# *Some aspects of measured and estimated evaporation in the Sudan*

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# SOME ASPECTS OF MEASURED AND ESTIMATED EVAPORATION IN THE SUDAN

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## ABSTRACT

The present work analyses, for the Sudan, the methods of evaporation measurement by Piche evaporimeter and Class 'A' pan, together with the estimation of open-water evaporation (EO) from Penman's formula (1948) and potential evapotranspiration (PE) by Thornthwaite's method (1948).

Measured Class 'A' pan and Piche evaporation tend to follow similar fluctuations during the various seasons. Monthly and seasonal fluctuations of the measured water loss are large compared with the computed evaporation which displays limited variations. During the dry season, measured evaporation is greater than the computed, but, in the wet season, the measured values are slightly exceeded by the (PE) and even more so by the (EO).

Regression analysis shows a close correlation between measured and computed evaporation at some stations in northern Sudan where the correlation coefficients are large (over 0.70). At some stations in central and southern Sudan the correlation coefficients are low (under 0.50), and the correlation is rather poor and may not be statistically significant.

In a comparative study between Penman's (EO) and Thornthwaite's (PE), the former usually gives larger values than the latter. But the disparity between them is relatively small in the dry season.

The final aspect of the thesis discusses the distribution of average annual, seasonal and monthly Piche evaporation over the Sudan. Annual values reveal a steady decrease from north to south, and evaporation isolines seem to run roughly along latitudes from east to west. This pattern of isolines is interrupted by the uplands of Jebel Marra, the Red Sea hills, and Nuba mountains where evaporation tends to decrease with high altitudes.

# Table of Contents

# List of Figures

# List of Tables

## PREFACE

Knowledge of the evaporation taking place from the soil surface and from free water surfaces as well as the transpiration from plants is of importance to meteorologists, agricultural researchers and water engineers, particularly in the arid and semi-arid regions of the Sudan. Over much of this country, the potential evapotranspiration exceeds the precipitation on an annual as well as seasonal basis. Therefore a quantitative knowledge of such water losses is essential if greater benefits are to be expected from the limited water resources which are required for agricultural, animal and human consumption in different parts of the country.

The study of evaporation has been a neglected aspect of climatology in a vast country like the Sudan, where reliable data is often difficult to obtain, and research facilities are very limited. Only in recent years, have climatologists and meteorologists begun to show greater interest in the subject. An important contribution was the article of Professor J. Oliver (1965) on "Evaporation Losses and Rainfall Regime in Central and Northern Sudan", together with the publication of Mr. Y. Satakopan (1961) on "Water Balance in the Sudan" and the technical note of Sayed A. Saeed (1957) on "Water Saving - Through Reduction of Evaporation". However, this attempt has been made by the author to present a preliminary survey on some aspects of evaporation and prepare maps which may be of use to other research workers in the country.

The present work proposes to study the various methods of evaporation measurement in the Sudan, and to apply Thornthwaite's concept of potential evapotranspiration (1948) and Penman's equation (1948) for the estimation of open-water evaporation from available climatic data. Measured evaporation values are compared with calculated Penman's and Thornthwaite's results in an effort to study the possible relationship between the measured and computed for various climatic environments in the Sudan. The final part of the thesis discusses the average annual, seasonal and monthly Piche evaporation distribution over the entire country, as influenced by topographic and climatic factors.

Eight representative stations (Fig. 21), which are evenly distributed in the Sudan, were chosen to show the relationships between Class 'A' pan and Piche evaporation, on the one hand, and Penman's evaporation (EO) on the other. In the absence of comparable measurements of potential evapotranspiration the calculated (PE) results were also tested against the measured Class 'A' pan and Piche evaporation values. "This procedure may be justified since the accumulation of practical and theoretical evidence shows that potential evapotranspiration is essentially a climatic factor mainly dependent upon weather conditions and subject to the same influences as those controlling evaporation", Smith (1965).

The mean annual and monthly Piche and Class 'A' pan evaporation data, together with the computed Penman's evaporation (EO) and Thornthwaite's potential evapotranspiration (PE), have been calculated from 'Annual Meteorological Reports' published at Khartoum Met. Office, for an eight years period 1959-1966. Other climatic parameters, which are not measured at Sudanese meteorological stations but required for the computational procedure of Penman's evaporation (EO), have been calculated from special tables and nomograms. This eight year period (1959-1966) may appear to be rather short for a comparative study, but practically it might be quite satisfactory since the Sudanese tropical climate does not change very much from one year to another. On the other hand, the eight years period of data, as discussed in the text, is mainly dictated by the scarcity of Class 'A' pan evaporation data and the absence of other climatic parameters required for the calculation of Penman's evaporation at selected stations.

