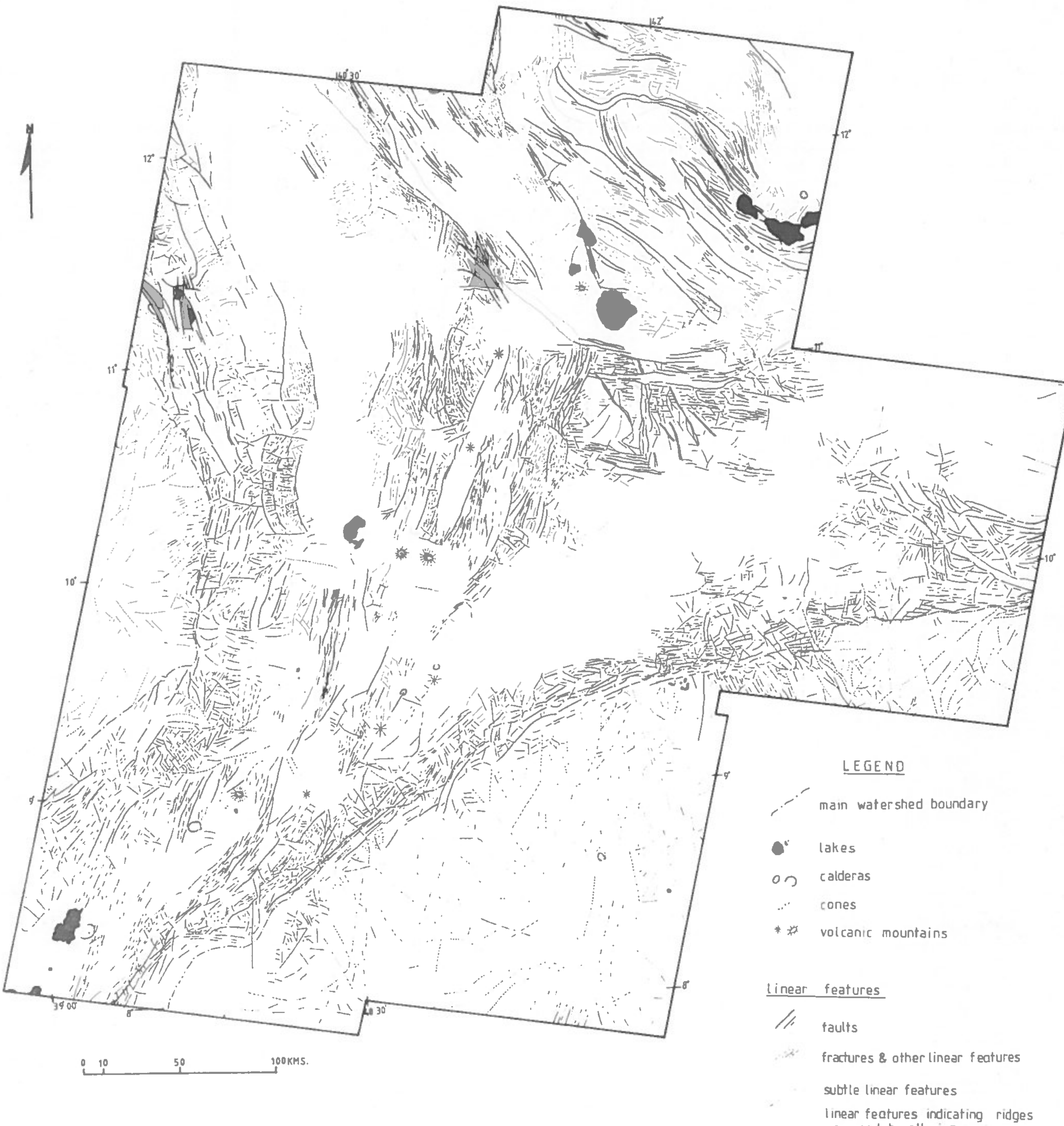


Figure 5

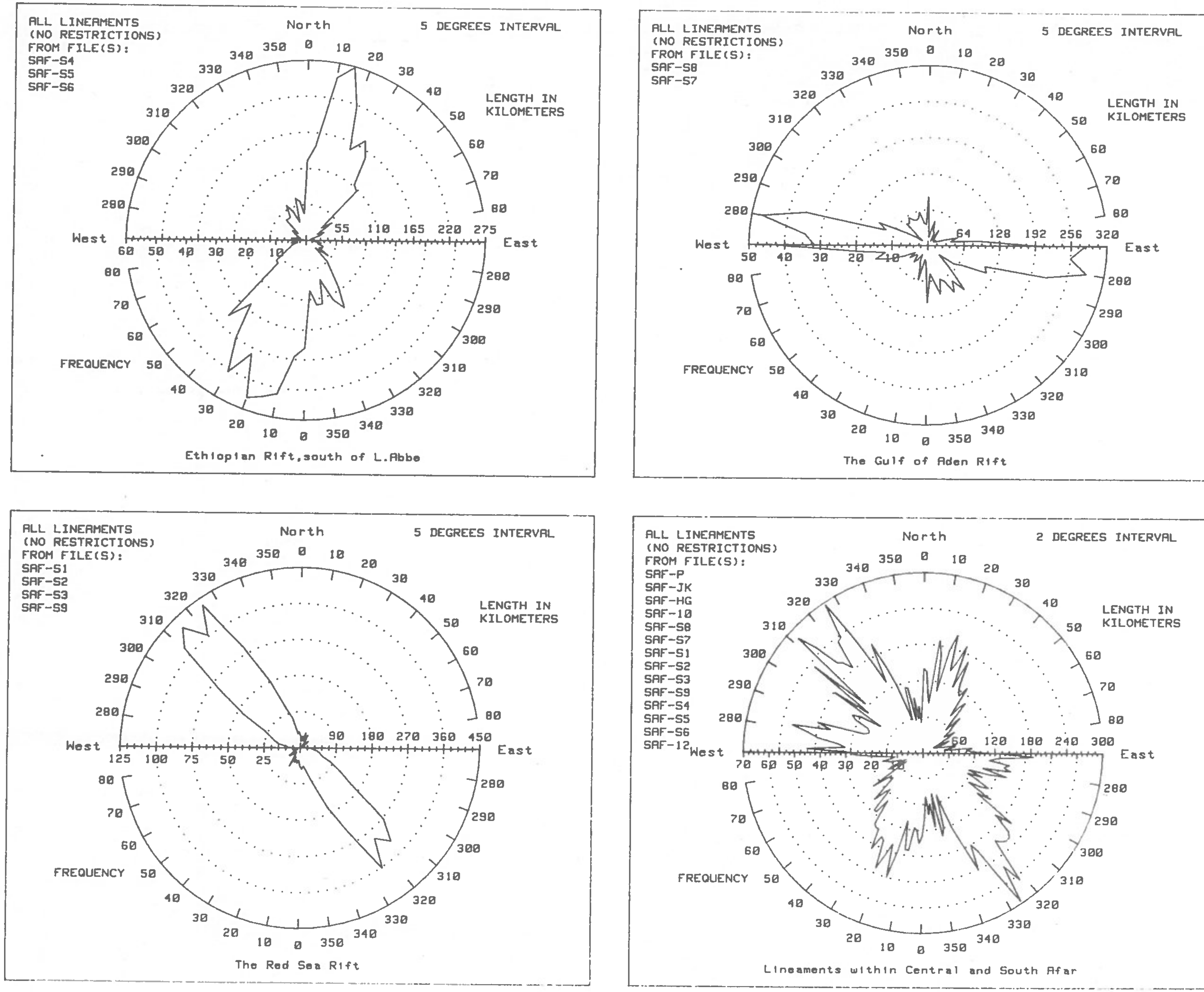

ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-S4
SAF-S5
SAF-S6
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
Ethiopian Rift, south of L.Abbe
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-S8
SAF-S7
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
The Gulf of Aden Rift
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-S1
SAF-S2
SAF-S3
SAF-S9
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
The Red Sea Rift
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-P
SAF-JK
SAF-HG
SAF-10
SAF-S8
SAF-S7
SAF-S1
SAF-S2
SAF-S3
SAF-S9
SAF-S4
SAF-S5
SAF-S6
SAF-12
North
2 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
Lineaments within Central and South Afar

Figure 6

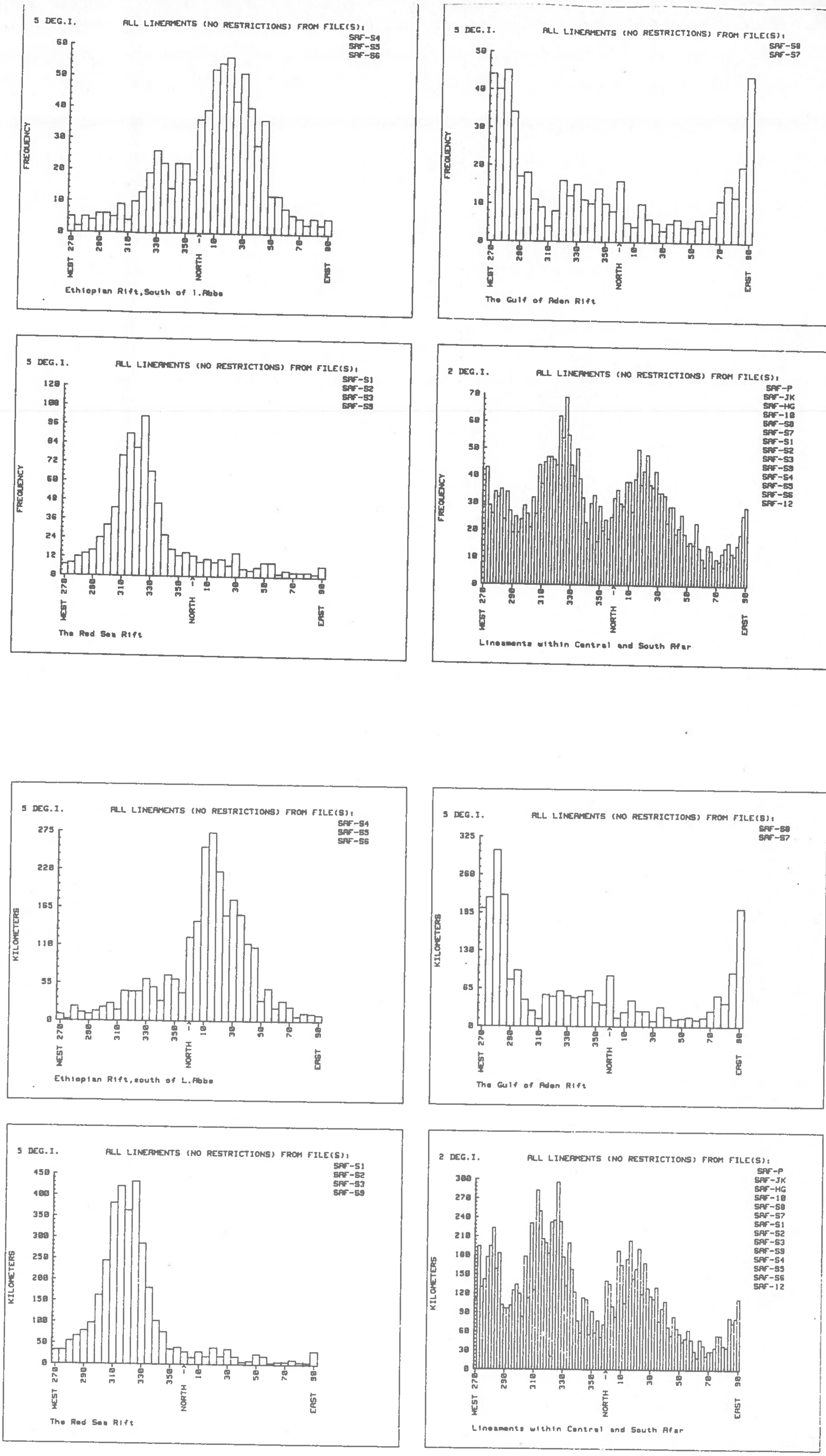

5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
SAF-S4
SAF-S5
SAF-S6
FREQUENCY
WEST 270
NORTH
EAST 90
Ethiopian Rift, South of l.Abbe
5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
SAF-S8
SAF-S7
FREQUENCY
The Gulf of Aden Rift
5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
SAF-S1
SAF-S2
SAF-S3
SAF-S9
FREQUENCY
The Red Sea Rift
2 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
SAF-P
SAF-JK
SAF-HG
SAF-10
SAF-S8
SAF-S7
SAF-S1
SAF-S2
SAF-S3
SAF-S9
SAF-S4
SAF-S5
SAF-S6
SAF-12
FREQUENCY
Lineaments within Central and South Afar
KILOMETERS
Ethiopian Rift, south of L.Abbe
The Gulf of Aden Rift
The Red Sea Rift
Lineaments within Central and South Afar

Figure 7

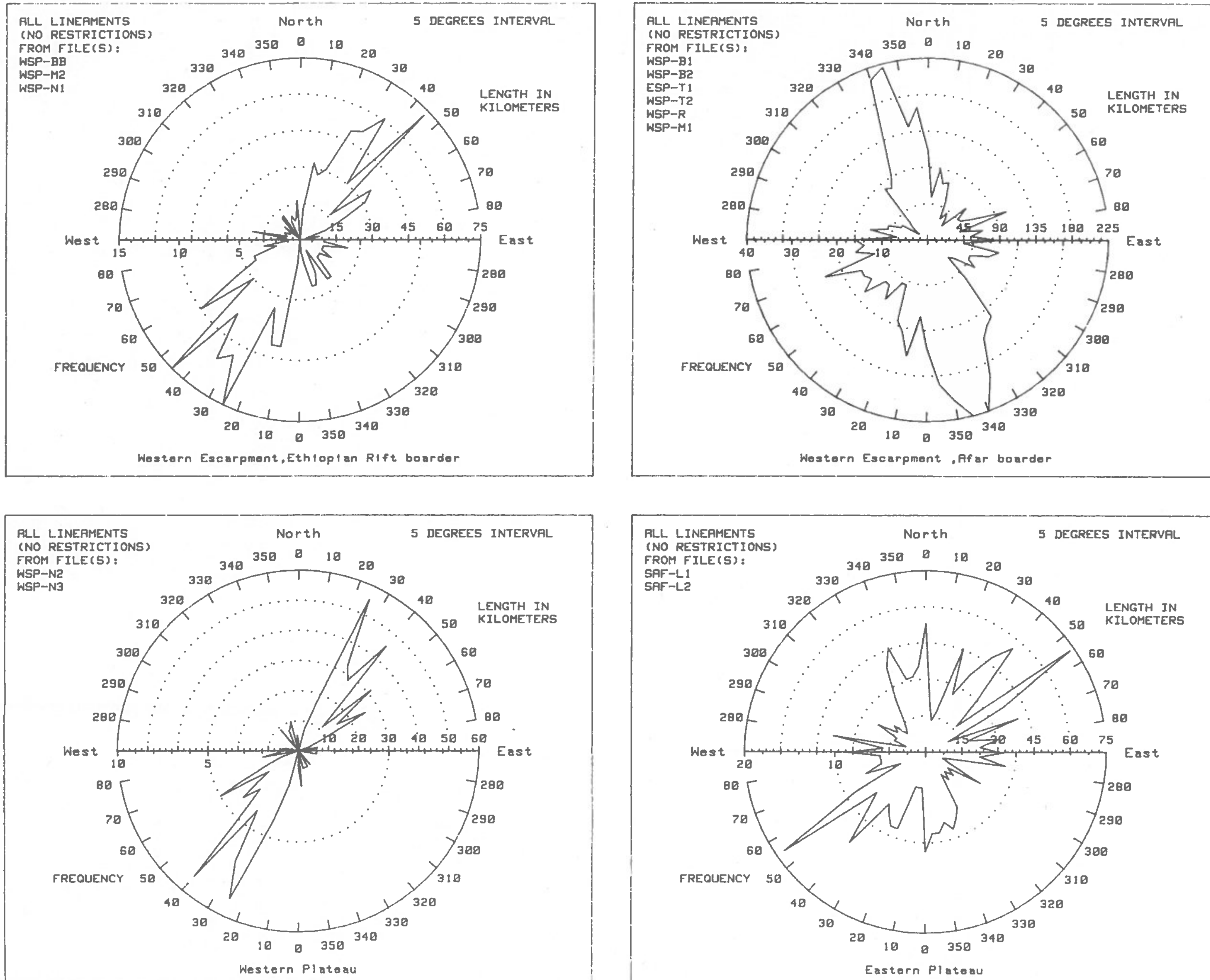

ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
WSP-B8
WSP-M2
WSP-N1
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
FREQUENCY
West
East
Western Escarpment,Ethiopian Rift boarder
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
WSP-B1
WSP-B2
ESP-T1
WSP-T2
WSP-R
WSP-M1
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
FREQUENCY
West
East
Western Escarpment ,Afar boarder
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
WSP-N2
WSP-N3
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
FREQUENCY
West
East
Western Plateau
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-L1
SAF-L2
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
FREQUENCY
West
East
Eastern Plateau

Figure 8

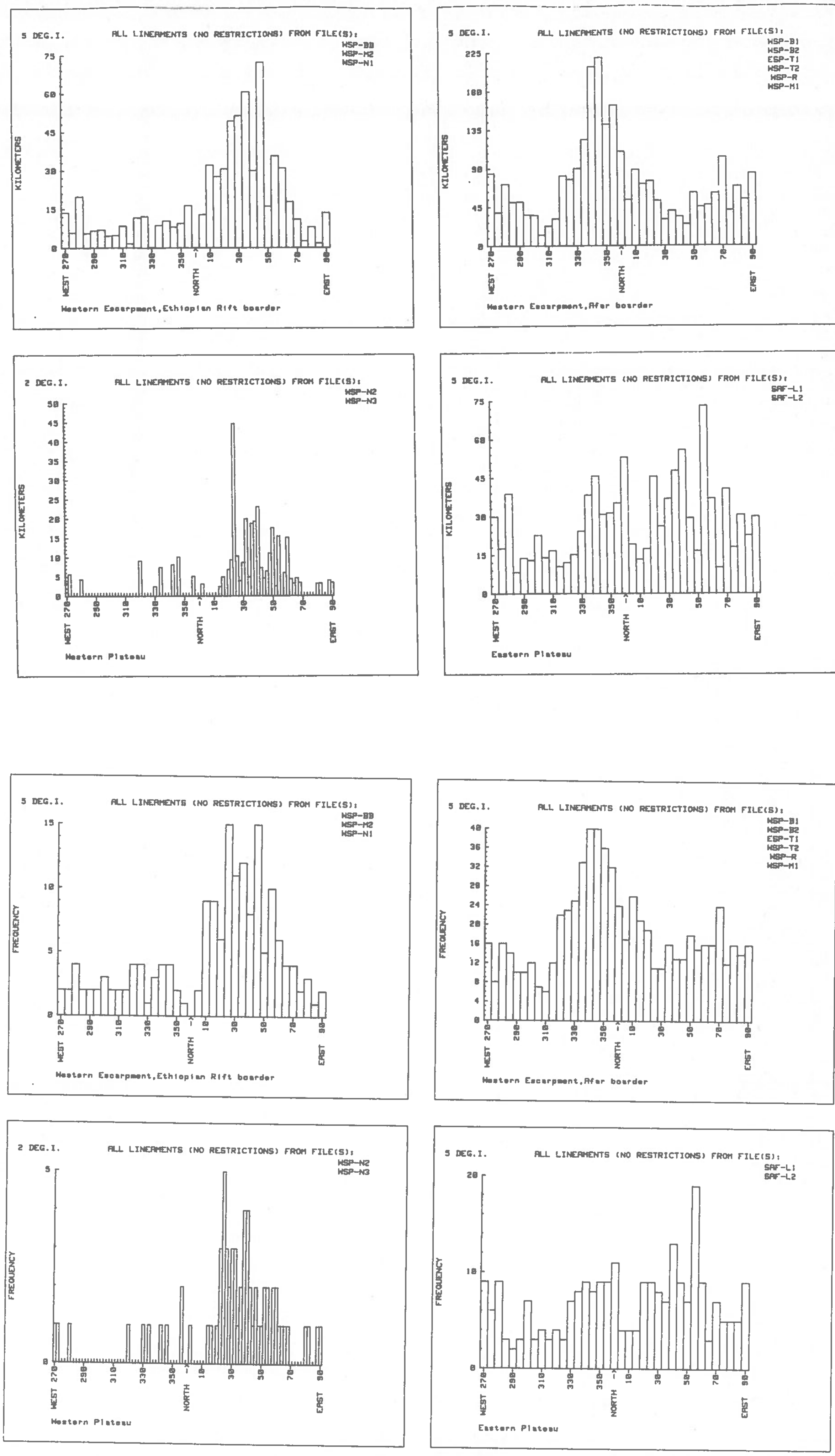

5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
WSP-B0
WSP-M2
WSP-N1
KILOMETERS
WEST 270
NORTH
EAST
Western Escarpment, Ethiopian Rift boarder
5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
WSP-B1
WSP-B2
ESP-T1
WSP-T2
WSP-R
WSP-M1
KILOMETERS
Western Escarpment, Afar boarder
2 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
WSP-N2
WSP-N3
KILOMETERS
Western Plateau
5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
SAF-L1
SAF-L2
KILOMETERS
Eastern Plateau
5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
WSP-B0
WSP-M2
WSP-N1
FREQUENCY
Western Escarpment, Ethiopian Rift boarder
5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
WSP-B1
WSP-B2
ESP-T1
WSP-T2
WSP-R
WSP-M1
FREQUENCY
Western Escarpment, Afar boarder
2 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
WSP-N2
WSP-N3
FREQUENCY
Western Plateau
5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
SAF-L1
SAF-L2
FREQUENCY
Eastern Plateau

Figure 9

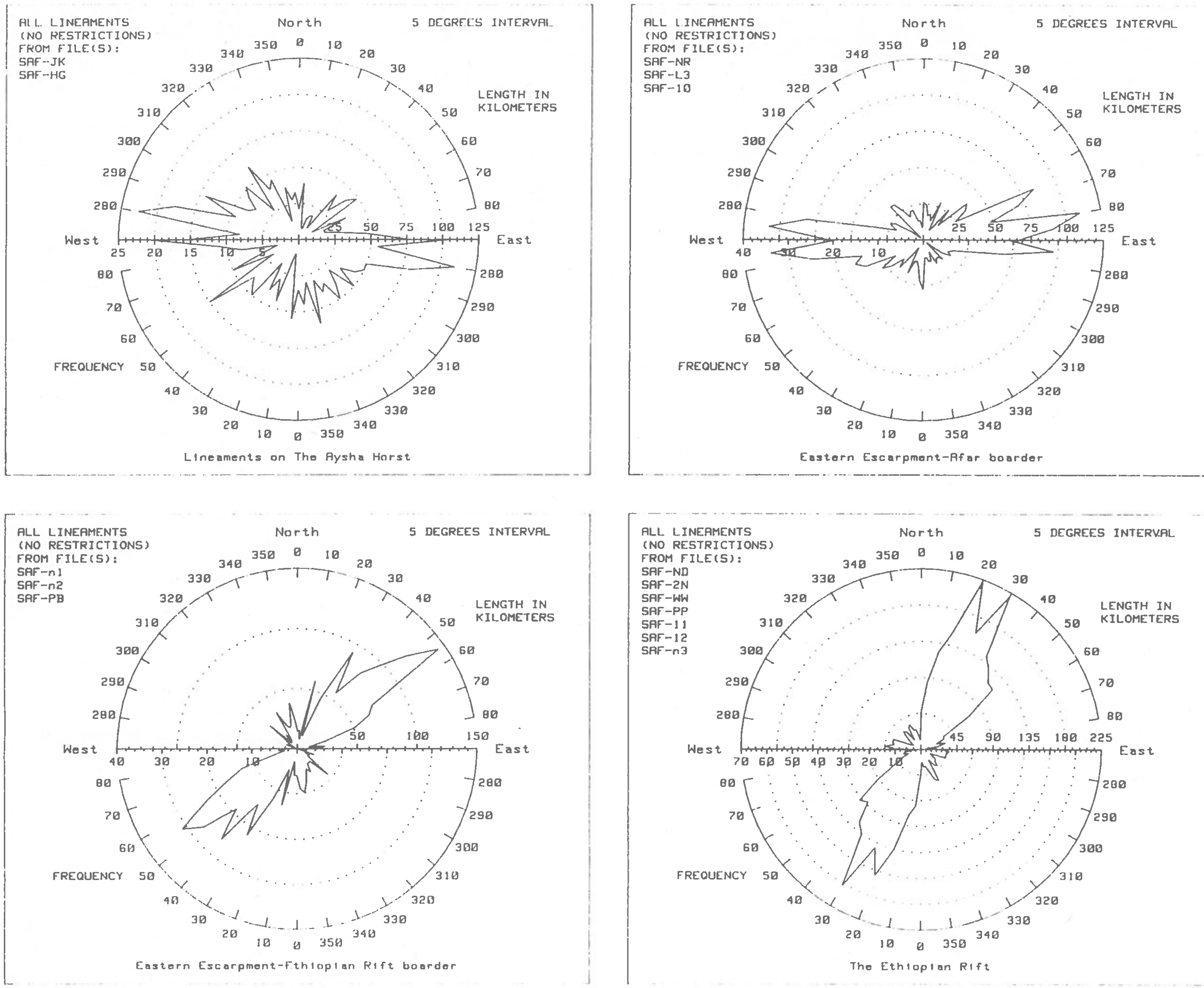

ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-JK
SAF-HG
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
Lineaments on The Aysha Horst
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-NR
SAF-L3
SAF-10
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
Eastern Escarpment-Afar boarder
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-n1
SAF-n2
SAF-PB
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
Eastern Escarpment-Ethiopian Rift boarder
ALL LINEAMENTS
(NO RESTRICTIONS)
FROM FILE(S):
SAF-ND
SAF-2N
SAF-WW
SAF-PP
SAF-11
SAF-12
SAF-n3
North
5 DEGREES INTERVAL
LENGTH IN KILOMETERS
West
East
FREQUENCY
The Ethiopian Rift

Figure 10.

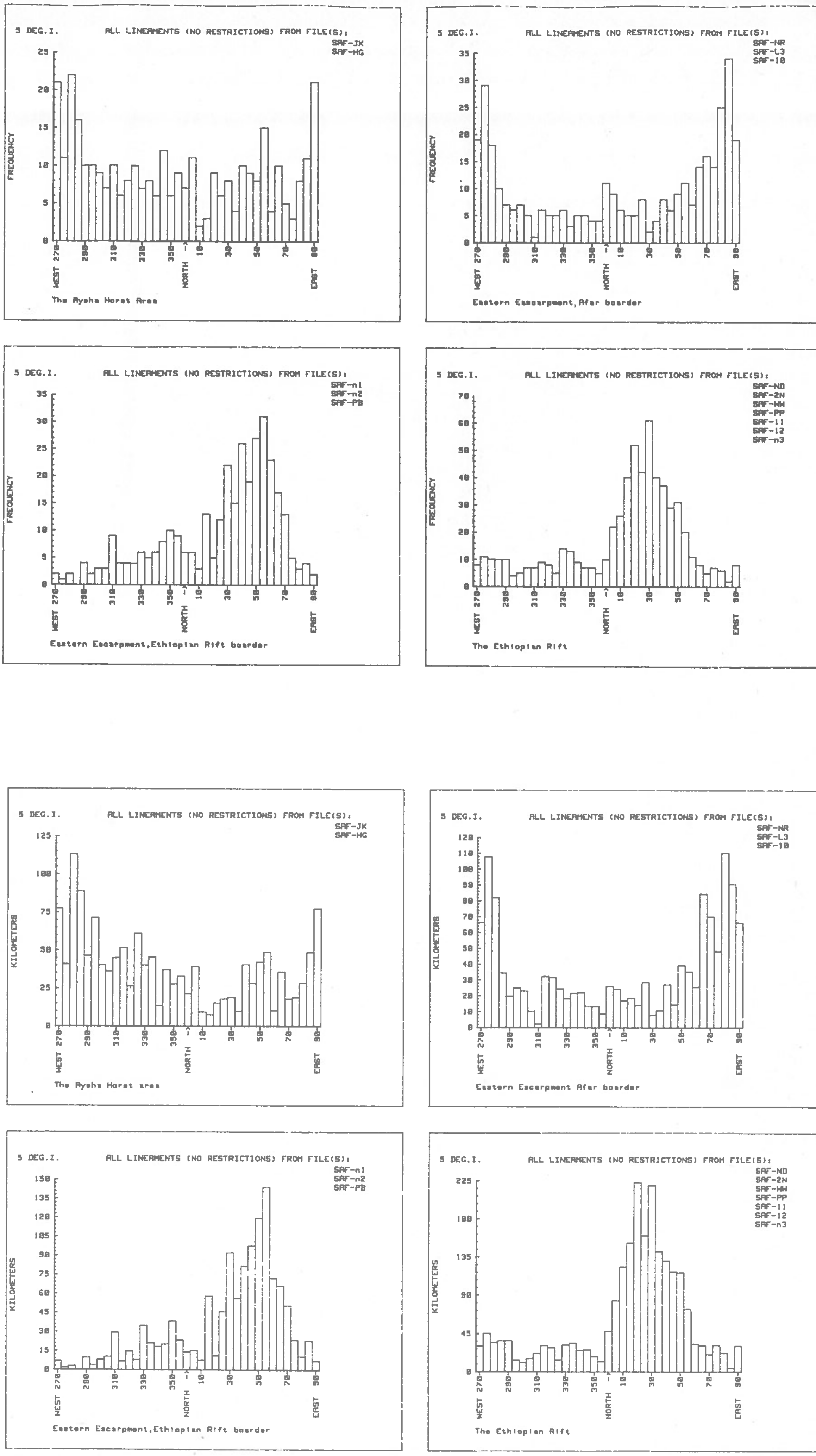

5 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
SAF-JK
SAF-HG
FREQUENCY
WEST
NORTH
EAST
The Ryshe Horst Area
SAF-NR
SAF-L3
SAF-10
Eastern Escarpment, Afar boarder
SAF-n1
SAF-n2
SAF-PB
Eastern Escarpment, Ethiopian Rift boarder
SAF-ND
SAF-2N
SAF-WH
SAF-PP
SAF-11
SAF-12
SAF-n3
The Ethiopian Rift
KILOMETERS
The Ryshe Horst area
Eastern Escarpment Afar boarder
Eastern Escarpment, Ethiopian Rift boarder
The Ethiopian Rift

Figure 11.

6.3 Lithology

Lithological mapping from Landsat imagery can be very difficult or impossible without the use of other geological maps. Most of the units in the study area were easily distinguished from black and white images. Colour print (Plate 6.) shows some of the units that can easily be distinguished from Landsat imagery.

2365-06424

Plate 6. Colour print shows the different rock units from Precambrian rocks (1), Mesozoic Sediments (2), Highly faulted basalts (3), and very dark Recent basalts (4), Eastern Plateau, Escarpment and Rift.

A brief description of the rock units compiled from different authors is given below:-

6.3a Precambrian (Hm)

The Precambrian rocks are exposed along the gorges of the Eastern Plateau and also at the Aysha Horst. They consist of granites, gneisses and migmatites. Metallic deposits are known to occur. The Precambrian rocks are subjected to several orogenic episodes since their formation. Rifting, associated with the development of the Red Sea and African-Ethiopian Rift valley, has resulted in considerable fracturing and shattering (Kazmin 1972).

6.3b Triassic - Lower Sandstone

The Lower Sandstone (Adigrat sandstone) lies unconformably over the Precambrian rocks. It is characterized by yellowish to pink brown, fine to medium grained, well bedded and cross-bedded sandstone. It becomes calcareous towards the top. It attains variable thickness - a few meters to about 300 mts.. It is almost impossible to distinguish this unit on 1:1 000 000 scale Landsat imagery, without the use of a pre-existing geological map.

6.3c Jurassic - Antalo Limestone (Ja)

The Antalo Limestone (about 800 mts. in thickness), lies over the Lower Sandstone. It is part of the Antalo group, which is typically of a calcareous nature, consisting of fossiliferous yellow marl and limestone. It is widely exposed on the Eastern Plateau with a gentle dip (5 to 10 degrees towards the southeast). It is highly affected by step faults towards the Eastern Escarpment along Diredawa - Kulubi area.

6.3d Lower Cretaceous - Upper Sandstone (Ks)

A small outcrop of Upper Sandstone is known to exist along the Eastern Watershed (Hirna - Doba area). It is difficult or impossible to distinguish this unit on Landsat imagery without consulting a base map.

The Upper Sandstone consists of reddish brown, fine to medium grained sandstone. Its thickness in the areas mentioned varies from a few meters to about 100 mts.

6.3e Upper Jurassic - Bihen Limestone (Ji)

The Bihen Limestone is exposed along the Aysha Horst (Ethiopia - Somalia border). It consists of fossiliferous neritic limestone with marly and shaly unit. It is underlain by variegated quartzose sandstones, similar to Adigrat Sandstone (G. Merla et al.,Geological map of Ethiopia and Somalia).

63f Lower Miocene - Alkaline and Per-alkaline granites and associated Aplites, Pegmatites and Porphyric Rhyolites associated with the volcanic rocks, and 'Lower Paleozoic and Precambrian' Granites and Quartz Diorites associated with the metamorphic rocks (Pg)

The former are exposed in patches towards the northern part (northwest of Tendaho). The latter are exposed along the Metamorphic rocks (northeast of Diredawa).

The granites generally display clear intrusive contact with either Precambrian basement or Mesozoic rocks.

6.3g Oligocene - Middle Miocene-Alaji Formation

The Alaji Formation generally consists of transitional and mildly alkaline and sub-alkaline basalts and rhyolites.
It is attempted in the present work to sub-divide the Alaji Formation from the point of view of the lineament characteristics it exhibits in different parts of the area, its vegetation cover and tonal contrast. Accordingly, the following units are distinguished and tentatively classified:-

a) Rhyolites (P3N1R) are distinguished in the Western Escarpment, south of Cheffa Graben and northeast of Bati.
They exhibit relatively low lineament density, low vegetation cover and light tone. These characteristics form well-marked differences from the rest of the rocks.
Most thermal springs in the Western Escarpment are associated with the rhyolites.

b) Transitional basalts and rhyolites (P3N1T) are distinguished in the Western Escarpment areas with relatively high lineaments, low vegetation cover and light tone.

c) Alaji basalts (P3N1B) occur both in the Eastern as well as in the Western Escarpments. They are distinguished on Landsat by their low lineament density, high vegetation cover and dark grey tone.

6.3h Middle Miocene-Termaber Formation

Termaber basalts are essentially porphyritic varieties of basalts, forming the top-most members of the succession of Alaji Formation.
Termaber basalts are hereby divided into two groups, based on interpretations from Landsat:-

a) Basalts and transitional basalts (N1tm) occur along the gorges of the Western Escarpment. They are multi-layered and attain considerable thickness. They are distinguished on Landsat by relatively high lineament density, relatively low vegetation cover and variable tonal contrast.

b) Termaber basalts (N1tb) occur at the highest parts of the Western Escarpment. They are highly weathered and exhibit low lineament density. Residual soils are developed, and vegetation is thick in some places. They usually appear as light grey tone on Landsat images.

6.3i Middle to Upper Miocene

Anchar basalts (N1n) and Arba Guuracha silicics (N1ar) have been recognized in the Escarpment margins of the Ethiopian Rift or the Afar. The two units are more or less contemporaneous (Middle to Upper Miocene). The Anchar basalts form the lower part of the rift volcanic succession and should not be confused with the pre-rift "traps" or plateau basalts (V. Kazmin and Seife Michael Berhe, 1978). Anchar basalts are flood basalts and siliceous rocks (several intercalations of ignimbrites) exposed at the eastern margin of the rift, whereas Arba Guracha silicics (predominantly of acidic varieties like welded and unwelded ash flows) are exposed at the eastern margin of the rift and in some parts of the Western Escarpment.

6.3j Upper Miocene to Pliocene-Nazret Group (A)

Stratoid silicics, ignimbrites, unwelded tuffs, ash flows, rhyolites and trachytes (N1-2N) are exposed in the southern part of the study area. Gara Gumbi rhyolites (N1-2gg) are exposed at Mount Asebot and Mount Afdem and at other small hills in the vicinity. The two units, which belong to the Nazret group attain a thickness of about 250 mts. and are restricted to the sagging rift (V. Kazmin and Seife Michael Berhe, 1978). The per-alkaline nature of these rocks was mentioned by Di Paola (1972).

Afar Group

i) Dalha basalts (N1-2db) are exposed in the northwestern part of the study area. They are mainly composed of basaltic flows with intercalations of ignimbrites and detritic deposits (up to 800 mts. of thickness). They are deeply eroded and often unconformably covered by the Stratoid series of the Afar.

ii) Stratoid Series (N1-2ab) covers about 2/3 of the rift floor. It is composed of Plio-Pleistocene volcanic units which are dominantly basalts. Sedimentary units and hyaloclastite layers are intercalated within the stratoid series.
This series is affected by faulting and block tilting; the lowest parts are deeply weathered and altered.

Due to the fact that the Stratoid Series are spread over a large area in the rift floor, different lineament intensity boundaries have been established (see fig.12). These boundaries may or may not correspond with different sub-units with varying characters in lithology.

iii) Silicic centers (N1-2ar) occur as small patches in the vicinity of central volcanoes. They are dominantly of rhyolitic composition, intercalated in the Stratoid Series. The rhyolites are end-products of fissural basaltic activity; alkaline rhyolites, commendites, pantellerites, rhyolitic trachytes and dark trachytes are found mainly as lava flows (Barberi F. and Varet J. 1976).

Nazret Group (B)

Bofa basalts (N1b) are fissure flood basalts named after their type locality at Bofa village (V. Kazmin and Seife Michael Berhe, 1978). Ignimbrites and flows, separated by paleosoils and scoraceous horizons, occur at other places.

6.3k Pleistocene to Holocene

Dino Ignimbrites (QWD) occur in the southern part of the area, south of Mount Fantale, where they cover topographically low and relatively flat areas. They can be distinguished on Landsat images by their light tone, due to partly grass cover. They comprise a number of flows of compact fiamme ignimbrites, in places intercalated with aphiric basalts and unwelded pyroclastics (V. Kazmin and Seife Michael Berhe).

Basalts of the rift floor

Pleistocene basalts (QWbp) - fissure flows (transitional basalts, ferro basalts and Hawaiites) are locally found around volcanic centers, like Dofan, Hertale, Ayelu, Abida, etc..
Recent basalts (QWbh) - basaltic lava flows and spatter cones (picritic basalts, porphyritic plagioclase basalts, andesine basalts of transitional nature, with alkaline tendencies) are associated with the former.
The recent basalts are easily recognizable on Landsat by their dark grey tone, whereas distinction between Pleistocene basalts and Stratoid Series is almost impossible on Landsat.

Central Volcanic Complexes

The central volcanic complexes of Fantale, Dofan and Ayelu are built mostly of alkaline and peralkaline rhyolites (QWa). The central volcanic complexes of Abida, Yangudi and Gabilema are mostly composed of peralkaline rhyolites, ignimbrites and pumice fall (QWi). Lavas of intermediate composition - mugearites, rhyolitic trachytes, hawaiites and ferrobasalts are associated with the latter, hence, are grouped together for the present purpose.

The sequence of rocks ranging from basalt to rhyolites observed around these volcanic complexes have been explained by Barberi F. and Varet J, 1976 as being the result of a process of crystal fractionation.

6.4 Soil units

Quaternary to recent alluvial sediments (Qa) cover a large part (about 1/3) of the study area.

One of the oldest (Upper Pleistocene) lacustrine deposits, known as Hadar Formation, occurs west of Gewani village (see Plate 7.)

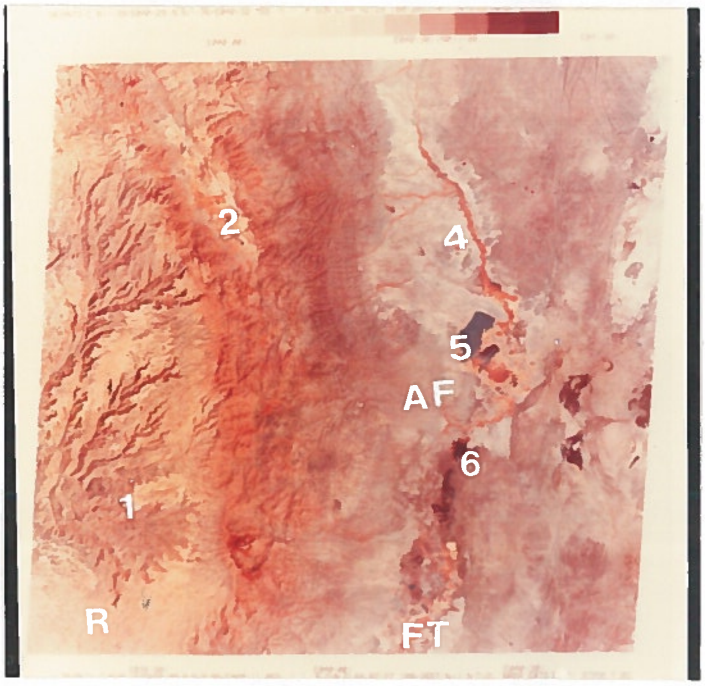


Plate 7. Colour print shows Ethiopian Plateau (1), Western Escarpment (2), Cheffa Graben within the Escarpment (3) and Graben at the foot-hills of the Escarpment filled by sedimentary formation (4).
Note the difference in colour between the turbid Yardi lake (5) and the clear Hertale lake (6).

