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STUDY OF HYDROLOGICAL VARIATIONS, DROUGHT AND DESERTIFICATION IN SUDAN

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By

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Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

May 1995

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DECLARATION

I declare that this work is the result of my own investigations and that it has neither been accepted nor being submitted in substance for any other degree.

Signed: _____ **Date:** June 4, 1995

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"STUDY OF HYDROLOGICAL VARIATIONS, DROUGHT AND DESERTIFICATION IN SUDAN"

submitted by Nadir Ahmed A. Rahman Elagib to the Department of Civil and Architectural Engineering satisfies the requirement for the Master of Science degree in Civil Engineering.

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The methodologies of interpreting the annual rainfall records are also used in the analysis of the data for the annual flow of the River Nile and its major tributaries.

Attention is also paid to much severe environmental problems facing Sudan, namely drought and desertification, as a result of the change in climtic conditions and human interference. The delimitation of various climatic regions and the evaluation of the degree of aridity are made using indices which have widely been proposed by investigators. An easier method of assessing aridity, using annual rainfall records, is also proposed. Some of the causes and remedial measures suggested to reduce the the risk of these problems in drought prone or desertifying areas are reviewed.

The study highlights the pressing ecosystem-change scenarios that afflict Sudan. Warming of air coupled with rainfall deficeincy as well as mismanagement and ill-oriented human activities have all interacted and led to increasing desertification features in the country. The study further recommends some actions to be taken in order to appraise better and solve or ameliorate the anomalous climatic and desertic conditions.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

a	= constant
A	= regression constant
A_L	= Lang's aridity index
B	= regression constant
C	= regression constant
C_p	= Piche coefficient
C_v	= coefficient of variation
D	= Budyko-Lettau dryness ratio
e	= actual vapour pressure of air; base of napierian logarithms
e_s	= saturation vapour pressure of water in air
E_a	= open water evaporation rate for equal air and water temperatures
E_o	= Penman evaporation for open water
E_p	= Piche evaporation
H	= short wave radiation actually received at the earth's surface from sun and sky
H_o	= maximum possible daily extraterrestrial solar radiation
j	= monthly heat index
J	= yearly heat index
L	= latent heat of vaporaization
M	= mode
n	= actual daily sunshine duration
N	= maximum possible daily sunshine duration
P	= precipitation
PET	= potential evapotranspiration
PET_x	= theoretical standard potential evapotranspiration
Pr	= probability of event in any year
r	= correlation factor; albedo of water
R_B	= outgoing radiation from the earth's surface
R_I	= net amount of radiation absorbed at the earth's surface after reflection
R_n	= net radiant energy finally remaining at a free water surface
t	= temperature
t_n	= average monthly temperature of the consecutive months
T_a	= absolute air temperature
T_r	= return period
u_2	= wind speed at 2 m height
X	= magnitude of an event
z	= z-score of a value

γ = psycrometer constant
Δ = slope of saturated vapour pressure-temperature curve
θ = Lummer and Pringsheim constant
μ = mean
Σ = summation
σ = standard deviation

Abbreviations

A = above normal
Avg. = average
°C = degree Celsius
cal = calorie
cm = centimetre
d = day
EA = extremely above normal
ES = extremely sub-normal
Exp. = exponential
g = gram
GA = greatly above normal
GS = greatly sub-normal
Hg = mercury
LTM = long term mean
m = metre
Mdcm = milliard cubic metres (10^9 m^3)
MJ = mega joule (10^6 joules)
mm = millimetre
N = normal
N.R. = no record
PM = percentage of mode
PMC = percentage of modal class
RH = relative humidity
s = seconds
S = sub-normal
TR = trend rate
UNEP = United Nations Environment Programme
UNCED = United Nations Conference on Environment and Development
WMO = World Meteorological Organization
Yr = year

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Chapter 1

INTRODUCTION

INTRODUCTION

1.1 Principal Characteristics of Sudan

1.1.1 Geography

The Republic of Sudan is the largest country in Africa with a total area of 2,505,813 square kilometres stretching between latitudes of about 4° N and 22° N and between longitudes of about 22° E and 38° E. It is bordered by Egypt, Libya, Chad, Republic of Central Africa, Zaire, Uganda, Kenya, Ethiopia, Eriterea and the Red Sea. Fig. 1.1 shows the map of Sudan and its frontiers.

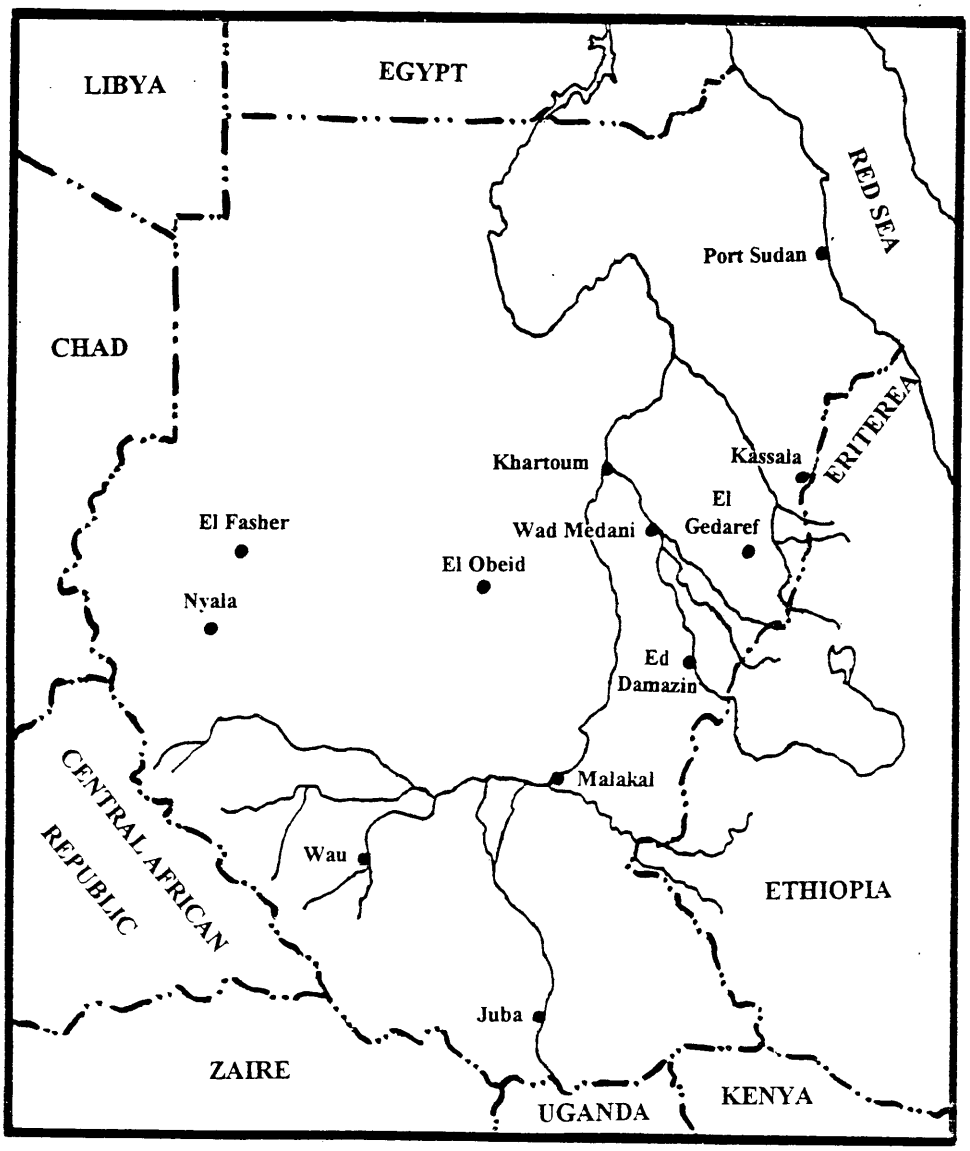


Fig. 1.1 Frontiers of Sudan and Selected Meteorological Stations

1.1.2 History and Culture

Sudan has a rich history dating back to and beyond Pharaonic Age. As the Nile crosses the desert of northern Sudan, flowing towards Egypt, it passes the ancient ruins, monumental buildings and temples, mirroring the past glories and triumphs of bygone era [1]. The great second Sudanese Kingdom, known as Merowe Kingdom, existed between 750 BC and the middle of the fourth century AD. The first written language in Sudan was Meroitic language. The Meroitic age was influenced by several civilizations, namely Greek, Roman and Pharaonic. The pharaonic imprint was left in hieroglyphic language, the religion of Amon and the simplified building of pyramids which are characterized by the non-existence of rooms and corridors.

The Sudanese kingdoms in the mid-sixth century AD adopted Christianity as the official religion. When Muslims invaded Egypt in 639 AD, they concluded agreements with the Christian Kingdoms that existed in northern Sudan at that time. Islam started to extend well in Sudan in 1250 AD and consequently number of Islamic kingdoms were established. Sudan is indeed a country of rich diversity. The religious groups consist of Muslim, forming the majority of the population, coming next are Animists and Christians forming the smallest minority.

The ethnic composition in Sudan comprises of more than 100 tribal communities of Arabs, Negroes, Nubas and Nubian [1, 2]. Although Arabic is the official language, there are numerous spoken local Sudanese languages beside English which is widely understood and spoken throughout Sudan [2]. The influence of Arab, Islamic and African cultures is clearly reflected in the literature, handicrafts, dress, music and dance of the people of Sudan [1].

1.1.3 Geology

Sudan is a huge plain crossed by the Nile and its tributaries. There are three distinct relief regions [2] of Sudan. The Nubian desert region in the north and the semi-desert region in the north-east where the Red Sea hills separate the huge plain from the narrow coastal strips. In the central region, the land rises to form the Nuba mountains which are surrounded by sand dunes. A third region consists of a clayey soil strip which extends to the east until it merges with the marshy lands of the south.

1.1.4 Water Resources

There are three decisive elements of water resources for human and animal consumption as well as agriculture and natural vegetation in Sudan. The main water resource is the Nile and its tributaries. The second important resource is rainfall. In the areas which are far away from the Nile with less or no rainfall, groundwater represents an essential resource. Sudan has a vast untapped groundwater resource more of which could be used in future for the supply of

drinking water and agricultural development. Only about 0.04% of groundwater in storage is abstracted annually from the different aquifers [3].

1.1.5 Vegetation

The vegetation in Sudan is governed mainly by rainfall, soil distribution and proximity to water resources [4]. The vegetation in the country can be divided into five main types: the sparse desert vegetation of the north, the semi-arid acacia shrub and short grassland further south, the woodland savanna, the vegetation of the flood lands and swamps of the Nile, and finally the flora of the mountain region [2].

1.1.6 Population

In 1993, the fourth population census estimated the total population of Sudan to be about 25 millions with an estimated yearly growth rate of 2.63% since 1983 [5]. Thus, the average population density of Sudan is only 10 persons per square kilometre. This density is low of course, but many parts of the country can certainly not be used for living at all.

1.1.7 Economy

Sudan has an agriculture-based economy. However, only one-tenth of the available 200 million feddan (1 feddan = 4200 m^2) is utilized for cultivation. Of the total world production, 40% of the long stable cotton and 90% of gum arabic are produced in Sudan. Other crops are groundnuts, oilseeds, karkadeh, durra (a type of sorghum), sugar cane, etc [1]. The industrial development of the country is dominated by the processing of the agricultural products. Many textile and sugar factories have been established. In addition to agricultural resources, Sudan has vast animal resources of about 56 million heads of cattle, sheep, goats and camels as well as large reserve of minerals such as gold, cromiteones, magnese, tungsten, etc [1]. Oil has been discovered in many areas especially in the western and southern parts.

With all these available resources and with the encouragement of the government investment in all fields, the prospects are very promising.

1.1.8 Wildlife

The southern region, with its great green forests and swamps, is a land of several species of birds and wildlife. The Dindir National Park, situated in the south-east of Khartoum, is one of the largest in the world with 6,475 square kilometres area of wild game. Fig. 1.2 shows the Sudanese bird and wild lives.

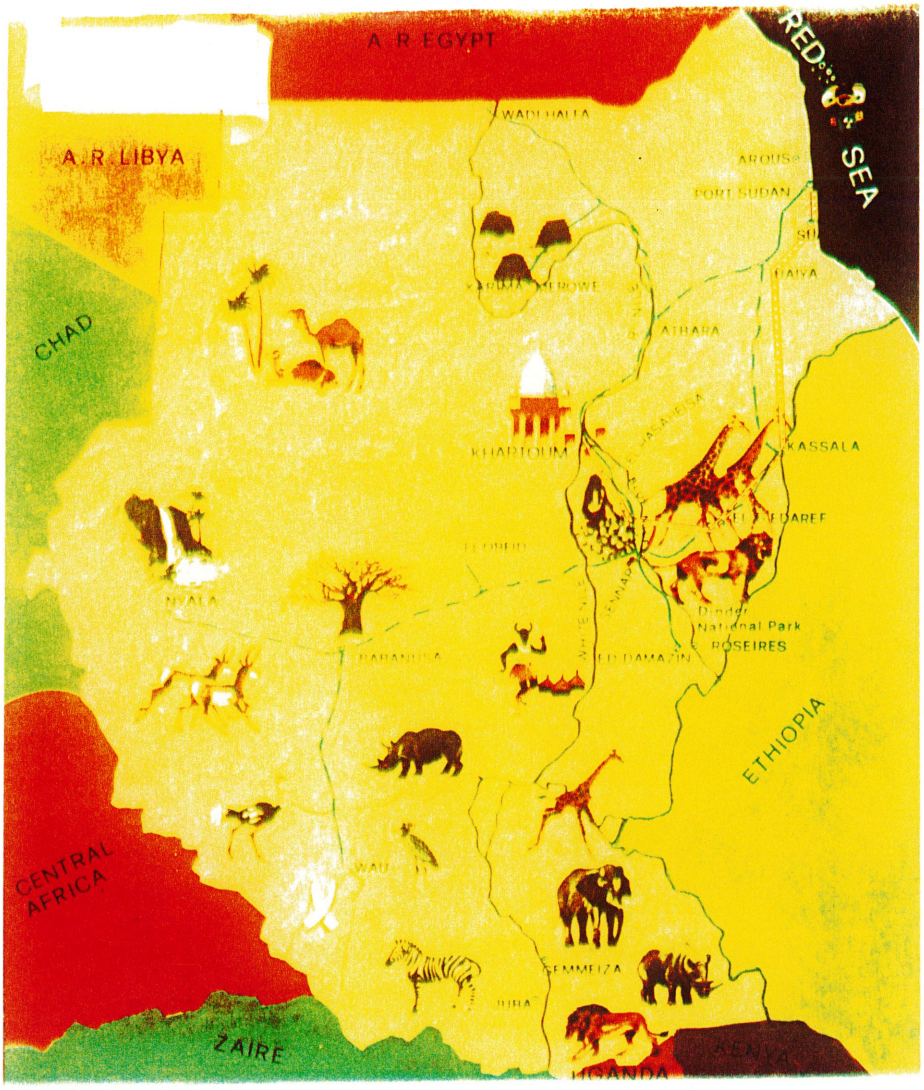


Fig. 1.2 Wildlife and Main Tourist Attractions in Sudan [1]

1.2 Hydrology

Hydrology is defined as the science dealing with the occurrence, circulation, distribution of water on and over the earth's surface and their interaction with the environment [6-8]. Water which is essential to people, animal and plant life is often a limiting factor, especially in arid and semi-arid zones [9]. In order to maintain better management of water, knowledge of the principal subjects of hydrology such as climatology, stream flow, groundwater, etc, is extremely important.

1.2.1 The Water Cycle

The concept of the water cycle is illustrated in Fig. 1.3. This cycle [4, 6] begins by the evaporation of water from oceans and from the land. The resulting water vapour is transported by the wind and under the proper conditions, it condenses to form clouds and rains down to the lands and oceans. This rain

infiltrates into the soil or runs off along the soil surface. A portion of this water is returned to the atmosphere by evaporation and transpiration by plants. The remainder plus the surface runoff feed streams and rivers and finally flows back to the oceans.

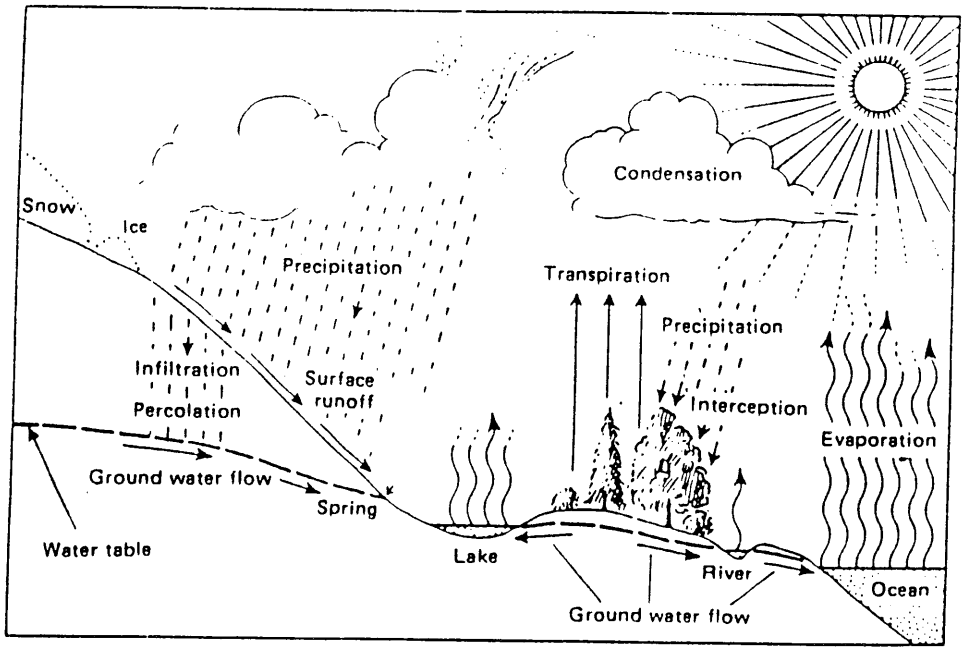


Fig. 1.3 The Water Cycle [8]

1.2.2 Climatology

It is the science which deals with climate. The hydrology of a region depends upon many aspects of climatology which include precipitation and its mode of occurrence, air temperature, humidity, evaporation and transpiration, wind, cloudiness and radiation [6, 7, 10]. It is a concern of the meteorologist to know how the various climatic factors relate to one another since the meaning of these relationships in a certain place is of importance in the weather forecast at a future time [11].

1.2.3 Collection of Data in Hydrology

The primary task in the study of any hydrological feature at a location necessitates the collection of its data [6, 7]. Observations should be taken as continuously as possible in order to obtain the information on which the analysis can be based [10]. The data on the hydrologic element should be collected over a long period of time to make reliable assessment. The period for which any assessment is made has to be specified, especially when the assessment is about climate, because it is subject to variation.

1.2.4 Use of Hydrological Observations

The data collected at the hydrological station have to be interpreted to make them amenable to discussion and findings regarding the patterns governing the hydrological element. Statistical methods are extensively used in the analysis of the hydrological parameters to organize and summarize independent observations in a clear and effective manner to facilitate presentation. These methods of summarization and information techniques include the construction of graphs, charts, tables and calculation of various descriptive measures, such as averages, frequencies, modes, deviations, variations, etc.

1.3 Environment and Awareness of its Problems

The environment is the natural world of land, sea, air, plants and animals that exist around us. Animal and plant lives are essentially influenced by changes in meteorological behaviour. It is well known that weather is not constant and the continuation of its enormous alteration causes drastic environmental problems such as drought and desertification.

At present, environmental problems have started receiving considerable attention, regionally and universally, especially in arid, semi-arid and adjacent sub-humid regions. These regions are assessed and regarded as areas subject to high or very high risk of desertification [12]. One of the countries which suffers heavily from hazards of drought and desertification is Sudan. The environmental features of Sudan have widely been observed to change in the last few decades due to the intrinsic variation in its hydrological characteristics. The vast extent of the country and the River Nile have both provided an excellent experimental field for local and international scientific teams who contribute to the formulation of the interesting combat plans to the recent episodes of harsh environment.

1.4 Data Collection

1.4.1 Meteorological Data

Twelve meteorological stations, spread all over Sudan, except the extremly desrtic northern part, with adequate record lengths were selected for the study. The locations of these stations are shown in Fig. 1.1 on the map of Sudan and listed in Table 1.1 with their coordinates and altitudes. The meteorological data for these stations were compiled from the Sudan Meteorological Department, Khartoum. The monthly temperature and rainfall records were available for a period of about fifty years (1941-91 for temperature and 1941-92 for rainfall). Extremes of temperature and rainfall were available for the period 1951 to 1990. The monthly data on relative humidity, sunshine duration, wind speed and Piche evaporation rate could be obtained for the study from 1961 onwards, whereas the monthly solar radiation data for ten of the stations were recorded for 15 to 33 years.

Table 1.1 Particulars of Selected Meteorological Stations

Station	Coordinates		Altitude (m)
	Latitude (N)	Longitude (E)	
Port Sudan	19° 35'	31° 46'	5
Khartoum	15° 36'	32° 23'	380
Kassala	15° 28'	36° 24'	500
Wad Medani	14° 23'	33° 29'	405
El Gedaref	14° 02'	35° 24'	600
El Fasher	13° 37'	25° 20'	730
El Obeid	13° 10'	30° 14'	570
Nyala	12° 04'	24° 53'	655
Ed Damazin	11° 49'	34° 24'	470
Malakal	09° 33'	31° 39'	390
Wau	07° 42'	28° 01'	435
Juba	04° 52'	31° 36'	460

1.4.2 River Nile Flow Data

Adequate essential historical annual flow data for the River Nile and most of its principal tributaries were obtained from the Ministry of Irrigation of Sudan, Khartoum, for a period ranging from 21 to 103 years. Table 1.2 lists the rivers under consideration at the given gauging stations which are further presented in Fig. 1.4.

Table 1.2 Rivers and Gauging Stations Used in the Study

River	Gauging Station
Main Nile	Wadi Halfa/Dongola
Blue Nile	Er Roseires/Ed Deim
White Nile	Malakal
River Atbara	Atbara (near the mouth)
River Atbara	Upsream from Khashm El Girba Dam
River Sobat	Hillat Doleib (near the mouth)
River Rahad	At the mouth
River Dindir	At the mouth

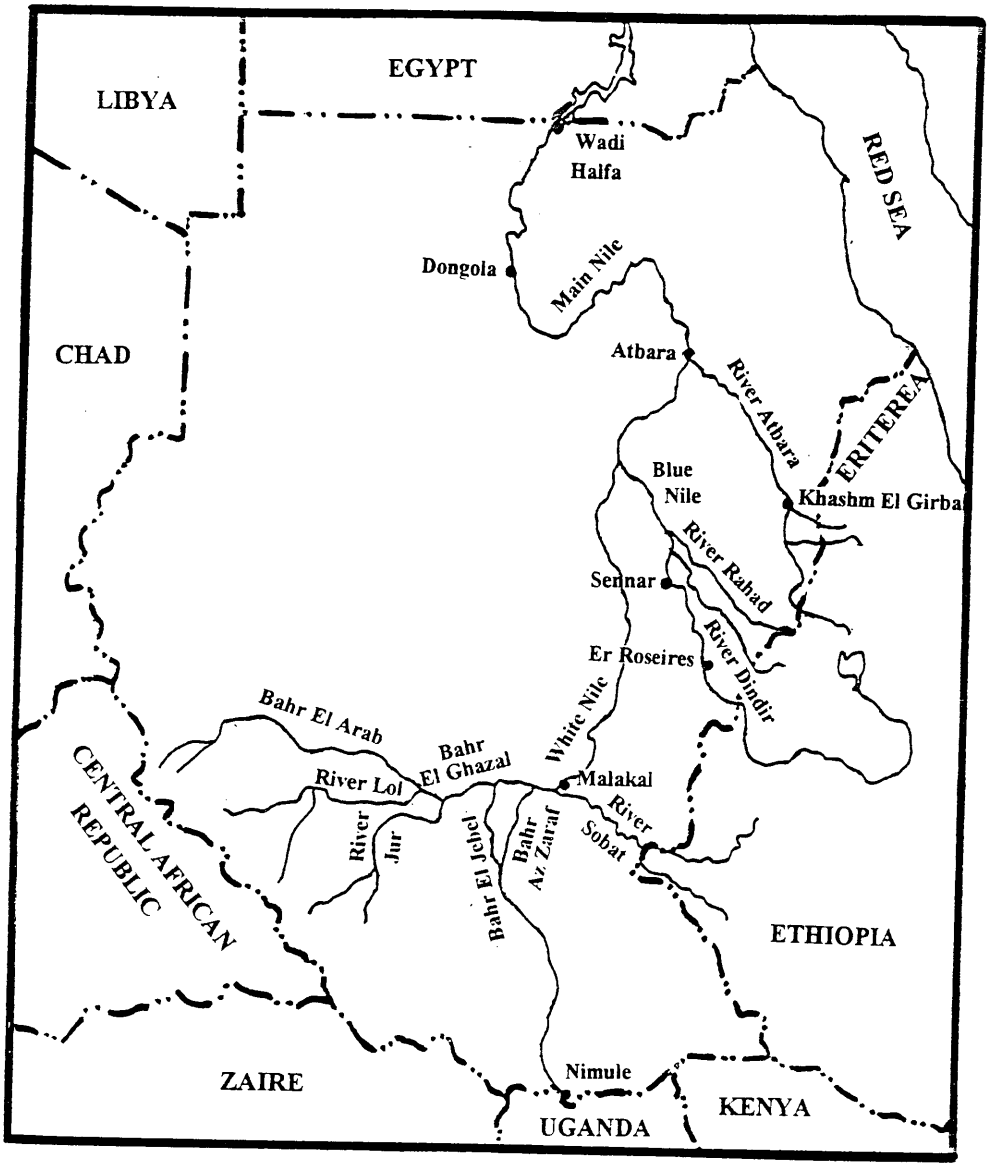


Fig. 1.4 The River Nile and its Tributaries with Gauging Stations under Consideration

1.4.3 Missing Data

For some years, records were missing due to breakdown of the recording instrument. Also, due to the civil war in the southern regions, data for some stations could not be updated.

1.5 Scope of the Study

The present study investigates the various climatic factors affecting the hydrologic characterstics of Sudan. It also evaluates the aridity situation in the country which is directly connected to the changes in the behaviour of these climatic elements. Based on statistical techniques, the collected long term meteorological and hydrological data are analysed.

Various aspects of the study are included in Chapters 2 through 8. The second chapter deals with the interpretation of temperature data. Chapter 3 discusses the methods used to analyse rainfall data and presents the results of the analysis. In Chapter 4, the available data on sunshine duration and solar radiation are extensively analysed to establish the correlationship between the two parameters. The observations on relative humidity, wind speed and evaporation are interpreted in Chapter 5. In addition, all the necessary data are employed in this chapter to estimate the evaporation and potential evapotranspiration rates using the theoretical methods proposed by the investigators. Chapter 6 is confined to the investigation of the river flow records. A few concepts are applied in Chapter 7 to measure the degree of aridity in the country. Finally, Chapter 8 summarizes the conclusions of the study and recommendations for future study and for the sake of achieving safe environment.

1.6 Statistical Terminologies

The following statistical terms [13] are widely used in the present study:

Mean (μ): The mean of the data set is defined as the sum of the data divided by the number of pieces of data.

Range: Is a measure of dispersion of a data set that is defined to be the difference between the largest and the smallest data values in the data set.

Standard Deviation (σ): Is a measure of dispersion of a data set which determines how far the data values are from the mean, on the average. The more the variation in a data set, the large is the standard deviation.

Coefficient of Variation (C_v): A descriptive measure that indicates the amount of variation in a data set as a percent of the mean, i.e. it is a ratio of the standard deviation to the mean value.

Trend Rate (TR): Is the slope of the best linear fit obtained by regression for a data set.

Correlation Factor (r): It is a number, always between -1 and $+1$, that can be used to describe the strength of the relationship between two variables. Values of this factor close to -1 or $+1$ indicate a strong relationship between the variables and that the regression equation is quite useful for making predictions. On the other hand, values of this factor near to 0 indicate a weak relationship between the variables and that the regression equation is not very valuable for making predictions.

Mode (M): Is a measure of central tendency, which is defined to be the data value(s) that occur most frequently. It is unaffected by the highest and lowest

values.

Class: Category for grouping data.

Class Mark: The midpoint of a class.

Lower Class Limit: The smallest value in a class.

Upper Class Limit: The largest value in a class.

Class Width: The difference between the lower class limit of the given class and the lower class limit of the next higher class.

Frequency: The number of data values in a class.

Frequency Distribution: It is a listing of classes and their frequencies. This statistical technique is especially introduced in the analysis of a parameter which cannot be certainly characterized and when it becomes inconvenient to treat each record of the parameter separately, because it varies in a wide range. In this way, the pattern of occurrence of the variable can be determined.

Relative Frequency: It is the ratio of the frequency to the total number of pieces of data. It is also called percentage of a class and can be expressed as a decimal or as percentage. The concept of relative frequency (percentages) is exactly the same as that of probability.

Z-Score: It is the number of standard deviations that a value is away from the mean of the data set. A negative z-score indicates that the value is below the mean, while a positive z-score indicates that the value is above the mean.

Chapter 2

TEMPERATURE

TEMPERATURE

2.1 Measurement of Temperature

Air temperature is measured by thermometers placed in white, louvred, wooden shelter which allows a relatively unobstructed air circulation and protects the thermometers from the direct rays of the sun and from precipitation as shown in Fig. 2.1. These thermometers record maximum and minimum temperatures.



Fig. 2.1 Ordinary Stevenson Screen (Photographed at Station of Shambat)

2.2 Mean Monthly Temperature

The mean monthly temperature is the average of the mean monthly maximum and minimum temperatures [6]. The variation of the mean monthly temperatures for the twelve stations are presented in Figs. 2.2 through 2.13. It can be noticed that the temperatures differ markedly between northern Sudan and southern Sudan: the hottest period of the year in the northern parts becomes the coldest season in the southern parts. The mean monthly temperature in Port Sudan shows quite a different pattern: the heat reaches its peak during the short season where the temperature is tempered in the other parts of Sudan.

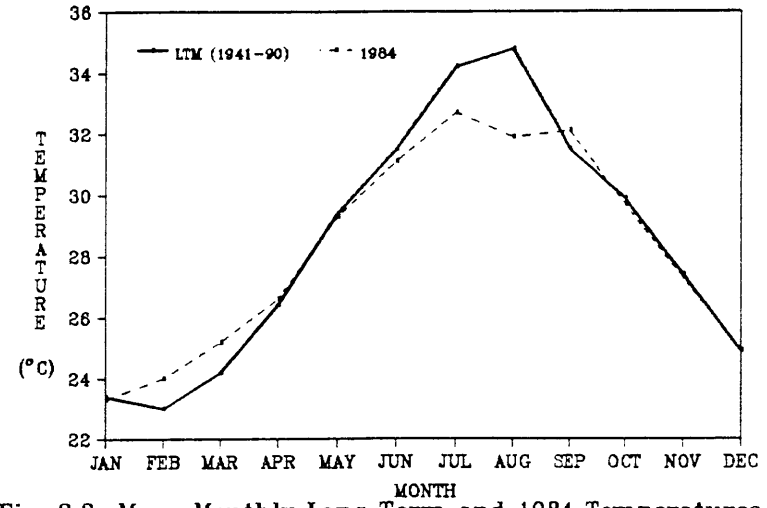


Fig. 2.2 Mean Monthly Long Term and 1984 Temperatures (Port Sudan)

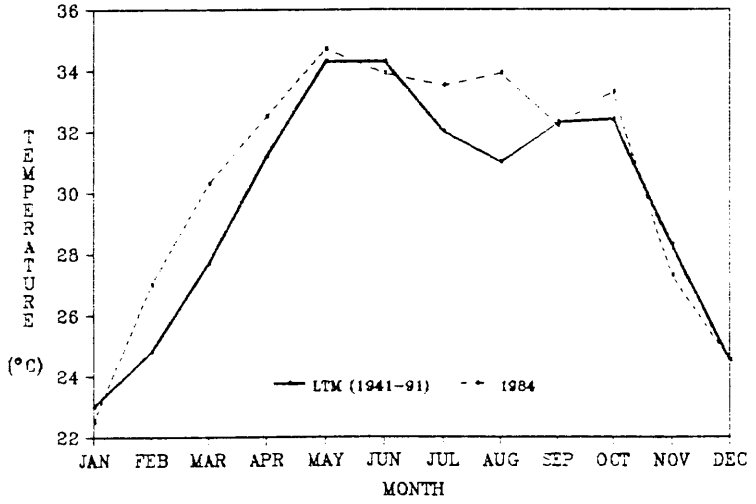


Fig. 2.3 Mean Monthly Long Term and 1984 Temperatures (Khartoum)

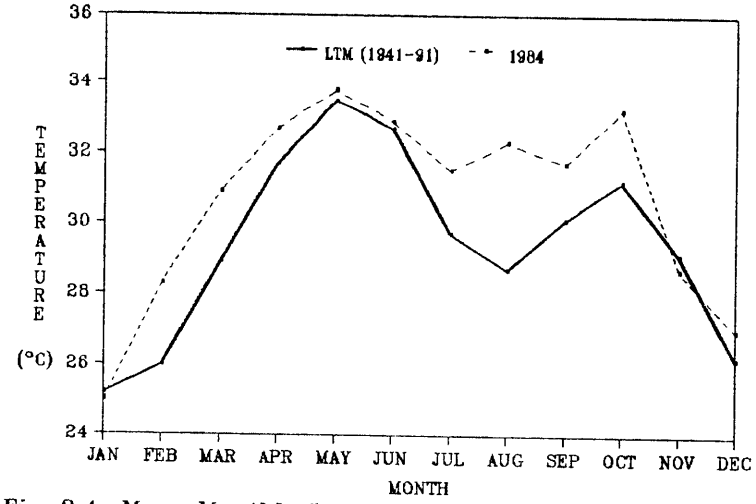


Fig. 2.4 Mean Monthly Long Term and 1984 Temperatures (Kassala)

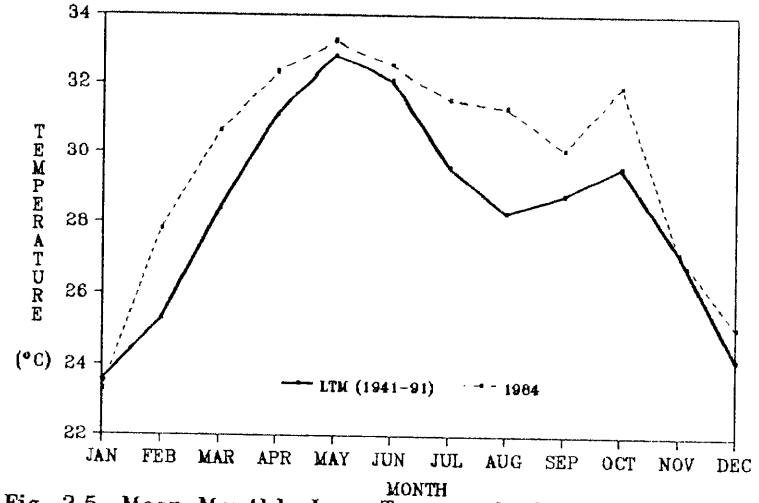


Fig. 2.5 Mean Monthly Long Term and 1984 Temperatures (Wad Medani)

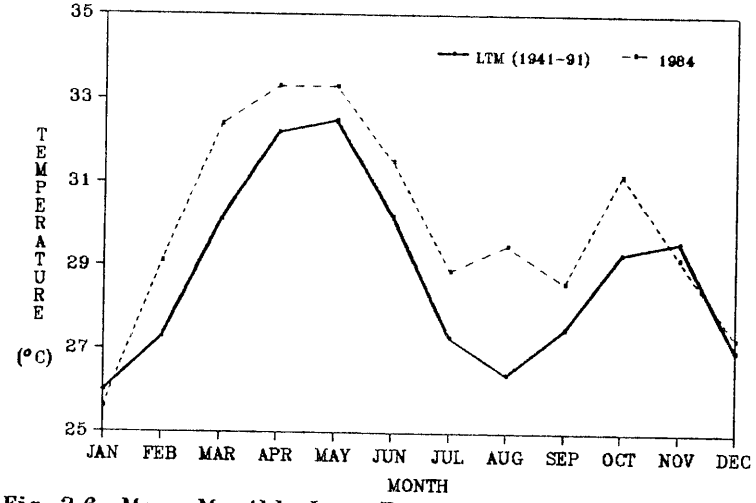


Fig. 2.6 Mean Monthly Long Term and 1984 Temperatures (El Gedaref)

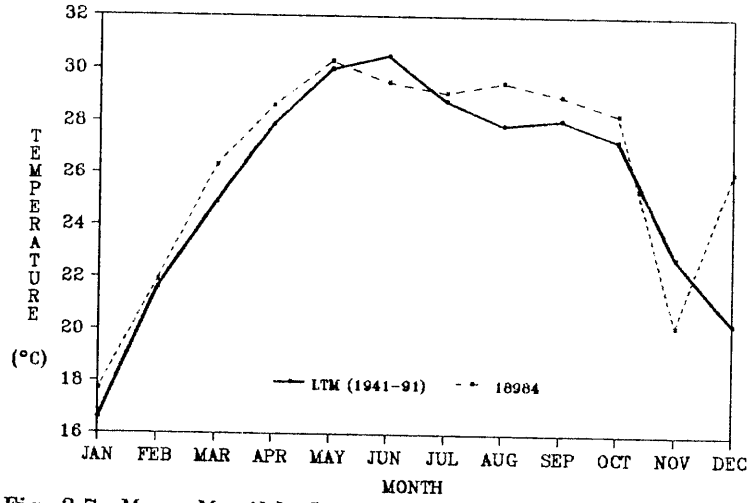


Fig. 2.7 Mean Monthly Long Term and 1984 Temperatures (El Fasher)

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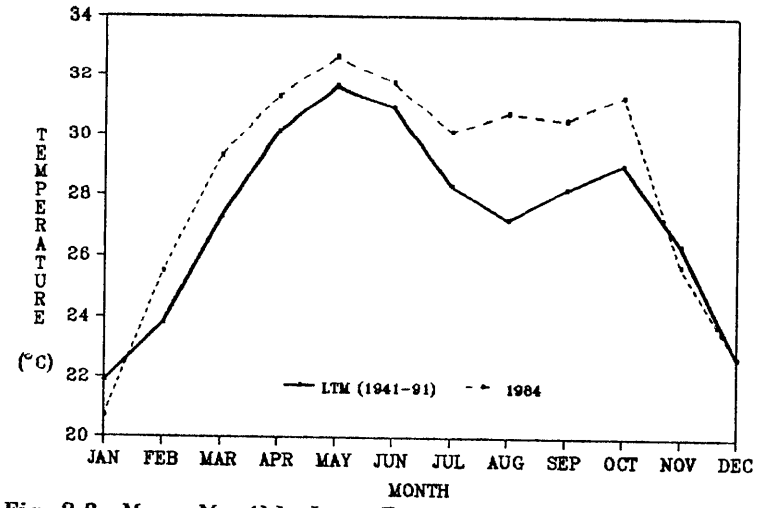


Fig. 2.8 Mean Monthly Long Term and 1984 Temperatures (El Obeid)

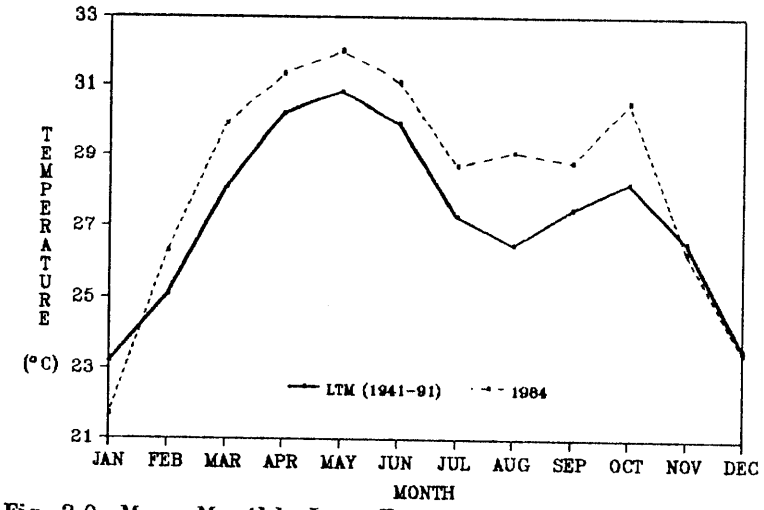


Fig. 2.9 Mean Monthly Long Term and 1984 Temperatures (Nyala)

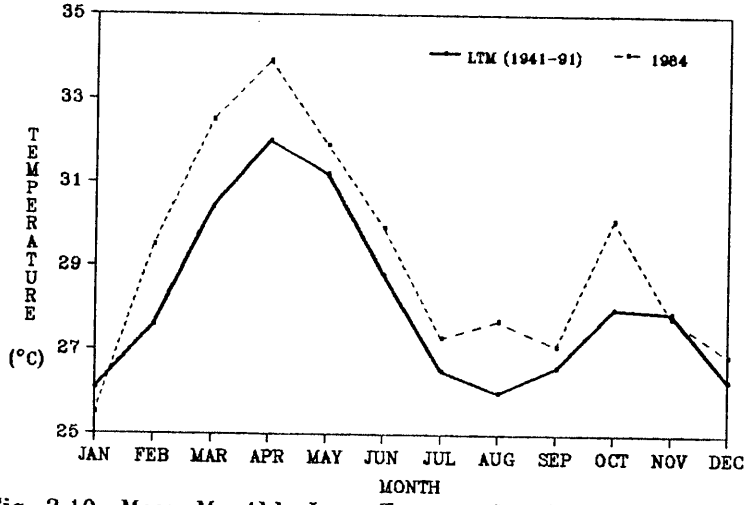


Fig. 2.10 Mean Monthly Long Term and 1984 Temperatures (Ed Damazin)

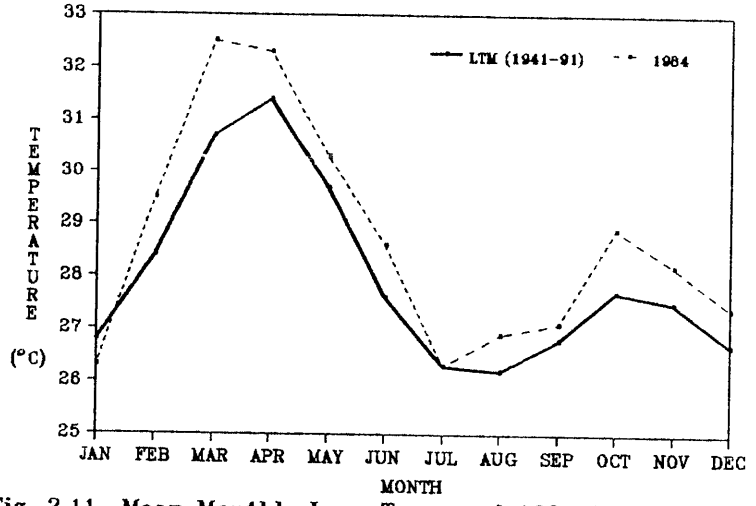


Fig. 2.11 Mean Monthly Long Term and 1984 Temperatures (Malakal)

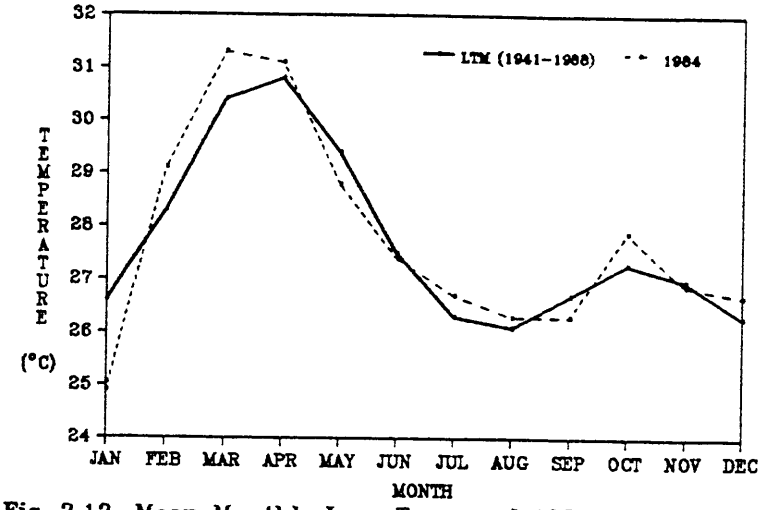


Fig. 2.12 Mean Monthly Long Term and 1984 Temperatures (Wau)

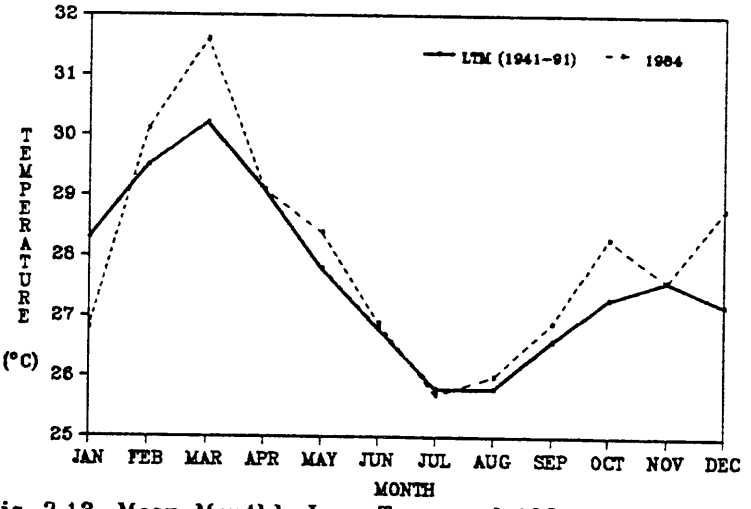


Fig. 2.13 Mean Monthly Long Term and 1984 Temperatures (Juba)

The hottest month of the year is May in Kassala, Wad Medani, El Gedaref, El Obeid and Nyala, June in El Fasher, April in Ed Damazin, Malakal and Wau, March in Juba and August in Port Sudan. In Khartoum, the highest mean monthly temperature occurs in the months of both May and June. The lowest mean temperature occurs in August in Ed Damazin, Malakal and Wau and in July and August in Juba, but occurs in February in Port Sudan. January is the coldest month for the rest of the stations. Port Sudan has the highest mean monthly temperature among the stations under consideration, which is 34.8°C, but the lowest one (16.6°C) is obtained in El Fasher.

2.3 Regimes and Ranges

The definition of the temperature regimes of any zone is based on the mean temperature of the hottest and coldest months of the year [14]. Table 2.1 classifies the summers and winters in the regions under consideration according to the temperature regimes. The summer in Sudan is very warm and the winter is warm except in El Fasher where the winter is classified as mild.

Table 2.1 Temperature Regimes and Ranges

Station	Summer			Wniter			Range
	Hottest Month	Mean t (°C)	Classification	Coldest Month	Mean t (°C)	Classification	(°C)
Port Sudan	Aug	34.8	Very warm summer *	Feb	23.0	Warm winter **	11.8
Khartoum	May/Jun	34.3	"	Jan	23.0	"	11.3
Kassala	May	33.5	"	"	25.1	"	8.4
Wad Medani	"	32.8	"	"	23.6	"	9.2
El Gedaref	"	32.5	"	"	26.0	"	6.5
El Fasher	Jun	30.5	"	"	16.6	Mild winter ***	13.9
El Obeid	May	31.6	"	"	21.9	Warm winter	9.7
Nyala	"	30.8	"	"	23.2	"	7.6
Ed Damazin	Apr	32.0	"	Aug	26.0	"	6.0
Malakal	"	31.4	"	"	26.2	"	5.2
Wau	"	30.8	"	"	26.1	"	4.7
Juba	Mar	30.2	"	Jul/Aug	25.8	"	4.4

* Mean temperature of the hottest month (> 30°C)

** Mean temperature of the coldest month (20 to 30°C)

*** Mean temperature of the coldest month (10 to 20°C)

Further classification of the stations can be made based on the mean monthly temperature ranges as given in Table 2.1 as well. Arranging the stations according to their increasing latitudes (from Juba to Port Sudan), the range increases from Juba to El Fasher and generally from El Gedaref to Port Sudan - Juba and El Fasher having the narrowest (4.4°C) and widest (13.9°C) ranges respectively.

2.4 Extremes

All absolute daily maximum and absolute daily minimum temperatures for the months are indicated in Figs. 2.14 to 2.25. The highest maximum recorded temperatures range from 43.4°C (occurred in May for El Fasher) to 47.5°C (occurred in August for Port Sudan). The range of the lowest minimum recorded temperature is between 0.7°C (observed in January for El Fasher) and 11.4°C (recorded in January for Juba).

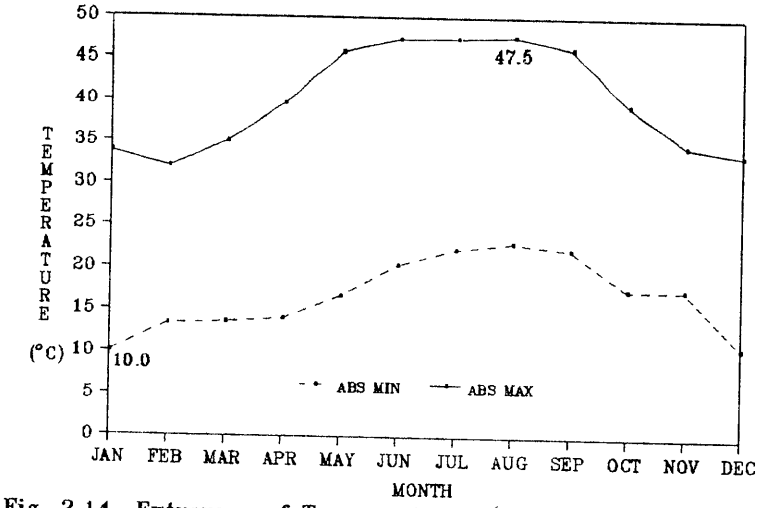


Fig. 2.14 Extremes of Temperatures (Port Sudan 1951-90)

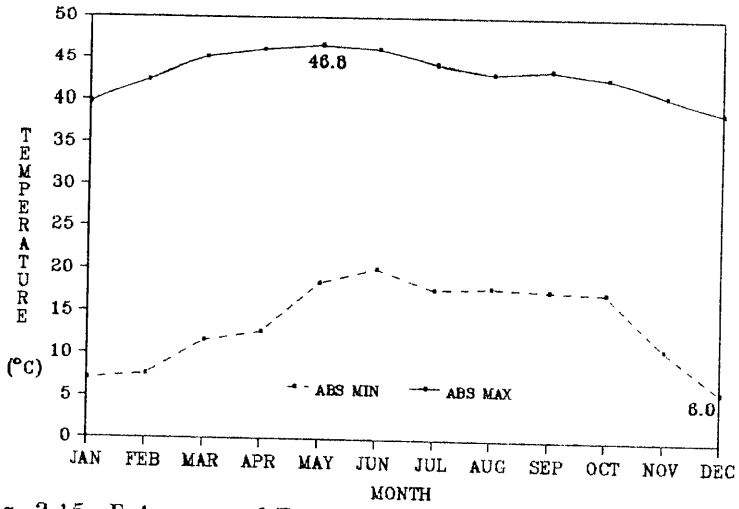


Fig. 2.15 Extremes of Temperatures (Khartoum 1951-90)

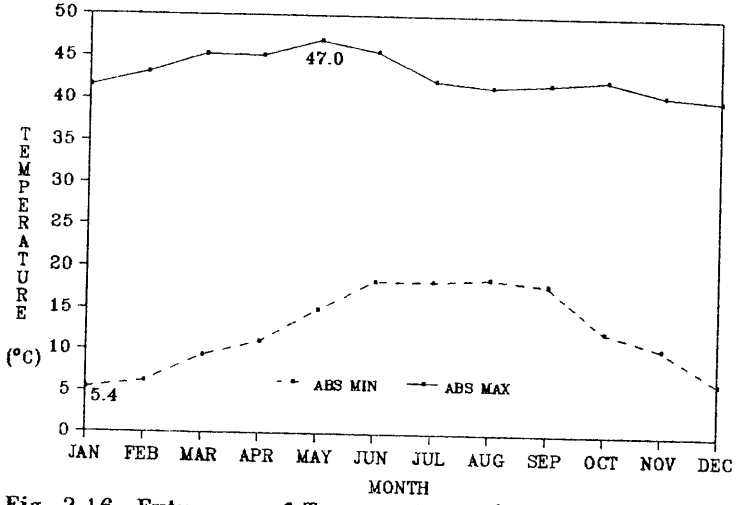


Fig. 2.16 Extremes of Temperatures (Kassala 1951-90)

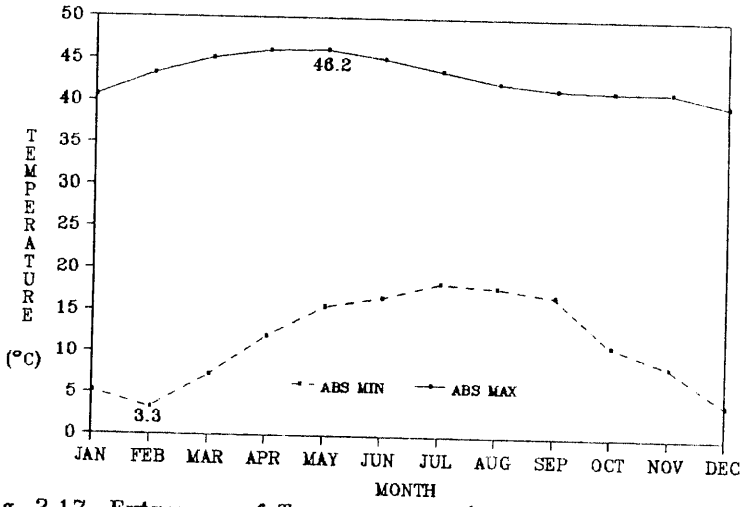


Fig. 2.17 Extremes of Temperatures (Wad Medani 1951-90)

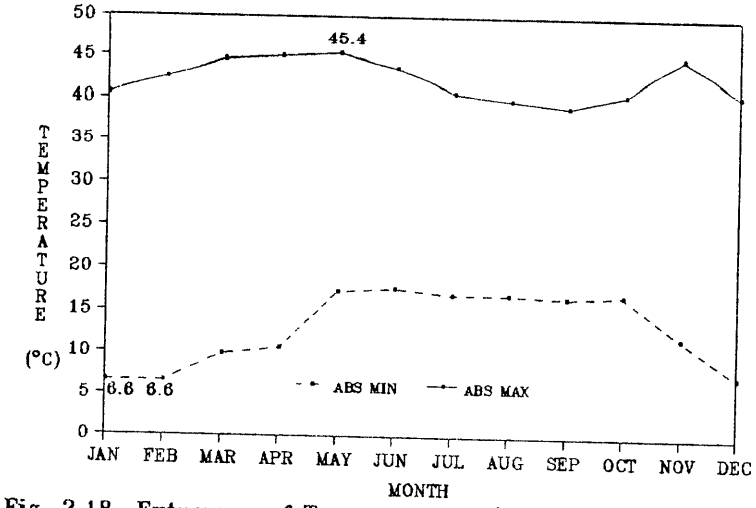


Fig. 2.18 Extremes of Temperatures (El Gedaref 1951-90)

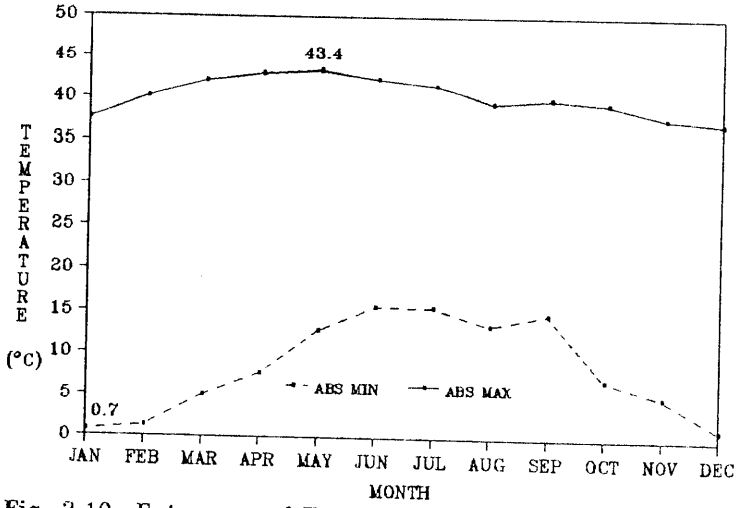


Fig. 2.19 Extremes of Temperatures (El Fasher 1951-90)

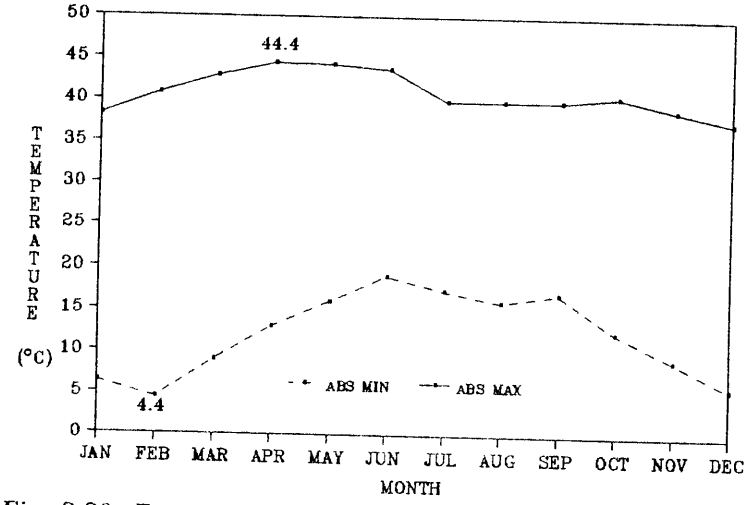


Fig. 2.20 Extremes of Temperatures (El Obeid 1951-90)

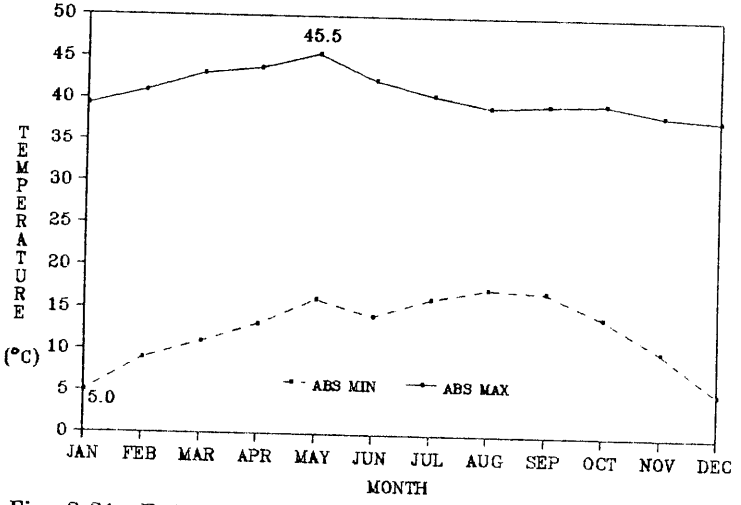


Fig. 2.21 Extremes of Temperatures (Nyala 1951-90)

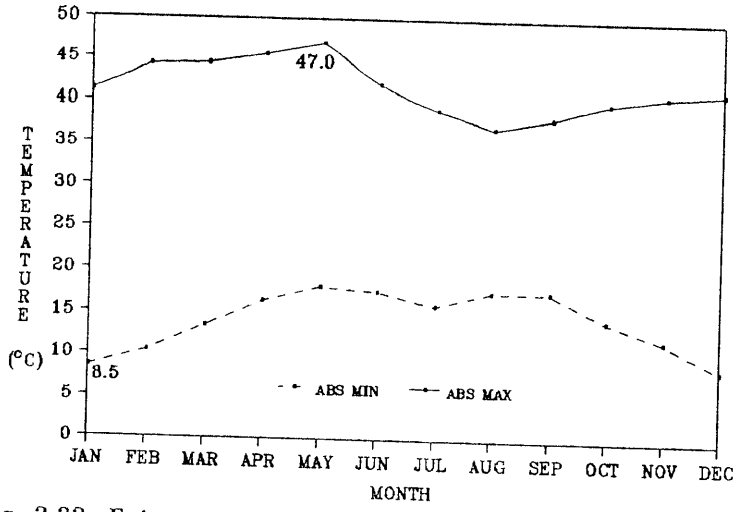


Fig. 2.22 Extremes of Temperatures (Ed Damazin 1951–90)

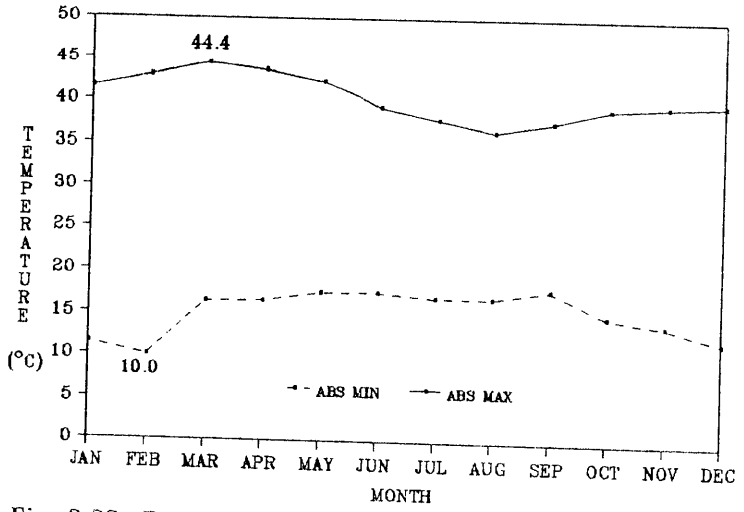


Fig. 2.23 Extremes of Temperatures (Malakal 1951–90)

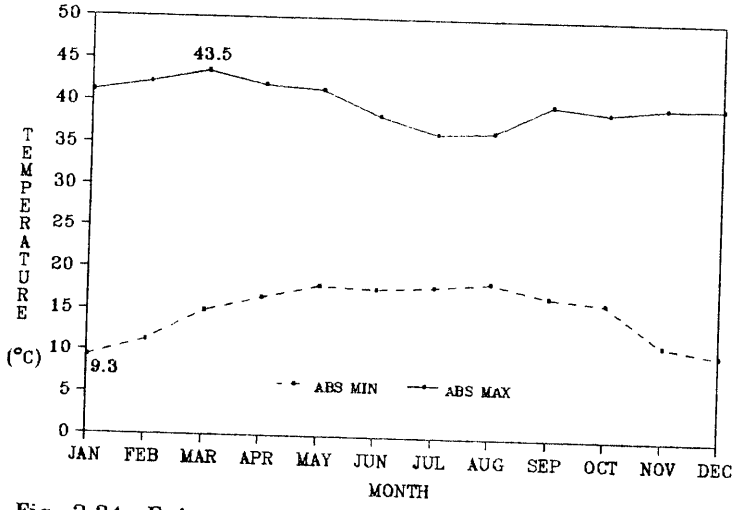


Fig. 2.24 Extremes of Temperatures (Wau 1951–90)

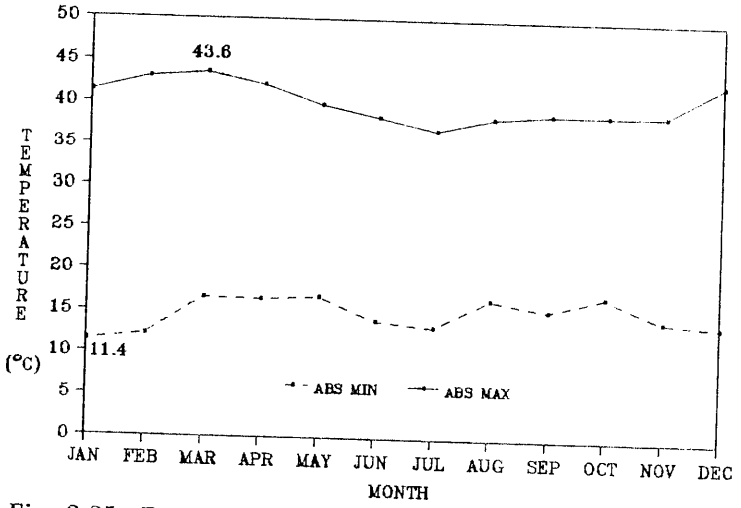


Fig. 2.25 Extremes of Temperatures (Juba 1951–90)

2.5 Mean Annual Temperature

The mean annual temperature is the average of the monthly means for the year [6]. Figs. 2.26 through 2.37 illustrate the long term behaviour of mean annual temperature. These figures show a striking increase in temperature above the long term mean (LTM is the mean of the entire data series) during the last three decades. The highest mean annual temperature ever recorded among the study areas was 31.3°C at the station of Khartoum and the lowest one was obtained as 24.8°C in El Fasher. All the highest mean annual temperatures for all the meteorological stations were recorded in a short period of 1980 to 1990, except for El Fasher the highest value was recorded in 1973.