Sixty two stations (Fig. 28) for which Piche evaporation data is available during the standard 30 years period (1931-1960) were utilized in constructing annual and monthly maps of evaporation distribution over Sudan. But, in some cases it has been found inevitable to include stations with less than thirty years records. These Stations (Fig. 28) are fairly distributed for most of the country. Unfortunately not too many stations are found west of the Red Sea hills. Also in the desert, between the river Nile and the north-western borders, there are hardly any meteorological stations, since this part of the country is practically uninhabited. Therefore, the evaporation isolines over these parts of Sudan might be relatively unreliable, since they are drawn roughly to accord with the general trend of other isolines in the country. Over upland areas such as the Nuba mountains, Jebal Marra region and the Red Sea hills, the interpolation of isolines was guided, to some extent, by the relief pattern.

Some climatic factors that influence the evaporation distribution, like temperature and humidity, have also been presented on seasonal maps which are constructed from available data at 50 stations (Fig. 6) during the period 1931-1960.

Most of the data used in this investigation have been either extracted or calculated from statistics published by the Sudan Meteorological Service. Some of the unpublished data have been extracted from files which are kept in the head-quarters of the Meteorological Service at Khartoum.

Note! _

The abstract is on Page 150

## ACKNOWLEDGEMENTS

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At Durham University, thanks to Professor W.B. Fisher, head of the Geography Department, and the staff members, for the excellent provision of research facilities in the department of Geography. I am also thankful to the staff members of the Computer Unit of Durham University for their great help in the computational procedure of data used in this work.

Finally, but by no means least, I am very much indebted and grateful to Dr. K. Smith, of the Geography Department, Durham University, for his excellent supervision and efficient guidance throughout my research. It should be admitted that, without his keen interest, and valuable advice this work would have never come to its present form.

# Chapter One

## RELIEF AND CLIMATE OF THE STUDY AREA

The Republic of the Sudan is the largest political unit in Africa. It has an area of just under one million square miles, which is equal to 8.3% of the area of Africa and 1.7% of the land area of the world (Lebon, 1965). Except for a few hundred miles along the Red Sea, the country is completely land-locked. The whole of the country lies in the northern hemisphere, roughly between latitudes $3^{\circ}$ and $23^{\circ}$ North, whilst longitudinally it extends between $21\frac{1}{2}^{\circ}$ and $38\frac{1}{2}^{\circ}$ East.

### RELIEF:

The relief of Sudan consists mainly of vast plains stretching from the desert in the north to the borders of the equatorial forest land in the South (Fig. 1). South of Khartoum there is a clay plain which appears to be almost flat. It stretches as far as Juba (1200 km. away), rising only 80 metres in that distance. Similarly, the sandy area of the west (the Qoz) has slight relief or almost level sand (Barbour, 1961). To the west and north, the plain lands extend far beyond the frontier, and to the east and south are limited by the Congo and East Africa.

Except for the Nile and its tributaries, there are hardly any water bodies or inland lakes that may give rise to local climatic conditions. The only possible exception to this is a large swampy area known as the "Sudd Region", which is found in the southern part of the country between latitudes 5° and 10° North. Here there are extensive pools resulting from the overspilling of the White Nile waters beyond its banks during the rainy season. This region is responsible for the loss of large amounts of water from the White Nile and its tributaries through evaporation and evapotranspiration.

This low and simple relief of the country is broken only by a few small hills and mountain ranges, such as the Jebel Marra range in Darfur (10,000 ft. above sea level), the Nuba Mountains in southern Kordofan (2,000-5,000 ft. above sea level), the Imatong Mountains in the extreme south of Equatoria Province (11,000 ft. above sea level), and a narrow belt of high