The deposit is a thick sedimentary formation (180 - 240 mts), consisting of clays with fish ostracoda, calcereous mud, sands and gravel, separated by tuff horizons. More than 50 species of mammalia have been inventoried (F. Gasse, 1978). Remains of Hominidae (Austrolipithecus and other species) have been observed (Johanson and Taieb, 1976).

Other lacustrine deposits of different age (Upper Pleistocene : 50 000 - 20 000 years before present) occur at several places, along the Middle Awash area. They are mostly composed of limestones and diatomites. Younger deposits (less than 2 500 years before present), composed of lacustrine sediments, silt, clay, diatomite, volcanoclastic sediments and tuffs, occur in the Middle Awash area. Due to ecological conditions (total salinity, alkalinity) organic remains are practically non-existent within these deposits (F. Gasse, 1978).

Continental conglomerates, gravel sand, silt and clay occur at foot slope areas and within the grabens of the escarpments. The age of these sediments could extend from Pliocene to Holocene up to the present time. Eolian sediments mostly occur in the interior part of the rift floor. Flood terraces are common along the Awash river, whereas sheet flood deposits occur along intermittent and seasonal streams.

Soil units have been interpreted from the false colour composites. During sub-division of the soil units, dynamical geomorphological processes have been taken into consideration.

Local variations are caused by the combination of either two or more of the following processes:-

- fluviation
- gravity
- sheet flood
- wind
- lake

Taking into account the above factors and the geomorphological situations in the background, the following classification of soil units have been made possible:

- Non or thin soil cover
- Residual soil
- Colluvium
- Alluvial fan

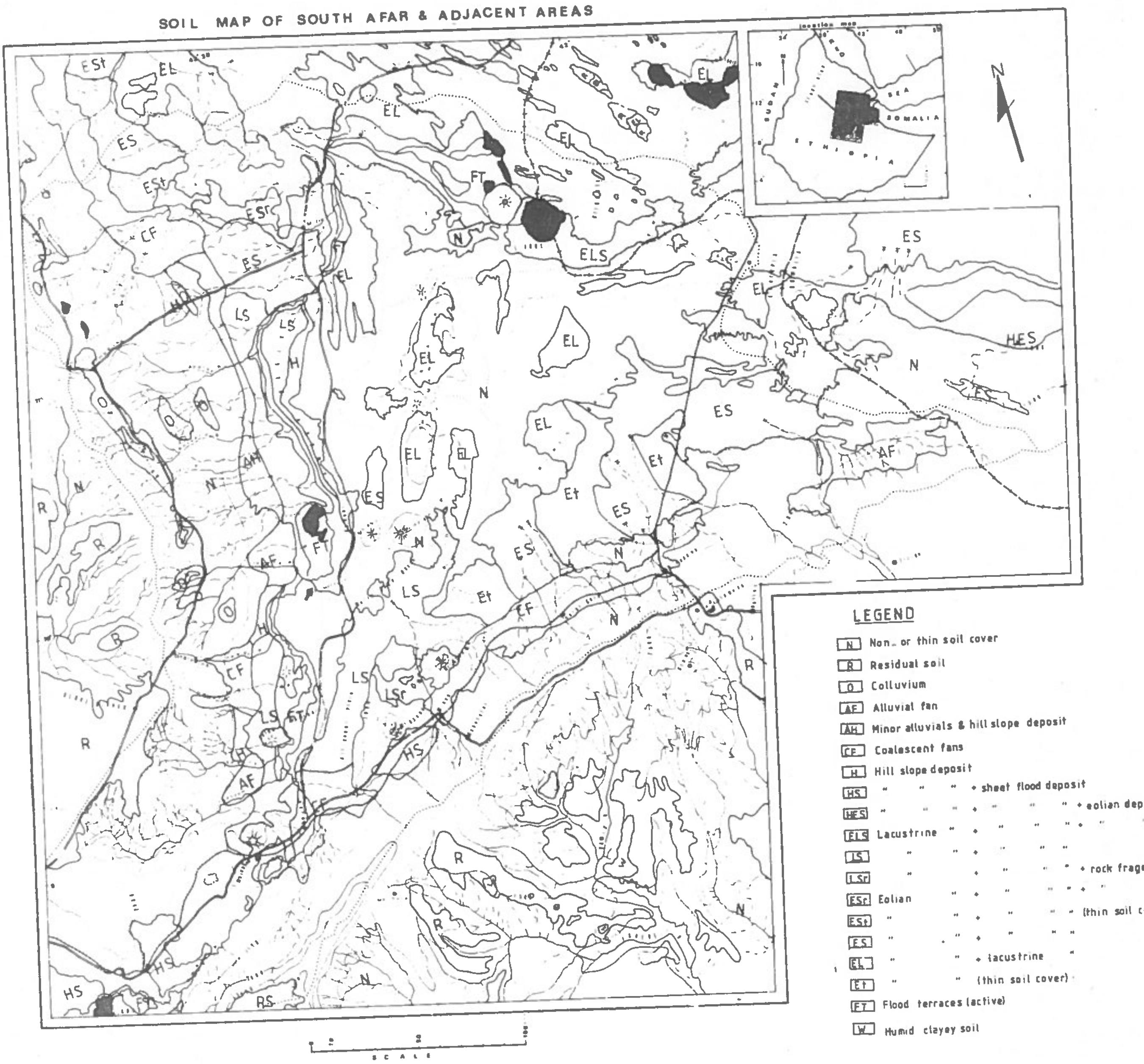

SOIL MAP OF SOUTH AFAR & ADJACENT AREAS
LEGEND
N Non- or thin soil cover
R Residual soil
O Colluvium
AF Alluvial fan
AH Minor alluvials & hill slope deposit
CF Coalescent fans
H Hill slope deposit
HS " " " + sheet flood deposit
HES " " " + " " " + eolian dep
ELS Lacustrine " + " " " + "
LS " " + " " "
LSr " + " " " + rock frag
ESr Eolian " + " " " +
ESt " " + " " " (thin soil c
ES " " + " " "
EL " " + lacustrine "
Et " " (thin soil cover)
FT Flood terraces (active)
W Humid clayey soil
SCALE
SUDAN
SOMALIA
ETHIOPIA
RED SEA
N

Figure 12

- Minor alluvials and hill slope deposits
- Coalescent fans
- Hill slope deposits
- Hill slope deposits plus sheet flood deposits
- Hill slope deposits plus sheet flood deposits plus eolian deposits
- Lacustrine deposits plus sheet flood deposits plus eolian deposits
- Lacustrine deposits plus sheet flood deposits
- Lacustrine deposits plus sheet flood deposits plus rock fragments
- Eolian deposits plus sheet flood deposits plus rock fragments
- Eolian deposits plus sheet flood deposits (thin soil cover)
- Eolian deposits plus sheet flood deposits
- Eolian deposits plus lacustrine deposits
- Eolian deposits (thin soil cover)
- Flood terraces (active)
- Humid clayey soil.

7. HYDROGEOLOGY

7.1 Permeability of the granular sediments

Although about 1/8 of the area is covered by granular aquifers, which are mostly considered as having isotropic and homogeneous properties, no quantitative data has been available for the determination of aquifer parameters, such as transmissibility and storativity. Therefore, permeability of these aquifers has qualitatively been determined from the point of view of the granular properties of the sediments.

The major soil units derived from hydro-geomorphological processes, and the permeability characters subsequently reflected, are qualitatively evaluated as in the following table:-

Major soil units	Permeability
1) Alluvials: river side deposits (gravel, sand and fines)---	high
2) Alluvial fans and coalescent fans: high level terraces along river beds at the lowland margines (interfingering of coarse and fine sediments) -------------------	very high
3) Colluvials: intermontane deposits (incoherent and loose deposits of fine medium to coarse sediments)---	very high
4) Sheet flood deposits: along intermittent and seasonal streams at the alluvial plains (mostly fines)----------	medium
5) Residuals: mostly over plateau rocks (rock fragments and clayey sediments)------------------------------	medium to low depending on rock type
6) Lacustrine: graben areas within the rift (limestones,diatomites and other clayey sediments)-------	low
7) Eolian: alluvial plains and grabens (well sorted sand and fine sediments)--------------------------------------	high

The soil units mentioned in chapter 7. are derived from the combination of two or more of the above major soil units. Their permeabilities are deduced from the above chart (see hydrogeological map attached to this thesis).

7.2 Permeability of the rock units

The rock units in the area vary from high grade metamorphic rocks to sandstones and limestones, volcanic rocks (basic, intermediate to acidic varieties) and intrusives.

Except the volcanic rocks, other rock units occur in the adjacent areas of the Afar. Permeability of the volcanic rocks is hereby discussed.

7.2a Fracture porosity

The fracture pattern of volcanic rocks may create a type of porosity known as fracture porosity, which could, in turn, affect permeability. The flow of water through a fracture can be visualized by a discrete model with a fracture between two blocks. The flow of water between the blocks could be laminar, turbulent or in between, depending on the width of the fissure and rate of movement of water. The flow of water through narrow fractures may be laminar, whereas turbulence occurs in wide fractures. An immediate entry of water from a narrow fracture to a wider one may result in turbulence, whereas the turbulence decreases with distance. Considering these conditions, the flow of water through fractured rocks differs from the flow through granular aquifers (laminar flow), and from the flow through pipes (turbulent flow).

A formula that may satisfy the above situation, ie. without any restriction or Reynolds number (R.H. Brown et al, International Hydrological Decade, UNESCO, 1978) is given below:

$$I^{3/4} = \left(\frac{v}{K}\right)^{3/4} + \left(\frac{C}{100gl}v^2\right)^{3/4}$$

where: I = hydraulic gradient

v = mean flow velocity in the fissures

K = hydraulic conductivity (permeability)

g = acceleration due to gravity

l = width of the fissure

C = a constant between 6 and 30 depending on the roughness of the walls and the density of the fissured network.

The volume of water through a single fissure representing a large surface area, can be used in calculating the parameter of the hydraulic flow through a fissured layer.

Permeability of a mass of rock unit depends on collective permeability of the fractures of the interconnecting system.

By using the above formula, permeability of some fissures can be calculated with data obtained from the field and the results can be extrapolated to the other areas, where the proportion of surface openings has defined mean and small variance.
Some of the factors affecting permeability of the volcanic rocks in the area are:-

1) Number of fractures
2) Length of fractures
3) Width of fractures
4) Depth of fractures
5) Degree of intercommunication between fractures.

7.2b Lineament characteristics of the aquifers

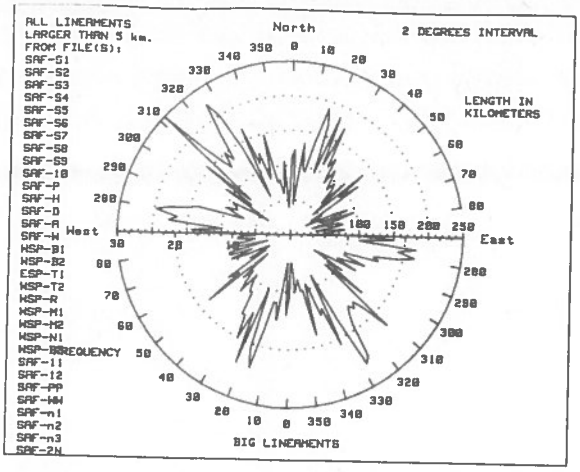
A method of estimating relative permeability of the rock units and areas of increased porosity and permeability is given below:-

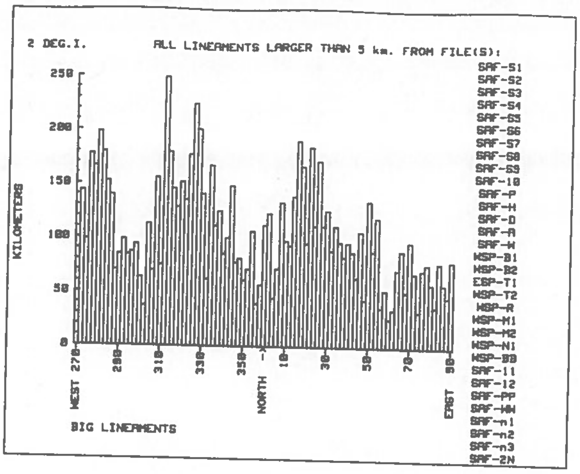
1) Linear features and possibly fracture traces that may represent sub-surface vertical zones of fracture concentrations (undesirable linear features like roads being avoided) were carefully mapped from Landsat imagery.
2) Lineaments greater than 5 km. were compared with lineaments of less than 5 km, in order to see the relationship between the two (see fig. 13).
3) Areas of rock unit boundaries were calculated.
4) Areas with similar lineament concentrations were delineated and their areas calculated.
5) All the lineaments within the boundaries mentioned were separately digitized and the following lineament parameters obtained:

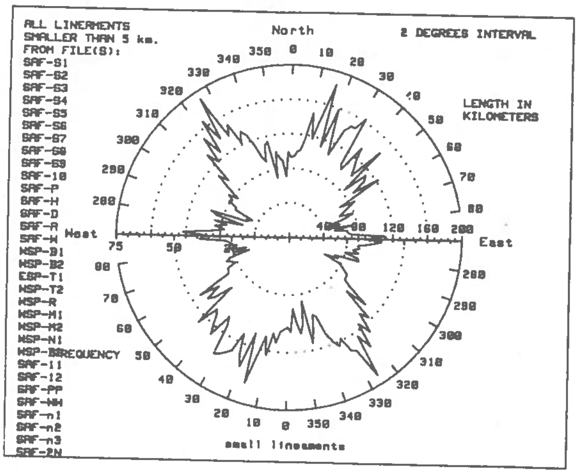
   L/A (Total length/area of the units considered) from which relative lineament length was obtained.

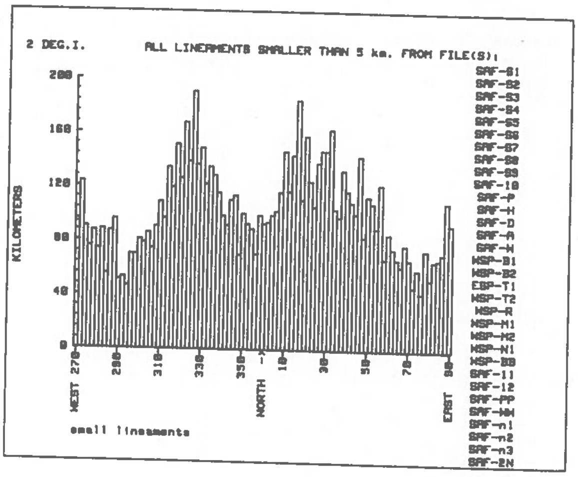
   N/A (Number of lineaments/area of the units considered) from which relative intensity of lineaments was obtained.
6) The above two parameters were multiplied by each other, so that best possible lineament characteristics be obtained.
7) The lineament characteristics obtained from 6) (LN/A^2) are plotted against the corresponding units considered (see fig.14).

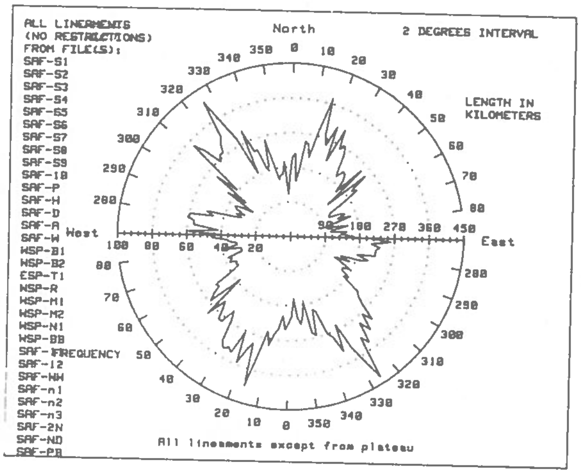
Although close relationships exist between short lineaments and long

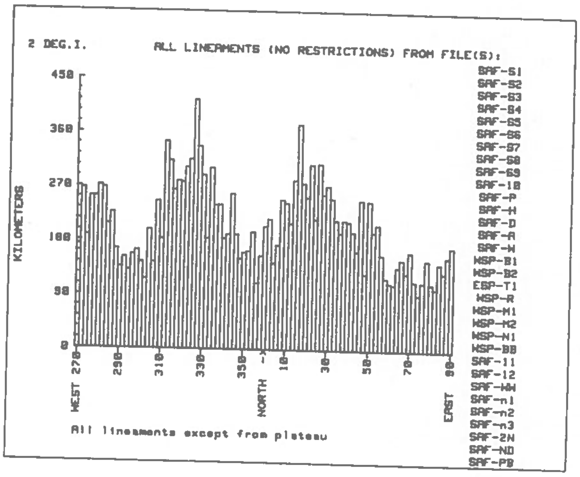

ALL LINEAMENTS LARGER THAN 5 km.
2 DEGREES INTERVAL
North
East
West
LENGTH IN KILOMETERS
FREQUENCY
BIG LINEAMENTS


2 DEG.I.
ALL LINEAMENTS LARGER THAN 5 km. FROM FILE(S):
KILOMETERS
WEST
NORTH
EAST
BIG LINEAMENTS


ALL LINEAMENTS SMALLER THAN 5 km.
2 DEGREES INTERVAL
North
East
West
LENGTH IN KILOMETERS
FREQUENCY
small lineaments


2 DEG.I.
ALL LINEAMENTS SMALLER THAN 5 km. FROM FILE(S):
KILOMETERS
WEST
NORTH
EAST
small lineaments


ALL LINEAMENTS (NO RESTRICTIONS)
2 DEGREES INTERVAL
North
East
West
LENGTH IN KILOMETERS
FREQUENCY
All lineaments except from plateau


2 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
KILOMETERS
WEST
NORTH
EAST
All lineaments except from plateau

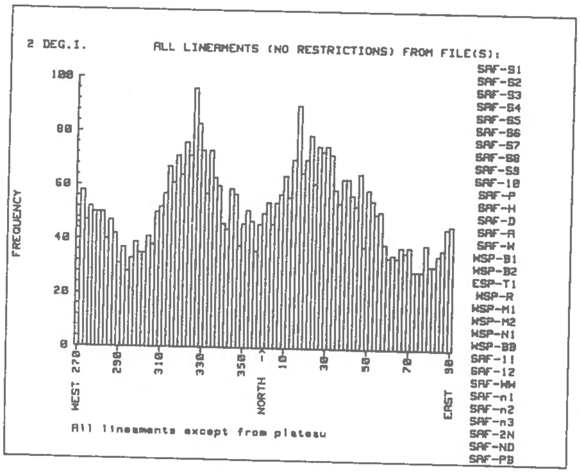

2 DEG.I.
ALL LINEAMENTS (NO RESTRICTIONS) FROM FILE(S):
FREQUENCY
WEST
NORTH
EAST
All lineaments except from plateau

Figure 13

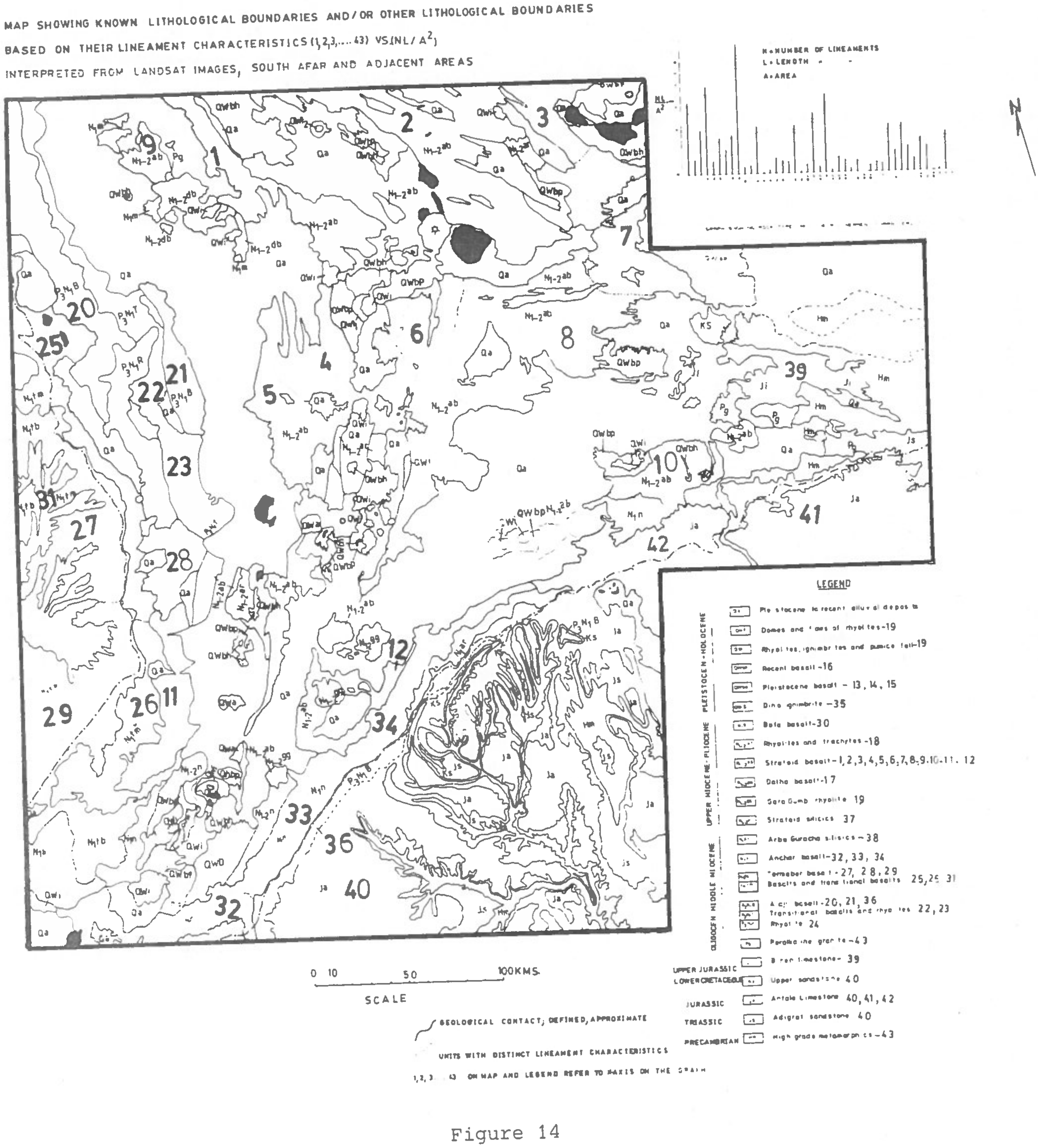

MAP SHOWING KNOWN LITHOLOGICAL BOUNDARIES AND/OR OTHER LITHOLOGICAL BOUNDARIES
BASED ON THEIR LINEAMENT CHARACTERISTICS (1,2,3,....43) VS (NL/A²)
INTERPRETED FROM LANDSAT IMAGES, SOUTH AFAR AND ADJACENT AREAS
N = NUMBER OF LINEAMENTS
L = LENGTH
A = AREA
N
LEGEND
PLEISTOCENE - HOLOCENE
UPPER MIOCENE - PLIOCENE
OLIGOCENE MIDDLE MIOCENE
Recent basalt -16
Pleistocene basalt - 13, 14, 15
Bofa basalt-30
Rhyolites and trachytes -18
Stratoid basalt-1,2,3,4,5,6,7,8,9,10,11,12
Dalha basalt-17
Stratoid silicics 37
Arba Guracha silicics - 38
Anchar basalt-32, 33, 34
Basalts and transitional basalts 25,26 31
Transitional basalts and rhyolites 22, 23
Rhyolite 24
UPPER JURASSIC
LOWER CRETACEOUS
Upper sandstone 40
JURASSIC
Antalo Limestone 40, 41, 42
TRIASSIC
Adigrat sandstone 40
PRECAMBRIAN
High grade metamorphics - 43
0 10 50 100KMS.
SCALE
GEOLOGICAL CONTACT, DEFINED, APPROXIMATE
UNITS WITH DISTINCT LINEAMENT CHARACTERISTICS
1, 2, 3 ... 43 ON MAP AND LEGEND REFER TO X AXIS ON THE GRAPH

Figure 14

lineaments (from the rosette diagram on p. 37, the median values of the long lineaments areclose to the median value of the short lineaments) the following should be noted as well:

a) Not all lineaments can ever be traced; there could be an infinite number of smaller lineaments that can not be detected from Landsat.

b) Other common properties of volcanic rocks, like columnar jointing of basalts, pillow lavas of sub-marine eruptions, pahoehoe or blocky lavas of basic rocks, attribute to high secondary porosity and permeability that are not detectable from Landsat.

c) Some lineaments that are important for groundwater flow, like fissures and open faults, may be concealed under grass or soil cover.

Some of the primary characteristics and other features affecting permeability of volcanic rocks are given below:-

1) Volcanic rocks which are deficient in silica and rich in iron and magnesia, generally, have the tendency to be good aquifers, whereas silica-rich rocks like rhyolites and trachytes are often poor aquifers.

2) Permeability characteristics of basic rocks mostly depend on the nature of deposition of the flows; the nature of deposition of volcanic rocks almost always causes unisotropic and inhomogeneous permeability:- the flows could be radial, planar or linear, the voids and zones of brecciation, on the other hand, could be parallel or transverse to these flows, hence, affecting groundwater flow through volcanic rocks.

3) Scoraceous crust due to escape of gases, pahoehoe lava with undulating ropy surface, pillow lava formed under sub-marine condition, shrinkage cracks, lava tubes, fracture as a result of mechanical forces acting on the cooled lava, tree mold, etc., contribute to permeability of volcanic rocks.

4) Bigger fragments of volcanic products, which remain near their source, have higher permeability than the finer ones, which cover larger areas.

5) Intercalation of sedimentary pyroclastics, layers of soil units in between flows, reduce permeability of volcanic rocks.

6) Intrusion of dykes and other intrusive bodies may reduce permeability of volcanic rocks.

In the present work, all the factors mentioned above are taken into consideration while classifying permeability of the rock units. Permeability of the rock units after considering their primary and secondary characteristics is summarized below.
It should be noted that a certain rock unit may exhibit different permeability characteristics depending on its secondary features. On the other hand, rocks with different primary characteristics may have the same permeability group (see hydrogeological map).

7.2c Relative permeability of rocks

1) Very high to excellent permeability:- Recent basaltic lava flows and spatter cones (QWbh) and Pleistocene basalts, fissure flows (QWbp) show very little or no lineaments from Landsat. However, field evidence proves that these rocks attain typical aa or pahoehoe surfaces which favour free groundwater movement.
2) Very high permeability:- Stratoid basalts (N1-2ab), south of lake Abbe attain very high lineament length and density (see fig.). The Jurassic Limestones (Ja), southeast of Diredawa city, are highly faulted with numerous lineaments. Bofa basalts (N1b) are included in this group.
3) High permeability:- Stratoid basalts south of lake Abbe and north-east of lake Abbe have fewer lineaments; their permeabilities could, therefore, be relatively lower than the former. Pleistocene basalts east of lake Abbe and the Delha basalts (N1-3db),consisting of series of basaltic flows with intercalations of ignimbrites and detritic bodies, which are relatively less faulted, are included in this group. Adigrat Sandstone (Js), Jurassic Limestone (Ja), Upper Sandstone (Ks) and Bihen Limestone (Ji) are included within this group.
4) Medium permeability:- Termaber basalts (N1tb), Alaji basalts (P3N1B) and Anchar basalts (N1n) have variable permeability characteristics, depending upon their primary nature (basic to acidic varieties are encountered). The existence of numerous springs emerging from the Termaber Formation proves the permeable nature of these rocks. Anchar basalts comprise basaltic rocks as well as intercalations of ignimbrites, which are highly faulted.
Transitional basalts and rhyolites (P3N1t) west of lake Yardi, which are highly affected by faults, are included in this group.

5) Low permeability:- Basalts and transitional basalts along the Western Escarpment (N1tm) have variable permeability due to their variable primary nature. Weathered tuff and ash are interlayered between their flows, which reduces permeability of these rocks. Although rhyolites and trachytes are primarily aquicludes, the rhyolites and trachytes north of Gewani (N1-2ar) are highly faulted, this might be attributed to fracture porosity.
Transitional basalts and rhyolites (P3N1t), northwest of Eliwoha are included within this group.

6) Very low permeability:- The metamorphic rocks (Hm), Dino Ignimbrites (QWD), Stratoid silicics (N1-2n) Arbaguracha silicics (N1ar) may be aquicludes, but due to the development of fractures and faults, may attain very low permeability.

7) Aquicludes:- Rhyolites, ignimbrites and trachytes (Qwi), rhyolites and trachytes (N1-2ar) and peralkaline granites (Pg) are considered to be aquicludes.

8) Groundwater barriers:- Domes and flows of rhyolites (QWa), Gara Gumbi rhyolites (N1-2gg) and, sometimes, rhyolites, ignimbrites and trachytes (QWi) occur at and around volcanoes and may act as groundwater barriers.

8. HYDROMETEOROLOGY

8.1 Precipitation

Distribution of rainfall stations in the study area is shown in the climatic map (see fig. 17).
Data for eleven years (1969 - 1979) were processed and analysed in various ways:

1) An isohyetal map is prepared, based on the relationship between precipitation and altitude. A very strong relationship (correlation coefficient of .96) was observed (see fig. 15). The rainfall pattern over the whole area is extrapolated from the graph and an isohyetal map prepared by using the extrapolated results and actual values obtained from the stations. (See fig. 16)

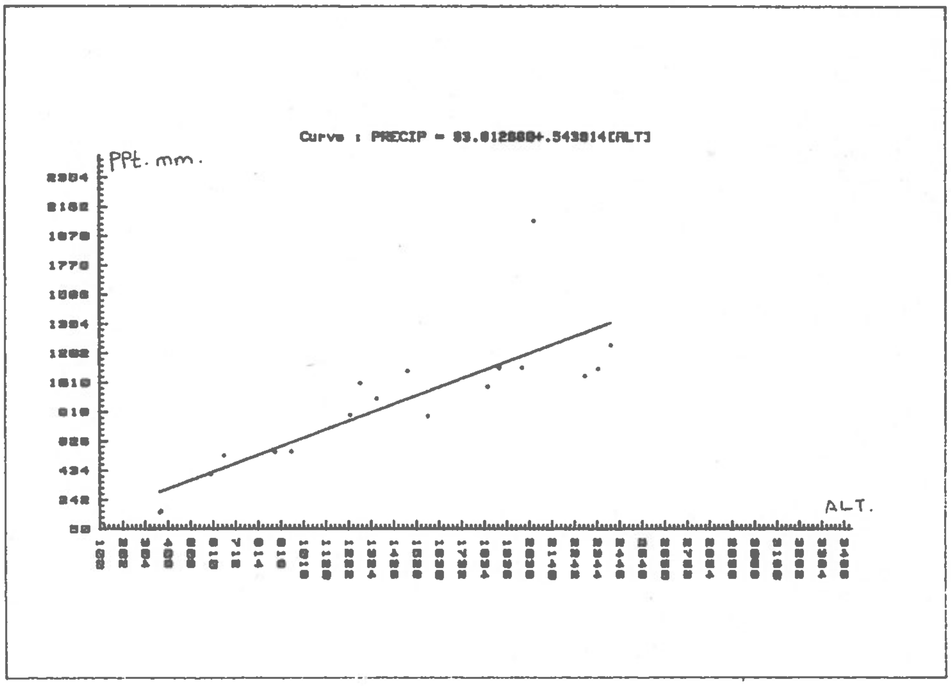


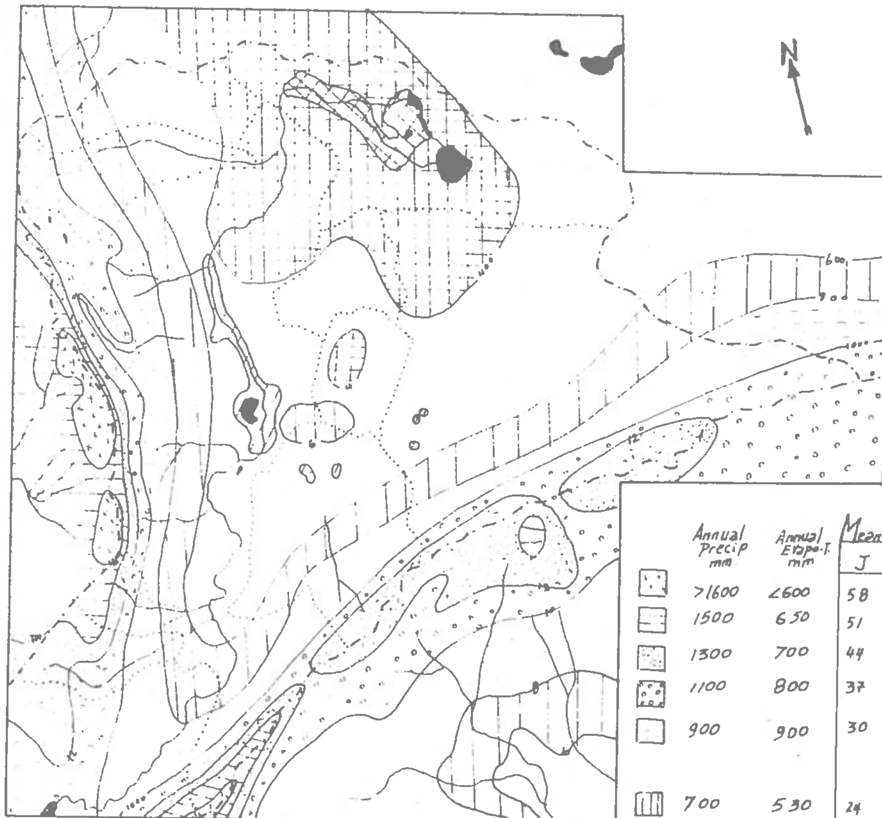
Fig. 15. Figure shows the relationship between rainfall and altitude.

2) Frequency analysis was made by computer. The cumulative probability curves are produced from the data. The observations are ranked in decreasing order and the cumulative probability is calculated by using the following formula:

$P = R/N + 1$ where R = rank of observations and

N = number of observations

MEAN ANNUAL PRECIPITATION & EVAPOTRANSPIRATION MAP OF SOUTH AFAR & ADJACENT AREAS



Scale: 1 2898511

Mean Monthly Precipitation Calculated from Percentages of Precip.

Annual Precip mm	Annual Evapo.T. mm	J	F	M	A	M	J	J	A	S	O	N	D
>1600	<600	58	103	148	140	125	71	326	419	183	65	39	47
1500	650	51	90	130	123	110	63	288	370	161	57	34	42
1300	700	44	78	113	107	96	54	249	320	140	50	30	36
1100	800	37	66	96	90	81	46	211	271	118	42	25	31
900	900	30	54	78	74	66	38	173	222	97	34	21	25
700	530	24	42	61	58	51	29	139	172	75	27	16	19
500	425	17	30	43	41	37	21	96	123	54	19	11	14
300	315	10	18	26	25	22	13	58	74	32	11	7	8
500	2350	17	30	43	41	37	21	96	123	54	19	11	14
300	2400	10	18	26	25	22	13	58	74	32	11	7	8

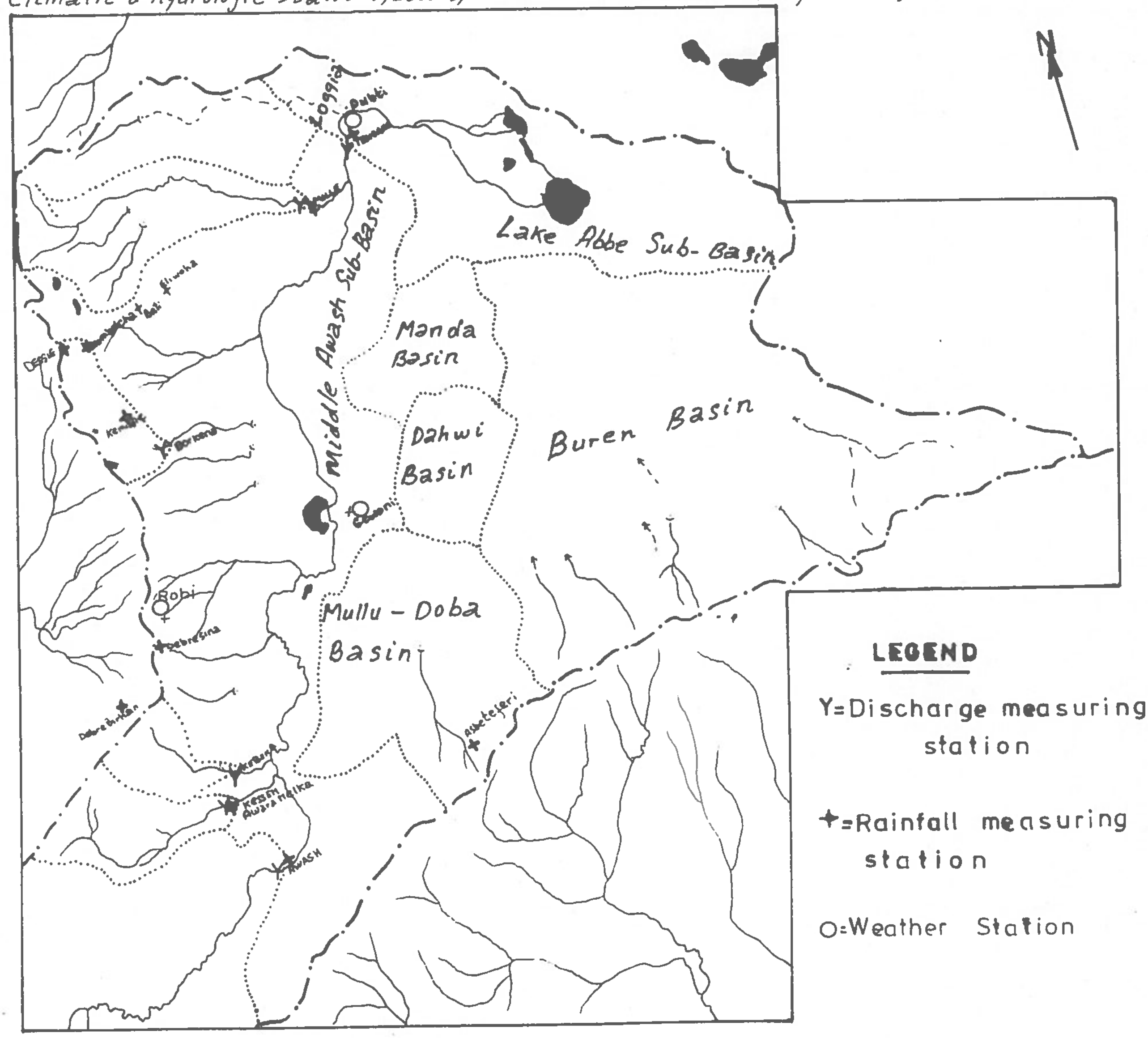
~ Isohuets

Mean monthly Evapotranspiration calculated from Percentages of Eva.T

J	F	M	A	M	J	J	A	S	O	N	D
37	41	49	50	54	59	48	47	47	42	39	36
44	48	58	59	64	70	57	56	56	49	46	43
48	52	62	64	69	75	62	60	60	53	49	46
54	59	71	73	79	86	70	69	69	61	56	53
61	67	80	82	89	96	79	77	77	68	63	59
Actual Evapotranspiration											
25	36	43	42	52	73	50	43	58	45	33	30
20	28	34	33	42	58	40	34	46	36	26	24
15	21	26	25	31	43	30	26	34	26	20	18
Potential Evapotranspiration (Penman method)*											
110	157	190	186	233	321	223	190	256	197	146	132
113	161	194	190	238	329	228	194	262	202	149	134

Figure 16

Climatic & Hydrologic Stations, Basins, Sub-basins & Catchments (S. Afar & adjacent areas).