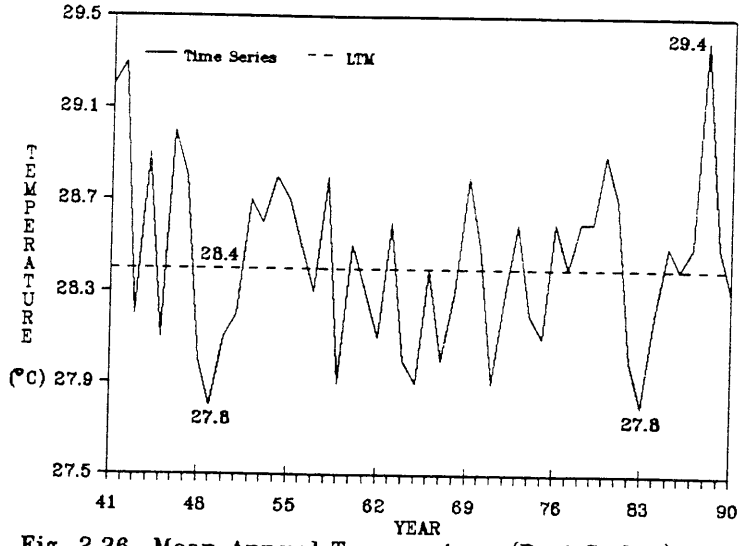


Fig. 2.26 Mean Annual Temperature (Port Sudan)

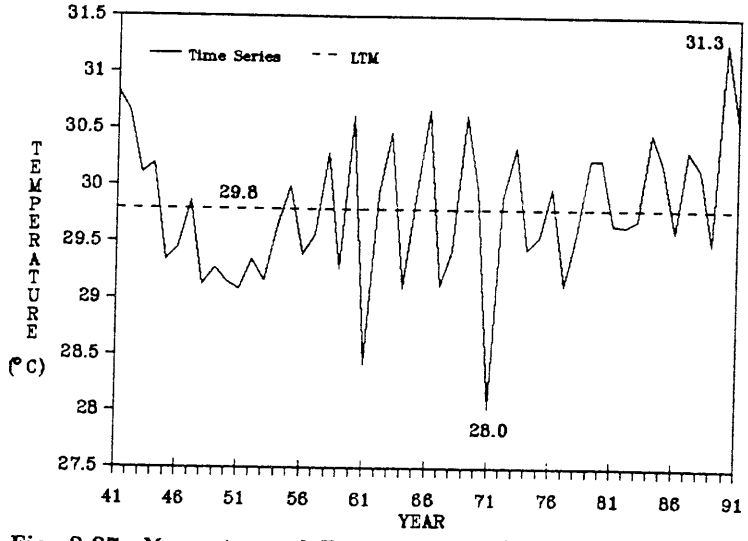


Fig. 2.27 Mean Annual Temperature (Khartoum)

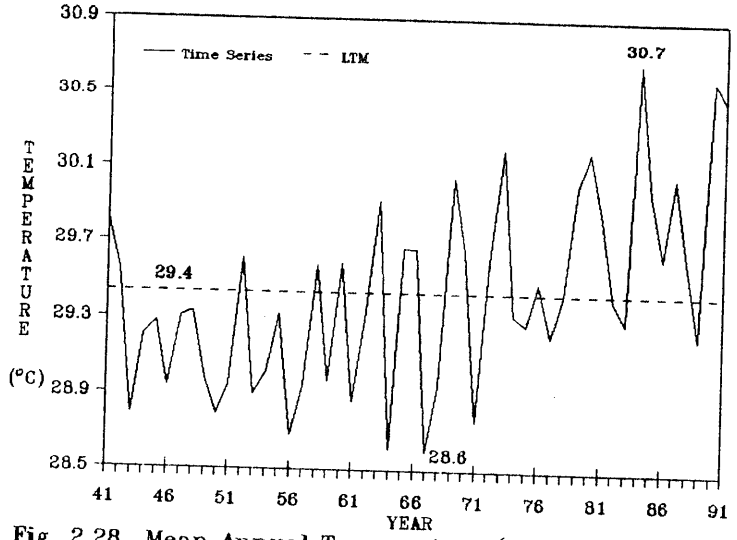


Fig. 2.28 Mean Annual Temperature (Kassala)

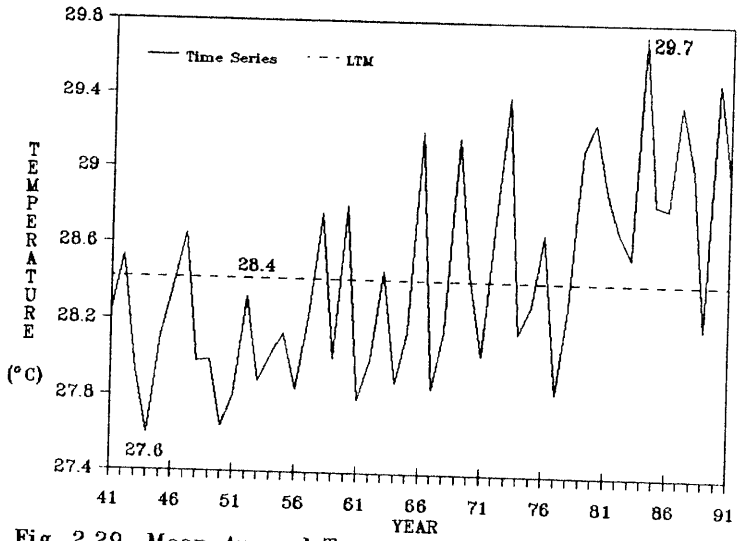


Fig. 2.29 Mean Annual Temperature (Wad Medani)

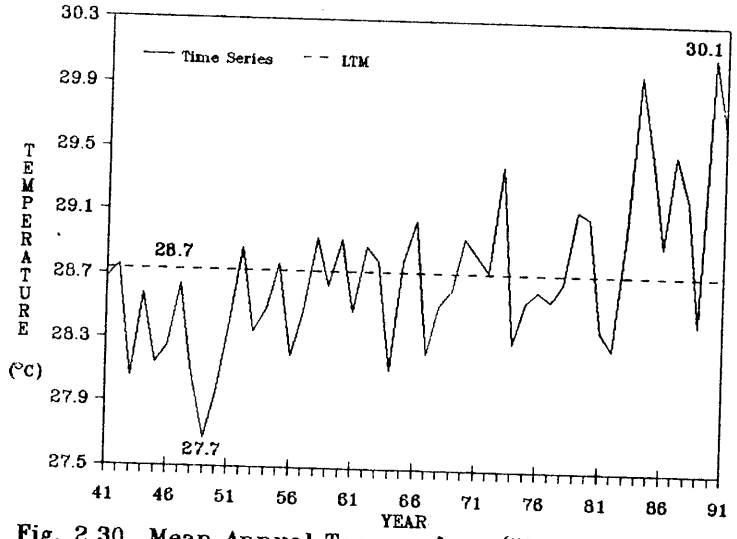


Fig. 2.30 Mean Annual Temperature (El Gedaref)

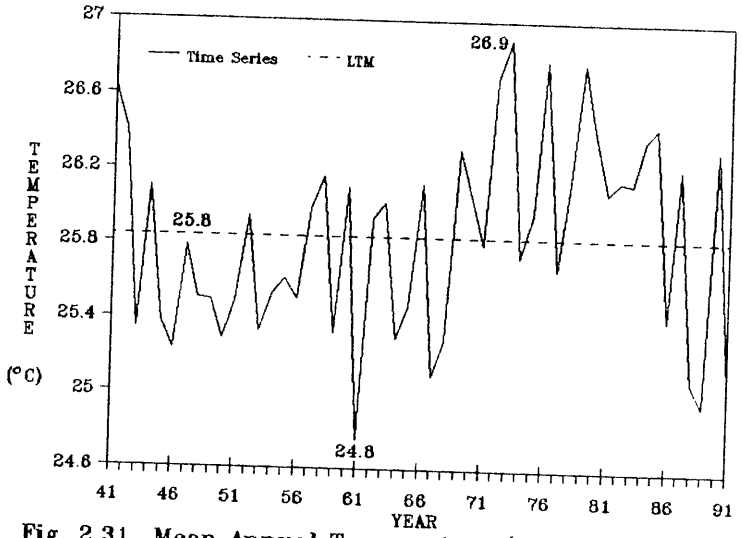


Fig. 2.31 Mean Annual Temperature (El Fasher)

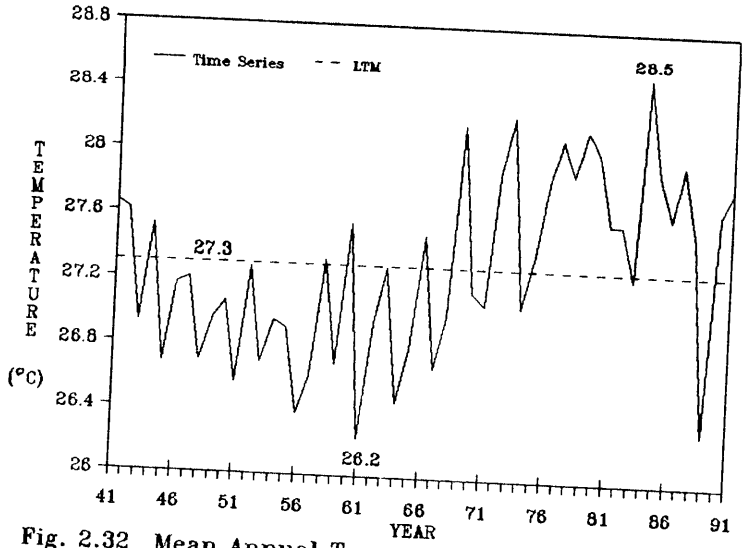


Fig. 2.32 Mean Annual Temperature (El Obeid)

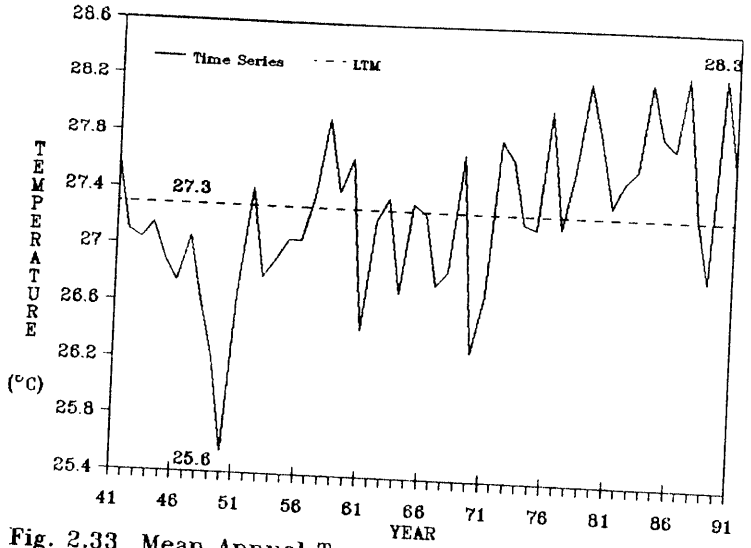


Fig. 2.33 Mean Annual Temperature (Nyala)

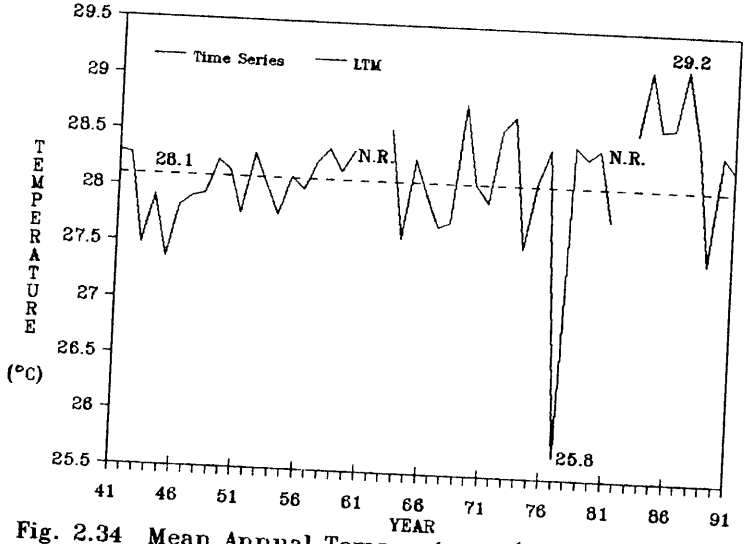


Fig. 2.34 Mean Annual Temperatures (Ed Damazin)

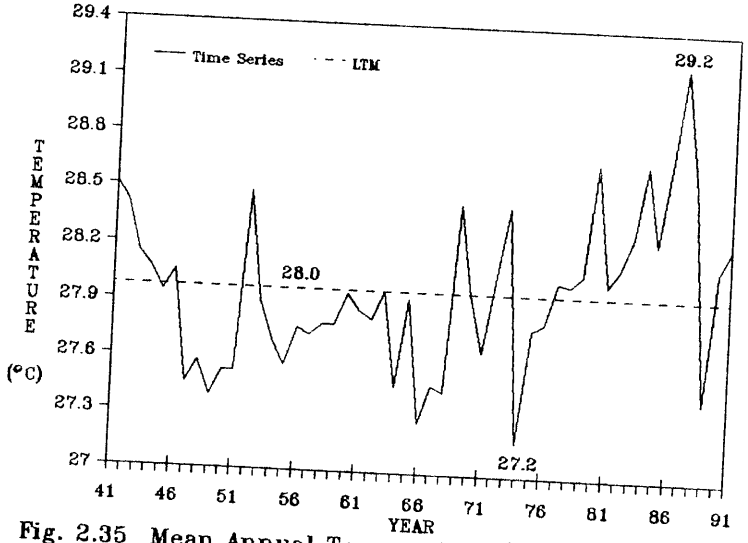


Fig. 2.35 Mean Annual Temperature (Malakal)

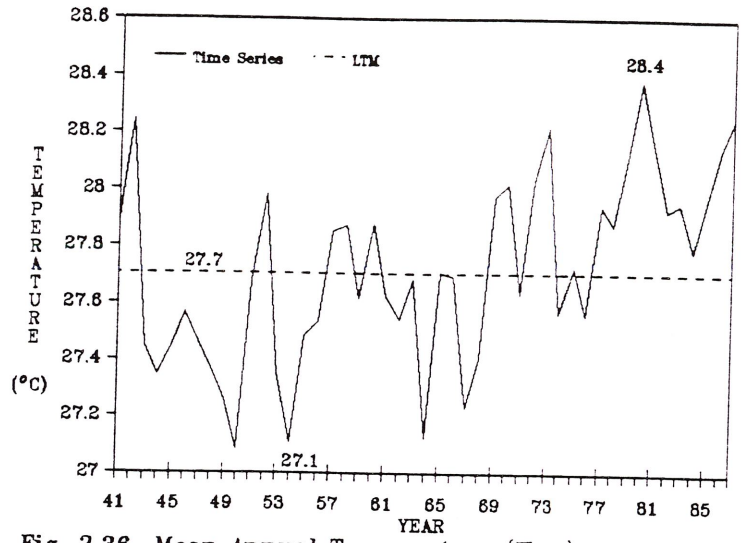


Fig. 2.36 Mean Annual Temperature (Wau)

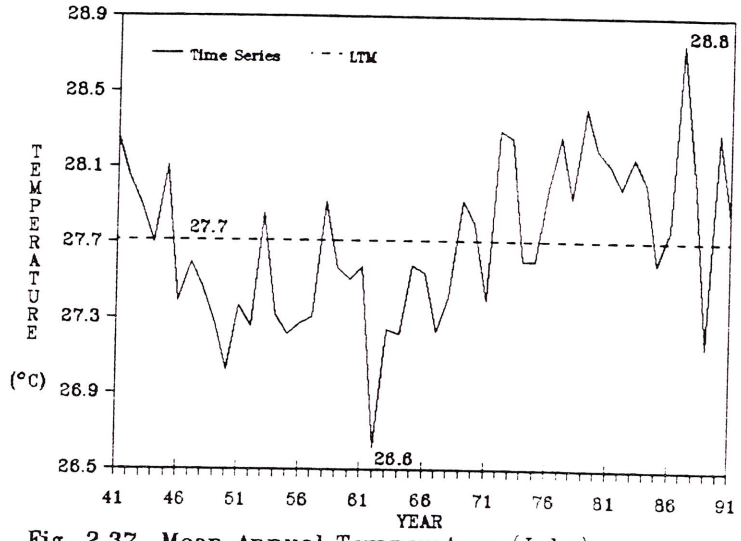


Fig. 2.37 Mean Annual Temperature (Juba)

2.5.1 Long Term Mean and Normal Temperatures

To study clearly the temperature behaviour in the twelve regions, statistical analysis was carried out for both long term and for last 30 years (normal) data by developing a computer program (Appendix) and the various statistical descriptors are provided in Table 2.2. The variation in the pattern is quantitatively indicated by the coefficient of variation which ranges between 1.2 and 2.1% for long term data and between 1.1 and 2.3% for 30-year data. To confirm the warming situation in the regions, two approaches have been adopted; the regression analysis and the mean. The first approach relies on the best linear fit for the entire data points which when obtained for the study areas revealed increasing trends of the time series with higher rates during the latest 30-year period as shown in Table 2.2 (the maximum rate of increase is observed for Wad Medani as 0.034°C per year). The

second approach is based on comparing the mean values of the two data sets, LTM and normal. From Table 2.2, it can be seen that normal temperature in some of the locations rises above the LTM by as much as 0.2°C.

Table 2.2 Characteristics of Long Term Mean, Normal and 1984 Annual Temperatures

Station	Long Term					Normal					1984
	Period	μ (°C)	σ (°C)	Cv (%)	TR (°C/Yr)	Period	μ (°C)	σ (°C)	Cv (%)	TR (°C/Yr)	μ (°C)
Port Sudan	1941-90	28.4	0.378	1.3	– 0.028	1961-90	28.4	0.335	1.2	0.012	28.2
Khartoum	1941-91	29.8	0.620	2.1	0.008	1962-91	29.9	0.613	2.1	0.018	30.5
Kassala	"	29.4	0.505	1.7	0.018	"	29.6	0.525	1.8	0.028	30.7
Wad Medani	"	28.4	0.523	1.9	0.022	"	28.6	0.531	1.9	0.034	29.7
El Gedaref	"	28.7	0.507	1.8	0.020	"	28.9	0.511	1.8	0.025	30.0
El Fasher	"	25.8	0.522	2.0	0.007	"	26.0	0.540	2.1	– 0.001	26.4
El Obeid	"	27.3	0.556	2.1	0.018	"	27.5	0.544	2.0	0.024	28.5
Nyala	"	27.3	0.570	2.1	0.019	"	27.5	0.510	1.9	0.031	28.3
Ed Damazin	"	28.1	0.537	1.9	0.010	1963-91	28.2	0.652	2.3	0.017	29.2
Malakal	"	28.0	0.421	1.5	0.010	1962-91	28.0	0.467	1.7	0.029	28.7
Wau*	1941-87	27.7	0.330	1.2	0.010	1958-87	27.8	0.308	1.1	0.013	27.8
Juba	1941-91	27.7	0.424	1.5	0.011	1962-91	27.8	0.454	1.7	0.029	28.0

* Because of the civil war, the observations could not be taken after 1987.

The findings of warming conditions in arid and semi-arid regions were also reported by Alvi [15-17] for Bahrain and Oman and by Alvi and Elagib [18, 19] for Malakal and for Eastern-Sudan. The rise in global temperature is attributed by scientists to the green house effect (the ability of the upper layers of the earth's atmosphere to hold heat as a result of increased levels of carbon dioxide and methane gas which are produced largely by the burning of fossil fuels) [20]. This phenomenon has the potential of devastating consequences for the future like rising seas, widening of ozone hole and enlarging drought prone and flood prone areas.

Among all the stations, the LTM and normal annual temperatures are found to be maximum for Khartoum, 29.8 and 29.9°C respectively, and minimum for El Fasher, 25.8 and 26.0°C respectively.

2.5.2 Classification of Mean Annual Temperature

Conrad [10] used the standard deviation to classify the departure of individual value in a climatological series from the mean by expressing the departure as number of standard deviations (z-score). His classification is as follows:

beyond -3σ	extremely sub-normal (ES)
-3σ to -2σ	greatly sub-normal (GS)
-2σ to $-\sigma$	sub-normal (S)
$-\sigma$ to $+\sigma$	normal (N)
$+\sigma$ to $+2\sigma$	above normal (A)
$+2\sigma$ to $+3\sigma$	greatly above normal (GA)
beyond $+3\sigma$	extremely above normal (EA)

This method is used herein to classify the highest and lowest mean annual temperatures recorded as presented in Table 2.3. The highest mean annual temperatures for all the stations, arranged in order of decreasing latitudes, are classified as greatly above normal except for Nyala which is classified as above normal. The lowest mean annual temperatures recorded during the long period range between sub-normal for eight stations, namely Port Sudan, Kassala, Wad Medani, El Gedaref, El Fasher, El Obeid, Malakal and Wau, and extremely sub-normal for Ed Damazin. For Khartoum, Nyala and Juba, they fall in the greatly sub-normal class. These results clearly reflect the wide variation in the time series of the mean annual temperatures for the various stations.

Table 2.3 Classification of the Highest and Lowest Mean Annual Temperature Departures from the Long Term Mean

Station	Highest				Lowest			
	t (°C)	Deviation (°C)	z-score	Classi-fication	t (°C)	Deviation (°C)	z-score	Classi-fication
Port Sudan	29.4	1.0	2.65	GA	27.8	−0.6	−1.58	S
Khartoum	31.3	1.5	2.42	GA	28.0	−1.8	−2.90	GS
Kassala	30.7	1.3	2.57	GA	28.6	−0.8	−1.58	S
Wad Medani	29.7	1.3	2.48	GA	27.6	−0.8	−1.53	S
El Gedaref	30.1	1.4	2.76	GA	27.7	−1.0	−1.97	S
El Fasher	29.9	1.1	2.11	GA	24.8	−1.0	−1.92	S
El Obeid	28.5	1.2	2.16	GA	26.2	−1.1	−1.98	S
Nyala	28.3	1.0	1.75	A	25.6	−1.7	−2.98	GS
Ed Damazin	29.2	1.1	2.05	GA	25.8	−2.3	−4.28	ES
Malakal	29.2	1.2	2.85	GA	27.2	−0.8	−1.90	S
Wau	28.4	0.7	2.12	GA	27.1	−0.6	−1.82	S
Juba	28.8	1.1	2.59	GA	26.6	−1.1	−2.59	GS

2.5.3 Mean Annual Temperature Frequency Distribution

Further description of the temperature series can be given by computing the frequency of a certain deviation from the mean [10]. The time series of mean annual temperatures for all the stations are used to represent the frequencies of deviations in the form of bar graphs with classes of 0.1°C (Figs. 2.38 to 2.49). Informations such as the LTM, the range, the mode and the percentage of mode (PM is defined as the ratio of the frequency of the mode to the total number of cases, expressed as percentage, which also represents the probability of having a modal value) are given in the figures too. The Narrowest range is observed for Wau as 1.3°C whereas the widest range is observed for Malakal as 3.5°C. As is illustrated in the figures, six annual temperature series have more than one modal temperature as in the case of Khartoum, Wad Medani, El Fasher, El Obeid, Nyala and Malakal. This may be explained by the wide variation in the temperature patterns. The LTM for El Obeid and Malakal are found to be modal. The percentage of mode ranges between 7.8 and 17.4%. Three stations have 9.8% as PM, namely Khartoum, Wad Medani and Nyala, two stations have PMs equal to 15.7%, viz. Kassala and El Fasher, and other two stations have 13.7% as PM which are Malakal and Juba.

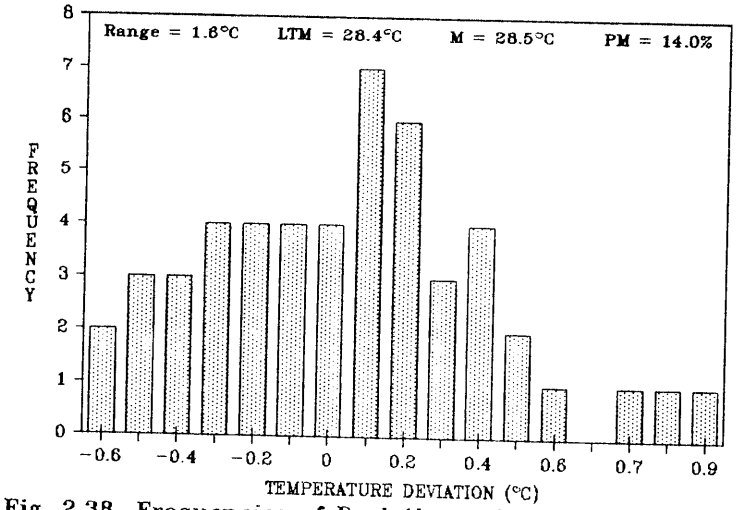


Fig. 2.38 Frequencies of Deviations of Mean Annual Temperature from LTM (Port Sudan 1941–90)

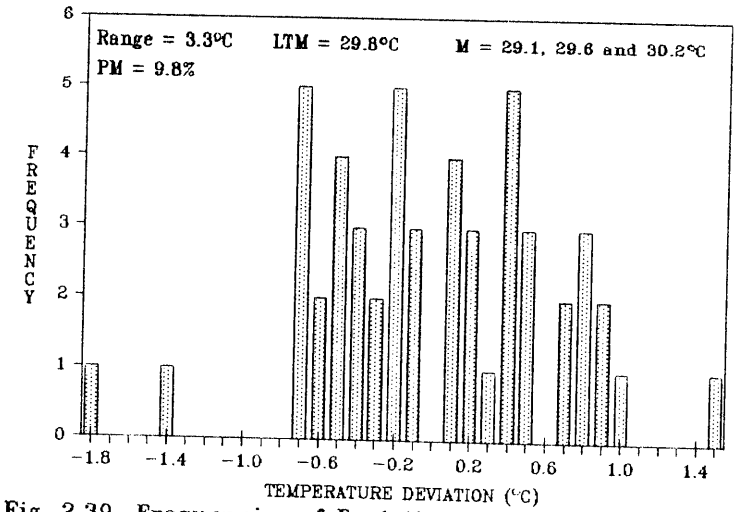


Fig. 2.39 Frequencies of Deviations of Mean Annual Temperature from LTM (Khartoum 1941–91)

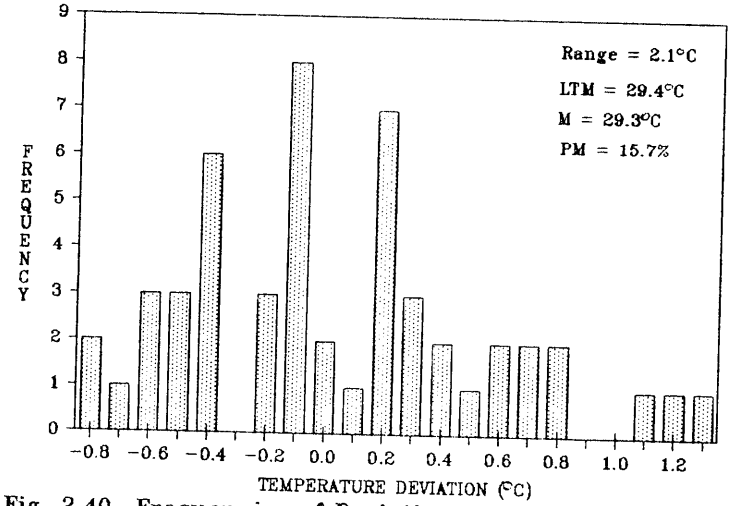


Fig. 2.40 Frequencies of Deviations of Mean Annual Temperature from LTM (Kassala 1941–91)

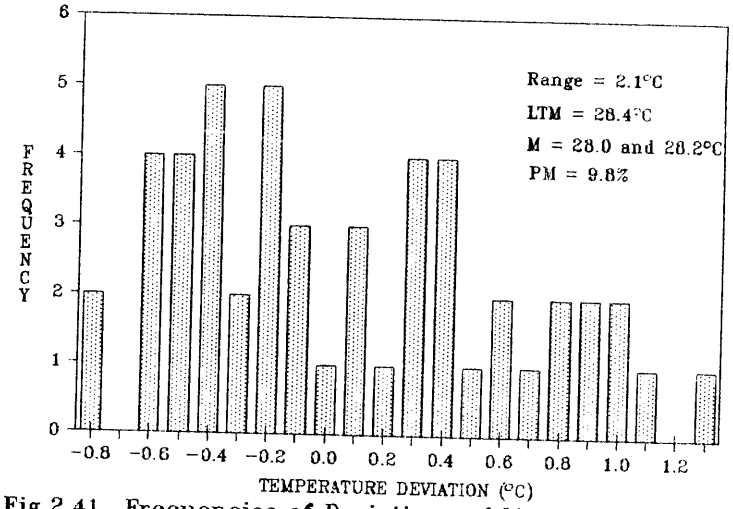


Fig.2.41 Frequencies of Deviations of Mean Annual Temperature from LTM (Wad Medani 1941–91)

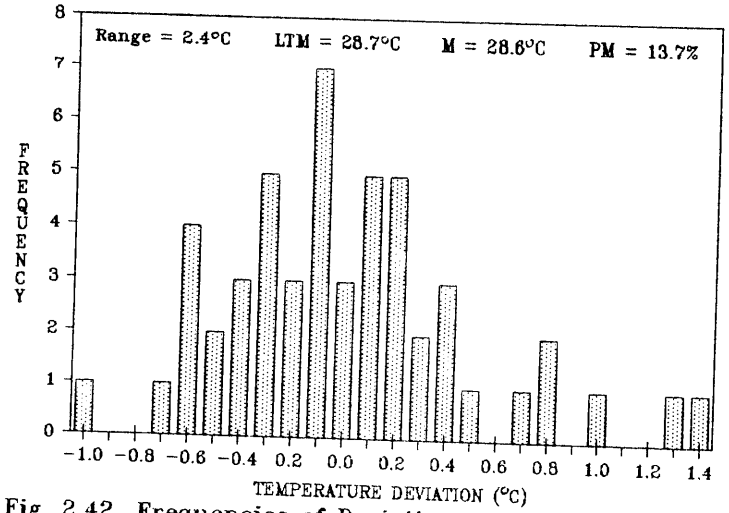


Fig. 2.42 Frequencies of Deviations of Mean Annual Temperature from LTM (El Gedaref 1941–91)

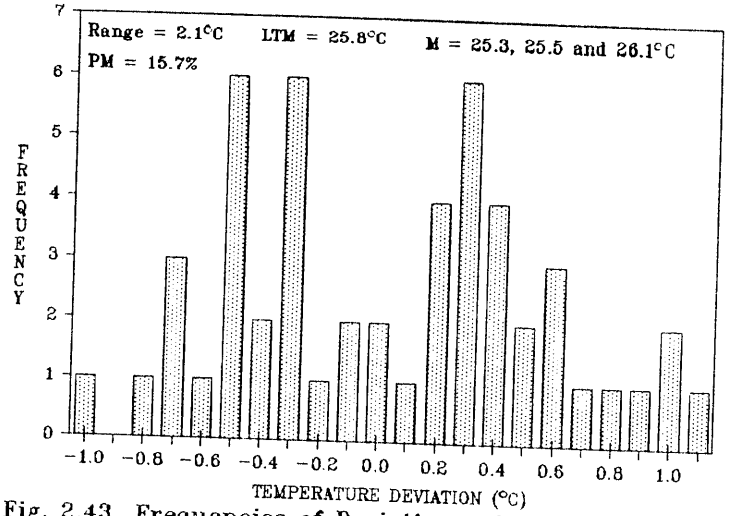


Fig. 2.43 Frequencies of Deviations of Mean Annual Temperature from LTM (El Fasher 1941–91)

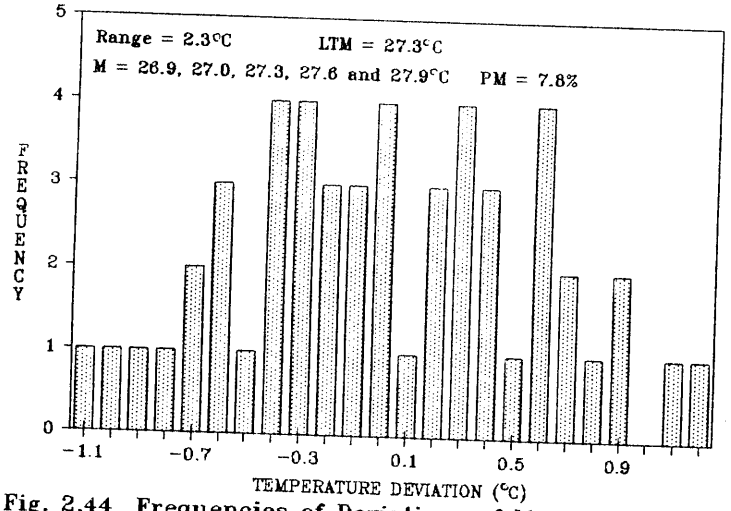


Fig. 2.44 Frequencies of Deviations of Mean Annual Temperature from LTM (El Obeid 1941–91)

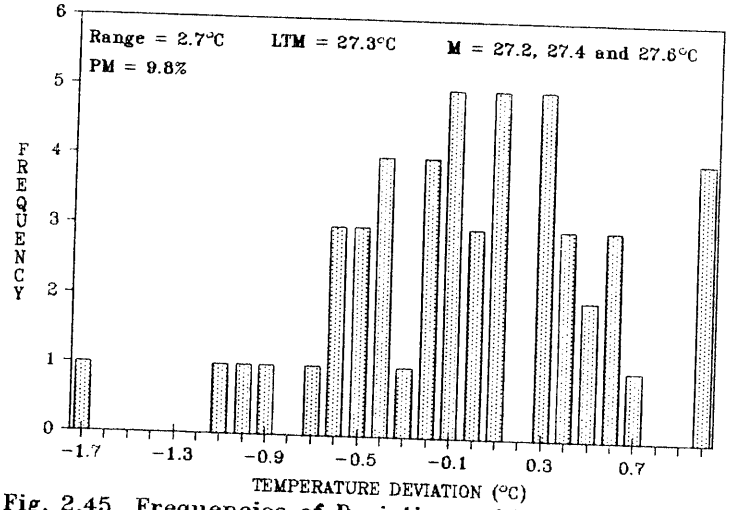


Fig. 2.45 Frequencies of Deviations of Mean Annual Temperature from LTM (Nyala 1941–91)

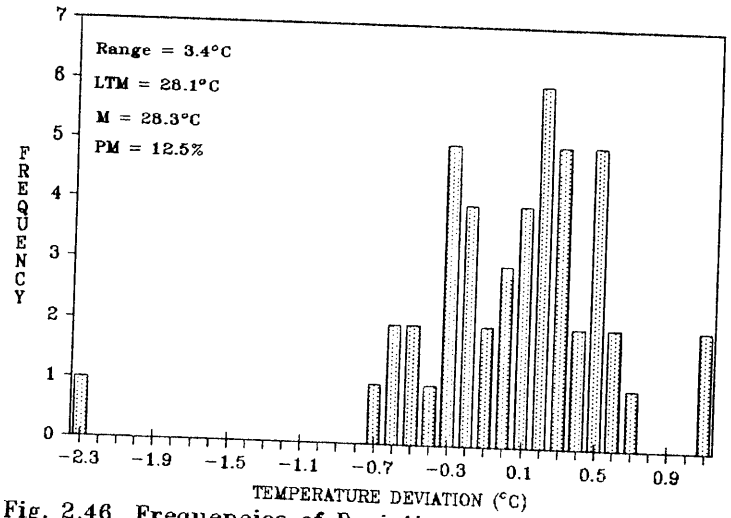


Fig. 2.46 Frequencies of Deviations of Mean Annual Temperature from LTM (Ed Damazin 1941–91)

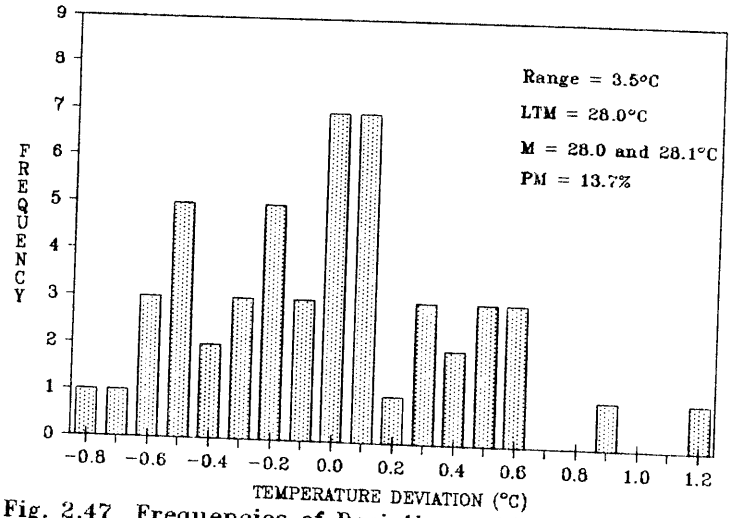


Fig. 2.47 Frequencies of Deviations of Mean Annual Temperature from LTM (Malakal 1941–91)

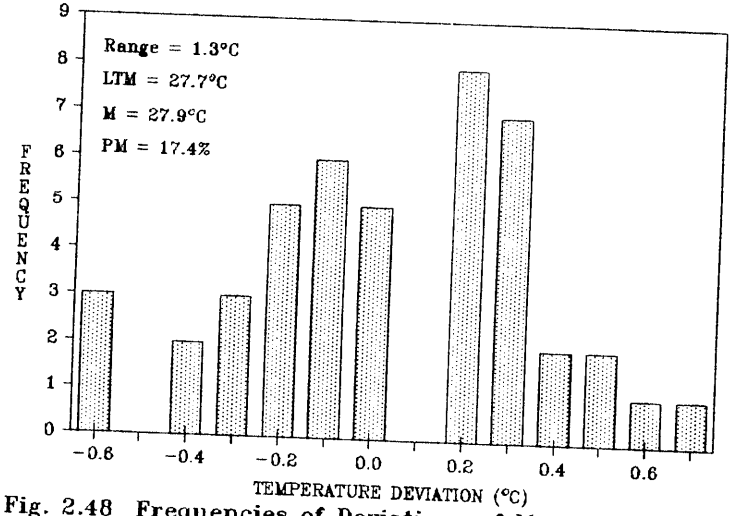


Fig. 2.48 Frequencies of Deviations of Mean Annual Temperature from LTM (Wau 1941–87)

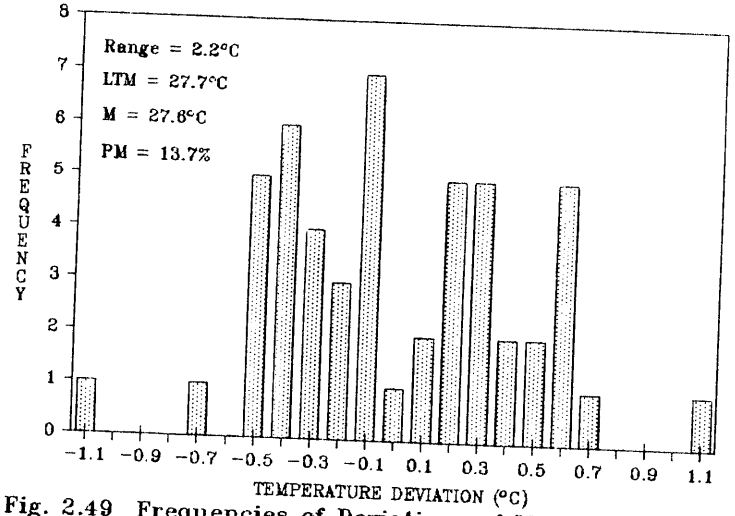


Fig. 2.49 Frequencies of Deviations of Mean Annual Temperature from LTM (Juba 1941–91)

Although the number of cases above the LTM for most of the series is less than the number of cases below the LTM, this is not reflected in the trend of the time series, indicating that the higher temperature effects have a stronger bearing on the slope of the best linear fit over the lower ones, which further emphasizes the significance of increase in temperature levels.

Chapter 3

RAINFALL

RAINFALL

3.1 Measurement of Rainfall

Continuous record of rain is extremely useful, because it provides better information about the frequency, duration and intensity of rain. Rainfall in Sudan is measured by ordinary or standard rain gauges. Figs. 3.1.a, 3.1.b and 3.1.c show the types of rain gauges used at the station of Shambat.



Fig. 3.1.a Recording Rain Gauge (Photographed at Station of Shambat)



Fig. 3.1.b Recording Rain Gauge (Photographed at Station of Shambat)



Fig. 3.1.c Recording Rain Gauge (Photographed at Station of Shambat)

3.2 Monthly Rainfall

The monthly rainfall is highly variable from year to year. The number of consecutive months with adequate rainfall determines the growth season for natural vegetation and rain-fed crops [4]. The distribution of precipitation over the year is obviously of relevance for the use of grazing as well.

3.2.1 Mean Monthly Rainfall

The long term mean monthly rainfalls for the twelve index stations are given in Figs. 3.2 through 3.13. Excluding Port Sudan, the rainiest month is August throughout the regions with an exception of Juba where the rainiest month is May but is very closely comparing with August. The amount of rain in this month (August) varies from 61.5 mm for Khartoum to as much as 214.9 mm for Wau. At the station of Port Sudan, which has different rainy season, the wettest month is November with 42.8 mm of rain.