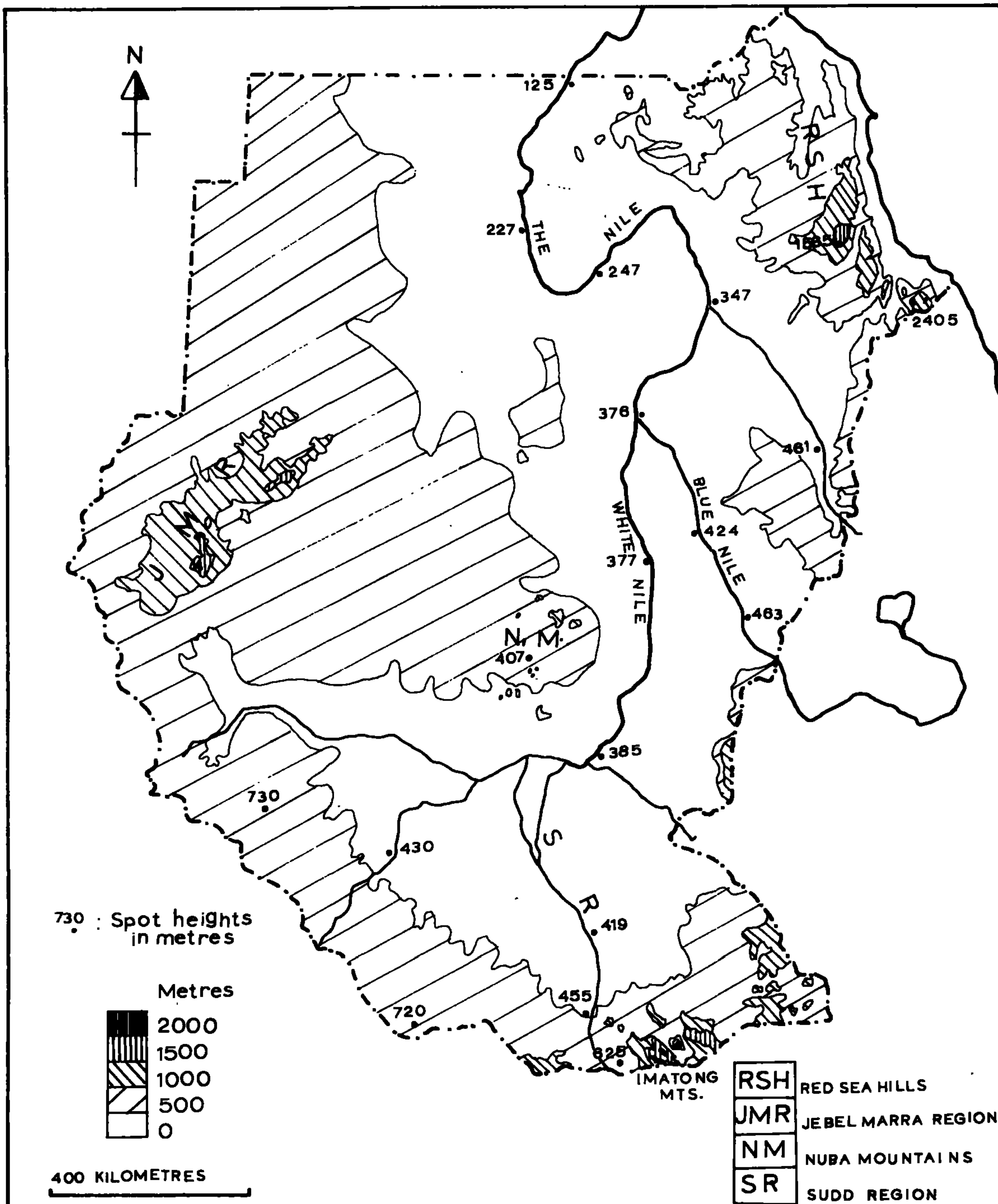


Fig. 1. Relief (after Barbour, 1961)

land along the western coast of the Red Sea (3,000-4,000 ft. above sea level) (Bhalotra, 1963). According to Barbour (1961), less than 2% of the whole country lies lower than 1,000 ft., about 45% lies between 1,000 ft. and 1,500 ft. and a further 50% lies below 4,000 feet. This suggests that there are only small areas that are sufficiently high to enjoy a markedly different climate from other parts of the country at the same latitude.

CLIMATE:

Over much of the country, a tropical continental climate prevails. In the south, this type of climate merges into the equatorial rainy climate; in the north, into desert. This tropical continental climate is itself transitional. In the south, it is distinguished from the equatorial climate by a short yet distinct dry season. In the north, it is differentiated from the desert by a short and unreliable rainy season. In between, as one proceeds from south to north, the dry season gradually lengthens, and the total rainfall decreases (Lebon, 1965). In the case of the Red Sea hills and the coastal plain, Barbour (1961) indicated that there is a cool winter with a slight rain, while for the rest of the year there is little or no rain.