scale=1:2898551

Figure 17

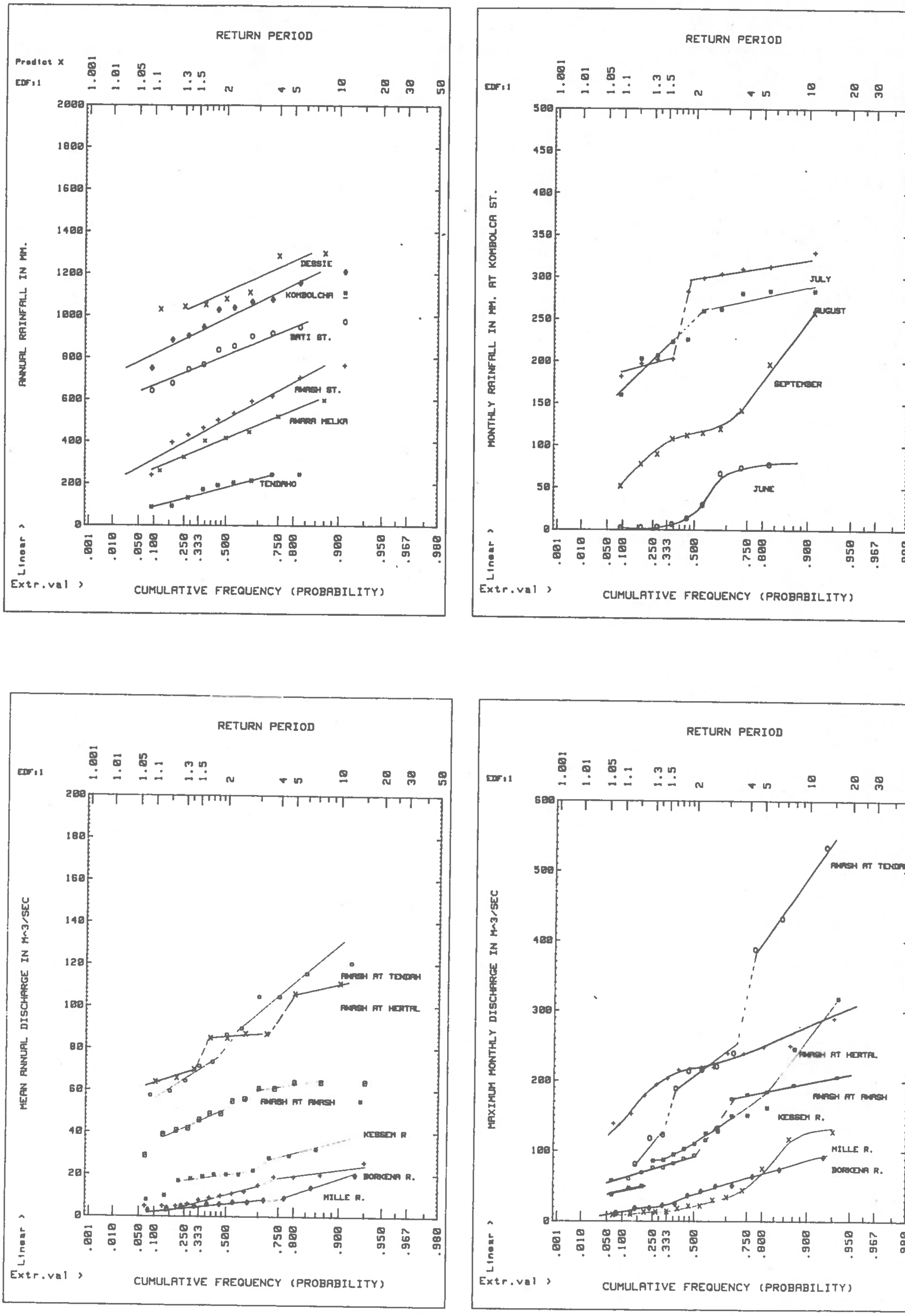
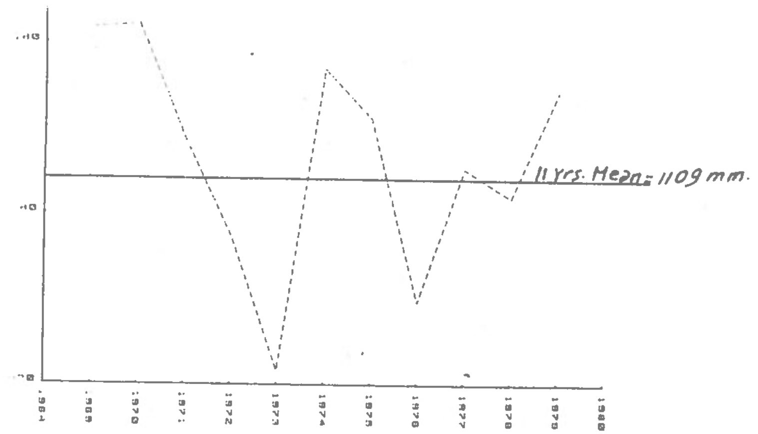
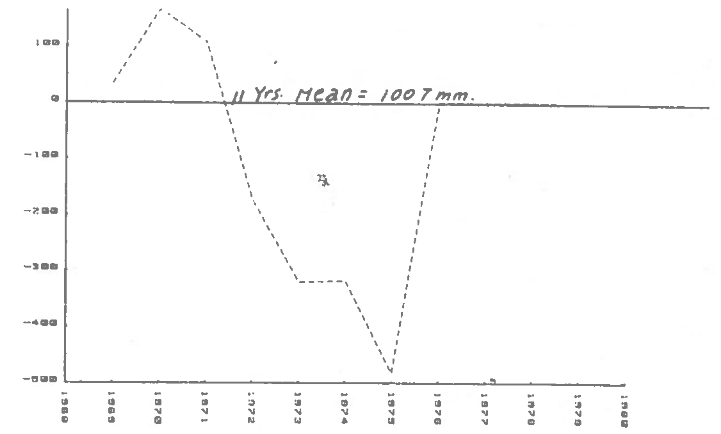

RETURN PERIOD
Predict X
EDF:1
ANNUAL RAINFALL IN MM.
DESSIE
KOMBOLCHA
BATI ST.
AWASH ST.
AWARA MELKA
TENDAHO
MONTHLY RAINFALL IN MM. AT KOMBOLCA ST.
JULY
AUGUST
SEPTEMBER
JUNE
MEAN ANNUAL DISCHARGE IN M^3/SEC
AWASH AT TENDAH
AWASH AT HERTAL
AWASH AT AWASH
KESSEM R
BORKENA R.
MILLE R.
MAXIMUM MONTHLY DISCHARGE IN M^3/SEC
AWASH AT TENDAH
AWASH AT HERTAL
AWASH AT AWASH
KESSEM R.
MILLE R.
BORKENA R.
Linear >
Extr.val >
CUMULATIVE FREQUENCY (PROBABILITY)

Figure 18

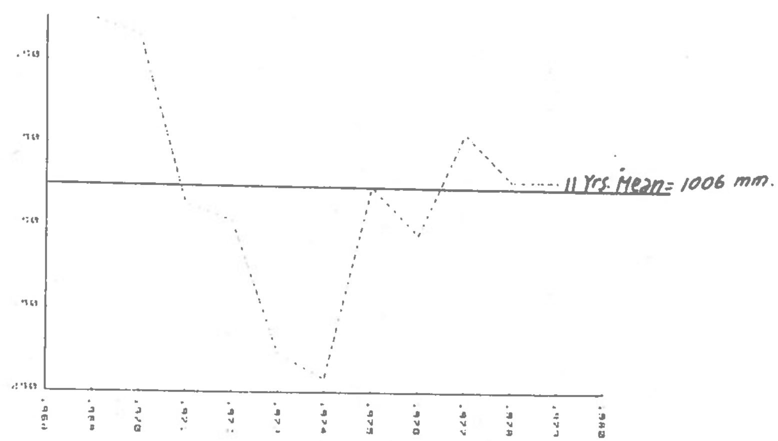
Figure 19



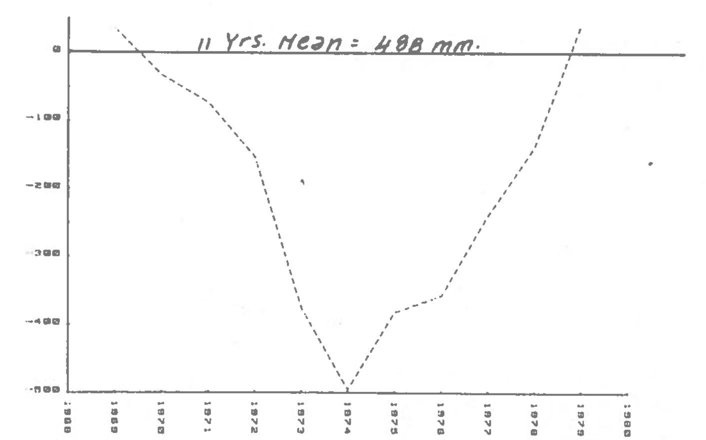
DESSIE. CUMMULATIVE DEVIATION FROM THE MEAN OF ANNUAL RAINFALL IN MM.



ROBI. CUMMULATIVE DEVIATION FROM THE MEAN OF ANNUAL RAINFALL IN MM.

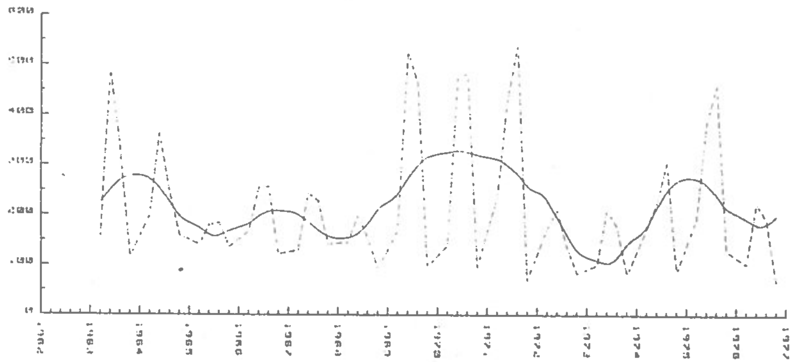


WOLDIYA ST. CUMMULATIVE DEVIATION FROM THE MEAN OF RAINFALL DATA IN MM

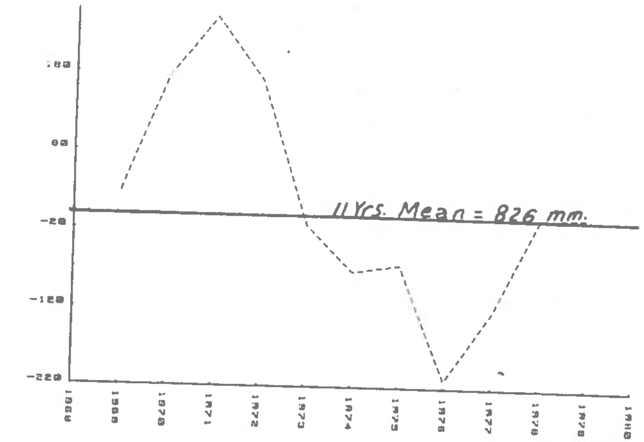


AWARA MELKA. CUMMULATIVE DEVIATION FROM THE MEAN OF ANNUAL RAINFALL IN MM.

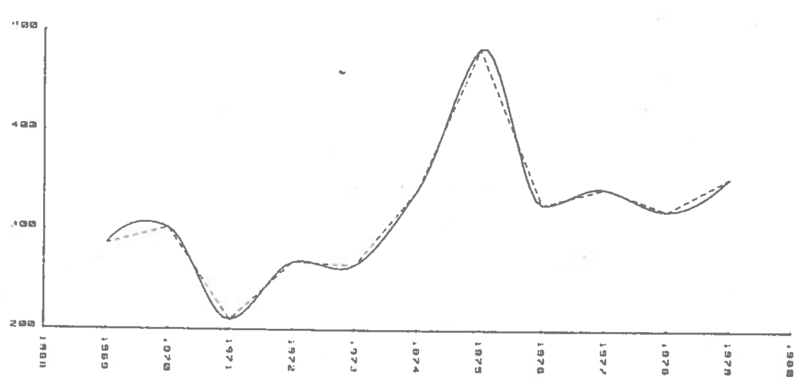
Figure 20



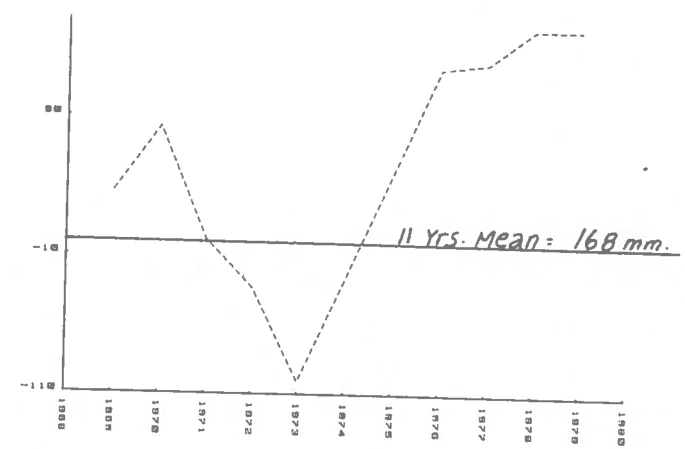
AWASH RIVER DISCHARGE IN MILLION M3/MONTH (MONTHS-7,8,9,10)
USING FOURIER ANALYSIS WITH 6 HARMONICS



BATI. CUMMULATIVE DAVIATION FROM THE MEAN OF ANNUAL RAINFALL IN MM.



MILLE STATION - MEAN ANNUAL RAINFALL IN MM
USING FOURIER ANALYSIS WITH 6 HARMONICS



TENDAHO ST. CUMMULATIVE DEVIATION FROM THE MEAN OF RAINFALL DATA IN MM.

The return period or recurrence interval is calculated by the following formula:

$$T = \frac{1}{(1-P)}$$ where T = return period and P = probability

Mean annual rainfall data of six selected stations and monthly rainfall data of one station were used in the frequency analysis. The salient features of the graphs (see fig. 18) are given below:

i) Mean annual rainfall values show considerable differences in rainfall between low altitude areas (Afar region) and high altitude areas (the Escarpment regions).

ii) The slope of the regression lines, which are directly proportional to the standard deviations, shows a slight increase from low to high rainfall; from this we can conclude that variability of rainfall increases with increase of rainfall.

iii) Monthly rainfall distribution at Kombolcha station shows the relative differences between dry and wet months (see fig. 18). The magnitude of relative dryness and relative wetness of the years considered is also reflected by the concentration of the data into two populations.

3) Cumulative deviations from the long term mean (11 years) of some stations were calculated and the results presented on graphs (see fig. 19 & 20). The graphs reflect the possibility of a defined cycle of occurrence of the events discussed above; the drought situations that existed between the years 1971 and 1974 can be observed.

4) The effect of wet and dry years on stream flows, for a period of eleven years, is compared by plotting discharge data for four months (July, August, September, October) of Awash river for the eleven years; the results are then compared with the plot of mean annual rainfall data of Mille station. The Fourier analysis was used to compare the general pattern and the effect of particular events (see fig. 20). In both cases the dry and wet period can readily be observed.

8.2 Temperature

Air temperature variations are mainly determined by height, although minor variations are caused by orientation of slopes and prevailing winds. A very close relationship (correlation coefficient of .95) was obtained between temperature and height (see fig. 21). Although the entire country lies within the tropics, only the low-land areas have high temperatures. The mean annual temperature of the Afar region around Dubti is about 30° C., whereas the mean annual temperature of the highland areas around Debre Sina is about 12° C. Regional classification of climate, based mainly on temperature, is shown in fig.21.

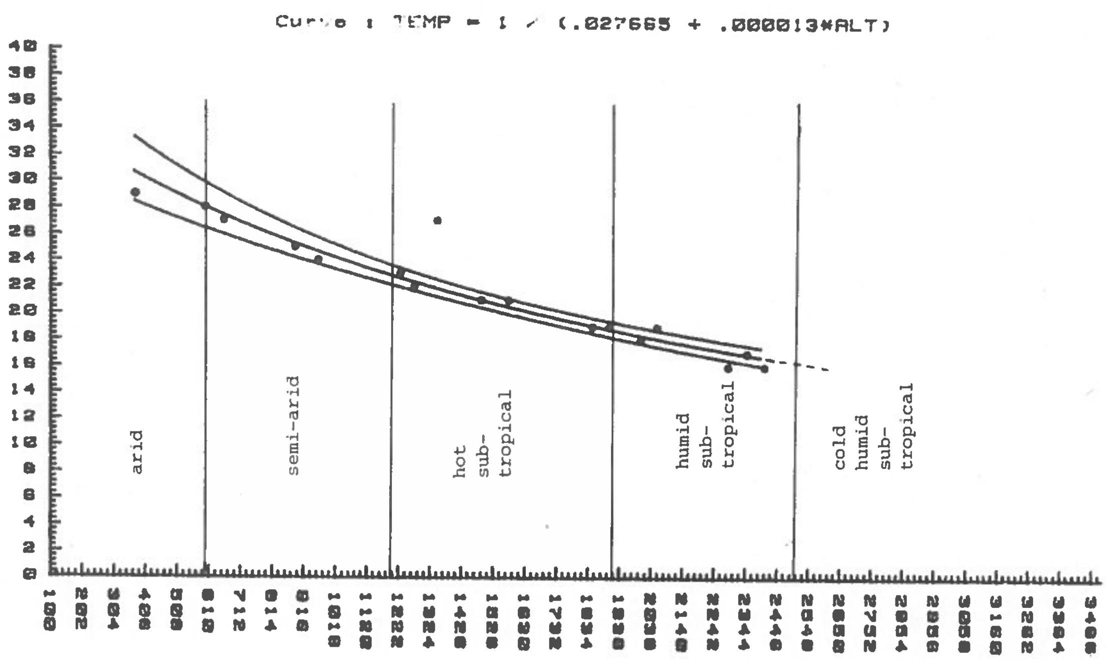


Fig. 21 . Figure shows the relationship between altitude and temperature.

8.3 Evaporation

Evaporation (Eo) is a process by which water becomes vapour directly from a free water surface or indirectly from sub-surface storage. The main factor affecting evaporation is the total solar radiation. Evaporation values, representing a large free water surface, were obtained from Colorado pan measurements. The annual values obtained from the pan measurements were corrected by multiplying with a factor of .8. The annual evaporation values obtained were plotted against altitude, and a non-linear regression analysis employed with the help of a computer program.

A non-linear curve, the equation of which can be written as

$$E = \frac{1}{(k + b(a))}$$

was used; correlation coefficient of .9 and mean square error of .0001 was obtained (see fig.24).

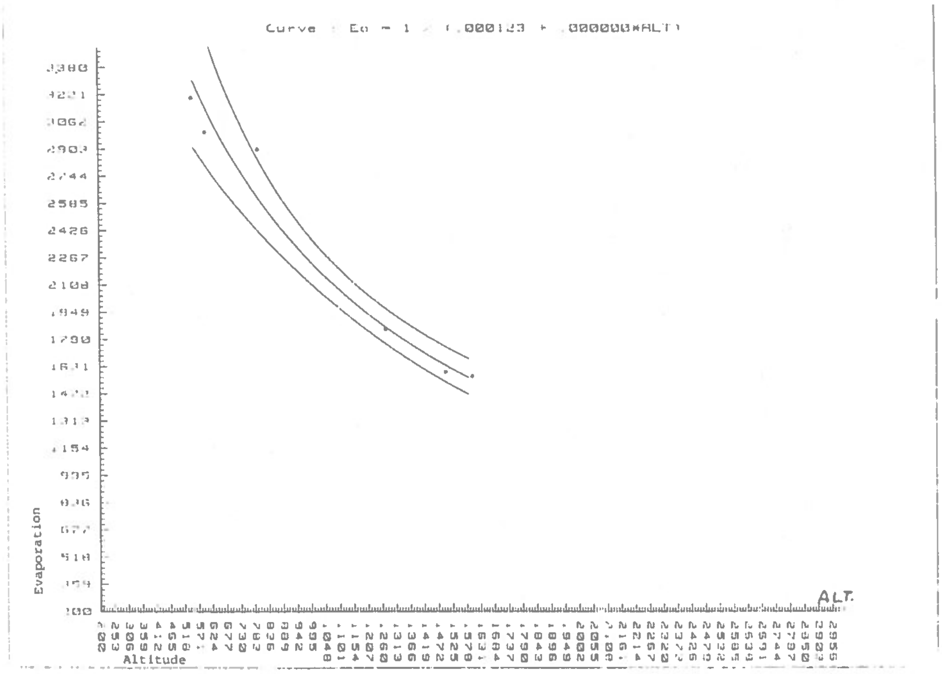


Fig. 22. Figure shows the relationship between altitude and evaporation.

8.4 Evapotranspiration

Transpiration is evaporation through the stomata of leaves.
Evapotranspiration (Et) is simultaneous occurrence of evaporation and transpiration.
Potential evapotranspiration (Eto) is the quantity of water which would be evaporated and transpired under a given climatic situation, if water supply was sufficient to meet all vegetation requirements.
Actual evapotranspiration (Eta) is the quantity of water actually evaporated and transpired under a given climatic situation.
Evapotranspiration can be divided into two parts:

a) Soil- and surface evapotranspiration is the part of evapotranspiration derived from soil moisture and by evaporation from the surface of water, vegetation, buildings and other objects.

b) Groundwater evapotranspiration is the part of evapotranspiration derived from the water table. It is applicable in areas where groundwater is shallow enough for the capillary fringe to extend from the water level to the surface.

A number of factors affect the rate of evapotranspiration. The main influencing factors are:

- solar radiation
- air and surface temperature
- humidity
- wind
- pressure
- water quality (colour, salinity, etc.)
- soil moisture content
- type, density and height of vegetation
- availability of water (rain, irrigation, etc.)

It is difficult to assess the relative importance of the above factors; we can, however, delineate areas of major climatic significance where the above factors play an important role.

Different evapotranspiration formulae have been developed by different people, using a few or several of the above factors.

It should, however, be clear that a certain formula would give better results in water balance calculations, if it were applied to areas where it could be more effective. For example, an area without vegetation, with high solar radiation, high temperature, low humidity, high wind speed, but without surface water or soil moisture content, will give high evapotranspiration if a formula containing these factors were applied, whereas, in fact, very little or no evapotranspiration takes place in this type of area.

It is attempted in the present study to delineate areas that have a major climatic significance influencing the above factors, so that the formula relevant to a particular situation can be applied.

Geomorphological and vegetation maps prepared from Landsat imagery (see p. 10,13) are used in order to distinguish areas of major climatic significance.

From the geomorphological map we can readily observe the existence of topographically contrasted regions with their effect on climatic situations.

From the vegetation map we can readily see the concentration and distribution of vegetation which, indirectly, shows the existence of excess water available for evapotranspiration.

It should be noted that evapotranspiration may be high during the vegetative growth and flowering period, and low during maturity. The degree of cover and rooting depth also affect the amount of evapotranspiration.

Marshy areas and lakes are delineated from dry areas, with the aim of distinguishing areas where potential rates are more important than the actual rate of evapotranspiration.

The topographically contrasted regions (above 3500 m.a.s.l. and below 400 m.a.s.l.) could possibly be divided into major climatic groups, that are liable to affect the degree of evapotranspiration.

The table below shows a regional classification of climates in the study area, partly based on regional classification of climates which fit in well with the one traditionally used in Ethopia (FAO, Survey of the Awash river basin, vol. iii). It is attempted in this study to evaluate the relative order of magnitude of the various factors affecting evapotranspiration.

TYPE OF CLIMATE		ALTITUDE mts.	ORDER OF MAGNITUDE OF THE FACTORS AFFECTING EVAPOTRANSPIRATION
climatic zones	Ethiopian classification		
arid	desert (bereha)*	below 600	very high temperature (more than 25°C.), rainfall is scarce and not sufficient for one crop, generally sparse vegetation, lakes and marshes present, wind speed is light (less than 2m/sec)
semi-arid	semi-desert (kefil bereha)*	600-1200	high temperature (20-25°C.), rainfall amount is not normally sufficient for one crop season, sparse vegetation, wind speed is light (less than 2m/sec)
hot sub-tropical	dry or humid (kolla)*	1200-1900	high to medium temperature (18-20°C.), dryness or wetness of climate is determined by degree of exposure to prevailing winds. The rainfall amount is sufficient for one crop season, vegetation is usually sparse with shrub and grass cover
humid sub-tropical	temperate (woinadega)*	1900-2500	low temperature (14-18°C.), the rainfall amount is sufficient, at least for one crop season, vegetation is moderate to dense with trees and grass cover, usually high soil moisture content
cold humid sub-tropical	cool temperature (dega)*	more than 2500	air temperature is less than 14°C., the rainfall amount is sufficient for at least one crop season, dense vegetation, high wind speed (greater than 2m/sec.

* Amharic words

The amount of measured values on the factors affecting evapotranspiration in the study area is very limited. From the existing data, however, the following formulae were considered.

Potential evapotranspiration ---------Penman
Thornthwaite
Khosla

Actual evapotranspiration ------------Turc
Langbein
Coutagne

The results, obtained by applying the above formulae, are given in Appendix, pages 93 to 112.

Potential evapotranspiration

Measured data on temperature, humidity, wind speed and sunshine duration for three stations (Dubti, Gewani, Robi) were employed in Penman's formula. The form of Penman's equation, which combines energy (radiation) balance and aerodynamic (wind and humidity) balance is given below:

$$ETo = c(\underbrace{w.Rn}_{\text{radiation term}} + \underbrace{(1-w) \times f(u) \times (ea-ed)}_{\text{aerodynamic term}})$$

where ETo = reference crop evapotranspiration in mm/day
w = temperature related weighting factor
Rn = net radiation in equivalent evaporation in mm/day
f(u) = wind related function
(ea-ed) = difference between the saturation vapour pressure at mean air temperature and the mean actual vapour of the air, both in m bar
c = adjustment factor to compensate for the effect of day and night weather conditions.

The calculations were carried out by computer, in which data input consists of a reflectance coefficient of .25 and .15, allocated for the wet seasons and dry seasons respectively (see Appendix, p.101).
The total annual values of the three stations showed close relationship with measured evaporation values:

	Dubti	Gewani	Robi
ETo	2390 mm	2360 mm	1810 mm
Eo	3100 mm	3000 mm	1900 mm
Eo/ETo	1.3	1.3	1.1

Annual potential evapotranspiration values obtained by applying Thornthwaite's formula showed a similar curve to that of the Eo curve when plotted against altitude. The three values obtained by applying Penman's formula lie between the curves obtained by applying Thornthwaite's method and evaporation curve (see fig.23).
Khosla's formula which is simply: ETo = 4.8 x T gave ETo values close to those of Penman for a specific climatic region (hot sub-tropical climate). This situation may also indicate the importance of considering climatic regions as given in the table on page 52.

Actual evapotranspiration

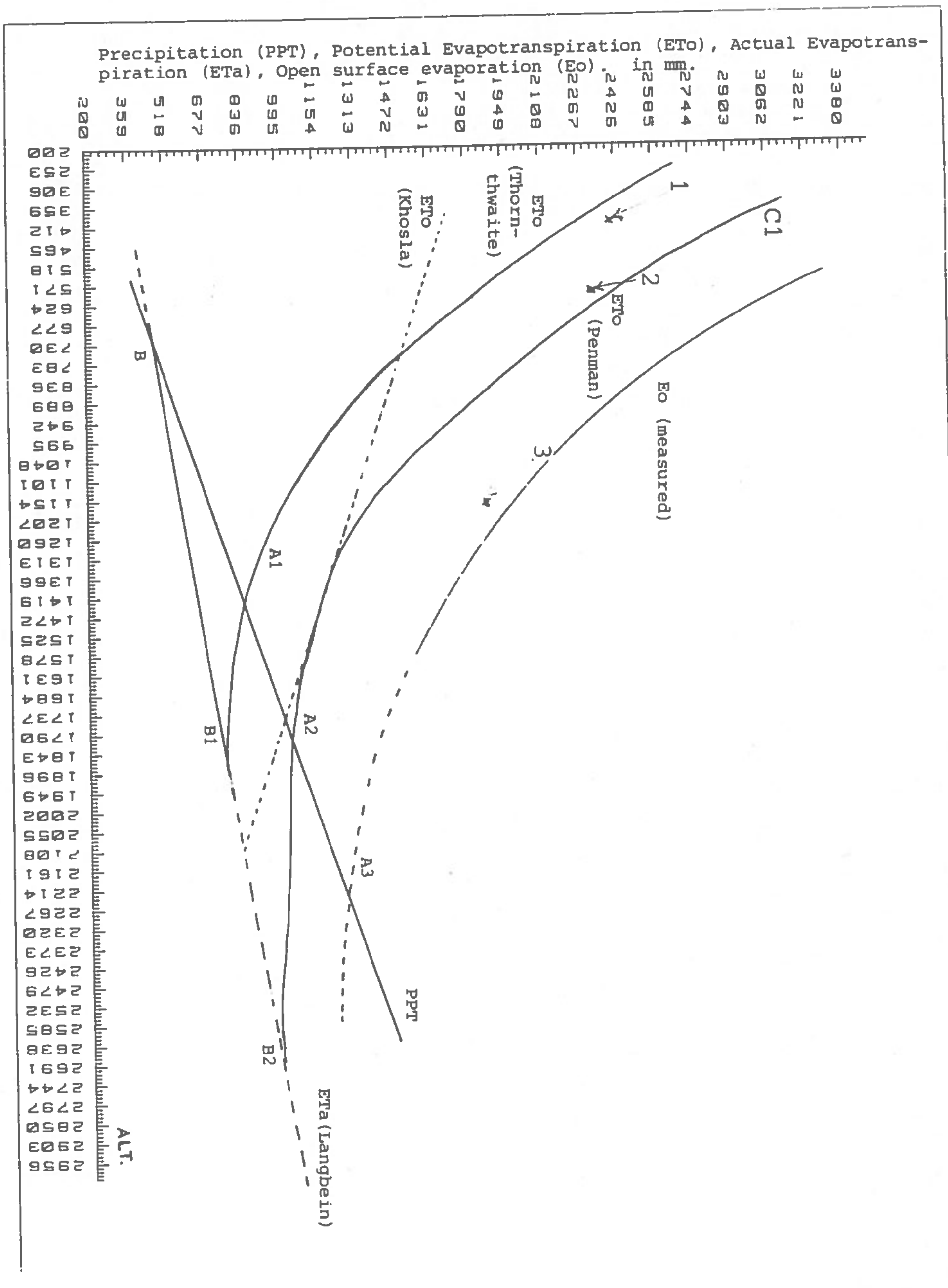
Yearly ETa values are obtained by applying the three formulae previously mentioned. The results are compared with one another by using linear regression analysis (see Appendix pages 105 to 113), for the purpose of chosing the best formula representing the actual rate of evapotranspiration for the areas considered.
Turc's and Langbein's formulae, which are based on temperature and precipitation factors, showed close correlation with altitude. Langbein's formula is chosen for the present purpose, based merely on its close correlation with altitude, as compared with other formulae.
Monthly ETa values of June, July and August for certain catchment areas have been obtained by subtracting the shifted runoff hydrograph from the precipitation curve (see page 62).
Monthly ETa values have also been obtained by applying Thornthwaite and Mather's method. The former method is found to be applicable in areas where soil moisture is not important.

Conclusions

In the present study, it has been attempted to analyse the effect of topography on hydrometeorological factors. The behaviour of these factors with respect to altitude has been studied under different climatic zones by applying different formulae. The situation can best be visualized from the series of graphs plotted on the same axes (see fig. 23):

1) ETo and Eo values show a rapid increase for low altitude areas, and decrease slightly (almost constant) for high altitude areas.

Figure 23
Altitude versus Meteorologic Factors



ETo values from Penman's equation. 1 = Dubti : 2 = Gewani
3 = Robi.
Note:- After considering the three plots C1 - B2 line is drawn to pass between ETo (measured) and ETo (Thornthwaite)

2) At B1 and B2: ETa = ETo, indicating areas where soil moisture conditions are suitable; when precipitation is greater than the actual rate: ETo = ETa.

3) The areas below B, on the other hand, suffer from soil moisture deficiency; groundwater evapotranspiration may take place if groundwater is shallow enough to rise up through the capillary fringe to the surface.

4) The area between A1 and A3 (1800 m.a.s.l.) marks the boundary between arid and dry regions.

In dealing with water balance techniques, superfluous results may be obtained if the appropriate evapotranspiration formula is not used for a certain place.

In the present study, the following procedure has been adhered to while applying water balance calculations; the same procedure* can be adopted for other parts of Ethiopia, where situations are similar to this area:

1) Measured Eo values and ETo values obtained from Penman's formula can be used interchangeably for free water surface and marshy areas; Eo = 1.2 x ETo could be applied.

2) ETo values obtained from Thornthwaite's formula, but preferably from Penman's formula can be used for areas above A1 and A2, respectively, as indicated in fig. 23.

3) Khosla's formula can be used in a hot, sub-tropical climate.

4) ETa values calculated by Langbein's formula can best be used for dry areas.

*The procedures discussed are tentative; they could be modified when more data are available.

9. RUNOFF

Soil surface acts as a sieve capable of separating rainfall into two basic components (Horton, 1973).
The flow of water over land surfaces before it reaches a defined stream channel is called surface runoff or overland flow.
The flow of water, initially into the soil,through the groundwater flow, and again to the stream, is called base flow.
It is difficult to make a clear-cut distinction between surface and groundwater flow.
The hydrograph of outflow from river basins with fluctuations of varying magnitude and shape express features of river basins.
Analysis of hydrographs helps in the study of particular characteristics of a basin.

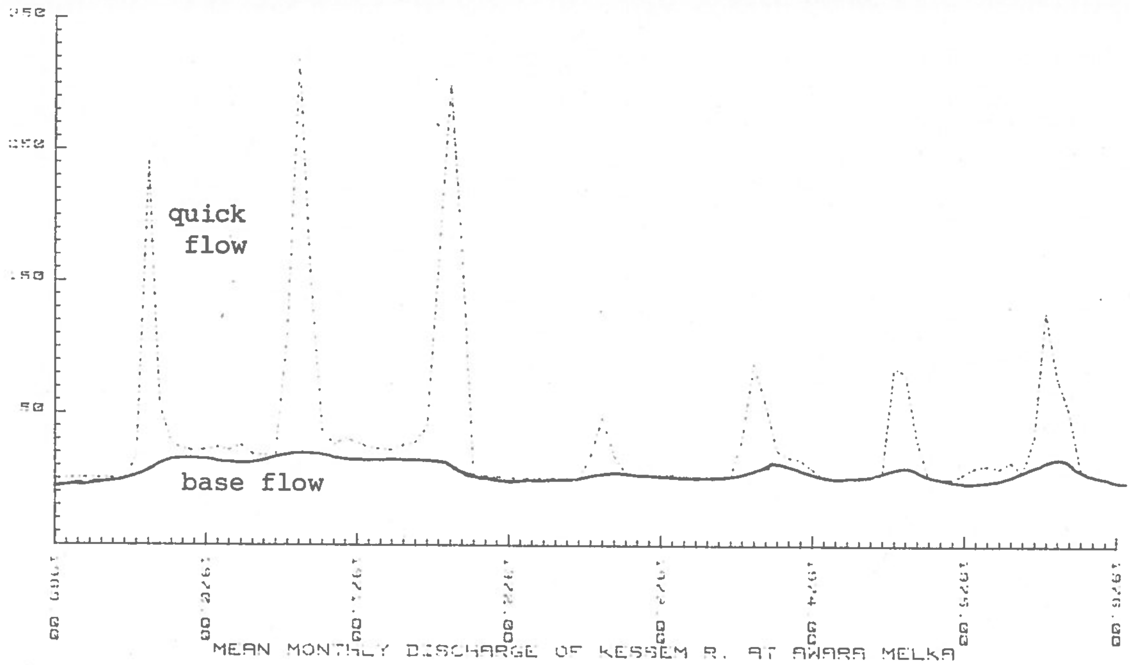
1) Analytical separation of hydrographs into two components

Monthly runoff measurements of 6 to 8 years,obtained from daily measurements for 6 river catchments, were compiled in the form of hydrographs. The hydrographs may be considered as a superposition of the surface runoff hydrograph and groundwater hydrograph.
The two basic components were separated; surface runoff, channel precipitation and interflow are grouped together as direct or stream runoff; groundwater or base flow is considered as the second component.
The method of separation is simple:- A line is extended back from the point where direct runoff ends. This line represents the recession of the groundwater hydrograph. The rising limb is selected arbitrarily.
If direct runoff does not end between peak values, groundwater recession is prolonged towards the second peak (see fig.24-26).
From the hydrographs on page 58/60 the following can be deduced:

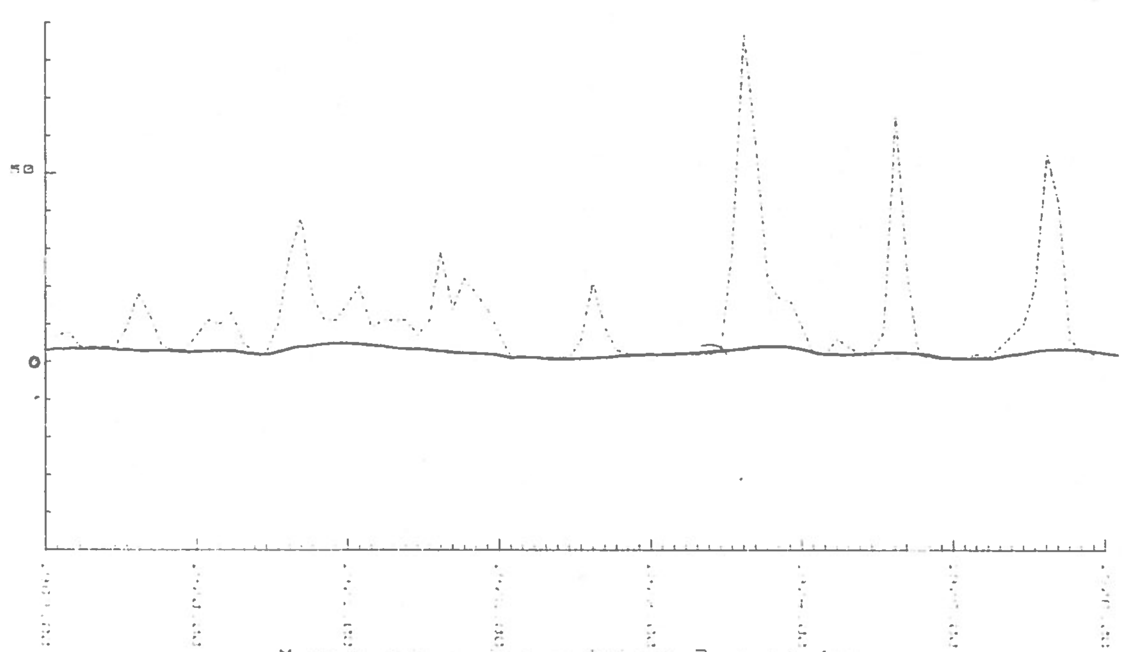
i) Peak discharges occur within particular months of the year (June, July, August, September).

ii) Large streams with a relatively high base flow have relatively low quick runoff values, as opposed to smaller streams with a relatively smaller base flow. This situation can also be observed from the curves obtained in the frequency analysis of annual discharge and maximum discharge measurements (see page 45).

Separation of Hydrographs
into two components

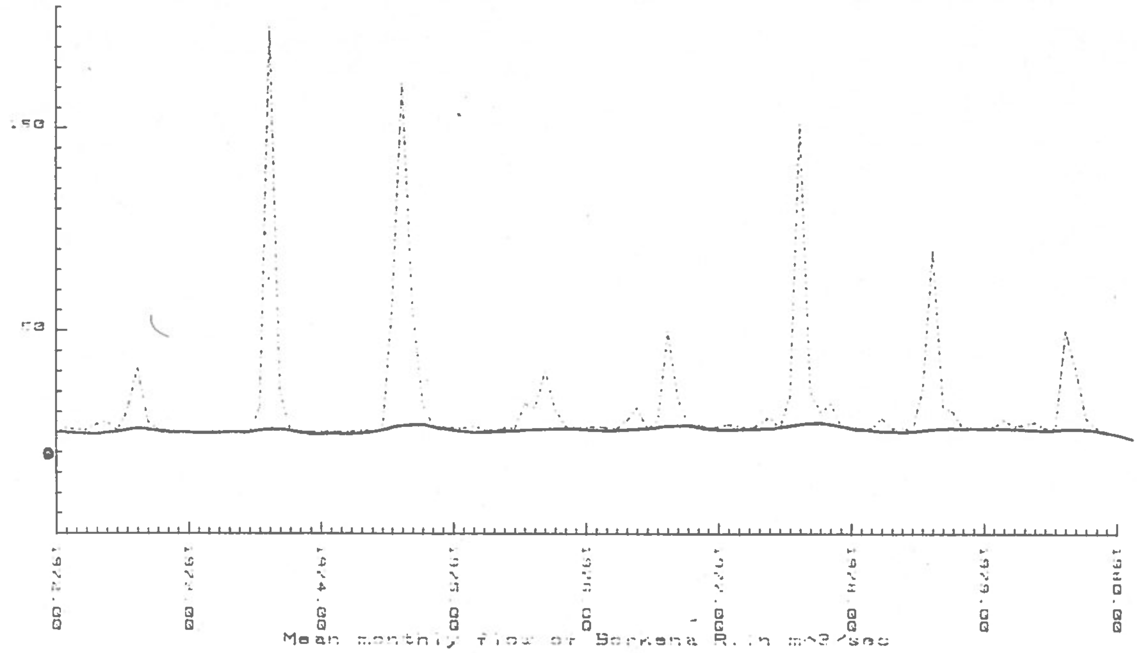


Kessem R. at Awara Melka

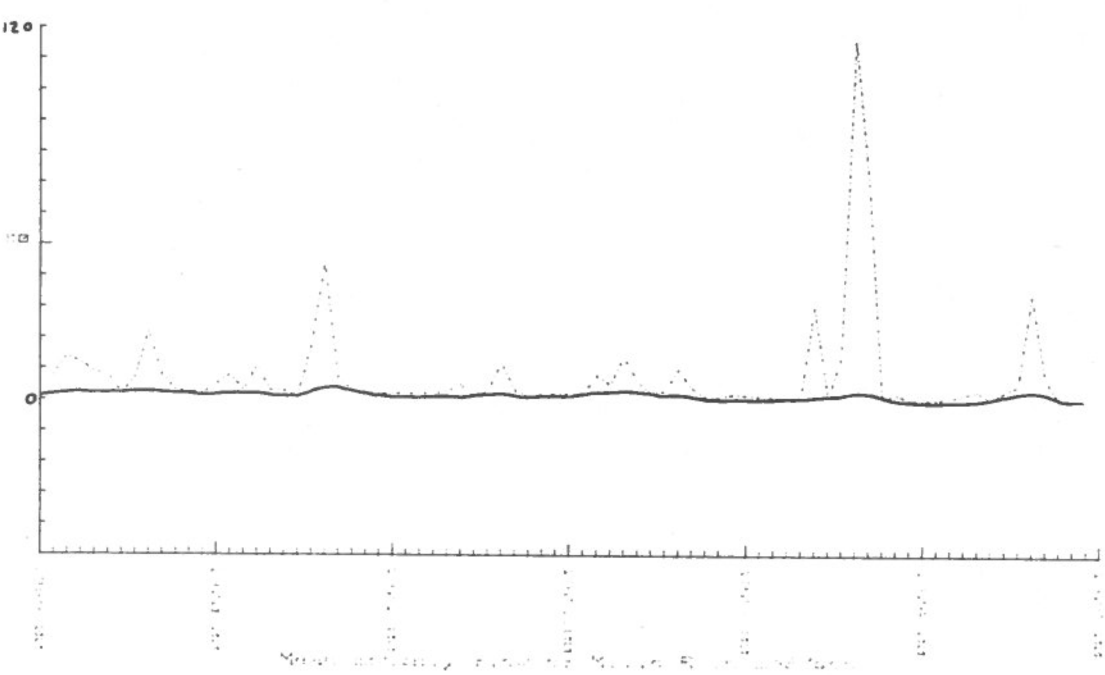


Kebana R.