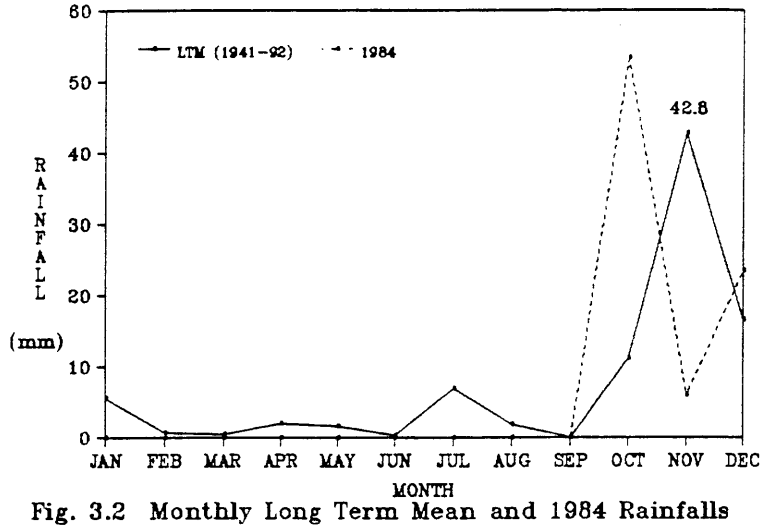


Fig. 3.2 Monthly Long Term Mean and 1984 Rainfalls (Port Sudan)

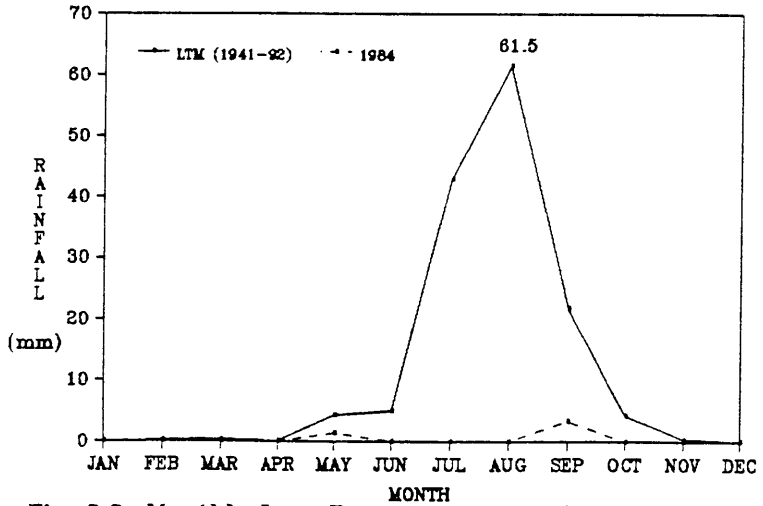


Fig. 3.3 Monthly Long Term Mean and 1984 Rainfalls (Khartoum)

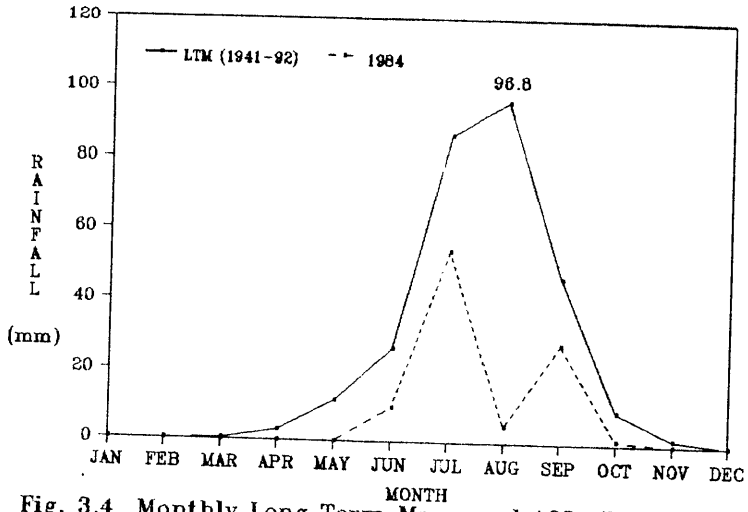


Fig. 3.4 Monthly Long Term Mean and 1984 Rainfalls (Kassala)

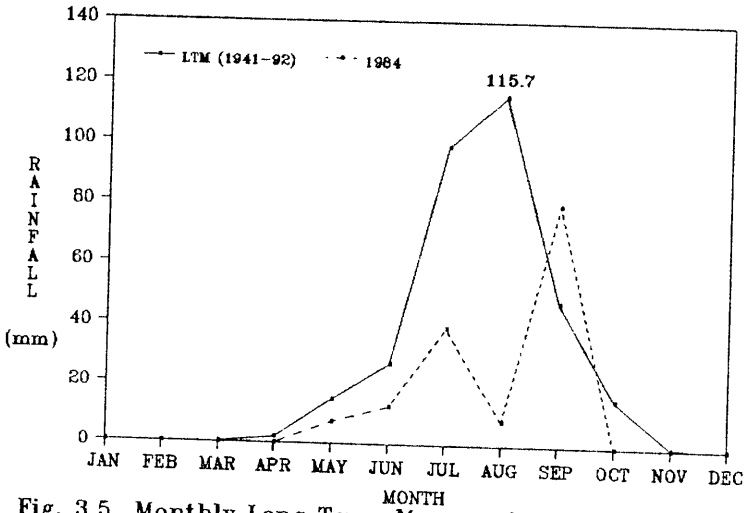


Fig. 3.5 Monthly Long Term Mean and 1984 Rainfalls (Wad Medani)

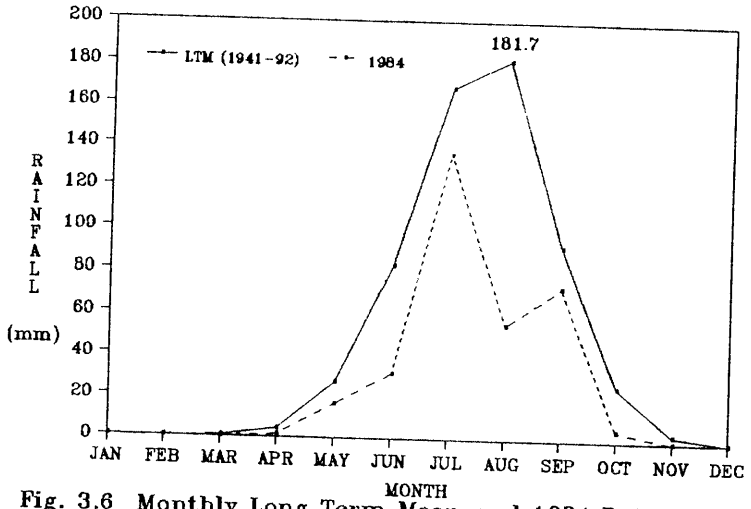


Fig. 3.6 Monthly Long Term Mean and 1984 Rainfalls (El Gedaref)

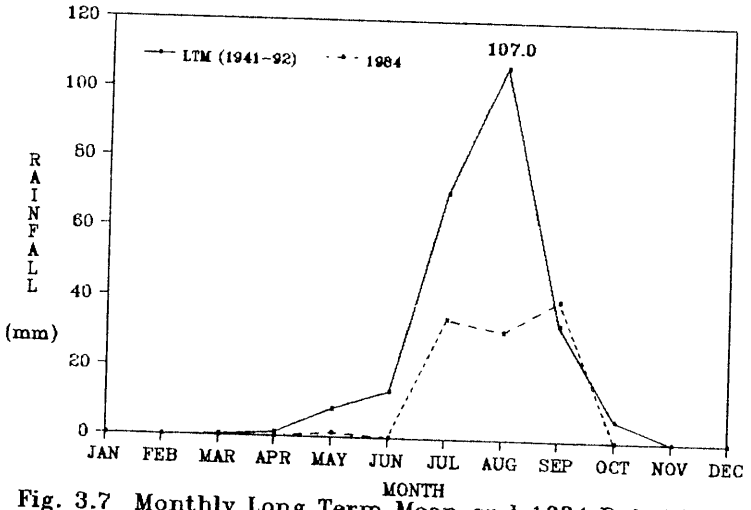


Fig. 3.7 Monthly Long Term Mean and 1984 Rainfalls (El Fasher)

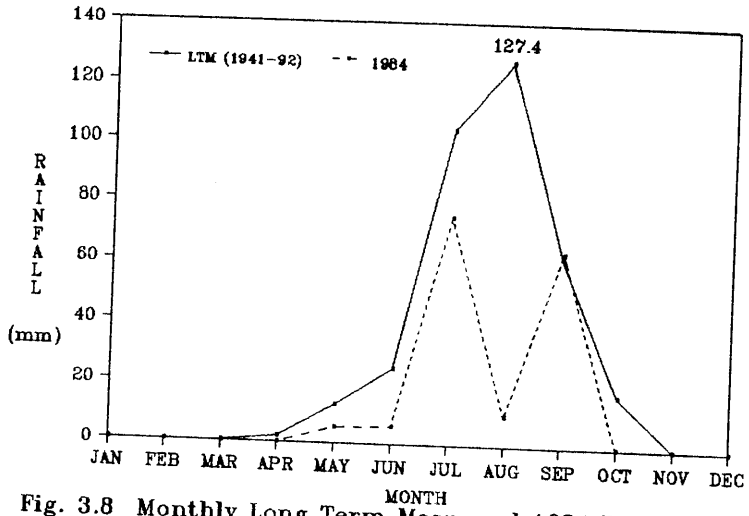


Fig. 3.8 Monthly Long Term Mean and 1984 Rainfalls (El Obeid)

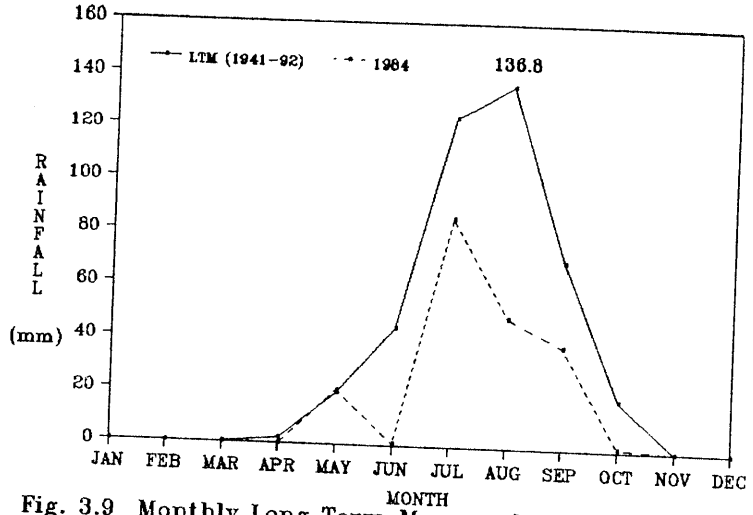


Fig. 3.9 Monthly Long Term Mean and 1984 Rainfalls (Nyala)

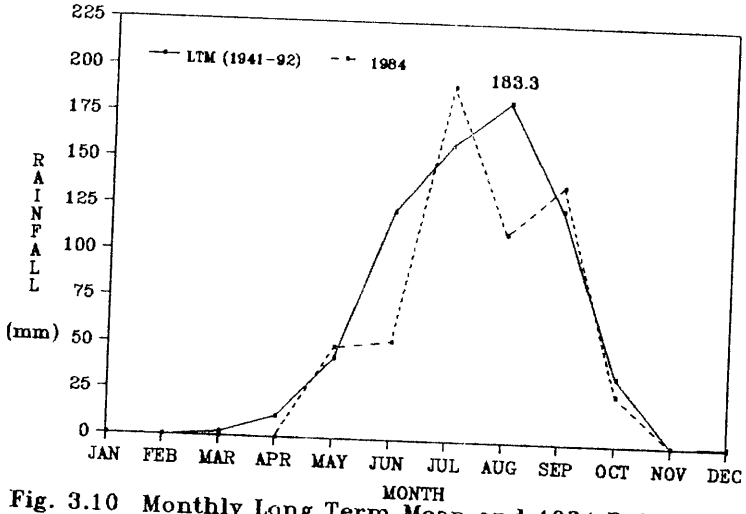


Fig. 3.10 Monthly Long Term Mean and 1984 Rainfalls (Ed Damazin)

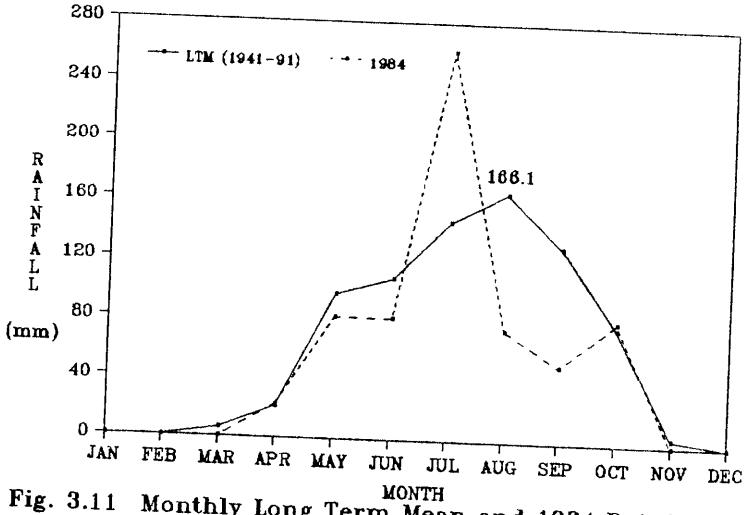


Fig. 3.11 Monthly Long Term Mean and 1984 Rainfalls (Malakal)

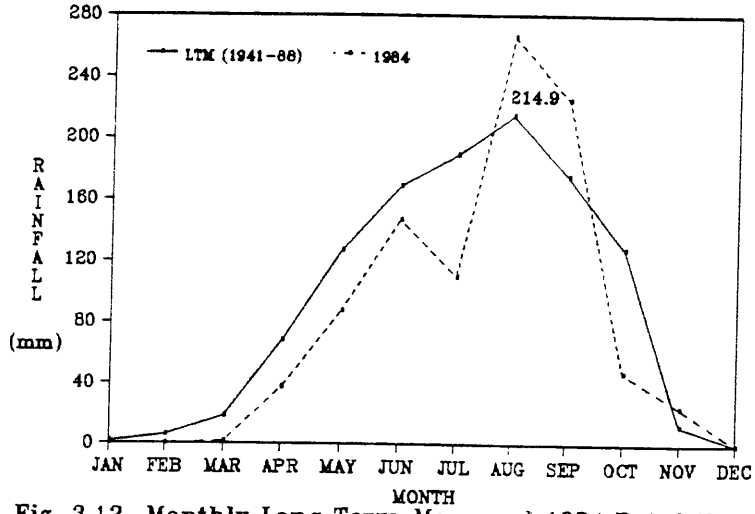


Fig. 3.12 Monthly Long Term Mean and 1984 Rainfalls (Wau)

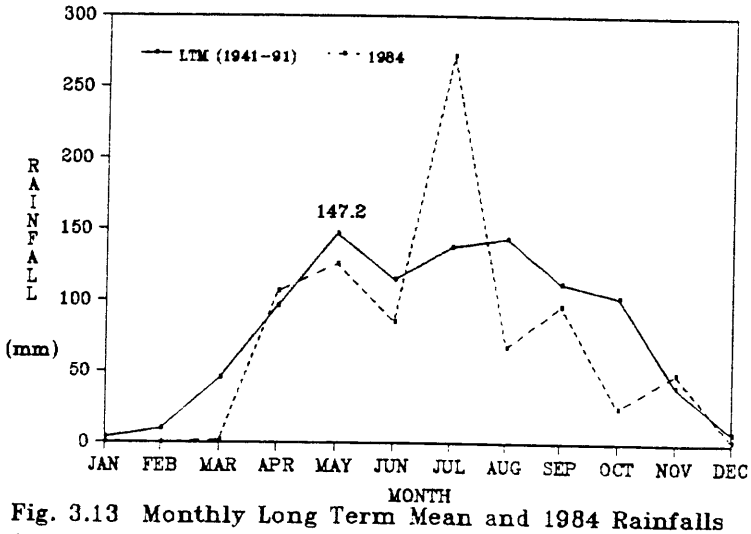


Fig. 3.13 Monthly Long Term Mean and 1984 Rainfalls (Juba)

3.2.2 Distribution over the Year

The distribution of rainfall over the year can be recognized better by expressing the mean monthly rainfall as percentage of the mean annual rainfall which is demonstrated in Figs. 3.14 to 3.25. The percentage of rain falling in the rainiest month varies from Juba to Port Sudan within the range of 15.2 to 47.4% of the annual. Around 90% of the mean annual rainfall, for instance, is distributed over 3 to 8 months; the period extends from north to south. Along the Red Sea coast, the distribution is quite irregular.

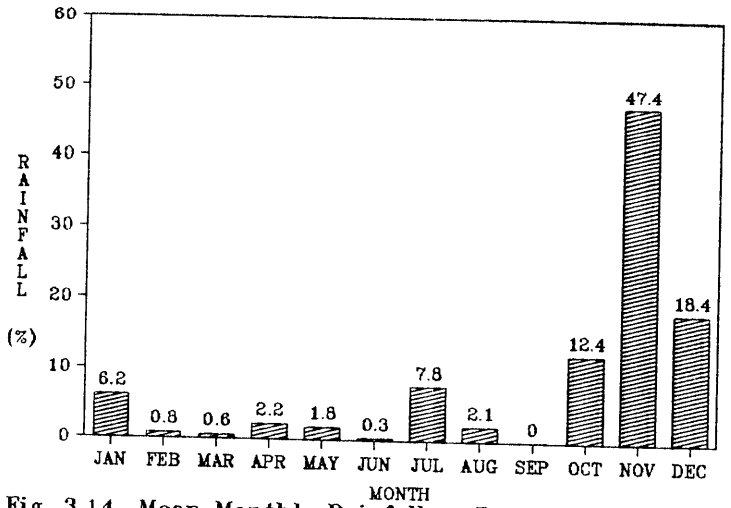


Fig. 3.14 Mean Monthly Rainfall as Percentage of the Mean Annual (Port Sudan 1941-92)

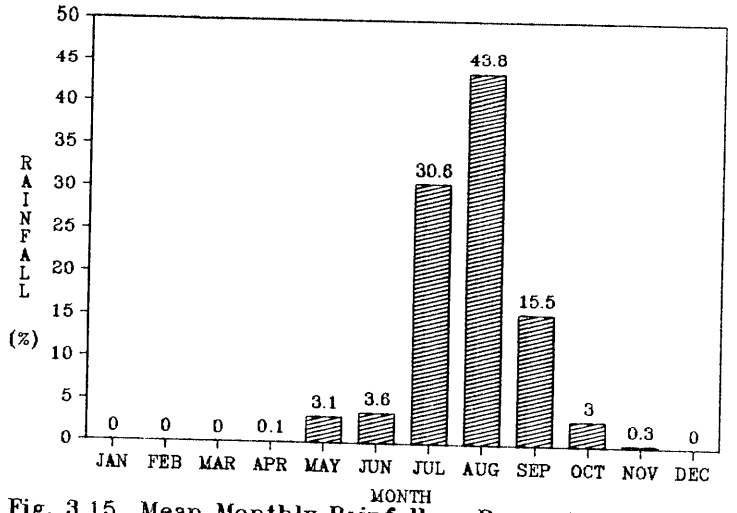


Fig. 3.15 Mean Monthly Rainfall as Percentage of the Mean Annual (Khartoum 1941-92)

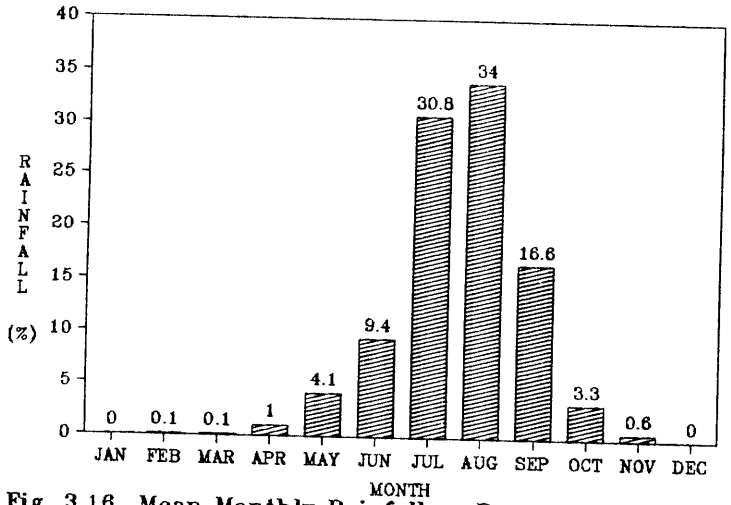


Fig. 3.16 Mean Monthly Rainfall as Percentage of the Mean Annual (Kassala 1941-92)

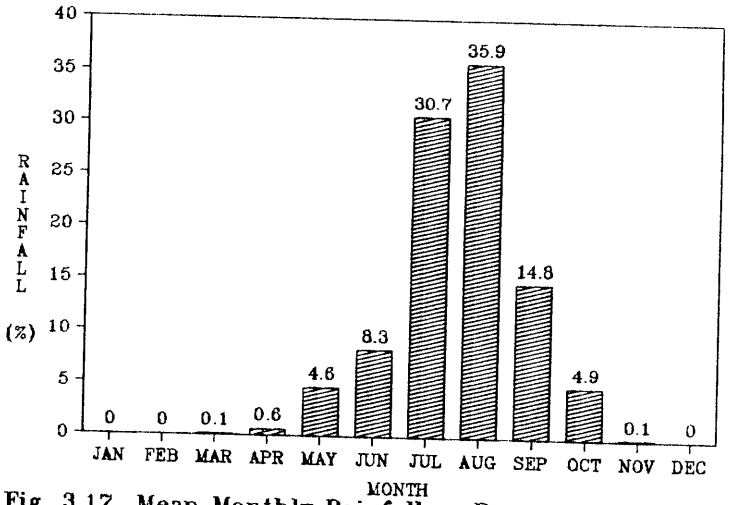


Fig. 3.17 Mean Monthly Rainfall as Percentage of the Mean Annual (Wad Medani 1941-92)

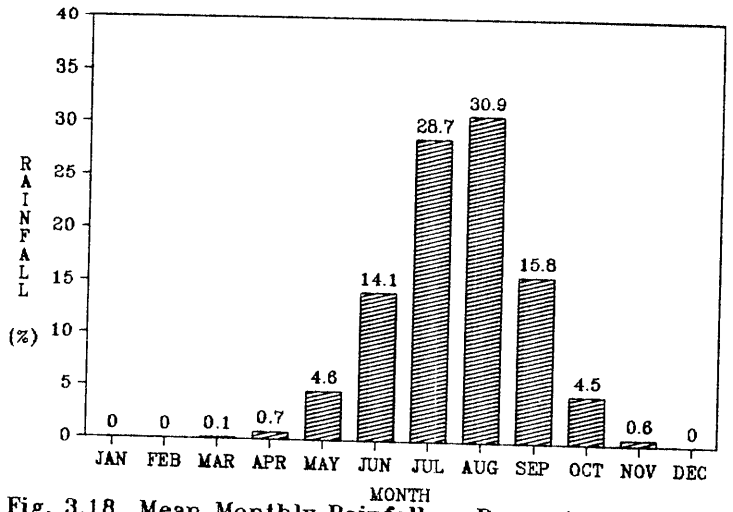


Fig. 3.18 Mean Monthly Rainfall as Percentage of the Mean Annual (El Gedaref 1941–92)

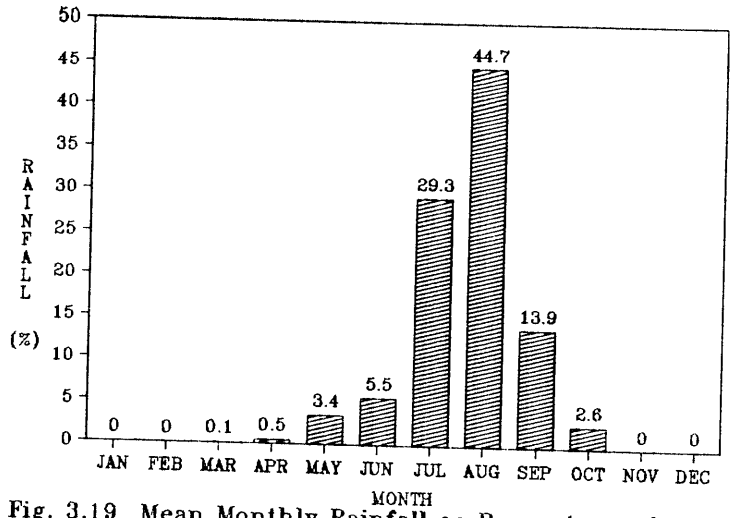


Fig. 3.19 Mean Monthly Rainfall as Percentage of the Mean Annual (El Fasher 1941–92)

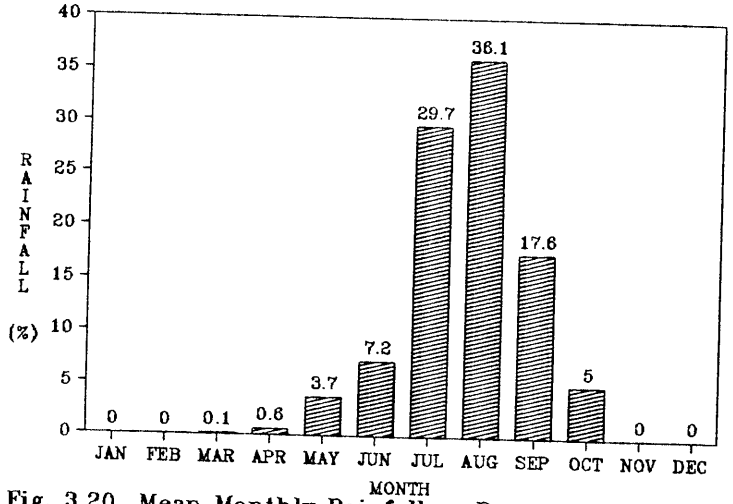


Fig. 3.20 Mean Monthly Rainfall as Percentage of the Mean Annual (El Obeied 1941–92)

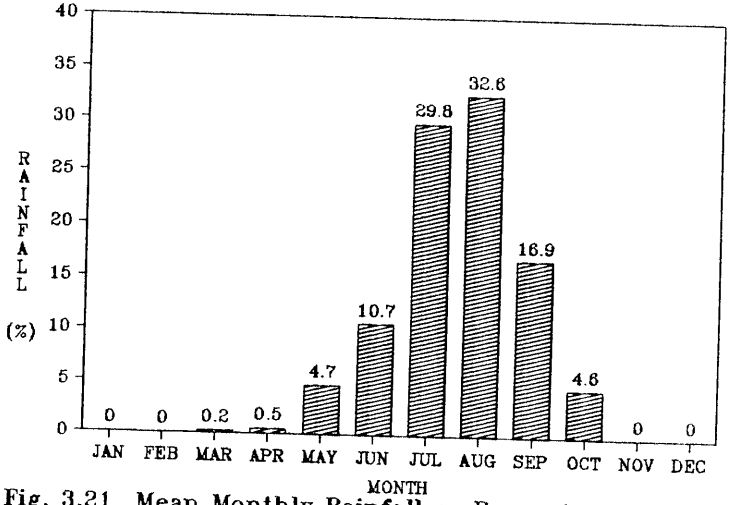


Fig. 3.21 Mean Monthly Rainfall as Percentage of the Mean Annual (Nyala 1941–92)

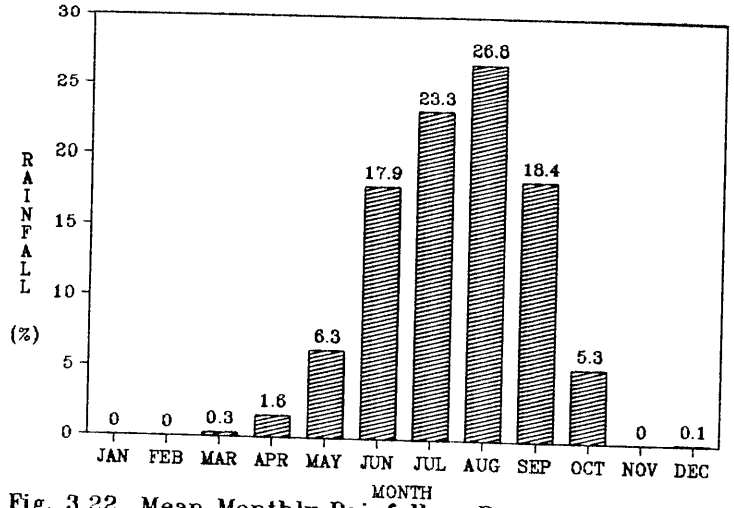


Fig. 3.22 Mean Monthly Rainfall as Percentage of the Mean Annual (Ed Damazin 1941-92)

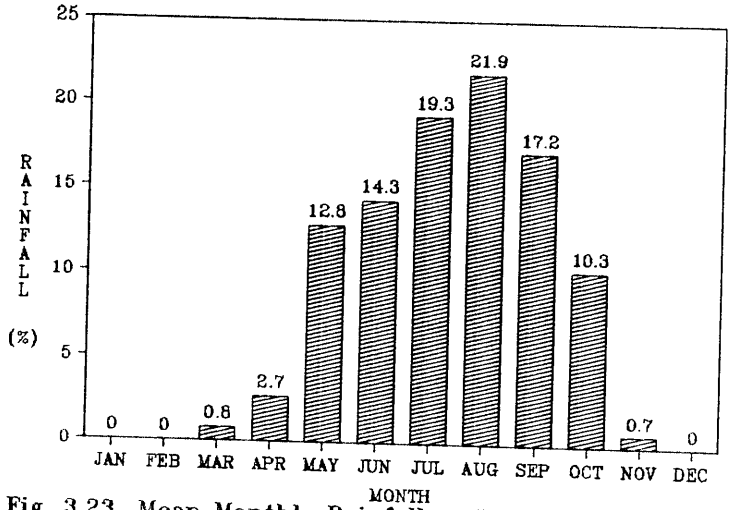


Fig. 3.23 Mean Monthly Rainfall as Percentage of the Mean Annual (Malakal 1941-92)

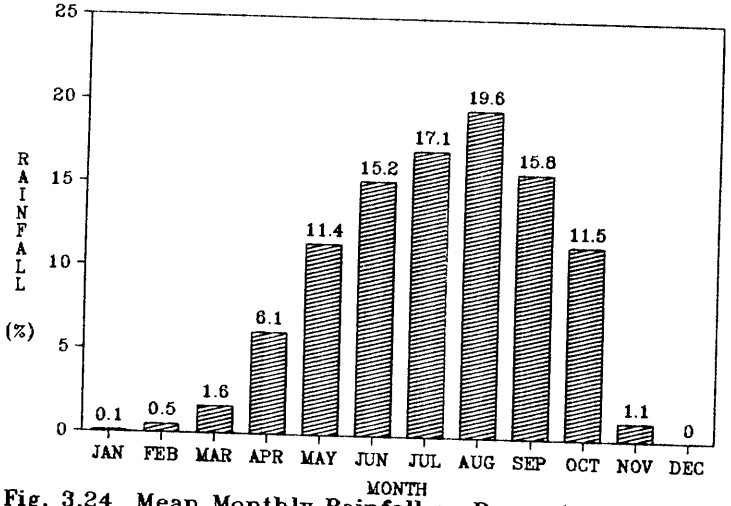


Fig. 3.24 Mean Monthly Rainfall as Percentage of the Mean Annual (Wau 1941-88)

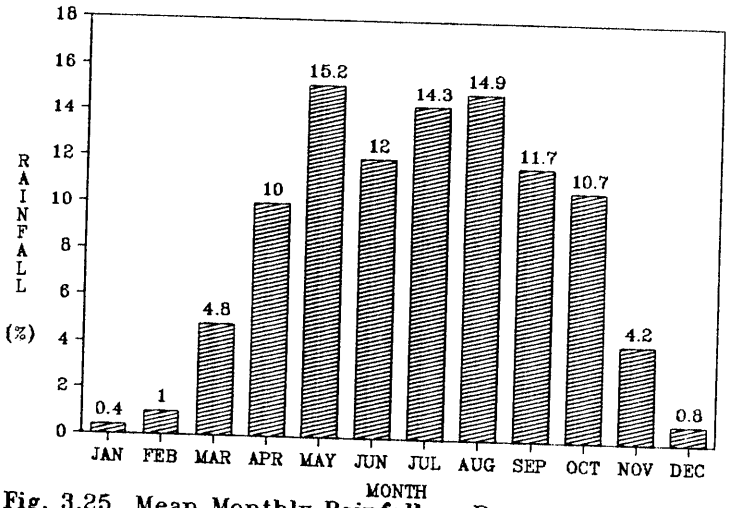


Fig. 3.25 Mean Monthly Rainfall as Percentage of the Mean Annual (Juba 1941-91)

3.2.3 Rainy Season

The method due to Bagnols and Gaussen [21] is used to define the dry period of the year. Gaussen defined the dry month as the month for which the mean rainfall, measured in millimetres, is less than or equal to twice the mean temperature in °C, i.e.

$$P \leq 2\,t \tag{3.1}$$

It follows that $P/t \leq 2$ indicates a dry month, whereas $P/t > 2$ indicates a wet month. This method is used in the study for Eastern-Sudan [19]. It is worthwhile to identify the rainy season for the whole country. Thus, the P/t values have been calculated based on monthly mean records as well as the records for the particular drought year of 1984. Results of mean records have shown that P/t correlates linearly with P as:

$$P/t = -0.0429 + 0.0371\,P \qquad r = 0.999 \tag{3.2}$$

Eq. (3.2) shows, by substituting $P/t \leq 2$, that any month for which $P \leq 55$ mm can be defined as dry, otherwise ($P > 55$ mm) it is considered wet. Accordingly, Table 3.1 is constructed to determine the wet period of the year or rainy season which generally spans for 0-7 months from Port Sudan to Juba. The disastrous effect of drought on the the rainy season of the year 1984 will be discussed later in Chapter 7.

Table 3.1 Average and 1984 Spans of Rainy Season

Station	Average		1984	
	Length (Months)	Period	Length (Months)	Period
Port Sudan	0	-	0	-
Khartoum	1	Aug	0	-
Kassala	2	Jul-Aug	0	-
Wad Medani	2	Jul-Aug	1	Sep
El Gedaref	4	Jun-Sep	2	Jul, Sep
El Fasher	2	Jul-Aug	0	-
El Obeid	3	Jul-Sep	2	Jul, Sep
Nyala	3	Jul-Sep	1	Jul
Ed Damazin	4	Jun-Sep	3	Jul-Sep
Malakal	6	May-Oct	5	May-Aug, Oct
Wau	7	Apr-Oct	5	May-Sep
Juba	7	Apr-Oct	6	Apr-Sep

3.3 Extremes

Extreme values of rainfall are very valuable for the design of hydraulic structures, sewerages and drainage systems.

3.3.1 Maximum Rainfall Recorded in One Day

The daily rainfall is extremely important for runoff calculations. The highest rainfall recorded in one day at the twelve stations during the period 1951 to 1990 are presented in Figs. 3.26 to 3.37. These figures reveal that the stations recorded their absolute maxima in 24 hours in the range of 96.7 to 200.3 mm. The lower and upper limits were recorded in El Obeid and Khartoum respectively.

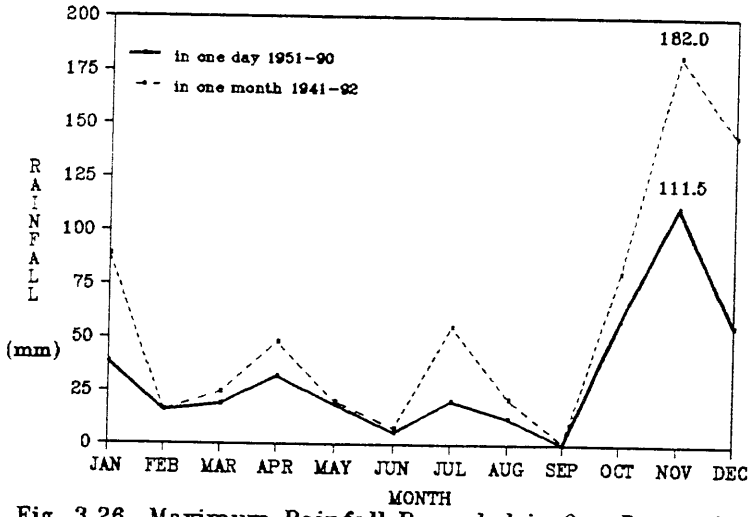


Fig. 3.26 Maximum Rainfall Recorded in One Day and in One Month (Port Sudan)

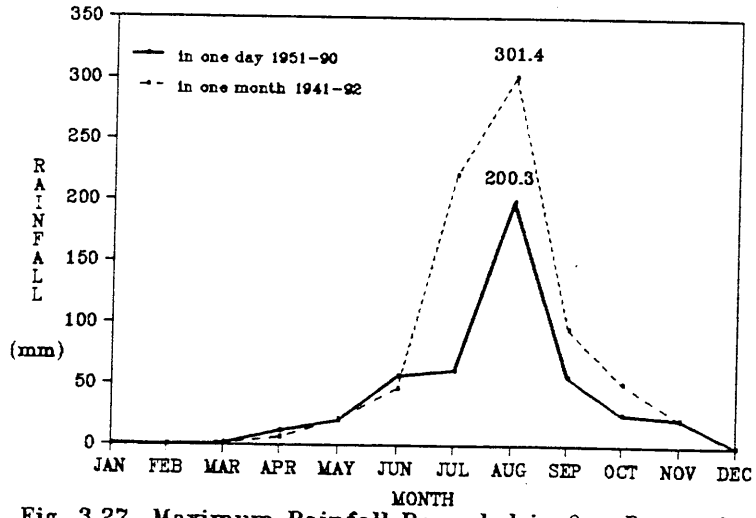


Fig. 3.27 Maximum Rainfall Recorded in One Day and in One Month (Khartoum)

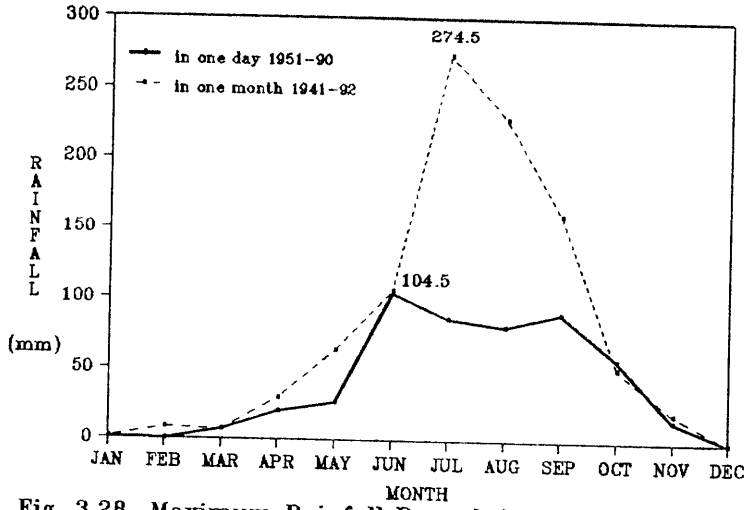


Fig. 3.28 Maximum Rainfall Recorded in One Day and in One Month (Kassala)

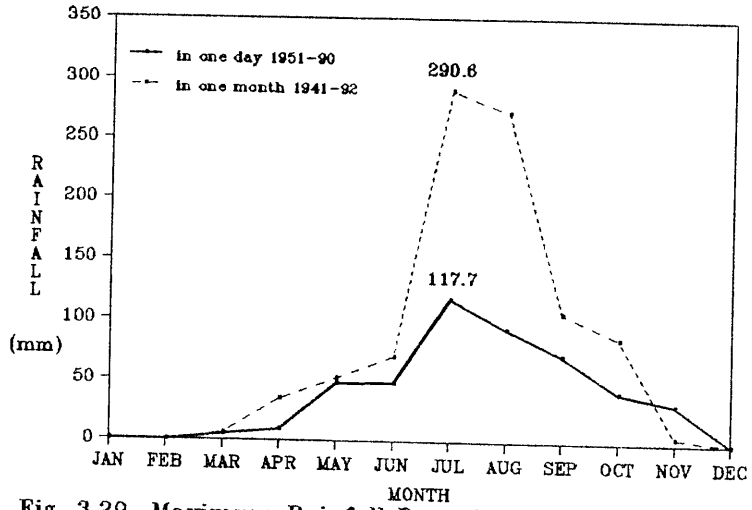


Fig. 3.29 Maximum Rainfall Recorded in One Day and in One Month (Wad Medani)

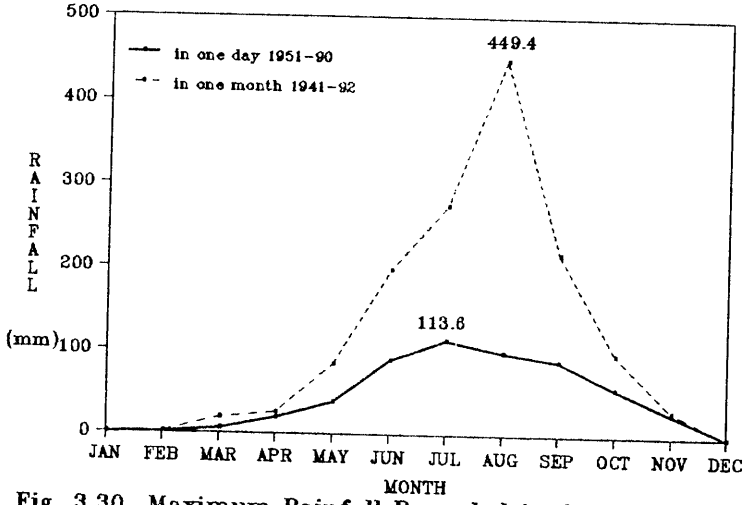


Fig. 3.30 Maximum Rainfall Recorded in One Day and in One Month (El Gedaref)

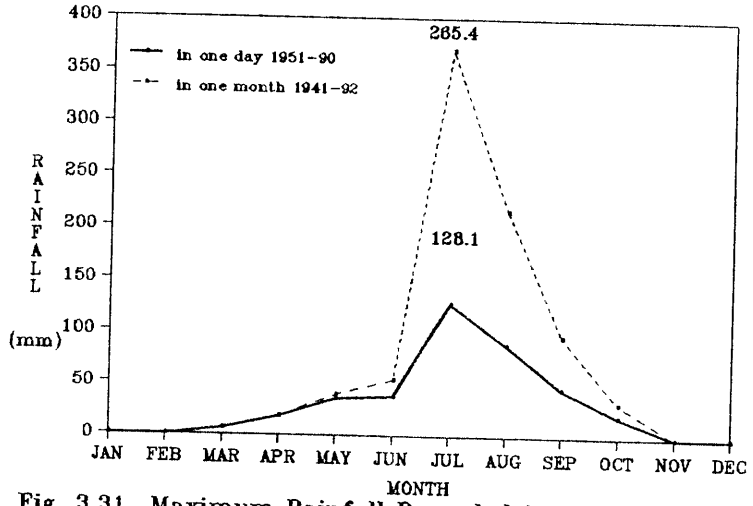


Fig. 3.31 Maximum Rainfall Recorded in One Day and in One Month (El Fasher)

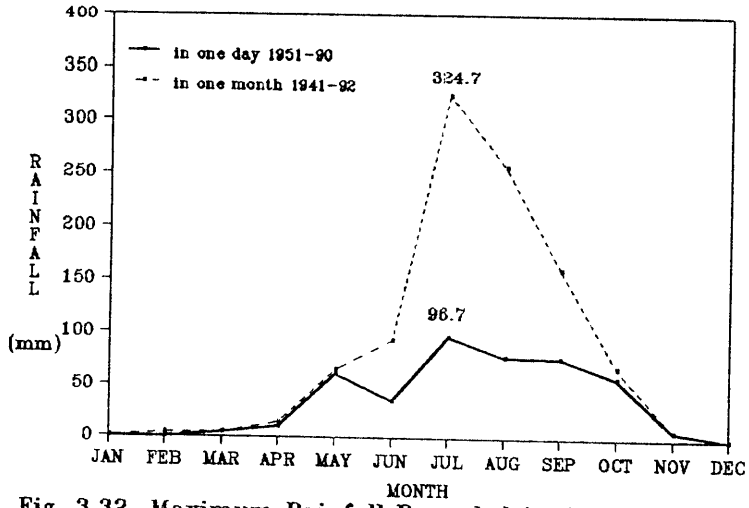


Fig. 3.32 Maximum Rainfall Recorded in One Day and in One Month (El Obeid)

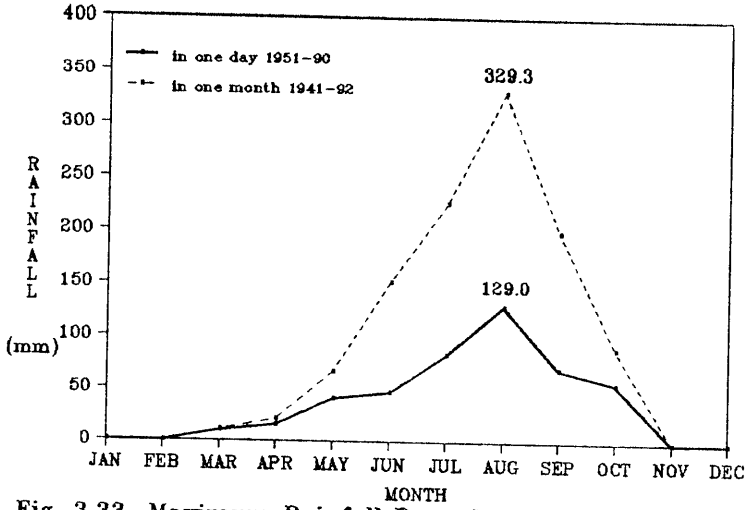


Fig. 3.33 Maximum Rainfall Recorded in One Day and in One Month (Nyala)

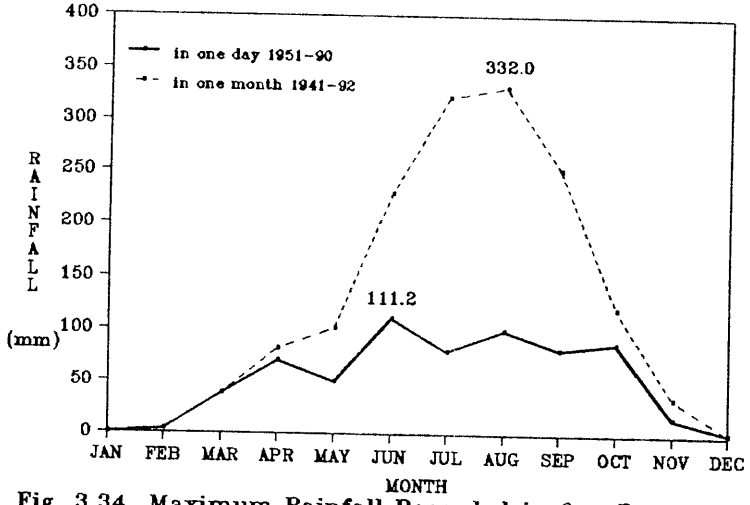


Fig. 3.34 Maximum Rainfall Recorded in One Day and in One Month (Ed Damazin)

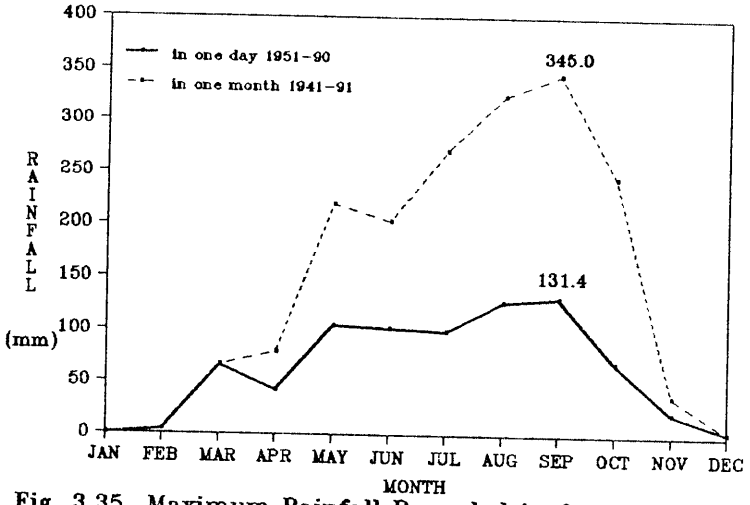


Fig. 3.35 Maximum Rainfall Recorded in One Day and in One Month (Malakal)

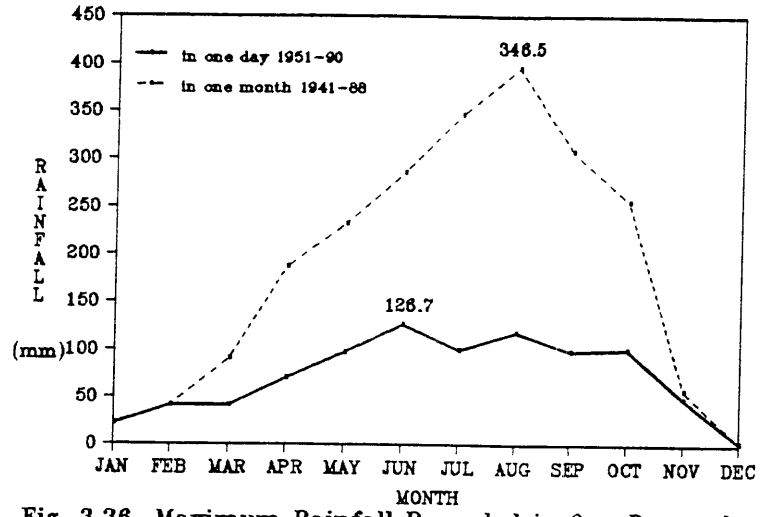


Fig. 3.36 Maximum Rainfall Recorded in One Day and in One Month (Wau)

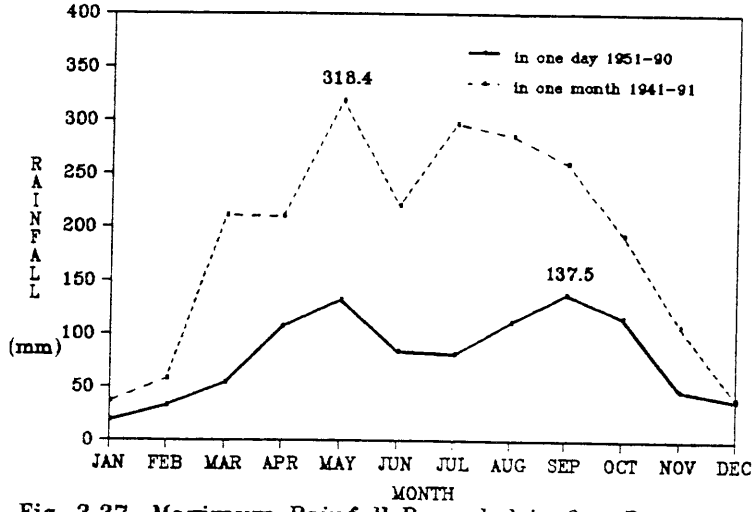


Fig. 3.37 Maximum Rainfall Recorded in One Day and in One Month (Juba)

3.3.2 Maximum Rainfall Recorded in One Month

Figs. 3.26 to 3.37 also present the highest monthly rainfall recorded at the stations during the entire period (1941-92). The maximum rainfall ever recorded during the period ranges between 182.0 mm (observed for Port Sudan) and 449.4 mm (obtained for El Gedaref).

3.4 Annual Rainfall

A brief look at the annual rainfall series plotted in Figs. 3.38 to 3.49 makes it possible to observe the most dominating characteristic of rainfall, which is the tendency to fluctuate significantly from year to year. Such a situation is a typical characteristic of arid regions. The highest and lowest records between which these

widespread irregularities occur are given in the figures. indicating that annual rainfalls lie between 0 and 1488.1 mm in the study areas. These two extremes were recorded in Port Sudan and Wau respectively. Nine of the twelve stations received their lowest rainfall amounts between 1980 and 1990. About half or more of the annual rainfall records were well below the mean. A few exceptionally very wet years did occur in the last decade as in the case of 1988.

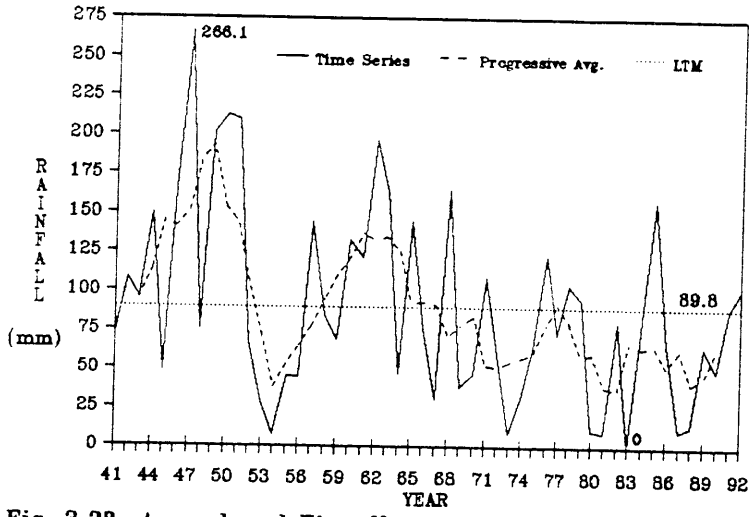


Fig. 3.38 Annual and Five-Year Moving Average Rainfalls (Port Sudan)

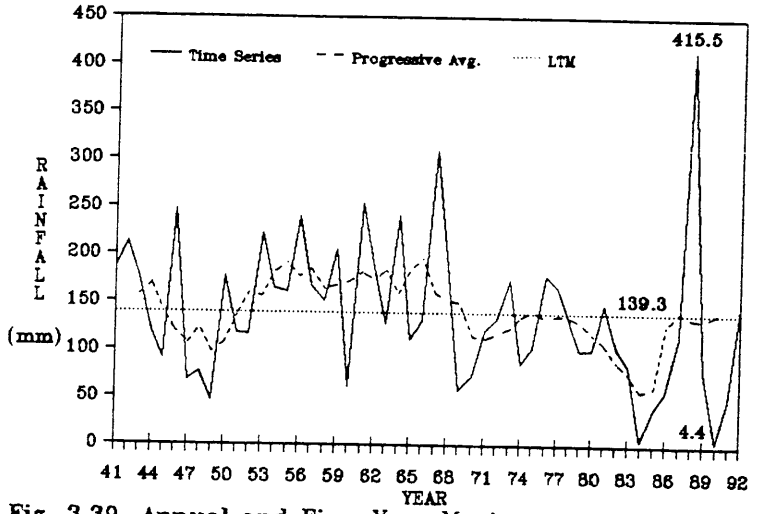


Fig. 3.39 Annual and Five-Year Moving Average Rainfalls (Khartoum)

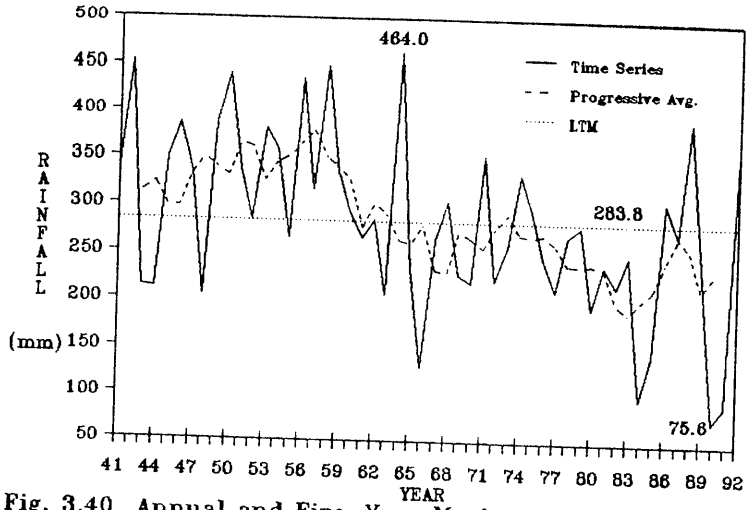


Fig. 3.40 Annual and Five-Year Moving Average Rainfalls (Kassala)

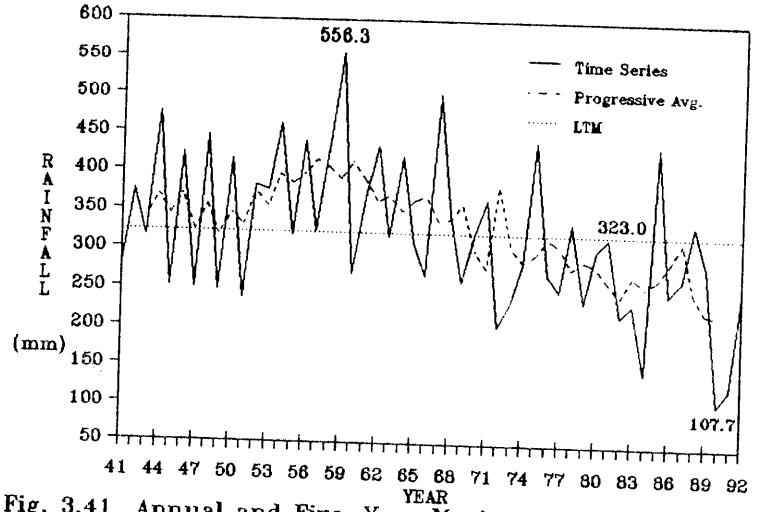


Fig. 3.41 Annual and Five-Year Moving Average Rainfalls (Wad Medani)

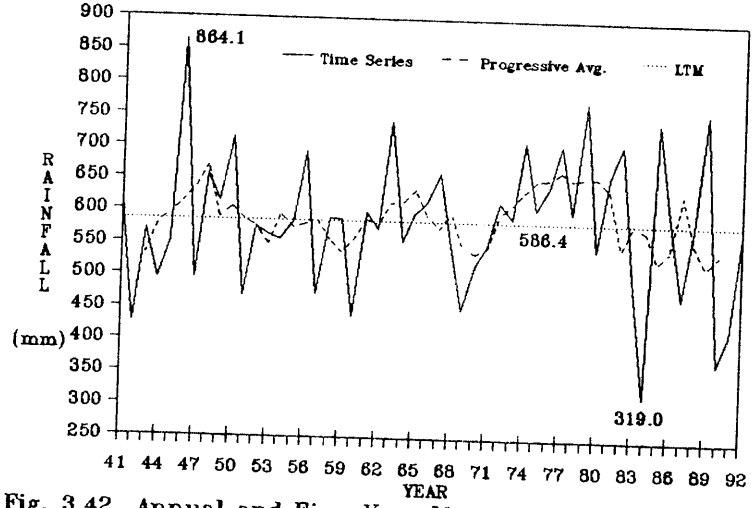


Fig. 3.42 Annual and Five-Year Moving Average Rainfalls (El Gedaref)

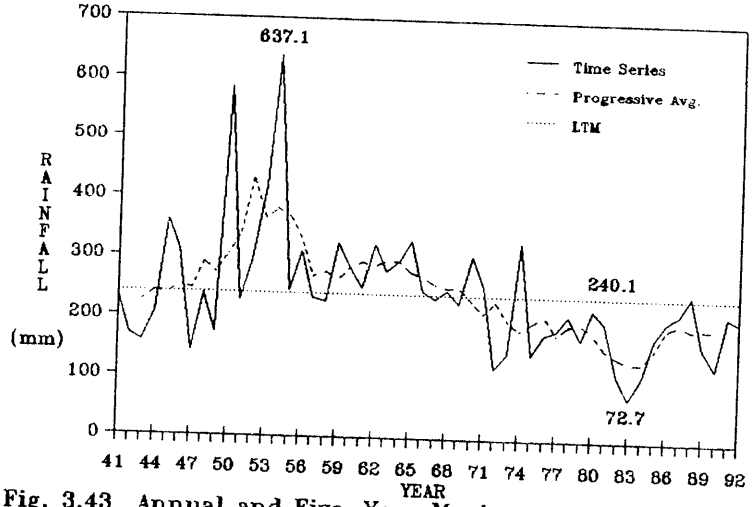


Fig. 3.43 Annual and Five-Year Moving Average Rainfalls (El Fasher)

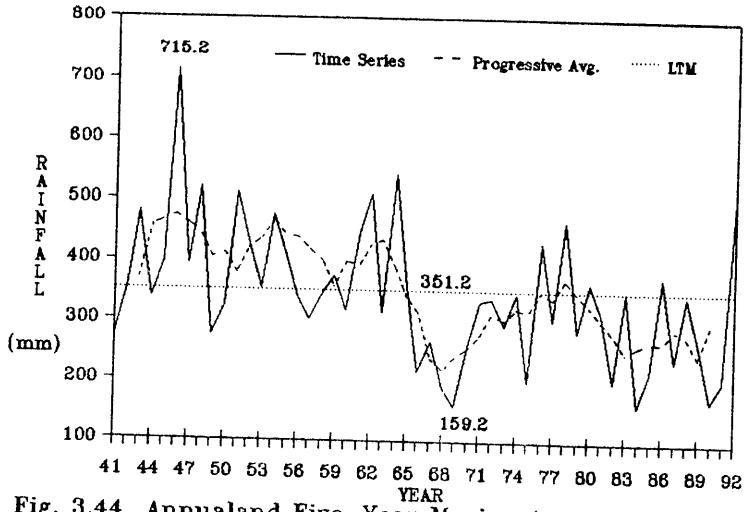


Fig. 3.44 Annualand Five-Year Moving Average Rainfalls (El Obeid)

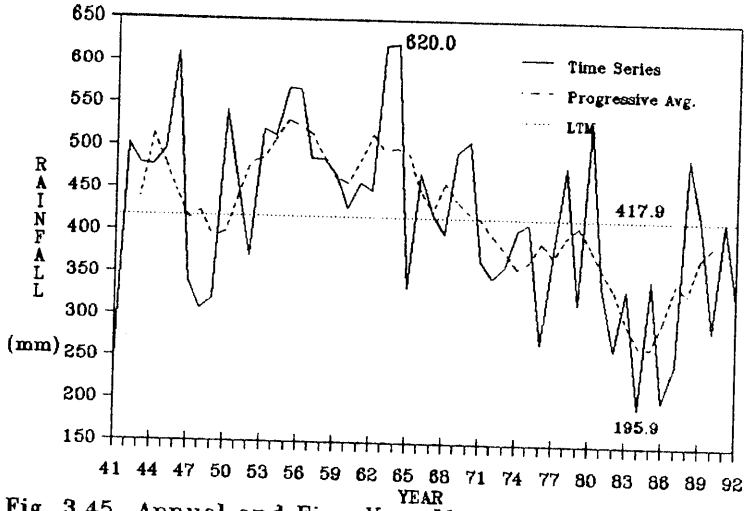


Fig. 3.45 Annual and Five-Year Moving Average Rainfalls (Nyala)

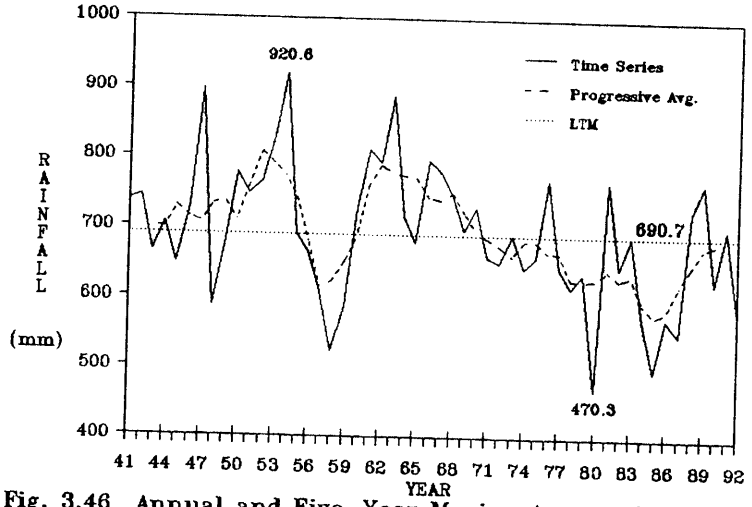


Fig. 3.46 Annual and Five-Year Moving Average Rainfalls (Ed Damazin)

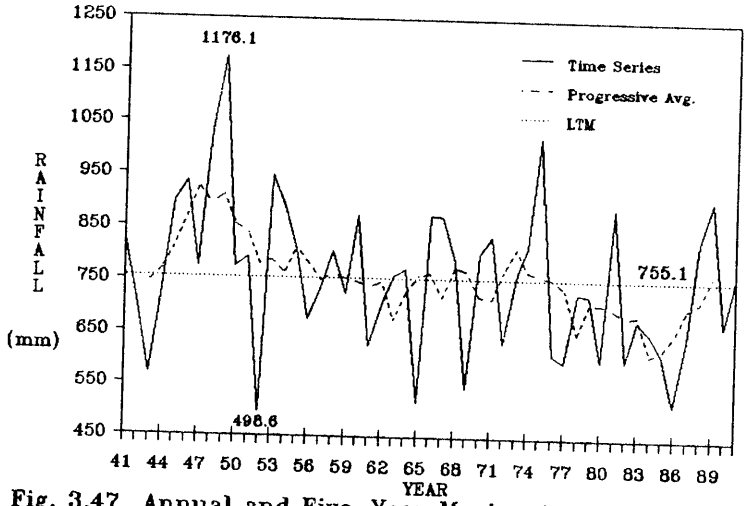


Fig. 3.47 Annual and Five-Year Moving Average Rainfalls (Malakal)

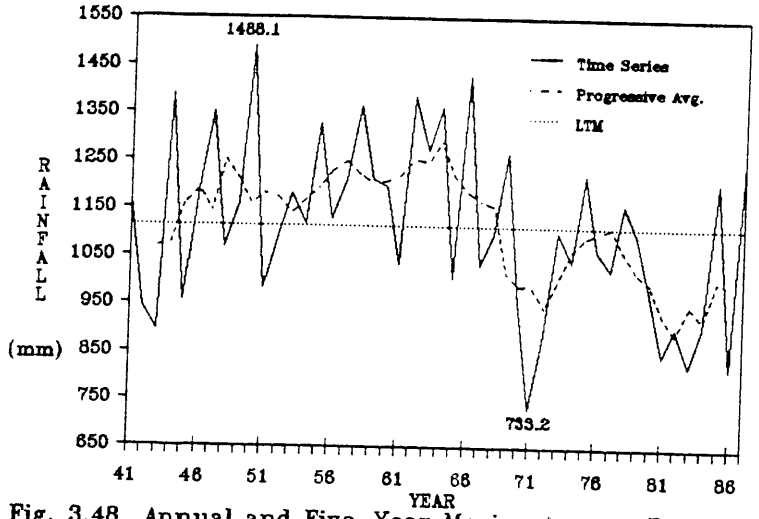


Fig. 3.48 Annual and Five-Year Moving Average Rainfalls (Wau)

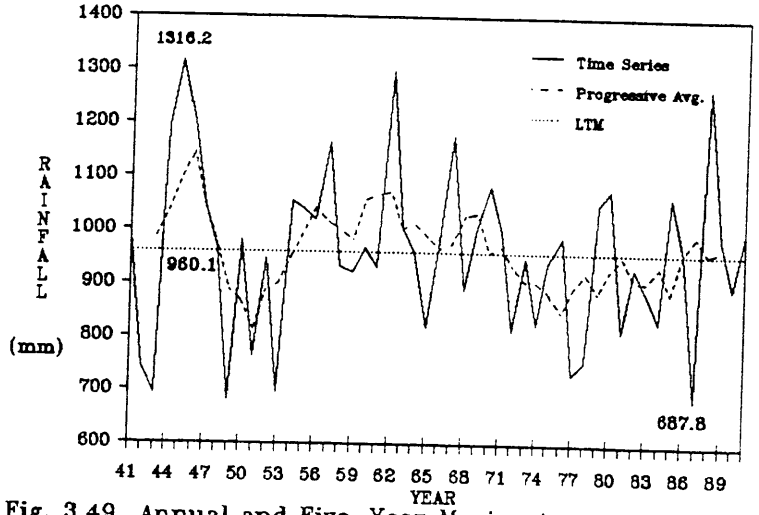


Fig. 3.49 Annual and Five-Year Moving Average Rainfalls (Juba)

3.4.1 Long Term Mean and Normal Annual Rainfalls

The main concern in investigating the available annual rainfall records over a period of 30 years and long term period of 50 or 52 years is to make some observations about the rainfall behaviour by applying statistical measures as mean, standard deviation and coefficient of variation. It is also interesting to discover any possible trend, representing an increasing or decreasing behaviours in the parameter. The statistical characteristics of the two data periods were computed by a specially developed program (see Appendix) and are given in Table 3.2.