However, there is no obvious classification of seasons for the Sudan, which applies satisfactorily to the entire country. Nevertheless, Bhalotra (1963) suggested four seasons which may be accepted broadly for most of the country (central and much of southern Sudan), though the duration of each season varies with latitude. These seasons have been defined as follows: (1) The cool dry winter (December to February), (2) The hot, dry season of early summer, between the winter and rainy season, (March to May), (3) The hot, rather damper rainy season (June to September) and (4) the hot humid season at the end of the rains before the onset of the north wind (October to November). This last season is identified by Bhalotra (1963) as the "retreating monsoon" i.e. the transitional period between the rainy season and winter season.

## PRESSURE AND WINDS:-

In order to explain the climate of Sudan, it is necessary to study the pressure field and wind flow which affect the country at different times of the year. Average annual rainfall, temperature and prevailing winds over Sudan are, generally, related to the surface pressure system and annual oscillations of the Inter-Tropical Convergence Zone (I.T.C.Z.) particularly in the northern hemisphere (El-Fandy, 1949).

The general pressure distribution and the prevailing surface winds are outlined briefly for each season; mainly from the available information and isobaric maps in Bhalotra's report "General Pressure Distribution and Wind Circulation over Sudan" (Bhalotra, 1963).

### (i) WINTER SEASON:-

The pressure distribution and the associated wind flow during this season, represented by January, are illustrated in Fig. 2. It may be seen from this figure that the Sahara high controls the air circulation over Sudan and there is a general north to northeasterly flow over the whole country, except for the southern part of

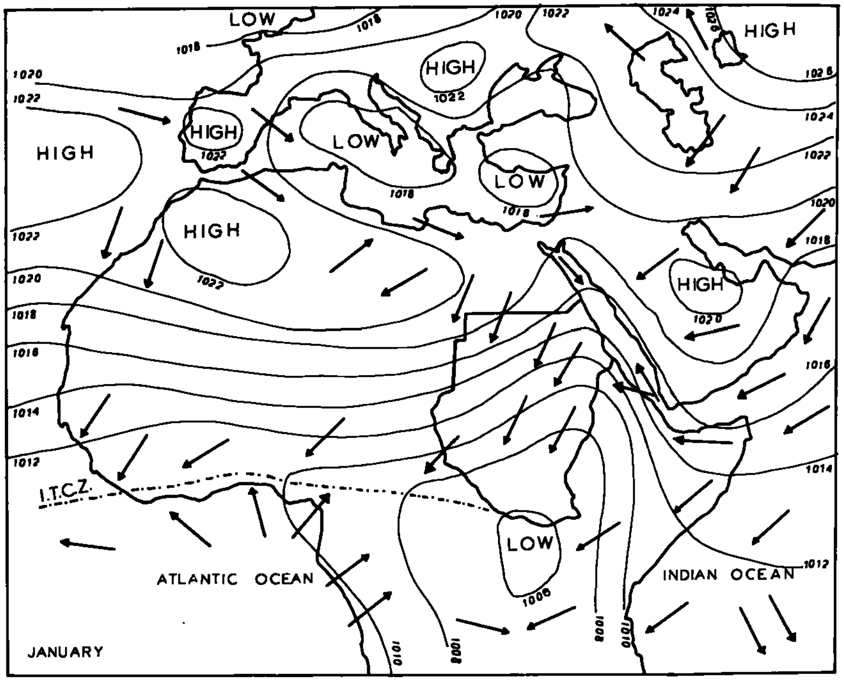


Fig. 2. January Pressure and Wind
(after Bhalotra, 1963)