Figure 24

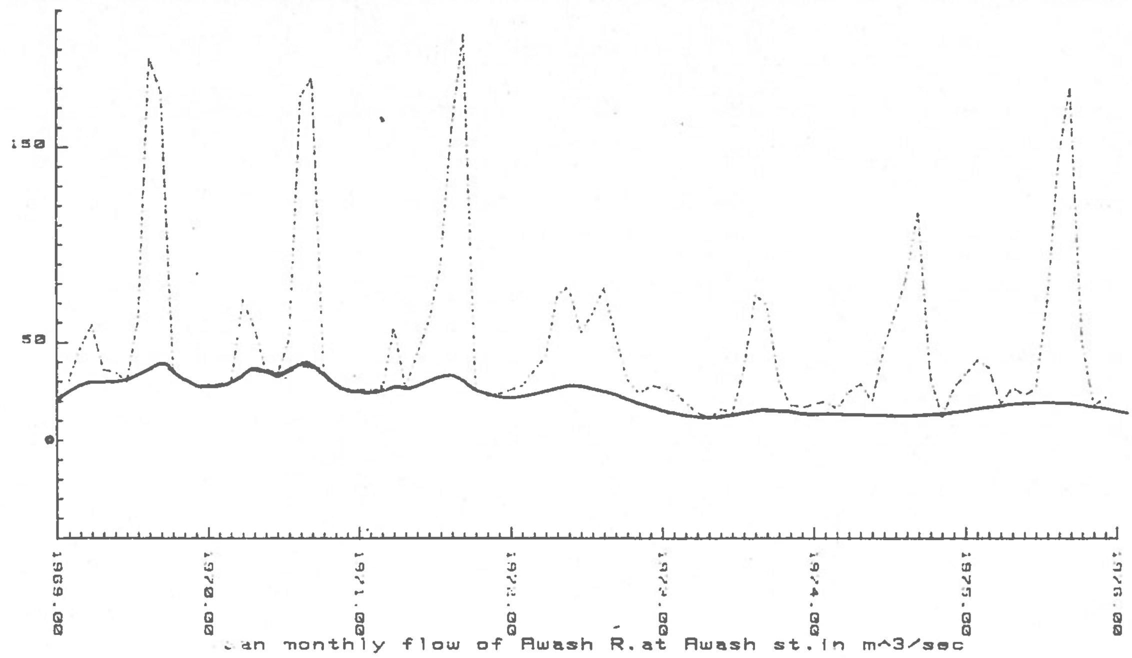


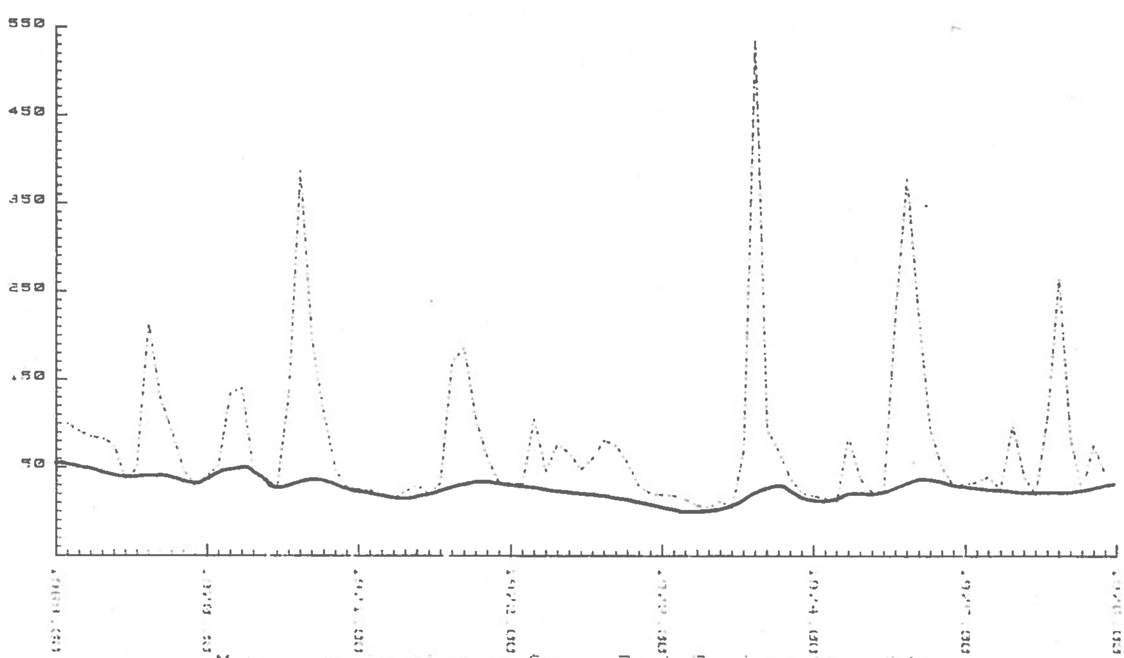
Borkena R.



Mille R.

Figure 25





Awash R. at Tendaho

Figure 26

iii) Base flow/quick runoff relations reflect response of catchments which are dependent on various factors, such as seasonal pattern and distribution, physical characteristics of the drainage basin, like drainage density, relief, soil moisture content and permeability. This last part (sub iii) is further explained in the following section:

2) Hydrograph shape and basin characteristics

Mean monthly runoff data of 6 to 8 years was obtained for four river catchments. The data were divided by the respective catchment areas and converted in mm/day. Rainfall data of the corresponding stations was also obtained in mm/day by applying the isohyetal method. Average hydrographs, representing rainfall runoff relations, were plotted by computer.
The following basin characteristics have been deduced from the shape and symmetry of the hydrographs. The relative magnitude of runoff and rainfall curves also reflects discharge coefficients (see figures on p. 62).
a) Quick response to runoff is not observed when rainfall values are relatively low. Most catchments show quick response to rainfall during wet seasons, except the large river Awash, whose catchment boundary is partly defined in the area.
This situation may explain the possibility of soil moisture utilization and/or land use pattern during dry seasons and excess of water during wet seasons. In other words, a storm of an intensity less than the infiltration capacity does not produce any direct runoff.
b) The hydrograph of Mille river catchment reflects a relatively low runoff coefficient; its hydrograph has a gently rising limb and gentle recession, its shape is also symmetrical, which implies slow response and depletion. This situation confirms the fact that the braided Mille river looses a significant amount of water along its course.
c) The rising limb and falling limb of Borkena river hydrograph are steep and symmetrical, which implies quick response and depletion. The catchment is relatively small and is characterized by its permanent marsh; the relatively small amount of rainfall during the dry seasons accounts for the amount of water lost by evapotranspiration in keeping the marsh throughout the year. The actual rate of evapotranspiration for this catchment, determined by subtracting runoff from precipitation,

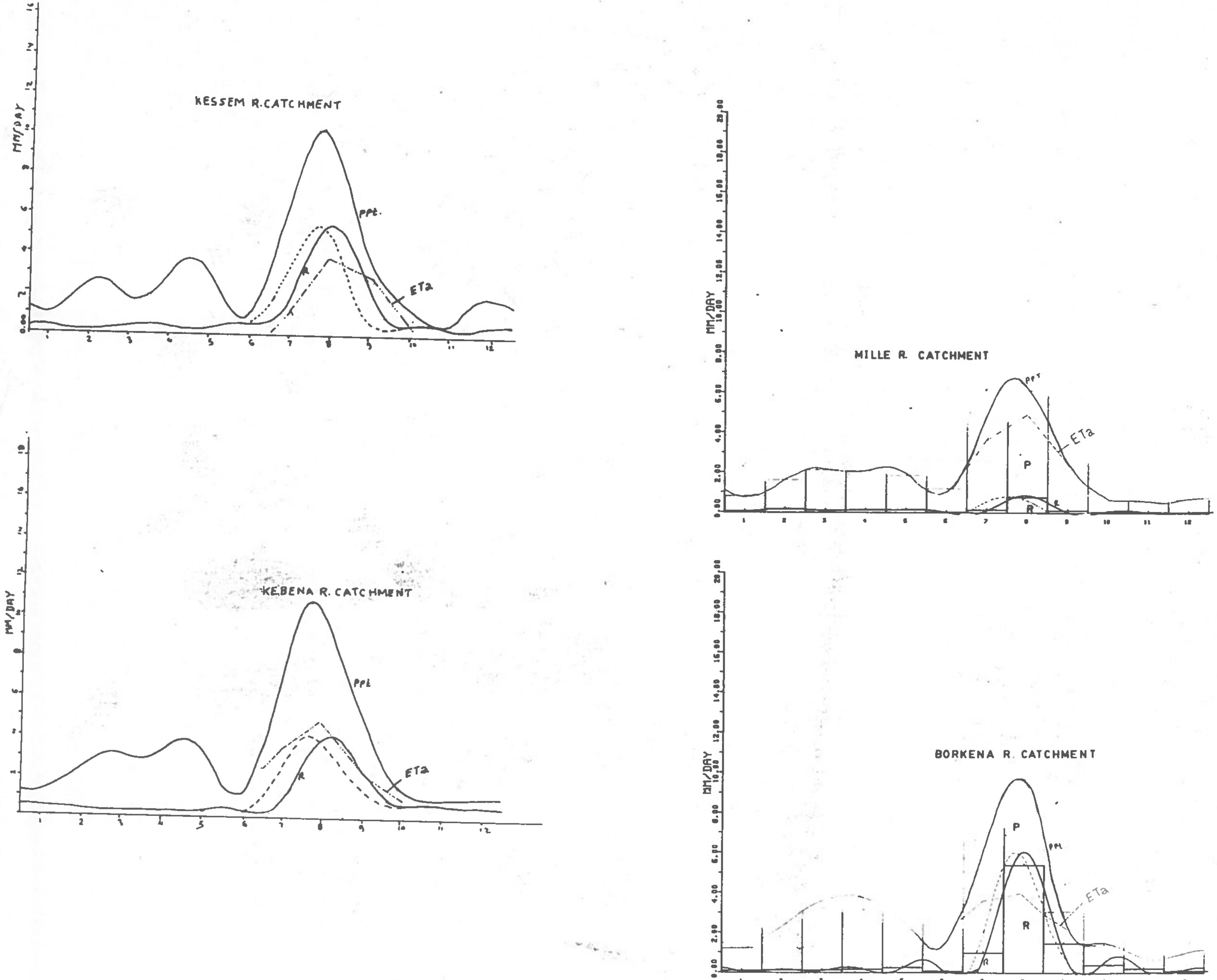

KESSEM R.CATCHMENT
MM/DAY
PPt.
R
ETa
KEBENA R. CATCHMENT
MM/DAY
PPt
R
ETa
MILLE R. CATCHMENT
MM/DAY
PPT
ETa
P
R
BORKENA R. CATCHMENT
MM/DAY
P
PPt
ETa
R

Figure 27

gave close values when compared to ETa values by the Thornthwaite and Mather method (see fig. 30).

d) The hydrograph of Kessem river is symmetrical with a steep rising limb and falling limb which shows quick response and depletion. This situation explains the steep topography of the catchment.

e) The hydrograph of Kebena river is asymmetrical, with a steeper rising limb compared to the falling limb, which denotes quick response and slower depletion. The relatively low runoff coefficient suggests that a considerable amount of water is lost, perhaps by influent condition, towards the foot-hill areas, before the measuring station.

The amount of water lost by actual evapotranspiration from the above catchment areas can be obtained by the following procedure:

- the runoff curve representing the wet seasons is copied and shifted horizontally to the left and traced below the rainfall curve.
- monthly discharge values are graphically determined from the copied curve.
- rainfall minus discharge of the corresponding months representing ETa values is plotted (see fig. 27).

This method assumes that after some time (in the present cases 10-20 days) the water lost during initial infiltration into the soil will return to the stream through groundwater flow.

This method of obtaining ETa values, however, may not be applicable to large areas where the probability of deep percolation through permeable rocks is high, or to large areas where response to rainfall is not easily observed. However, it works quite well in small catchments where soil moisture is not very important.

Frequency analysis of mean annual discharge and peak discharge measurements is employed by the same procedure as discussed on page 42.

The salient features of the graphs are similar to the rainfall graphs (see fig. 18).

It is interesting to note from the peak discharge curves, that variability of the slopes increases when base flow is low.

10. RECHARGE

In evaluation of groundwater resources, recharge rates for aquifers are one of the most important factors to be considered.
In the previous chapters we have discussed permeability of the rock and soil units. The factors affecting infiltration in the rock units are primarily those which characterize their secondary features, like fracturing and weathering. The factors affecting infiltration in the soil units are those which characterize the pore size of the soil and their relative permanence.
The recharge possibility by some of the streams with measured data has been analysed from the shape of the respective hydrographs. A number of other streams, whose discharges have not been measured, may also exhibit similar characteristics in the hydrographs, and it is likely that a considerable amount of water is recharged to the groundwater by those streams.
In the valley bottoms of the Escarpment areas, the water table occurs above the water surface of the streams, hence, effluent conditions are prevalent. In the Rift floor and Rift borders (foot-hills), the water table is below the water surface of the streams,and recharge occurs, by influent condition, wherever the stream-bed is permeable.
Basic rocks, occurring extensively in the Rift, have a relatively high heat conductance, which may facilitate vaporization during the day. Regardless of high evapotranspiration rates within the Rift floor, however, rain drops over the permeable units could directly percolate to the groundwater body, before evapotranspiration could take place. It should be noted that, in areas where the amount of precipitation is relatively small, the intensity of rainfall becomes very important. In the volcanic terrain of the Afar floor, high intensity of rainfall favours high infiltration.
Residual soils developed over the soil units in the area, usually retard deep percolation of groundwater. Permeability of some of the highly permeable rocks, like the limestones on the Eastern Plateau, are reduced by the presence of the residual soils.
The amount of water that reaches the regional groundwater body is equal to the total infiltration minus the amount of water absorbed by the alluvial sediments. Soil particles have the ability to soak

up a certain amount of water and to hold it in capillaries against the pull of gravity. Water starts to percolate through the non-saturated zone into the saturated zone, when the soil moisture has reached its field capacity. The part of groundwater accreted in the soil is called soil moisture accretion.
The movement of water towards the underlying groundwater system depends on the height of the water table, the size of pores between grains and the nature of the rock beneath the soil. The amount of effective rainfall is greater, when the water table is deeper than when it is very shallow. Crops with high water consumption create a greater deficit of moisture in the soil.
The hydrogeological map shows that the area, especially the Rift floor, is largely covered by soil. The amount of water retained in the soil is, therefore, quantitatively determined in the following chapter.

11. WATER BALANCE

In the previous chapters, several factors affecting the total amount of water gain or loss have been discussed. In this chapter, the order of magnitude of these factors is numerically tabulated, and the hydrologic budget, defining water loss from or gain in a basin, is calculated by means of a very useful tool, known as water balance.

The water balance can be used in the evaluation of water resources, for studying and planning various schemes related to surface water or groundwater and land use.

In the Afar (Middle and Lower Awash regions), where extensive agricultural schemes, like cotton plantation are in progress, an understanding of the soil moisture conditions, during wet and dry periods, will certainly help in agricultural planning. The soil moisture conditions of the area can be understood by the water balance technique.

Ten years' average monthly water balance, by the Thornthwaite and Mather method

The water budget in the area has been treated by using the Thornthwaite and Mather method.

The water balance of a basin, underlain by impervious rock at depth, can be expressed as follows:

$$P=I+ETa+OF+dSM+d(GWS)+GWR$$

where P=precipitation

I=interception

ETa=actual evapotranspiration

OF=overland flow

dSM=change in soil moisture

d(GWS)=change in groundwater storage

GWR=groundwater runoff

The water balance of the area was calculated by means of the computer, where input values are the average monthly runoff in percent of water available for runoff, direct storm runoff in percent of precipitation, available water capacity of the root zone, precipitation and potential evapotranspiration. Since the available water capacity (percent volume) depends on the type of soil and vegetation, the method employed in obtaining the available water capacity of the root

LONG TERM AVERAGE MONTHLY WATER BALANCE - MULLU DOBA BASIN

Average monthly runoff : 0 % of available water for runoff
Direct storm runoff : 0 % of precipitation
Available watercapacity : 150 mm.
of rootzone

mm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
P	20	65	75	90	80	45	210	250	100	45	25	30	1035
PET	25	55	65	65	75	115	65	60	65	55	50	45	740
P-PET	-5	10	10	25	5	-70	145	190	35	-10	-25	-15	295
AC POT WLS	-55					-70				-10	-35	-50	
SM	104	114	124	149	150	94	150	150	150	140	119	107	
dSM	-4	10	10	25	1	-56	56	0	0	-10	-22	-11	
AET	24	55	65	65	75	101	65	60	65	55	47	41	717
D	1	0	0	0	0	14	0	0	0	0	3	4	23
S	0	0	0	0	4	0	89	190	35	0	0	0	318

All values in the table are in millimeters.

P = precipitation

PET = potential evapotranspiration

P-PET = precipitation minus potential evapotranspiration

AC POT WLS = accumulated potential waterloss

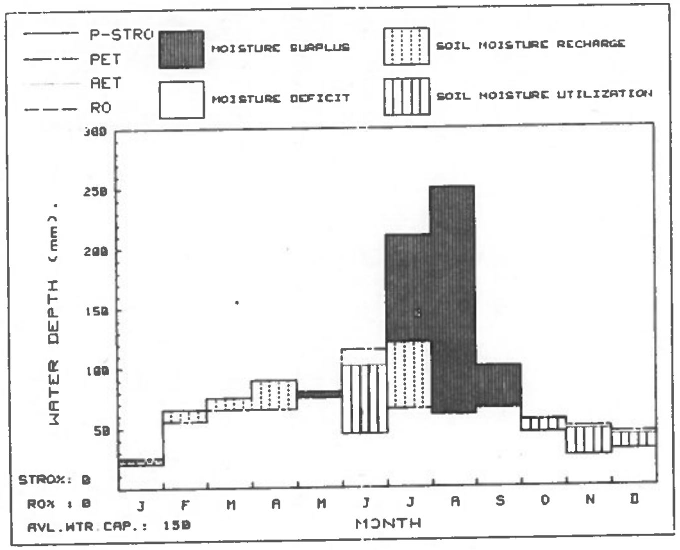
SM = soilmoisture

dSM = change in soilmoisture during the month indicated

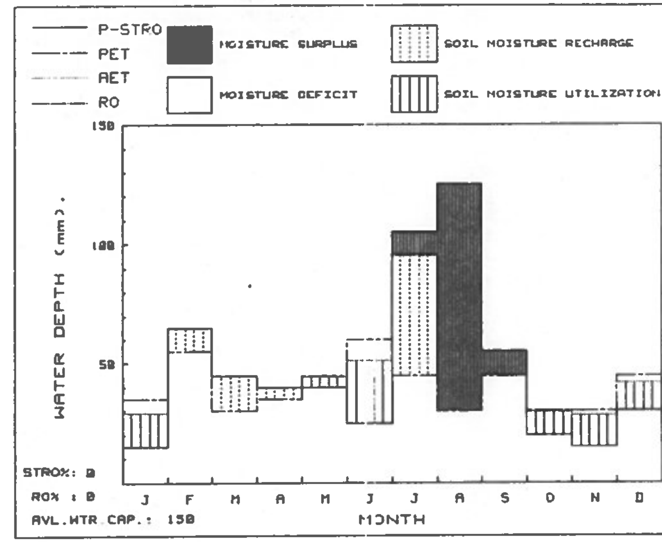
AET = actual evapotranspiration

D = soil moisture deficit

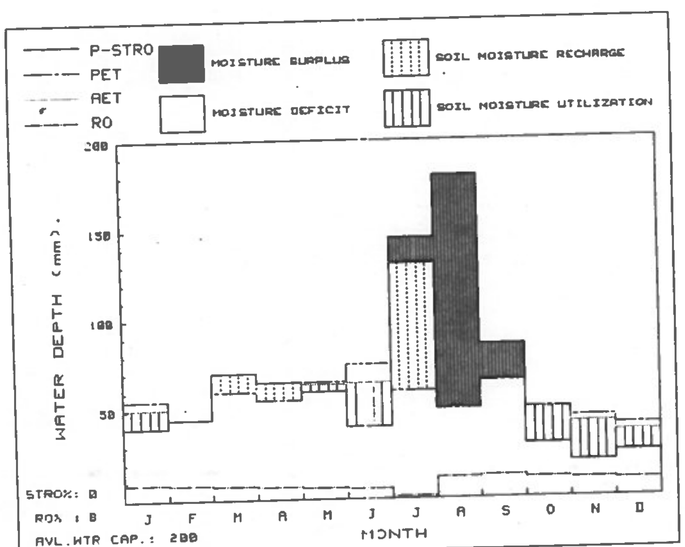
S = surplus



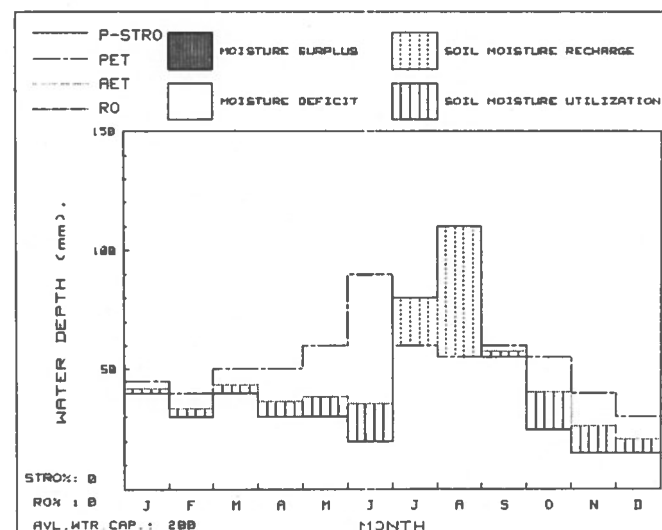
Mullu-Doba basin



Loggiya Catchment

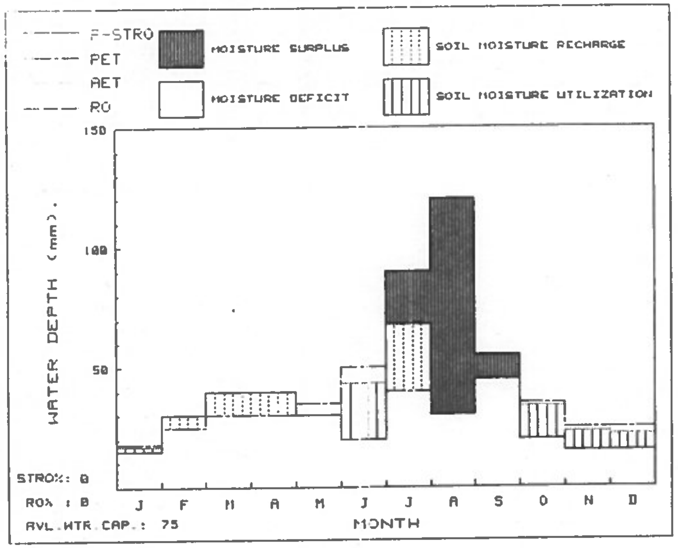


Mille Catchment

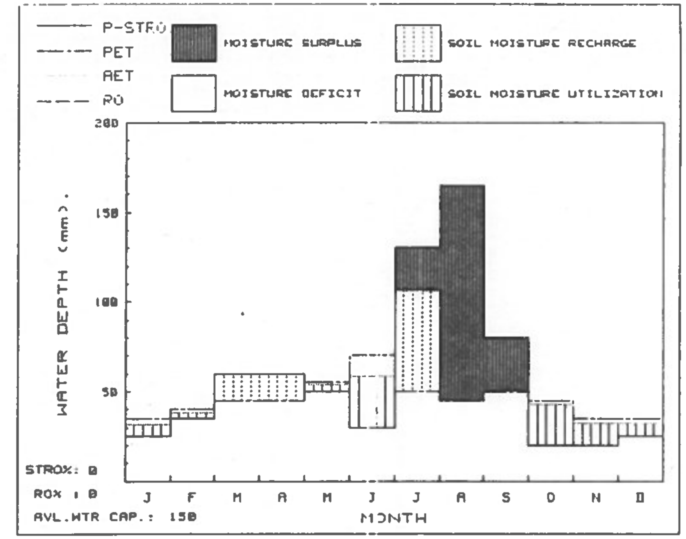


Lake Abbe basin

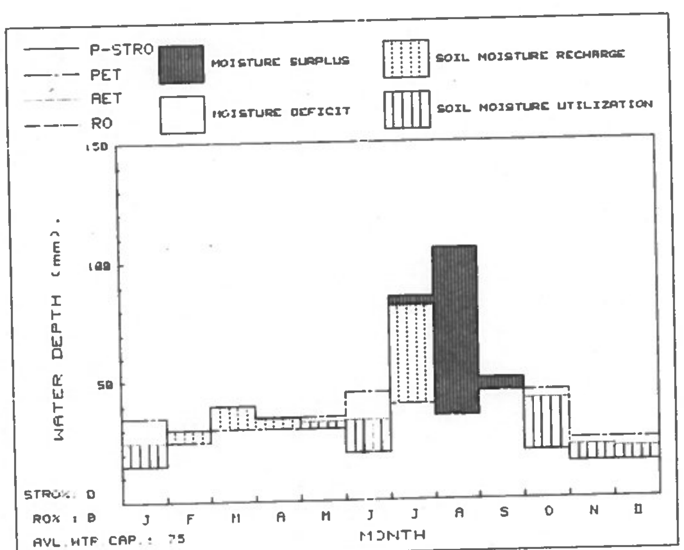
Figure 28



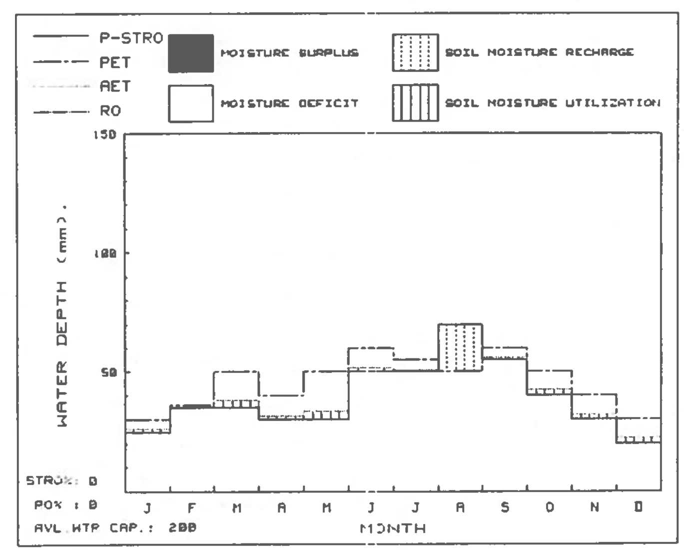
Manda basin



Buren basin

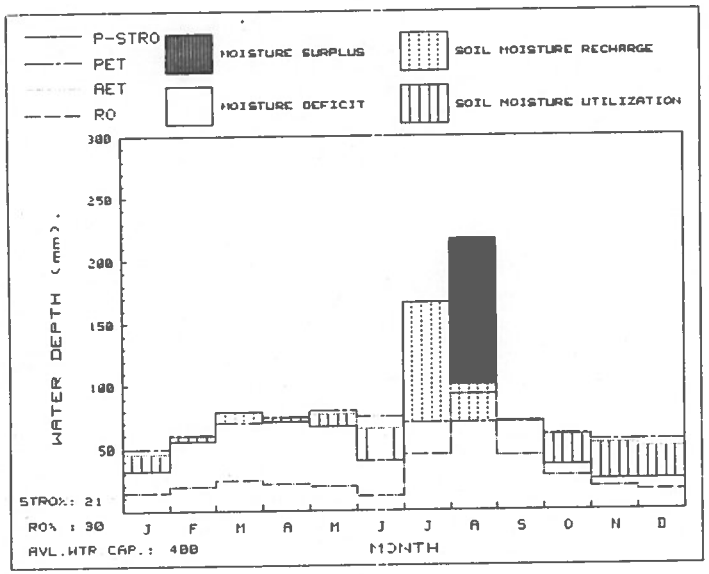


Dahwi basin

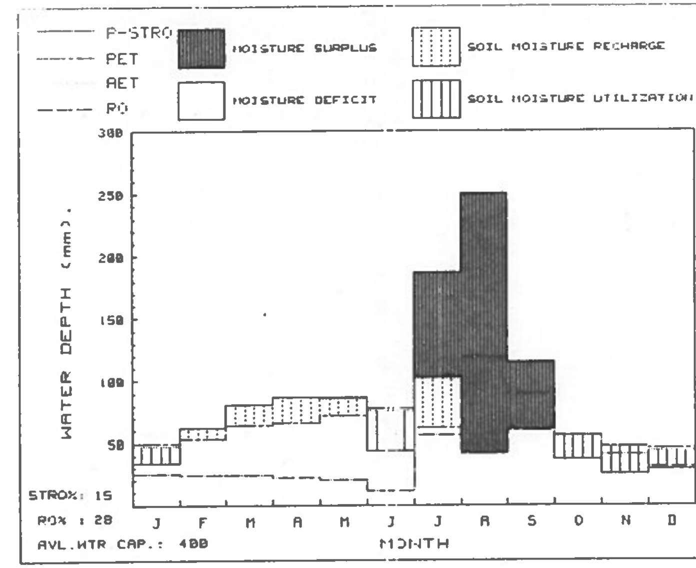


Middle Awash basin

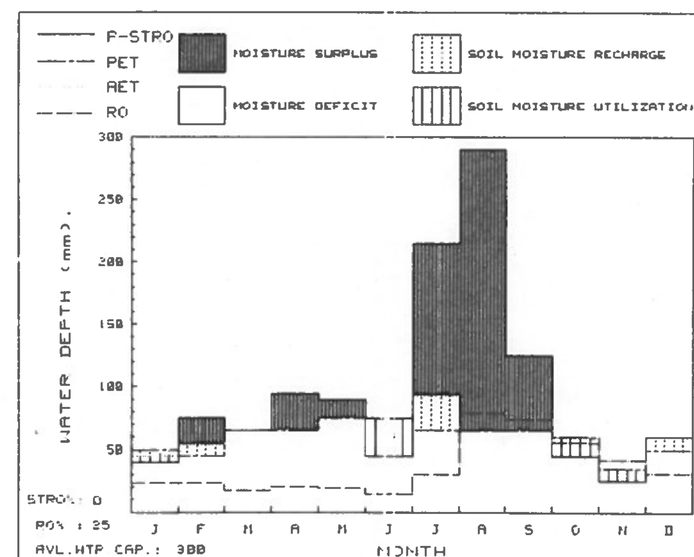
Figure 29



Borkena Catchment



Kebena Catchment



Kessem Catchment

Figure 30

zones is explained as in the following table.

Available water capacities of soil texture and vegetation
(after Thornthwaite and Mather)

basins	area km²	% soil cover	vegetation	soil texture	available water capacity in %	rooting depth in m.	available capacity of root zones in mm.
Kessem	2406	10	mature forest	silt loam	20	2	300
Kebena	1212	10	" "	" "	20	2	400
Borkena	1481	70	" "	clay loam	25	1.6	400
Mille	4600	50	deep rooted (grass)	silt loam	20	1.25	250
Middle Awash	28140	40	moderately deep rooted (cotton)	" "	20	1.0	200
Loggya	3922	50	deep rooted	fine loam	15	1	150
Mullu-Doba	8460	25	" "	" "	15	1	150
Buren	25465	30	" "	" "	15	1	150
Dahwi	2755	90	shallow rooted	fine sandy loam	15	.5	75
Manda	2966	50	" "	" " "	25	.8	200
L.Abbe	12653	30	moderately deep rooted	loam	25	.8	200

The soil moisture content (ST) is calculated from the following formula:

$$ST = STo \times e^{\frac{-APWL}{sto}}$$

where STo = moisture content at field capacity

APWL = accumulated potential water loss

e = known constant (base of natural logarithm = 2.71)

The water retained in the soil (ST) for various amounts of accumulated potential water loss, can also be obtained from the following figure.

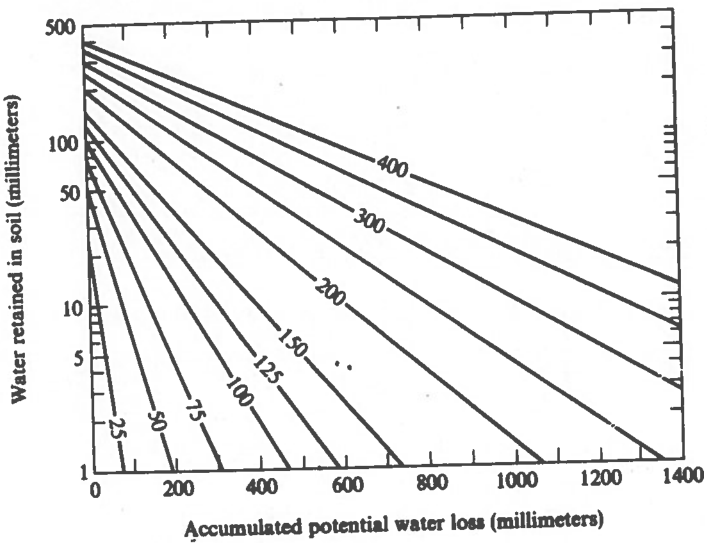


Fig. 31. Water retained in the soil against an accumulated potential water loss. The number on each curve is the available water capacity for the soil in millimeters (data from Thornthwaite and Mather, 1957)

-- When precipitation exceeds potential evapotranspiration, the actual rate equals the potential rate.

-- The difference between actual evapotranspiration and precipitation is the change in soil moisture.

-- The difference between the actual rate and potential rate is the soil moisture deficit.

-- The amount of water that cannot be stored (PPT - ETo) is surplus.

The water balance programme employed in this study enables us to see the above situation.

An example (Mullu-Doba, closed basin) of water balance technique, reflecting the interrelationship of hydrometeorology and soil moisture conditions is presented in a table (see page 67).

The results of calculation by computer enable us to immediately see water balance situations by means of diagrams (see figures on pages 68 to 70).

Ten years' average yearly and monthly water balance

The yearly water balance of the whole basin has been calculated by hand; the monthly water balance is graphically presented by the computer.

In both cases, the general water balance equation was employed:

$$dS = P - ET \pm R$$

where dS = change in storage in channels and reservoirs, in soil moisture and in groundwater

P = precipitation

ET = evapotranspiration

R = difference between stream inflow (+) and stream outflow (-).

Groundwater inflow is assumed to be equal to groundwater outflow. The values assigned to the right hand side of the equation and the procedures followed in calculating the water balance are given below:

a) The yearly values of the meteorological factors within certain contour intervals were represented in a map (see fig. 16).

b) The yearly water balance was obtained by multiplying the magnitude of the factors within the intervals by the corresponding areas, and summing up the results. The table below shows yearly water balance in km^3:

For river catchments $Pi \times Ai - Ei \times Ai - R = ds$

where Pi = precipitation within contour intervals

Ai = area between the contour intervals

R = runoff

ds = change in storage

Ei = evapotranspiration within the contour intervals

	$\Sigma PiAi$		$\Sigma EiAi$		R	ds
1) Kessem	2.80915	-	1.792294	-	.92716	= .089696
2) Kebena	1.50417	-	.88054	-	.37843	= .2452
3) Borkena	1.70348	-	1.161135	-	.46253	= .079815
4) Mille	3.5443	-	2.9618195	-	.19579	= .3866905
5) Middle Awash	19.05256	-	18.3622	-	1.1626 (inflow-outflow)	=-.348662
6) Loggiya	2.12036	-	1.815129 = .30251 (change in storage,plus runoff)			

For other closed basins $Pi \times Ai - Ei \times Ai = R + ds$

	$\sum$ PiAi		$\sum$ EiAi			ds
7) Mullu-Doba	9.30259	-	6.2443575		=	3.0582325
8) Manda	1.48295	-	1.2605075		=	.2224425
9) Dahwi	1.21192	-	1.079746		=	.132174
10)Buren	17.234668	-	14.563071		=	2.6715966
11)L. Abbe	4.50728	+	2.8272 (inflow)	-	8.4104969	= -1.0860169

By adding all the values on the right hand side and dividing the result by the total area, $\frac{5.9536782}{94060}$, we obtain 61.2 mm of water recharged into the area by direct precipitation and also by an inflow from the Awash river.

The Awash river contributes $\frac{(2.8272 \; - 1.1626)}{94060 \times 1000000}$ = 17.7 millimeters of water to the entire area.

The total amount of water infiltrated into the soil and the rock units by direct precipitation is 44 millimeters.

c) For the monthly water balance, the average monthly percentages of precipitation and temperature for the particular months were calculated from the monthly percentage values of the ten years' data; close inspection of the data has revealed more or less the same percentage values for the same months at different places (see table on page 43).