Table 3.2 Characteristics of Long Term Mean, Normal and 1984 Annual Rainfalls

Station	Long Term					Normal					1984
	Period	μ (mm)	σ (mm)	Cv (%)	TR (mm/Yr)	Period	μ (mm)	σ (mm)	Cv (%)	TR (mm/Yr)	Annual (mm)
Port Sudan	1941-92	89.8	61.4	68.4	– 1.558	1963-92	70.7	47.3	66.9	– 1.174	83.0
Khartoum	"	139.3	75.9	54.5	– 1.182	"	126.4	82.9	65.6	– 2.359	4.7
Kassala	"	283.8	91.4	32.2	– 2.820	"	247.3	85.7	34.7	– 2.029	98.8
Wad Medani	"	323.0	95.9	29.7	– 2.830	"	289.8	88.4	30.5	– 4.736	147.2
El Gedaref	"	586.4	105.4	18.0	– 0.142	"	592.5	111.3	18.8	– 2.596	319.0
El Fasher	"	240.1	102.4	42.6	– 2.776	"	204.4	65.2	31.9	– 3.945	107.5
El Obeid	"	351.2	120.1	34.2	– 3.409	"	301.4	98.7	32.7	– 0.884	161.7
Nyala	"	417.9	105.4	25.2	– 2.944	"	388.0	106.0	27.3	– 6.212	195.9
Ed Damazin	"	690.7	94.0	13.6	– 2.336	"	672.6	89.7	13.3	– 5.195	571.7
Malakal	1941-91	755.1	140.2	18.6	– 2.793	1962-91	723.4	123.2	17.0	– 1.988	654.1
Wau *	1941-87	1114.7	176.4	15.8	– 4.203	1958-87	1091.4	181.1	16.6	– 10.233	908.3
Juba	1941-91	960.1	154.0	16.0	– 0.785	1962-91	957.2	140.7	14.7	– 2.801	832.2

* Because of the civil war , the observations could not be taken after 1987.

In the light of the informations given in Table 3.2, it is fair to say that rainfall at all the locations exhibits a typical pattern of drastic downward trend. General dry episodes have prevailed since the beginning of the 1960s. The rainfall decrease observed since then in the regions operates at a rate of 0.884 mm per year, as noticed for El Obeid, to 10.233 mm per year, as noticed for Wau. By viewing the long term mean and normal annual rainfalls, it is generally seen that the latter has lower values than the former by an amount ranging between 2.9 mm in Juba and 49.8 mm in El Obeid, which reinforces the point discussed above for rainfall decay. This drop in the annual rainfall series appears to be part of a global trend throughout the arid and semi-arid regions [16-19]. One point is worth mentioning that the situation is reversed in El Gedaref where the normal value is higher than the LTM by 6.1 mm due to the short term effect of the wet spell during the 1970s.

With respect to the distribution of mean annual rainfall over Sudan, the rainfall increases from north to extreme south or south-west. For instance, Port Sudan receives 89.8 mm per year on average, whereas 1114.7 mm per annum falls in Wau as average rainfall. Interesting correlations have been established between the various statistical parameters. The standard deviation is found to increase linearly with increasing mean annual rainfall. On the other hand, the coefficient of variation is found to decrease with increasing mean annual rainfall. The relationships are obtained as follows:

$$\sigma = 65.768 + 0.0896\,\mu \qquad r = 0.893 \qquad (3.3)$$

$$C_V = 1383.9\,\mu^{-0.659} \qquad r = -0.966 \qquad (3.4)$$

(Long term)

$$\sigma = 56.183 + 0.0964\,\mu \qquad r = 0.908 \qquad (3.5)$$

$$C_v = 1045.6\,\mu^{-0.623} \qquad r = -0.959 \qquad (3.6)$$

(Normal)

General σ-μ and C_v-μ relationships has been developed by incorporating long term and normal data as:

$$\sigma = 60.725 + 0.0934\ \mu \qquad r = 0.897 \tag{3.7}$$

$$C_v = 1174.5\ \mu^{-0.637} \qquad r = -0.960 \tag{3.8}$$

The correlations given in Eqs. (3.7) and (3.8) are presented in Figs. 3.50 and 3.51 respectively.

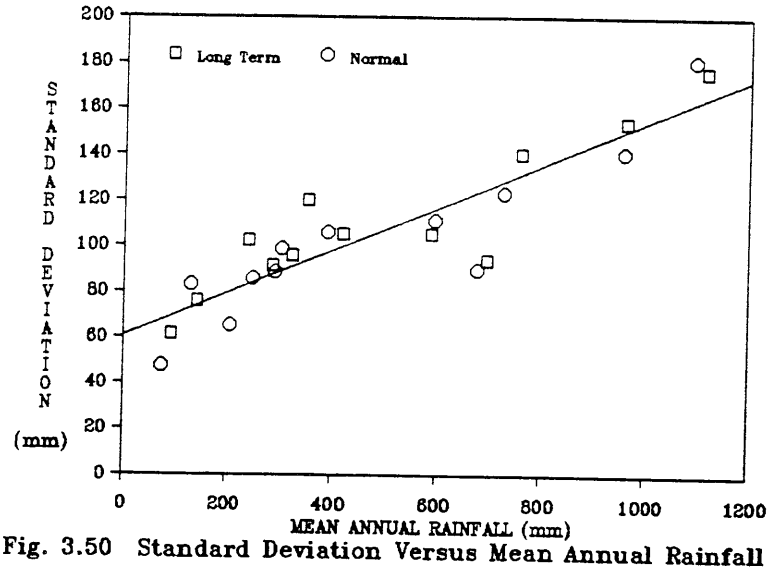


Fig. 3.50 Standard Deviation Versus Mean Annual Rainfall

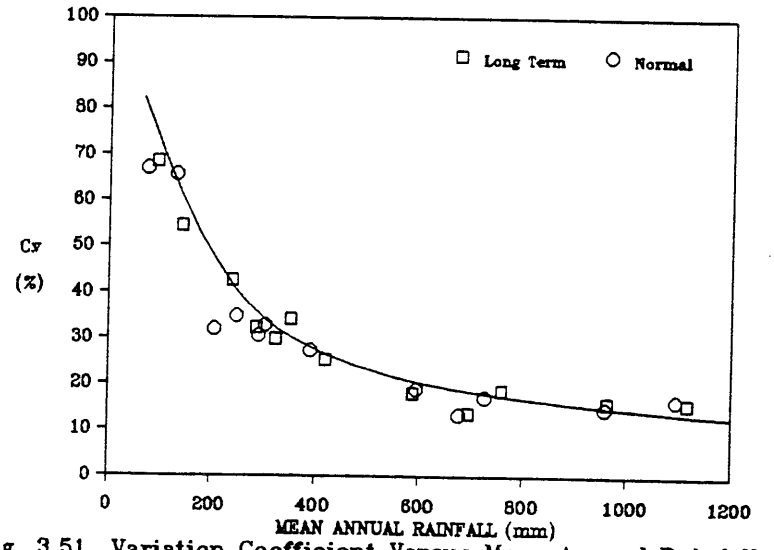


Fig. 3.51 Variation Coefficient Versus Mean Annual Rainfall

3.4.2 Trend from Progressive Averages

Determination of a possible trend is very essential in the analysis of hydrological parameters. Applying moving averages to the data is a simple statistical technique which is used for this purpose where the wide variation of the particular years is smoothed out [7, 22]. The long term data for the regions have been examined by calculating the five-year moving averages, the results of which are shown graphically as time series in Figs. 3.38 to 3.49. These trends easily identify the accelerating pace of change in rainfall patterns in the regions, i.e. the very dry phases following the wet features of the 1940s and 1950s. A wet year is defined as a year in which the total rainfall exceeds the mean of the series by an amount which is a function of the standard deviation [23].

3.4.3 Classification of Annual Rainfall

It is of interest to classify the highest and lowest records among the long term data of annual rainfall as has been done in Chapter 2 on Temperature. Table 3.3 categorizes these extremes. The highest rainfall observations for Kassala and Nyala are classified as above normal. Those for Khartoum, El Fasher and El Obeid are classified as extremely above normal and the rest fall in between these two classes, i.e. greatly above normal. Regarding the lowest annual rainfall records, they fall within three classes, viz. normal, sub-normal and greatly sub-normal; included in the first class are the records obtained for El Fasher, in the second class the records for Port Sudan, Khartoum, El Obeid, Malakal and Juba, and in the last class the records obtained for the remaining six stations. These classifications clearly indicate the wide variations among the annual rainfall data.

Table 3.3 Classification of the Highest and Lowest Annual Rainfall Departures from the Long Term Mean

Station	Highest				Lowest			
	Rainfall (mm)	Deviation (mm)	z-score	Classi-fication	Rainfall (mm)	Deviation (mm)	z-score	Classi-fication
Port Sudan	266.1	176.3	2.87	GA	0.0	– 89.8	– 1.46	S
Khartoum	415.5	276.2	3.64	EA	4.4	– 134.9	– 1.78	S
Kassala	464.0	180.2	1.97	A	75.6	– 208.2	– 2.28	GS
Wad Medani	556.3	233.3	2.43	GA	107.7	– 215.3	– 2.25	GS
El Gedaref	864.1	277.7	2.63	GA	319.0	– 267.4	– 2.54	GS
El Fasher	637.1	397.0	3.88	EA	72.7	– 167.4	– 0.71	N
El Obeid	715.2	364.0	3.03	EA	159.2	– 192.0	– 1.60	S
Nyala	620.0	202.1	1.92	A	195.9	– 222.0	– 2.11	GS
Ed Damazin	920.6	229.9	2.45	GA	470.3	– 220.4	– 2.34	GS
Malakal	1176.1	421.0	3.00	GA	498.6	– 256.5	– 1.83	S
Wau	1488.1	373.4	2.12	GA	733.2	– 381.5	– 2.16	GS
Juba	1316.2	356.1	2.31	GA	687.8	– 272.3	– 1.77	S

3.4.4 Annual Rainfall Frequency Distribution

The determination of a representative pattern of annual rainfall frequency requires the use of as many years of measurements as possible. The number of classes to be selected must be between 15-20 classes [8].

The whole bulk quantities of rainfall records (52 years) for the regions were subjected to frequency analysis. Class widths of 15, 25, 30 and 40 mm were chosen to give the required number of classes. The patterns of occurrence of rainfall quantities for the year are displayed in Figs. 3.52 through 3.63 as histograms. In the figures, the frequencies are plotted against the class marks. The range, the modal class, the estimated mode and the percentage of modal class (PMC is the relative frequency of the modal class expressed as percentage) are provided in the figures as well. It can be noticed from the figures that considerable difference in the pattern of occurrence is experienced in the different climatic zones, but generally the maximum frequency of occurrence tends to shift close to the middle of the range of the values and the pattern approximately approaches the characteristic shape of the normal distribution as the mean annual rainfall increases.

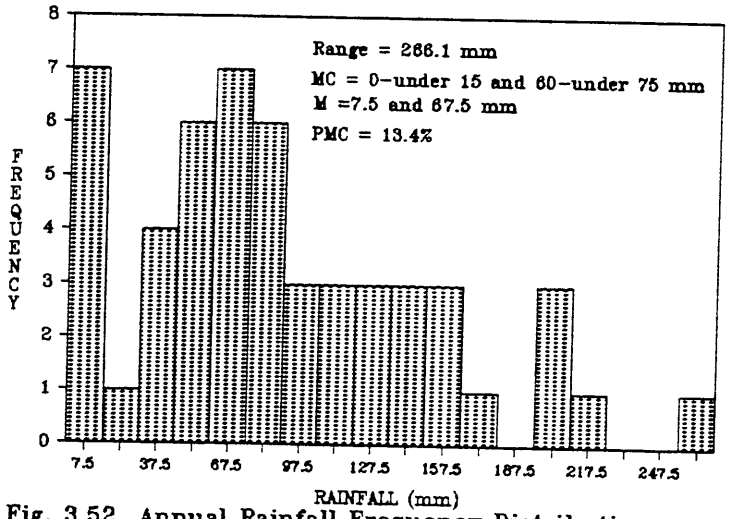


Fig. 3.52 Annual Rainfall Frequency Distribution (Port Sudan 1941-92)

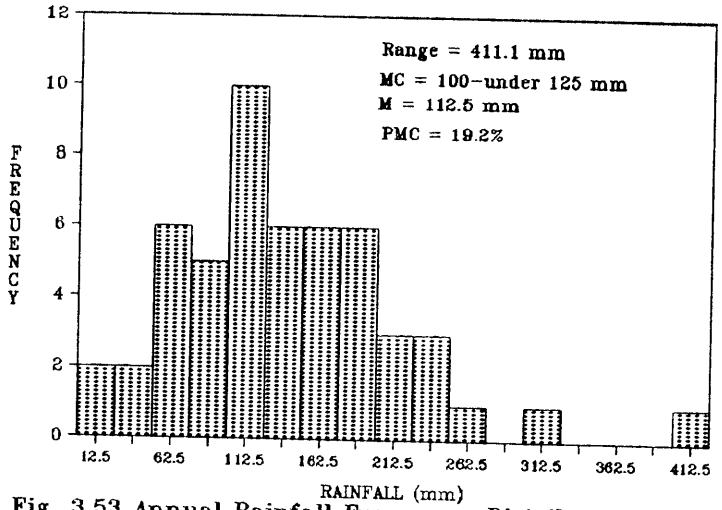


Fig. 3.53 Annual Rainfall Frequency Distribution (Khartoum 1941-92)

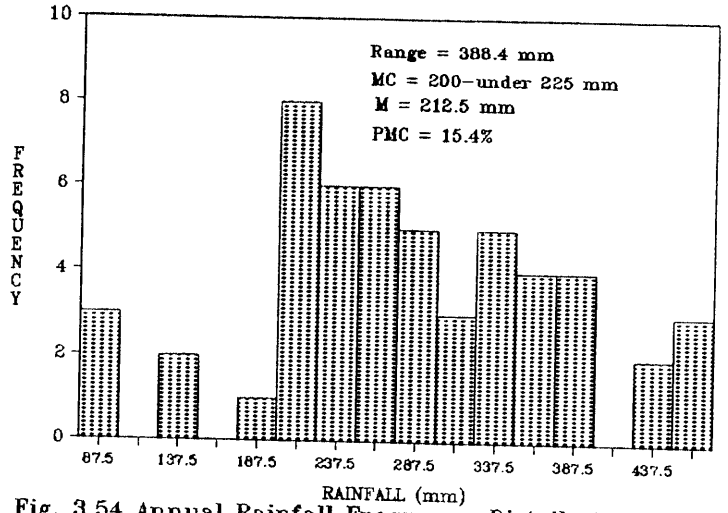


Fig. 3.54 Annual Rainfall Frequency Distribution (Kassala 1941-92)

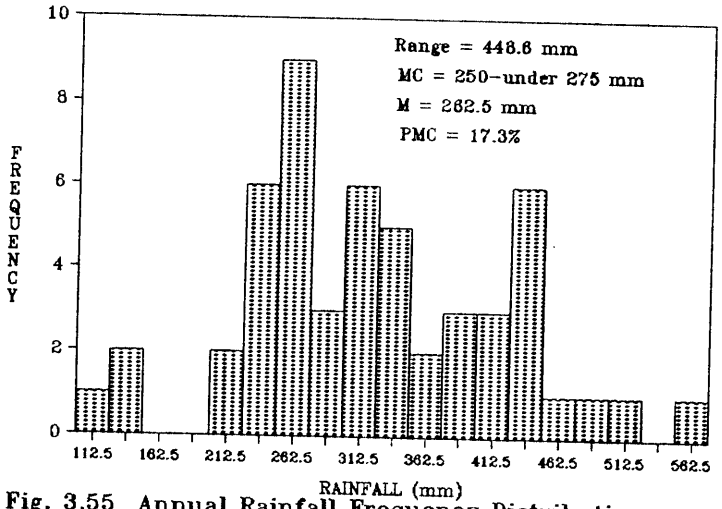


Fig. 3.55 Annual Rainfall Frequency Distribution (Wad Medani 1941-92)

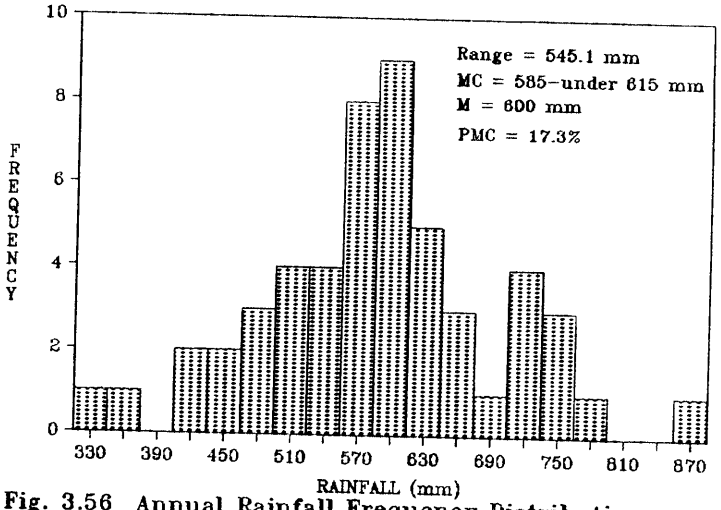


Fig. 3.56 Annual Rainfall Frequency Distribution (El Gedaref 1941-92)

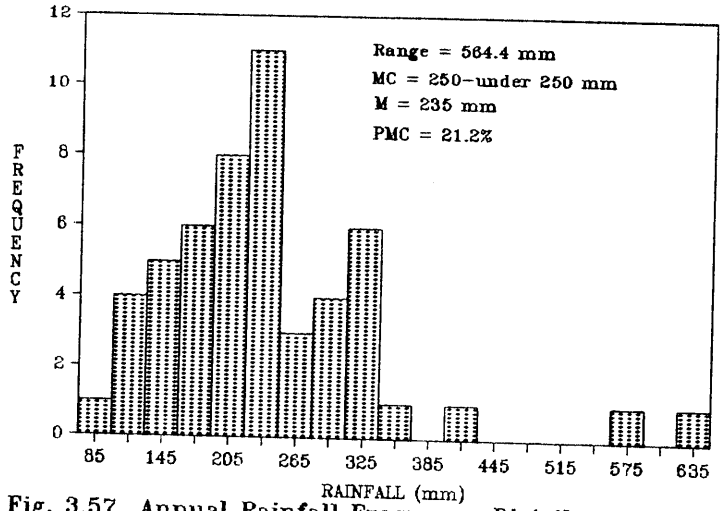


Fig. 3.57 Annual Rainfall Frequency Distribution (El Fasher 1941-92)

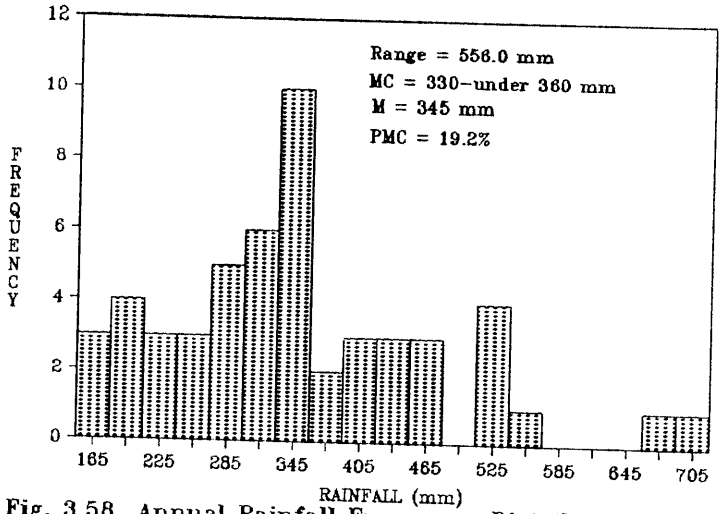


Fig. 3.58 Annual Rainfall Frequency Distribution (El Obeid 1941-92)

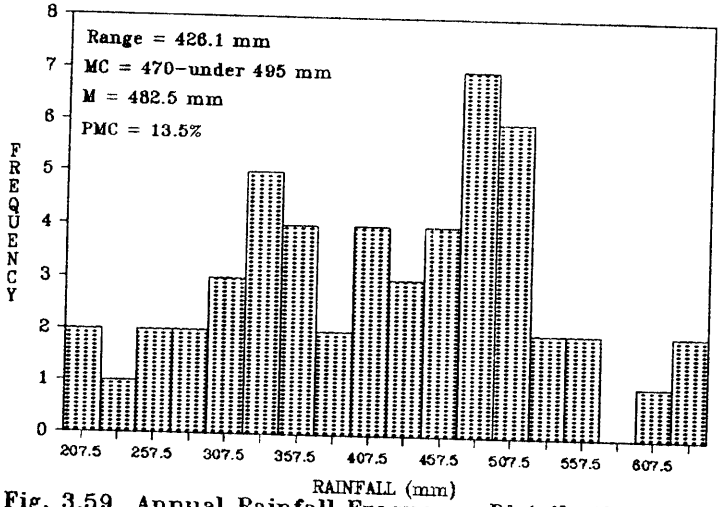


Fig. 3.59 Annual Rainfall Frequency Distribution (Nyala 1941-92)

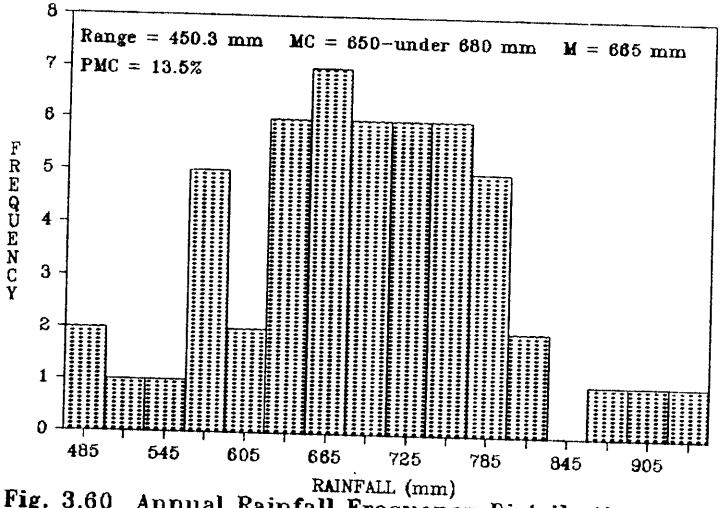


Fig. 3.60 Annual Rainfall Frequency Distribution (Ed Damazin 1941-92)

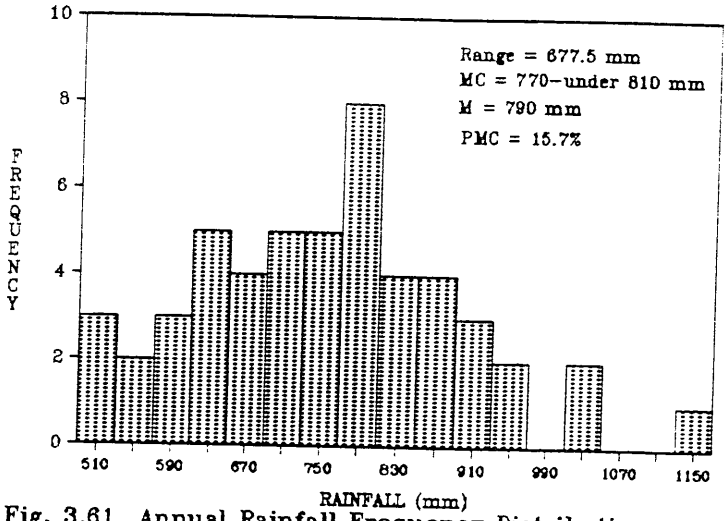


Fig. 3.61 Annual Rainfall Frequency Distribution (Malakal 1941–91)

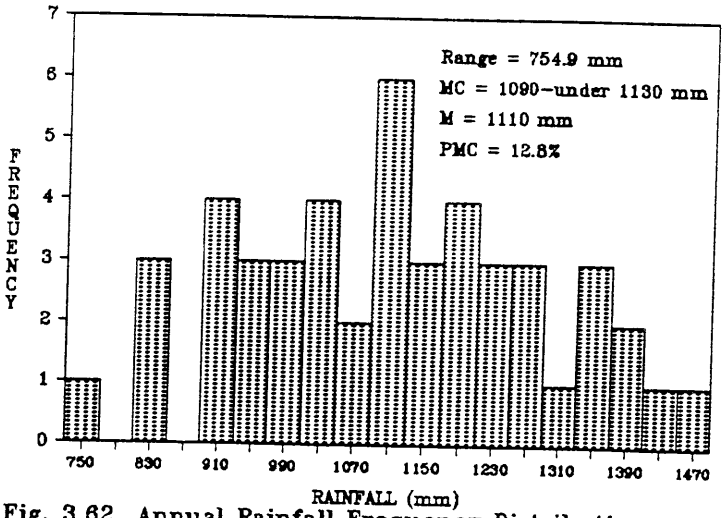


Fig. 3.62 Annual Rainfall Frequency Distribution (Wau 1941–87)

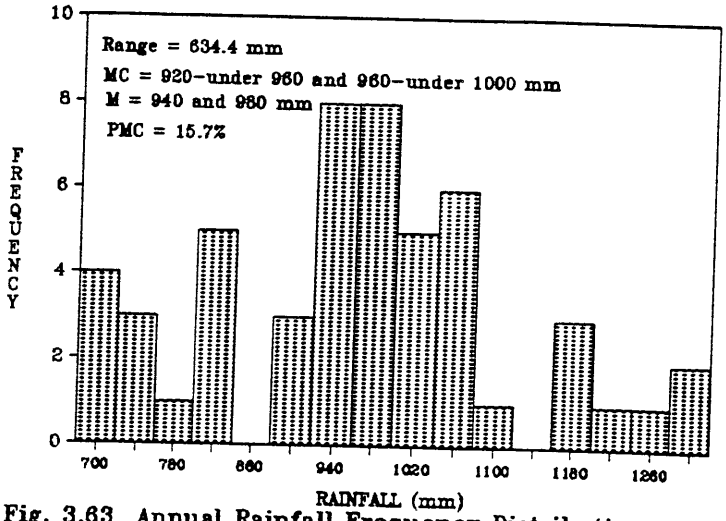


Fig. 3.63 Annual Rainfall Frequency Distribution (Juba 1941–91)

The widest annual rainfall range (754.9 mm) is observed for Wau and the narrowest range (266.1 mm) is obseved for Port Sudan. For about 37 mm mean annual rainfall or more, the estimated modal annual rainfall is well correlated with the long term mean (Fig. 3.64). The following relationship has been obtained:

$$M = -38.818 + 1.050\,\mu \qquad r = 0.995 \qquad (3.9)$$

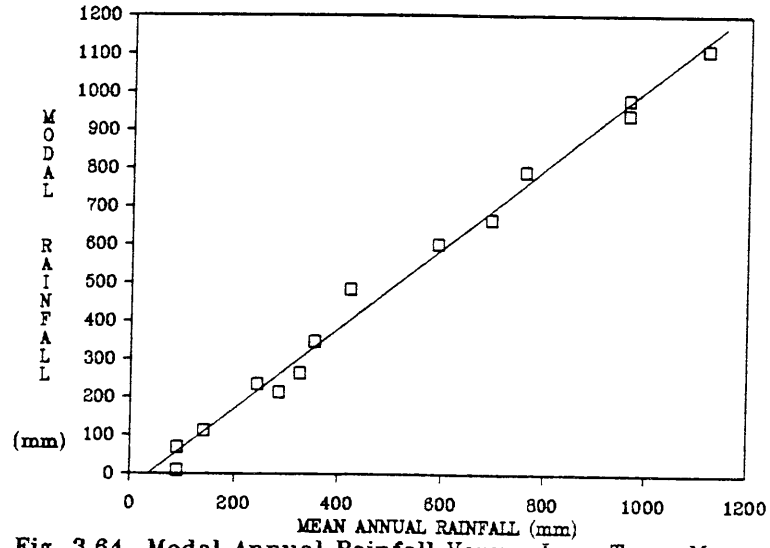


Fig. 3.64 Modal Annual Rainfall Versus Long Term Mean

3.4.5 Probability Analysis of Annual Rainfall

The design of any hydraulic structure or the evaluation of water resources potential would be based on average probabilities. Frequency analysis can be very useful in the interpretation and assessment of future events and the consequences of their occurrence in specific time [7, 8].

Data series selected for probability analysis must be relevant, adequate and accurate [6]. Given proper records, statistical methods can be used to extend the available data and hence predict the likely frequency of occurrence or expect certain magnitudes of events of every specific time period [7].

Figs. 3.52 to 3.63 which present the frequency distribution of annual rainfall can also be used to give the probability of having a certain amount of rainfall within a given rainfall class by computing the percentage of cases in this class. For example, the probability of certain quantity of rainfall to occur within the modal class, denoted in the figures by PMC, ranges between 12.8 to 21.2%. It is assumed that most series of hydrological elements are normally distributed and their frequency functions can be generalized to [6, 7, 22]:

$$X = \mu + z\,\sigma \qquad (3.10)$$

where X = magnitude of hydrological element of specified probability

The magnitude of the N-year event can be determined either by plotting the variable against return period or probability on a log-normal paper or by calculation using Eq. (3.10) if the characteristic parameters of normal curve μ and σ are available [7]. The z value or z-score corresponding to the specific probability (area under standard normal curve) is taken from any standard statistical text. The return period of a given event or the recurrence interval, T_r, is defined as the average interval in years within which this event will be equalled or exceeded [6, 22]. In mathematical form, it is defined as the reciprocal of the probability, given by [6]:

$$T_r = 1/\Pr \tag{3.11}$$

where the probability Pr is expressed as ratio.

Accordingly, the specific rainfall in millimetres expected with 1.25, 10 and 50-year return periods were computed based on the 52-year data. These quantities associated with 80, 10 and 2% probabilities respectively are presented in Table 3.4.

Table 3.4 Amount of Rainfall in mm Expected to be Equalled or Exceeded within Different Return Periods

Station	Return Period (Yrs)		
	1.25	10	50
Port Sudan	38.2	168.4	215.7
Khartoum	75.5	236.5	294.9
Kassala	207.2	400.8	471.2
Wad Medani	242.4	445.8	519.6
El Gedaref	497.9	721.3	802.5
El Fasher	154.1	371.2	450.0
El Obeid	250.3	504.9	597.4
Nyala	329.4	552.8	634.0
Ed Damazin	611.7	811.0	883.4
Malakal	637.3	934.6	1042.5
Wau	966.5	1340.5	1476.3
Juba	830.7	1157.2	1275.8

Three relationships between the expected amount of rainfall and the mean value of the data set are derived for the three respective return periods as:

$$RF = -55.257 + 0.925\,\mu \qquad r = 0.999 \tag{3.12}$$

$$RF = 84.204 + 1.115\ \mu \qquad r = 0.997 \qquad (3.13)$$

$$RF = 134.844 + 1.184\ \mu \qquad r = 0.997 \qquad (3.14)$$

In Sudan, the rainfall expected with 80% probability is usually taken as suitable for planning purposes [3]. Eqs. (3.12) to (3.14) are represented in Fig. 3.65. Obviously, the relationship of Eq. (3.12) is valid only for places with mean annual rainfall of greater than or equal to 60 mm. Eq. (3.12) closely compares with that established by others for 30 stations in Sudan [3] as:

$$80\%\ \text{rainfall} = 0.92 \times \text{mean rainfall} - 53 \qquad (3.15)$$

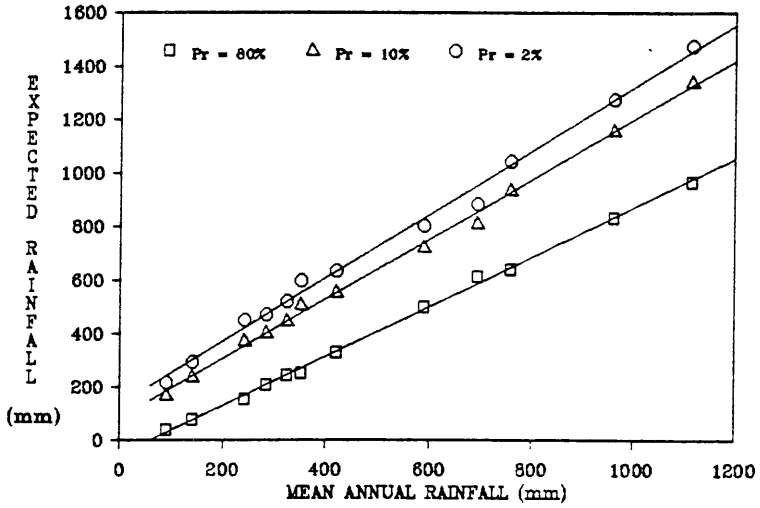


Fig. 3.65 Amount of Annual Rainfall Expected with 80, 10 and 2% Probabilities

Chapter 4

SUNSHINE DURATION AND SOLAR RADIATION

4.1 Solar Radiation at Earth's Surface

The radiant energy from the sun or solar radiation is the chief source of energy of earth [6, 8]. The amount of radiant energy arriving at the earth's surface is governed by geographic latitude, season of the year, time of day and degree of cloudiness [7, 24]. Less solar radiation is received at higher latitudes than at lower latitudes [6]. A considerable amount of the incoming solar radiation is scattered and absorbed in the atmosphere or reflected from clouds and the ground back into space [6, 8]. The difference between the incoming short and long wave radiations and the reflected outgoing short and long wave radiations from the surface of the earth is called net radiation [7, 8]. The amount of incident solar radiation reflected by clouds is dependent on the amount of clouds and their albedo which is defined as the ratio of the amount of solar radiation reflected by a surface to the amount incident upon it [6]. The albedo of the earth's surface or its reflectivity for solar radiation varies widely, depending on solar altitude as well as type of surface. It is less for higher solar altitudes than for lower altitudes and tends to be less for moist soil surfaces than for dry.

Assuming there were no clouds and the atmosphere was perfectly transparent, the total radiation is tabulated by Duffie and Beckman [25] as a function of the month of the year and the latitude. For latitudes ranging from equator to 25° N, covering the area of Sudan, the radiation values, H_o, are presented in Table 4.1 and further given in a graphical form in Figs. 4.1.a and 4.1.b.

Table 4.1 Average Daily Maximum Possible Extraterrestrial Radiation, Ho, in MJ/m²/day * as a Function of the Month of the Year and Latitude

Latitude (° N)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	35.9	37.0	37.4	36.4	34.4	33.2	33.6	35.3	36.8	36.9	36.0	35.3
5	33.9	35.7	37.1	37.1	35.9	35.0	35.3	36.3	36.8	35.9	34.1	33.1
10	31.7	34.1	36.4	37.5	37.1	36.6	36.7	37.1	36.6	34.6	32.1	30.8
15	29.3	32.3	35.5	37.6	38.1	38.0	37.9	37.6	36.1	33.1	29.8	28.2
20	26.7	30.2	34.4	37.5	38.9	39.1	38.9	37.8	35.3	31.3	27.4	25.5
25	23.9	27.9	32.9	37.1	39.4	40.0	39.6	37.8	34.2	29.3	24.8	22.6

* The conversion is 1 MJ/m² = 23.889 g cal/cm²

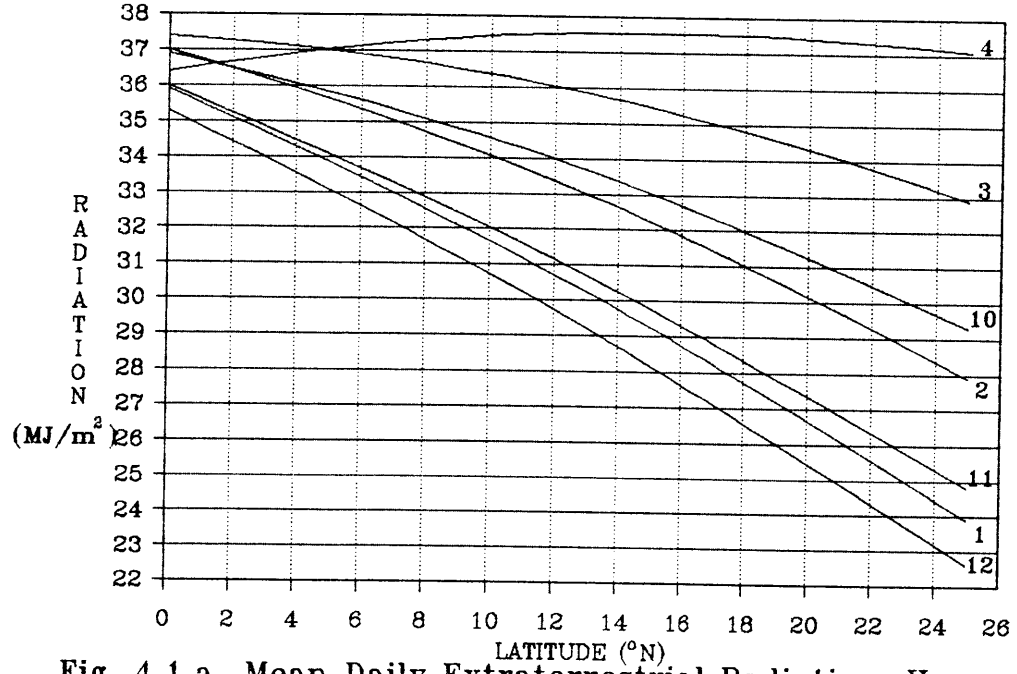


Fig. 4.1.a Mean Daily Extraterrestrial Radiation, Ho, for the Month

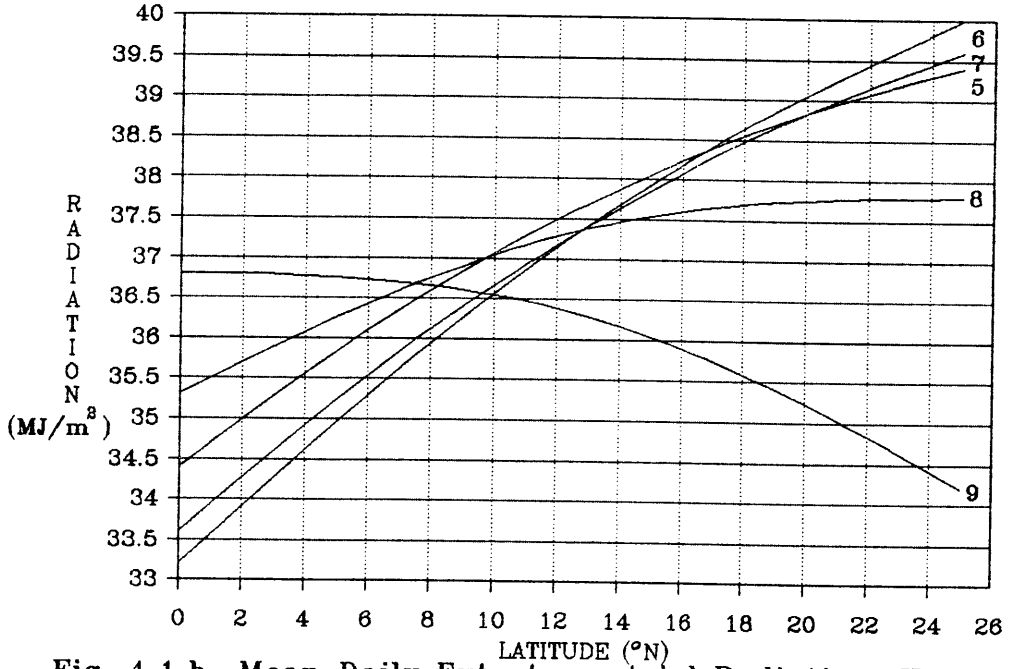


Fig. 4.1.b Mean Daily Extraterrestrial Radiation, Ho, for the Month

4.2 Measurement of Sunshine Duration and Solar Radiation

Campbell-Stokes sunshine recorder shown in Fig. 4.2, photographed at Shambat Station, is the instrument used in Sudan to give a measure of the total length of bright sunshine in hours. This recorder [8] has a glass sphere which focusses the sun's rays on to a specially treated calibrated card where they burn a trace. The accumulated lengths of burnt trace give the measurement. The short wave radiation reaching the earth's surface from sun and sky was measured by radiometer.



Fig. 4.2 Campbell-Stokes Sunshine Recorder (Photographed at Station of Shambat)

4.3 Mean Monthly Sunshine Duration

The times of sunrise and sunset of the day at various stations in Sudan were obtained from the Sudan Meteorological Services. The maximum possible mean daily sunshine durations for the months in hours have then been computed for the twelve stations and are given in Table 4.2.

Table 4.2 Mean Maximum Possible Daily Sunshine Duration, N, in Hours

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port Sudan	11.109	11.496	12.049	12.587	13.061	13.288	13.710	13.742	13.139	11.738	11.207	10.998
Khartoum	11.309	11.629	12.049	12.487	12.861	13.055	13.510	13.609	13.122	11.788	11.407	11.215
Kassala	11.309	11.629	12.049	12.470	12.844	13.038	13.510	13.603	13.105	11.788	11.407	11.248
Wad Medani	11.359	11.662	12.049	12.437	12.794	12.972	13.460	13.576	13.089	11.821	11.407	11.315
El Gedaref	11.409	11.662	12.066	12.454	12.761	12.955	13.443	13.576	13.089	11.821	11.507	11.315
El Fasher	11.376	11.696	12.049	12.420	12.761	12.938	13.410	13.542	13.105	11.821	11.474	11.348
El Obeid	11.442	11.696	12.049	12.420	12.728	12.922	13.377	13.542	13.089	11.855	11.540	11.348
Nyala	11.476	11.729	12.066	12.337	12.694	12.838	13.343	13.492	13.089	11.888	11.574	11.448
Ed Damazin	11.509	11.762	12.049	12.370	12.661	12.805	13.310	13.476	12.889	11.855	11.607	11.482
Malakal	11.642	11.829	12.049	12.404	12.528	12.672	13.177	13.409	13.055	11.921	11.674	11.615
Wau	11.709	11.862	12.066	12.254	12.444	12.555	13.077	13.359	13.089	11.955	11.774	11.715
Juba	11.842	11.857	12.082	12.237	12.344	12.422	12.943	13.242	13.055	12.021	11.740	11.848

The actual and maximum possible mean daily sunshine hours, n and N respectively, for the months are plotted in Figs. 4.3 through 4.14. Data for n are not available for Nyala. For a perfectly clear sky, N values vary from 11.109 to 13.742 hours. These two extremes happen to be for Port Sudan. The maximum N value for all the stations is reached in August while the minimum value is reached in January for Port Sudan and Wau, in November for Juba and in December for the other stations.

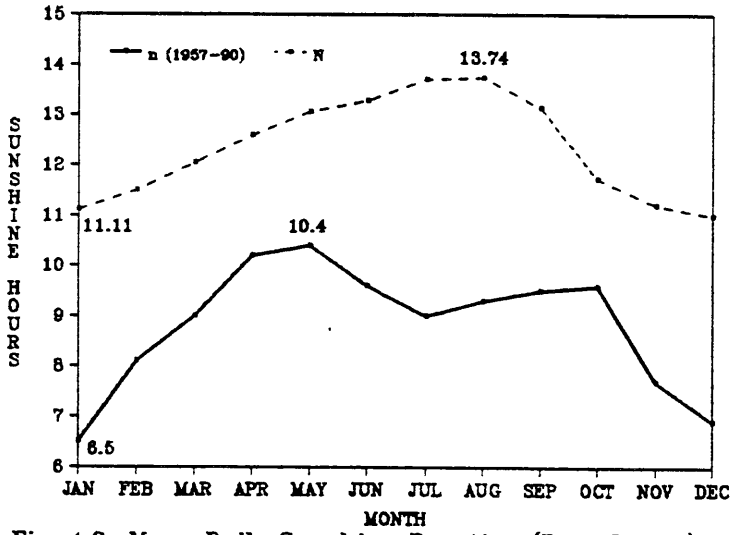


Fig. 4.3 Mean Daily Sunshine Duration (Port Sudan)

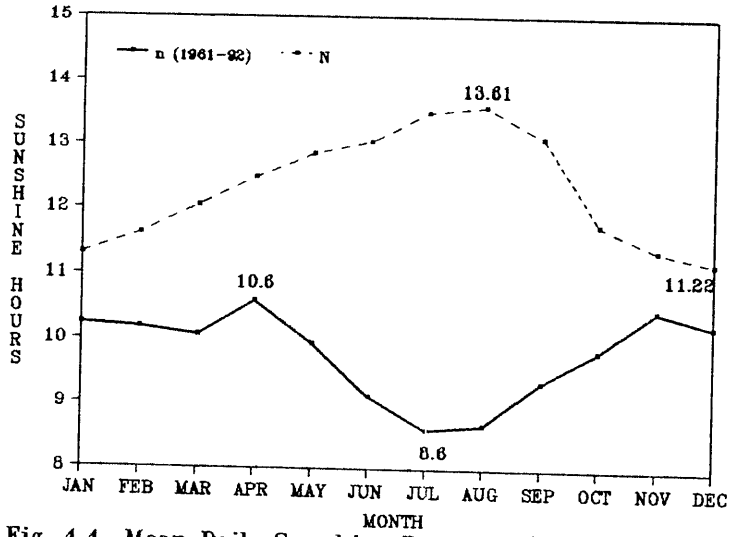


Fig. 4.4 Mean Daily Sunshine Duration (Khartoum)

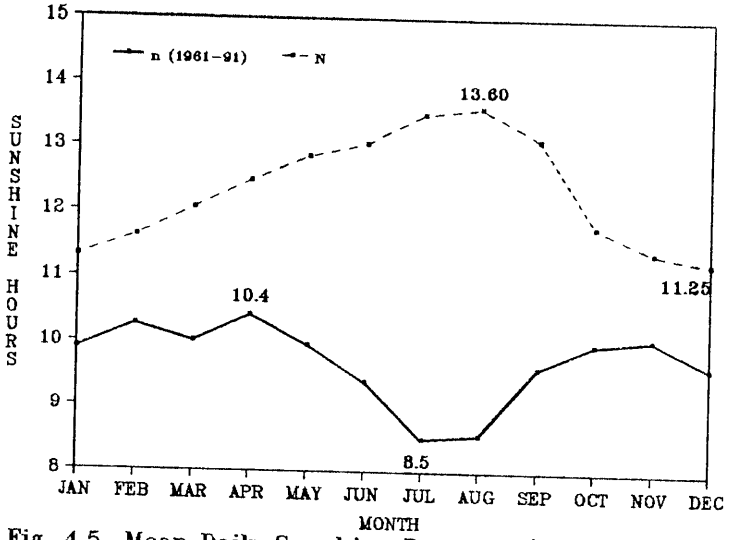


Fig. 4.5 Mean Daily Sunshine Duration (Kassala)

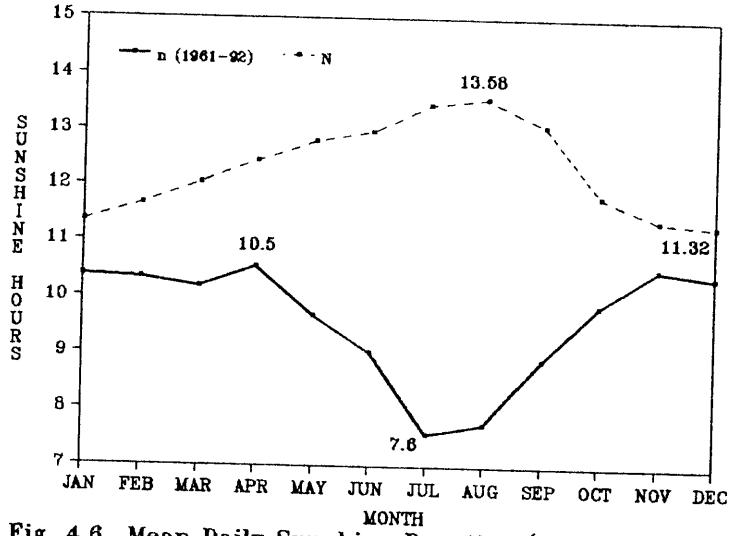


Fig. 4.6 Mean Daily Sunshine Duration (Wad Medani)

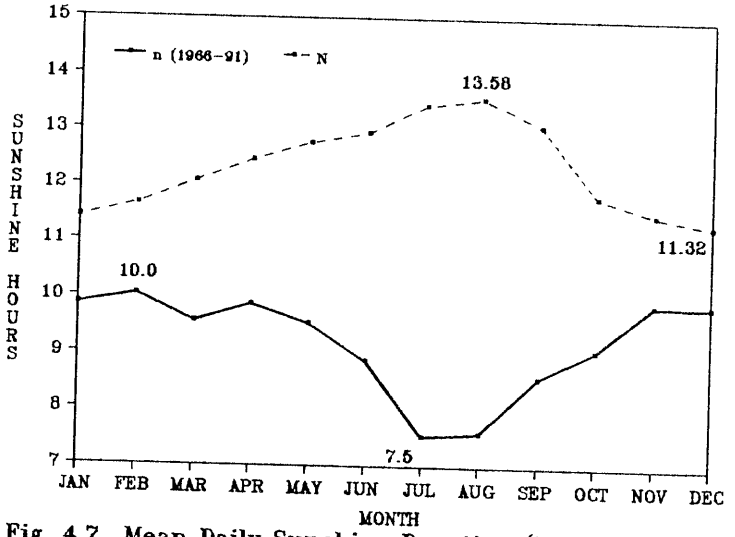


Fig. 4.7 Mean Daily Sunshine Duration (El Gedaref)

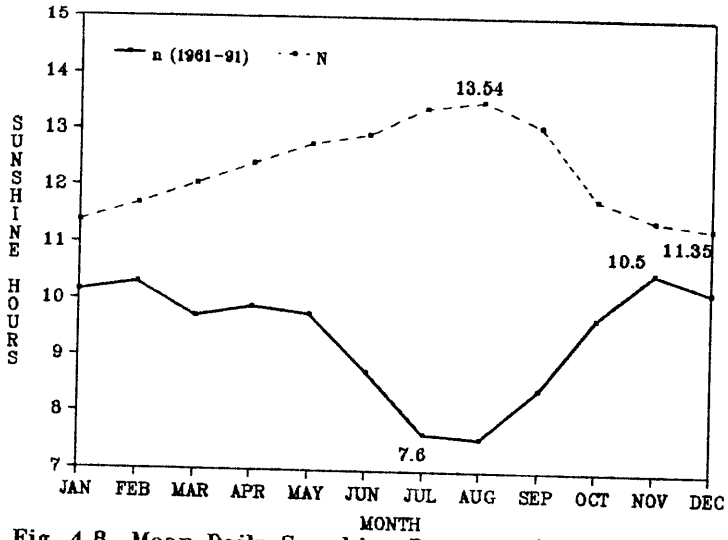


Fig. 4.8 Mean Daily Sunshine Duration (El Fasher)

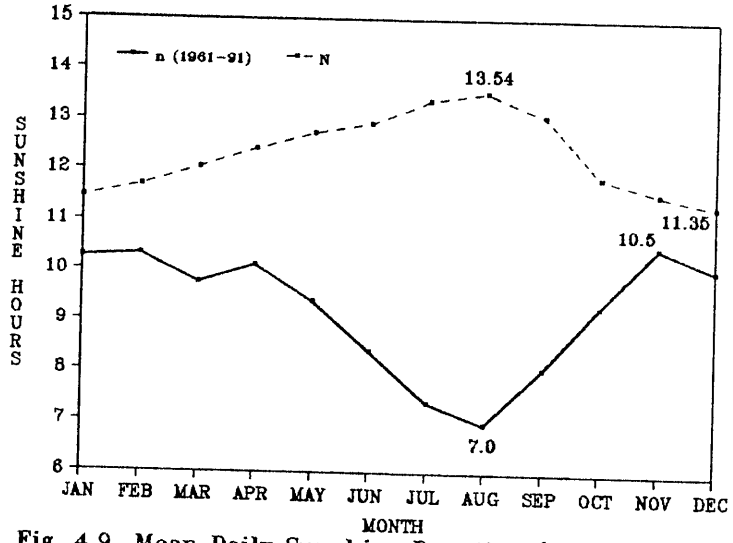


Fig. 4.9 Mean Daily Sunshine Duration (El Obeid)

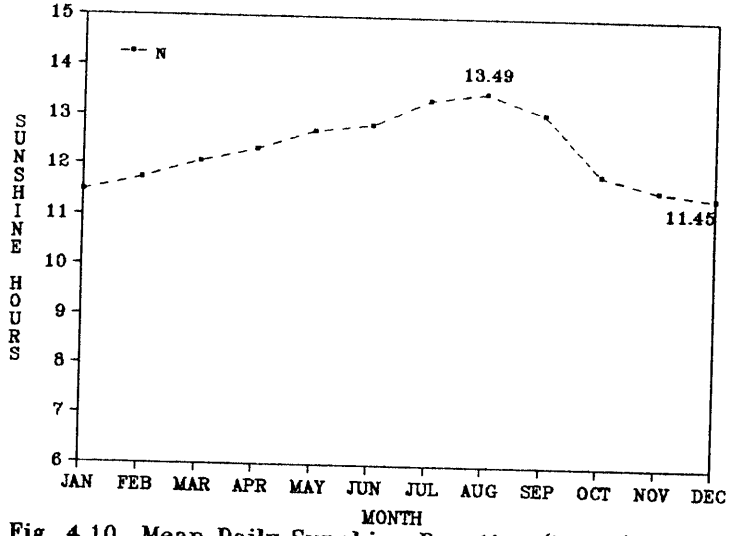


Fig. 4.10 Mean Daily Sunshine Duration (Nyala)

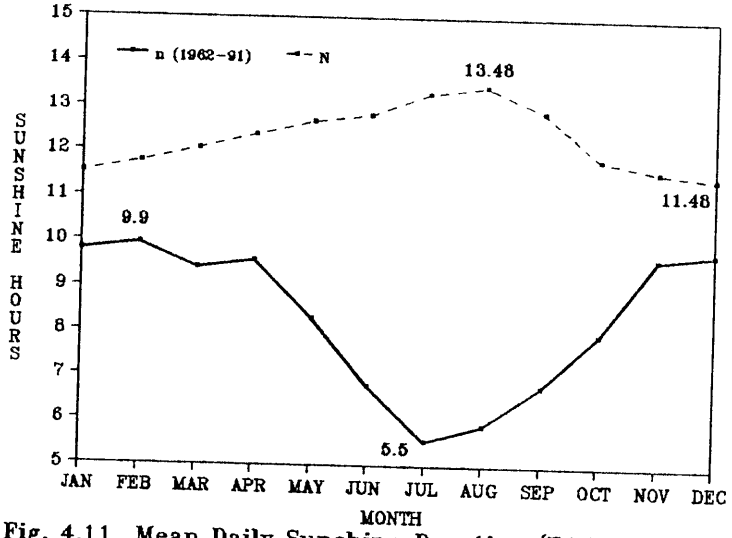


Fig. 4.11 Mean Daily Sunshine Duration (Ed Damazin)

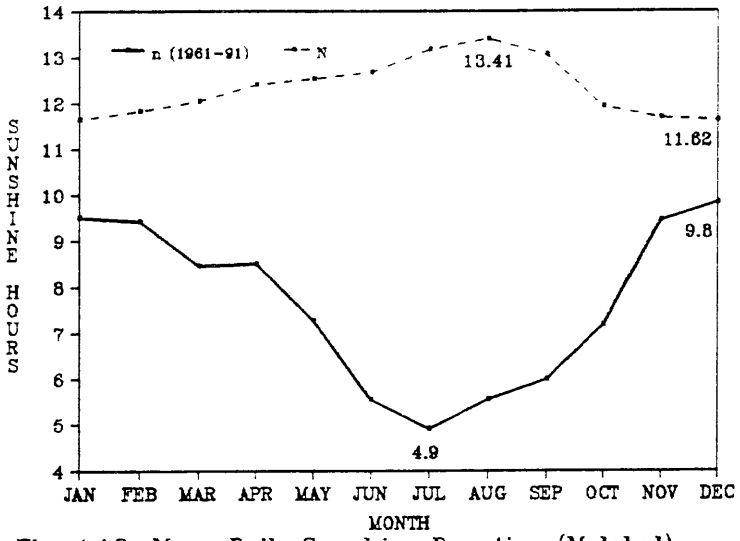


Fig. 4.12 Mean Daily Sunshine Duration (Malakal)

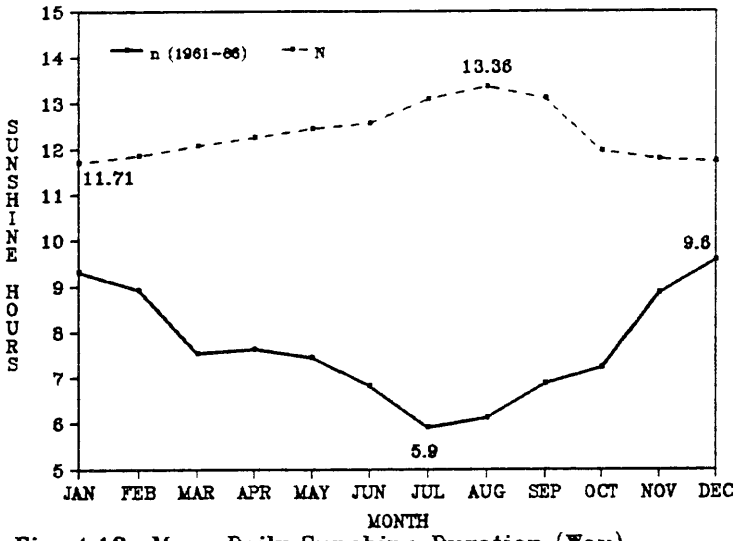


Fig. 4.13 Mean Daily Sunshine Duration (Wau)

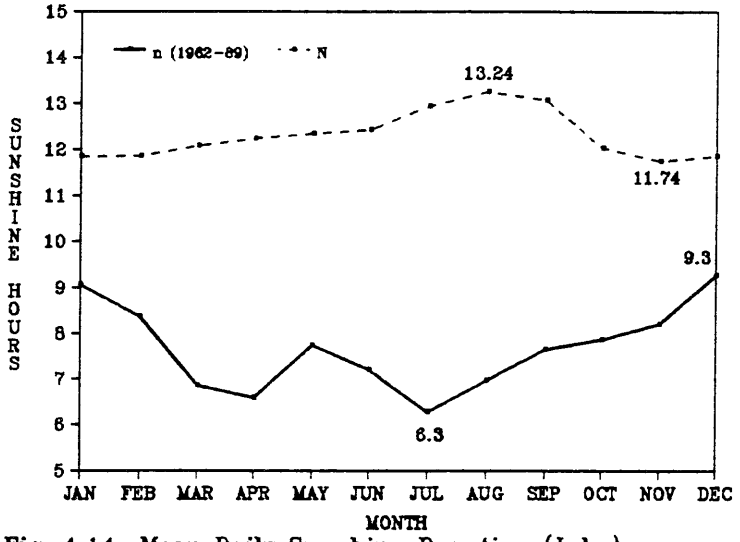


Fig. 4.14 Mean Daily Sunshine Duration (Juba)

The actual sunshine duration, n, for the stations varies in the range of 4.9 to 10.6 hours. The minimum value is obtained in July for Malakal and the maximum value is obtained in April for Khartoum. The effect of rainy season is markedly observed in the pattern of the mean monthly actual sunshine duration, especially in the month of January for Port Sudan and in the months of July and August for the other locations, where the duration of sunshine becomes shortest.

4.4 Mean Monthly Solar Radiation

The daily maximum possible extraterrestrial radiation, H_o, for the months computed from Table 4.1 for the twelve regions are given in Table 4.3 and further graphically presented in Figs. 4.15 to 4.26. The mean values of the global solar radiation actually reaching the earth's surface, H, are presented in the figures as well. Limited H records were taken for El Obeid from a nearby station (Kadugli 11° 00′ N 29° 43′ E 500 m). Neither Nyala nor Wau has H records.

Table 4.3 Average Daily Maximum Possible Extraterrestrial Radiation, Ho, in MJ/m²/day *

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port Sudan	26.92	30.38	34.49	37.51	38.83	39.01	38.82	37.78	35.37	31.45	27.60	25.73
Khartoum	28.99	32.05	35.37	37.45	38.96	39.21	38.98	37.80	35.17	31.06	27.09	25.15
Kassala	29.06	32.10	35.40	37.59	38.17	38.10	37.99	37.62	36.07	32.93	29.58	27.95
Wad Medani	29.60	32.52	35.61	37.59	37.98	37.83	37.75	37.54	36.16	33.28	30.08	28.52
El Gedaref	29.76	32.65	35.67	37.58	37.91	37.73	37.67	37.50	36.20	33.39	30.24	28.70
El Fasher	29.96	32.80	35.75	37.57	37.82	37.61	37.57	37.46	36.24	33.52	30.44	28.92
El Obeid	30.18	32.96	35.83	37.56	37.73	37.49	37.46	37.42	36.28	33.65	30.64	29.15
Nyala	30.71	33.36	36.03	37.54	37.51	37.18	37.20	37.31	36.39	33.98	31.15	29.73
Ed Damazin	30.83	33.45	36.07	37.54	37.46	37.11	37.14	37.28	36.42	34.06	31.27	29.86
Malakal	31.90	34.24	36.46	37.46	36.99	36.46	36.57	37.03	36.62	34.72	32.28	31.01
Wau	32.71	34.84	36.72	37.32	36.55	35.86	36.06	36.73	36.69	35.20	33.03	31.86
Juba	33.95	35.74	37.11	37.08	35.86	34.95	35.25	36.27	36.80	35.93	34.15	33.16

* The conversion is 1 MJ/m² = 23.889 g cal/cm²

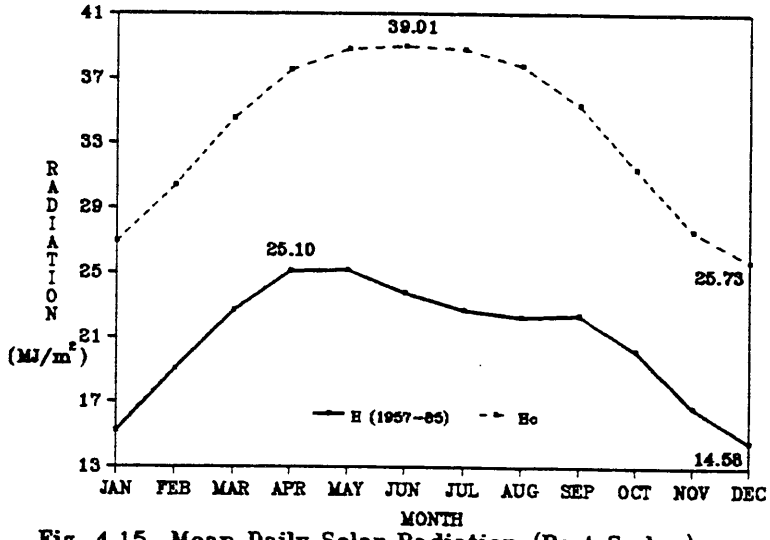


Fig. 4.15 Mean Daily Solar Radiation (Port Sudan)

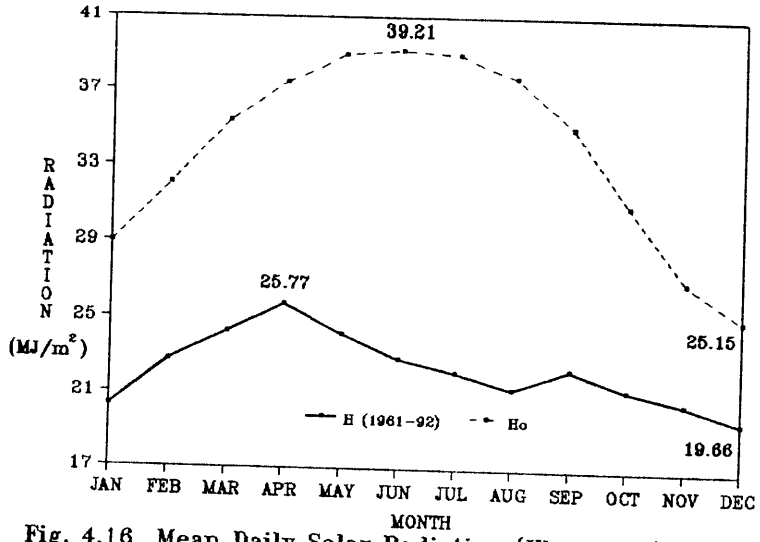


Fig. 4.16 Mean Daily Solar Radiation (Khartoum)

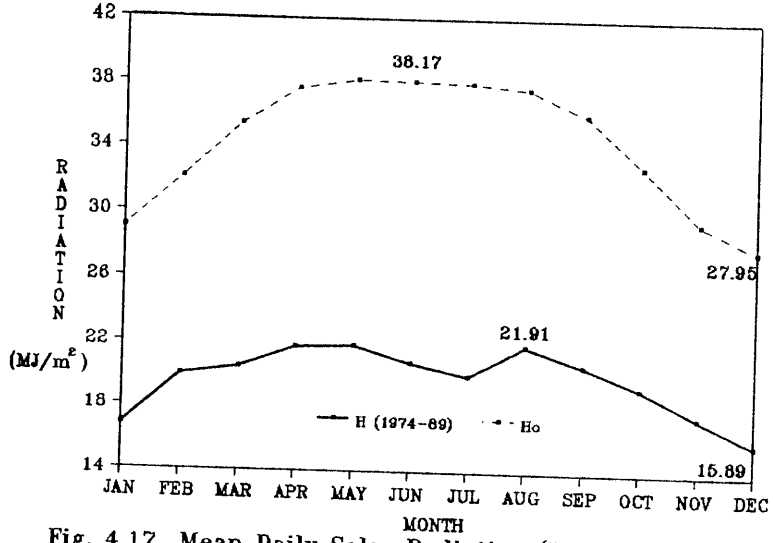


Fig. 4.17 Mean Daily Solar Radiation (Kassala)

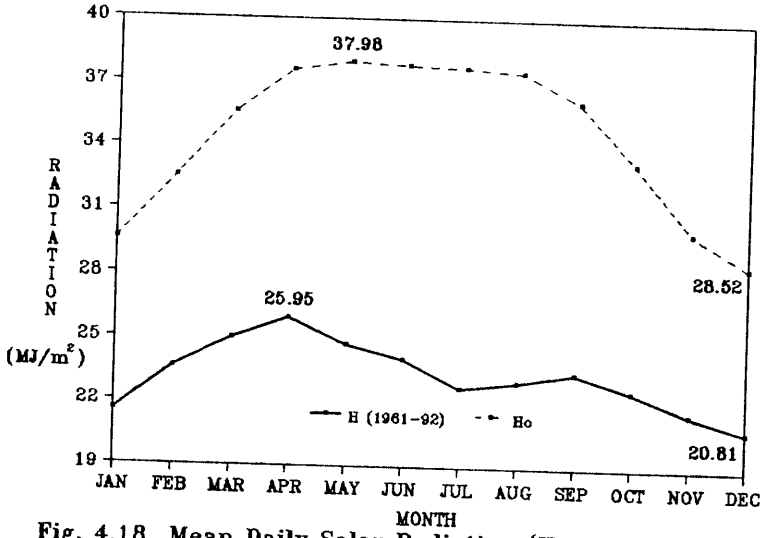


Fig. 4.18 Mean Daily Solar Radiation (Wad Medani)

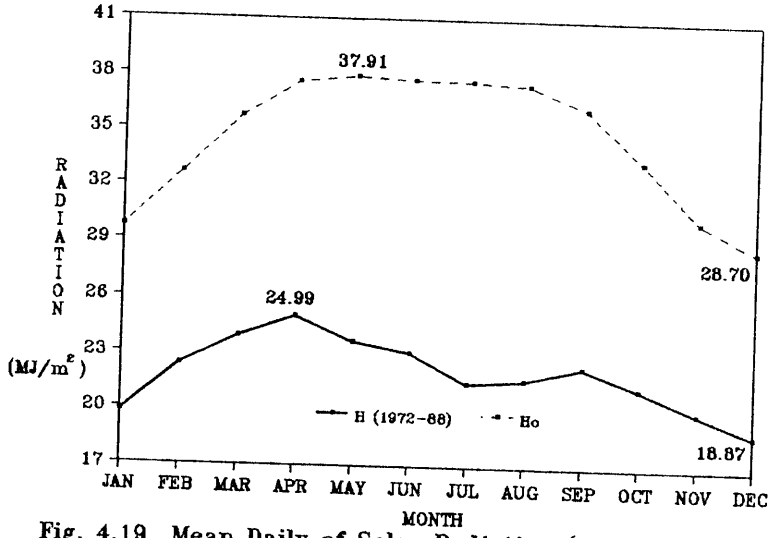


Fig. 4.19 Mean Daily of Solar Radiation (El Gedaref)

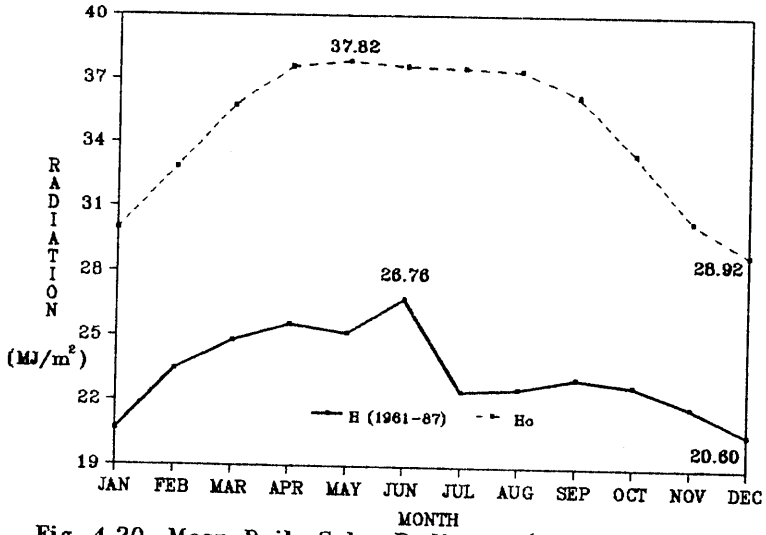


Fig. 4.20 Mean Daily Solar Radiation (El Fasher)

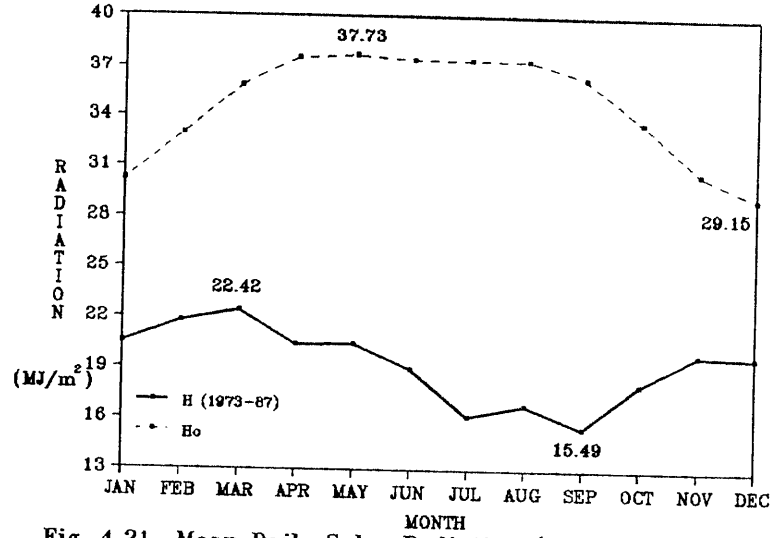


Fig. 4.21 Mean Daily Solar Radiation (El Obeid)

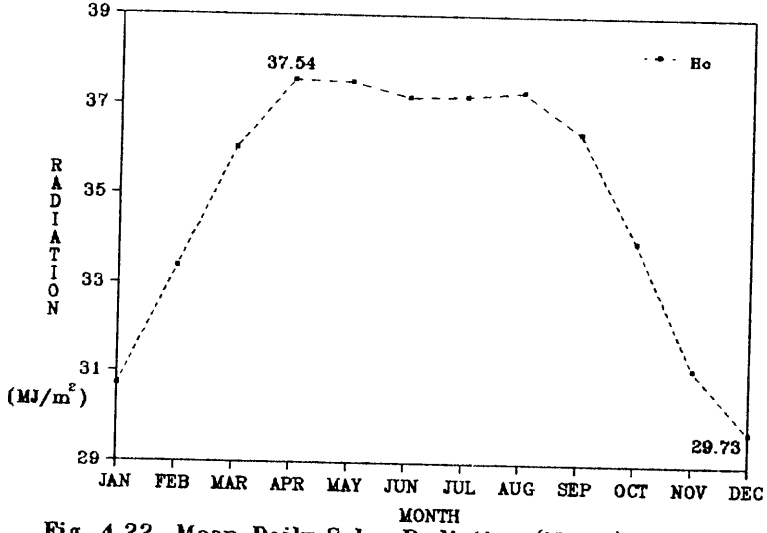


Fig. 4.22 Mean Daily Solar Radiation (Nyala)

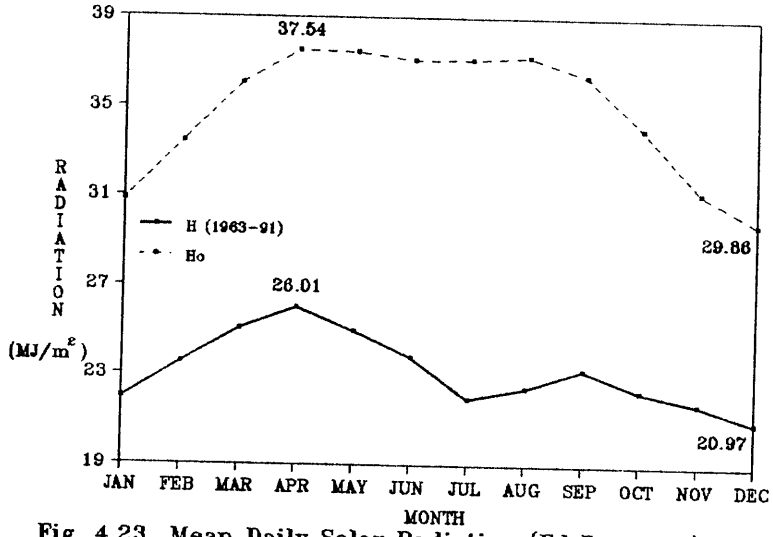


Fig. 4.23 Mean Daily Solar Radiation (Ed Damazin)

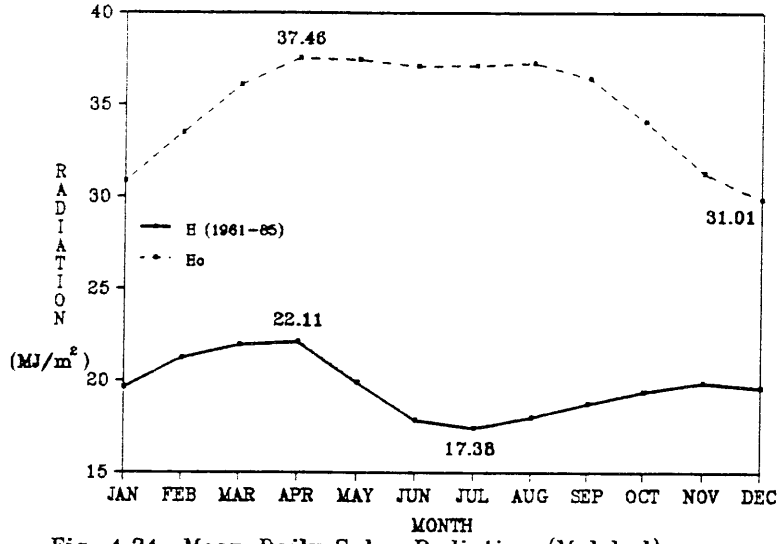


Fig. 4.24 Mean Daily Solar Radiation (Malakal)

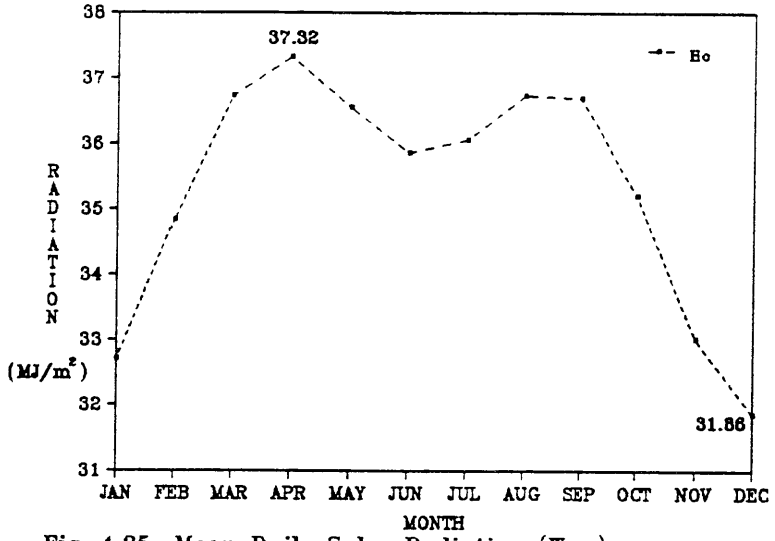


Fig. 4.25 Mean Daily Solar Radiation (Wau)

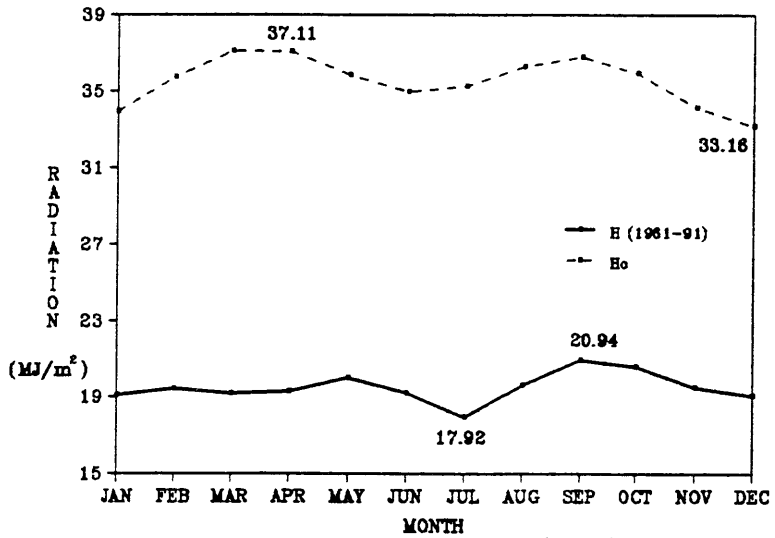


Fig. 4.26 Mean Daily Solar Radiation (Juba)

The values of short wave radiation H_o at the outer limits of the atmosphere for the stations fall in the range of 25.15 to 39.21 MJ/m^2/day. The upper and lower limits of this range are found to be for Khartoum. The maximum values of H_o for all the twelve stations occurred to be in the months of March, April, May or June, while the minimum values are obtained to be in the month of December. On the other hand, the mean H values are found to vary from 14.58 MJ/m^2/day, which is recorded in December for Port Sudan, to 26.76 MJ/m^2/day, which is recorded in June for El Fasher.

4.5 Mean Monthly Cloudiness Ratio and Relative Solar Radiation

The cloudiness ratio (also sometimes termed as brightness ratio or relative duration of sunshine) is defined as the ratio of the actual to maximum possible hours of daily sunshine. Relative radiation, on the other hand, is the ratio of the actual to maximum possible solar radiation per day. The variations of the mean monthly values of n/N and H/H_o, expressed as percentages, are shown in Figs. 4.27 to 4.37. The pattern of the two ratios for Port Sudan is quite different from the patterns observed for the other regions. For Port Sudan, January is the month that has minimum n/N and H/H_o ratios, while October and April are the months with maximum n/N and H/H_o values respectively. In the other regions, the minimum n/N and H/H_o values occur mostly in the months of July and August. The maximum n/N ratios are registered either in November or in December, whereas the maximum H/H_o ratios are recorded in January, February, November or December. The available data suggest that the magnitudes of n/N change from 37.3% in Malakal to 92.3% in Wad Medani. With respect to H/H_o values, they range between 47.5% (Khartoum) and 78.2% (Malakal).

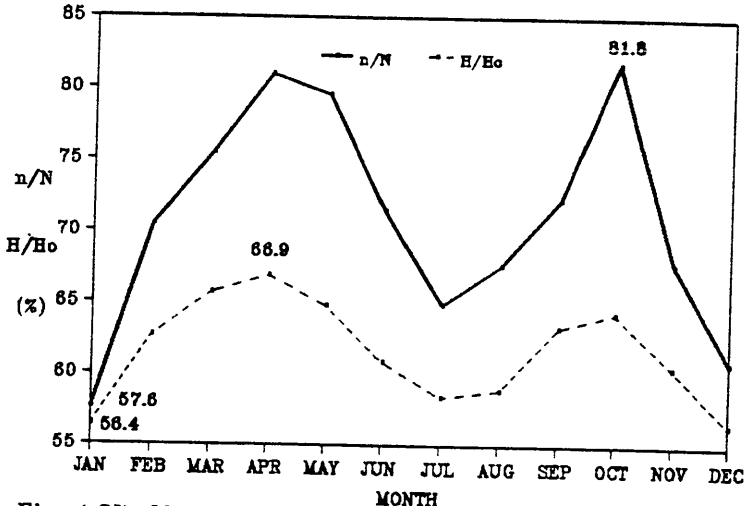


Fig. 4.27 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (Port Sudan)

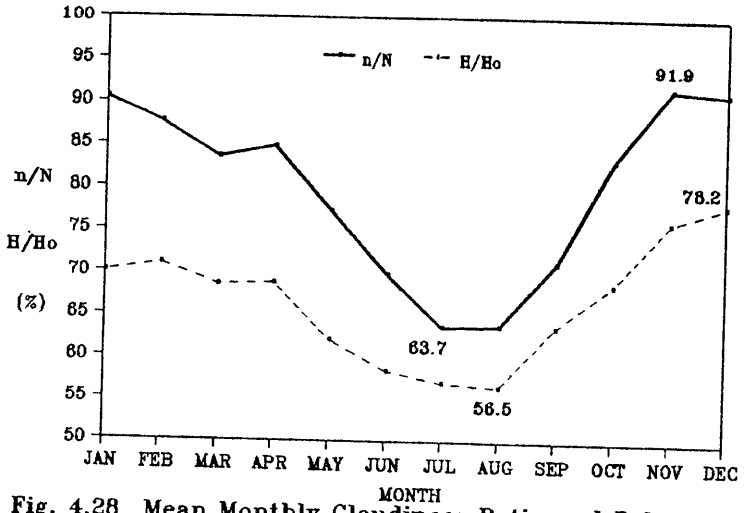


Fig. 4.28 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (Khartoum)

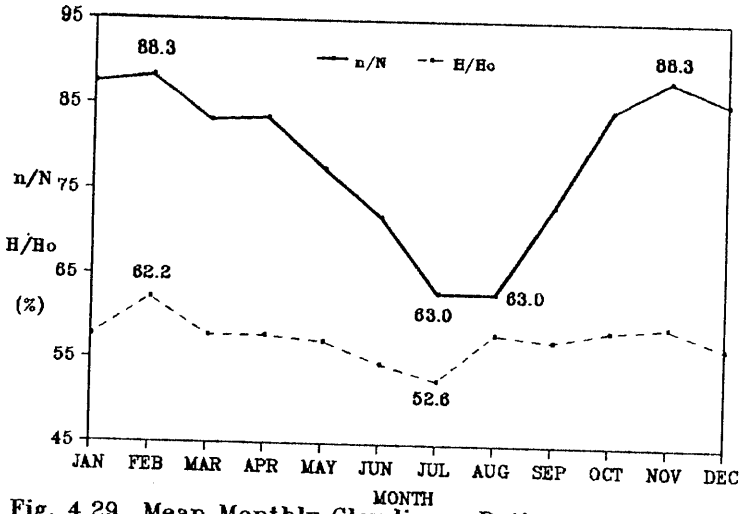


Fig. 4.29 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (Kassala)

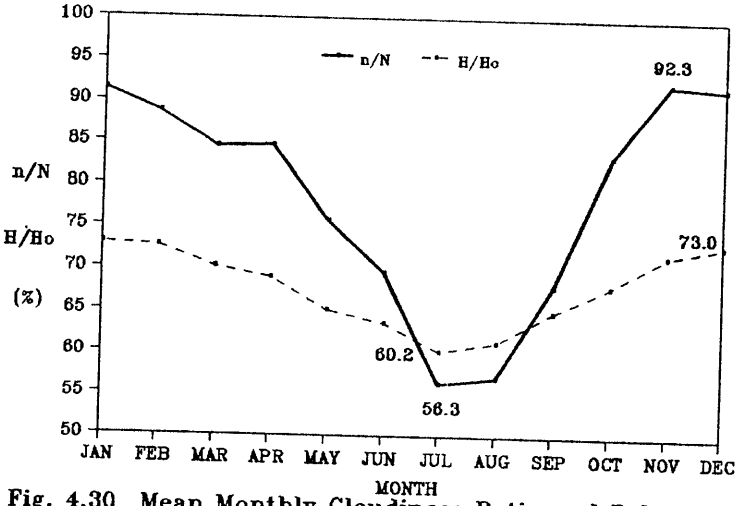


Fig. 4.30 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (Wad Medani)

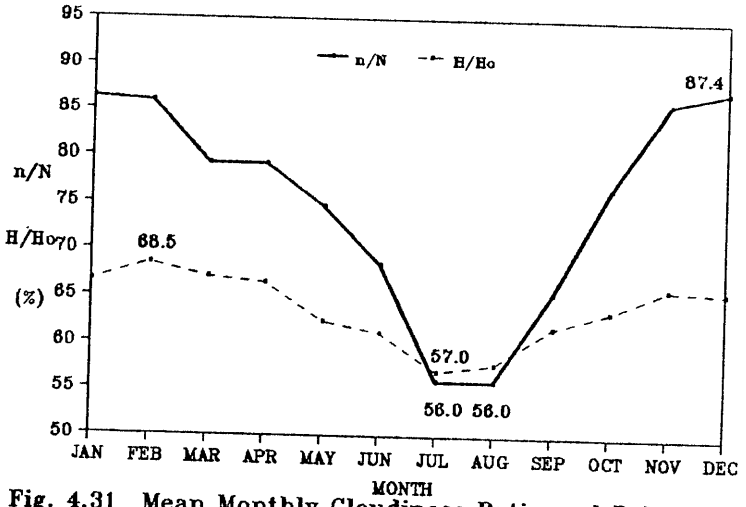


Fig. 4.31 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (El Gedaref)

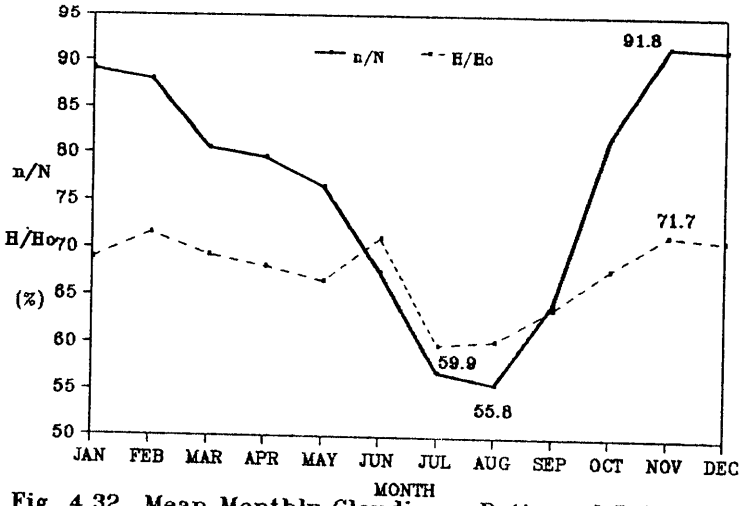


Fig. 4.32 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (El Fasher)

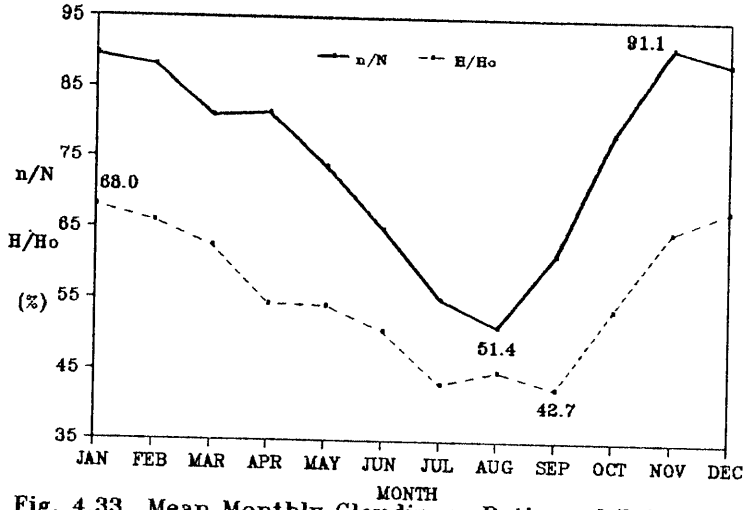


Fig. 4.33 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (El Obeid)

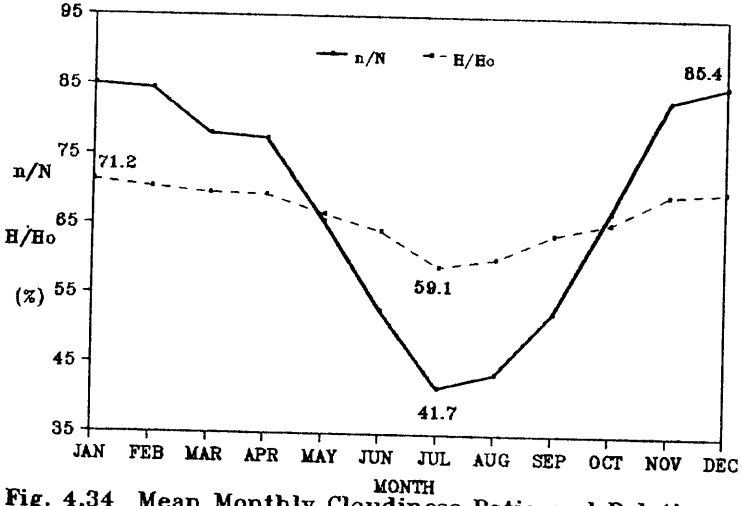


Fig. 4.34 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (Ed Damazin)

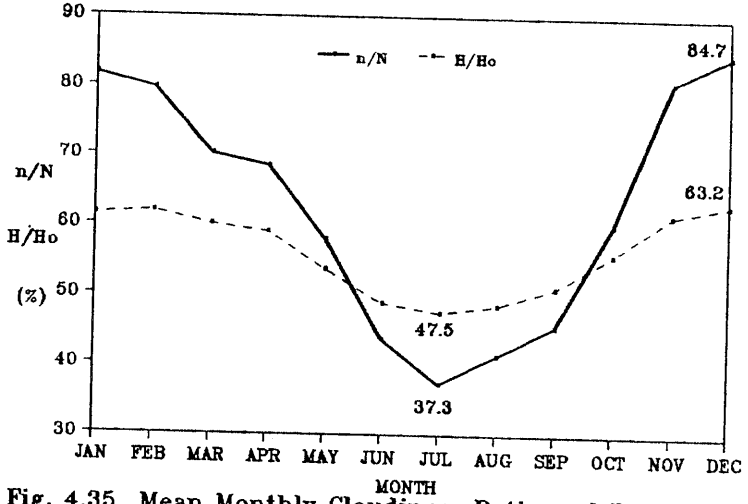


Fig. 4.35 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (Malakal)

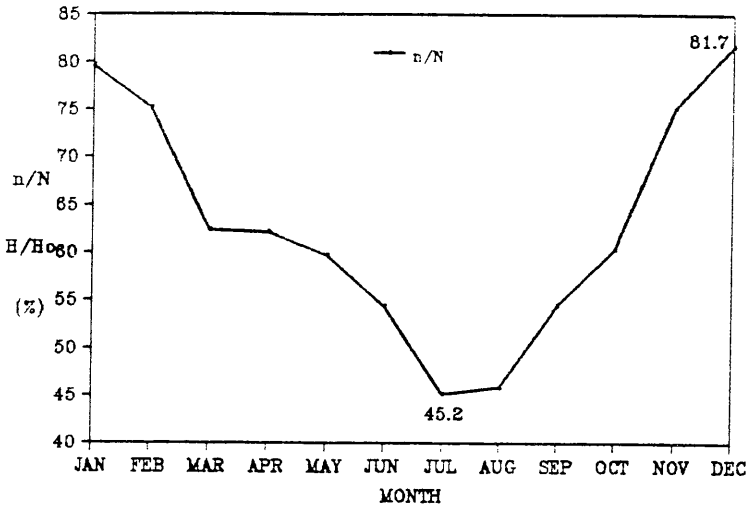


Fig. 4.36 Mean Monthly Cloudiness Ratio (Wau)

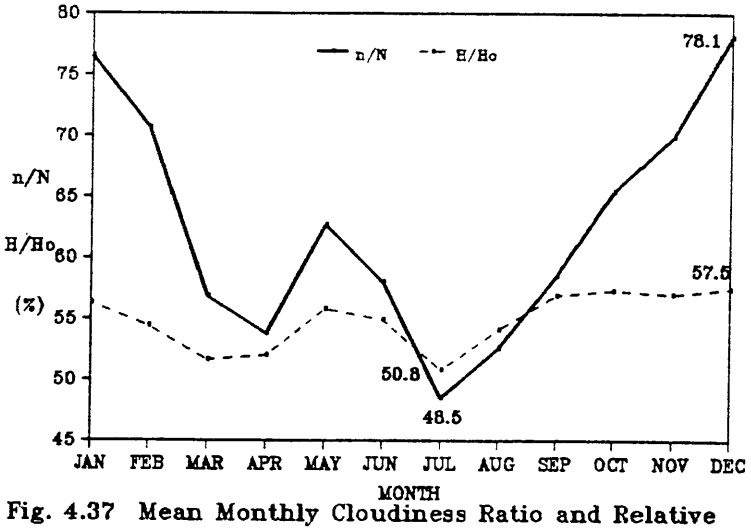


Fig. 4.37 Mean Monthly Cloudiness Ratio and Relative Solar Radiation (Juba)

4.6 Regional Formulae for Short Wave Solar Radiation

The estimate of the actual short wave radiation is particularly important for the evaluation of evaporation. Many formulae have been given by different investigators for different places for this purpose. The form in common use is:

$$H = H_o (A + B\, n/N) \qquad (4.1)$$

where A and B are the constants for a particular region.

With the availability of measured data on sunshine duration and solar radiation for a region, the development of such a formula becomes possible based on statistical techniques. Fortunately, many stations in Sudan have adequate records. Hence, an attempt has been made to derive the regional formulae for

the stations considered in this study. Regression is the statistical approach applied to find the best fit for the relationships between H/H_o and n/N. Three regression forms are tried, namely linear ($H/H_o = A + B\ n/N$), exponential ($H/H_o = A\ e^{B\ n/N}$) and power ($H/H_o = C + A\ (n/N)^B$). The computer program written for the purpose of determining the constants A, B and C is given in Appendix.

Two approaches have been adopted in order to establish the H/H_o - n/N relationships. Table 4.4 shows the results of the first approach which makes use of the available monthly records on n and H. The second approach [26] uses the mean values of n and H, the results of which are listed in Table 4.5. The use of mean values did considerably conceal the large scatter observed when monthly records were used. The enhanced correlation factor is quite obvious in Table 4.5. Inspite of the substantial differences in the correlation factors, the two results are very comparable. It is to be emphasized, however, that the correlationships given in Tables 4.4 and 4.5 are best valid for the ranges of n/N indicated in the tables. The power form proved to give the best fit to this natural phenomenon in Sudan. However, the linear relationship gave correlation factors close to those of power form. Thus, the linear equation can still be adopted due to its simplicity in application.

Table 4.4 Regional Short Wave Solar Radiation Formulae (First Approach)

Station	Linear H/Ho =A+ B (n/N)			Exponential H/Ho = A e^(B n/N)			Power H/Ho = C + A (n/N)^B				Range of n/N
	A	B	r	A	B	r	A	B	C	r	
Port Sudan	0.314	0.418	0.596	0.367	0.709	0.598	0.708	0.481	0.010	0.599	0.387-0.890
Khartoum	0.243	0.540	0.715	0.349	0.816	0.735	0.359	1.813	0.425	0.742	0.503-0.964
Kassala	0.460	0.153	0.236	0.464	0.274	0.246	0.274	0.505	0.329	0.251	0.474-0.912
Wad Medani	0.424	0.319	0.735	0.460	0.482	0.743	0.312	1.000	0.426	0.742	0.431-0.963
El Gedaref	0.393	0.330	0.655	0.429	0.530	0.666	0.305	1.243	0.423	0.684	0.508-0.919
El Fasher	0.451	0.284	0.678	0.478	0.434	0.686	0.347	0.768	0.384	0.690	0.394-0.969
El Obeid	0.107	0.614	0.716	0.243	1.103	0.700	0.703	0.768	0.000	0.689	0.449-0.949
Ed Damazin	0.532	0.188	0.430	0.534	0.301	0.448	0.253	1.022	0.476	0.517	0.233-0.930
Malakal	0.341	0.348	0.824	0.372	0.633	0.820	0.658	0.377	0.011	0.821	0.212-0.913
Juba	0.425	0.203	0.476	0.438	0.365	0.471	0.614	0.227	0	0.471	0.394-0.861

Table 4.5 Regional Short Wave Solar Radiation Formulae (Second Approach)

Station	Linear H/Ho =A+ B (n/N)			Exponential H/Ho = A e^(B n/N)			Power H/Ho = C + A (n/N)^B				Range of n/N
	A	B	r	A	B	r	A	B	C	r	
Port Sudan	0.309	0.433	0.939	0.372	0.708	0.940	0.304	3.180	0.510	0.949	0.576-0.818
Khartoum	0.146	0.651	0.951	0.300	0.992	0.959	0.341	3.667	0.504	0.968	0.637-0.919
Kassala	0.446	0.163	0.647	0.458	0.287	0.651	0.113	2.525	0.509	0.665	0.630-0.883
Wad Medani	0.409	0.341	0.974	0.452	0.512	0.977	0.209	2.477	0.556	0.983	0.563-0.923
El Gedaref	0.404	0.310	0.943	0.438	0.496	0.946	0.232	1.801	0.496	0.957	0.560-0.874
El Fasher	0.465	0.273	0.850	0.489	0.417	0.853	0.213	1.940	0.543	0.877	0.558-0.918
El Obeid	0.077	0.641	0.938	0.227	1.179	0.944	0.439	1.831	0.290	0.935	0.514-0.911
Ed Damazin	0.501	0.242	0.982	0.517	0.371	0.979	0.733	0.233	0	0.987	0.417-0.854
Malakal	0.351	0.335	0.991	0.381	0.608	0.989	0.669	0.358	0	0.993	0.373-0.847
Juba	0.437	0.179	0.729	0.446	0.330	0.728	0.607	0.213	0	0.748	0.485-0.781

Using mean values for all the stations, the best regression relation between H/H_o and n/N has been found to be a single linear with a correlation factor of 0.710 as:

$$H = H_o\,(0.350 + 0.368\ n/N) \qquad (4.2)$$

The plotted points of H/H_o versus n/N for all the stations together with the three fits, namely linear, exponential and power, are shown in Fig. 4.38. The scatter of the points can be justified partly due to the difference in latitudes and partly due to the difference in period of data belonging to each station. However, the application of this equation in the regions where H data are unavailable for the development of regional formulae seems quite justifiable, for example Wau, because these locations fall within the range of latitudes under consideration.

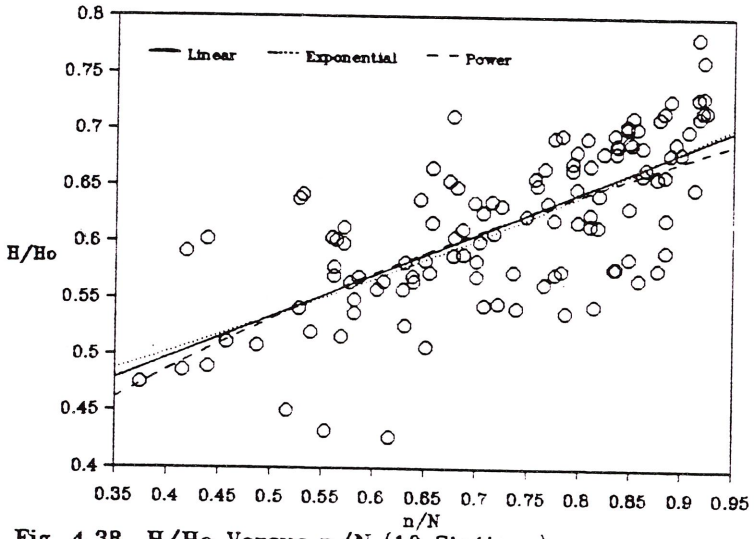


Fig. 4.38 H/Ho Versus n/N (10 Stations)

From Table 4.5, it can be seen that the power form gives C values equal to zero for the southern regions (Ed Damazin, Malakal and Juba). Obviously, this result is inadmissible since the constants A and C (Y-intercepts) cannot be zero, because there will be some amount of solar radiation reaching the earth's surface even on days of complete cloud cover (n/N = 0). Hence, the equations of the power form developed for these stations should be applied for high n/N ratios.

Substituting n/N = 0 and n/N = 1 in the developed relationships of Table 4.5, the percentage of solar radiation received at the surface of the earth on cloudy and bright days respectively is given in Table 4.6. A brief look at this table reveals that on average a minimum of 29% of solar radiation arrives the surface of the earth in Sudan on extremely cloudy days and around 85% of radiation as a maximum gets through on days of cloudless sky. These limits occur to be for El Obeid and Khartoum respectively as can be seen in Table 4.6. The substantially low H/H_o value for n/N = 0, obtained for Khartoum by linear regression, conforms

with the recurring severe sandstorms experienced in about the last ten years [26].

Table 4.6 Relative Solar Radiation, H/Ho, at n/N = 0 and n/N = 1 Expressed as Percentage

Station	Linear Form		Exp. Form		Power Form	
	n/N = 0	n/N = 1	n/N = 0	n/N = 1	n/N = 0	n/N = 1
Port Sudan	30.9	74.2	37.2	75.5	51.0	81.4
Khartoum	14.6	79.7	30.0	80.9	50.4	84.5
Kassala	44.6	60.9	45.8	61.0	50.9	62.2
Wad Medani	40.9	75.0	45.2	75.4	55.6	76.5
El Gedaref	40.4	71.4	43.8	71.9	49.6	72.8
El Fasher	46.5	73.8	48.9	74.2	54.3	75.6
El Obeid	7.7	71.8	22.7	73.8	29.0	72.9
Ed Damazin	50.1	74.3	51.7	74.9	0	73.3
Malakal	35.1	68.6	38.1	70.0	0	66.9
Juba	43.7	61.6	44.6	62.0	0	60.7

Chapter 5

RELATIVE HUMIDITY, WIND SPEED AND EVAPORATION

RELATIVE HUMIDITY, WIND SPEED AND EVAPORATION

5.1 Definitions

Evaporation and transpiration are vital processes in the hydrological cycle through which water is transformed into vapour. The first process refers to the water loss from a free-water surface, e.g. lakes, reservoirs, streams, etc, while the second process is thought of as the water loss occurring from a vegetated surface [8]. Both phases are regulated by the same climatic conditions and are thus linked together to refer to the total loss of water from a land surface and its vegetation and called evapotranspiration [7, 8]. The evapotranspiration is very difficult to quantify, because it varies considerably over an area, depending on the type of vegetation, its ability to transpire and the availability of water in the soil. The maximum possible water loss from a vegetated land by evaporation plus transpiration under the prevailing meteorological conditions is known as potential evapotranspiration [8]. The total evaporation from an area plus the water used directly in building plant tissues is referred to as consumptive use [6]. In addition to the climatic factors defined below, the consumptive use of water in a vegetation-covered land area is dependent on the supply of soil moisture, growing vegetation, type of soil and methods of land management [7].

Evaporation is a very important hydrological parameter to be taken into account in any water resources studies and in determining water supply requirements. Consumptive use is the key element to be considered in the design of any irrigation system, particularly under extremely arid climates.

5.2 Factors Affecting Evaporation

Meteorological variables and nature of the evaporating surface play an important role in controlling the process of evaporation. The latter affects evaporation by the turbulence it causes to the air flow according to the roughness, irregularities and friction of the surface [8]. The pertinent meteorological factors influencing evaporation rate are [6-8]:

Solar Radiation: Most of the energy required to change liquid water into gaseous state is supplied by the sun. This energy is known as latent heat of vaporization, L. Approximately 600 calories are required for each gram of water to be evaporated. Since solar radiation is the most important single factor, evaporation rate also varies according to latitude, season, time of day and sky condition as being cloudy or bright. Clouds slow down the evaporation.

Temperature: The rate of evaporation is directly proportional to the ambient temperature of both air and evaporating surface, i.e. the vaporization of water proceeds more readily at high temperatures.

Humidity: Air easily absorbs moisture in the form of water vapour. The water vapour capacity of air depends upon the temperatures of the air and of the water. The amount of water vapour that can be taken up by the air before it becomes saturated is known as saturation deficit. More evaporation occurs when air's humidity is low.

Wind Speed: The amount of evaporation is increased as drier air replaces the humid air over the evaporating surface. The movement of air is dependent on the wind and thus the wind speed is an important factor. Evaporation is enhanced in exposed localities since air is allowed to move freely.

Rainfall: Evaporation is appreciably decreased during rainy season. Therefore, valuable water is lost in arid regions through evaporation.

5.3 Measurement of Relative Humidity, Wind Speed and Evaporation

Relative humidity is determined from the daily dry and wet bulb readings. Wind directions and speeds are recorded by Dines pressure tube anemograph having two traces on a graduated chart revolving daily on a clockwork drum (Fig. 5.1.a) or by cup generator anemometer with wind vanes and pressure heads (Figs. 5.1.b and 5.1.c). The most widely used instrument in measuring evaporation in Sudan is the Piche evaporimeter which can give a direct reading of evaporation in millimetres over a chosen time period, usually a day. Piche atmometer is simple, inexpensive and easy to operate. The device that is in common use nowadays all over the world is the US Class A pan [8]. The annual evaporation from Piche evaporemeter has been found to be approximately equivalent to open water evaporation from US Class A pan when the former instrument is exposed in a standard temperature screen [8]. Pan characteristics like undetected leaks, accumulation of debris on the water surface, boundary conditions with the soil and heat exchange through the sides influence the evaporation from pans [22].



Fig. 5.1.a Dines Pressure Tube Anemograph (Photographed at Station of Shambat)



Fig. 5.1.b Cup Anemometers (Photographed at Station of Shambat)



Fig. 5.1.c Cup Generator Anemometer and Wind Vane (Photographed at Station of Shambat)

5.4 Mean Monthly Relative Humidity

Monthly maximum and minimum records on relative humidity were available for eleven stations. Only the mean monthly records could be obtained for Port Sudan. It can be noticed from Figs. 5.2 to 5.13 that the pattern of the monthly relative humidities are characterized by a hump during the rainy season of the year, i.e. reaching the peak. The maximum occurs in November for Port Sudan but occurs in August at the rest of the stations. Excluding Port Sudan, the mean monthly maximum relative humidity ranges between 61 and 87%. Higher values can be registered for Port Sudan in the coastal area of the Red Sea, where the air remains generally humid. The mean monthly minimum relative humidity, on the other hand, varies between 9 and 25%. This minimum occurs in July as in the case of Port Sudan, in April at the stations located between the latitudes of Khartoum and El Fasher, in March at the stations of El Obeid, Nyala and Ed Damazin and finally in February at the stations located in the southern region of the country.