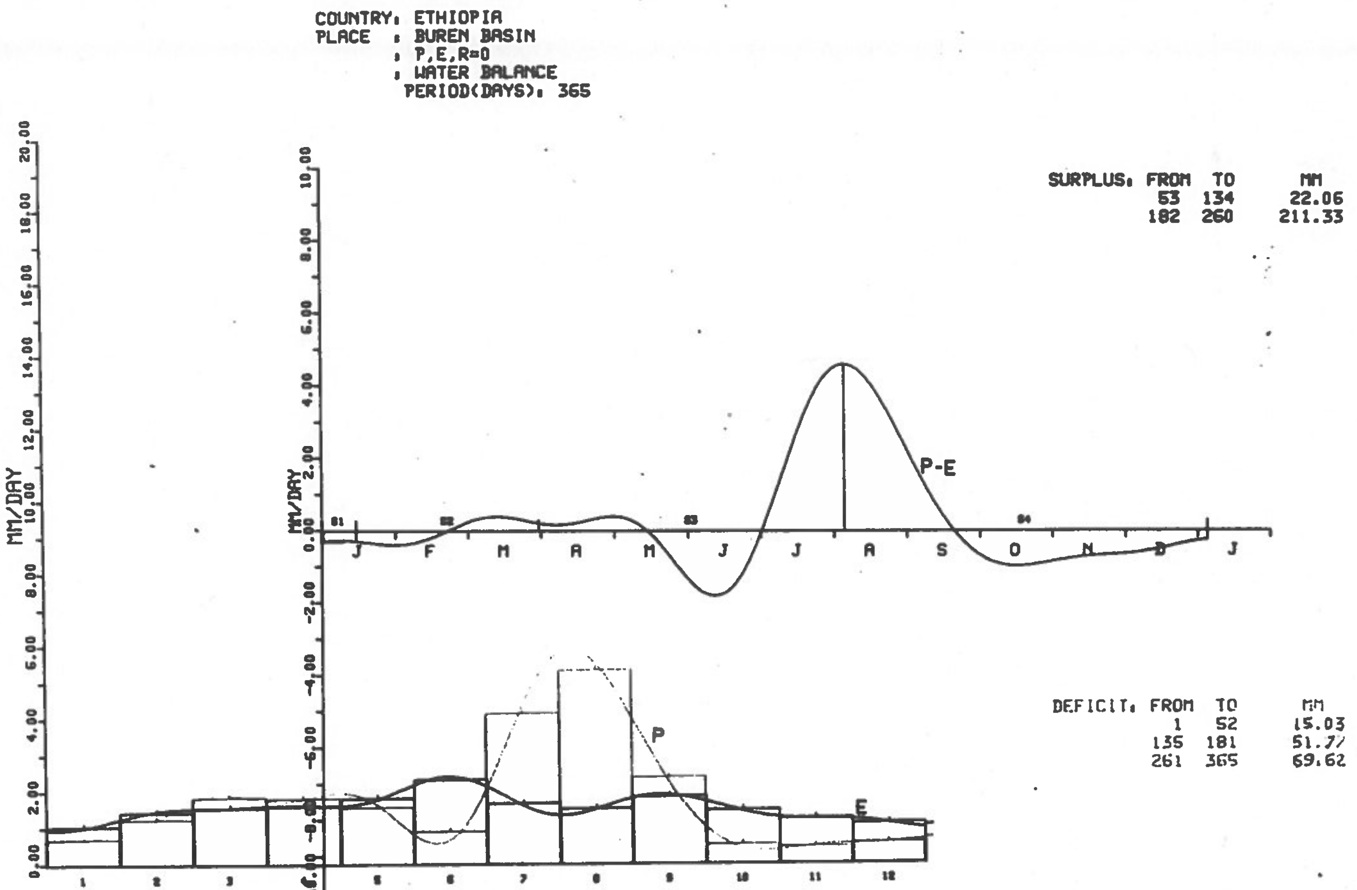
d) Monthly precipitation and evapotranspiration values were obtained by multiplying the percentages by the yearly values (all values were converted to millimeters per day).

e) Discharge measurements for the river catchment areas were converted to millimeters per day.

f) By applying the computer programmes, curves - representing inflow and outflow relations - were obtained.

g) The programme adds the two curves and separately draws the resulting curve (see figures, page 75 to 80). The water balance situations,representing the number of days with a deficit or surplus amount of water, are numerically tabulated at the right corner of the curves.

The yearly values obtained by this method are compared with the yearly values from the earlier method; the yearly values in the latter case have been converted to millimeters per day.


COUNTRY: ETHIOPIA
PLACE : BUREN BASIN
: P,E,R=0
: WATER BALANCE
PERIOD(DAYS): 365
MM/DAY
P-E
P
E
J F M A M J J A S O N D J
SURPLUS: FROM TO MM
53 134 22.06
182 260 211.33
DEFICIT: FROM TO MM
1 52 15.03
135 181 51.77
261 365 69.62

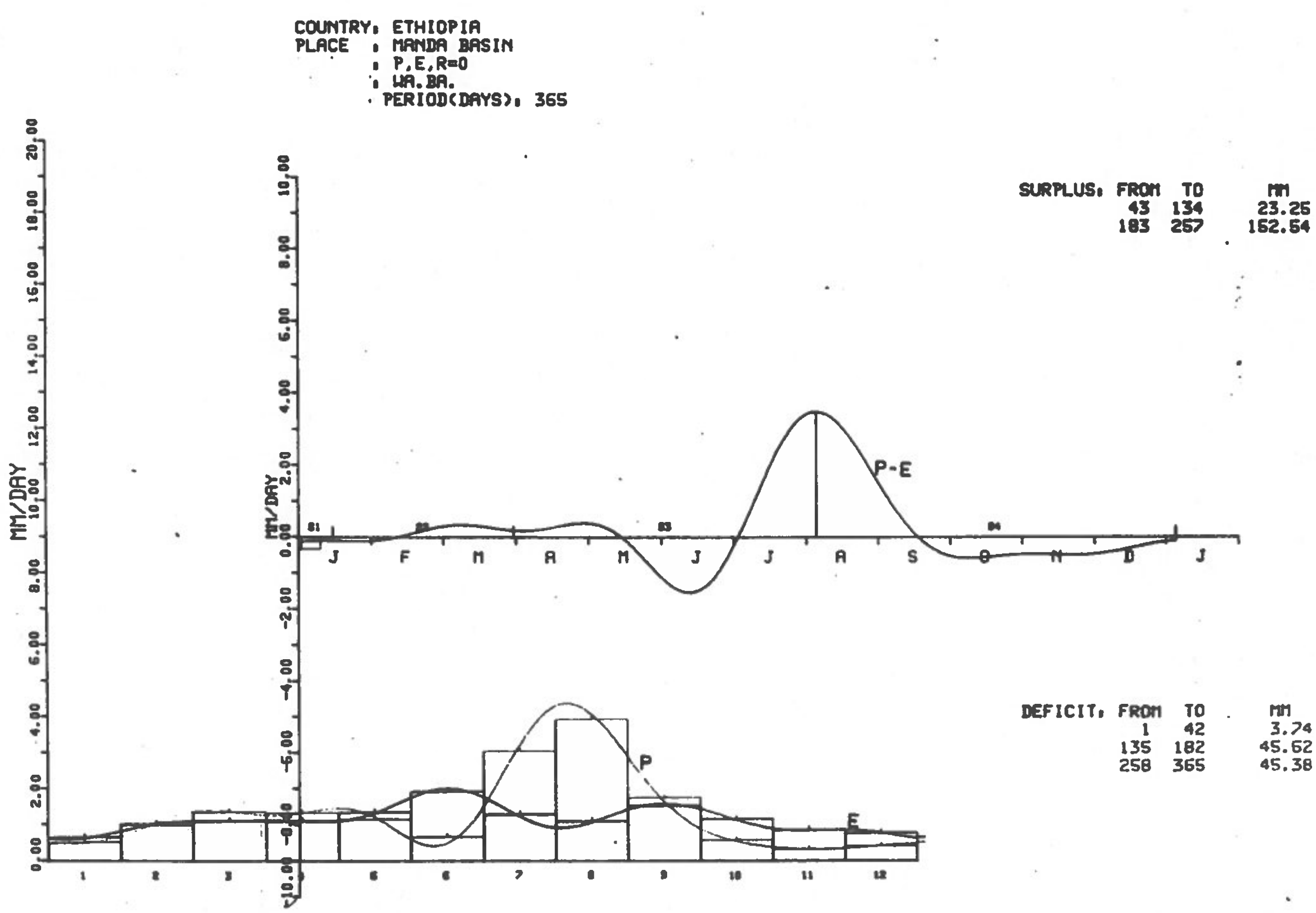
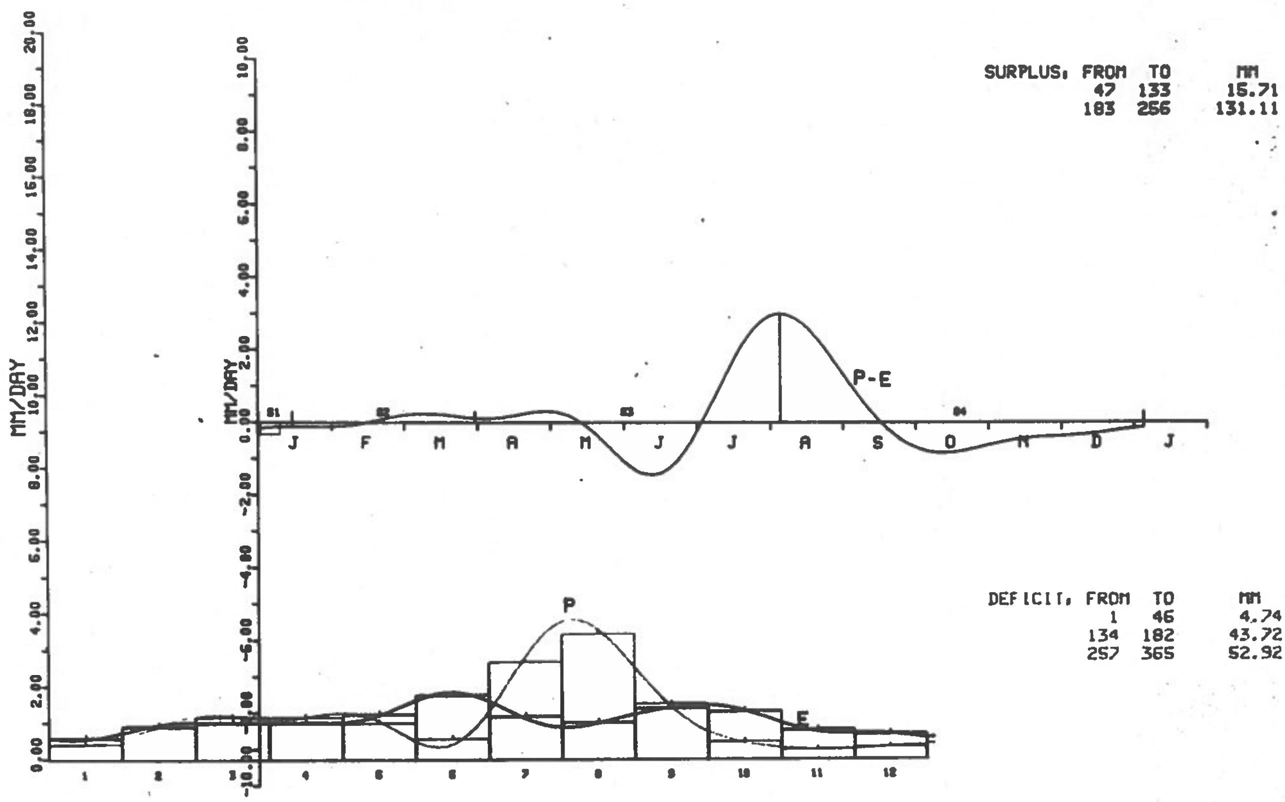

COUNTRY: ETHIOPIA
PLACE : MANDA BASIN
: P,E,R=0
: WA.BA.
PERIOD(DAYS): 365
MM/DAY
P-E
P
E
J F M A M J J A S O N D J
SURPLUS: FROM TO MM
43 134 23.25
183 257 162.54
DEFICIT: FROM TO MM
1 42 3.74
135 182 45.62
258 365 45.38

Figure 32

COUNTRY: ETHIOPIA
PLACE : DAHWI BASIN
: P,E,R=0
: WATER BALANCE
PERIOD(DAYS): 365



COUNTRY: ETHIOPIA
PLACE : LOGGIA CATCHEMENT
: P,E,R=---
: CURVE=P-E=I+R
PERIOD(DAYS): 365

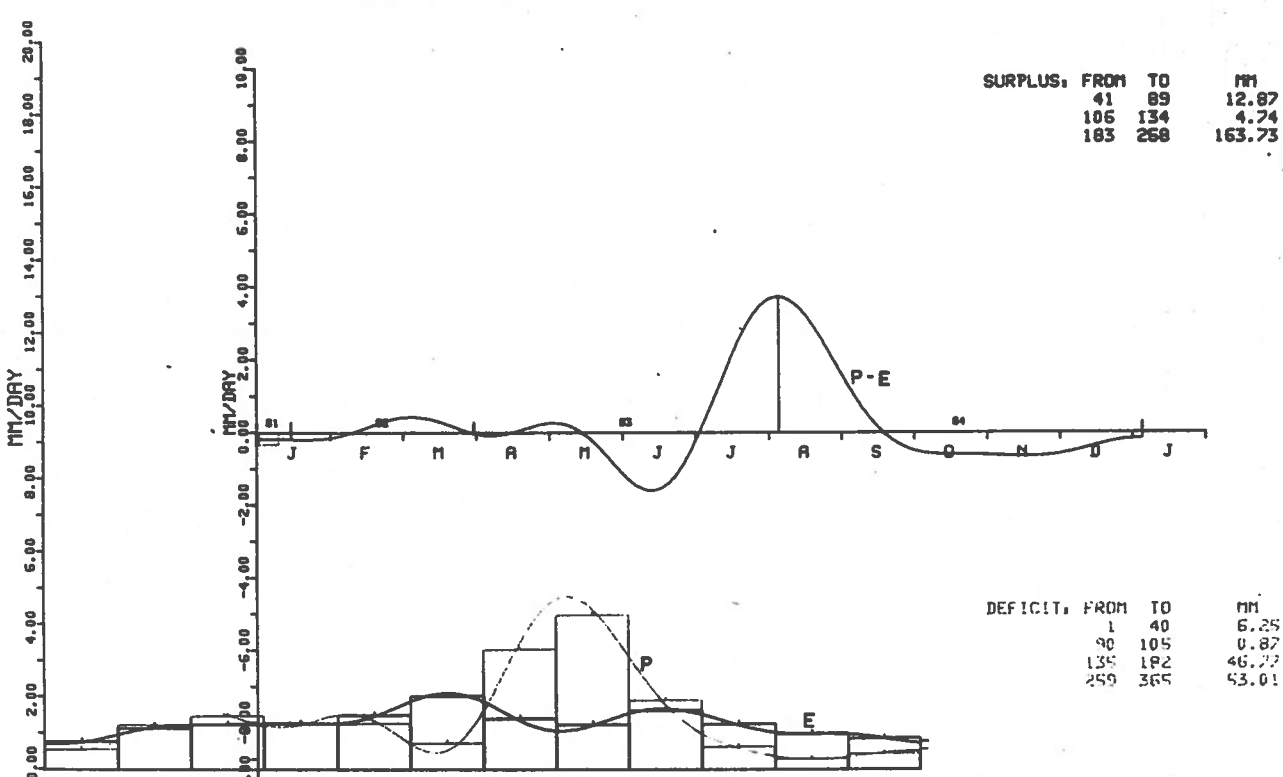
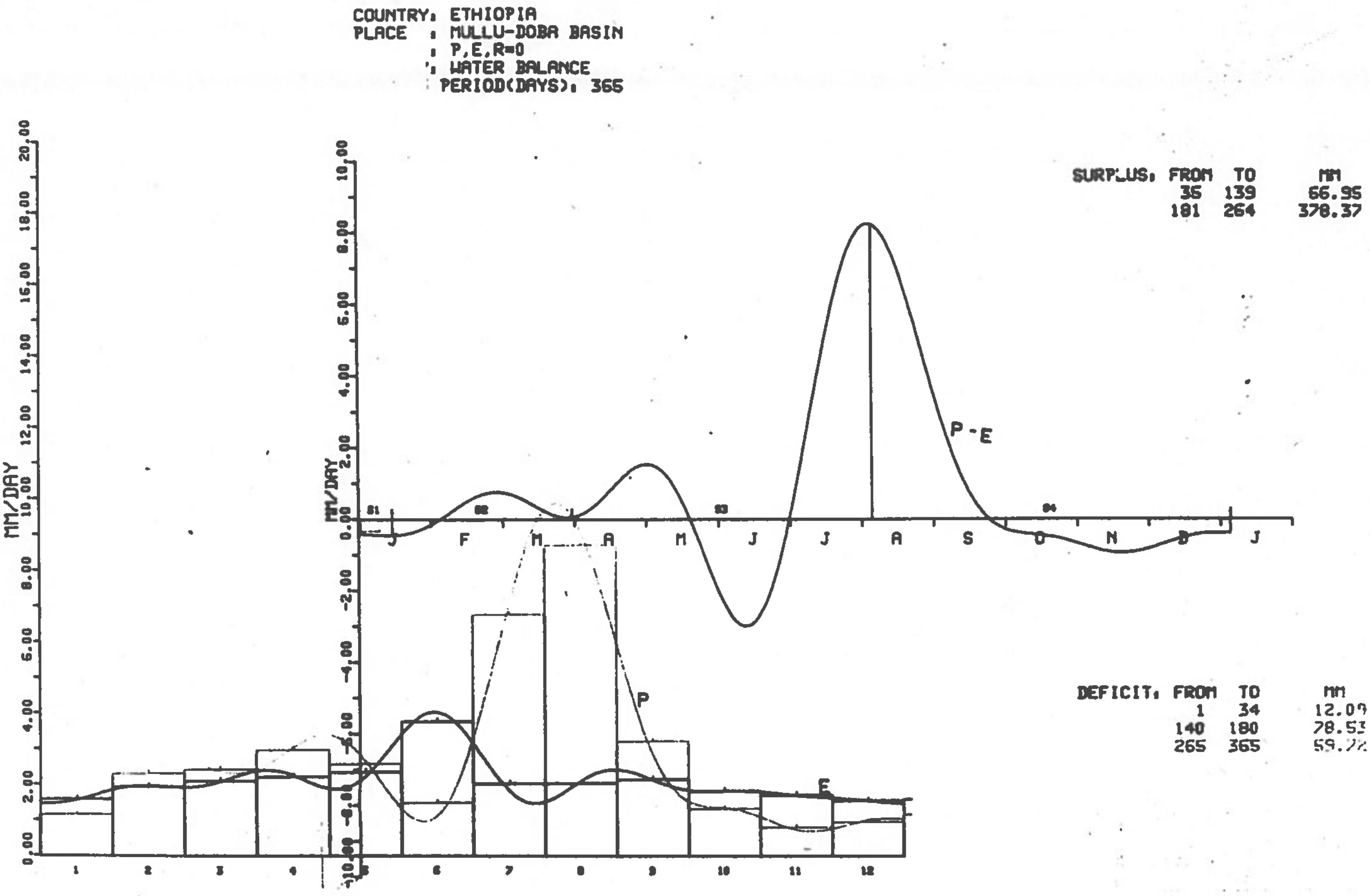


Figure 33


COUNTRY: ETHIOPIA
PLACE : MULLU-DOBA BASIN
: P,E,R=0
: WATER BALANCE
PERIOD(DAYS): 365
SURPLUS: FROM TO MM
35 139 66.95
181 264 378.37
DEFICIT: FROM TO MM
1 34 12.09
140 180 78.53
265 365 59.72
MM/DAY
P-E
P
E
J F M A M J J A S O N D J
1 2 3 4 5 6 7 8 9 10 11 12

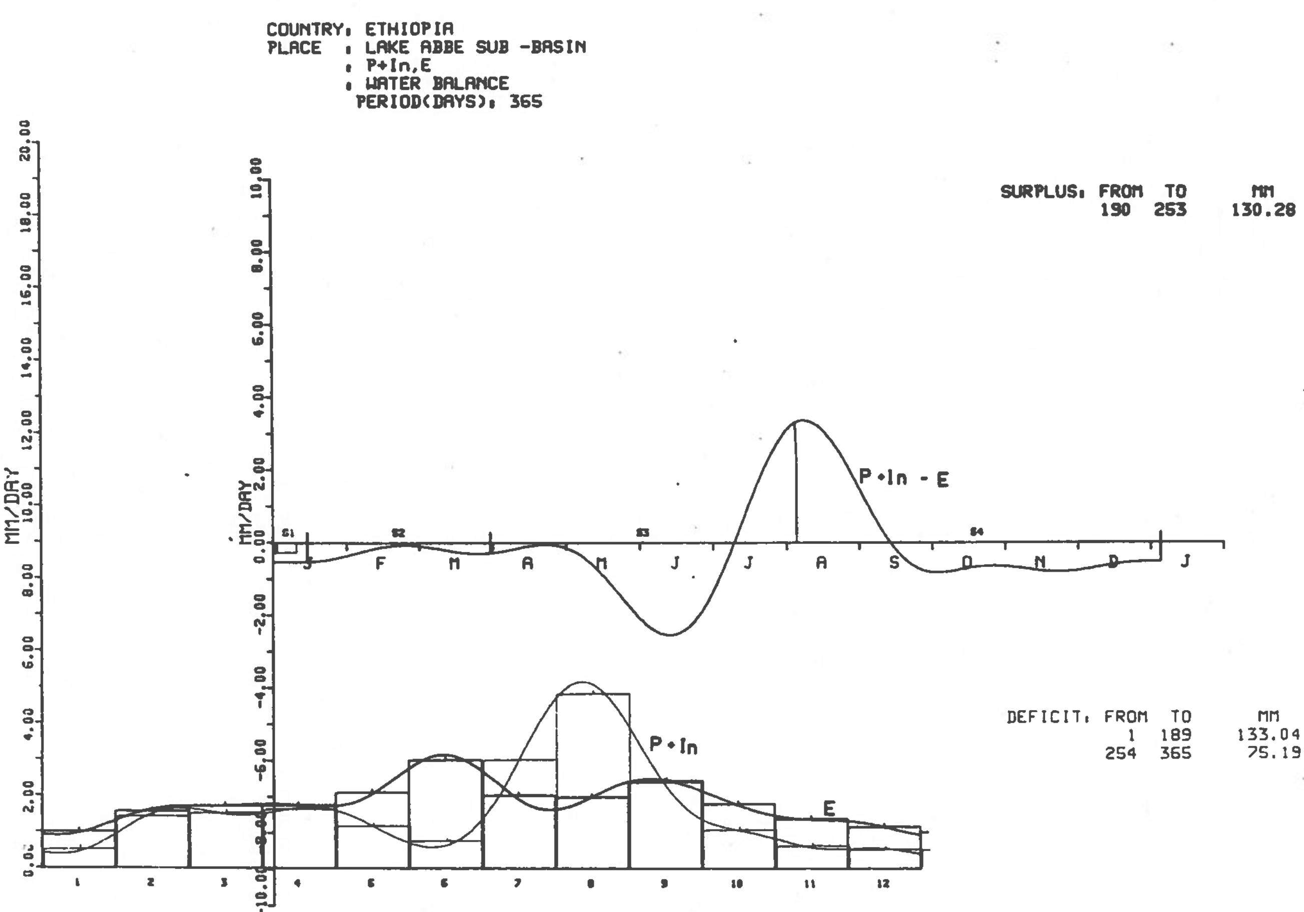
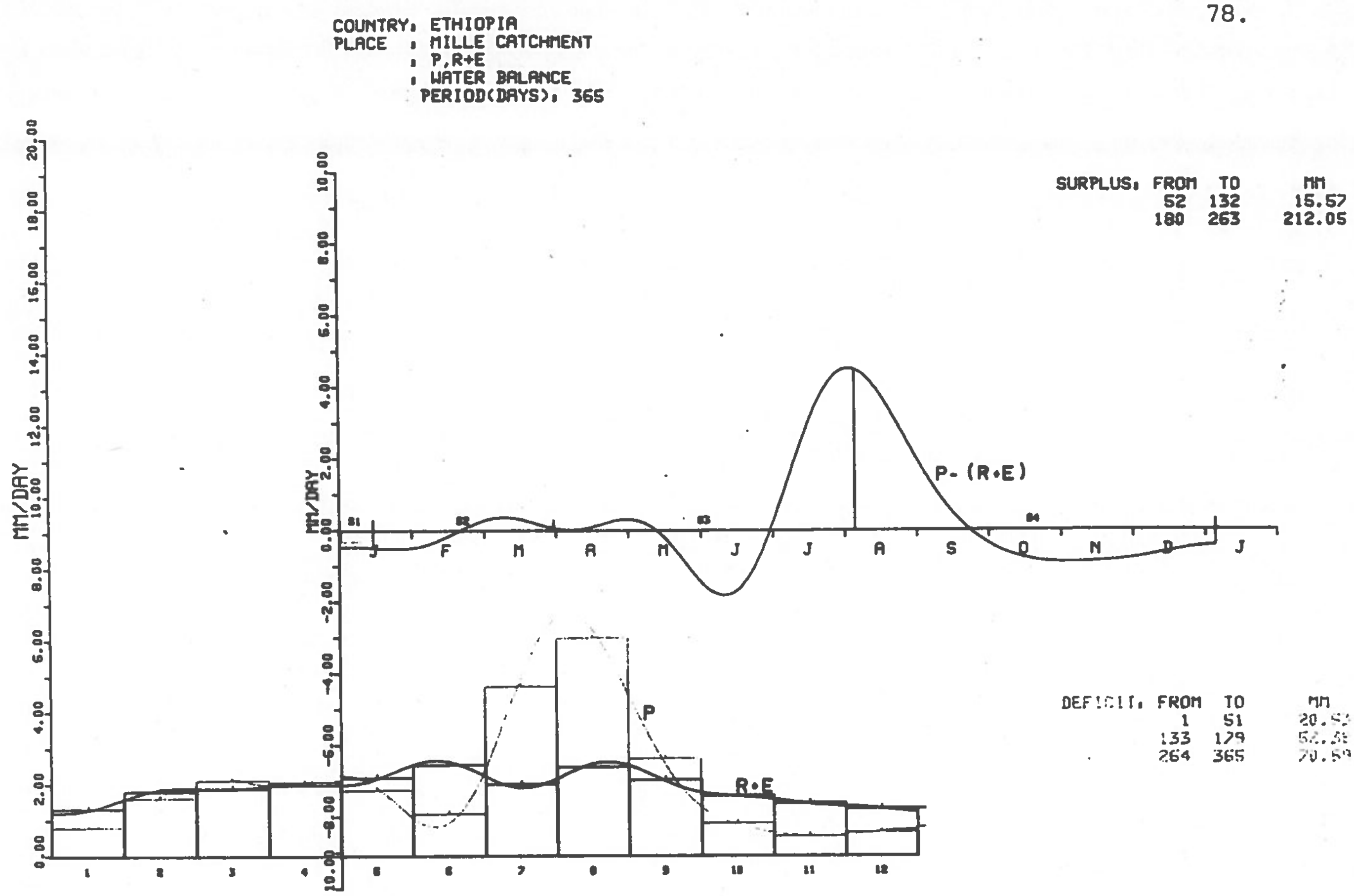

COUNTRY: ETHIOPIA
PLACE : LAKE ABBE SUB -BASIN
: P+In,E
: WATER BALANCE
PERIOD(DAYS): 365
SURPLUS: FROM TO MM
190 253 130.28
DEFICIT: FROM TO MM
1 189 133.04
254 365 75.19
MM/DAY
P+In - E
P+In
E
J F M A M J J A S O N D J
1 2 3 4 5 6 7 8 9 10 11 12

Figure 34


COUNTRY: ETHIOPIA
PLACE : MILLE CATCHMENT
: P,R+E
: WATER BALANCE
PERIOD(DAYS): 365
SURPLUS: FROM TO MM
52 132 15.57
180 263 212.05
DEFICIT: FROM TO MM
1 51 20.5[illegible]
133 179 5[illegible].[illegible]
264 365 70.5[illegible]
MM/DAY
P-(R+E)
P
R+E
J F M A M J J A S O N D J
S1 S2 S3 S4
1 2 3 4 5 6 7 8 9 10 11 12

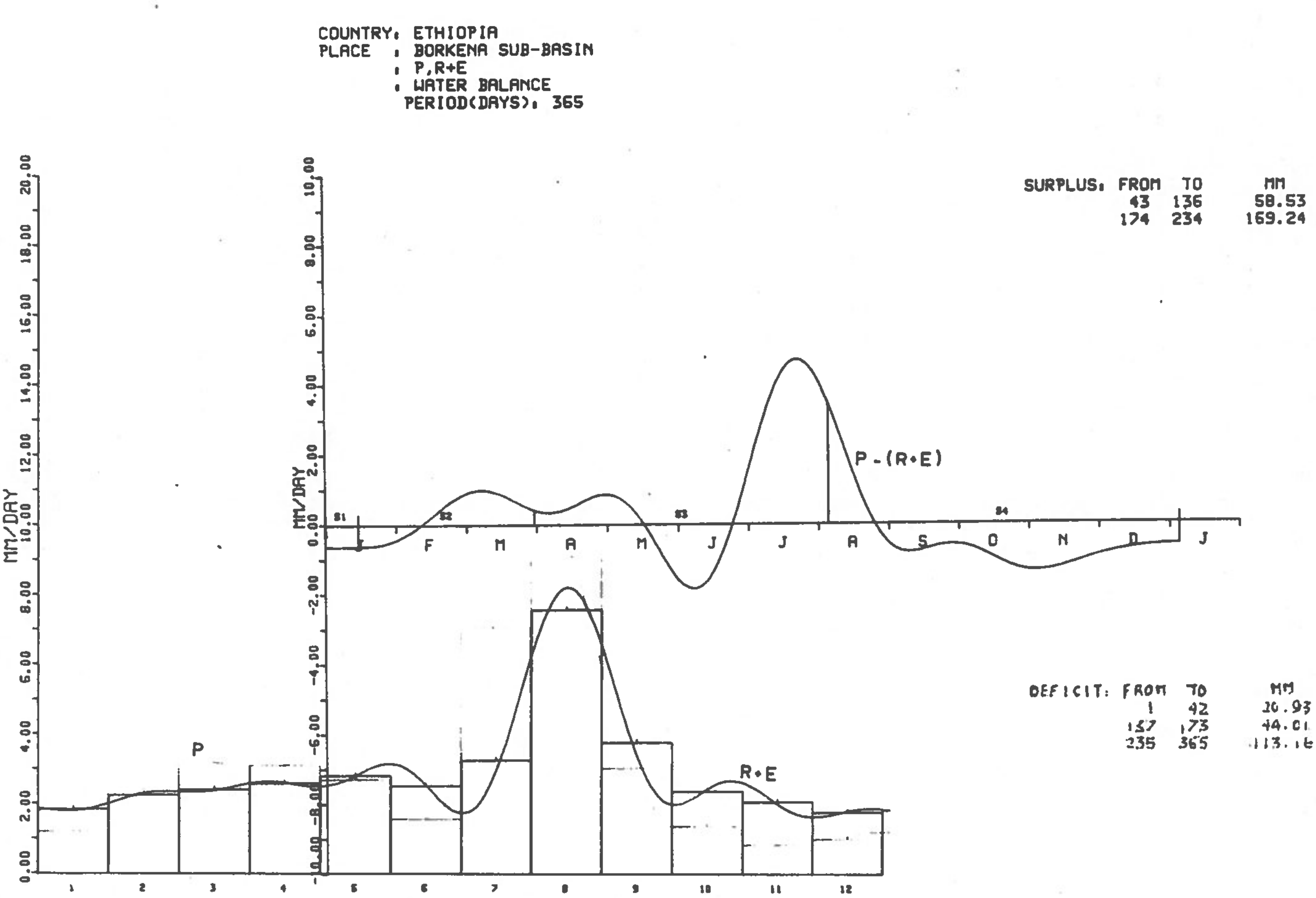
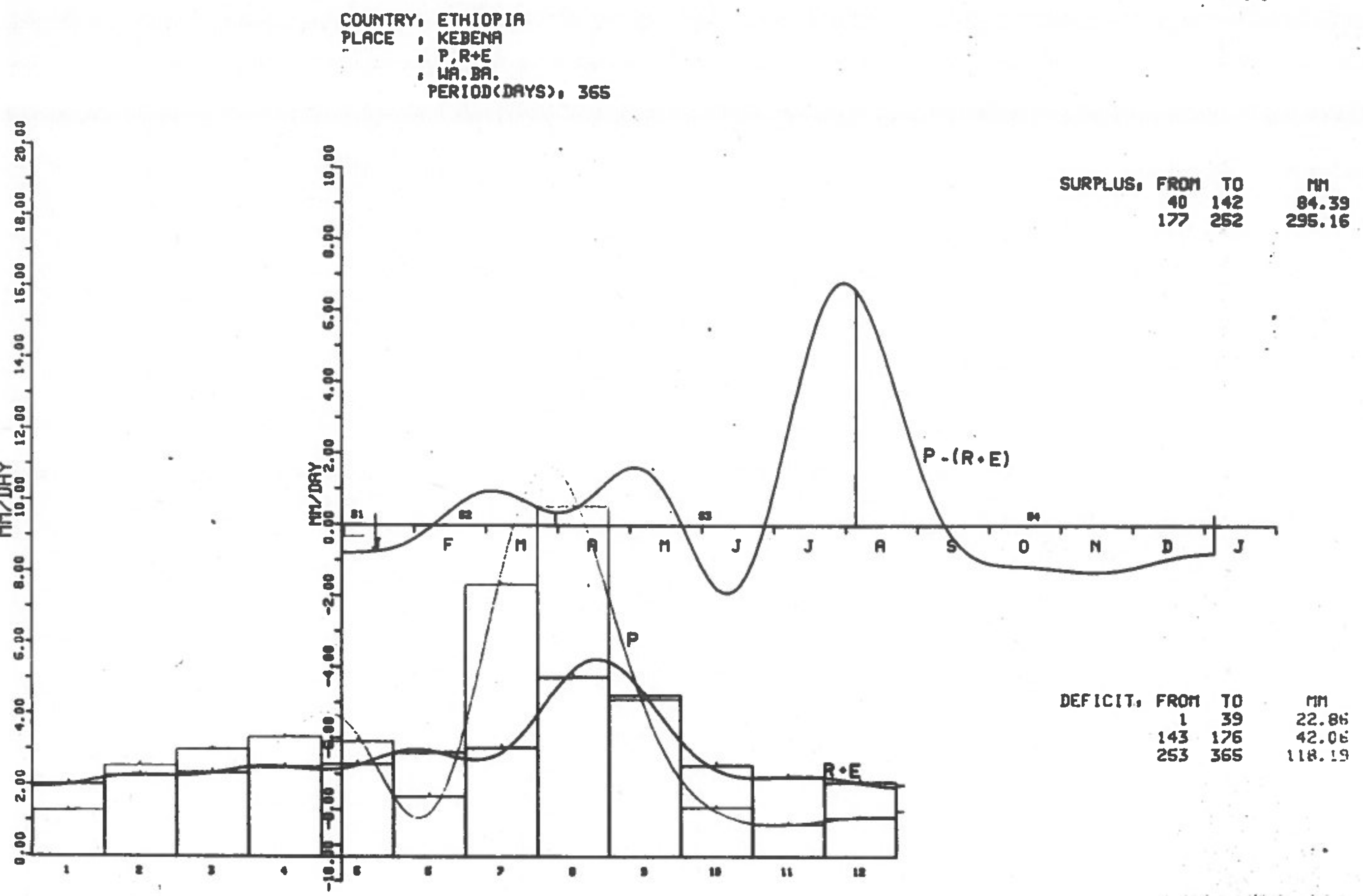

COUNTRY: ETHIOPIA
PLACE : BORKENA SUB-BASIN
: P,R+E
: WATER BALANCE
PERIOD(DAYS): 365
SURPLUS: FROM TO MM
43 136 58.53
174 234 169.24
DEFICIT: FROM TO MM
1 42 30.93
137 173 44.01
235 365 113.16
MM/DAY
P-(R+E)
P
R+E
J F M A M J J A S O N D J
S1 S2 S3 S4
1 2 3 4 5 6 7 8 9 10 11 12

Figure 35


COUNTRY: ETHIOPIA
PLACE : KEBENA
: P,R+E
: WA.BA.
PERIOD(DAYS): 365
SURPLUS: FROM TO MM
40 142 84.39
177 252 296.16
DEFICIT: FROM TO MM
1 39 22.86
143 176 42.06
253 365 118.19
MM/DAY
P-(R+E)
P
R+E
J F M A M J J A S O N D J

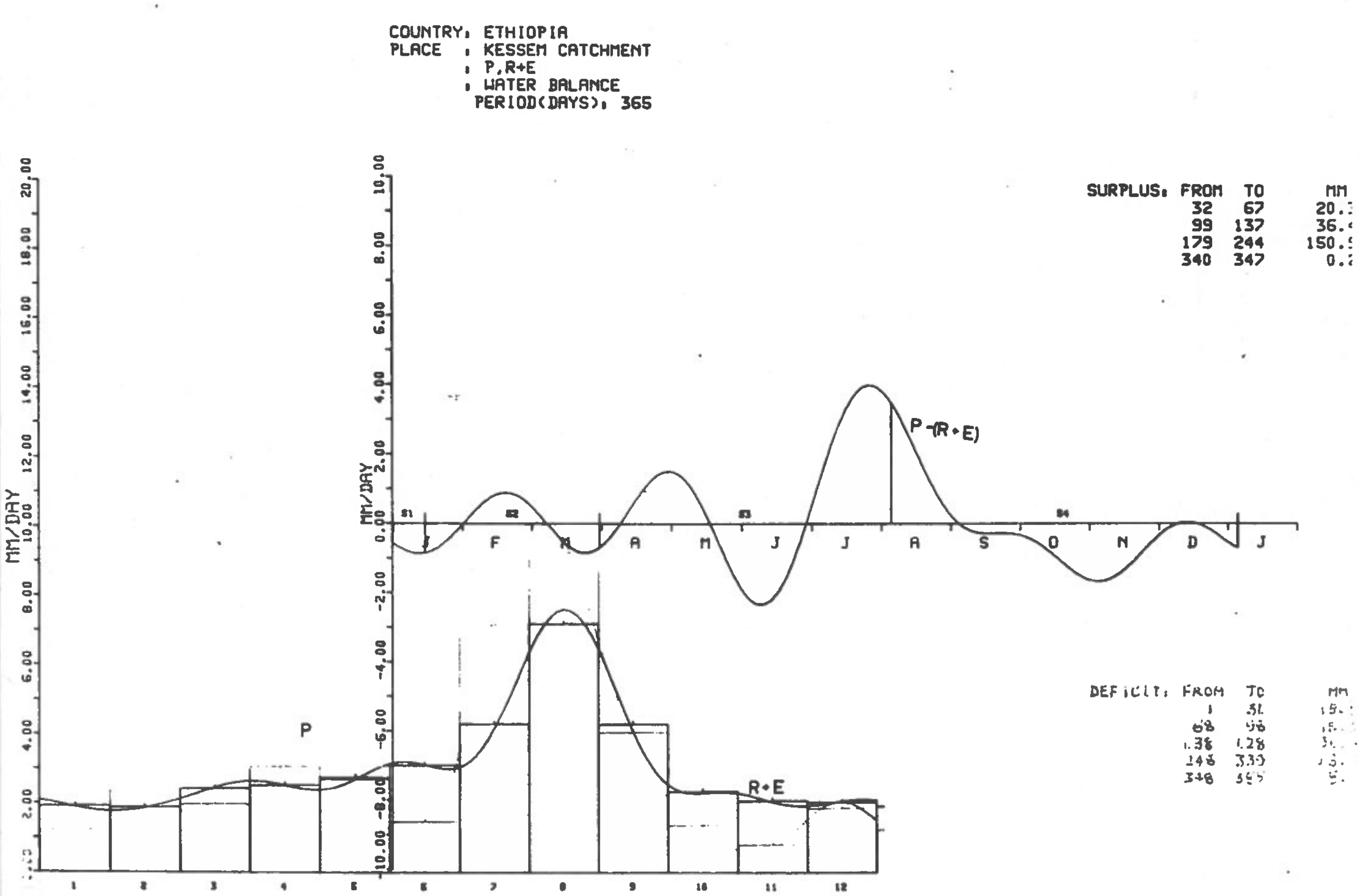
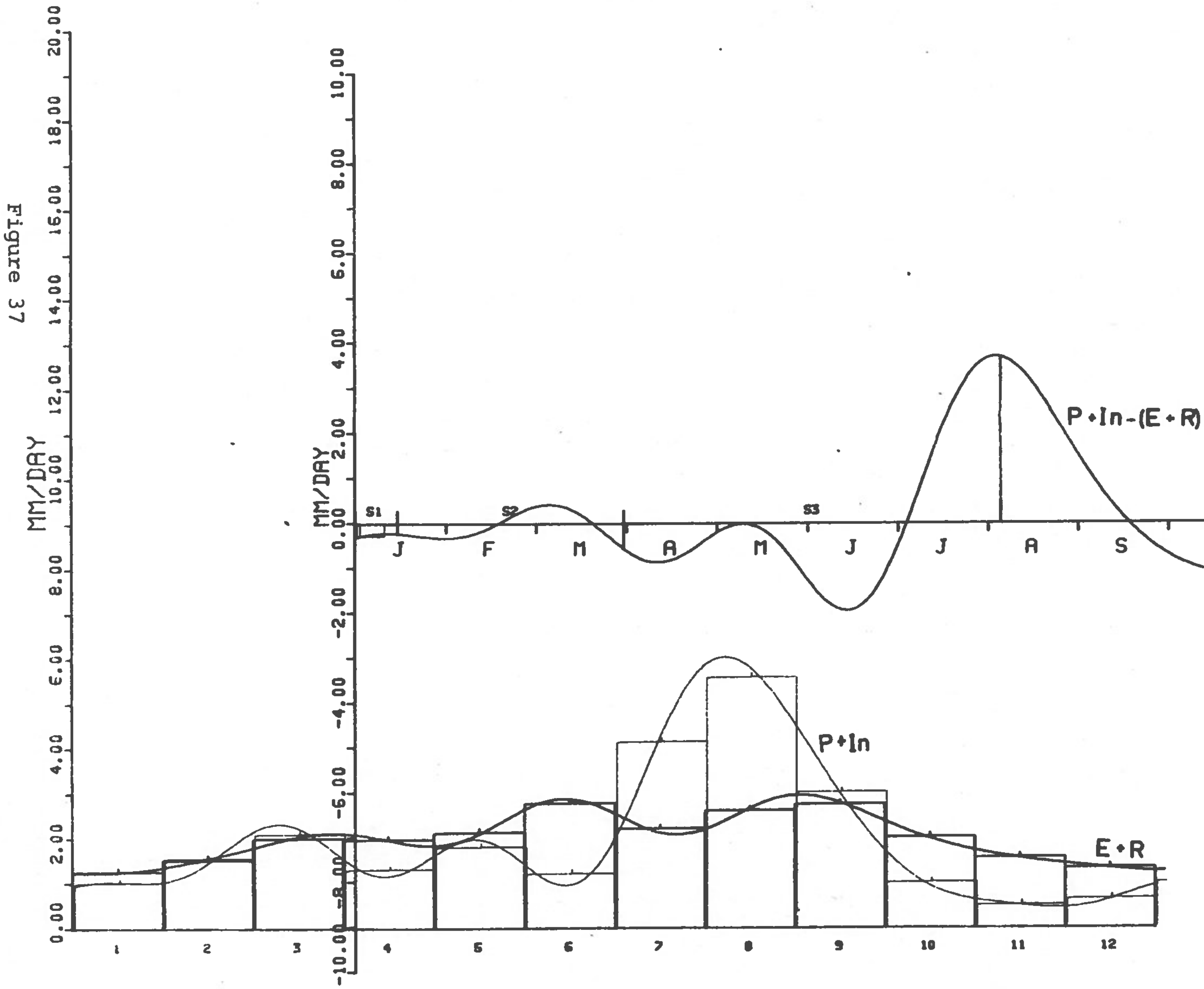

COUNTRY: ETHIOPIA
PLACE : KESSEM CATCHMENT
: P,R+E
: WATER BALANCE
PERIOD(DAYS): 365
SURPLUS: FROM TO MM
32 67
99 137
179 244
340 347
DEFICIT: FROM TO MM
MM/DAY
P-(R+E)
P
R+E
J F M A M J J A S O N D J

Figure 36

COUNTRY: ETHIOPIA
PLACE : MIDDLE AWASH SUB-BASIN
: P+In,E+R
: WATER BALANCE
PERIOD(DAYS): 365



SURPLUS: FROM	TO	MM
49	79	8.35
184	257	159.87

DEFICIT: FROM	TO	MM
1	48	11.76
80	183	82.42
258	365	88.94

Figure 37

	From the yearly water balance method	From the monthly water balance method
1) Kessem	37.3	30.12
2) Kebena	202.3	196.4
3) Borkena	56.7	46.67
4) Mille	84.1	83.82
5) Middle Awash	-12.4	-14.9
6) Loggiya	77.1	77.44
7) Mullu-Doba	247.1	294.98
8) Manda	75	81.05
9) Dahwi	48	45.44
10) Buren	104.9	96.97
11) L. Abbe	-85.8	-77,95

By multiplying the values obtained from the monthly water balance method by the respective areas, and dividing the result by the total area, we obtain 50 millimeters of water recharged into the entire area by precipitation and also by the Awash river.