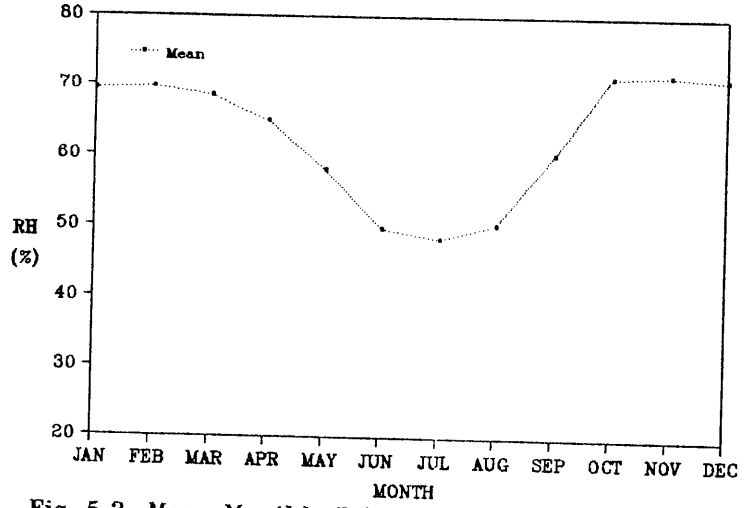


Fig. 5.2 Mean Monthly Relative Humidity (Port Sudan 1961-90)

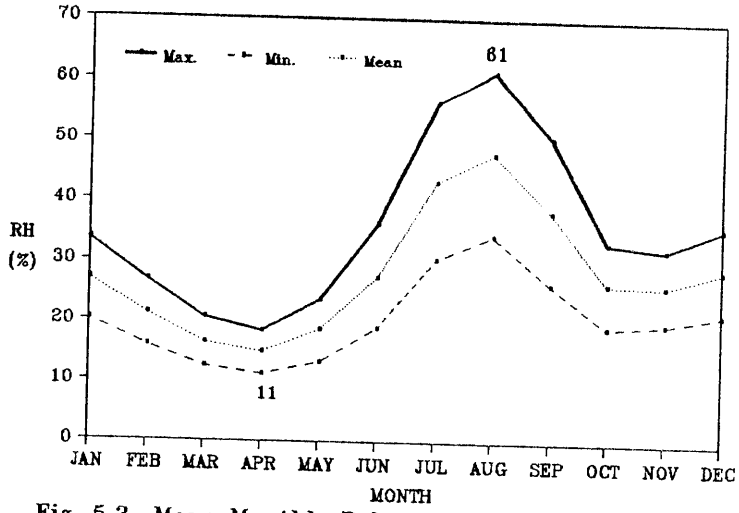


Fig. 5.3 Mean Monthly Relative Humidity (Khartoum 1961-91)

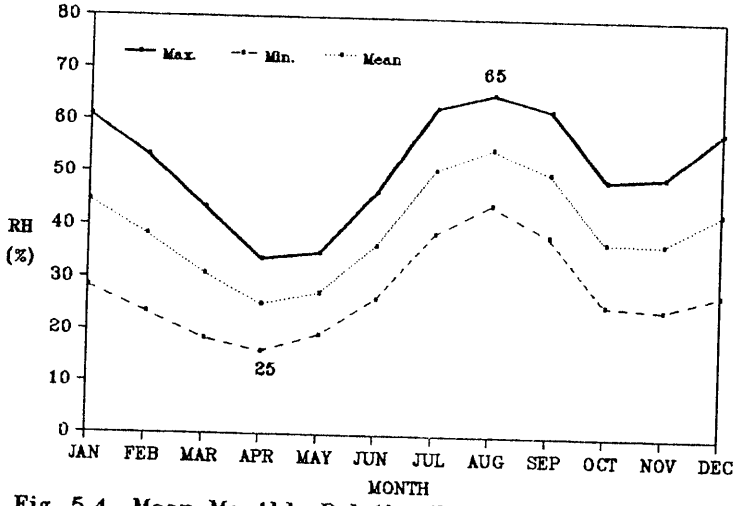


Fig. 5.4 Mean Monthly Relative Humidity (Kassala 1961-91)

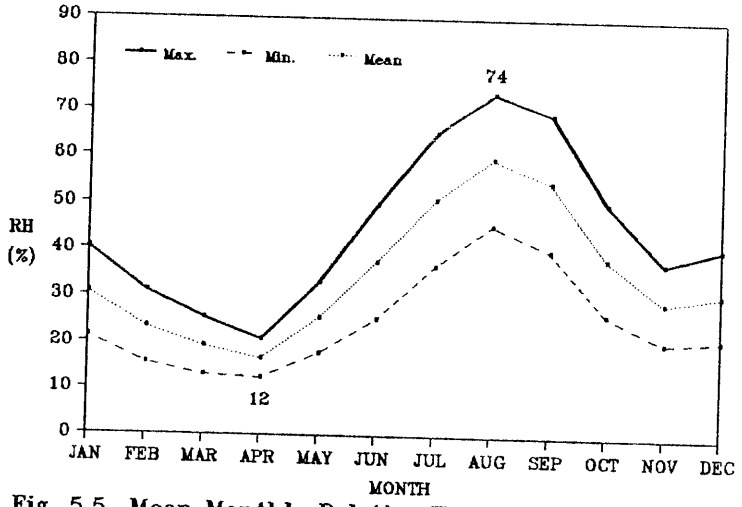


Fig. 5.5 Mean Monthly Relative Humidity (Wad Medani 1961-89)

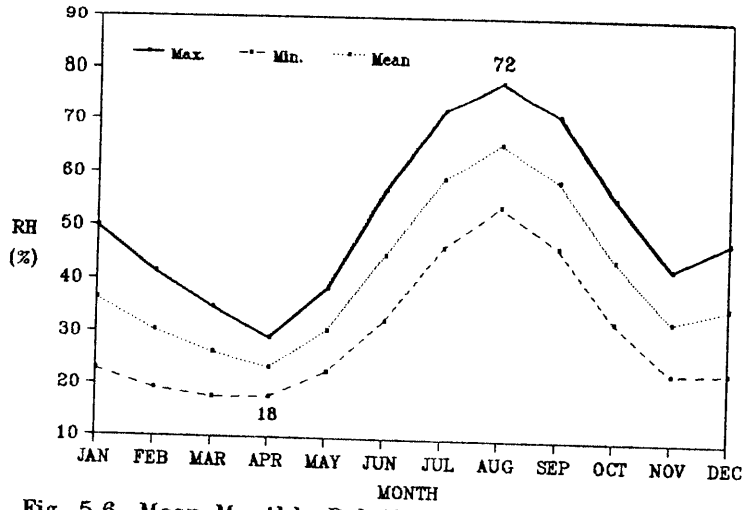


Fig. 5.6 Mean Monthly Relative Humidity (El Gedaref 1961–89)

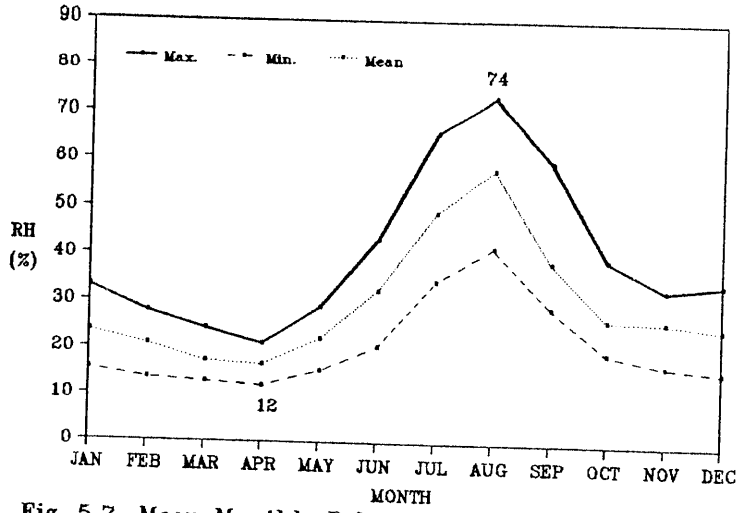


Fig. 5.7 Mean Monthly Relative Humidity (El Fasher 1961–89)

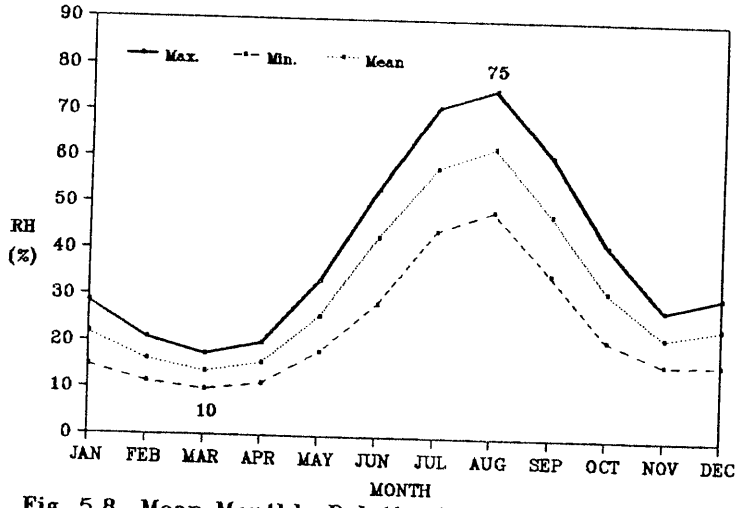


Fig. 5.8 Mean Monthly Relative Humidity (El Obeid 1961–91)

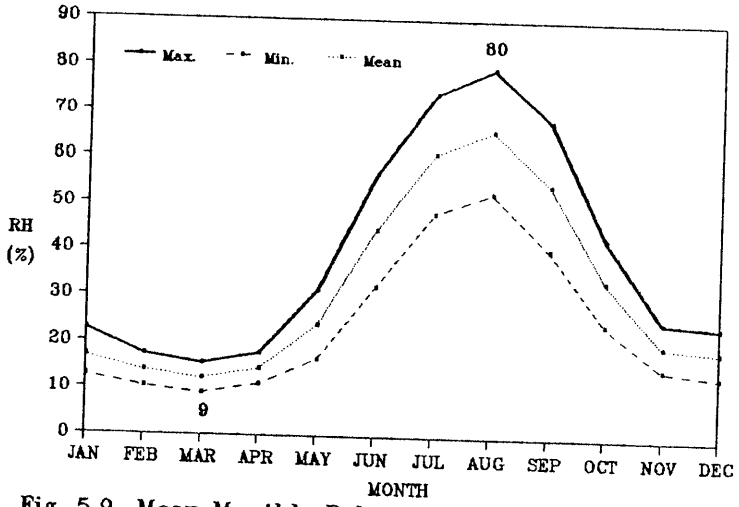


Fig. 5.9 Mean Monthly Relative Humidity (Nyala 1961–91)

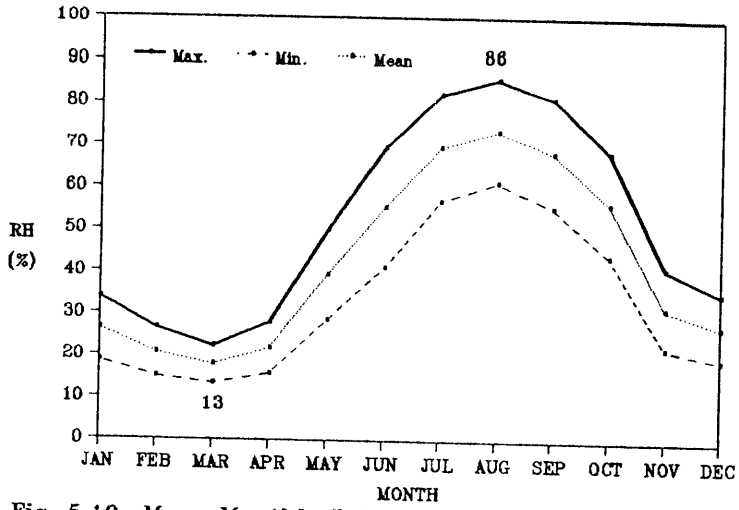


Fig. 5.10 Mean Monthly Relative Humidity (Ed Damazin 1962-91)

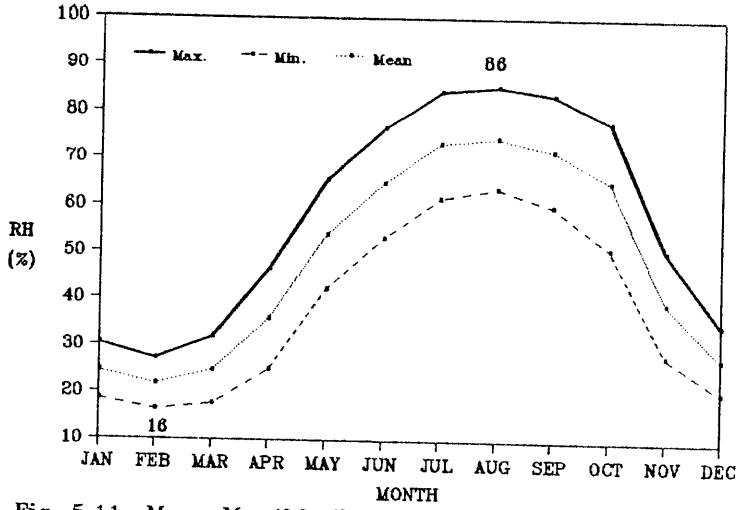


Fig. 5.11 Mean Monthly Relative Humidity (Malakal 1961-91)

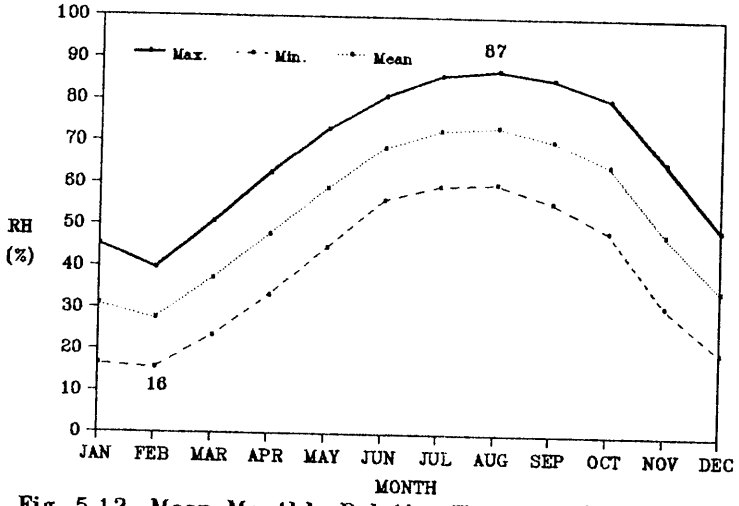


Fig. 5.12 Mean Monthly Relative Humidity (Wau 1961-88)

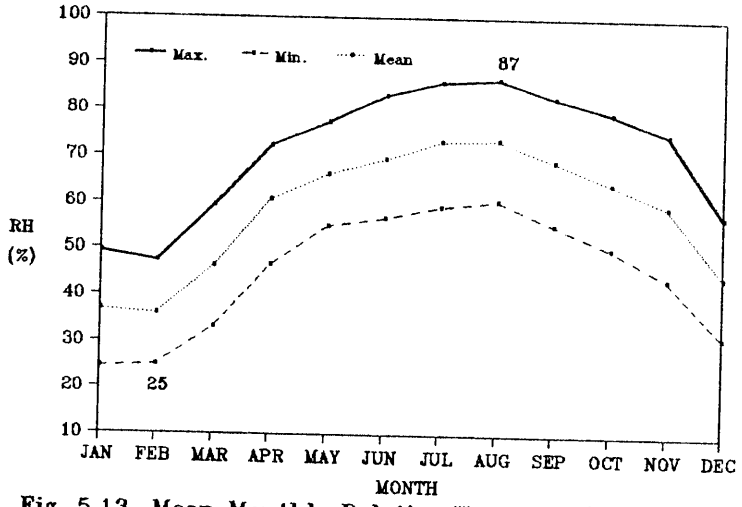


Fig. 5.13 Mean Monthly Relative Humidity (Juba 1961-91)

5.5 Mean Monthly Wind Speed

The available 31-year data of monthly wind speed are averaged and presented in Figs. 5.14 to 5.25 as bar graphs. The pattern of the mean monthly wind speed differs significantly from one station to another. The mean monthly wind speed reaches up to about 9.5 knots (Wad Medani) as maximum and reduces to a minimum of about 1.8 knots (Juba).

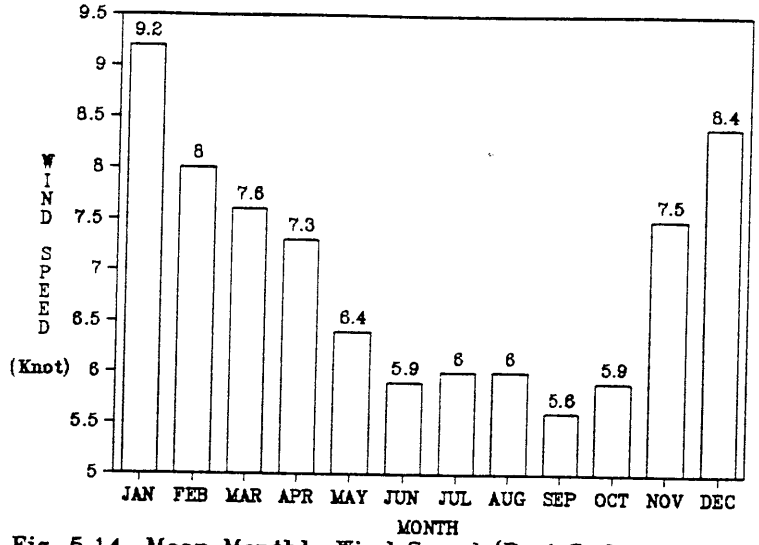


Fig. 5.14 Mean Monthly Wind Speed (Port Sudan 1961-90)

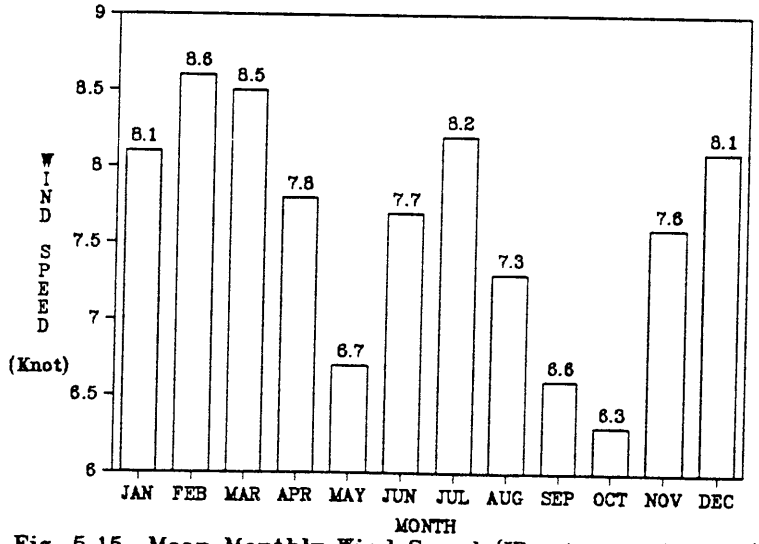


Fig. 5.15 Mean Monthly Wind Speed (Khartoum 1961-91)

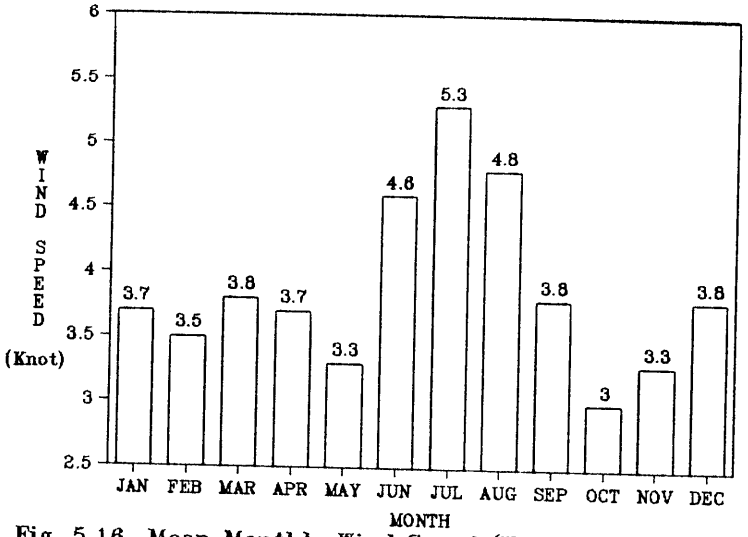


Fig. 5.16 Mean Monthly Wind Speed (Kassala 1961-91)

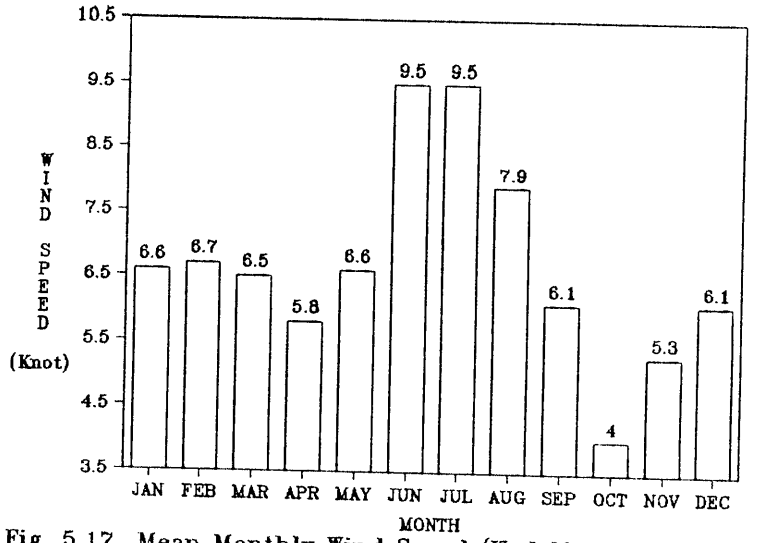


Fig. 5.17 Mean Monthly Wind Speed (Wad Medani 1961-91)

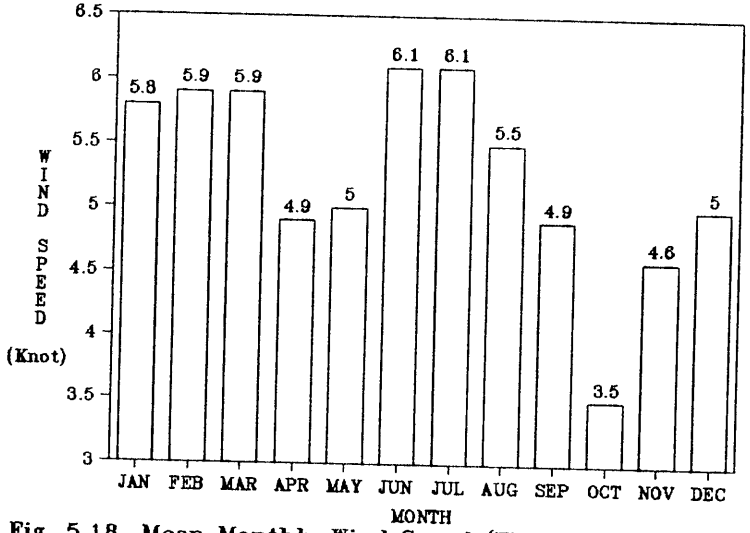


Fig. 5.18 Mean Monthly Wind Speed (El Gedaref 1961-91)

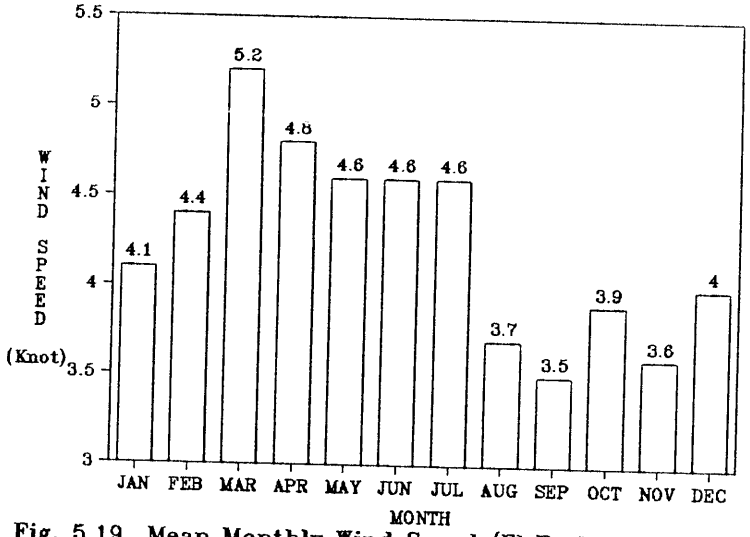


Fig. 5.19 Mean Monthly Wind Speed (El Fasher 1961-91)

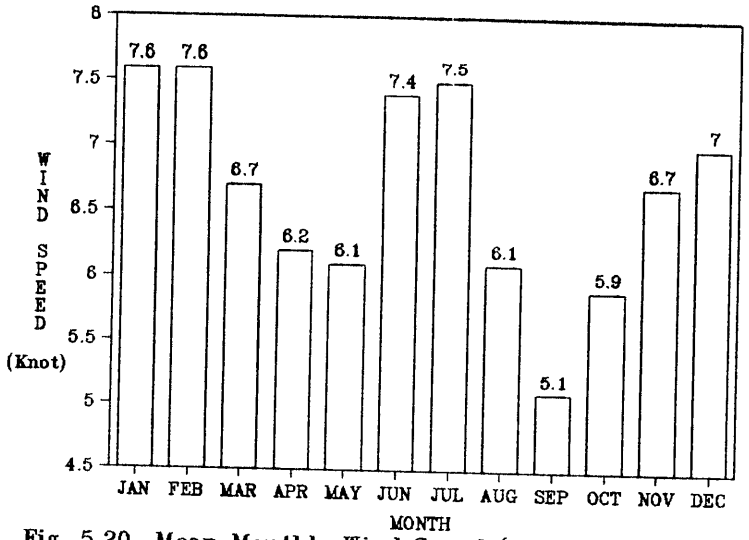


Fig. 5.20 Mean Monthly Wind Speed (El Obeid 1961-91)

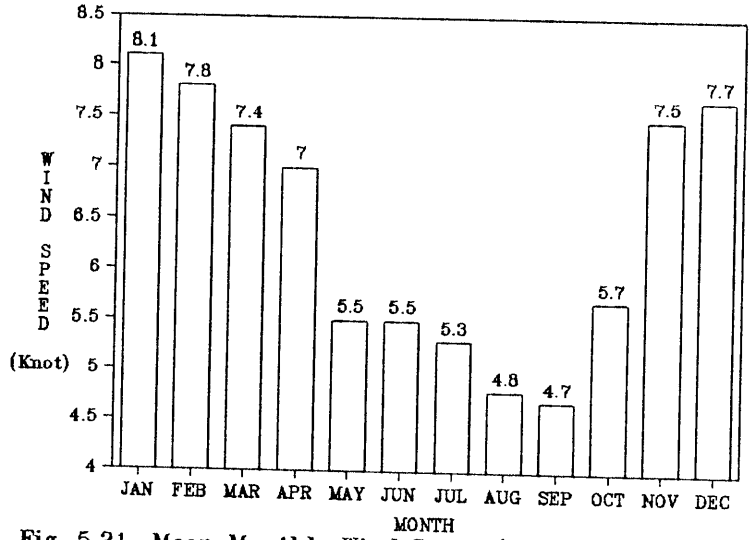


Fig. 5.21 Mean Monthly Wind Speed (Nyala 1961-91)

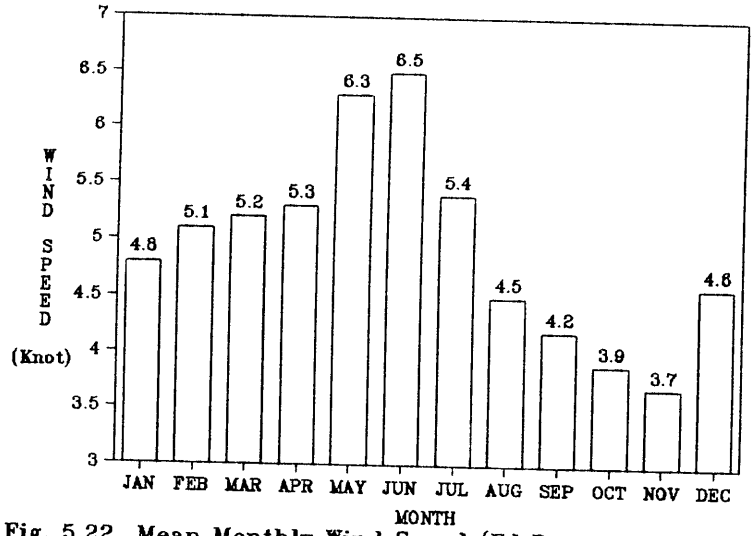


Fig. 5.22 Mean Monthly Wind Speed (Ed Damazin 1961-91)

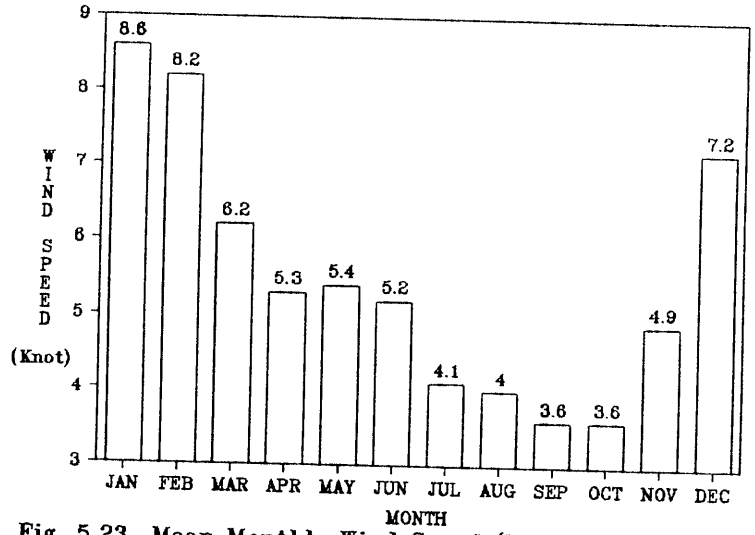


Fig. 5.23 Mean Monthly Wind Speed (Malakal 1961-91)

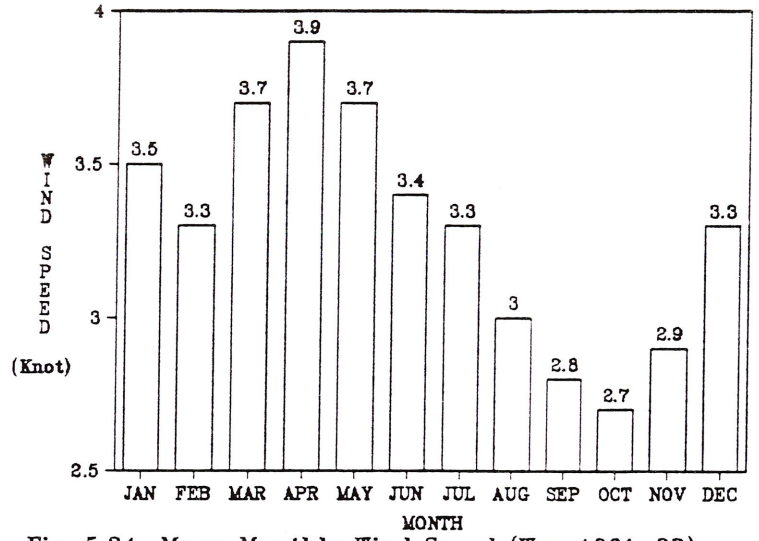


Fig. 5.24 Mean Monthly Wind Speed (Wau 1961-88)

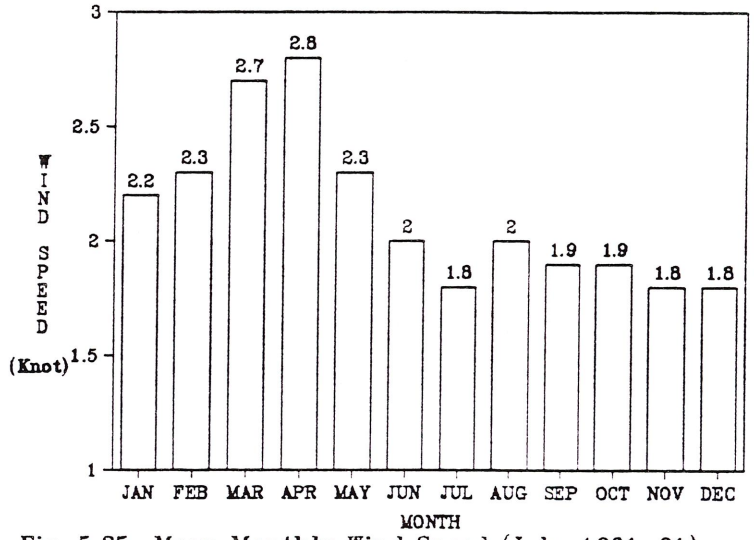


Fig. 5.25 Mean Monthly Wind Speed (Juba 1961-91)

5.6 Estimation of Evaporation and Potential Evapotranspiration from Meteorological Data

The estimation of evaporation and evapotranspiration demonstrated below has been done by a computer program given in the appendix.

5.6.1 Estimation of Evaporation

One of the commonest formulae used for computing evaporation from an open water surface is the one developed by Penman [6-8, 22, 24]. This formula is based on the combined meteorological variables of mean air temperature, relative humidity, wind velocity at a standard height and duration of sunshine regularly

measured at climatological stations. The method of Penman [7] necessitates the satisfaction of two requirements for the achievement of continuous evaporation; the first being the supply of energy to provide latent heat of vaporaization and the second being the mechanism for removing the produced vapour. His method is presented below.

The net amount of radiation absorbed at surface of the earth after reflection, R_I, in g cal/cm^2/day is given by:

$$R_I = H\,(1 - r) \tag{5.1}$$

where H = short wave radiation actually received at the earth's surface from sun and sky in g cal/cm^2/day
r = albedo of water, taken as 0.06

Penman developed an equation for a specific region for the calculation of H, which is of the form of Eq. (4.1) discussed in Chapter 4.

Next, the outgoing radiation from the earth's surface, R_B, in g cal/cm^2/day is expressed as:

$$R_B = \theta\, T_a^4\,(0.47 - 0.077\,\sqrt{e})\,(0.20 + 0.80\,n/N) \tag{5.2}$$

where θ = Lummer and Pringsheim constant = 117.74×10^{-9} g cal/cm^2/day

T_a = absolute earth temperature = t°C + 273 (5.3)

e = actual vapour pressure of air in mm of Hg = $e_s \times RH$ (5.4)

The saturation vapour pressure of water in air, e_s, as a function of temperature is given in a tabulated form [27]. An attempt is made in this study to derive an equation which expresses this relationship. The following exponential equation is obtained for a range of temperature between 0 and 60°C with a correlation factor of 0.998:

$$e_s = 5.120\, e^{0.0591t} \tag{5.5}$$

Moreover, the term RH, which is the relative humidity, is defined as the percentage ratio of e/e_s generally expressed as percentage, i.e. it is a measure of the air's capacity, at its existing temperature, to absorb further moisture.

Thus, the net amount of energy finally remaining at a free water surface, R_n, in g cal/cm^2/day is:

$$R_n = R_I - R_B \tag{5.6}$$

Noting that 600 calories are required to evaporate 1 g of water (equivalent to 1 cm^3), where the depth of evaporation is 1 cm over an area of 1cm^2, the amount of water evaporated by 1 cal is 1/600 cm or 1/60 mm. Hence, the term R_n obtained from Eq. (5.6) is to be multiplied by 1/60 to give the equivalent evaporation in mm per day.

To obtain the open water evaporation in mm per day for the hypothetical case of equal air and water temperatures, given by E_a, the following equation is used:

$$E_a = 0.35\ (e_s - e)\ (0.5 + 0.54\ u_2) \qquad (5.7)$$

where $(e_s - e)$ = saturation deficit (mm Hg)
u_2 = wind speed at 2 m height (m/s)

Now, by differentiating both sides of Eq. (5.5) with respect to t, the slope of saturated vapour pressure–temperature curve, Δ, can be obtained as:

$$\Delta = \frac{d\ e_s}{dt} = 0.3026\ e^{0.0591t} \qquad (5.8)$$

and if γ represents the psycrometer constant which is equal to 0.485 mm of Hg when t is measured in °C, then the evaporation from open water in mm/day, based on the normally occurring case of different air and water surface temperatures, can be found from:

$$E_o = (\Delta\ R_n/60 + \gamma\ E_a)/(\Delta + \gamma) \qquad (5.9)$$

where Eq. (5.9) represents the basic Penmann's equation in its general form.

Example 5.1: Using Penman method explained above, estimation of E_o is made from the following meteorological data for the station of Wad Medani for the month of August.

t = 28.3°C
RH = 60%
u_2 = 7.9 knots = 4.061 m/s
n = 7.7 hours

For Wad Medani:

N = 13.576 hours (Table 4.2)
H_o = 37.54 MJ/m^2/day (Table 4.3) = 896.8 g cal/cm^2/day

Now, from Table 4.5,

$$H = H_o(0.556 + 0.209\ (n/N)^{2.477})$$

Substituting the parameters given above, then H = 544.6 g cal/cm^2/day. Further, substituting the values of H and r in Eq. (5.1), then

$$R_I = 544.6\ (1 - 0.06) = 511.924 \text{ g cal/cm}^2\text{/day}$$

T_a and e_s are found from Eqs. (5.3) and (5.5) respectively as follows:

$$T_a = 28.3 + 273 = 301.3°C$$
$$e_s = 5.120\ e^{(0.0591 \times 28.3)} = 27.267 \text{ mm Hg}$$

From Eq. (5.4),

$$e = 27.267 \times 60/100 = 16.360 \text{ mm Hg}$$

Hence, Eq. (5.2) gives

$$R_B = 117.74 \times 10^{-9} \times 301.3^4\ (0.47 - 0.077\sqrt{16.360}) \times (0.20 + 0.80 \times 7.7/13.576)$$
$$= 970.332 \times 0.159 \times 0.654$$
$$= 100.901 \text{ g cal/cm}^2\text{/day}$$

Thus, R_n from Eq. (5.6) is

$$R_n = 511.924 - 100.901 = 411.023 \text{ g cal/cm}^2\text{/day}$$

Next, using Eq. (5.7)

$$E_a = 0.35\ (27.267 - 16.360)(0.5 + 0.54 \times 4.061)$$
$$= 0.35 \times 10.907 \times 2.963$$
$$= 10.280 \text{ mm/day}$$

Finally, Δ is found from Eq. (5.8) as 1.612. Then

$$E_o = (1.612 \times 411.023/60 + 0.485 \times 10.280)/(1.612 + 0.485)$$
$$= 16.029/2.097$$
$$= 7.6 \text{ mm/day}$$

5.6.2 Estimation of Potential Evapotranspiration

Thornthwaite [7] extensively studied the correlation between temperature and evapotranspiration in the USA and designed a method of estimating potential evapotranspiration using only temperature and duration of possible sunshine. This method has been found to give reasonably good results whatever the vegetation

cover. He derived the following equations wherein the monthly heat index, j, is given as a function of the average monthly temperature of the consecutive months of the year, t_n, in degrees Celsius as:

$$j = (t_n/5)^{1.514} \tag{5.10}$$

where n = 1, 2, 3, ..., 12.

Then the yearly heat index, J, is found from:

$$J = \sum_{1}^{12} j \qquad \text{(for the twelve months)} \tag{5.11}$$

To find the theoretical standard potential evapotranspiration in millimetres per month, based on 30 days and 12 hours of sunshine per day, the following equation is used:

$$PET_x = 16\,(10\,t_n/J)^a \tag{5.12}$$

where

$$a = 675 \times 10^{-9}\,J^3 - 771 \times 10^{-7}\,J^2 + 179 \times 10^{-4}\,J + 0.492 \tag{5.13}$$

Then

$$PET = PET_x \times \frac{N}{360} \tag{5.14}$$

gives the adjusted value of potential evapotranspiration rate in mm/day. To obtain annual potential evapotranspiration, twelve adjusted values are calculated for each of the 12 months and totalled after being multiplied by the number of days in the month.

Example 5.2: Given the average monthly temperatures of the consecutive months of the year for Juba as 28.3, 29.5, 30.2, 29.1, 27.8, 26.8, 25.8, 25.8, 26.6, 27.3, 27.6 and 27.2°C respectively, estimate the PET for the month of May by Thornthwaite method.

Using Eq. (5.10), for the month of January,

$$j = (28.3/5)^{1.514}$$
$$= 13.796$$

Similarly, the j values for the next consecutive months (February to December) are calculated as 14.692, 15.223, 14.391, 13.429, 12.704, 11.994, 11.994, 12.561, 13.065, 13.283 and 12.993 respectively.

Thus, using Eq. (5.11), the summation of the above j values is J = 160.125. Then by substituting the value of J in Eq. (5.13), a = 4.153.

Next, PET_x for May is obtained from Eq. (5.12) as:

$$PET_x = 16\,(10 \times 27.8/160.125)^{4.153}$$
$$= 158.081 \text{ mm/month}$$

N = 12.344 hours (Table 4.2). Thus, the adjusted value of PET per day is found from Eq. (5.14) as:

$$PET = 158.081 \times 12.344/360$$
$$= 5.4 \text{ mm/day}$$

Finally, the monthly PET value is obtained by multiplying the above PET value for the day by the number of days in May, i.e.

$$\text{PET for the month of May} = 5.4 \times 31$$
$$= 167.4 \text{ mm}$$

5.7 Mean Monthly and Mean Annual Evaporation Rates

The daily rates of Piche evaporation are averaged and presented in Figs. 5.26 through 5.37. Since Piche evaporation, E_p, for the months provides only an indication of the evaporation rather than the precise measurement of it [3, 28], Penman evaporations are computed and the configuration of the monthly patterns is depicted in the figures as well. Piche evaporation increases till it reaches its maximum value in early summer, but it is considerably disturbed during the autumn giving its minimum value in the rainiest month. Comparing for all the stations, the maximum daily Penman evaporation is around 9.8 mm during June in Wad Medani and the minimum is around 4.1 mm during December in Kassala.

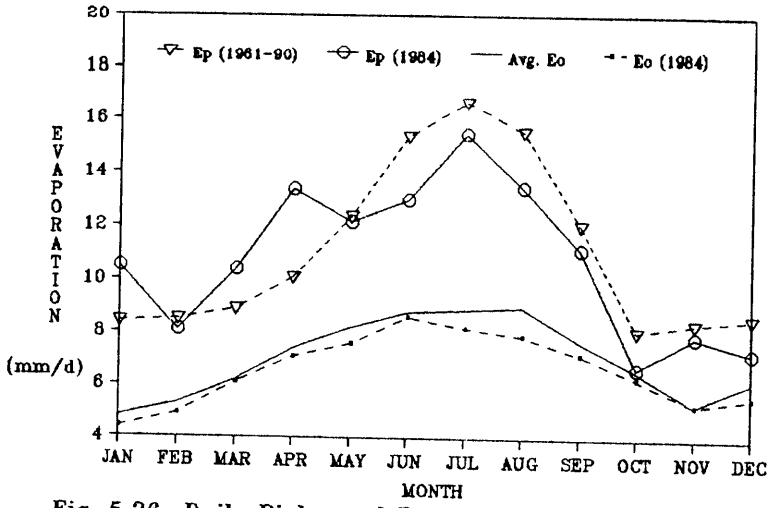


Fig. 5.26 Daily Piche and Penman Evaporation Rates (Port Sudan)

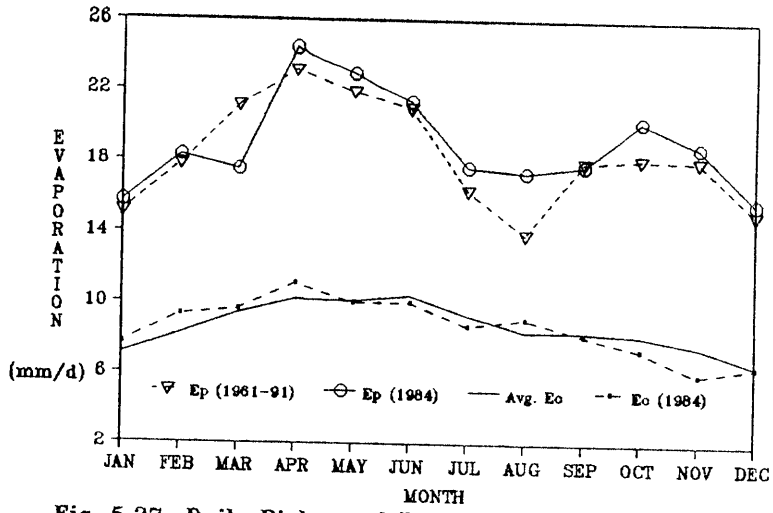


Fig. 5.27 Daily Piche and Penman Evaporation Rates (Khartoum)

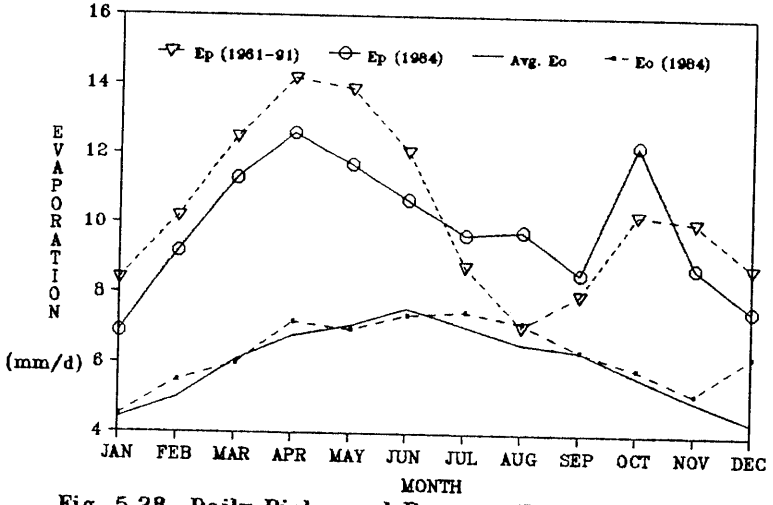


Fig. 5.28 Daily Piche and Penman Evaporation Rates (Kassala)

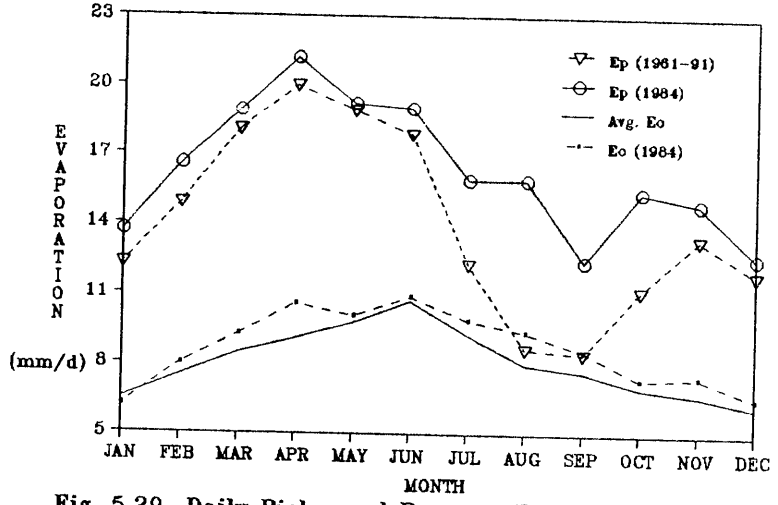


Fig. 5.29 Daily Piche and Penman Evaporation Rates (Wad Medani)

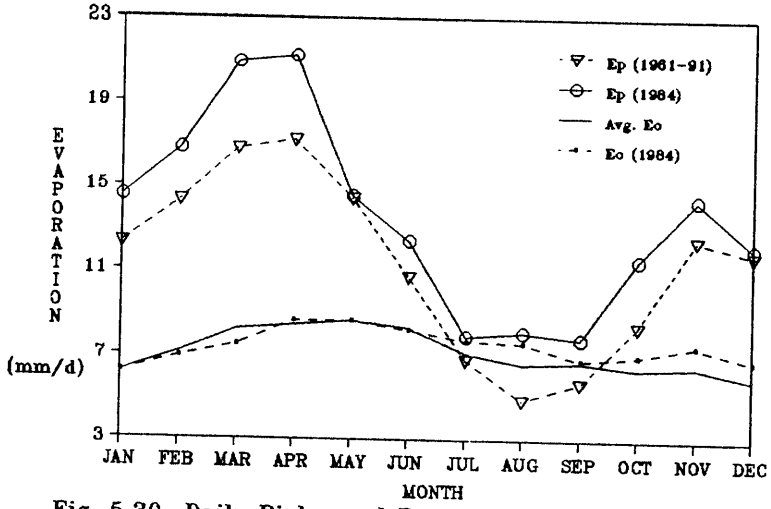


Fig. 5.30 Daily Piche and Penman Evaporation Rates (El Gedaref)

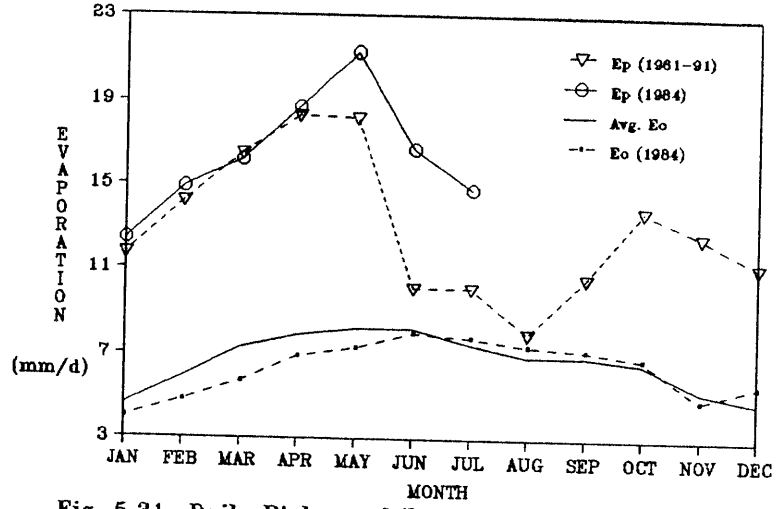


Fig. 5.31 Daily Piche and Penman Evaporation Rates (El Fasher)

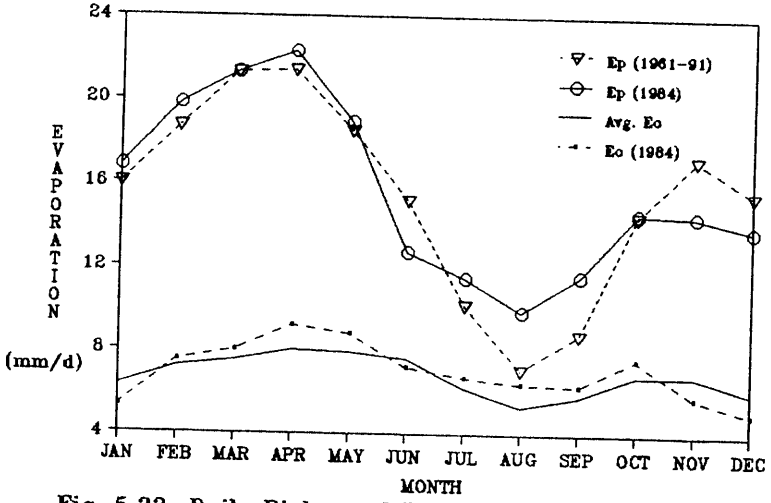


Fig. 5.32 Daily Piche and Penman Evaporation Rates (El Obeid)

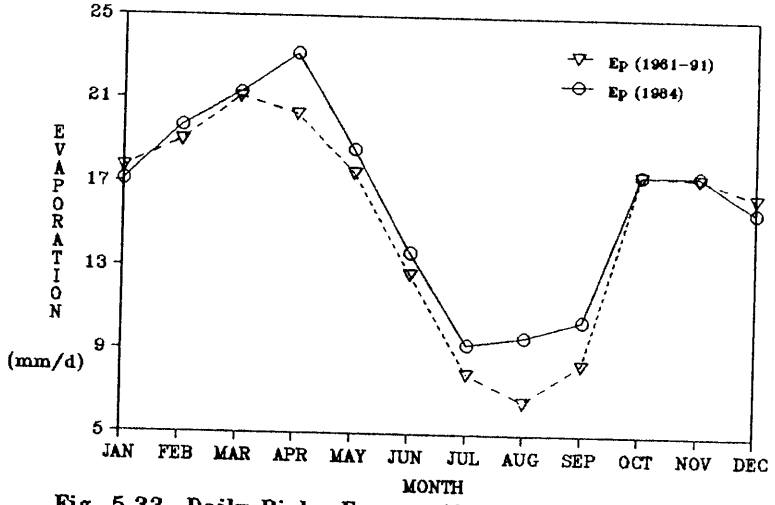


Fig. 5.33 Daily Piche Evaporation Rate (Nyala)

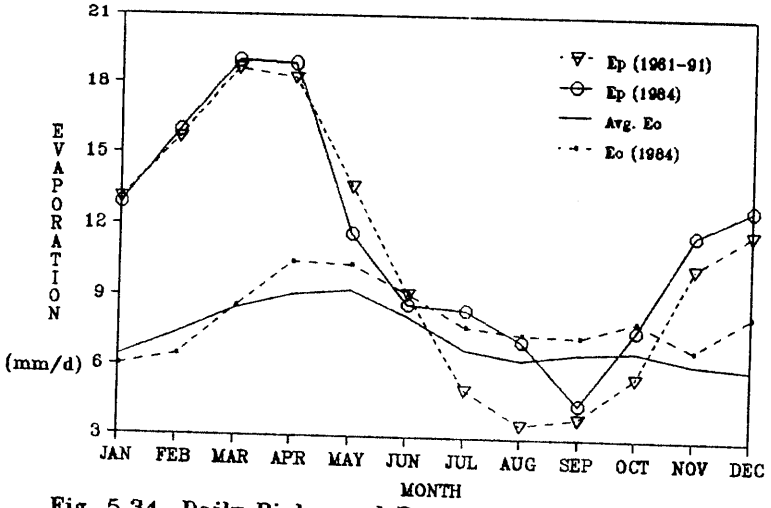


Fig. 5.34 Daily Piche and Penman Evaporation Rates (Ed Damazin)

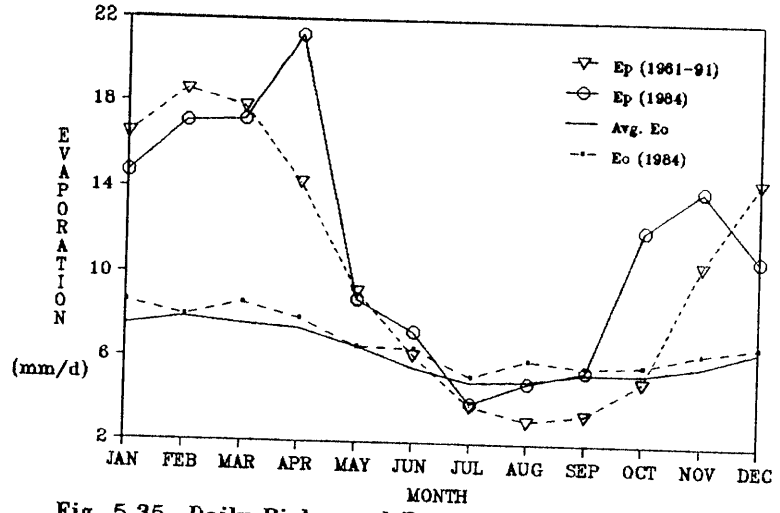


Fig. 5.35 Daily Piche and Penman Evaporation Rates (Malakal)

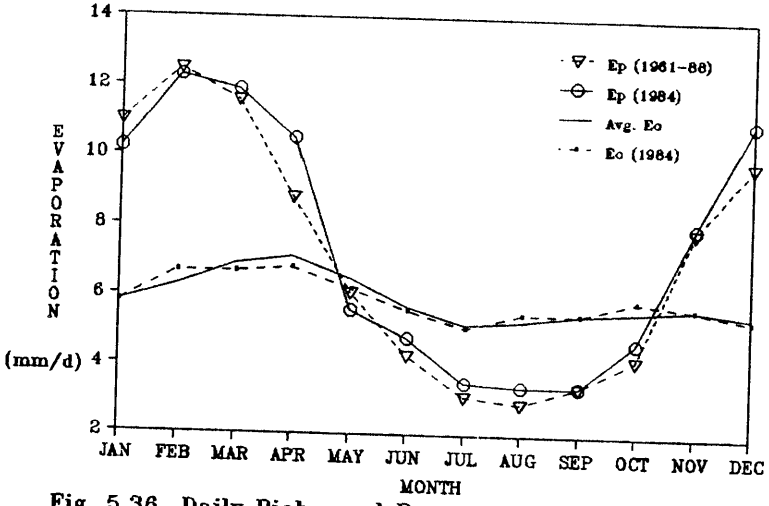


Fig. 5.36 Daily Piche and Penman Evaporation Rates (Wau)

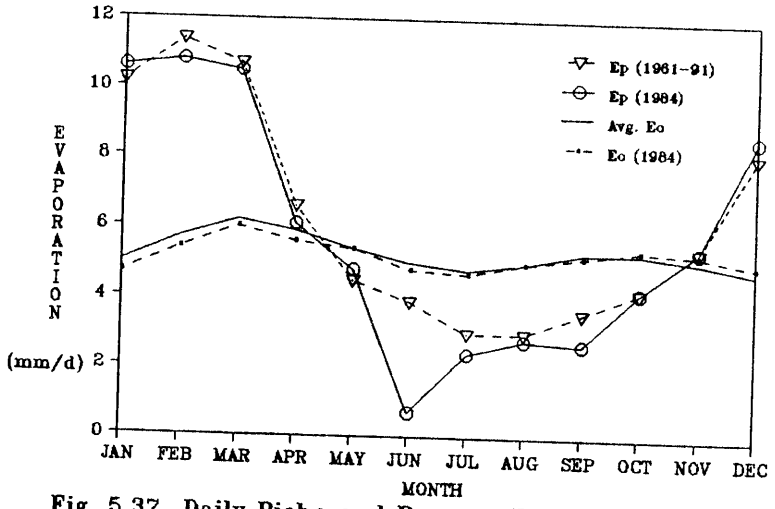


Fig. 5.37 Daily Piche and Penman Evaporation Rates (Juba)

On the other hand, the distribution of the total annual Penman evaporation among the stations, given in Table 5.1, shows that the evaporation is quite enormous. Around 1840-2932 mm can be evaporated annually. The maximum evaporation occurs in Khartoum, whereas the minimum occurs in Juba.

Table 5.1 Mean and 1984 Annual Evaporations in mm

Station	Piche		Penman	
	Mean	1984	Mean	1984
Port Sudan	4057.7	3959.0	2423.4	2287.4
Khartoum	6662.0	6930.6	2931.5	2907.1
Kassala	3781.0	3636.1	2044.8	2142.7
Wad Medani	5107.4	5966.0	2772.4	2958.4
El Gedaref	4118.2	4935.7	2457.4	2554.9
El Fasher	4715.6	-	2339.6	2227.3
El Obeid	5601.1	5718.0	2004.2	2521.9
Nyala	5559.7	5906.6	-	-
Ed Damazin	3912.2	4257.9	2531.6	2795.1
Malakal	3719.1	4189.5	2301.5	2506.6
Wau	2591.4	2717.0	2063.5	2053.8
Juba	2263.3	2121.1	1839.9	1815.4

It can be noticed from the figures that the difference in values found by using Penman method and those obtained by Piche instrument is very substantial. Due to the heat storage effects (heat gain or heat loss through the sides and bottom of measuring device of evaporation) and other pan characteristics mentioned in Section 5.3, the application of coefficients (lake-to-pan evaporation) was proposed to adjust pan evaporation [3, 6-8, 22]. Similarly, Piche coefficients, C_p, are obtained to give Penman estimates of reservoir evaporation from Piche measurements as follows:

$$C_p = E_o/E_p \tag{5.15}$$

The monthly and annual ratios for the stations considered in this study are given in Table 5.2. The table demonstrates that the monthly coefficients vary over different climatic regions from 0.33 to 1.74. On an annual basis, a range of 0.42 to 0.81 can be noted.

Table 5.2 Piche Coefficients, Cp

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Port Sudan	0.55	0.60	0.67	0.70	0.63	0.53	0.49	0.53	0.60	0.76	0.60	0.69	0.60
Khartoum	0.46	0.45	0.42	0.40	0.42	0.45	0.53	0.56	0.43	0.41	0.39	0.42	0.44
Kassala	0.50	0.46	0.45	0.44	0.46	0.58	0.76	0.89	0.78	0.51	0.45	0.47	0.54
Wad Medani	0.51	0.48	0.44	0.42	0.48	0.55	0.71	0.88	0.86	0.59	0.47	0.50	0.54
El Gedaref	0.48	0.47	0.46	0.45	0.55	0.73	1.00	1.30	1.12	0.72	0.48	0.47	0.60
El Fasher	0.40	0.41	0.42	0.41	0.42	0.76	0.71	0.82	0.62	0.46	0.41	0.42	0.50
El Obeid	0.39	0.37	0.33	0.35	0.39	0.46	0.56	0.71	0.62	0.44	0.38	0.37	0.42
Ed Damazin	0.46	0.44	0.42	0.46	0.63	0.84	1.30	1.74	1.67	1.14	0.57	0.49	0.65
Malakal	0.45	0.43	0.43	0.52	0.72	0.90	1.29	1.63	1.59	1.08	0.55	0.45	0.62
Wau	0.50	0.48	0.56	0.76	1.01	1.28	1.64	1.73	1.56	1.28	0.69	0.54	0.80
Juba	0.46	0.47	0.55	0.85	1.15	1.23	1.55	1.63	1.41	1.19	0.89	0.56	0.81

Monthly coefficient varies depending on the climatic regimes [22]. As Class A pan water temperature in dry seasons and arid areas is less than air temperature, the coefficient may be 0.60 or less, whereas in humid seasons and climates, 0.80 or higher values of pan coefficients can be noted as the temperature of pan water is higher than air temperature [22]. Thus, it is satisfying to note that C_p values, given in Table 5.2, for the areas studied (during wet and dry periods of the year) are quite comparable with these ranges. Further, the estimated coefficients compare with those obtained by Salih et al [3] for some regions of Sudan. This finding confirms the suitability of the correlations developed in Chapter 4 for the purpose of estimating solar radiation.

5.8 Mean Monthly and Mean Annual Potential Evapotranspiration Rates

Figs. 5.38 to 5.49 show the monthly variation of mean daily potential evapotranspiration computed by Thornthwaite method. The pattern resembles more closely that of temperature. The water loss from vegetation-covered land areas is enhanced in the summer, but it slows down during the winter and autumn. 16.4 mm per day can be lost during the month of August in Port Sudan, constituting the mean maximum among the stations. The average water loss can reach a minimum value of 0.8 mm per day as observed for El Fasher during January.

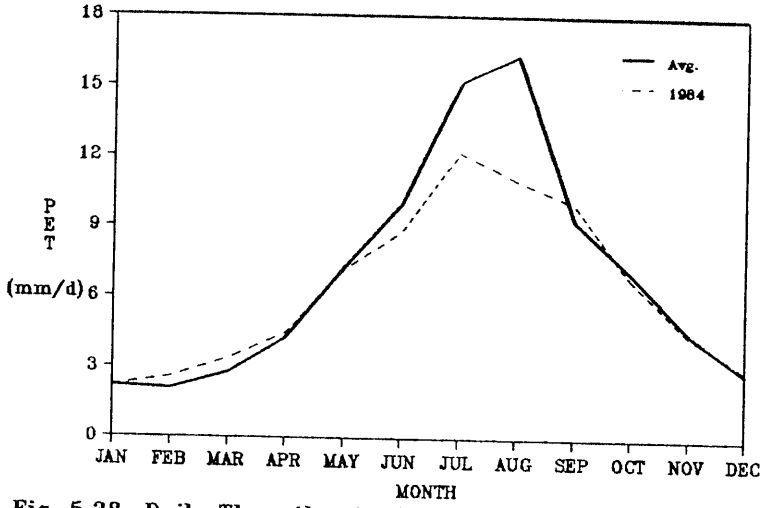


Fig. 5.38 Daily Thornthwaite Potential Evapotranspiration Rate (Port Sudan)

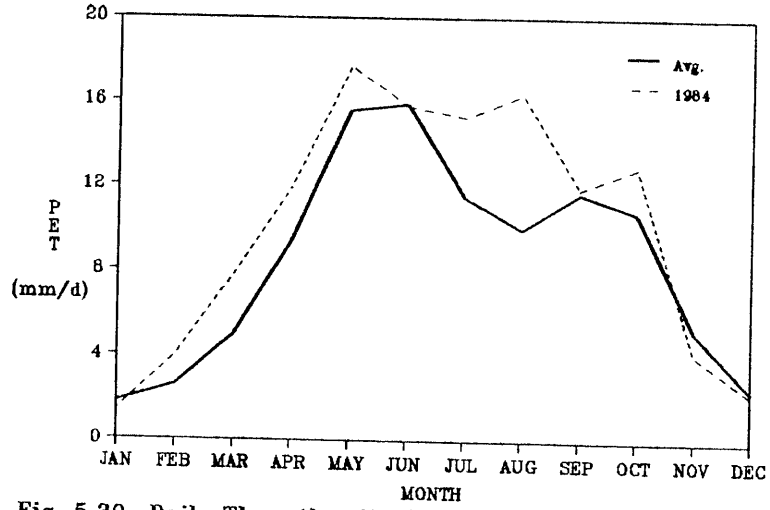


Fig. 5.39 Daily Thornthwaite Potential Evapotranspiration Rate (Khartoum)

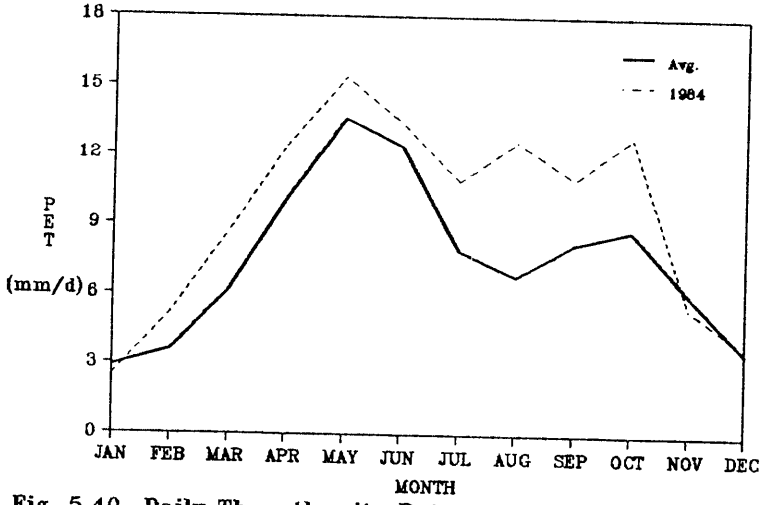


Fig. 5.40 Daily Thornthwaite Potential Evapotranspiration Rate (Kassala)

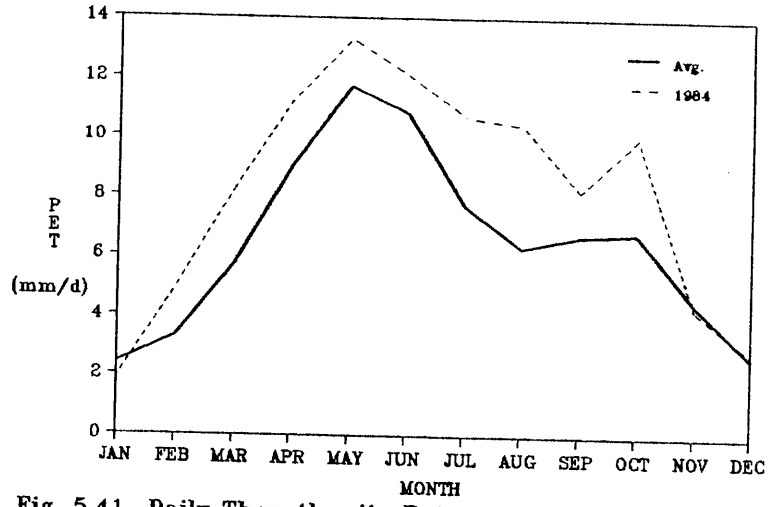


Fig. 5.41 Daily Thornthwaite Potential Evapotranspiration Rate (Wad Medani)

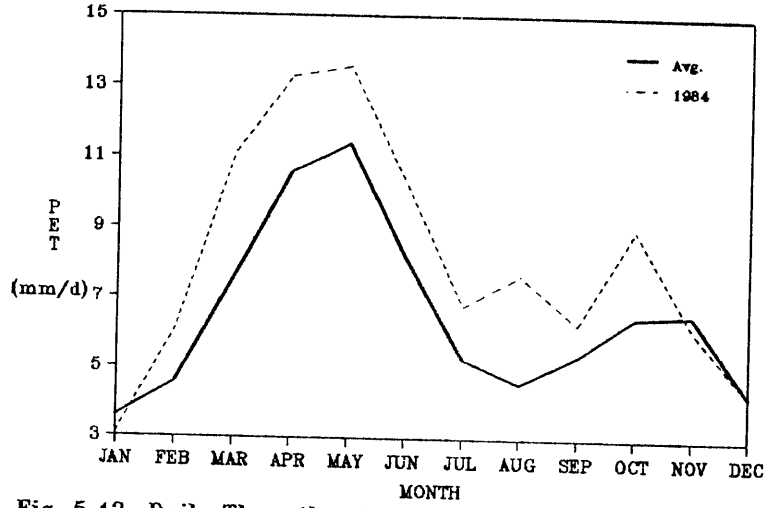


Fig. 5.42 Daily Thornthwaite Potential Evapotranspiration Rate (El Gedaref)

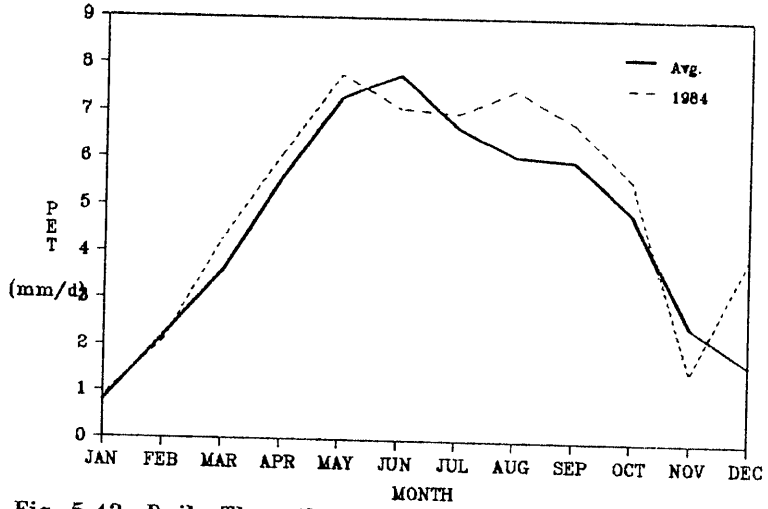


Fig. 5.43 Daily Thornthwaite Potential Evapotranspiration Rate (El Fasher)

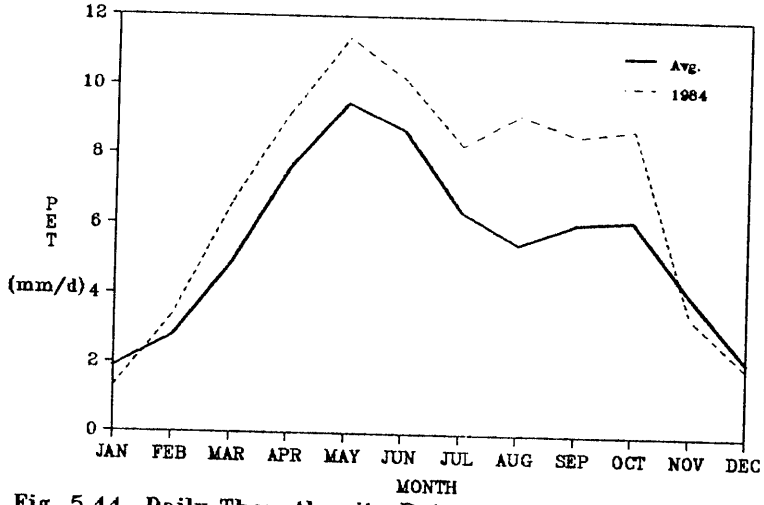


Fig. 5.44 Daily Thornthwaite Potential Evapotranspiration Rate (El Obeid)

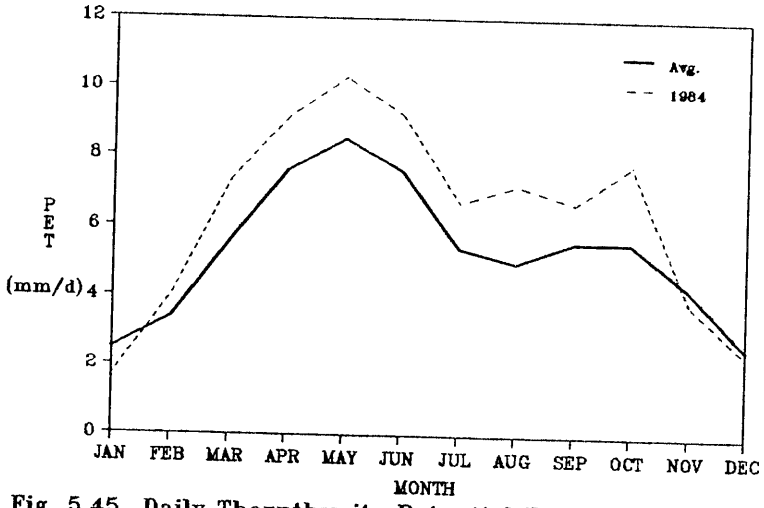


Fig. 5.45 Daily Thornthwaite Potential Evapotranspiration Rate (Nyala)

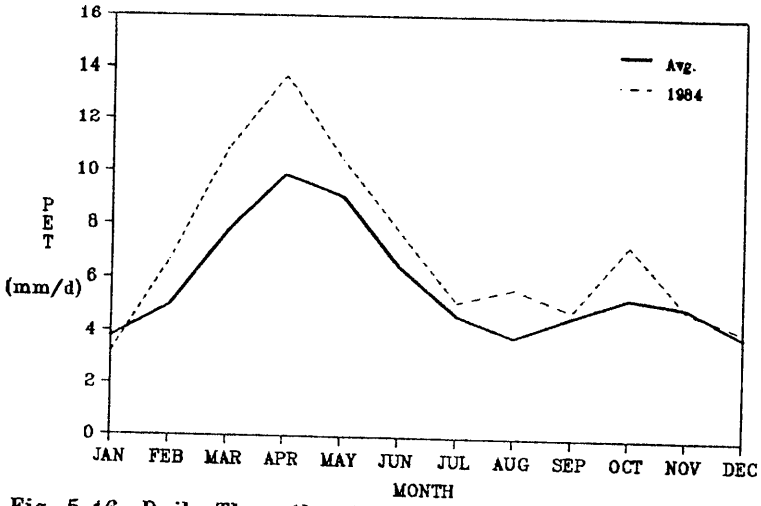


Fig. 5.46 Daily Thornthwaite Potential Evapotranspiration Rate (Ed Damazin)

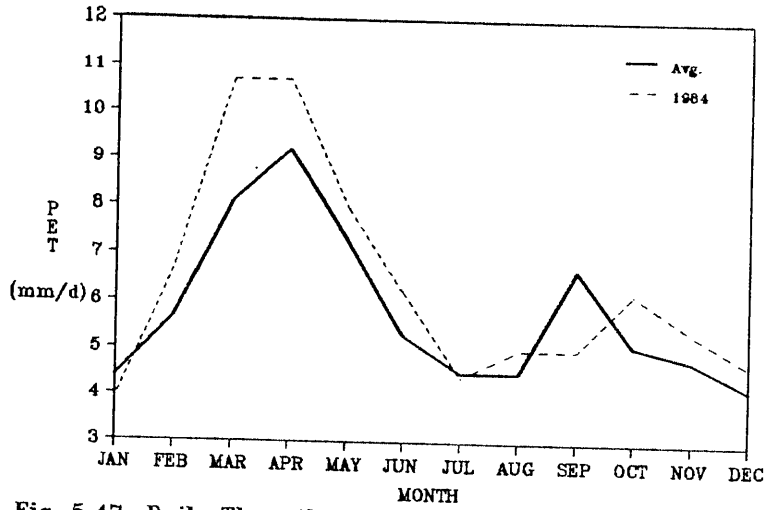


Fig. 5.47 Daily Thornthwaite Potential Evapotranspiration Rate (Malakal)

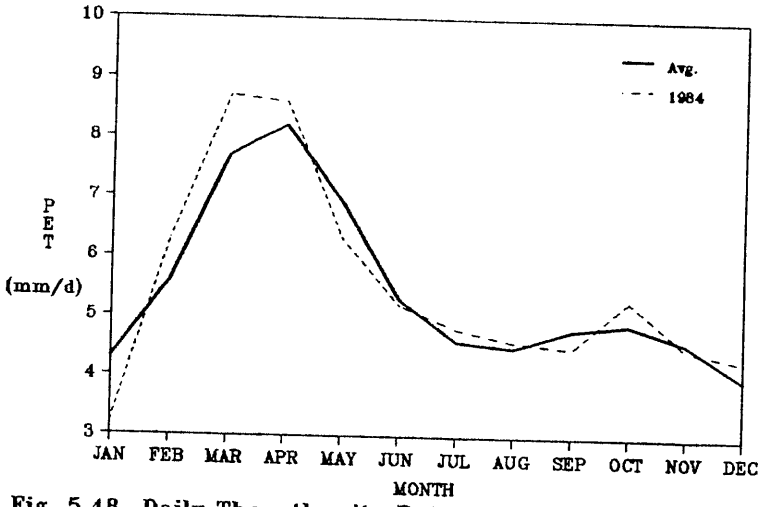


Fig. 5.48 Daily Thornthwaite Potential Evapotranspiration Rate (Wau)

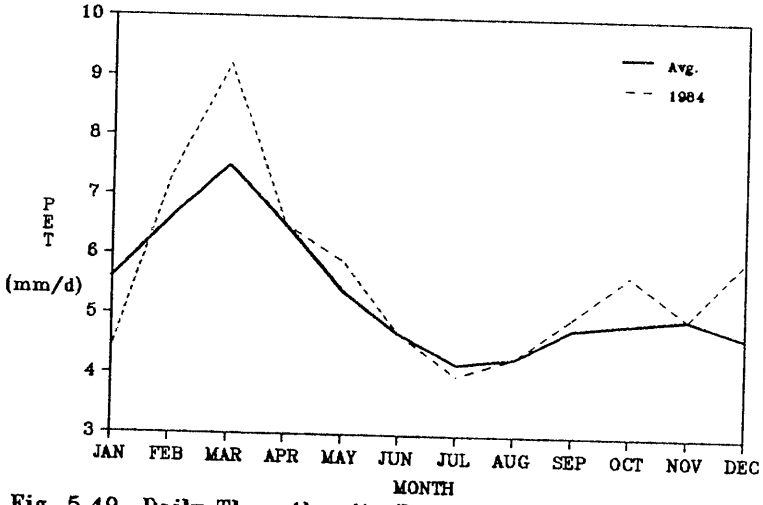


Fig. 5.49 Daily Thornthwaite Potential Evapotranspiration Rate (Juba)

The mean annual potential evapotranspiration presented in Table 5.3 suggests that Khartoum has the maximum PET value of about 3114 mm per year and El Fasher has the minimum value of around 1680 mm per year.

Table 5.3 Mean and 1984 Annual Potential Evapotranspirations in mm

Station	Thornthwaite	
	Mean	1984
Port Sudan	2574.3	2328.7
Khartoum	3113.5	3717.4
Kassala	2745.2	3484.1
Wad Medani	2368.4	2991.9
El Gedaref	2395.8	2982.1
El Fasher	1679.9	1855.0
El Obeid	2004.2	2521.9
Nyala	1937.8	2324.5
Ed Damazin	2125.9	2595.6
Malakal	2124.8	2344.5
Wau	1989.2	2028.4
Juba	1949.1	2075.0

To determine how the potential evapotranspiration from vegetated land compares with open water evaporation, the ratio PET/E_o is computed on both monthly and annual basis as provided in Table 5.4. The range of the monthly PET/E_o is limited to within 0.18-2.11 and that of the annual ratios is limited to within 0.72-1.34. If it is required to estimate the PET from E_p, this ratio is directly multiplied by $C_p \times E_p$.

Table 5.4 Values of PET/Eo Ratio

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Port Sudan	0.48	0.42	0.46	0.61	0.93	1.22	1.85	2.00	1.29	1.15	0.91	0.48	1.06
Khartoum	0.26	0.33	0.57	1.00	1.71	1.70	1.33	1.28	1.52	1.45	0.74	0.39	1.06
Kassala	0.70	0.76	1.08	1.62	2.11	1.76	1.18	1.08	1.38	1.68	1.33	0.86	1.34
Wad Medani	0.38	0.46	0.71	1.07	1.30	1.10	0.89	0.83	0.92	1.04	0.72	0.45	0.85
El Gedaref	0.62	0.69	0.99	1.36	1.43	1.06	0.79	0.73	0.84	1.08	1.10	0.77	0.97
El Fasher	0.18	0.37	0.51	0.74	0.95	1.02	0.93	0.91	0.90	0.78	0.50	0.35	0.72
El Obeid	0.31	0.40	0.70	1.02	1.31	1.24	1.10	1.10	1.12	0.98	0.63	0.38	0.86
Ed Damazin	0.63	0.72	0.99	1.17	1.05	0.84	0.72	0.62	0.73	0.83	0.87	0.68	0.84
Malakal	0.59	0.72	1.07	1.24	1.10	0.95	0.93	0.90	1.24	0.94	0.83	0.64	0.92
Wau	0.77	0.95	1.17	1.23	1.12	0.97	0.90	0.89	0.91	0.90	0.86	0.77	0.96
Juba	1.19	1.24	1.27	1.45	1.04	0.98	0.91	0.89	0.95	0.96	1.04	1.04	1.06

Chapter 6

FLOW OF THE RIVER NILE AND THE TRIBUTARIES

FLOW OF THE RIVER NILE AND THE TRIBUTARIES

6.1 General Hydrological Features

Fig. 1.4 shows the River Nile and its tributaries which comprise some of the land of Sudan. Following is a brief description of the hydrological features of the Nile basin [3, 4, 29]:

The River Nile is the longest river in the world (6,671 km). It receives its water from three main basins, namely the equatorial lakes plateau which comprises the lakes Victoria, Kioga, George, Edward and Albert, Bahr El Ghazal basin and the basins of the rivers Sobat, the Blue Nile and Atbara. The contributions of the basins to the Nile flow differ considerably. The Nile flow fluctuates both seasonally and annually.

6.1.1 Bahr El Jebel

The Nile enters Sudan at Nimule. Between Nimule and Mongolla, it is characterized by a rapid flow in between mountains, so it is named as Bahr El Jebel. The main sources of Bahr El Jebel are the equatorial lakes and several seasonal torrential rivers of the south-east Sudan. North of Mongolla, the river passes through the swamps of the Sudd region where nearly 50% of its discharge is lost by evaporation and over-spilling. The river reaches Lake No afterwards where it is joined by Bahr El Ghazal.

6.1.2 Bahr El Ghazal

The basin of Bahr El Ghazal comprises the catchments of about 20 tributaries. The river passes through swamps and loses approximately over 98% of its water. The rest reaches the White Nile and thus contributes virtually nothing to the Nile.

6.1.2 White Nile

Just under half the discharge of the White Nile comes from river Sobat which joins in at Malakal after about 128 kilometres form Lake No. The total length of the White Nile from Lake No to Khartoum is about 960 kilometres.

6.1.4 River Sobat

River Sobat is the principal tributary of the Whit Nile. It is strongly seasonal, fed through the Baro and the Pibor. The former rises and runs almost

in Ethiopia and the latter runs in Sudan but drains most of its water from Ethiopia as well. All the streams forming the Sobat are characterized by overflow and water loss through the swamps they create on reaching the flat plain.

6.1.5 Blue Nile

The Blue Nile runs steeply from Lake Tana in Ethiopia and joins the White Nile at Khartoum. Its course in Sudan is nearly 800 kilometres long. Lake Tana contributes only about 7% of its discharge. Between Khartoum and Sennar, the Blue Nile is joined by two tributaries, Dindir and Rahad rivers through which about 10% of the total flood water of the Blue Nile is drawn. These two tributaries are seasonal and dry up to form a series of pools.

6.1.6 River Atbara

River Atbara joins the Main Nile about 320 kilometres north of Khartoum and gets its water from the northern part of the Ethiopian plateau. This river as well as its major tributaries, viz. Bahr El Salam, Setit and Atbara, are seasonal and torrential.

6.1.7 Main Nile

At Khartoum, the confluence of the White and Blue Niles, the Main Nile forms and flows to Lake Aswan along a 1,520 kilometres course in Sudan.

6.2 Annual River Flow

The configurations of the annual flow series of the rivers under consideration are presented in Figs. 6.1 to 6.8. The series for rivers Dindir and Rahad are presented as bar graphs to show the discontinuity of records. All the series are mainly characterized by ups and downs. The highest and lowest flows are indicated in the figures. A long duration jump starting from 1962 and lasting for about 20 years is seen at Malakal gauging station on the White Nile. Noordwijk [4] and Shahin [30] explained the existance of this jump by the corresponding jump in the water level of Lake Victoria during the same period. The time series also show exceptionally high flows during the second decade of this century and in 1988.

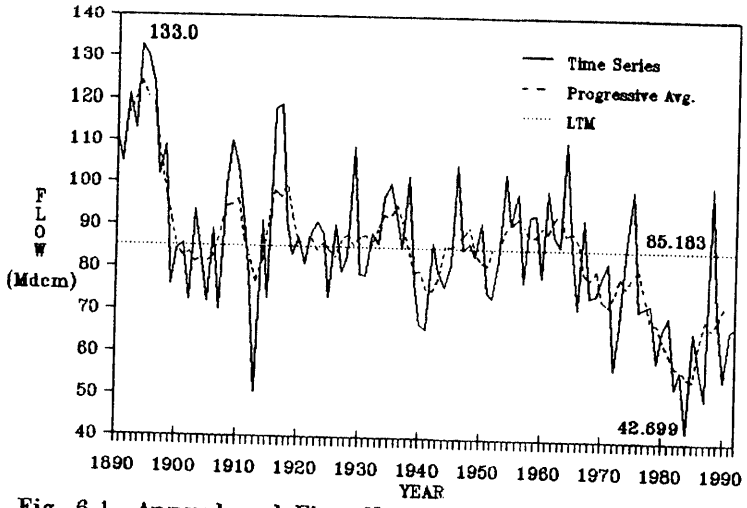


Fig. 6.1 Annual and Five-Year Moving Average Flows of the Main Nile at Wadi Halfa/Dongola

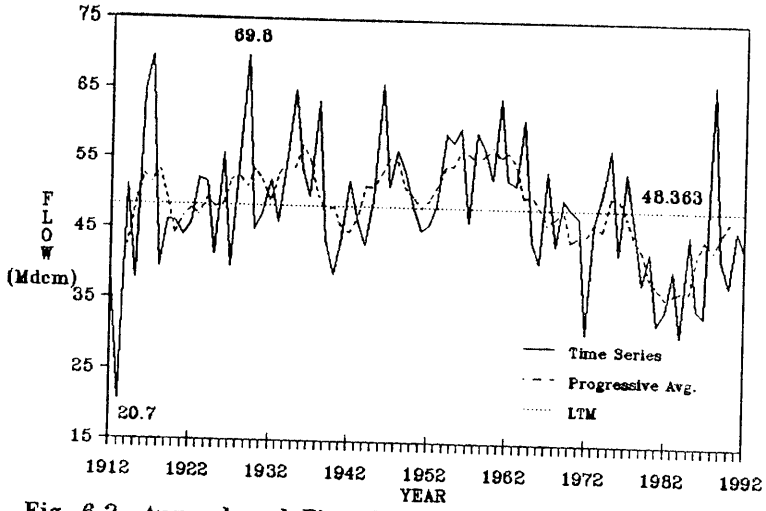


Fig. 6.2 Annual and Five-Year Moving Average Flows of the Blue Nile at Er Roseires/Ed Deim

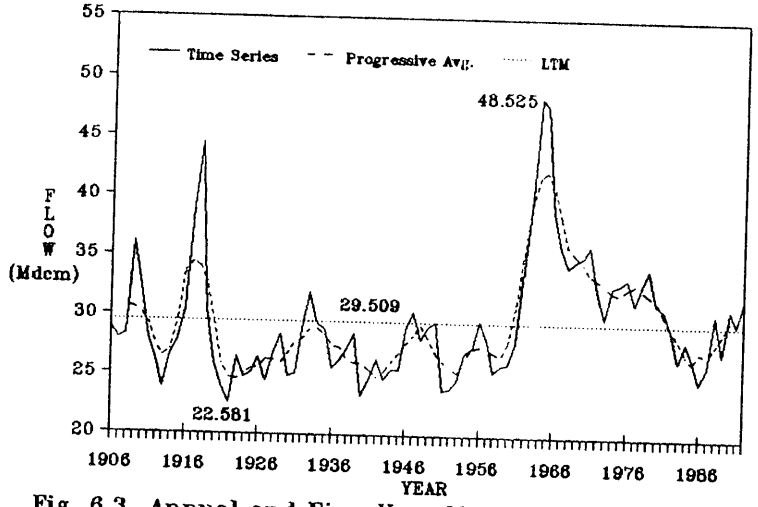


Fig. 6.3 Annual and Five-Year Moving Average Flows of the White Nile at Malakal

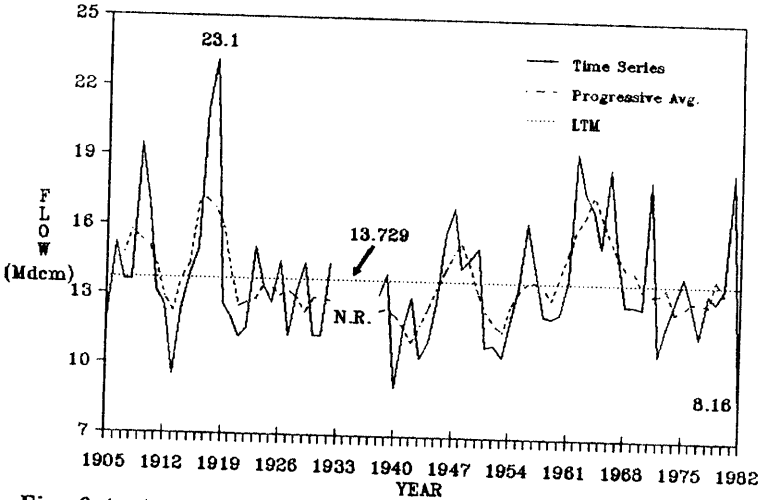


Fig. 6.4 Annual and Five-Year Moving Average Flows of River Sobat at Hillat Doleib (Near the Mouth)

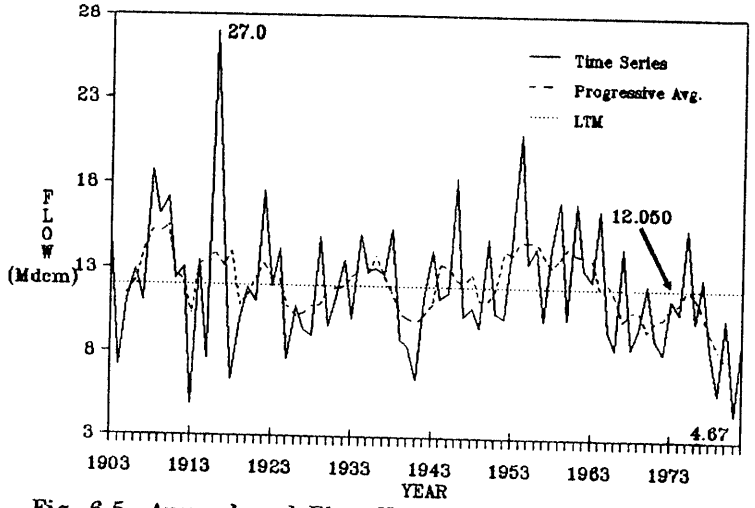


Fig. 6.5 Annual and Five-Year Moving Average Flows of River Atbara at Atbara (Near the Mouth)

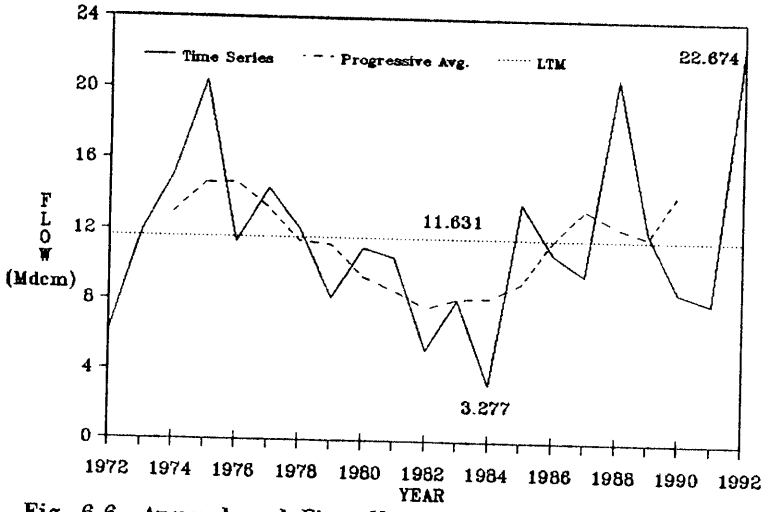


Fig. 6.6 Annual and Five-Year Moving Average Flows of River Atbara (Upstream from Khashm El Girba Dam)

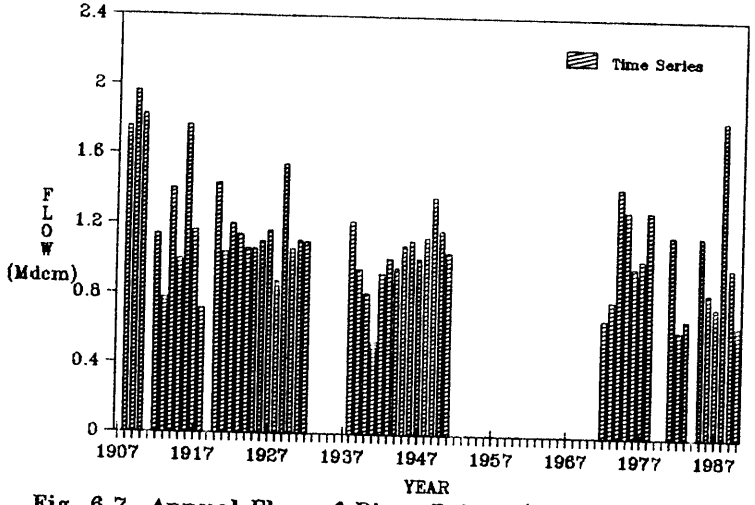


Fig. 6.7 Annual Flow of River Rahad (Near the Mouth)

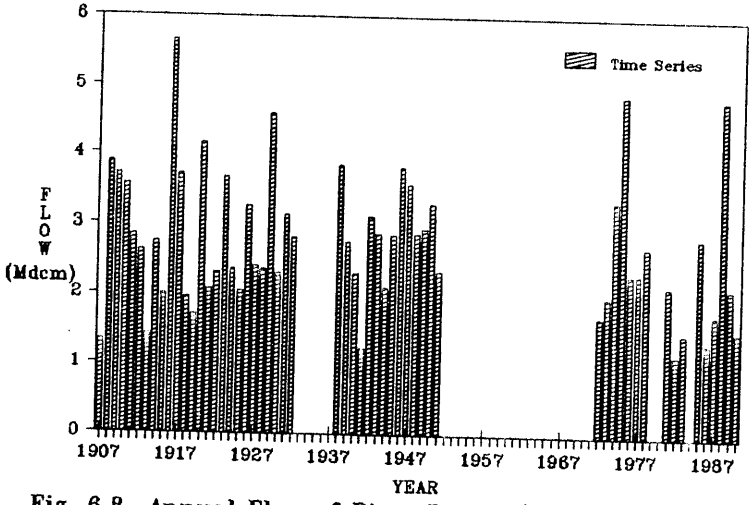


Fig. 6.8 Annual Flow of River Dindir (Near the Mouth)

6.2.1 Long Term Mean and Normal Annual River Flows

The time series of the annual river flows have been investigated by employing statistical techniques twice: once for long term and then for latest 30 years. The results are reported in Table 6.1. Due to the discontinuity in records of river Rahad and river Dindir, such analysis was not possible. Therefore, the records were divided into three different sequences, namely before 1933, 1938-51 and 1972-90, and the averages for the three were calculated. The short series of river Atbara at Khashm El Girba gauging station does not help to reach a definite conclusion about it.

Table 6.1 Characteristics of Long Term Mean, Normal and 1984 Annual River Flows

River	Long Term					Normal					1984
	Period	μ (Mdcm)	σ (Mdcm)	Cv (%)	TR (Mdcm/Yr)	Period	μ (Mdcm)	σ (Mdcm)	Cv (%)	TR (Mdcm/Yr)	Annual (Mdcm)
Main Nile	1890-92	85.183	17.539	20.6	– 0.329	1963-92	72.340	47.300	21.4	– 0.936	42.699
Blue Nile	1912-92	48.363	9.393	19.4	– 0.076	"	44.456	82.900	19.3	– 0.322	30.793
White Nile	1906-92	29.509	5.038	17.1	0.046	"	32.835	85.700	16.6	– 0.492	28.137
Sobat	1905-82	13.729	2.713	19.8	– 0.005	1953-82	13.925	65.200	18.9	– 0.031	-
Atbara *	1903-82	12.050	3.701	30.7	– 0.029	"	11.818	88.400	30.4	– 0.261	-
Atbara ^	1972-92	11.631	4.878	41.9	0.057	-	-	-	-	-	3.277

* Atbara gauging station ^ Khashm El Girba gauging station

From the figures, one can readily observe the onset and persistency of significant below average flows of the time series three decades earlier. The falling trends of the time series for this period are quite obvious from the estimated rates given in Table 6.1. The rivers exhibit reduction in the normal annual flows compared to the long term mean flows. The exceptional increase in the normal annual flows of the White Nile and river Sobat in the south can possibly be attributed to the wide jumps observed during the 1960s. River Rahad shows drops in the annual flow from 1.238 to 1.020 to 1.007 milliard cubic metres (1 Mdcm = 10^3 million cubic metres) and river Dindir shows drops from 2.873 to 2.788 to 2.415 Mdcm for the periods mentioned above respectively.

The σ-μ and C_v-μ relationships are developed for the rivers studied (rivers Rahad and Dindir are excluded). Similar correlations have been found earlier for rainfall. The parameters σ in Mdcm and C_v in % are plotted against μ in Mdcm as illustrated in Figs. 6.9 and 6.10 respectively. The regression equations derived from the analysis are:

$$\sigma = 0.9801 + 0.1865\ \mu \qquad r = 0.978 \qquad \text{(Long term)} \qquad (6.1)$$

$$\sigma = -0.0327 + 0.2046\ \mu \qquad r = 0.982 \qquad \text{(Normal)} \qquad (6.2)$$

$$\sigma = 0.5896 + 0.1929\ \mu \qquad r = 0.978 \qquad \text{(General)} \qquad (6.3)$$

Fig. 6.10 reveals that the coefficient of variation initially reduces sharply as the mean annual flow increases then increases slightly to reach a fairly constant value.

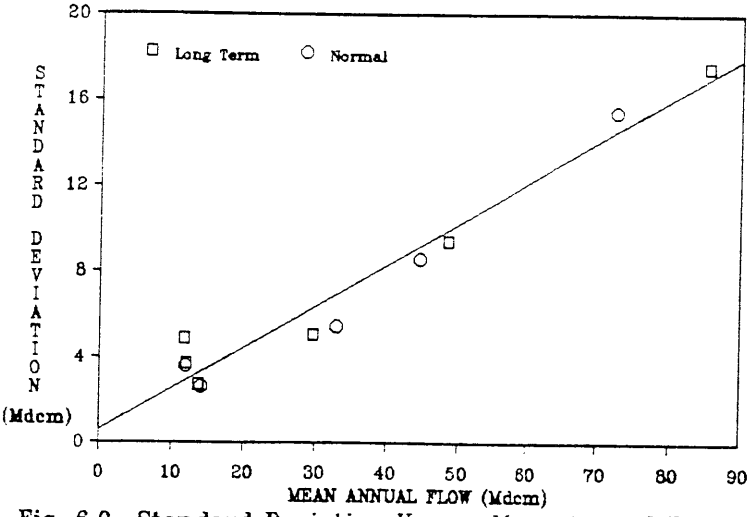


Fig. 6.9 Standard Deviation Versus Mean Annual River Flow

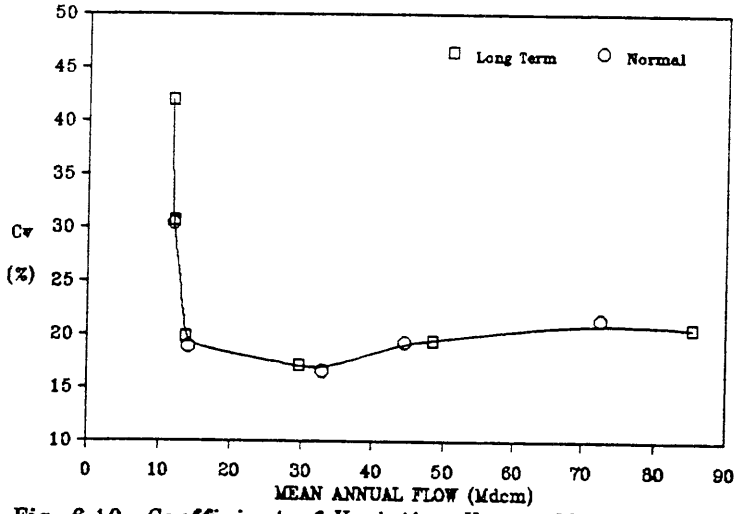


Fig. 6.10 Coefficient of Variation Versus Mean Annual River Flow

6.2.2 Trend from Progressive Averages

The structures of the annual flow time series are examined by the technique of progressive five-year moving averages to detect any possible trends in an exaggerated manner. As can be seen from Figs. 6.1 through 6.6, the trends show approximately regular cyclic fluctuations till the early 1960s after which steep falls are very noticeable.

6.2.3 Classification of Annual River Flow

The highest and lowest records in the time series of each river considered in this study, except the rivers Dindir and Rahad, are classified using the method suggested by Conrad as demonstrated in Table 6.2. The highest records of the Main Nile, the Blue Nile and river Atbara (at Khashm El Girba) are classified to be greatly above normal, whereas those of the White Nile, river Atbara (at Atbara)

and river Sobat are classified to be extremely above normal. The lowest records, on the other hand, are either greatly sub-normal as for the Main Nile, the Blue Nile and river Sobat or sub-normal as for the White Nile and river Atbara at the two sites.

Table 6.2 Classification of the Highest and Lowest Annual River Flow Departures from the Long Term Mean

River	Highest				Lowest			
	Flow (Mdcm)	Deviation (Mdcm)	z-score	Classi-fication	Flow (Mdcm)	Deviation (Mdcm)	z-score	Classi-fication
Main Nile	133.000	47.817	2.73	GA	42.699	– 42.484	– 2.42	GS
Blue Nile	69.800	21.437	2.28	GA	20.700	– 27.663	– 2.95	GS
White Nile	48.525	19.016	3.77	EA	22.581	– 6.928	– 1.38	S
Sobat	23.100	9.371	3.45	EA	8.160	– 5.569	– 2.05	GS
Atbara *	27.000	14.950	4.04	EA	4.670	– 7.380	– 1.99	S
Atbara ^	22.674	11.043	2.26	GA	3.277	– 8.354	– 1.71	S

* Atbara gauging station ^ Khashm El Girba gauging station

6.2.4 Annual River Flow Frequency Distribution

Frequency analysis has been carried out for the long term flow records for the rivers studied, except for the rivers Dindir and Rahad which have discontinuous records. The results of the analysis are displayed as histograms in Figs. 6.11 to 6.16. Unlike the graphs of the rivers under investigation, the frequency distribution bar graph of the White Nile tends to reach its modal class very rapidly. With only 21-year records, a representative pattern of the flow frequency distribution for river Atbara at Khashm El Girba Dam gauging station could not be determined. 14.6 to 20.0% of the total number of observations fall within the modal class. Analysis has shown that both the range of the annual flow records and the estimated modal annual flow correlate well with the mean flow as:

$$\text{Range} = 4.521 + 0.971\,\mu \qquad r = 0.984 \qquad (6.4)$$

$$M = -3.345 + 1.050\,\mu \qquad r = 0.998 \qquad (6.5)$$

where Range, M and μ are all in Mdcm. Eq. (6.5) is graphically presented in Fig. 6.17.

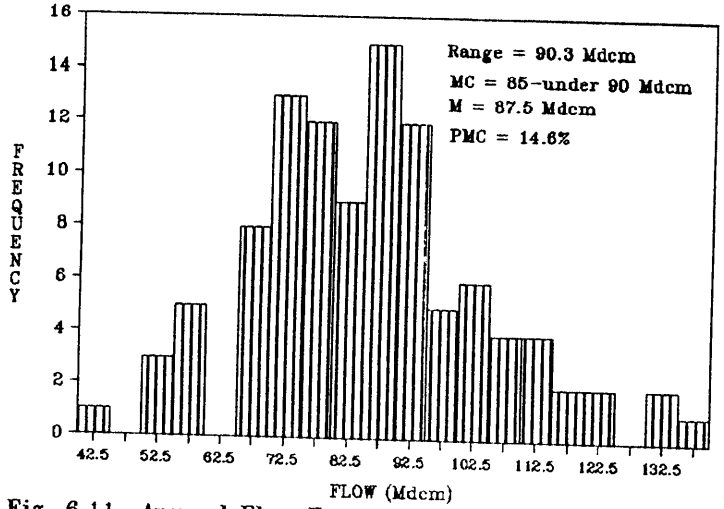


Fig. 6.11 Annual Flow Frequency Distribution (Main Nile at Wadi Halfa/Dongola 1890-92)

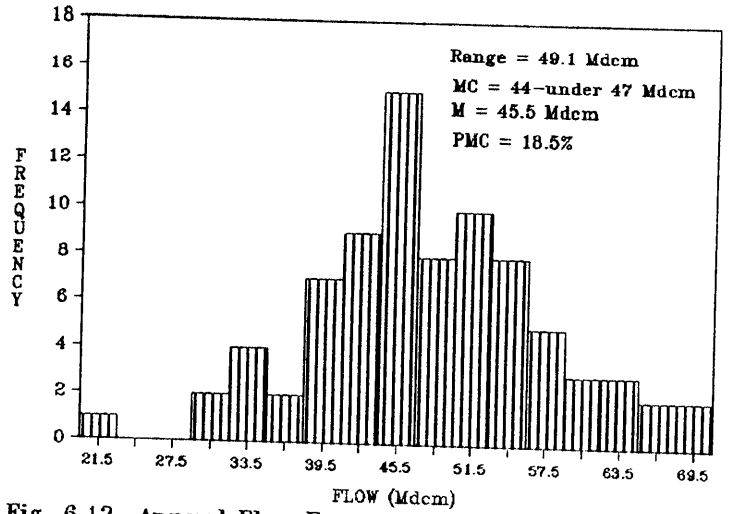


Fig. 6.12 Annual Flow Frequency Distribution (Blue Nile at Er Roseires/Ed Deim 1912-92)

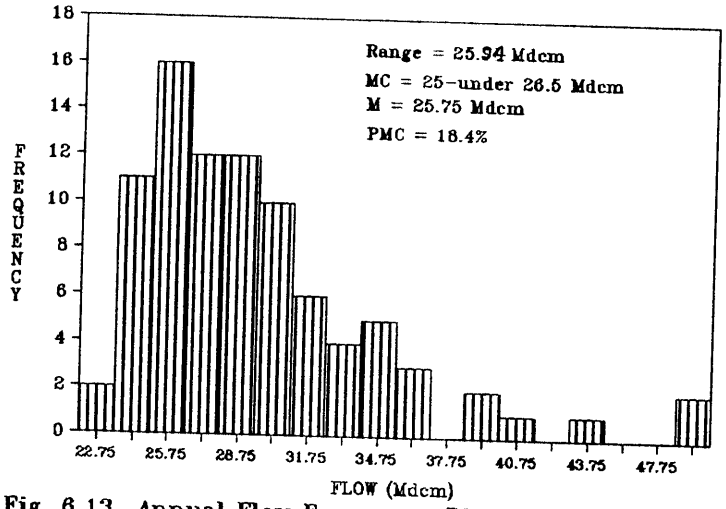


Fig. 6.13 Annual Flow Frequency Distribution (White Nile at Malakal 1906-92)

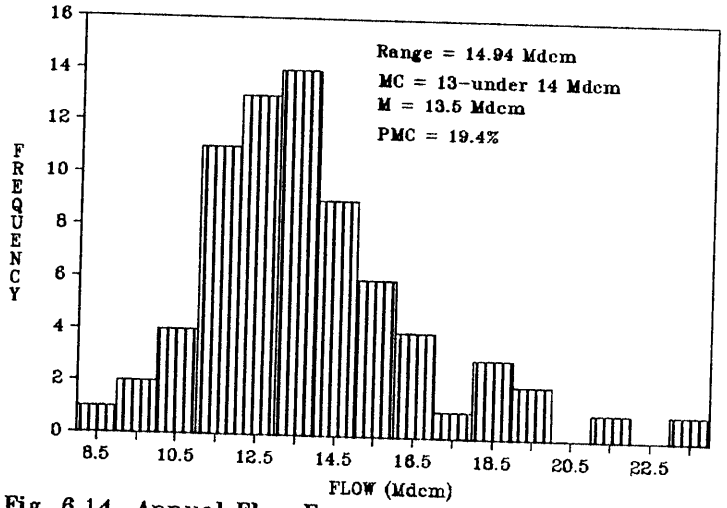


Fig. 6.14 Annual Flow Frequency Distribution (River Sobat at Hillat Doleib, Near the Mouth 1905-82)

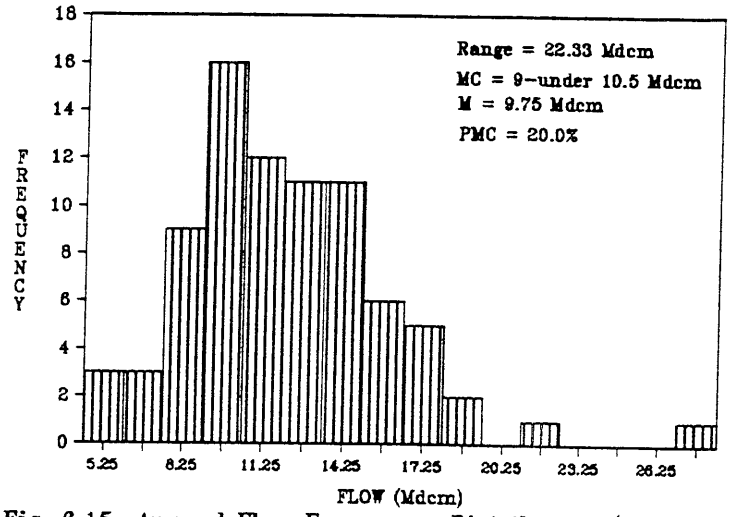


Fig. 6.15 Annual Flow Frequency Distribution (River Atbara at Atbara, Near the Mouth 1903-82)

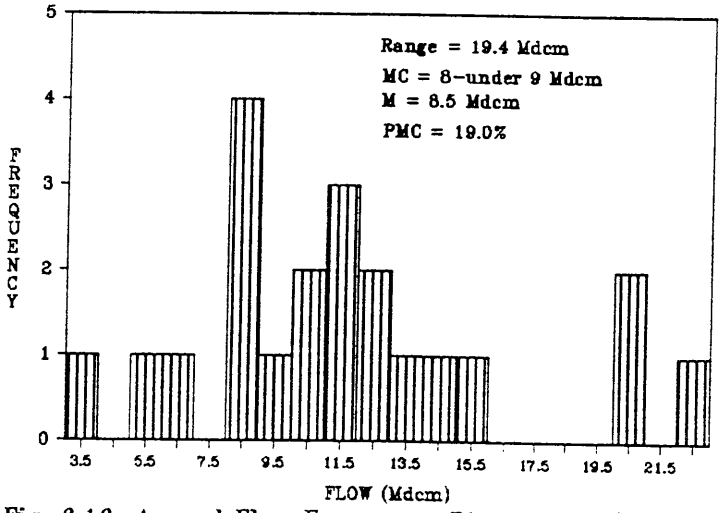


Fig. 6.16 Annual Flow Frequency Distribution (River Atbara, Upstream from Khashm El Girba Dam 1972-92)

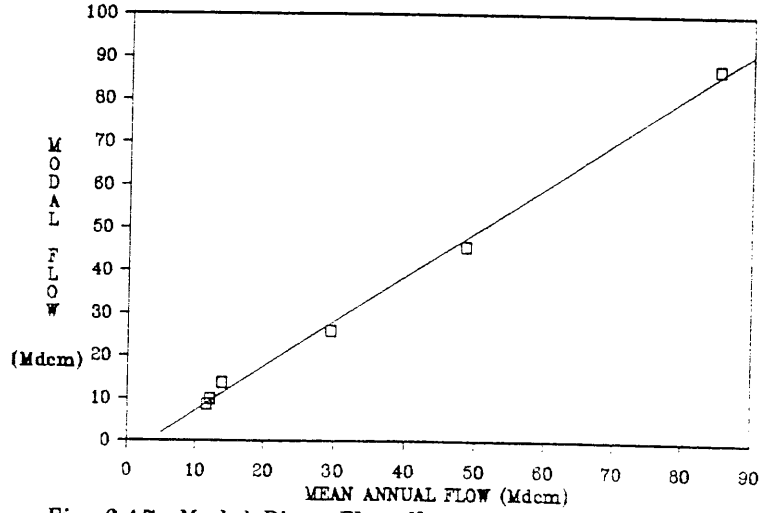


Fig. 6.17 Modal River Flow Versus Mean Annual River Flow

6.2.5 Probability Analysis of Annual River Flow

The method discussed in Chapter 3 for the computation of the N-year event is applied in this chapter as well to determine the expected amount of river flow with different probabilities. The expected values in milliard cubic metres, given in Table 6.3, have been found to correlate with the mean of the data values as:

$$\text{Flow} = -0.8234 + 0.8434\,\mu \qquad r = 0.999 \qquad (6.6)$$

for Pr = 80% and T_r = 1.25 year,

$$\text{Flow} = 1.255 + 1.239\,\mu \qquad r = 0.999 \qquad (6.7)$$

for Pr = 10% and T_r = 10 years and

$$\text{Flow} = 2.011 + 1.382\,\mu \qquad r = 0.998 \qquad (6.8)$$

for Pr = 2% and T_r = 50 years.

The relationships of Eqs. (6.6) to (6.8) are shown in Fig. 6.18.