Conclusions

-- The three methods employed in the calculation of the water balance formula gave more or less the same results.

-- Possible discrepancy should be attributed to the data rather than to the methods.

-- The general situation concerning the water budget of the area has quantitatively been understood.

-- The water balance shows that the Middle Awash and Lake Abbe areas suffer from water loss, whereas other areas gain some water.

-- The ten years' water balance shows that around 55 millimeters of water is gained in the entire region by precipitation and inflow from the Awash river.

About 40 millimeters of water is gained per year by precipitation and about 17 mm by inflow from the Awash river.

As this basin is closed towards the north, no surface outflow occurs. The water balance technique indicates the occurrence of groundwater; where the water goes, will be discussed in the next chapter.

The water balance, calculated by the Thornthwaite and Mather method, reflects the monthly hydro-meteorological situation; the water balance of the soil profile is best understood by this method.

12. MORPHO-TECTONICS AND GROUNDWATER MOVEMENT

The figures obtained from the water balance calculations indicate the order of magnitude of the amount of water available in storage as a groundwater body within the whole basin, in general, and, within the individual basins, sub-basins and catchments, in particular. The occurrence and movement of groundwater in particular areas, on the other hand, depends on permeability of the units and morpho-tectonic situations. Detailed analysis of groundwater situations under different hydrogeological provinces may reveal particular groundwater models.

In the present chapter, we shall concentrate on the possible movement of groundwater, as it can be assessed from the existing morpho-tectonic situations.

The Afar floor, which has developed as a result of crustal separation, exhibits fracture systems that are of tectonic origin. The flow of water through these fractures can be viewed as flow between discrete blocks, as discussed in chapter 7.2a.

In the absence of measured data on extent and depth of the fracture systems, the existing pattern of joint systems, in relation to the axes of principal stress, can be visualized, so that the existence of an open system of joints, as well as a closed system of joints be understood.

The Afar area is considered to be an area of upwelling heat, where plates move away from each other. It is, therefore, an area where volcanoes are aligned along certain axes!

It is an area where shallow earthquakes, hot springs, geysers and fumaroles concentrate.

Fissures and open faults are known to occur in the area.

In order to visualize the movement of groundwater, it is important to mark distinctions between the open system of joints and the closed system of joints. The graben areas in the central parts of the Rift represent tensile stresses, which have caused 'rift in rift' structures. The transform faults associated with these grabens are likely to be open.

It is not very difficult to visualize the existence of open faults that can possibly be formed by tensile forces on a regional scale, but the distribution and relative magnitude of tensile stresses, forming the open system of joints over the entire area can change from time to time.

Although the Afar region is an area that is spreading, the tensile stresses that cause the open system of joints may result in the compression of other joint systems on a minor scale.

In this respect, the entire Afar area can be viewed as representing series of open and closed joints, parallel to one another.

The direction of groundwater movement indicated in the hydrogeological map follows the morpho-tectonic set-up of the area.

In the Escarptment areas, movement of groundwater is governed by the main tectonic trends and also by the transverse faults. The axes of these transverse faults dip parallel to the general landscape, so that the groundwater would finally move towards the topographically lower places, as indicated in the hydrogeological map.

Numerous dyke systems are known to exist in the Escarpment regions, parallel to the main tectonic trends of the Escarpments (NS and SE,NE). These dykes obstruct free movement of groundwater.

Water balance and groundwater movement

According to the figures obtained from the water balance, a significant amount of water is available in all the basins, except the Middle Awash and Lake Abbe areas; negative storage values were obtained in the latter. However, in reality, the most prominent lakes and marshes are localized within these basins. The input into the basin (about 17 mm. per year) by the Awash river is effective in creating the marshes and lakes. However, this alone may not explain the situation. According to the water balance, the lake levels should decrease and the marshy areas dry up in time. An alternative explanation to this situation can be furnished from the direction of the groundwater movement. According to the direction of the groundwater movement, flow lines are directed towards these areas.

As the main tectonic trends meet around Lake Abbe area, the flow lines of the South Afar basin also follow the same tectonic trend, and converge around the same place. This situation reveals the existence of abundant groundwater in this particular place. It also confirms the importance of the intersection of joint systems for the occurrence of potential groundwater resources.

In the Afar area, where volcanic activity and tectonism are still active, the depth and extent of the faults determine the existence and circulation of deep groundwater; the amount of water, expected to occur as storage in a certain basin, could be available at a greater depth in the form of superheated steam, depending on geothermal situations.

13. HYDROCHEMISTRY

In this chapter we shall briefly discuss the applications of cluster analysis and factor analysis to understand the general chemical characteristics of the water analysis from the 139 samples that were collected from the Western Afar and adjacent areas (Hydrogeology Department, Ethiopian Institute of the Geological Surveys, 1976-1979).

The raw data matrix is given in the Appendix, page 114).

The components analysed are major cations (Ca, Mg, K, Na), major anions (HCO_3, Cl, SO_4) and minor constituents (F, Br, I and SIO_2).

Chemical analysis data can be illustrated in various ways. As it is not intended in the present study to go into detail, we shall focus only on three aspects.

1) The relationship between total dissolved solids (TDS) and the major components.
2) The intercorrelation between the individual components themselves.
3) The relative importance of the individual components.

In order to understand the above situation, it was found to be important to group the 139 samples in such a way that the samples, which have originated from a certain geologic environment, will cluster together.

The clustering technique employed in the computer programme is the weighted-group average, which uses the euclidian distance coefficient as coefficient of resemblance. In this method, members of a cluster are averaged together and treated as a new object. Mutually highest correlations in the matrix form centers of a cluster.

Cluster grouping into several numbers was tried. Cluster grouping into 10 groups is given in Appendix, page 116.

In all the cases of grouping, close association was observed between the source from which the samples were collected; samples collected from hot springs cluster with hot lakes, those from springs with borewells, and those from dugwells with water holes.

Few borewells cluster with dugwells and water holes.

From this situation, we understand that some relation exists between the source and chemical quality of the waters.

The general quality distribution of the waters can be understood from the TDS contour map.

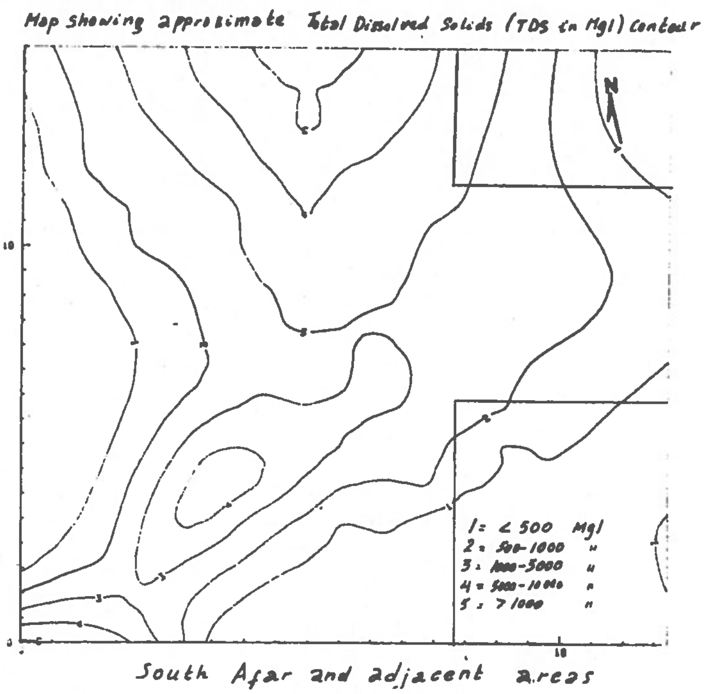


Fig. 38. Map shows the general pattern of Total Dissolved Solids.

The cluster programme only displays the relative differences between the individual samples, but it does not show what the relative differences are. A factor analysis programme was employed in order to understand the intercorrelations.
The data matrix for this programme was based on cluster grouping. After close inspection of the groupings, it was found to be more useful to carry out the factor analysis by preparing separate data matrices for the cold springs, water holes and dugwells, boreholes, hot springs and hot lakes.
First, the relation of the individual components with TDS was envisaged. From the five matrices (see page 120), the following can readily be observed (+ means correlation greater than .5 :
- means correlation less than .5):-

	Ca	Mg	Na	K	HCO_3	Cl	SO_4	SIO_2
cold springs	+	+	+	-	+	+	+	-
water holes and dugwells	-	-	+	-	+	+	+	-
boreholes	-	-	+	-	-	+	+	-
hot springs	+	+	+	+	-	+	+	-
hot lakes	-	-	+	+	+	-	+	-

The above matrix reflects the importance of the individual component. From the five matrices, we can see that the amount of SO_4 becomes more important as the total ions increase, etc.
Water quality of the area is presented in the Water Resources map (see page 88). Most waters from hot springs and hot lakes in the Rift are beyond the permissible limit of the Ethiopian Standard for drinking purposes.
In order to understand the intercorrelation between the individual components themselves, the TDS was purposely avoided, and intercorrelation between the seven major components, in this case, analysed. The matrices containing TDS do not represent true intercorrelation between the components, because the vector representing TDS will be taken as component affecting the others.
The factor analysis programme displays intercorrelation matrices of the major components. It also displays the eigenvalues and eigenvectors, extracted from the matrices of correlations (see pages 121 to 125).
From the eigenvalues the relative magnitude of the individual components can be understood.
A great deal of information, like the importance of HCO_3 in the lake waters and their non-significance in the hot springs, the possible combinations of cations with the respective anions, can be drawn from the matrices prepared.
Further transformation of the matrices could reveal more information.

14. WATER RESOURCES

A number of separate maps, reflecting certain hydrogeological characteristics, were prepared. These maps were used to evaluate certain hydrogeological parameters. In this chapter we will see how information from these maps was integrated with hydrometeorological factors to produce a water resources map.

1) From the geomorphological map, high runoff areas were delineated from recharge zones; favourable areas for the accumulation of groundwater were marked.

2) From the vegetation map, wet areas, reflecting suitable soil moisture conditions, leading to the possible occurrence of shallow groundwater and high concentration of springs, were extracted.

3) From the water balance, the permeability of the rock and soil units, and from the morpho-tectonic situations, the occurrence and movement of groundwater has been understood.

4) From the location and flow of known springs, and from the location and dimensions of known borewells, dugwells, and water holes, the water table situations are partly known.

5) Information gathered from 1 up to 4 has enabled us to approximate the water table conditions of the area.

6) A Water REsources map is prepared which includes the above information and also water quality information; the relative amount of exploitable groundwater is presented.(See fig. 39)

From the map one can readily see that a large proportion of the Afar floor has deep and hot groundwater. The quality of the water in the volcanic rocks and deep aquifers is usually undesirable.

The graben areas and some of the depressions, as well as the foothill areas of the Escarpments, are potential sources of water of good quality.

WATER RESOURCE AND WATER QUALITY MAP OF SOUTH AFAR ADJACENT AREAS

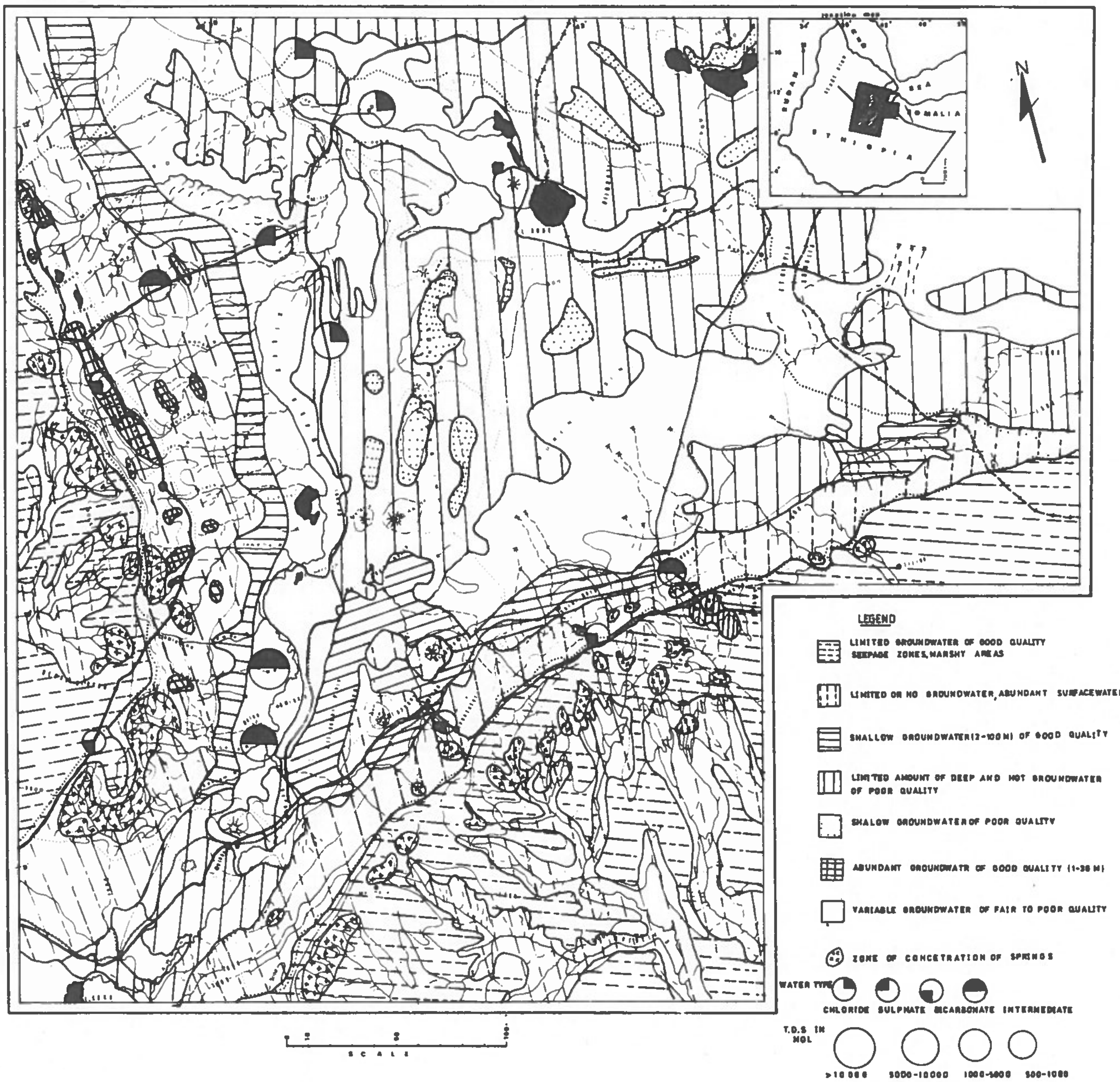


Figure 39

15. CONCLUSIONS

Applications of Landsat imagery are prominent in the various fields of study, including hydrogeology. It is obvious that hydrogeology of an area cannot be known only from Landsat. However, valuable information can be drawn, if Landsat imagery is carefully interpreted for the particular purposes which would be of interest to a hydrogeologist.

In the present study, interpretation of Landsat imagery has played its part as a medium, whereby information on areas with ample data was transmitted to areas where data is scarce.

Due to the fact that the nature of volcanic rocks is unisotropic and heterogeneous, conventional methods of pump test analysis may not be of great help in quantitatively evaluating aquifers. In this respect, indirect methods, like lineament analysis from Landsat, may help in understanding permeability of the rock units; other geological factors should also be considered.

After processing and analysing hydrometeorological factors, the water balance of the area has been calculated in different ways. In all the methods, the order of magnitude of the water that is stored into the whole area is about 55 millimeters per year.

From the total amount of water that is stored, a certain amount is utilised by the soil. Deep groundwater recharge occurs only after the soil has reached its field capacity. In this respect, it is very difficult to estimate the actual amount of water recharged into the deep groundwater body.

Due to the relative permanence of an open system of joints, and the permeable nature of the basic rocks, a considerable amount of recharge could take place in the volcanic rocks, either by direct infiltration from precipitation or by recharge from runoff. The depth of the fault systems determines the depth to which groundwater could circulate. The movement of groundwater in the area is largely controlled by the morpho-tectonics.

Location of target areas for exploitable groundwater resources should be based on careful study of the joint systems, and the possible movement of groundwater in relation to the theory of plate tectonics.

The hydrogeological map, attached to this thesis, shows the relative permeability of the rock and soil units; possible lineaments, representing faults and fractures, are traced and possible movement of groundwater is indicated. This map can be used as a stepping stone for a detailed hydrogeological study of the area.

The existence of hot springs, fumaroles and geysers in the area is an indication of the possibility of geothermal situations. Among other considerations, the present work reveals the existence of a considerable amount of water, which, under favourable geothermal situations, may be exploited for geothermal power production.