Table 6.3 Amount of River Flow in Mdcm Expected to be Equalled or Exceeded within Different Return Periods

River	Return Period (Yrs)		
	1.25	10	50
Main Nile	70.450	107.633	121.138
Blue Nile	40.473	60.386	67.619
White Nile	25.277	35.958	39.837
Sobat	11.450	17.202	19.291
Atbara *	8.941	16.787	19.637
Atbara ^	7.533	17.875	21.631

* Atbara gauging station

^ Khasm El Girba gauging station

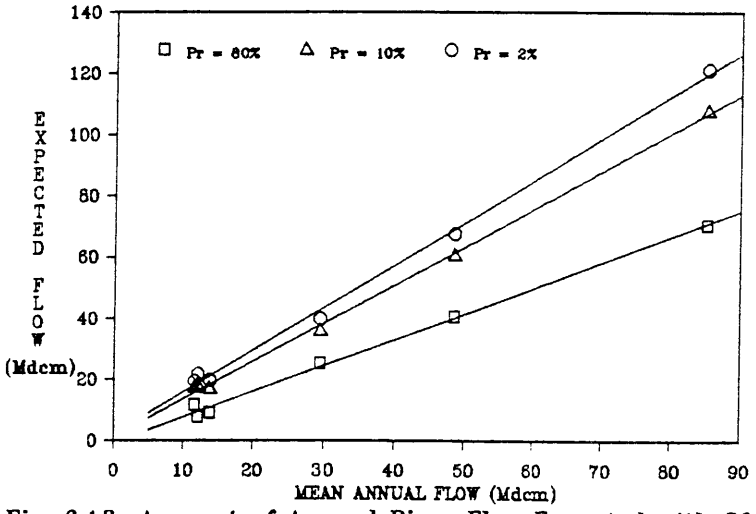


Fig. 6.18 Amount of Annual River Flow Expected with 80, 10 and 2% Probabilities

Chapter 7

DROUGHT AND DESERTIFICATION

7.1 Identification of the Problem

Drought and desertification are environmental issues now increasing the concern amongst scientific investigators and planners at the national and international levels. These are considered as the 20th century top killer-phenonmena [31]. About three million people died in the mid-1980s when a serious drought struck the sub-Sahran Africa [20].

Out of many definitions of drought given by various investigators, it is widely accepted as a temporary situation of severe and prolonged insufficiency of water to meet the requirement (rainfall is often used as the best single index of drought) [20, 22, 23, 32, 33]. Fig. 7.1 identifies various types of drought [34]. This aspect is known to occur in all climates, but mostly in arid, semi-arid and sub-humid regions [20]. The arid, semi-arid and hyper-arid lands constitute about 30 percent or 45 million square kilometres of the world's land surface [12].

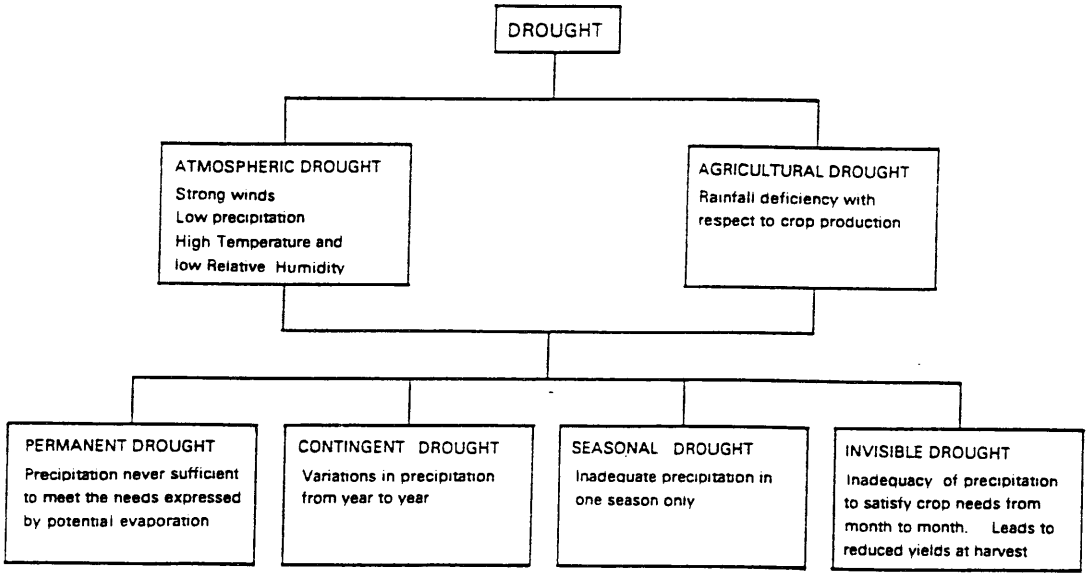


Fig. 7.1 Types of Drought [34]

On the other hand, desertification is yet an intricate phenomenon which is more difficult to define, because its manifestation is erratic and its process can become visible only after many years of observation [35]. The definition given to the term desertification as a process of expansion or intensification of desert-like conditions [12, 32] becomes inadequte if further definition of desert conditions and its causes and measures of the degree of intesification are not provided. Desertification as per UNCED (United Nations Conference on Environment and Development) is defined as degradation of natural vegetation cover in arid, semi-arid and sub-humid regions caused by climatic changes and human activities [20]. Desertic regions are characterized by rainfall deficiency to support most forms of life, extremely limited agricultural potential and possible cultivation only with special adaptation [12, 20]. Desertification occurs when drought becomes permanent [31]. Unfortunately, prediction as to when there is going to be a severe drought is not yet possible [35], however there are at least some climatic indicators of dryness and desertification, namely increasing temperature, decreasing rainfall or synchronous occurrence of both conditions [33]. Not only climatic factors like degree of deficiency and uncertainity of rainfall and its occurrence between hot and cool seasons, but also non-climatic factors such as soil structure and texture and topograghy and types of vegetation encountered govern the vulnerability to desertification and the severity of its impact [12].

In Sudan, desertification has become a major environmental problem caused by harsh persistent climatic events and human-induced forces. Climatic anomalies have resulted in aridity phases like higher temperatures, lower rainfall amounts and intensive dust storms. The degree of the susceptibility to the process of desertification varies from region to region. At the moment, a land area of 725,200 km^2 of Sudan (about 29%) is desert and an additional area of 650,000 km^2 (about 26%) is directly threatened with desertification [36].

7.2 Causes of Desertification

Many factors are responsible for the enhancment of desert, but ironically most of them are induced by man. Some of these factors [4, 20, 37] are briefly reviewed below:

7.2.1 Climatic Changes

Climate shows considerable alteration, dry periods are followed by wet periods and vice versa. During dry period, the receding of the vegetaion zone becomes extra serious and the destructive human actions increase as demand for fire wood and animal fodder increases. Under these circumstances, people move to more green lands looking for other resources and therefore population pressure on these areas becomes more acute.

7.2.2 Overcropping

Man extends cultivated lands during wet years, by removing natural vegetation, beyond the limits, i.e. to areas which are not really suitable for crop growth, because the rainfall is unreliable. Extensive mechanized cultivation schemes result in land degradation through water and wind erosion because they do not leave any plant cover to break the wind, thus they are far worse than traditional agricultural methods.

7.2.3 Overgrazing

Heavy and disorganized grazing by livestock around permanent water resources contributes to the rapid and widespread desertification, because it yilelds to the hardening of the soil by trampling. Hence, the infiltration rate of rain water into the soil reduces and much of the rain will be lost through surface runoff causing soil erosion. The plants lost by overgrazing are impossible to replace in the created drier conditions (Fig. 7.2).



Fig. 7.2 Degradation of Pasturelands due to Over-exploitation [38]

7.2.4 Deforestation

Lands denuded of the original vegetation cover for cropping or by cutting wood for building purposes or for providing fuel (Figs. 7.3 and 7.4) do not regrow vegetation on many sites even after heavy rainfall. Clearing natural plants accelerates soil erosion, leading to the development of very bad lands even beyond the immediately affected lands (Fig. 7.5).



Fig. 7.3 Collection of Fire-Wood [39]



Fig. 7.4 Extensive Wood-Cutting Resulting in Sand Encroachment and Development of Dunes [39]

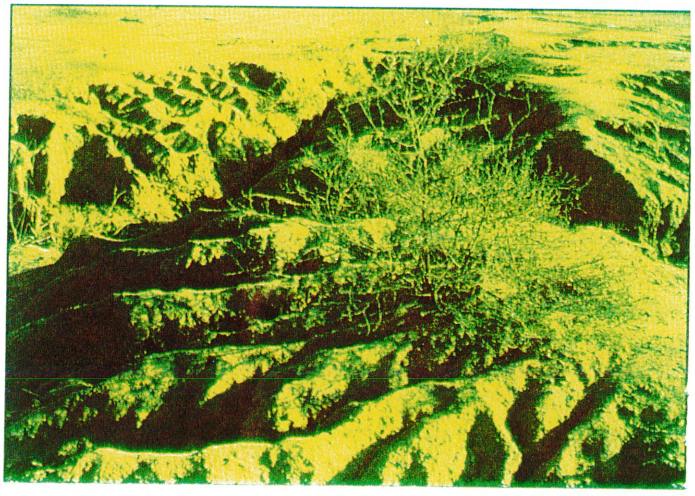


Fig. 7.5 Removal of Natural Vegetation Accelerating Soil Erosion and Leading to the Development of Bad Lands [38]

7.2.5 Uncontrolled Forest Fires

Fires are used for the purpose of cleaning and creating crop-fields, grazing on the green regrowth after a fire, driving the animals into nets or towards the hunters, collecting honey by smooking out bees of nets, etc. These fires are usually responsible for a gradual loss of forests (Fig. 7.6).



Fig. 7.6 Forest Fires [38]

7.2.6 Increasing Population

Increasing human and animal population is a prime factor in the advance of desert. It leads to the large increase of the energy consumption (sources of energy being the fossil supplies like charcoal, wood and gases produced by decomposition of organic waste material by bacteria) and the expansion of dwelling areas which all contribute to the formation of the urban heat islands that endangers the situation of climatic warming.

7.3 Impact of Environmental Changes on Hydrological Characteristics

Cilmate anomalies in Sudan began more than two decades ago and turned to be persistent as have been highlighted earlier in the previous chapters. These prolonged climate fluctuations acted to reinforce the conditions of drought until it culminated in the early 1980s. The worst known is the so-called 1984 drought which evoked havoc of the ecosystem. With special reference to the year 1984, some of the profound influences of this catastrophe on the regions' hydrological characteristics are studied below.

7.3.1 Impact on Temperature

Figs. 2.2 to 2.13 reflect the warming of environment in the drought-striken areas of Sudan in 1984. The mean monthy temperatures increased drastically even during the rainy season of the year due to the abrupt rainfall drop. The rise in some regions reached to more than 3°C over the long term mean and in El Fasher it

reached to as much as 5.8°C. The mean annual temperature of the year 1984 is given in Table 2.2. As shown, all air temperatures for the stations, excluding Port Sudan, deviated from the long term mean by 0.1 to 1.3°C.

7.3.2 Impact on Rainfall

In 1984, Sudan was afflicted by a severe rainfall desiccation as were many other parts of Africa. Quite densely settled agricultural areas were influenced and famine occurred which resulted in massive hunger-relief schemes. The erratic behaviour of rainfall of this year is quite visible in Figs. 3.2 to 3.13. Table 3.1 indicates short term rainy seasons and poor distribution of rain over the year. The severest impact was discerned for Khartoum, Kassala and El Fasher where the length of rainy season shortened to zero. The recorded annual rainfalls of 1984 are shown in Table 3.2 for the twelve meteorological stations. In some areas like Wad Medani, El Fasher, El Obeid and Nyala, the rainfall amounted to about 45-47% of the average annual figures. The rainfall in El Gedaref and Kassala diminished to about 54 and 35% of the long term means respectively. The most significant decrease over the regions studied was recorded for Khartoum which received only about 3% of the average annual rainfall. Port Sudan, Ed Damazin, Malakal, Wau and Juba in 1984 were the least affected regions, recorded annual rainfall of around 80% of the long term averages.

7.3.4 Impact on Evaporation

Figs. 5.26 to 5.37 compare the daily evaporation rates during the year of 1984 with the average rates. As shown, the process of evaporation was enhanced particularly during the rainy season of the year 1984 due to the absence of rain for much of the season. Table 5.2 provides the comparison between the mean and the 1984 levels of evaporation on an annual basis. Measurements of Piche instrument showed an increase in the evaporation of about 2-20%. The condition of drought could not be inferred from annual Penman evaporation, so it was thought reasonable to estimate the number of times the annual evaporation exceeded the annual precipitation by calculating the ratio E_o/P as an index. Four zones have been delimited: the south where evaporation exceeded the precipitation by 2-5 times, the central zone with annual evaporation equalled 8-22 times the annual precipitation, the Red Sea area having E_o/P ratio of about 28 and finally the northern parts, including Khartoum, where the evaporation exceeded the rainfall by around 600 times.

The siginificant increase in water loss from vegetated areas through evapotranspiration during the drought year of 1984 can be recognized from Figs. 5.38 through 5.49 as well as from Table 5.3. With the exception of Port Sudan, the extra heat during this year increased the potential evapotranspiration by about 2-27% over the average magnitudes. In Port Sudan, the PET reduced to around 90% of the mean value.

7.3.5 Impact on River Nile Flow

From Table 6.1, it can be seen that all the tributaries of the Rive Nile showed a remarkable drop in their annual flows in 1984, especially those flowing in the northern parts of Sudan. This drop can be traced back to the low level rainfalls of this year. Expressing the 1984 annual flows as percentages of the long term mean annual flows, the amounts reduced to about 50, 64, 95 and 28% for the Main Nile, the Blue Nile, the White Nile and River Atbara respectively.

7.4 Measurement and Classification of Aridity

A large number of investigators have dealt at length with the formulation of an applicable definition of aridity that can be used to classify the climate of the arid world. To better delimit the arid and semi-arid lands and to provide the basis for useful comparison between different regions, aridity indices and available data on bioclimates (climate, soil, relief and vegetation) are used [14].

In the present study, some comparative measures of aridity are adopted to facilitate the task of categorizing the regions under consideration as hyper-arid, arid, semi-arid or sub-humid. This classification is made on the basis of the available climatic data, which are either means calculated over the last 30 years or records for the terrible drought year of 1984.

7.4.1 Classification by UNEP P/PET Ratio

Since the degree of bioclimtic aridity is related to the relative amounts of water gained from rainfall and lost by evaporation and transpiration [14], the ratio expressing annual precipitation, P, as a fraction of annual potential evapo-transpiration, PET, is used to delimit climate regions. Aridity rises as precipitation decreases and as evaporation increases, i.e. as values of this ratio decline [14]. In identifying the dry climates of the world by P/PET ratios, the usage by UNEP, 1992, is as follows [20]:

Climate Zone	**P/PET Ratio**
Hyper-arid	$P/PET < 0.05$
Arid	$0.05 \leq P/PET < 0.2$
Semi-arid	$0.2 \leq P/PET < 0.5$
Dry sub-humid	$0.5 \leq P/PET < 0.65$
Moisture climates	$P/PET \geq 0.65$
- Humid	
- Cold	

To give an overview of the phenomenon, the ratio is calculated for the twelve stations as shown in Table 7.1. Analysis made for this ratio and

corresponding precipitation in the regions has shown that the two parameters are strongly correlated by the following relationship:

$$P/PET = 1.979 \times 10^{-4} P^{1.133} \qquad r = 0.993 \qquad (7.1)$$

which is graphically presented in Fig. 7.7. Alvi and Elagib found a linear relationship between P/PET and P for Eastern-Sudan as [19]:

$$P/PET = -0.0094 + 4.224 \times 10^{-4} P \qquad (7.2)$$

This interesting finding enables the computation of P/PET ratio when annual precipitation is known without the need for the sophisticated method of estimating PET. Thereupon, the previous climatic zones are reclassified in terms of precipitation amounts by substituting the upper and lower limits of P/PET class in Eq. (7.1) to find the corresponding upper and lower limits of precipitation class as follows:

Climate Zone	**Annual P (mm)**
Hyper-arid	$P < 132$
Arid	$132 \leq P < 448$
Semi-arid	$448 \leq P < 1006$
Dry sub-humid	$1006 \leq P < 1268$
Humid	$P \geq 1268$

Table 7.1 Evaluation of Aridity by UNEP P/PET Ratio

Station	Latest 30 Years		1984	
	P/PET	Climate Zone	P/PET	Climate Zone
Port Sudan	0.03	Hyper-arid	0.03	Hyper-arid
Khartoum	0.04	"	0.001	"
Kassala	0.09	Arid	0.03	"
Wad Medani	0.12	"	0.05	"
El Gedaref	0.25	Semi-arid	0.11	Arid
El Fasher	0.12	Arid	0.06	"
El Obeid	0.15	"	0.06	"
Nyala	0.20	Semi-arid	0.08	"
Ed Damazin	0.32	"	0.22	Semi-arid
Malakal	0.34	"	0.28	"
Wau	0.55	Dry sub-humid	0.45	"
Juba	0.49	Semi-arid	0.40	"

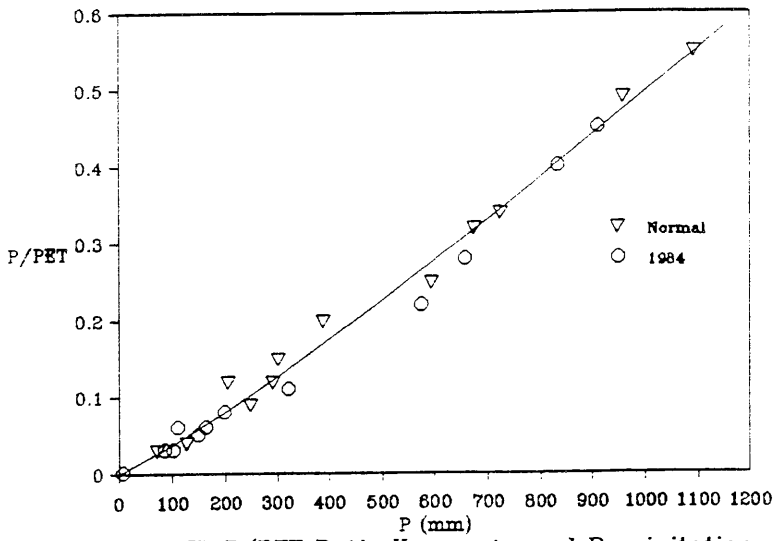


Fig. 7.7 UNEP P/PET Ratio Versus Annual Precipitation

7.4.2 Classification by Budyko-Lettau Dryness Ratio

Budyko's radiational index of dryness, also called the dryness ratio by Lettau [12], is a measure of aridity that depends on the relative magnitudes of energy supply and rainfall. The dryness ratio, D, expresses the number of times the net radiant energy at the earth's surface could evaporate the annual precipitation. The Budyko-Lettau ratio is given as:

$$D = R_n/LP \tag{7.3}$$

and the classification guidelines of the aridity zones are:

D	**Vegetation Zone**
> 3.4	Desert
2.3-3.4	Semi-desert
1.1-2.3	Steppe or savanna

Table 7.2 gives the climatic aridity zones among the regions studied. The dryness ratio can be expressed in terms of annual precipitation of the region as:

$$D = 0.134 + 1729\ P^{-0.993} \qquad r = -0.995 \tag{7.4}$$

which is presented in Fig. 7.8. The correlationship established for Eastern-Sudan is [19]:

$$D = 1.837 + 9533.4\ P^{-1.359} \tag{7.5}$$

The method of calculating D from this developed equation is very easy compared to Budyko-Lettau method due to the complications associated with estimating R_n

in the latter method. Thus, the vegetation zones classified by Budyko-Lettau can be defined by the yearly precipitation received, i.e. by substituting D values in Eq. (7.4) and finding P as described below:

Annual P (mm)	Vegetation Zone
P < 553	Desert
553-837	Semi-desert
837-1887	Savanna

Table 7.2 Evaluation of Aridity by Budyko-Lettau Dryness Ratio, D

Station	Latest 30 Years		1984	
	D	Vegetation Zone	D	Vegetation Zone
Port Sudan	31.3	Desert	26.5	Desert
Khartoum	14.0	"	350.3	"
Kassala	6.6	"	16.5	"
Wad Medani	6.9	"	13.4	"
El Gedaref	3.3	Semi-desert	5.9	"
El Fasher	9.4	Desert	17.5	"
El Obeid	4.6	"	8.6	"
Nyala *	-	-	-	-
Ed Damazin	3.2	Semi-desert	3.8	Desert
Malakal	2.5	"	2.7	Semi-desert
Wau	1.8	Savanna	2.1	Savanna
Juba	2.1	"	2.3	Savanna

* Data for actual sunshine duration are not available

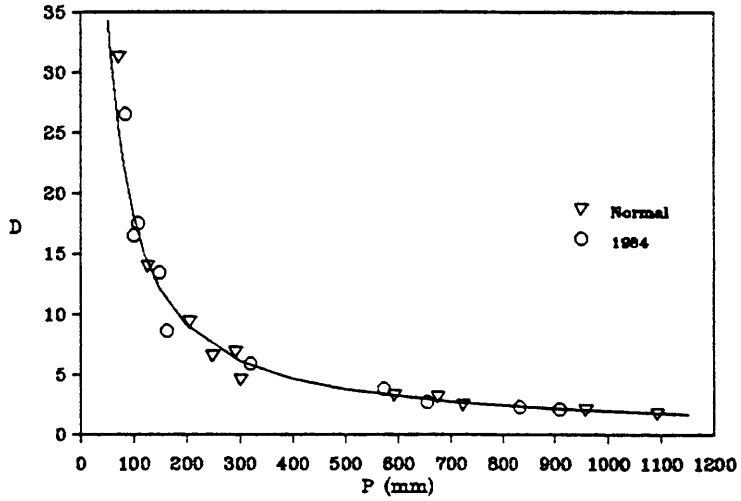


Fig. 7.8 Budyko-Lettau Dryness Ratio Versus Annual Precipitation

7.4.3 Classification by Lang's Aridity Index

As the quantity of water evaporated from a free-water surface is related to temperature, this index of aridity, A_L, takes into account the temperature and rainfall. Lang [21] gives:

$$A_L = P/t \tag{7.6}$$

The degree of aridity or humidity of a region is given as follows:

A_L	Climate Zone
0-20	Arid
20-40	Semi-arid
40-60	Sub-humid
60-80	Humid

Table 7.3 describes the regions considered in the study according to the above method. By plotting Lang's aridity index against precipitation, as shown in Fig. 7.9, a linear relationship is obtained as:

$$A_L = -0.1571 + 0.0358\ P \qquad r = 0.9995 \tag{7.7}$$

The study for Eastern-Sudan gives [19]:

$$A_L = -0.0964 + 0.0345\ P \tag{7.8}$$

These relationnships are very useful, because they give the value of the index if the annual precipitation is known. Using Eq. (7.7) above, the limits of climate zones can be established by replacing Lang's index by the annual precipitation as follows:

Annual P (mm)	Climate Zone
< 563	Arid
563-1122	Semi-arid
1122-1681	Sub-humid
1681-2239	Humid

Table 7.3 Evaluation of Aridity by Lang's Aridity Index, AL

Station	Latest 30 Years		1984	
	Index	Climate Zone	Index	Climate Zone
Port Sudan	2.5	Arid	2.9	Arid
Khartoum	4.2	"	0.2	"
Kassala	8.4	"	3.2	"
Wad Medani	10.1	"	5.0	"
El Gedaref	20.5	Semi-arid	10.6	"
El Fasher	7.9	Arid	4.1	"
El Obeid	11.0	"	5.7	"
Nyala	14.1	"	6.9	"
Ed Damazin	23.9	Semi-arid	19.6	Arid
Malakal	25.8	"	22.8	Semi-arid
Wau	39.3	"	32.7	"
Juba	34.4	"	29.7	"

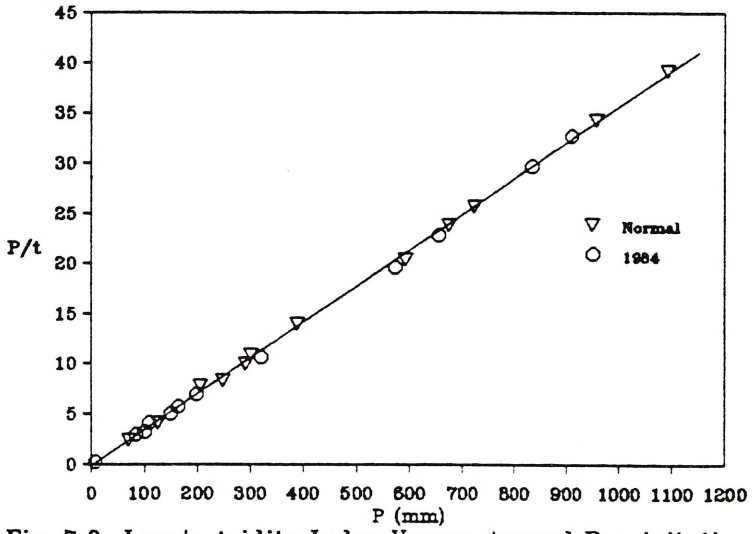


Fig. 7.9 Lang's Aridity Index Versus Annual Precipitation

7.4.4 Inference from Aridity Indices

The results obtained from the assessment of aridity in Sudan has demonstrated how the regions were worst affected by drought in 1984. The very high correlation factors obtained for the relationships between the various aridity indices and precipitation are clearly reflected in the figures where the points do not show any sigificant scatter. The classifications presented in the above sections for the regions under consideration may be considered satisfactory since they are, to a large extent, matching one another even according to various approaches. Thus, the various aridity indices used herein are to a great degree interchangeable. Whichever criterion is used in this study to measure the aridity, there is one important point that has figured out conclusively that the pace of the

southward aridification process in the country is a genuine feature and is not a myth. Over half the country is either arid or semi-arid and the rest of the lands are desert prone areas.

7.5 Possible Solutions for Drought and Desertification Problems

Many plans are being set forth by scientific teams and organizations and numerous solutions are suggested by them to mitigate the adverse effects of drought and desertification. Some of the suggested remedial measures [4, 20, 31] are summarized below:

(a) Preservation of a good tree cover in crop land and regulation of fires help to alleviate the problem of deforestation.

(b) Keeping or planting trees in between cropping areas can help to maintain the soil and secure fodder resources for animal and wood as well.

(c) Minimizing wind-erosion by maintaining solitary trees on the field and planting rows of trees between fields which form shelter-belts that reduce the wind speed.

(d) Extensive grazing potential can be avoided by restricting animal numbers and by allowing the regrowth of vegetation by fencing off certain parts and establishing rotational grazing.

(e) Afforestation and reforestation activities also contribute to desertification control as will be explained in the following setion.

(f) Avoiding all causes of desertification discussed earlier, especially under the prevailing conditions of arid and semi-arid regions where climatic-change processes are experienced.

(g) Public awareness of the magnitude of the problem and adequate understanding of its roots are major prerequisites to push such solutions to the realization.

7.6 Promotion of Rainfall by Reafforestaion

Leaves and plants of trees create an effective canopy [31, 33] which holds the rain drop from falling onto the ground surface in such a way to prevent loss of rainwater by seepage. The water evaporates to the atmosphere and produces clouds which pass into the hinterland and encourage precipitation. Unfortunately, this canopy zone in the tropical forests of Africa has receded towards south-west due to deforestation and uncontrolled fires and many parts of Africa are deprived of its effective role. It is believed that normal crop plants do not have the same canopy

effect on rainfall as forest. In addition, forests entirely removed cannot be regenerated or substituted by farms.

Based on this vital role which forests play, an interesting strategy could be suggested to keep the rainfall amounts in the present rate of fall or to return the rain to its normal amounts, that is by starting reafforestation in the south where the canopy is receding (the rainfall being still abundant and soils yet undegraded) and progressing northward. Furthermore, the preservation of natural forests would attract the rain to the far north.

Chapter 8

CONCLUSIONS

CONCLUSIONS

The worldwide awareness and concern to the environment-related issues particularly gave motivation and encouragement to conduct a thorough study for Sudan. This country, which should have been the food basket of the world because of its fertile soil, plenty of untapped water resources and huge cultivable land, is now exposed to hydrological variations, drought and desertification that impede the economical growth and social welfare.

The study is focussed on the investigation of the climate of Sudan during the recent three to five decades as well as the hydrological aspects of the country's River Nile and its tributaries since the beginning of this century. The study is also concerned with the interaction between the behaviour of these variables and aridification processes. The data have been interpreted on extensive statistical basis and the following are the main conclusions and recommendations offered from the comprehensive results obtained throughout the preceding chapters.

8.1 Conclusions

(a) The average climatic conditions in Sudan are summarized as follows: the weather is very warm in summer and is mostly warm in winter. Rain falls in the summer except the Red Sea area which has winter rainfall. The amount of the rain and the length of rainy season increase from north to south or south-west. Based on the definition of the dry month given by Bagnols and Gaussen, the study shows that any month for which the mean rainfall is less than or equal to 55 mm can be identified as dry. The annual rainfall in the country varies from zero in the extreme north to around 1500 mm in the extreme south-west. A general wild climate of large-scale anomalies has been witnessed in the country especially in the past three decades.

(b) One of these hostile episodes of climate is the warming phase of atmosphere. The upward trend of the mean annual temperature series during the last three decades has been observed at a rate reaching to as significant value as 0.034°C per year as in the case of Wad Medani. This increase in temperature would doubtedless become hazardous to the environment.

(c) Rainfall was generally sufficient or abundant during the mid of this century, then there began a phenomenon of remarkable unpleasant low level rainfalls. Since the early 1960s, the desiccation has been brought about by a reduction in rainfall amounts at an alarming rate in all the regions. An illustrative example for this decreasing rate is the one which has been

estimated for Wau during the period stretching from 1958 to 1987 as around 10 mm per annum. The continuation of failure of expected rainfall for the coming few years will emphasize the severity of its noticeable decline. Isolated events of highly above average rainfalls, however, should not create a false image of the true state of climate.

(d) Once dryness becomes frequent, heavy rain might then have far greater adverse impact on people, because they tend to discard dry-land problems and protective measures against flooding during very wet spells as was the case in 1988.

(e) The study of sunshine duration and solar radiation has shown that the country has huge resources of solar energy (on average, the brightness ratio reaches to around 0.922 and the relative solar radiation, when the sky is absolutely cloudless, reaches to around 85%).

(f) The loss of water resources through evaporation is quite significant in all climatic zones. The total annual evaporation has been observed to very much exceed the total annual rainfall (the average loss has been estimated between 1840 and 2932 mm). Coefficients have been found in order to estimate both Penman evaporation rate and Thornthwaite potential evapotranspiration rate from Piche measurements and are given in Tables 5.2 and 5.4 respectively. The monthly Piche coefficient varies over different climatic conditions from 0.33 to 1.74 and the annual values have the range of 0.42 to 0.81. On monthly basis, PET/E_o values range between 0.18 to 2.11 and on annual basis, the range is 0.72 to 1.34.

(g) The flow of the River Nile and its tributaries which is directly influenced by the quantity of rainfall that runs off has also acutely reduced. The Main Nile, for example, showed a considerable falling trend of 936 million cubic metres per year during the period 1963-92. Frequent occurrence of below average flows have been experienced for the rivers. This is liable to exaggerate more the present hydro-electric power crisis in this vast country and cause unsatisfaction to the anticipated agricultural requirements for irrigation.

(h) The hydrological droughts have repeatedly stressed the agriculture and livestock systems and hence caused great human suffering. The recent 10 to 15 years experienced recurrent droughts of which the most drastic was the mid-1980s drought that brought catastrophic poverty.

(i) The previous mentioned natural forces in conjunction with human wrongdoings such as unwise agricultural and pastoral techniques have all collaborated with each other and aggravated the damaging process of desertification.

(j) The problem of desertification in Sudan has been assessed in this study and it has been recognized that many parts of the country have become very vulnerable to the problem. Strong dust-loaded winds during hot-dry season have become normal events in these areas. The unfavourable desert-like condition is progressing southward. Most of the regions have been regarded as between semi-arid and hyper-arid. This situation is indeed alarming of dangerous environmental consequences in the future.

(k) Many interesting correlations governing the climatological, hydrological and environmental features have been derived with very high correlation factors. The equations and graphs produced in this study may easily be utilized in water resources planning and in the evaluation of aridity in Sudan.

- The standard deviation in mm and coefficient of variation in % have been found to correlate with the mean annual rainfall as:

$$\sigma = 60.725 + 0.0934\ \mu \tag{3.7}$$

$$C_v = 1174.5\ \mu^{-0.637} \tag{3.8}$$

- The relationship between the estimated modal annual rainfall and the mean, both parameters are in mm, is given as:

$$M = -38.818 + 1.050\ \mu \tag{3.9}$$

- For the estimation of the 1.25, 10 and 50-year annual rainfall in mm, expected with 80, 10 and 2% probabilities respectively, the following equations have been established:

$$RF = -55.257 + 0.925\ \mu \tag{3.12}$$

$$RF = 84.204 + 1.115\ \mu \tag{3.13}$$

$$RF = 134.844 + 1.184\ \mu \tag{3.14}$$

- The relationship between the mean relative solar radiation, H/H_o, and the mean relative duration of sunshine duration, n/N, has been developed to assist in estimating H values for the regions. Three regression models have been used, namely linear, exponential and power. The power model is found to be very marginally superior over others, thus the linear relationship can still be used with almost the same accuracy. All the three models are given in Table 4.5 (equations are not numbered). The developed linear correlationships are:

$$H/H_o = 0.309 + 0.433\ n/N \quad \text{(Port Sudan)} \quad (8.1)$$

$$H/H_o = 0.146 + 0.651\ n/N \quad \text{(Khartoum)} \quad (8.2)$$

$$H/H_o = 0.446 + 0.163\ n/N \quad \text{(Kassala)} \quad (8.3)$$

$$H/H_o = 0.409 + 0.341\ n/N \quad \text{(Wad Medani)} \quad (8.4)$$

$$H/H_o = 0.404 + 0.310\ n/N \quad \text{(El Gedaref)} \quad (8.5)$$

$$H/H_o = 0.465 + 0.273\ n/N \quad \text{(El Fasher)} \quad (8.6)$$

$$H/H_o = 0.077 + 0.641\ n/N \quad \text{(El Obeid)} \quad (8.7)$$

$$H/H_o = 0.501 + 0.242\ n/N \quad \text{(Ed Damazin)} \quad (8.8)$$

$$H/H_o = 0.351 + 0.335\ n/N \quad \text{(Malakal)} \quad (8.9)$$

$$H/H_o = 0.437 + 0.179\ n/N \quad \text{(Juba)} \quad (8.10)$$

Using the data for all the above stations, an overall linear equation has been derived as:

$$H/H_o = 0.350 + 0.368\ n/N \quad (8.11)$$

The application of Eq. (8.11) in the regions which fall within the range of latitudes under consideration seems quite justifiable, especially in the locations where H records are not available for the development of their regional formulae.

- The analysis made for the standard deviation and mean annual flow for the rivers has yielded the following relationship:

$$\sigma = 0.5896 + 0.1929\ \mu \quad (6.3)$$

where σ and μ are in Mdcm.

- The modal annual river flow in Mdcm can be estimated from the mean by the equation:

$$M = -3.345 + 1.050\ \mu \quad (6.5)$$

- The derived equations for the determination of annual river flow in milliard cubic metres with 80, 10 and 2% probabilities are respectively:

$$\text{Flow} = -0.8234 + 0.8434\ \mu \tag{6.6}$$

$$\text{Flow} = 1.255 + 1.239\ \mu \tag{6.7}$$

$$\text{Flow} = 2.011 + 1.382\ \mu \tag{6.8}$$

- Also, interesting relationships have been developed to facilitate the estimation of various aridity indices from annual precipitation, hence avoiding the complications associated with the cumbersome methods of estimation. The established relationships for UNEP P/PET ratio, Budyko-Lettau dryness ratio and Lang's aridity index are respectively:

$$P/PET = 1.979 \times 10^{-4}\ P^{1.133} \tag{7.1}$$

$$D = 0.134 + 1729\ P^{-0.993} \tag{7.3}$$

$$A_L = -0.1571 + 0.0358\ P \tag{7.5}$$

where P is measured in mm. Based on the above equations, the various climatic zones, which are in the category of humid to hyper-arid, have been reclassified by the annual rainfall amounts as demonstrated in Chapter 7.

8.2 Recommendations

Under the present critical situation of drought and desertification, the following recommendations need particular attention to achieve satisfactory and stable environmental conditions and thereby help to restore the prosperity of the country.

(a) Developing and strengthening the capability of national meteorological and hydrological services to collect the necessary dependable data and information.

(b) Formation of a system or a data bank for easy processing, analysis and publication of data and information so as to prepare appropriate guidance material for scientific community.

(c) Developing national programmes to assist researchers and hydrologists to properly monitor and assess the problem and formulate suitable polices to be implemented to mitigate and fight distress in drought-stricken and drought-prone areas.

(d) Encouragement and support to various meteorological, hydrological and environmental research works and studies are found necessary in order to improve the flimsy understanding of drought and desertification processes.

(e) Creation of popular perception of drought and desertification as human hazards is the key to ensure allround cooperation in avoiding actions that spread deserts to areas which have not been desertified or which are only slightly desertified.

(f) The country should have the great benifit of the significant potential of solar energy available. For instance, it can be used as a source of power supply for domestic and industrial applications.

(g) Although this study attempts to achieve adequate coverage of the meteorological and hydrological stations in the country, other remaining stations, which could not be taken due to the size and time constraints, still need to be taken into consideration. The present study could be adopted as a guideline for further studies that treat all these stations.

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Appendix

COMPUTER PROGRAMS

COMPUTER PROGRAMS

Three *Basic* computer programs, which have been developed in the present study, are presented here. The first program (Section A.1) evaluates the various statistical parameters like the mean, the standard deviation and the coefficient of variation. It also derives the regression equations (linear, exponential and power) for any two variables. The second program, listed in Section A.2, develops the relationship between the relative solar radiation and cloudiness ratio which is used to estimate the short wave solar radition for a region. Finally, the program of Section A.3 can be used to estimate Penman evaporation and Thornthwaite potential evapotranspiration rates from the measured meteorological data, Piche coefficients and the ratio of potential evapotranspiration to Penman evaporation. All the three programs include comment statements to indicate the purpose of various parts of the program.

A.1 Statistical Analysis Program

```
REM   THIS PROGRAM EVALUATES STATISTICAL PARAMETERS (MEAN, STANDARD
REM   DEVIATION AND COEFFICIENT OF VARIATION) AND PERFORMS REGRESSION
REM   ANALYSIS AS WELL AS PROGRESSIVE AVERAGES (FIVE-YEAR MOVING AVERAGES)
REM
      READ N
      DIM XX(N), YY(N), X(N), Y(N), AVE5(N)
REM
      READ STAT$, TYPE$, PERIOD$
REM
REM   INPUTING THE DATA
      FOR I = 1 TO N: READ XX(I): NEXT I
      FOR J = 1 TO N: READ YY(J): NEXT J
      CLS
REM
REM   EVALUATION OF STATISTICAL PARAMETERS
      PRINT "STATISTICAL ANALYSIS (1), FIVE-YEAR MOVING AVERAGE (2) OR BOTH (3)"
      INPUT "1, 2 OR 3"; ANS$
      IF ANS$ = "2" THEN GOTO 400
      PRINT : PRINT TAB(20); "S T A T I S T I C A L  A N A L Y S I S"
      LPRINT TAB(20); "S T A T I S T I C A L  A N A L Y S I S"
      PRINT TAB(20); "---------------------------------------": PRINT
      LPRINT TAB(20); "---------------------------------------": LPRINT
      LPRINT "STATION: "; STAT$, "  DATA TYPE: "; TYPE$,
      LPRINT "PERIOD: "; PERIOD$
      LPRINT : LPRINT "LINEAR REGRESSION [Y = A + B * X]:": LPRINT
      PRINT : PRINT "LINEAR REGRESSION [Y = A + B * X]:": PRINT
      FOR K = 1 TO N
            X(K) = XX(K): Y(K) = YY(K)
      NEXT K
      Q = 0
      GOSUB 600
```

```
        Q = 1
        LPRINT : LPRINT "EXPONENTIAL REGRESSION [Y = A eX^B]:": LPRINT
        PRINT : PRINT "EXPONENTIAL REGRESSION [Y = A eX^B]:": PRINT
        FOR M = 1 TO N: Y(M) = LOG(YY(M)): NEXT M
        GOSUB 600
        LPRINT : LPRINT "POWER REGRESSION [Y = C + A * X^B]:": LPRINT
        PRINT : PRINT "POWER REGRESSION [Y = C + A * X^B]:": PRINT
        QQ$ = "P"
100     INPUT "CONSTANT C IN POWER FORMULA [Y = C + A * X^B]="; C: PRINT
        FOR L = 1 TO N
                Y(L) = YY(L) - C: IF Y(L) <= 0 THEN GOTO 200
                X(L) = LOG(XX(L)): Y(L) = LOG(Y(L))
                GOTO 300
200             PRINT TAB(25); "**** TRY ANOTHER VALUE OF C ****": GOTO 100
300     NEXT L
        GOSUB 600
        PRINT : PRINT "WOULD YOU LIKE TO CHANGE C VALUE? Y OR N?";
        INPUT Q1$: PRINT
        IF Q1$ = "Y" OR Q1$ = "y" THEN 100
        IF ANS$ = "1" THEN GOTO 500
400     PRINT : PRINT
REM
REM     ANALYSIS BY PROGRESSIVE AVERAGES
        PRINT TAB(10); "F I V E - Y E A R  M O V I N G  A V E R A G E"
        PRINT TAB(10); "-----------------------------------------------": PRINT
        PRINT TAB(23); "YEAR", "     5-YEAR AVE."
        PRINT TAB(23); "----", "     -----------": PRINT
        FOR L = 1 TO N - 4
                AVE5(L + 2) = (YY(L) + YY(L + 1) + YY(L + 2) + YY(L + 3) + YY(L + 4)) / 5
                PRINT TAB(23); "19"; XX(L); : PRINT USING "     ####.###"; AVE5(L)
        NEXT L
        OPEN "B:SUDAN.OUT" FOR OUTPUT AS #2
        FOR LL = 1 TO N
                PRINT #2, XX(LL), YY(LL), AVE5(LL)
        NEXT LL
        CLOSE #2
500     END
REM
REM     SUBROUTINE FOR EVALUATING STATISTICAL PARAMETERS
600     X = 0: Y = 0: X2 = 0: Y2 = 0: XY = 0
        FOR JJ = 1 TO N
                X = X + X(JJ): Y = Y + Y(JJ)
                XY = XY + X(JJ) * Y(JJ)
                X2 = X2 + X(JJ) ^ 2: Y2 = Y2 + Y(JJ) ^ 2
        NEXT JJ
        IF Q = 1 THEN 700
REM     EQUATION FOR STANDARD DEVIATION
        SX = ((X2 - X ^ 2 / N) / N) ^ .5
        SY = ((Y2 - Y ^ 2 / N) / N) ^ .5
REM     EQUATION FOR MEAN VALUE
        MEANX = X / N: MEANY = Y / N
        LPRINT "    MEANx="; MEANX, "          MEANy="; MEANY
        LPRINT "    STD DEV. (Sx)="; SX, "STD DEV. (Sy)="; SY
REM     EQUATION FOR VARIATION COEFFICIENT
        CV = SX / MEANX
        CVY = SY / MEANY
        LPRINT "    VAR. COEFF. (Cvx)= "; CVX
        LPRINT "    VAR. COEFF. (Cvy)= "; CVY
```

```
        LPRINT "VAR. COEFF. (Cvy)= "; SY / MEANY
REM     EQUATION FOR CONSTANT B
700     B = (N * XY - X * Y) / (N * X2 - X ^ 2)
REM     EQUATION FOR CONSTANT A
        A = (Y - B * X) / N
        IF Q = 1 THEN A = EXP(A)
REM     EQUATION FOR CORRELATION FACTOR
        R = B * ((N * X2 - X ^ 2) / (N * Y2 - Y ^ 2)) ^ .5
        LPRINT : LPRINT "     A="; A, "B="; B,
        IF QQ$ = "P" THEN LPRINT "C= "; C,
        PRINT : PRINT "     A="; A, "B="; B, : IF QQ$ = "P" THEN PRINT "C= "; C,
        LPRINT "r= "; R
        PRINT "r= "; R
        RETURN
```

A.2 Program for the Development of Regional Solar Radiation Formulae

```
REM     THIS PROGRAM DEVELOPS THE REGIONAL REGRESSION EQUATIONS OF THE
REM     FORMS LINEAR, EXPONENTIAL AND POWER FOR SHORT WAVE SOLAR
REM     RADIATION USING AVAILABLE MEASURED DATA FOR SUNSHINE DURATION AND
REM     SOLAR RADIATION FOR THE REGION
REM
        DIM X(12, 50), Y(12, 50), YY(12, 50), N0(12), H0(12), H(12, 50)
        DIM N(12, 50), MONTH$(12), M(50), NN(12, 50), HH(12, 50)
REM
        OPEN "B:SUDAN.DAT" FOR INPUT AS #1
REM     INPUT NAME OF STATION AND DATA PERIOD
        INPUT #1, STAT$, PERIOD$
        N = 0
REM     INPUT MONTHS
        FOR I = 1 TO 12: INPUT #1, MONTH$(I): NEXT I
REM     INPUT NUMBER OF RECORDS FOR EACH MONTH
        FOR I = 1 TO 12: INPUT #1, M(I): N = N + M(I): NEXT I
REM     INPUT MAX. POSSIBLE SUNSHINE DURATION (N) FOR EACH MONTH
        FOR I = 1 TO 12: INPUT #1, N0(I): NEXT I
REM     INPUT EXTRATERRETRIAL SOLAR RADITION (Ho) FOR EACH MONTH
        FOR I = 1 TO 12: INPUT #1, H0(I): NEXT I
REM             INPUT ACTUAL SUNSHINE HOURS (n) FOR EACH MONTH
        FOR J = 1 TO 12
                FOR K = 1 TO M(J)
                        INPUT #1, N(J, K): NN(J, K) = N(J, K) / N0(J)
                NEXT K
        NEXT J
        FOR J = 1 TO 12
REM     INPUT ACTUAL SOLAR RADIATION (H) FOR EACH MONTH
                FOR K = 1 TO M(J)
                        INPUT #1, H(J, K): HH(J, K) = H(J, K) / H0(J)
                NEXT K
        NEXT J
        CLOSE #1
REM
        OPEN "B:SUDAN.OUT" FOR OUTPUT AS #2
        CLS
        LPRINT TAB(20); "DEVELOPMENT OF REGIONAL SOLAR RADIATION FORMULA"
        LPRINT TAB(20); "----------------------------------------"
        LPRINT : LPRINT : LPRINT "STATION: "; STAT$, "DATA PERIOD: "; PERIOD$
        LPRINT "----------------------------------------": LPRINT
```

```
        LPRINT "  n/N    H/Ho   n/N    H/Ho   n/N    H/Ho   n/N    H/Ho";
        LPRINT "  n/N    H/Ho": LPRINT
REM     PRINT CLOUDINESS RATIO AND RELATIVE SOLAR RADIATION
        FOR M = 1 TO 12
                LPRINT MONTH$(M); ":"
                FOR KK = 1 TO M(M)
                        LPRINT USING "###.### "; NN(M, KK); HH(M, KK);
                        PRINT #2, NN(M, KK), HH(M, KK)
                        X(M, KK) = NN(M, KK): Y(M, KK) = HH(M, KK)
                NEXT KK
                LPRINT
        NEXT M
        CLOSE #2
REM     DEVELOPMENT OF REGIONAL SOLAR RADIATION FORMULAE BY REGRESSION
REM     ANALYSIS
        LPRINT : LPRINT "LINEAR REGRESSION [H/Ho=A+B*(n/N)]:": LPRINT
        PRINT : PRINT "LINEAR REGRESSION [H/Ho=A+B*(n/N)]:": PRINT
        Q = 0
        GOSUB 400
        Q = 1
        LPRINT : LPRINT "EXPONENTIAL REGRESSION [H/Ho=Ae^(B*n/N)]:": LPRINT
        PRINT : PRINT "EXPONENTIAL REGRESSION [H/Ho=Ae^(B*n/N)]:": PRINT
        FOR I = 1 TO 12
                FOR J = 1 TO M(I): Y(I, J) = LOG(HH(I, J)): NEXT J
        NEXT I
        GOSUB 400
        LPRINT : LPRINT "POWER REGRESSION [H/Ho=C+A*(n/N)^B]:": LPRINT
        PRINT : PRINT "POWER REGRESSION [H/Ho=C+A*(n/N)^B]:": PRINT
        QQ$ = "P"
100     INPUT "CONSTANT C IN POWER FORMULA [H/Ho=C+A*(n/N)^B]="; C: PRINT
        FOR I = 1 TO 12
                FOR J = 1 TO M(I)
                        YY(I, J) = HH(I, J) - C: IF YY(I, J) <= 0 THEN GOTO 200
                        X(I, J) = LOG(NN(I, J)): Y(I, J) = LOG(YY(I, J))
                NEXT J
                GOTO 300
200     PRINT TAB(25); "**** TRY ANOTHER VALUE OF C ****": GOTO 200
300     NEXT I
        GOSUB 400
        PRINT : PRINT "WOULD YOU LIKE TO CHANGE C VALUE? Y OR N?";
        INPUT Q1$: PRINT
        IF Q1$ = "Y" OR Q1$ = "y" THEN 100
        END
REM     SUBROTINE FOR REGRESSION ANALYSIS
400     X = 0: Y = 0: X2 = 0: Y2 = 0: XY = 0
        FOR I = 1 TO 12
                FOR J = 1 TO M(I)
                        X = X + X(I, J): Y = Y + Y(I, J)
                        XY = XY + X(I, J) * Y(I, J)
                        X2 = X2 + X(I, J) ^ 2: Y2 = Y2 + Y(I, J) ^ 2
                NEXT J
        NEXT I
        IF Q = 1 THEN 500
        SX = ((X2 - X ^ 2 / N) / N) ^ .5
        SY = ((Y2 - Y ^ 2 / N) / N) ^ .5
        MEANX = X / N: MEANY = Y / N
        LPRINT TAB(5); " FOR n/N VALUES:", "      FOR H/Ho VALUES:"
        LPRINT TAB(11); "MEAN="; MEANX, "         MEAN="; MEANY
```

```
        LPRINT TAB(11); "STD DEV.="; SX, "STD DEV.="; SY
        LPRINT TAB(11); "VAR. COEFF.= ", SX / MEANX,
        LPRINT "VAR. COEFF.= ", SY / MEANY
500     B = (N * XY - X * Y) / (N * X2 - X ^ 2)
        A = (Y - B * X) / N
        IF Q = 1 THEN A = EXP(A)
        R = B * ((N * X2 - X ^ 2) / (N * Y2 - Y ^ 2)) ^ .5
        LPRINT : LPRINT "     A="; A, "B="; B,
        IF QQ$ = "P" THEN LPRINT "C= "; C,
        PRINT : PRINT "     A="; A, "B="; B, : IF QQ$ = "P" THEN PRINT "C= "; C,
        LPRINT "r= "; R
        PRINT "r= "; R
        RETURN
```

A.3 Program for the Estimation of Evaporation and Potential Evapotranspiration

```
REM     THIS PROGRAM ESTIMATES PENMAN EVAPORATION AND THORNTHWAITE
REM     POTENTIAL EVAPOTRANPIRATION RATES, PICHE COEFFICIENTS AND
REM     THORNTHWAITE POTENTIAL EVAPOTRANSPIRATION TO PENMAN
REM     EVAPORATION RATIOS
REM
        DIM H0(12), EP(12), T(12), U2(12), N(12), CP(12), E0(12), PET(12)
        DIM N0(12), RH(12), MONTH$(12), DAYS(12), RN(12), RPET(12)
REM
        OPEN "B:SUDAN.DAT" FOR INPUT AS #1
        CLS
REM             **** HOW TO INPUT THE DATA ****
REM     INPUT NAME OF STATION
REM     INPUT VALUES OF A, B AND C IN RADIATION FORMULA
REM     INPUT MEAN PICHE EVAPORATION RATE (Ep) IN mm/day
REM     INPUT MONTHLY AVERAGE DAILY EXTRATERRESTRIAL SOLAR
REM     RADIATION (Ho) IN MJ/m^2/d
REM     INPUT MEAN MONTHLY ACTUAL SUNSHINE HOURS (n)
REM     INPUT MAXIMUM POSSIBLE SUNSHINE HOURS (N)
REM     INPUT MEAN MONTHLY TEMPERATURE IN DEGREES CELSIUS (t)
REM     INPUT MEAN MONTHLY RELATIVE HUMIDITY (RH) IN %
REM     INPUT MEAN WIND SPEED (u2) IN KNOTS
        INPUT #1, STAT$
        INPUT #1, A, B, C
        PRINT "*** CHOOSE REGRESSION FORM FOR SOLAR RADIATION EQUATION ***"
        INPUT "LINEAR (1), EXPONENTIAL (2) OR POWER (3)? 1, 2 OR 3"; Q
        FOR I = 1 TO 12: INPUT #1, EP(I): NEXT I
        FOR I = 1 TO 12: INPUT #1, H0(I): NEXT I
        FOR I = 1 TO 12: INPUT #1, N(I): NEXT I
        FOR I = 1 TO 12: INPUT #1, N0(I): NEXT I
        FOR I = 1 TO 12: INPUT #1, T(I): NEXT I
        FOR I = 1 TO 12: INPUT #1, RH(I): NEXT I
        FOR I = 1 TO 12: INPUT #1, U2(I): NEXT I
        FOR I = 1 TO 12: READ MONTH$(I): NEXT I
        DATA JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC
        FOR I = 1 TO 12: READ DAYS(I): NEXT I
        DATA 31, 28,31, 30, 31, 30, 31, 31, 30, 31, 30, 31
REM
        CLOSE #1
REM
        OPEN "B:SUDAN.OUT" FOR OUTPUT AS #2
```

```
        CLS
        LPRINT "STATION: ": STAT$
        LPRINT "-------------------": LPRINT
        LPRINT "PENMAN EVAPORATION Eo IN mm/day:": LPRINT
        FOR I = 1 TO 12
                IF Q = 1 THEN H = H0(I) * (A + B * N(I) / N0(I))
                IF Q = 2 THEN H = H0(I) * A * EXP(B * N(I) / N0(I))
                IF Q = 3 THEN H = H0(I) * (C + A * (N(I) / N0(I)) ^ B)
                H = H / .0419
                R = .06: RI = H * (1 - R)
                ES = 5.119989 * EXP(5.910864E-02 * T(I))
                EE = ES * RH(I) / 100
                TA = T(I) + 273
                XXX = (.2 + .8 * N(I) / N0(I))
                RB = 1.1774E-07 * TA ^ 4 * (.47 - .077 * EE ^ .5) * XXX
                RN = RI - RB
                ARN = ARN + RN * DAYS(I)
                EA = .35 * (ES - EE) * (.5 + .54 * U2(I) * .514)
                D = .302635586# * EXP(.0591086 * T(I))
                E0(I) = (D * RN / 60 + .485 * EA) / (D + .485)
                AE0 = AE0 + E0(I) * DAYS(I)
                AEP = AEP + EP(I) * DAYS(I)
                LPRINT MONTH$(I); "= "; : LPRINT USING "###.#"; E0(I);
                : LPRINT "   ";
REM     CALCULATIONS FOR MONTHLY PICHE COEFFICIENTS
                CP(I) = E0(I) / EP(I)
        NEXT I
        LPRINT : LPRINT : LPRINT "ANNUAL PENMAN EVAPORATION=";
        : LPRINT USING "#####.#"; AE0; : LPRINT "mm/year"
        PLRINT: LPRINT "ANNUAL NET RADIATION=";
        : LPRINT USING "########.#"; ARN; : LPRINT "g cal/cm2/year"
        LPRINT : LPRINT "ANNUAL PICHE EVAPORATION Ep=";
        : LPRINT USING "#####.#"; AEP; : LPRINT "mm/year"
        LPRINT : LPRINT : LPRINT "PICHE COEFFICIENT Cp:": LPRINT
        FOR L = 1 TO 12
                LPRINT MONTH$(L); "="; : LPRINT USING "##.##"; CP(L);
                : LPRINT "   ";
        NEXT L
REM     CALCULATIONS FOR ANNUAL PICHE COEFFICIENT
        ACP = AE0 / AEP
        LPRINT : LPRINT "WHOLE YEAR="; : LPRINT USING "##.##"; ACP
        LPRINT : LPRINT : LPRINT "THORNTHWAITE EVAPOTRANSPIRATION PET";
        : LPRINT " IN mm/day:": LPRINT
        FOR K = 1 TO 12
                J = (T(K) / 5) ^ 1.514
                JJ = JJ + J
        NEXT K
        AA = 6.75E-07 * JJ ^ 3 - .0000771 * JJ ^ 2 + .0179 * JJ + .492
        FOR M = 1 TO 12
                PETX = 16 * (10 * T(M) / JJ) ^ AA
                PET(M) = PETX * N0(M) / 360
                LPRINT MONTH$(M); "="; : LPRINT USING "###.#"; PET(M);
                : LPRINT "   ";
                APET = APET + PET(M) * DAYS(M)
REM     CALCULATIONS FOR MONTHLY PET/Eo RATIOS
                RPET(M) = PET(M) / E0(M)
        NEXT M
        LPRINT : LPRINT : LPRINT "ANNUAL POTENTIAL EVAPOTRANSPIRATION=";
```