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A P P E N D I C E S

(Pages 93 - 125)

```
10   REM "THORNWHAITH----POTENTIAL EVAPOTRANSPIRATION "
20   DIM T(100,12),A(100),E(12),S$(100)
30   READ N
40   FOR K=1 TO N
50   S=0
60   READ S$(K),A(K)
70   FOR I=1 TO 12
80   READ T(K,I)
90   S=S+(T(K,I)/5)^1.514
100  NEXT I
110 Z=.000000675*S^3-.0000771*S^2+.01792*S+.49239
120  S1=0
130  S2=0
140  FOR I=1 TO 12
150  E(I)=16*(10*T(K,I)/S)^Z
160  S1=S1+E(I)
170  S2=S2+T(K,I)/12
180  NEXT I
190  PRINT "STATION ";S$(K)
200  PRINT "--------------------------------------------------------------
------------"
205 T1: IMAGE "ALTITUDE=",M4D.D,"  ANNUAL EVAPOTRANSPIRATION = ",M4D.D," MEAN AN
NUAL TEMP.=",2D.D
210 ! PRINT "ALTITUDE=####.#  ANNUAL EVAPOTRANSPIRATION = ####.# MEAN ANNUAL TEM
P.=##.# ",A(K),S1,S2
215   PRINT USING T1;A(K),S1,S2
220  PRINT "        JAN.  FEB.  MAR.  APR.  MAY.  JUN.  JUL.  AUG.  SEP.  OCT.
NOV.  DEC.  "
230  PRINT
240  PRINT "TEMP. ";
250  A$="#,M3D.D"
251  FOR I=1 TO 12
260  PRINT USING A$;T(K,I)
261  NEXT I
270  PRINT
280  PRINT "EVAP. ";
281  FOR I=1 TO 12
290  PRINT USING A$;E(I)
291  NEXT I
300  PRINT
310  PRINT
320  PRINT
330  NEXT K
340  DATA 12
350  DATA DUBTI,370,25.3,27.3,27.9,27.9, 30.8,34.0,30.8,29.4,32.8,30.8,26.7,27.9
360  DATA GEWANI,600,24.9,27.1,29.1,29.1,29.7,31.9,29.1,28.5,29.7,28.0,27.1,24.9
370  DATA METEHARA,964,23.0,25.3,26.3,25.6,26.8,28.1,26.6,25.3,26.6,25.0,24.5,23
.5
380  DATA ROBI,1275,19.9,19.4,23.3,23.3,23.9,25.5,23.3,22.6,22.4,21.5,21.4,21.3
390  DATA CHEFFA,1490,18.4,19.7,21.2,21.5,23.5,24.4,23.1,22.1,22.9,22.5,19.3,18.
2
400  DATA WONJI,1580,18.8,19.8,21.9,22.1,23.2,22.7,20.9,20.9,21.1,19.2,18.8,18.6
410  DATA ALABA,1850,19.6,19.8,20.4,20.13,19.4,18.9,18.0,18.3,18.8,18.3,17.9,17.
9
420  DATA KOMBOLCHA,1903,16.8,18.2,19.3,19.5,21.2,22.5,20.8,20.4,19.8,18.2,16.6,
16.2
430  DATA WOLLAYITA,2060,20.2,21 0.20.1,19.3,18.2,17.1,15.5,15.7,17.6,18.4,19.8,
19.3
440  DATA HOSSAINA,2290,15.5,16.9,18.1,17.6,16.8,15.8,15.4,15.1,15.8,15.9,16.3,1
5.7
450  DATA MAICHEW,2350,14.5,15.2,16.7,17.7,19.1,19.7,18.4,18.4,16.9,15.2,16.0,14
.5
460  DATA ADDIS ABABA,2408,15.6,16.9,17.9,17.7,17.9,16.7,15.1,15.7,15.6,15.8,15.
3,15.3
470  END
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STATION DUBTI

ALTITUDE= 370.0 ANNUAL EVAPOTRANSPIRATION = 2547.5 MEAN ANNUAL TEMP.=29.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	25.3	27.3	27.9	27.9	30.8	34.0	30.8	29.4	32.8	30.8	26.7	27.9
EVAP.	96.9	140.5	156.2	156.2	253.1	410.2	253.1	201.7	344.2	253.1	126.0	156.2

STATION GEWANI

ALTITUDE= 600.0 ANNUAL EVAPOTRANSPIRATION = 2098.6 MEAN ANNUAL TEMP.=28.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	24.9	27.1	29.1	29.1	29.7	31.9	29.1	28.5	29.7	28.0	27.1	24.9
EVAP.	96.8	140.5	192.3	192.3	210.4	288.3	192.3	175.5	210.4	162.3	140.5	96.8

STATION METEHARA

ALTITUDE= 964.0 ANNUAL EVAPOTRANSPIRATION = 1444.6 MEAN ANNUAL TEMP.=25.6

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	23.0	25.3	26.3	25.6	26.8	28.1	26.6	25.3	26.6	25.0	24.5	23.5
EVAP.	83.1	115.0	131.3	119.7	140.0	164.6	136.5	115.0	136.5	110.4	103.1	89.4

STATION ROBI

ALTITUDE= 1275.0 ANNUAL EVAPOTRANSPIRATION = 1056.1 MEAN ANNUAL TEMP.=22.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	19.9	19.4	23.3	23.3	23.9	25.5	23.3	22.6	22.4	21.5	21.4	21.3
EVAP.	64.7	60.6	97.3	97.3	103.9	122.8	97.3	89.9	87.9	79.1	78.1	77.2

STATION CHEFFA

ALTITUDE= 1490.0 ANNUAL EVAPOTRANSPIRATION = 986.6 MEAN ANNUAL TEMP.=21.4

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	18.4	19.7	21.2	21.5	23.5	24.4	23.1	22.1	22.9	22.5	19.3	18.2
EVAP.	56.4	66.5	79.3	82.0	101.5	111.0	97.4	87.6	95.4	91.4	63.3	55.0

STATION WONJI

ALTITUDE= 1580.0 ANNUAL EVAPOTRANSPIRATION = 931.9 MEAN ANNUAL TEMP.=20.7

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	18.8	19.8	21.9	22.1	23.2	22.7	20.9	20.9	21.1	19.2	18.8	18.6
EVAP.	62.2	69.9	87.8	89.7	100.1	95.2	79.0	79.0	80.7	65.2	62.2	60.7

STATION ALABA

ALTITUDE= 1850.0 ANNUAL EVAPOTRANSPIRATION = 834.3 MEAN ANNUAL TEMP.=19.0

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	19.6	19.8	20.4	20.1	19.4	18.9	18.0	18.3	18.8	18.3	17.9	17.9
EVAP.	74.2	75.7	80.3	78.2	72.7	69.0	62.7	64.7	68.3	64.7	62.0	62.0

STATION KOMBOLCHA

ALTITUDE= 1903.0 ANNUAL EVAPOTRANSPIRATION = 847.6 MEAN ANNUAL TEMP.=19.1

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	16.8	18.2	19.3	19.5	21.2	22.5	20.8	20.4	19.8	18.2	16.6	16.2
EVAP.	53.9	63.3	71.2	72.7	86.0	97.0	82.8	79.6	75.0	63.3	52.6	50.1

STATION WOLLAYITA

ALTITUDE= 2060.0 ANNUAL EVAPOTRANSPIRATION = 817.8 MEAN ANNUAL TEMP.=18.5

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	20.2	21.0	20.1	19.3	18.2	17.1	15.5	15.7	17.6	18.4	19.8	19.3
EVAP.	80.0	86.1	79.2	73.3	65.4	58.1	48.1	49.3	61.4	66.8	76.9	73.3

STATION HOSSAINA

ALTITUDE= 2290.0 ANNUAL EVAPOTRANSPIRATION = 730.1 MEAN ANNUAL TEMP.=16.2

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	15.5	16.9	18.1	17.6	16.8	15.8	15.4	15.1	15.8	15.9	16.3	15.7
EVAP.	56.3	64.8	72.5	69.2	64.2	58.1	55.7	54.0	58.1	58.7	61.1	57.5

STATION MAICHEW

ALTITUDE= 2350.0 ANNUAL EVAPOTRANSPIRATION = 752.5 MEAN ANNUAL TEMP.=16.9

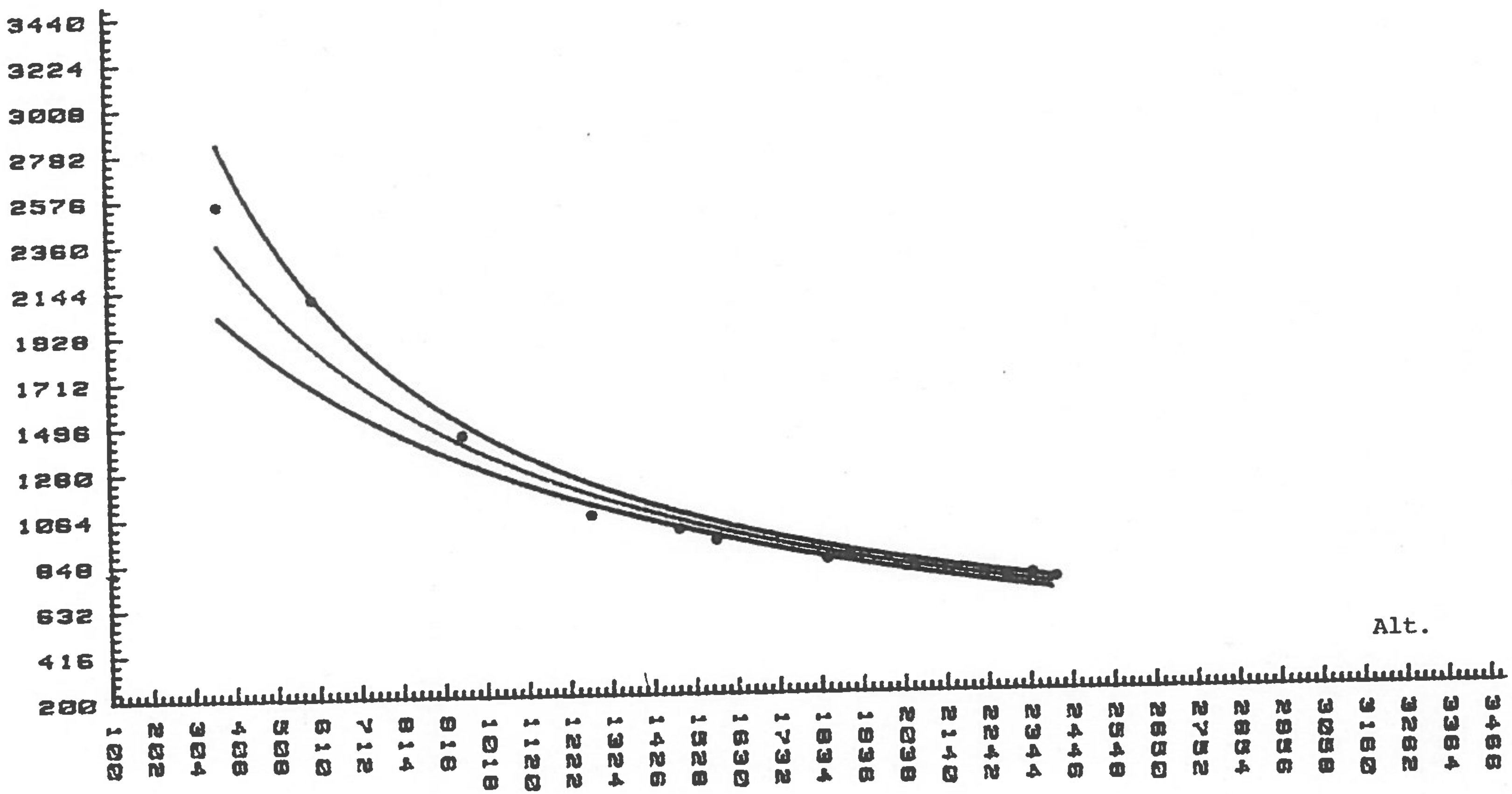
	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	14.5	15.2	16.7	17.7	19.1	19.7	18.4	18.4	16.9	15.2	16.0	14.5
EVAP.	48.2	52.2	61.3	67.7	77.1	81.2	72.3	72.3	62.6	52.2	57.0	48.2

STATION ADDIS ABABA

ALTITUDE= 2408.0 ANNUAL EVAPOTRANSPIRATION = 731.9 MEAN ANNUAL TEMP.=16.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	15.6	16.9	17.9	17.7	17.9	16.7	15.1	15.7	15.6	15.8	15.3	15.3
EVAP.	56.7	64.6	71.0	69.7	71.0	63.4	53.8	57.3	56.7	57.9	54.9	54.9

Curve : ET1 = 1 / (.000243 + .000000*ALT)



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10  REM "KHOSLA --- POTENTIAL EVAPOTRANSPIRATION (MONTHLY)"
20  DIM S$(100),H(100),T(100,12),E(12)
30  READ N
40  FOR K=1 TO N
50  READ S$(K),H(K)
60  FOR I=1 TO 12
70  READ T(K,I)
71  NEXT I
72  FOR I=1 TO 12
75  E(I)=4.8*T(K,I)
76  NEXT I
100 LET S1=0
101 LET S2=0
102 FOR I=1 TO 12
120 LET S1=S1+E(I)
130 LET S2=S2+T(K,I)/12
140 NEXT I
150 PRINT "STATION  ";S$(K)
160 PRINT "-----------------------------------------------------------------
---------"
170 T1:   IMAGE "ALTITUDE=",M4D.D,"  ANNUAL EVAPOTRANSPIRATION=",M4D.D,"MEAN ANN
UAL TEMP.=",2D.D
175 FOR I=1 TO 12
180 PRINT USING T1;H(K),S1,S2
181 PRINT "         JAN.  FEB.  MAR.  APR.  MAY.  JUN.  JUL.  AUG.  SEP.  OCT.
 NOV.  DEC."
200 PRINT
210 PRINT "TEMP.  ";
220 A$="$,M3D.D"
230 FOR I=1 TO 12
240 PRINT USING A$;T(K,I)
250 NEXT I
251 PRINT
260 PRINT "EVAP.  ";
270 FOR I=1 TO 12
280 PRINT USING A$;E(I)
290 NEXT I
300 PRINT
310 PRINT
320 PRINT
330 NEXT K
340 DATA 12
350 DATA DUBTI,370,25.3,27.3,27.9,27.9,30.8,34.0,30.8,29.4,32.8,30.8,26.7,27.9
360 DATA GEWANI,600,24.9,27.1,29.1,29.1,29.7,31.9,29.1,28.5,29.7,28.0,27.1,24.9
370 DATA METEHARA,964,23.0,25.3,26.3,25.6,26.8,28.1,26.6,25.3,26.6,25.0,24.5,23
.5
380 DATA ROBI,1275,19.9,19.4,23.3,23.3,23.9,25.5,23.3,22.6,22.4,21.5,21.4,21.3
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400 DATA WONJI,1580,18.8,19.8,21.9,22.1,23.2,22.7,20.9,20.9,21.1,19.2,18.8,18.6
410 DATA ALABA,1850,19.6,19.8,20.4,20.1,19.4,18.9,18.0,18.3,18.8,18.3,17.9,17.9
420 DATA KOMBOLCHA,1903,16.8,18.2,19.3,19.5,21.2,22.5,20.8,20.4,19.8,18.2,16.6,
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430 DATA WOLLAYITA,2060,20.2,21.0,20.1,19.3,18.2,17.1,15.5,15.7,17.6,18.4,19.8,
19.3
440 DATA HOSSAINA,2290,15.5,16.9,18.1,17.6,16.8,15.8,15.4,15.1,15.8.15.9,16.3,1
5.7
450 DATA MAICHEW,2350,14.5,15.2,16.7,17.7,19.1,19.7,18.4,18.4,16.9,15.2,16.0,14
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460 DATA ADDIS ABABA,2408,15.6,16.9,17.9,17.7,17.9,16.7,15.1,15.7,15.6,15.8,15.
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STATION DUBTI

ALTITUDE= 370.0 ANNUAL EVAPOTRANSPIRATION= 1687.7MEAN ANNUAL TEMP.=29.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	25.3	27.3	27.9	27.9	30.8	34.0	30.8	29.4	32.8	30.8	26.7	27.9
EVAP.	121.4	131.0	133.9	133.9	147.8	163.2	147.8	141.1	157.4	147.8	128.2	133.9

STATION GEWANI

ALTITUDE= 600.0 ANNUAL EVAPOTRANSPIRATION= 1627.7MEAN ANNUAL TEMP.=28.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	24.9	27.1	29.1	29.1	29.7	31.9	29.1	28.5	29.7	28.0	27.1	24.9
EVAP.	119.5	130.1	139.7	139.7	142.6	153.1	139.7	136.8	142.6	134.4	130.1	119.5

STATION METEHARA

ALTITUDE= 964.0 ANNUAL EVAPOTRANSPIRATION= 1471.7MEAN ANNUAL TEMP.=25.6

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	23.0	25.3	26.3	25.6	26.8	28.1	26.6	25.3	26.6	25.0	24.5	23.5
EVAP.	110.4	121.4	126.2	122.9	128.6	134.9	127.7	121.4	127.7	120.0	117.6	112.8

STATION ROBI

ALTITUDE= 1275.0 ANNUAL EVAPOTRANSPIRATION= 1285.4MEAN ANNUAL TEMP.=22.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	19.9	19.4	23.3	23.3	23.9	25.5	23.3	22.6	22.4	21.5	21.4	21.3
EVAP.	95.5	93.1	111.8	111.8	114.7	122.4	111.8	108.5	107.5	103.2	102.7	102.2

STATION CHEFFA

ALTITUDE= 1490.0 ANNUAL EVAPOTRANSPIRATION= 1232.6MEAN ANNUAL TEMP.=21.4

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	18.4	19.7	21.2	21.5	23.5	24.4	23.1	22.1	22.9	22.5	19.3	18.2
EVAP.	88.3	94.6	101.8	103.2	112.8	117.1	110.9	106.1	109.9	108.0	92.6	87.4

STATION WONJI

ALTITUDE= 1580.0 ANNUAL EVAPOTRANSPIRATION= 1190.4MEAN ANNUAL TEMP.=20.7

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	18.8	19.8	21.9	22.1	23.2	22.7	20.9	20.9	21.1	19.2	18.8	18.6
EVAP.	90.2	95.0	105.1	106.1	111.4	109.0	100.3	100.3	101.3	92.2	90.2	89.3

STATION ALABA

ALTITUDE= 1850.0 ANNUAL EVAPOTRANSPIRATION= 1091.5MEAN ANNUAL TEMP.=19.0

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	19.6	19.8	20.4	20.1	19.4	18.9	18.0	18.3	18.8	18.3	17.9	17.9
EVAP.	94.1	95.0	97.9	96.5	93.1	90.7	86.4	87.8	90.2	87.8	85.9	85.9

STATION KOMBOLCHA

ALTITUDE= 1903.0 ANNUAL EVAPOTRANSPIRATION= 1101.6MEAN ANNUAL TEMP.=19.1

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	16.8	18.2	19.3	19.5	21.2	22.5	20.8	20.4	19.8	18.2	16.6	16.2
EVAP.	80.6	87.4	92.6	93.6	101.8	108.0	99.8	97.9	95.0	87.4	79.7	77.8

STATION WOLLAYITA

ALTITUDE= 2060.0 ANNUAL EVAPOTRANSPIRATION= 1066.6MEAN ANNUAL TEMP.=18.5

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	20.2	21.0	20.1	19.3	18.2	17.1	15.5	15.7	17.6	18.4	19.8	19.3
EVAP.	97.0	100.8	96.5	92.6	87.4	82.1	74.4	75.4	84.5	88.3	95.0	92.6

STATION HOSSAINA

ALTITUDE= 2290.0 ANNUAL EVAPOTRANSPIRATION= 935.5MEAN ANNUAL TEMP.=16.2

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	15.5	16.9	18.1	17.6	16.8	15.8	15.4	15.1	15.8	15.9	16.3	15.7
EVAP.	74.4	81.1	86.9	84.5	80.6	75.8	73.9	72.5	75.8	76.3	78.2	75.4

STATION MAICHEW

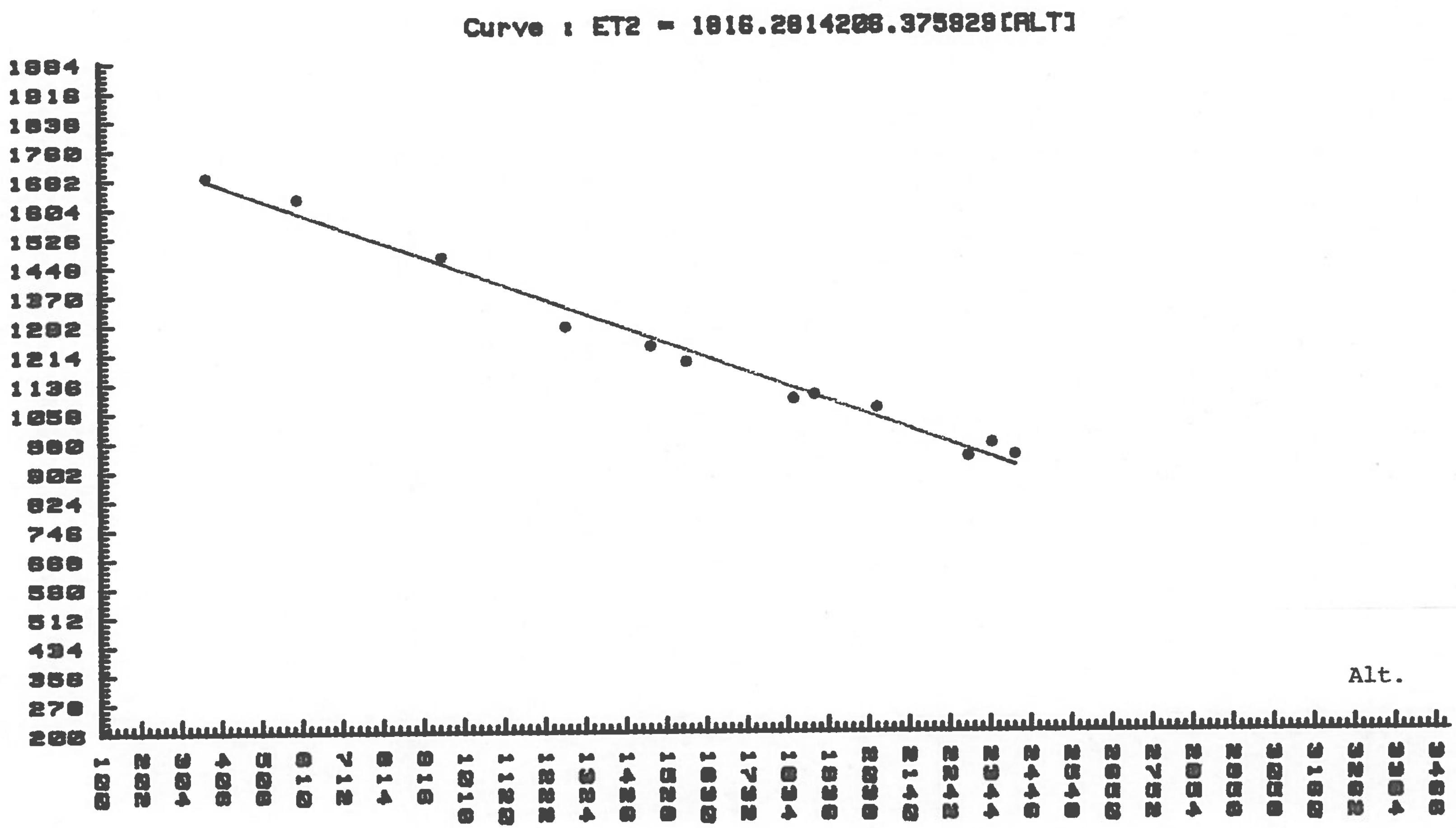
ALTITUDE= 2350.0 ANNUAL EVAPOTRANSPIRATION= 971.0MEAN ANNUAL TEMP.=16.9

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	14.5	15.2	16.7	17.7	19.1	19.7	18.4	18.4	16.9	15.2	16.0	14.5
EVAP.	69.6	73.0	80.2	85.0	91.7	94.6	88.3	88.3	81.1	73.0	76.8	69.6

STATION ADDIS ABABA

ALTITUDE= 2408.0 ANNUAL EVAPOTRANSPIRATION= 938.4MEAN ANNUAL TEMP.=16.3

	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.
TEMP.	15.6	16.9	17.9	17.7	17.9	16.7	15.1	15.7	15.6	15.8	15.3	15.3
EVAP.	74.9	81.1	85.9	85.0	85.9	80.2	72.5	75.4	74.9	75.8	73.4	73.4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3262
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ROGRAM ETO

COUNTRY : ETHIOPIA
PLACE : GEWANI
LATITUDE : 11,10 E
LONGITUDE: 40,40 N
ALTITUDE : 600 M
METHOD : PENMAN

DRY SEASON---REFLECTANCE COEFFICIENT = 0,15

PERIOD	TMEAN (C)	EA MBAR	RH /100	ED MBAR	EA-ED MBAR	F(U)	(1-W) T9	AT MMDAY	RA MMDAY	SN HRDAY	BN HRDAY	NRAT	ALP+ .5N/N	RS MMDAY	RNS MMDAY	F(T) T13	F(ED) T14	FN/N T15	RNL MMDAY	C T16	W.RN	U2 M/SEC	R MM	ETO MMDAY
OCT 1974	27.1	35.9	0.75	27.0	8.89	0.42	0.23	0.9	15.8	11.6	8.7	1.33	0.81	12.87	10.94	16.1	0.11	1.30	2.33	1.09	6.6	0.6	1	8.17
NOV 1974	23.9	29.6	0.73	21.9	7.76	0.43	0.26	0.9	16.5	11.0	10.0	1.10	0.70	11.55	9.82	15.4	0.13	1.09	2.25	1.09	5.6	0.7	1	7.03
DEC 1974	23.4	28.8	0.71	20.0	8.83	0.39	0.27	0.9	16.6	10.9	7.9	1.38	0.84	13.94	11.85	15.3	0.14	1.34	2.94	1.09	6.5	0.5	1	8.13
JAN 1974	25.9	33.4	0.50	17.0	16.41	0.73	0.24	2.9	16.7	11.4	12.6	0.90	0.60	10.04	8.53	15.9	0.16	0.91	2.30	0.99	4.7	2.0	1	7.55
FEB 1974	24.2	30.2	0.51	15.4	14.77	0.82	0.26	3.1	16.4	10.4	12.4	0.84	0.57	9.36	7.96	15.5	0.17	0.86	2.22	0.97	4.3	2.3	1	7.14
MAR 1974	25.0	31.7	0.65	20.8	10.90	0.64	0.25	1.8	15.3	9.9	12.1	0.82	0.56	8.55	7.27	15.7	0.14	0.84	1.82	1.04	4.1	1.6	1	6.08
APR 1974	28.2	38.3	0.62	23.4	14.82	0.57	0.22	1.9	13.7	11.7	11.8	0.99	0.64	8.83	7.50	16.3	0.13	0.99	2.05	1.06	4.3	1.3	1	6.47

ROGRAM ETO

COUNTRY : ETHIOPIA
PLACE : GEWANI
LATITUDE : 11,10 N
LONGITUDE: 40,40 E
ALTITUDE : 600 M
METHOD : PENMAN

WET SEASON---REFLECTANCE COFFIECIENT = 0.25

PERIOD	TMEAN (C)	EA MBAR	RH /100	ED MBAR	EA-ED MBAR	F(U)	(1-W) T9	AT MMDAY	RA MMDAY	SN HRDAY	RN HRDAY	NRAT	ALP+ .5N/N	RS MMDAY	RNS MMDAY	F(T) T13	F(ED) T14	FN/N T15	RNL MMDAY	C T16	W.RN	U2 M/SEC	R MM	ETO MMDAY
MAY 1974	29.5	41.3	0.66	28.0	13.22	0.62	0.21	1.7	15.7	10.4	12.6	0.83	0.66	10.40	7.80	16.6	0.11	0.84	1.50	1.06	5.0	1.5	1	7.14
JUN 1974	31.1	45.2	0.63	29.6	15.57	0.66	0.20	2.1	15.5	10.1	12.7	0.80	0.65	10.06	7.54	17.0	0.10	0.82	1.40	1.06	4.9	1.7	1	7.38
JUL 1974	29.0	40.1	0.70	28.4	11.75	0.64	0.22	1.6	15.5	9.7	12.6	0.77	0.64	9.86	7.40	16.5	0.11	0.80	1.39	1.06	4.7	1.6	1	6.71
AUG 1974	28.4	38.7	0.73	27.6	11.13	0.71	0.22	1.7	15.6	10.2	12.4	0.83	0.66	10.34	7.75	16.4	0.11	0.84	1.50	1.05	4.9	1.9	1	6.98
SEP 1974	28.8	39.6	0.77	30.9	8.76	0.84	0.22	1.6	15.2	10.3	12.1	0.85	0.67	10.25	7.69	16.5	0.10	0.86	1.36	1.04	5.0	2.4	1	6.81

ROGRAM ETO

COUNTRY : ETHIOPIA
PLACE : GEWANI
LATITUDE : 11,10 N
LONGITUDE: 40,40 E
ALTITUDE : 600 M
METHOD : PENMAN

DRY SEASON---REFLECTANCE COEFFICIENT = 0.15

PERIOD	TMEAN (C)	EA MBAR	RH /100	ED MBAR	EA-ED MBAR	F(U)	(1-W) T9	AT MMDAY	RA MMDAY	SN HRDAY	BN HRDAY	NRAT	ALP+ .5N/N	RS MMDAY	RNS MMDAY	F(T) T13	F(ED) T14	FN/N T15	RNL MMDAY	C T16	W.RN	U2 M/SEC	R MM	ETO MMDAY
OCT 1973	30.8	44.4	0.63	22.5	21.91	0.76	0.20	3.3	14.4	11.5	11.8	0.98	0.64	9.20	7.82	16.9	0.13	0.98	2.17	1.04	4.5	2.1	1	8.16
NOV 1973	27.7	37.2	0.54	20.7	16.46	0.75	0.22	2.7	13.3	11.0	11.6	0.95	0.62	8.30	7.06	16.2	0.14	0.95	2.16	0.96	3.8	2.0	1	6.26
DEC 1973	24.5	30.8	0.44	14.1	16.62	0.87	0.25	3.7	12.5	10.9	11.5	0.95	0.62	7.80	6.63	15.5	0.17	0.95	2.58	0.92	3.0	2.6	1	6.21
JAN 1973	27.0	35.7	0.85	30.4	5.35	0.73	0.23	0.9	12.8	11.4	11.6	0.78	0.64	8.19	6.96	16.1	0.10	0.98	1.54	1.02	4.2	2.0	1	5.18
FEB 1973	28.6	39.2	0.89	35.7	3.49	0.73	0.22	0.6	13.9	10.4	11.8	0.88	0.59	8.23	7.00	16.4	0.08	0.90	1.13	1.02	4.6	2.0	1	5.26
MAR 1973	30.9	44.7	0.78	35.0	9.63	0.78	0.20	1.5	15.1	11.8	12.0	0.98	0.64	9.67	8.22	16.9	0.08	0.98	1.32	1.04	5.5	2.2	1	7.31
APR 1973	32.3	48.4	0.77	36.7	11.76	0.84	0.19	1.9	15.7	11.7	12.3	0.95	0.62	9.80	8.33	17.3	0.07	0.95	1.21	1.04	5.8	2.5	1	7.91

ROGRAM ETO
COUNTRY : ETHIOPIA
PLACE : GEWANI
LATITUDE : 11,10 N
LONGITUDE: 40,40 E

WET SEASON---REFLECTANCE COEFFICIENT = 0.25

ALTITUDE : 600 M
METHOD : PENMAN

PERIOD	TMEAN (C)	EA MBAR	RH /100	ED MBAR	EA-ED MBAR	F(U)	(1-W) T9	AT MNDAY	RA MMDAY	SN HRDAY	BN HRDAY	NRAT	ALP+ .5N/N	RS MMDAY	RNS MMDAY	F(T) T13	F(ED) T14	FN/N T15	RNL MMDAY	C T16	W.RN	U2 M/SEC	R MM	ETO MMDAY
MAY 1973	32.4	48.7	0.84	40.0	8.70	0.75	0.19	1.2	15.7	10.4	12.6	0.83	0.66	10.40	7.80	17.3	0.06	0.84	0.90	1.05	5.6	2.0	1	7.18
JUN 1973	34.1	53.5	0.84	44.7	8.81	0.82	0.18	1.3	15.5	10.1	12.7	0.80	0.65	10.06	7.54	17.7	0.05	0.82	0.66	1.04	5.6	2.4	1	7.22
JUL 1973	31.1	45.2	0.81	36.6	8.53	0.97	0.20	1.6	15.5	9.7	12.6	0.77	0.64	9.86	7.40	17.0	0.07	0.80	0.99	1.02	5.1	3.0	1	6.92
AUG 1973	29.6	41.5	0.82	34.8	6.71	1.06	0.21	1.5	15.6	9.6	12.4	0.77	0.64	9.94	7.45	16.6	0.08	0.80	1.07	1.02	5.0	3.4	1	6.64
SEP 1973	30.6	43.9	0.70	31.7	12.20	0.80	0.20	2.0	15.2	9.1	12.1	0.75	0.62	9.49	7.12	16.9	0.09	0.77	1.20	1.04	4.7	2.3	1	6.96

ROGRAM ETO
COUNTRY : ETHIOPIA
PLACE : DUBTI
LATITUDE : 11,45 N
LONGITUDE: 41,5 E
ALTITUDE : 370 M
METHOD : PENMAN

WET SEASON ---- REFLECTANCE COEFFICIENT = 0.25

PERIOD	TMEAN	EA	RH	ED	EA-ED	F(U)	(1-W)	AT	RA	SN	BN	NRAT	ALP+	RS	RNS	F(T)	F(ED)	FN/N	RNL	C	W.RN	U2	R	ETO
	(C)	MBAR	/100	MBAR	MBAR		T9	MMDAY	MMDAY	HRDAY	HRDAY		.5N/N	MMDAY	MMDAY	T13	T14	T15	MMDAY	T16		M/SEC	MM	MMDAY
FEB 1974	26.3	34.2	0.52	17.7	16.56	0.60	0.24	2.4	13.9	10.4	11.8	0.88	0.69	9.62	7.22	16.0	0.16	0.90	2.22	1.00	3.8	1.4	1	6.19
MAR 1974	27.1	35.9	0.56	20.2	15.74	0.54	0.23	1.9	15.1	8.0	12.0	0.67	0.58	8.83	6.62	16.1	0.14	0.70	1.61	1.00	3.9	1.2	1	5.83
APR 1974	28.1	38.0	0.48	18.4	19.60	0.47	0.22	2.0	15.7	11.7	12.3	0.95	0.72	11.37	8.53	16.3	0.15	0.95	2.35	1.03	4.8	0.8	1	7.04
MAY 1974	31.5	46.3	0.40	19.3	26.97	0.50	0.20	2.7	15.7	10.4	12.6	0.83	0.66	10.40	7.80	17.1	0.15	0.84	2.11	1.02	4.6	1.0	1	7.39
JUN 1974	33.8	52.6	0.34	18.6	34.05	0.53	0.18	3.2	15.5	10.1	12.7	0.80	0.65	10.06	7.54	17.7	0.15	0.82	2.17	1.02	4.4	1.1	1	7.77
JUL 1974	22.3	26.9	0.41	19.8	7.11	0.63	0.28	1.2	15.5	9.7	12.6	0.77	0.64	9.86	7.40	15.1	0.14	0.80	1.73	1.00	4.1	1.6	1	5.35
AUG 1974	31.2	45.4	0.40	22.5	22.99	0.55	0.20	2.5	15.6	9.6	12.4	0.77	0.64	9.94	7.45	17.0	0.13	0.80	1.78	1.01	4.5	1.2	1	7.15
SEP 1974	31.6	46.5	0.48	23.3	23.24	0.48	0.19	2.2	15.2	10.3	12.1	0.85	0.67	10.25	7.69	17.1	0.13	0.86	1.89	1.02	4.7	0.9	1	7.01

ROGRAM ETO
COUNTRY : ETHIOPIA
PLACE : DUBTI
LATITUDE : 11,45 N
LONGITUDE: 41,5 E
ALTITUDE : 370 M
METHOD : PENMAN

DRY SEASON---- REFLECTANCE COEFFICIENT = 0.15

PERIOD	TMEAN	EA	RH	ED	EA-ED	F(U)	(1-W)	AT	RA	SN	BN	NRAT	ALP+	RS	RNS	F(T)	F(ED)	FN/N	RNL	C	W.RN	U2	R	ETO
	(C)	MBAR	/100	MBAR	MBAR		T9	MMDAY	MMDAY	HRDAY	HRDAY		.5N/N	MMDAY	MMDAY	T13	T14	T15	MMDAY	T16		M/SEC	MM	MMDAY
OCT 1975	28.0	37.8	0.51	19.3	18.48	0.38	0.22	1.6	14.4	10.3	11.8	0.88	0.59	8.47	7.20	16.3	0.15	0.89	2.12	1.02	4.0	0.5	1	5.62
NOV 1975	24.6	30.9	0.55	17.5	13.44	0.45	0.25	1.5	13.3	11.0	11.6	0.95	0.62	8.30	7.06	15.6	0.16	0.95	2.31	1.00	3.5	0.8	1	5.10
DEC 1975	22.9	27.9	0.61	17.2	10.71	0.49	0.27	1.4	12.5	10.9	11.5	0.95	0.62	7.80	6.63	15.2	0.16	0.95	2.28	1.05	3.2	0.9	1	4.82
JAN 1975	24.1	30.0	0.57	17.1	12.85	0.53	0.26	1.8	12.8	32.0	11.6	2.76	1.53	19.56	16.62	15.4	0.16	2.58	6.28	1.03	7.7	1.1	1	9.68
FEB 1975	26.9	35.5	0.57	20.6	14.89	0.59	0.23	2.0	13.9	10.9	11.8	0.92	0.61	8.50	7.23	16.1	0.14	0.93	2.10	0.99	3.9	1.4	1	5.89
MAR 1975	28.4	38.7	0.52	19.9	18.87	0.60	0.22	2.5	15.1	11.0	12.0	0.92	0.61	9.19	7.81	16.4	0.14	0.93	2.18	1.00	4.4	1.4	1	6.88

ROGRAM ETO
COUNTRY : ETHIOPIA
PLACE : DUBTI
LATITUDE : 11,45 N
LONGITUDE: 41,5 E
ALTITUDE : 370 M
METHOD : PENMAN

WET SEASON---- REFLECTANCE COEFFICIENT = 0.25

PERIOD	TMEAN	EA	RH	ED	EA-ED	F(U)	(1-W)	AT	RA	SN	BN	NRAT	ALP+	RS	RNS	F(T)	F(ED)	FN/N	RNL	C	W.RN	U2	R	ETO
	(C)	MBAR	/100	MBAR	MBAR		T9	MMDAY	MMDAY	HRDAY	HRDAY		.5N/N	MMDAY	MMDAY	T13	T14	T15	MMDAY	T16		M/SEC	MM	MMDAY
APR 1975	30.3	43.2	0.58	24.8	18.35	0.58	0.21	2.2	15.7	10.4	12.3	0.85	0.67	10.58	7.94	16.8	0.12	0.86	1.75	1.01	4.9	1.3	1	7.20
MAY 1975	32.2	48.1	0.41	19.6	28.53	0.50	0.19	2.7	15.7	11.1	12.6	0.88	0.69	10.82	8.11	17.3	0.15	0.89	2.23	1.02	4.8	1.0	1	7.66
JUN 1975	27.0	35.7	0.45	16.1	19.63	0.62	0.23	2.8	15.5	12.0	12.7	0.95	0.72	11.22	8.41	16.1	0.16	0.95	2.51	1.01	4.5	1.5	1	7.44
JUL 1975	33.3	51.2	0.41	20.7	30.45	0.76	0.18	4.2	15.5	11.1	12.6	0.88	0.69	10.68	8.01	17.5	0.14	0.89	2.18	0.99	4.8	2.1	1	8.94
AUG 1975	29.7	41.7	0.36	14.7	27.00	0.55	0.21	3.1	15.6	9.6	12.4	0.77	0.64	9.94	7.45	16.6	0.17	0.80	2.27	1.01	4.1	1.2	1	7.31
SEP 1975	30.3	43.2	0.51	21.9	21.27	0.54	0.21	2.4	15.2	9.7	12.1	0.80	0.65	9.87	7.40	16.8	0.13	0.82	1.84	1.01	4.4	1.1	1	6.87

----MONTHLY EVAPOTRANSPIRATION----

ROGRAM ETO
COUNTRY : ETHIOPIA
PLACE : ROBI
LATITUDE : 10,00 N
LONGITUDE: 39,55 E
ALTITUDE : 1275 M
METHOD : PENMAN

DRY SEASON---REFLECTANCE COEFFICIENT = 0.15

PERIOD	TMEAN (C)	EA MBAR	RH /100	ED MBAR	EA-ED MBAR	F(U)	(1-W) T9	AT MMDAY	RA MMDAY	SN HRDAY	BN HRDAY	NRAT	ALP+ .5N/N	RS MMDAY	RNS MMDAY	F(T) T13	F(ED) T14	FN/N T15	RNL MMDAY	C T16	W.RN	U2 M/SEC	R MM	ETO MMDAY
OCT 1972	23.6	29.1	0.45	13.4	15.71	0.55	0.25	2.2	14.7	9.7	11.8	0.82	0.56	8.27	7.03	15.3	0.18	0.84	2.31	0.99	3.5	1.2	1	5.66
NOV 1972	22.5	27.3	0.44	12.4	14.89	0.52	0.27	2.0	13.6	9.8	11.6	0.85	0.57	7.80	6.63	15.1	0.19	0.86	2.41	0.98	3.1	1.1	1	5.05
DEC 1972	21.7	26.0	0.48	12.7	13.28	0.49	0.27	1.8	12.9	9.5	11.5	0.83	0.56	7.26	6.17	14.9	0.18	0.84	2.31	0.97	2.8	0.9	1	4.47
JAN 1972	19.3	22.4	0.48	10.6	11.86	0.48	0.30	1.7	13.2	10.2	11.6	0.88	0.59	7.76	6.60	14.5	0.20	0.89	2.53	0.99	2.9	0.9	1	4.48

PROGRAM ETO
COUNTRY : ETHIOPIA
PLACE : ROBI
LATITUDE : 10,00 N
LONGITUDE: 39,55 E
ALTITUDE : 1275 M
METHOD : PENMAN

WET---SEASON---REFLECTANCE COEFFICIENT = 0,25

PERIOD	TMEAN (C)	EA MBAR	RH /100	ED MBAR	EA-ED MBAR	F(U)	(1-W) T9	AT MMDAY	RA MMDAY	SN HRDAY	BN HRDAY	NRAT	ALP+ .5N/N	RS MMDAY	RNS MMDAY	F(T) T13	F(ED) T14	FN/N T15	RNL MMDAY	C T16	W.RN	U2 M/SEC	R MM	ETO MMDAY
FEB 1972	20.6	24.3	0.70	17.4	6.87	0.44	0.28	0.9	14.2	5.5	11.8	0.47	0.48	6.86	5.14	14.7	0.16	0.52	1.20	1.04	2.8	0.7	1	3.84
MAR 1972	22.7	27.6	0.61	17.1	10.45	0.55	0.26	1.5	15.3	9.0	12.0	0.75	0.63	9.58	7.19	15.1	0.16	0.78	1.86	1.07	3.9	1.2	1	5.81
APR 1972	23.7	29.3	0.63	18.8	10.52	0.56	0.25	1.5	15.7	6.1	12.3	0.50	0.50	7.84	5.88	15.3	0.15	0.55	1.26	1.04	3.5	1.2	1	5.13
MAY 1972	24.6	30.9	0.57	18.1	12.87	0.56	0.24	1.8	15.5	7.1	12.6	0.57	0.53	8.26	6.20	15.6	0.15	0.61	1.45	0.99	3.6	1.3	1	5.28
JUN 1972	25.4	32.5	0.50	15.9	16.61	0.89	0.24	3.5	15.3	8.2	12.7	0.65	0.57	8.78	6.59	15.8	0.16	0.68	1.77	0.95	3.7	2.7	1	6.80
JUL 1972	25.7	33.0	0.53	17.8	15.22	0.55	0.23	2.0	15.3	8.4	12.6	0.67	0.58	8.95	6.71	15.8	0.15	0.70	1.72	1.00	3.8	1.2	1	5.82
AUG 1972	24.9	31.5	0.57	18.1	13.44	0.57	0.24	1.8	15.5	6.4	12.4	0.52	0.51	7.88	5.91	15.6	0.15	0.56	1.35	1.05	3.5	2.1	1	5.59

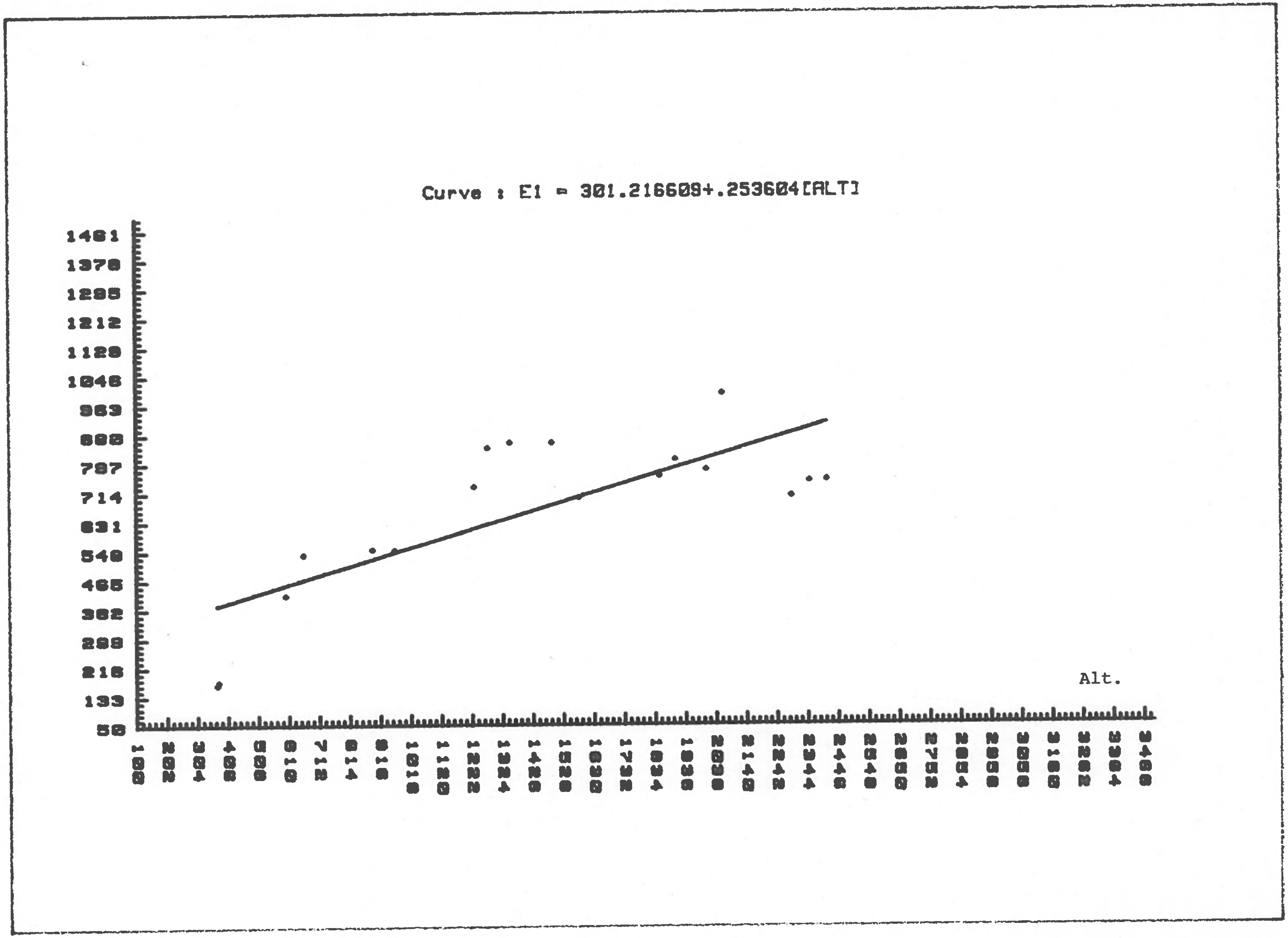
PROGRAM ETO
COUNTRY : ETHIOPIA
PLACE : ROBI
LATITUDE : 10,00 N
LONGITUDE: 39,55 E
ALTITUDE : 1275 M
METHOD : PENMAN

DRY SEASON---REFLECTANCE COEFFICIENT = 0.15

PERIOD	TMEAN (C)	EA MBAR	RH /100	ED MBAR	EA-ED MBAR	F(U)	(1-W) T9	AT MMDAY	RA MMDAY	SN HRDAY	BN HRDAY	NRAT	ALP+ .5N/N	RS MMDAY	RNS MMDAY	F(T) T13	F(ED) T14	FN/N T15	RNL MMDAY	C T16	W.RN	U2 M/SEC	R MM	ETO MMDAY
OCT 1975	22.5	27.3	0.57	16.2	11.04	0.43	0.27	1.3	14.7	6.1	11.8	0.51	0.41	5.98	5.09	15.1	0.16	0.56	1.38	0.95	2.7	0.7	1	3.79
NOV 1975	21.0	24.9	0.53	13.2	11.70	0.42	0.28	1.4	13.6	5.8	11.6	0.50	0.40	5.44	4.62	14.8	0.18	0.55	1.47	0.95	2.3	0.6	1	3.46
DEC 1975	20.0	23.4	0.46	10.9	12.47	0.42	0.29	1.5	12.9	5.7	11.5	0.50	0.40	5.15	4.38	14.6	0.19	0.55	1.56	0.94	2.0	0.6	1	3.33

```
10   REM "TURC [1952]....ACTUAL EVAPOTRANSPIRATION "
20   DIM S$(100),A(100),T(100),P(100),E(100),F$[160]
30   READ N
40   PRINT "STATION      ALTITUDE          TEMP.        PRECIPT.     ACT.EVAPO.
"
50   PRINT "-------      --------          -----        --------     ---- ------
     "
52 Ff:IMAGE  10A,2X,MDDDDD,12X,MDDDD,9X,MDDDDD,5X,MDDDDDDD.D
60   FOR K=1 TO N
70   READ S$(K),A(K),T(K),P(K)
80   L=300+25*T(K)+.05*T(K)^3
90   E(K)=P(K)/(.9+P(K)^2/L^2)^.5
91   FIXED 1
100  PRINT USING Ff;S$(K),A(K),T(K),P(K),E(K)
110  NEXT K
120  DATA 18
130 DATA DUBTI,370,29,160
140  DATA TENDAHO,375,29,168
150  DATA GEWANI,600,28,410
160  DATA ELIWOHA,660,27,532
170  DATA AWASH,890,25,555
180  DATA METEHARA,964,24,558
190  DATA KORA,1230,23,797
200  DATA ROBI,1275,22,1007
210  DATA MIESO,1350,27,903
220  DATA CHEFA,1490,21,1086
230  DATA WONJI,1580,21,789
240  DATA ALABA,1850,19,983
250  DATA KOMBOLCHA,1903,19,1106
260  DATA WUCHALE,2006,18,1107
270  DATA WOLLAYITA,2060,19,2069
280  DATA HOSSAINA,2290,16,1052
290  DATA MAICHEW,2350,17,1100
300  DATA ADDISABABA ,2408,16,1256
310  END
```

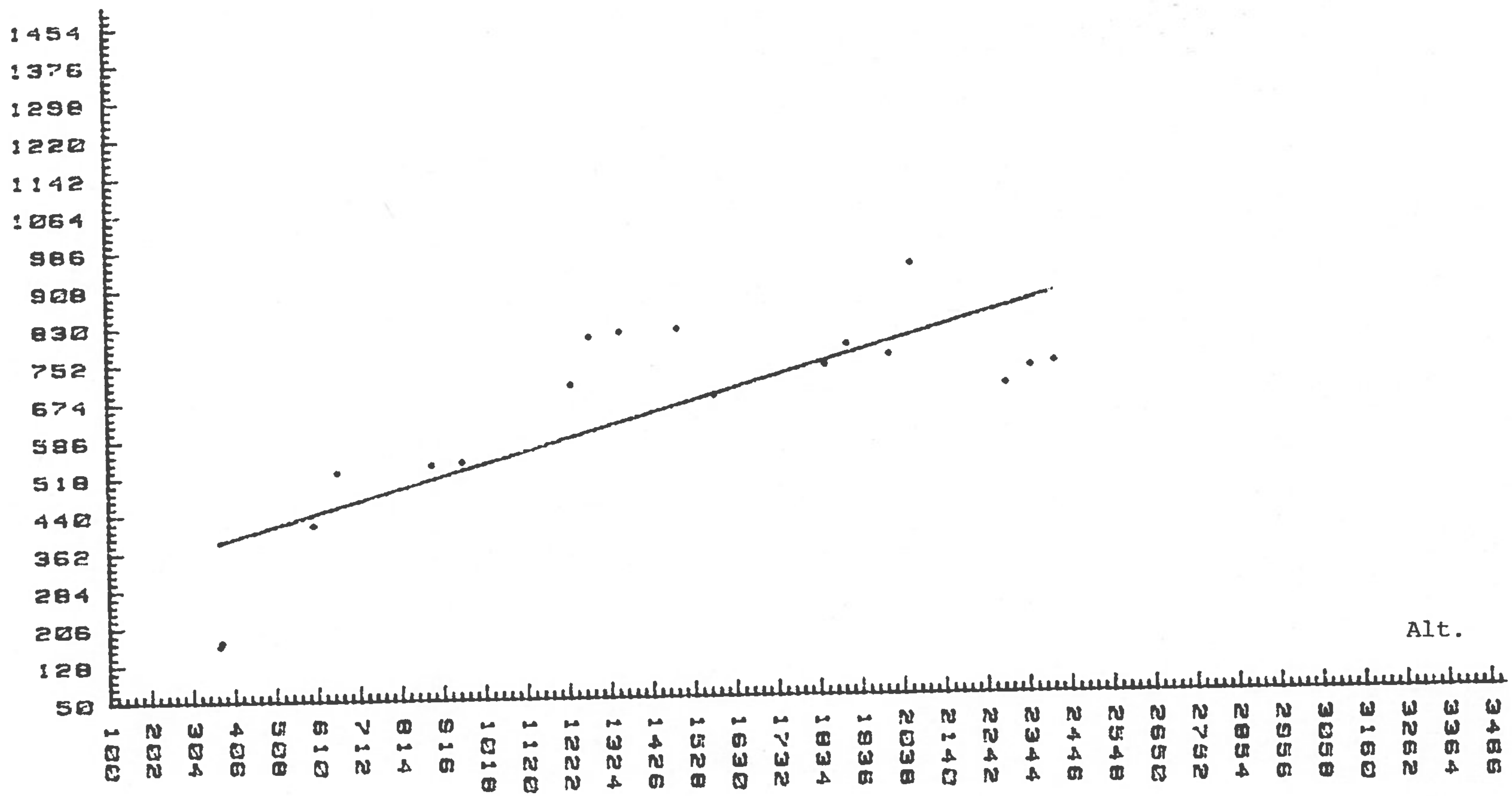
STATION	ALTITUDE	TEMP.	PRECIPT.	ACT.EVAPO.
DUBTI	370	29	160	168.2
TENDAHO	375	29	168	176.5
GEWANI	600	28	410	423.3
ELIWOHA	660	27	532	539.1
AWASH	890	25	555	553.4
METEHARA	964	24	558	551.7
KORA	1230	23	797	731.0
ROBI	1275	22	1007	841.9
MIESO	1350	27	903	856.1
CHEFA	1490	21	1086	855.7
WONJI	1580	21	789	698.7
ALABA	1850	19	983	760.0
KOMBOLCHA	1903	19	1106	806.9
WUCHALE	2006	18	1107	777.1
WOLLAYITA	2060	19	2069	994.9
HOSSAINA	2290	16	1052	701.0
MAICHEW	2350	17	1100	744.3
ADDISABABA	2408	16	1256	747.0


Curve : E1 = 301.216609+.253604[ALT]
Alt.

```
10   REM "LANGBEIN (1949)---ACTUAL EVAPOTRANSPIRATION"
20   DIM S$(100),A(100),T(100),P(100),E(100),F$[100]
30   READ N
40   PRINT "STATION     ALTITUDE            TEMP.        PRECIPT.   ACT.EVOPO
."
50   PRINT "-------     --------            -----        ---------  ---------
"
60   FOR K=1 TO N
70   READ S$(K),A(K),T(K),P(K)
80    L=325+21*T(K)+.9*T(K)^2
90   E(K)=P(K)/(.9+P(K)^2/L^2)^.5
100  FIXED 1
110  PRINT USING Ff;S$(K),A(K),T(K),P(K),E(K)
120  NEXT K
130 Ff: IMAGE  11A,2X,MDDDDD,12X,MDDDD,9X,MDDDDD,5X,MDDDDD.D
140  DATA 18
150  DATA DUBTI,370,29,160
160  DATA TENDAHO,375,29,168
170  DATA GEWANI,600,28,410
180  DATA ELIWOHA,660,27,532
190  DATA AWASH,890,25,555
200  DATA METEHARA,964,26,558
210  DATA KORA,1230,23,797
220  DATA ROBI,1275,22,1007
230  DATA MIESO,1350,27,963
240  DATA CHEFFA,1490,21,1086
250  DATA WONJI,1580,21,789
260  DATA ALABA,1850,19,983
270  DATA KOMBOLCHA,1903,19,1105
280  DATA WUCHALE,2006,18,1107
290  DATA WOLLAYITA,2060,19,2069
300  DATA HOSSAINA,2290,16,1052
310  DATA MAICHEW,2350,17,1100
320  DATA ADDIS ABABA,2408,16,1256
330  END
```

STATION	ALTITUDE	TEMP.	PRECIPT.	ACT.EVOPO.
DUBTI	370	29	160	167.8
TENDAHO	375	29	168	176.1
GEWANI	600	28	410	417.6
ELIWOHA	660	27	532	527.3
AWASH	890	25	555	540.5
METEHARA	964	26	558	546.6
KORA	1230	23	797	703.0
ROBI	1275	22	1007	801.5
MIESO	1350	27	903	810.8
CHEFFA	1490	21	1086	815.8
WONJI	1580	21	789	676.5
ALABA	1850	19	983	737.1
KOMBOLCHA	1903	19	1105	779.4
WUCHALE	2006	18	1107	756.9
WOI LAYITA	2060	19	2069	945.3
HOSSAINA	2290	16	1052	694.8
MAICHEW	2350	17	1100	731.2
ADDIS ABABA	2408	16	1256	739.4

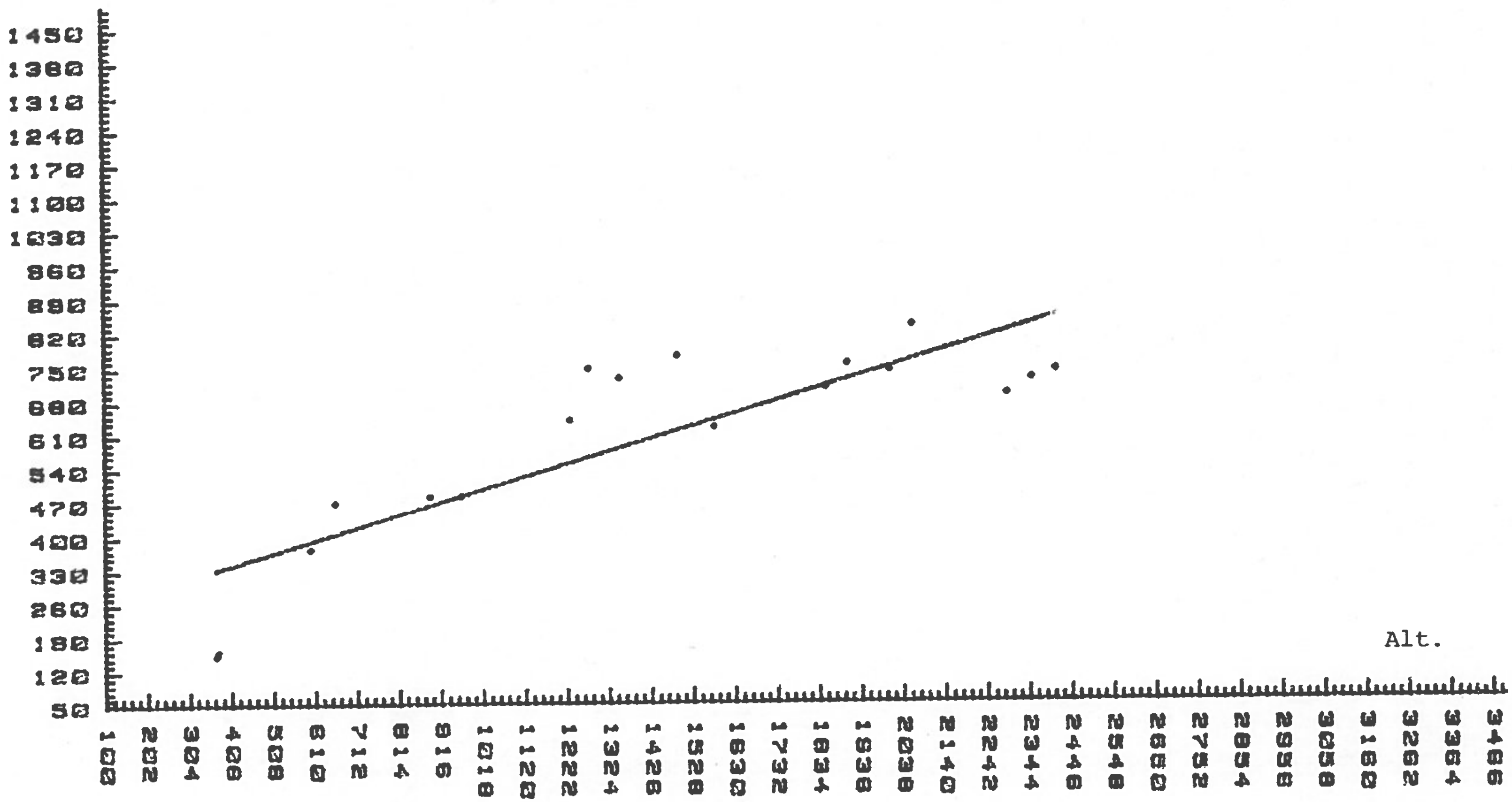
Curve : E2 = 291.850863+.246091[ALT]



```
10   REM "COUTAGNE---ACTUAL EVAPOTRANSPIRATION"
20   DIM S$(100),A(100),T(100),P(100),E(100),F$(100)
30   READ N
40   PRINT " STATION       ALTITUDE          TEMP.        PRECIPIT.   ACT.EVAPO
."
50   PRINT "--------       --------          -----        ---------   ---------
-"
60 Ff:  IMAGE  11A,2X,MDDDDD,12X,MDDDD,9X,MD.DDDD,5X,MD.DDDD
70   FOR K=1 TO N
80   READ S$(K),A(K),T(K),P(K)
90   Y=1/(.8+.14*T(K))
100  E(K)=P(K)-Y*P(K)^2
110  PRINT USING Ff;S$(K),A(K),T(K),P(K),E(K)
120  NEXT K
130  DATA 18
140  DATA DUBTI,370,29,.160
150  DATA TENDAHO,375,29,.168
160  DATA GEWANI,600,28,.410
170  DATA ELIWOHA,660,27,.532
180  DATA AWASH,890,25,.555
190  DATA METEHARA,964,24,.558
200  DATA KORA,1230,23,.797
210  DATA ROBI,1275,22,1.007
220  DATA MIESO,1350,27,.903
230  DATA CHEFFA,1490,21,1.086
240  DATA WONJI,1580,21,.789
250  DATA ALABA,1850,19,.983
260  DATA KOMBOLCHA,1903,19,1.106
270  DATA WUCHALE,2006,18,1.107
280  DATA WOLLAYITA,2060,19,2.069
290  DATA HOSSAINA,2290,16,1.052
300  DATA MAICHEW,2350,17,1.100
310  DATA ADDIS ABABA,2408,16,1.256
320  END
```

STATION	ALTITUDE	TEMP.	PRECIPIT.	ACT.EVAPO.
DUBTI	370	29	.1600	.1547
TENDAHO	375	29	.1680	.1622
GEWANI	600	28	.4100	.3744
ELIWOHA	660	27	.5320	.4702
AWASH	890	25	.5550	.4834
METEHARA	964	24	.5580	.4832
KORA	1230	23	.7970	.6390
ROBI	1275	22	1.0070	.7456
MIFSO	1350	27	.9030	.7250
CHEFFA	1490	21	1.0860	.7707
WONJI	1580	21	.7890	.6226
ALABA	1650	19	.9830	.7037
KOMBOLCHA	1903	19	1.1060	.7525
WUCHALE	2006	18	1.1070	.7379
WOLLAYITA	2060	19	2.0690	.8318
HOSSAINA	2290	16	1.0520	.6881
MAICHEW	2350	17	1.1000	.7195
ADDIS ABABA	2408	16	1.2560	.7371

Curve : E3 = 239.426606+.253086[ALT]



---CHEMICAL ANALYSIS--1=TDS,2=CA,3=MG,4=NA,5=K,6=HCO3,7=CL,8=SO4,9=SIO2---

PARAMETERS
============

COL 1- 5 =	139
COL 6-10 =	9
COL 11-15 =	1
COL. 16-20 =	0
COL 21-25 =	0
COL 26-30 =	0

Name of the cases & their index no. :

1 = CS1	2 = CS2	3 = CS3	4 = CS4	5 = CS5	6 = CS6
7 = CS7	8 = CS8	9 = CS9	10 = CS10	11 = CS11	12 = CS12
13 = CS13	14 = CS14	15 = CS15	16 = CS16	17 = CS17	18 = CS18
19 = CS19	20 = CS20	21 = CS21	22 = CS22	23 = CS23	24 = CS24
25 = CS25	26 = CS26	27 = CS27	28 = CS28	29 = CS30	30 = CS31
31 = CS32	32 = CS35	33 = CS36	34 = CS37	35 = CS38	36 = CS39
37 = CS40	38 = CS41	39 = CS42	40 = CS43	41 = CS44	42 = CS45
43 = CS46	44 = CS47	45 = CS48	46 = CS49	47 = CS50	48 = CS51
49 = CS52	50 = CS53	51 = CS54	52 = CS56	53 = CS57	54 = CS58
55 = CS59	56 = WH4	57 = WH5	58 = WH6	59 = WH7	60 = WH8
61 = WH9	62 = WH10	63 = WH11	64 = WH12	65 = WH13	66 = WH14
67 = WH15	68 = WH16	69 = WH20	70 = WH21	71 = WH22	72 = WH27
73 = WH28	74 = WH29	75 = WH30	76 = WH31	77 = WH32	78 = WH33
79 = WH34	80 = WH35	81 = WH36	82 = WH38	83 = WH40	84 = WH41
85 = WH42	86 = WH43	87 = DW1	88 = DW2	89 = DW3	90 = DW17
91 = DW18	92 = DW19	93 = DW23	94 = DW24	95 = RH1	96 = RH5
97 = BH8	98 = BH12	99 = BH32	100 = BH39	101 = BH41	102 = BH43
103 = BH44	104 = BH47	105 = BH48	106 = RH49	107 = RH52	108 = RH53
109 = BH54	110 = BH55	111 = BH56	112 = BH57	113 = BH58	114 = BH62
115 = BH63	116 = BH64	117 = BH65	118 = BH66	119 = HS1	120 = HS2
121 = HS4	122 = HS5	123 = HS6	124 = HS7	125 = HS8	126 = HS9
127 = HS10	128 = HS11	129 = HS12	130 = HS13	131 = HS14	132 = HS15
133 = HS16	134 = HL1	135 = HL2	136 = HL3	137 = HL4	138 = HL5
139 = HL6					

** Raw Data_matrix **

	1	2	3	4	5	6	7	8	9
CS1	1304.0000	135.0000	40.0000	158.0000	9.0000	564.0000	67.0000	278.0000	32.0000
CS2	817.0000	56.0000	58.0000	75.0000	12.0000	467.0000	87.0000	46.0000	13.0000
CS3	949.0000	88.0000	36.0000	86.0000	41.0000	421.0000	77.0000	146.0000	49.0000
CS4	543.0000	48.0000	24.0000	68.0000	8.0000	233.0000	34.0000	111.0000	15.0000
CS5	407.0000	39.0000	18.0000	16.0000	22.0000	232.0000	14.0000	26.0000	36.0000
CS6	275.0000	35.0000	6.0000	9.0000	1.9000	134.0000	13.0000	17.0000	67.0000
CS7	344.0000	50.0000	9.0000	11.0000	1.6000	201.0000	6.0000	20.0000	41.0000
CS8	319.0000	43.0000	10.0000	8.0000	1.6000	171.0000	11.0000	11.0000	62.0000
CS9	358.0000	54.0000	20.0000	9.0000	0.7000	207.0000	12.0000	8.0000	45.0000
CS10	588.0000	89.0000	24.0000	21.0000	0.7000	384.0000	12.0000	10.0000	45.0000
CS11	750.0000	108.0000	26.0000	39.0000	5.0000	445.0000	24.0000	39.0000	62.0000
CS12	508.0000	64.0000	24.0000	22.0000	2.0000	325.0000	15.0000	11.0000	41.0000
CS13	1063.0000	120.0000	54.0000	84.0000	6.0000	531.0000	138.0000	85.0000	41.0000
CS14	1015.0000	93.0000	41.0000	134.0000	4.0000	448.0000	150.0000	176.0000	15.0000
CS15	533.0000	63.0000	25.0000	20.0000	4.0000	337.0000	16.0000	8.0000	56.0000
CS16	1357.0000	12.0000	40.0000	24.0000	5.0000	395.0000	25.0000	21.0000	34.0000
CS17	408.0000	48.0000	19.0000	26.0000	1.0000	250.0000	11.0000	16.0000	30.0000
CS18	423.0000	58.0000	14.0000	20.0000	2.0000	257.0000	13.0000	11.0000	45.0000
CS19	550.0000	48.0000	34.0000	43.0000	3.0000	336.0000	4.0000	26.0000	36.0000
CS20	847.0000	88.0000	19.0000	54.0000	90.0000	420.0000	48.0000	23.0000	81.0000
CS21	823.0000	88.0000	20.0000	56.0000	7.0000	476.0000	38.0000	37.0000	98.0000
CS22	867.0000	56.0000	63.0000	74.0000	3.0000	543.0000	17.0000	44.0000	58.0000
CS23	488.0000	66.0000	22.0000	13.0000	1.0000	317.0000	1.0000	15.0000	51.0000
CS24	628.0000	60.0000	44.0000	20.0000	0.6000	405.0000	1.0000	34.0000	61.0000
CS25	379.0000	25.0000	5.0000	62.0000	0.6000	232.0000	2.0000	21.0000	30.0000
CS26	520.0000	63.0000	13.0000	36.0000	6.0000	327.0000	2.0000	8.0000	64.0000
CS27	652.0000	80.0000	26.0000	44.0000	2.0000	434.0000	3.0000	20.0000	39.0000
CS28	305.0000	45.0000	12.0000	11.0000	0.3000	229.0000	1.0000	10.0000	34.0000
CS30	285.0000	32.0000	7.0000	16.0000	4.0000	154.0000	1.0000	15.0000	54.0000
CS31	307.0000	49.0000	17.0000	12.0000	2.0000	246.0000	1.0000	16.0000	43.0000
CS32	406.0000	50.0000	16.0000	13.0000	2.0000	278.0000	1.0000	13.0000	30.0000
CS35	316.0000	38.0000	8.0000	24.0000	2.0000	203.0000	1.0000	14.0000	26.0000
CS36	424.0000	56.0000	8.0000	27.0000	27.0000	259.0000	1.0000	10.0000	35.0000
CS37	237.0000	36.0000	5.0000	14.0000	14.0000	154.0000	1.0000	5.0000	17.0000
CS38	476.0000	50.0000	22.0000	25.0000	25.0000	300.0000	2.0000	10.0000	32.0000
CS39	705.0000	83.0000	30.0000	30.0000	34.0000	447.0000	2.0000	26.0000	48.0000
CS40	535.0000	66.0000	27.0000	31.0000	31.0000	312.0000	3.0000	31.0000	32.0000
CS41	589.0000	67.0000	30.0000	32.0000	32.0000	366.0000	1.0000	26.0000	36.0000
CS42	697.0000	87.0000	41.0000	65.0000	19.0000	381.0000	8.0000	61.0000	33.0000
CS43	770.0000	75.0000	43.0000	65.0000	2.0000	461.0000	7.0000	74.0000	39.0000

CS44	814.0000	63.0000	58.0000	62.0000	0.5000	478.0000	3.0000	33.0000	50.0000
CS45	483.0000	56.0000	19.0000	30.0000	5.0000	377.0000	1.0000	4.0000	43.0000
CS46	437.0000	52.0000	16.0000	32.0000	6.0000	273.0000	2.0000	18.0000	36.0000
CS47	398.0000	58.0000	8.0000	19.0000	4.0000	249.0000	2.0000	11.0000	44.0000
CS48	725.0000	100.0000	34.0000	32.0000	2.0000	478.0000	4.0000	24.0000	50.0000
CS49	487.0000	38.0000	30.0000	41.0000	2.0000	327.0000	3.0000	13.0000	30.0000
CS50	537.0000	31.0000	32.0000	70.0000	6.0000	339.0000	5.0000	21.0000	32.0000
CS51	388.0000	54.0000	32.0000	15.0000	2.0000	256.0000	1.0000	13.0000	37.0000
CS52	582.0000	42.0000	13.0000	49.0000	1.0000	386.0000	4.0000	20.0000	32.0000
CS53	592.0000	45.0000	46.0000	47.0000	2.0000	425.0000	3.0000	9.0000	22.0000
CS54	703.0000	81.0000	20.0000	49.0000	3.0000	483.0000	3.0000	12.0000	50.0000
CS56	575.0000	76.0000	22.0000	32.0000	1.0000	395.0000	2.0000	4.0000	40.0000
CS57	922.0000	76.0000	61.0000	49.0000	12.0000	434.0000	4.0000	26.0000	58.0000
CS58	546.0000	61.0000	26.0000	48.0000	17.0000	344.0000	5.0000	22.0000	27.0000
CS59	427.0000	64.0000	17.0000	40.0000	4.0000	3.0000	31.0000	114.0000	150.0000
WH4	2908.0000	3.8000	88.0000	350.0000	10.0000	183.0000	61.0000	1821.0000	9.0000
WH5	1065.0000	72.0000	15.0000	176.0000	14.0000	390.0000	78.0000	249.0000	62.0000
WH6	921.0000	64.0000	39.0000	98.0000	3.0000	6.0000	23.0000	56.0000	674.0000
WH7	845.0000	104.0000	47.0000	34.0000	7.0000	488.0000	50.0000	100.0000	11.0000
WH8	1091.0000	48.0000	37.0000	184.0000	8.0000	641.0000	36.0000	54.0000	81.0000
WH9	2116.0000	64.0000	27.0000	500.0000	55.0000	1018.0000	216.0000	179.0000	51.0000
WH10	542.0000	80.0000	10.0000	22.0000	11.0000	390.0000	4.0000	14.0000	11.0000
WH11	673.0000	76.0000	10.0000	14.0000	6.0000	512.0000	10.0000	5.0000	19.0000
WH12	802.0000	88.0000	19.0000	80.0000	7.0000	451.0000	43.0000	64.0000	46.0000
WH13	1364.0000	72.0000	34.0000	258.0000	6.0000	482.0000	227.0000	237.0000	41.0000
WH14	745.0000	96.0000	8.0000	140.0000	4.0000	458.0000	18.0000	179.0000	39.0000
WH15	725.0000	32.0000	10.0000	156.0000	5.0000	311.0000	29.0000	151.0000	28.0000
WH16	2304.0000	18.0000	2.0000	640.0000	57.0000	384.0000	628.0000	255.0000	113.0000
WH20	908.0000	66.0000	15.0000	6.0000	6.0000	488.0000	40.0000	71.0000	94.0000
WH21	488.0000	40.0000	3.0000	84.0000	9.0000	238.0000	16.0000	65.0000	150.0000
WH22	1063.0000	85.0000	7.0000	176.0000	7.0000	281.0000	42.0000	312.0000	150.0000
WH27	1208.0000	56.0000	15.0000	310.0000	7.0000	354.0000	163.0000	270.0000	28.0000
WH28	2820.0000	8.0000	2.0000	900.0000	23.0000	769.0000	535.0000	424.0000	64.0000
WH29	5985.0000	24.0000	3.0000	2000.0000	38.0000	1787.0000	1304.0000	732.0000	56.0000
WH30	904.0000	36.0000	4.0000	221.0000	16.0000	299.0000	68.0000	216.0000	41.0000
WH31	2050.0000	79.0000	8.0000	550.0000	23.0000	90.0000	265.0000	162.0000	60.0000
WH32	3122.0000	168.0000	66.0000	775.0000	38.0000	647.0000	741.0000	654.0000	17.0000
WH33	1177.0000	10.0000	22.0000	320.0000	15.0000	580.0000	104.0000	69.0000	69.0000
WH34	1274.0000	8.0000	2.0000	325.0000	15.0000	677.0000	88.0000	58.0000	92.0000
WH35	488.0000	58.0000	15.0000	38.0000	7.0000	299.0000	18.0000	17.0000	30.0000
WH36	2189.0000	228.0000	243.0000	103.0000	325.0000	604.0000	373.0000	267.0000	39.0000
WH38	454.0000	60.0000	9.0000	15.0000	30.0000	281.0000	13.0000	24.0000	19.0000
WH40	777.0000	74.0000	30.0000	92.0000	42.0000	336.0000	107.0000	43.0000	48.0000
WH41	1228.0000	112.0000	47.0000	142.0000	10.0000	525.0000	204.0000	35.0000	48.0000
WH42	783.0000	112.0000	30.0000	16.0000	22.0000	561.0000	17.0000	18.0000	5.0000
WH43	537.0000	40.0000	22.0000	22.0000	3.0000	238.0000	16.0000	46.0000	150.0000
DW1	601.0000	56.0000	15.0000	26.0000	5.0000	238.0000	14.0000	95.0000	150.0000
DW2	250.0000	96.0000	44.0000	14.0000	2.0000	494.0000	18.0000	24.0000	45.0000
DW3	791.0000	98.0000	49.0000	14.0000	1.0000	519.0000	25.0000	26.0000	58.0000
DW17	636.0000	66.0000	15.0000	75.0000	11.0000	305.0000	52.0000	61.0000	49.0000
DW18	4545.0000	97.0000	11.0000	1400.0000	14.0000	171.0000	684.0000	2119.0000	36.0000
DW19	1245.0000	6.0000	2.0000	320.0000	15.0000	543.0000	64.0000	187.0000	98.0000
DW23	1070.0000	114.0000	36.0000	123.0000	7.0000	397.0000	125.0000	210.0000	49.0000
DW24	1063.0000	85.0000	7.0000	176.0000	7.0000	281.0000	42.0000	312.0000	150.0000
BH1	1208.0000	56.0000	15.0000	310.0000	7.0000	354.0000	163.0000	270.0000	28.0000
BH5	1176.0000	247.0000	90.0000	54.0000	2.0000	458.0000	233.0000	58.0000	30.0000
BH8	823.0000	64.0000	31.0000	124.0000	1.0000	561.0000	17.0000	26.0000	54.0000
BH12	810.0000	64.0000	31.0000	124.0000	1.0000	482.0000	53.0000	4.0000	49.0000
BH32	591.0000	64.0000	29.0000	50.0000	1.0000	281.0000	67.0000	58.0000	36.0000
BH39	632.0000	59.0000	20.0000	64.0000	4.0000	380.0000	25.0000	19.0000	65.0000
BH41	433.0000	41.0000	13.0000	31.0000	6.0000	230.0000	13.0000	8.0000	86.0000
BH43	802.0000	27.0000	14.0000	130.0000	17.0000	420.0000	38.0000	42.0000	112.0000
BH44	820.0000	24.0000	13.0000	2.0000	16.0000	378.0000	112.0000	64.0000	45.0000
BH47	1031.0000	17.0000	7.0000	220.0000	18.0000	450.0000	130.0000	69.0000	73.0000
BH48	555.0000	51.0000	23.0000	57.0000	7.0000	354.0000	28.0000	13.0000	47.0000
BH49	1109.0000	10.0000	5.0000	275.0000	13.0000	427.0000	135.0000	89.0000	150.0000
BH52	899.0000	10.0000	5.0000	225.0000	3.0000	379.0000	114.0000	105.0000	54.0000
BH53	880.0000	18.0000	7.0000	210.0000	8.0000	370.0000	51.0000	112.0000	86.0000
BH54	1325.0000	72.0000	39.0000	243.0000	11.0000	451.0000	113.0000	273.0000	116.0000
BH55	812.0000	10.0000	7.0000	180.0000	5.0000	360.0000	65.0000	88.0000	91.0000
BH56	2515.0000	52.0000	1.0000	830.0000	5.0000	38.0000	950.0000	600.0000	32.0000
BH57	698.0000	6.0000	2.0000	170.0000	3.0000	317.0000	58.0000	68.0000	66.0000
BH58	605.0000	37.0000	21.0000	72.0000	4.0000	300.0000	33.0000	63.0000	68.0000
BH62	529.0000	50.0000	22.0000	40.0000	1.0000	339.0000	1.0000	21.0000	54.0000
BH63	637.0000	81.0000	35.0000	36.0000	1.0000	449.0000	4.0000	22.0000	58.0000
BH64	807.0000	42.0000	51.0000	83.0000	2.0000	332.0000	3.0000	21.0000	64.0000
BH65	789.0000	58.0000	63.0000	46.0000	2.0000	537.0000	2.0000	32.0000	48.0000
BH66	524.0000	38.0000	26.0000	46.0000	7.0000	288.0000	1.0000	76.0000	40.0000
HS1	1675.0000	77.0000	17.0000	318.0000	90.0000	384.0000	159.0000	496.0000	120.0000
HS2	793.0000	19.0000	3.0000	200.0000	4.0000	238.0000	38.0000	211.0000	56.0000
HS4	711.0000	19.0000	18.0000	140.0000	4.0000	378.0000	25.0000	62.0000	62.0000
HS5	7722.0000	417.0000	26.0000	2650.0000	65.0000	49.0000	3901.0000	525.0000	103.0000
HS6	2005.0000	29.0000	1.0000	640.0000	57.0000	43.0000	805.0000	286.0000	49.0000
HS7	2183.0000	30.0000	2.0000	660.0000	57.0000	55.0000	772.0000	283.0000	310.0000
HS8	1717.0000	5.0000	2.0000	540.0000	53.0000	299.0000	545.0000	163.0000	94.0000
HS9	2047.0000	40.0000	18.0000	600.0000	38.0000	122.0000	796.0000	176.0000	238.0000
HS10	5668.0000	120.0000	19.0000	1970.0000	50.0000	647.0000	2379.0000	350.0000	111.0000
HS11	931.0000	11.0000	8.0000	237.0000	19.0000	348.0000	114.0000	77.0000	111.0000
HS12	1064.0000	8.0000	1.0000	300.0000	14.0000	427.0000	129.0000	102.0000	77.0000
HS13	1092.0000	40.0000	10.0000	214.0000	15.0000	512.0000	96.0000	77.0000	172.0000
HS14	1521.0000	4.0000	5.0000	425.0000	13.0000	763.0000	141.0000	75.0000	75.0000
HS15	872.0000	9.0000	1.0000	238.0000	4.0000	300.0000	56.0000	210.0000	36.0000
HS16	1125.0000	14.0000	4.0000	264.0000	14.0000	591.0000	49.0000	63.0000	123.0000
HL1	12316.0000	5.0000	2.0000	4200.0000	400.0000	1458.0000	43.0000	1025.0000	49.0000
HL2	860.0000	16.0000	12.0000	202.0000	79.0000	439.0000	64.0000	37.0000	62.0000
HL3	8896.0000	6.0000	1.0000	2852.0000	240.0000	2007.0000	1044.0000	300.0000	193.0000
HL4	2104.0000	8.0000	1.0000	650.0000	453.0000	555.0000	245.0000	165.0000	75.0000
HL5	2894.0000	10.0000	4.0000	950.0000	120.0000	787.0000	510.0000	412.0000	60.0000
HL6	321.0000	44.0000	8.0000	16.0000	5.0000	201.0000	9.0000	10.0000	17.0000

*** Separation into 10 Main groups ***
Threshold value = 0.9111

MAIN GROUPS	ATTRIBUTES	SIMILARITIES
1	CS1	0.9841
	WH13	0.9883
	BH54	0.9801
	WH27	1.0000
	BH1	0.9749
	WH8	0.9880
	WH33	0.9914
	HS16	0.9838
	BH47	0.9916
	HS13	0.9906
	BH49	0.9930
	HS12	0.9808
	WH34	0.9853
	DW19	0.9724
	CS3	0.9879
	CS13	0.9905
	CS14	0.9862
	WH5	0.9926
	DW23	0.9805
	WH22	1.0000
	DW24	0.9694
	CS16	0.9739
	WH41	0.9851
	BH5	0.9543
	HS14	0.9501
	HS1	0.9308
	WH9	0.9509
	HL4	0.9459
	WH36	0.9348
	WH16	0.9642
	HS6	0.9783
	HS7	0.9836
	HS9	0.9560
	WH31	0.9620
	HS8	0.8938
2	CS2	0.9931
	BH12	0.9923
	CS21	0.9938
	CS43	0.9954
	WH12	0.9944
	CS44	0.9910
	CS22	0.9939
	BH8	0.9904
	WH42	0.9935
	DW3	0.9952
	BH65	0.9901
	WH7	0.9881
	CS20	0.9895
	CS57	0.9916
	WH20	0.9856
	WH40	0.9903
	BH64	0.9890
	BH44	0.9824
	CS10	0.9979
	CS56	0.9961
	CS41	0.9960
	CS52	0.9951
	CS53	0.9943
	WH10	0.9903
	CS24	0.9955
	CS27	0.9947

	BH39	0.9927
	CS42	0.9881
	CS11	0.9948
	CS39	0.9969
	BH63	0.9961
	CS48	0.9970
	CS54	0.9922
	WH11	0.9792
	WH14	0.9862
	WH15	0.9913
	BH57	0.9938
	HS4	0.9827
	WH30	0.9962
	HS15	0.9905
	HS2	0.9832
	BH43	0.9923
	BH55	0.9898
	HL2	0.9885
	BH52	0.9941
	BH53	0.9931
	HS11	0.9595
	CS4	0.9913
	DW17	0.9960
	BH58	0.9951
	BH32	0.9910
	CS12	0.9976
	CS23	0.9980
	CS45	0.9968
	CS38	0.9975
	WH35	0.9967
	CS49	0.9950
	CS15	0.9976
	CS26	0.9978
	BH62	0.9960
	CS19	0.9982
	CS58	0.9971
	CS50	0.9968
	BH48	0.9956
	CS40	0.9936
	BH66	0.9880
	WH21	0.9916
	WH43	0.9936
	DW1	0.9811
	CS5	0.9962
	CS17	0.9980
	CS47	0.9978
	CS18	0.9972
	CS32	0.9974
	CS51	0.9968
	CS36	0.9976
	CS46	0.9950
	WH38	0.9938
	BH41	0.9931
	CS25	0.9874
	CS6	0.9978
	CS30	0.9961
	CS8	0.9939
	CS7	0.9981
	CS9	0.9966
	CS35	0.9987
	HL6	0.9960
	CS28	0.9984
	CS31	0.9925
	CS37	0.9773
	CS59	0.9651
	DW2	0.9349
	WH6	0.8314
3	WH4	0.8740
4	WH28	0.9895
	HL5	0.9612
	WH32	0.9284
	BH56	0.6972
5	WH29	0.8722
6	HS10	0.7864
7	DW18	0.4095
8	HS5	0.7133
9	HL3	0.5999
10	HL1	

Name of the cases & their index no. !

1 = ---C	2 = CS6	3 = CS7	4 = CS8	5 = CS9	6 = CS10
7 = CS11	8 = WH31	9 = WH32	10 = WH33	11 = WH34	12 = WH35
13 = WH40	14 = WH41	15 = WH42	16 = WH43	17 = BH5	18 = BH12
19 = BH8	20 = BH52	21 = BH53	22 = BH43	23 = BH47	24 = BH54
25 = BH48	26 = BH49	27 = HS2	28 = HS3	29 = HS4	30 = HS6
31 = HS7	32 = HS8	33 = HS9	34 = HS10	35 = HS11	36 = HS12
37 = HS14					

** Raw Data_matrix **

	1	2	3	4
---C	7.2000	1.4000	1.2500	36.0000
CS6	7.0000	0.8000	0.4500	62.0000
CS7	7.2000	3.7000	0.6000	41.0000
CS8	7.3000	0.9000	0.4400	62.0000
CS9	7.3000	0.8000	0.1500	45.0000
CS10	7.4000	0.5000	0.6300	45.0000
CS11	7.6000	0.8000	0.9000	62.0000
WH31	7.8000	1.6600	4.8000	17.0000
WH32	7.6000	6.0000	1.4000	69.0000
WH33	7.8000	5.6500	1.6000	92.0000
WH34	7.3000	0.9600	0.9000	30.0000
WH35	7.6000	1.1000	4.0000	39.0000
WH40	8.0000	0.8800	1.8400	48.0000
WH41	7.4000	0.5200	0.4000	4.6000
WH42	7.7000	0.2000	0.1800	150.0000
WH43	7.4000	1.4600	0.5600	150.0000
BH5	7.8000	0.8000	0.1100	54.0000
BH12	8.0000	0.3800	2.8000	36.0000
BH8	7.8000	0.3000	0.9000	49.0000
BH52	7.4000	1.6000	1.8500	54.0000
BH53	7.3000	1.6000	1.0800	86.0000
BH43	7.8000	1.4600	0.1000	45.0000
BH47	7.6000	0.4600	0.9000	47.0000
BH54	7.9000	1.0500	2.1000	116.0000
BH48	7.8000	2.6000	0.9000	150.0000
BH49	8.1000	2.5000	4.8000	39.0000
HS2	8.6000	4.1600	0.3000	56.0000
HS3	7.6000	1.9200	0.2000	58.0000
HS4	8.0000	1.4600	0.6000	62.0000
HS6	8.8000	0.9000	1.0500	49.0000
HS7	7.4000	0.8000	2.2300	310.0000
HS8	7.7000	2.3000	0.6000	94.0000
HS9	7.3000	1.5200	7.0000	238.0000
HS10	8.3000	7.7800	6.0000	111.0000
HS11	8.0000	1.8000	1.6000	111.0000
HS12	7.9000	1.6000	0.1000	77.0000
HS14	7.9000	4.5000	1.6500	75.0000

Minor Constituents

1 = Fluoride
2 = Bromide
3 = Iodide
4 = Silica

*** Separation into 10 Main groups ***
Threshold value = 0.9568

MAIN GROUPS	ATTRIBUTES	SIMILARITIES
1	---C	0.9940
	BH12	0.9868
	WH35	0.9945
	BH49	0.9825
	CS7	0.9734
	CS9	0.9981
	CS10	0.9967
	BH43	0.9884
	WH40	0.9951
	BH47	0.9939
	BH8	0.99[illegible]

	HS6	0.9569
	WH34	0.9151
2	WH31	0.9567
3	WH41	0.8043
4	CS6	0.9990
	CS8	0.9979
	CS11	0.9969
	HS4	0.9778
	BH5	0.9936
	BH52	0.9867
	HS2	0.9896
	HS3	0.9528
5	WH32	0.9747
	HS12	0.9874
	HS14	0.8837
6	WH33	0.9868
	HS8	0.9749
	BH53	0.9233
7	BH54	0.9834
	HS11	0.9727
	HS10	0.4806
8	WH42	0.9937
	WH43	0.9959
	BH48	0.5935
9	HS7	0.7637
10	HS9	

Intercorrelation Matrix : cold springs

	1	2	3	4	5	6	7	8	9
1	1.0000	0.5763	0.7233	0.7234	0.2104	0.8164	0.5952	0.5882	0.0181
2		1.0000	0.3733	0.5409	0.2246	0.6375	0.4967	0.5569	0.2110
3			1.0000	0.5505	0.0094	0.7278	0.3935	0.3570	-0.0875
4				1.0000	0.1309	0.6148	0.6893	0.8112	-0.1313
5					1.0000	0.1381	0.1673	0.1094	0.1091
6						1.0000	0.3708	0.3126	-0.1455
7							1.0000	0.6252	-0.0311
8								1.0000	0.0530
9									1.0000

Intercorrelation Matrix : water holes and dug wells

	1	2	3	4	5	6	7	8	9
1	1.0000	-0.0365	0.1164	0.9512	0.2392	0.5493	0.9203	0.7246	-0.1102
2		1.0000	0.6526	-0.1896	0.5359	-0.0467	0.0441	-0.0514	-0.1392
3			1.0000	-0.1392	0.8307	0.0421	0.0718	0.1269	-0.0602
4				1.0000	0.0637	0.5773	0.9259	0.6167	-0.0891
5					1.0000	0.1953	0.2753	0.0344	-0.0994
6						1.0000	0.6182	-0.0074	-0.2816
7							1.0000	0.4822	-0.1170
8								1.0000	-0.1379
9									1.0000

Intercorrelation Matrix : bore wells

	1	2	3	4	5	6	7	8	9
1	1.0000	0.1534	-0.0890	0.9175	0.1778	-0.3396	0.9285	0.9132	-0.0565
2		1.0000	0.8227	-0.1522	-0.3511	0.2120	0.1366	-0.0139	-0.3901
3			1.0000	-0.4058	-0.4050	0.4363	-0.1823	-0.2632	-0.3066
4				1.0000	0.1534	-0.4971	0.8933	0.9206	0.0274
5					1.0000	0.0373	0.0833	0.1498	0.4722
6						1.0000	-0.5869	-0.5595	0.2001
7							1.0000	0.8907	-0.2180
8								1.0000	-0.1083
9									1.0000

Intercorrelation Matrix : hot springs

	1	2	3	4	5	6	7	8	9
1	1.0000	0.9053	0.6519	0.9971	0.5418	-0.1886	0.9905	0.7124	0.1193
2		1.0000	0.7049	0.8884	0.4693	-0.3043	0.9149	0.7167	0.0266
3			1.0000	0.6176	0.3715	-0.0396	0.6329	0.4900	0.1358
4				1.0000	0.5039	-0.1940	0.9924	0.6821	0.0974
5					1.0000	-0.3854	0.5165	0.8186	0.3616
6						1.0000	-0.2947	-0.4293	-0.3063
7							1.0000	0.6912	0.1232
8								1.0000	0.1219
9									1.0000

Intercorrelation Matrix : hot lakes

	1	2	3	4	5	6	7	8	9
1	1.0000	-0.6015	-0.6218	0.9993	0.5688	0.8817	0.3186	0.8680	0.4248
2		1.0000	0.5837	-0.6032	-0.7096	-0.6530	-0.4526	-0.5575	-0.5396
3			1.0000	-0.6199	-0.7681	-0.6464	-0.5236	-0.5264	-0.4755
4				1.0000	0.5762	0.8665	0.2928	0.8852	0.3955
5					1.0000	0.4327	0.0858	0.5536	0.2469
6						1.0000	0.7145	0.5886	0.7879
7							1.0000	-0.0156	0.9146
8								1.0000	-0.0039
9									1.0000

Intercorrelation Matrix : cold springs

	1	2	3	4	5	6	7
1	1.0000	0.8790	0.8686	0.5587	0.7570	0.6074	0.7172
2		1.0000	0.8627	0.4601	0.7300	0.5920	0.6617
3			1.0000	0.4899	0.8821	0.7472	0.8662
4				1.0000	0.5346	0.3793	0.3887
5					1.0000	0.5645	0.6471
6						1.0000	0.7203
7							1.0000

I	Eigenvalue	Individual % Variance	Cumulative % Variance
1	0.51828854D+01	74.04	74.04
2	0.74987676D+00	10.71	84.75
3	0.60510425D+00	8.64	93.40
4	0.27063033D+00	3.87	97.26
5	0.11342487D+00	1.62	98.88
6	0.65574830D-01	0.94	99.82
7	0.12503531D-01	0.18	100.00

Eigen_vectors :

	1	2	3	4	5	6	7
1	-0.4139	0.1484	-0.2326	0.0197	0.7106	0.2184	0.4467
2	-0.4015	0.0753	-0.3849	-0.2025	0.4366	0.4420	0.2001
3	-0.4230	-0.1583	-0.0275	0.1667	0.2102	0.7745	0.3512
4	-0.2662	0.7368	0.6071	0.0586	0.1182	[illegible]	[illegible]
5	-0.4106	0.1910	-0.3673	-0.1199	-0.1465	0.2110	[illegible]
6	-0.3363	-0.4541	0.4841	-0.6551	-0.0964	-0.0621	0.0635
7	-0.3688	-0.4006	0.2431	0.6956	0.0291	-0.3287	0.2273

1 = Ca; 2 = Mg; 3 = Na; 4 = K; 5 = HCO_3; 6 = Cl; 7 = SO_4

Intercorrelation Matrix : water holes and dug wells

	1	2	3	4	5	6	7
1	1.0000	0.7664	0.4021	0.6074	0.7002	0.4721	0.4370
2		1.0000	0.2314	0.8565	0.4971	0.3532	0.3789
3			1.0000	0.2026	0.7379	0.9427	0.7260
4				1.0000	0.4412	0.4312	0.2742
5					1.0000	0.7316	0.4373
6						1.0000	0.4221
7							1.0000

I	Eisenvalue	Individal % Variance	Cumulative % Variance
1	0.42363608D+01	60.52	60.52
2	0.14976525D+01	21.40	81.91
3	0.58722187D+00	8.39	90.30
4	0.45145972D+00	6.45	96.75
5	0.14625481D+00	2.09	98.84
6	0.67180114D-01	0.96	99.80
7	0.13870217D-01	0.20	100.00

Eisen_vectors :

	1	2	3	4	5	6	7
1	-0.3880	-0.3018	-0.1696	0.5064	0.5927	0.1001	0.0450
2	-0.3568	-0.5088	0.2787	0.0146	-0.2587	0.6545	0.2474
3	-0.3935	0.4615	-0.0178	-0.1779	0.3502	0.1036	0.7540
4	-0.3372	-0.4729	0.1030	-0.5904	0.0058	0.5171	0.0927
5	-0.4119	0.0849	-0.5702	0.2165	0.6225	0.1176	0.2025
6	-0.4134	0.3329	-0.1257	-0.3721	0.3901	0.4143	0.4746
7	-0.3361	0.3090	0.7436	0.3005	-0.1868	-0.1997	0.1574

Intercorrelation Matrix : bore wells

	1	2	3	4	5	6	7
1	1.0000	0.9205	0.4171	0.4118	0.7445	0.4289	0.4239
2		1.0000	0.3132	0.4131	0.8054	0.2530	0.3062
3			1.0000	0.5909	0.5485	0.9004	0.9466
4				1.0000	0.7474	0.4113	0.5306
5					1.0000	0.3152	0.4439
6						1.0000	0.9129
7							1.0000

I	Eigenvalue	Individal % Variance	Cumulative % Variance
1	0.43830669D+01	62.62	62.62
2	0.16167457D+01	23.10	85.71
3	0.70819542D+00	10.12	95.83
4	0.15992252D+00	2.28	98.11
5	0.72003890D-01	1.03	99.14
6	0.45624009D-01	0.65	99.79
7	0.14441619D-01	0.21	100.00

Eigen_vectors :

	1	2	3	4	5	6	7
1	-0.3701	0.3860	0.4060	0.3779	0.2097	0.5040	0.1426
2	-0.3398	0.5039	0.2777	-0.0566	-0.3915	-0.6058	0.1733
3	-0.4130	-0.3642	-0.0207	-0.4105	0.2255	0.0093	[illegible]
4	-0.3535	0.0434	-0.7561	0.5210	-0.0957	-0.0617	0.1306
5	-0.3943	0.3491	-0.2999	-0.5433	0.3073	0.0075	-0.4052
6	-0.3698	-0.4313	0.2920	0.3280	0.4105	-0.4202	-0.3733
7	-0.3997	-0.3933	0.1036	-0.1060	-0.6927	0.3208	0.2845

Intercorrelation Matrix : **hot springs**

	1	2	3	4	5	6	7
1	1.0000	0.7732	0.9016	0.6354	0.2707	0.9355	0.7549
2		1.0000	0.8052	0.7372	0.6163	0.7563	0.7971
3			1.0000	0.7583	0.4931	0.9910	0.8370
4				1.0000	0.5384	0.6914	0.9338
5					1.0000	0.3237	0.5650
6						1.0000	0.7741
7							1.0000

I	Eigenvalue	Individal % Variance	Cumulative % Variance
1	0.53341830D+01	76.20	76.20
2	0.92355737D+00	13.19	89.40
3	0.41166709D+00	5.88	95.28
4	0.20842862D+00	2.98	98.25
5	0.82712402D-01	1.18	99.44
6	0.39356818D-01	0.56	100.00
7	0.94652482D-04	0.00	100.00

Eigen_vectors :

	1	2	3	4	5	6	7
1	0.3834	0.4077	0.2074	0.1153	0.6277	0.4775	-0.0787
2	0.3897	-0.1300	-0.2707	0.0097	-0.2059	0.1401	0.0217
3	0.4154	0.1724	-0.1766	-0.3850	0.2064	0.1961	-0.7050
4	0.3773	-0.1962	0.6741	0.0033	0.2069	0.5307	0.0272
5	0.2559	-0.7761	-0.4200	0.3012	0.1501	0.1504	0.1204
6	0.3963	0.3633	-0.1678	-0.3022	-0.3354	0.0770	0.6877
7	0.4046	-0.1202	0.4400	-0.0100	0.4587	0.5323	0.0703

Intercorrelation Matrix : hot lakes

	1	2	3	4	5	6	7
1	1.0000	0.8155	0.2216	0.2977	0.3573	0.2557	0.2355
2		1.0000	0.2311	0.2933	0.3780	0.2359	0.2671
3			1.0000	0.8039	0.9261	0.6154	0.9400
4				1.0000	0.8031	0.5616	0.7905
5					1.0000	0.8468	0.8086
6						1.0000	0.4432
7							1.0000

I	Eisenvalue	Individal % Variance	Cumulative % Variance
1	0.43488701D+01	62.13	62.13
2	0.15249651D+01	21.79	83.91
3	0.65034738D+00	9.29	93.20
4	0.24979556D+00	3.57	96.77
5	0.18166467D+00	2.60	99.37
6	0.44357179D-01	0.63	100.00
7	-0.25992036D-17	0.01	100.00

Eisen_vectors :

	1	2	3	4	5	6	7
1	0.2301	0.6664	0.0180	-0.1216	0.6784	0.0071	-0.0032
2	0.2344	0.6607	0.0766	0.1789	-0.6779	-0.0045	0.1050
3	0.4438	-0.2277	0.1910	0.3194	0.1296	-0.5182	0.5719
4	0.4181	-0.1251	0.2042	-0.8572	-0.1724	-0.0258	0.0512
5	0.4637	-0.0960	-0.2151	0.1614	-0.0278	-0.3731	0.7494
6	0.3588	-0.0909	-0.8051	0.0052	-0.0122	0.3646	0.2957
7	0.4181	-0.1856	0.4699	0.3004	0.0720	0.6772	-0.1261