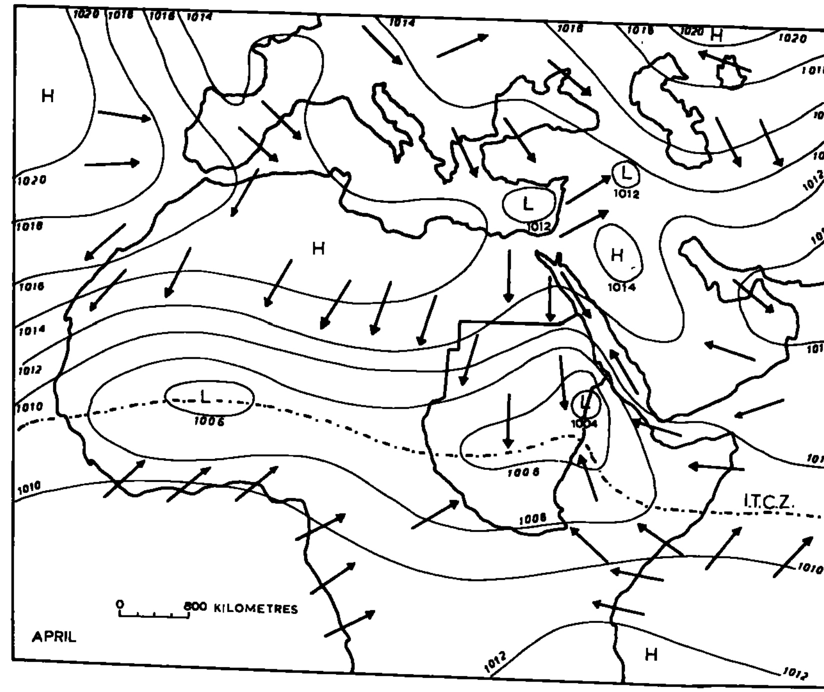


Fig. 3. April Pressure and Wind
(after Bhalotra, 1963)

the Red Sea coastal area. This northerly air is dry and relatively cooler in the northern parts of the country, and it becomes warmer as it travels southwards. The Arabian anticyclone induces a northeasterly air stream over the north Arabian sea. As stated by Bhalotra (1963) this air stream, because of sea travel, becomes moist in the lower levels and is relatively warmer. Over the Red Sea, this stream appears as a southerly current (Fig. 2) and on obtaining orographic lift from the coastal hills it gives showers and thunderstorms.

(ii) HOT DRY SEASON OF EARLY SUMMER:-

During this season, represented by April, the Inter-Tropical Convergence Zone (I.T.C.Z.) which was south of the Sudan in January has moved northwards, and by late April it lies north of latitude 10$^{\circ}$ north over eastern Sudan (Fig. 3). Associated with the I.T.C.Z., a low pressure area with its centre north of the I.T.C.Z. exists over northeast Sudan. This low pressure area, known as the "Sudan Low", is a part of the thermal equator and oscillates north and south with the declination of the sun (Bhalotra, 1963). According to Rath (1955) tropical continental air of Saharan origin continues to prevail over the areas of Sudan north of the I.T.C.Z. This warm and dry air mass gets progressively heated during its travel across the arid regions of the country. The Sahara high has now been displaced towards the northwest and extends over northwest Africa as a ridge of high pressure (Fig. 3). It also controls the dry northerly air flow north of the I.T.C.Z., whilst the Arabian high has relatively weakened, but still affects circulation in the southern Red Sea region.

(iii) THE RAINY SEASON:-

The general isobaric situation and the surface wind flow during this season, represented by July, are shown in Fig. 4. Comparing July pressure pattern with that of January, the surface pressure over North Arabia is now inverted. The high over Arabia has given place to a deep low pressure area which is an extension of the huge low pressure area, centred over Northeast India in this season. The lower level wind flow over eastern Egypt, and northeast Sudan forms part of this low pressure system. A thermal low has also appeared over the southern

Sahara (Fig. 4). This low is shallow and is replaced by the deep Saharan anticyclonic circulation (Bhalotra 1963). However, the anticyclonic circulation of winds over northwest Sudan and western Egypt still continues. During July the I.T.C.Z. reaches its northerly limit at about $18^{o}$ north (Rath, 1955) i.e. between Atbara and Abu Hamad, a little south of its most northern position in August. As stated by El-Fandy (1949), the I.T.C.Z. (over NE Sudan) becomes convex towards the north in the form of a tongue within which the south to south-west currents reach their maximum northward extension. To the south of the I.T.C.Z. lies the moist and relatively cool equatorial maritime air mass from the southern hemisphere, and to the north of it exists the dry and hot tropical continental air. On occasions south easterly flow from the Indian Ocean reaches southern Sudan, particularly when the seasonal low pressure over the extreme southwest Sudan and the adjoining parts of Congo accentuates (El-Fandy, 1949). The convergence of this moist southeasterly stream from the Indian Ocean and the

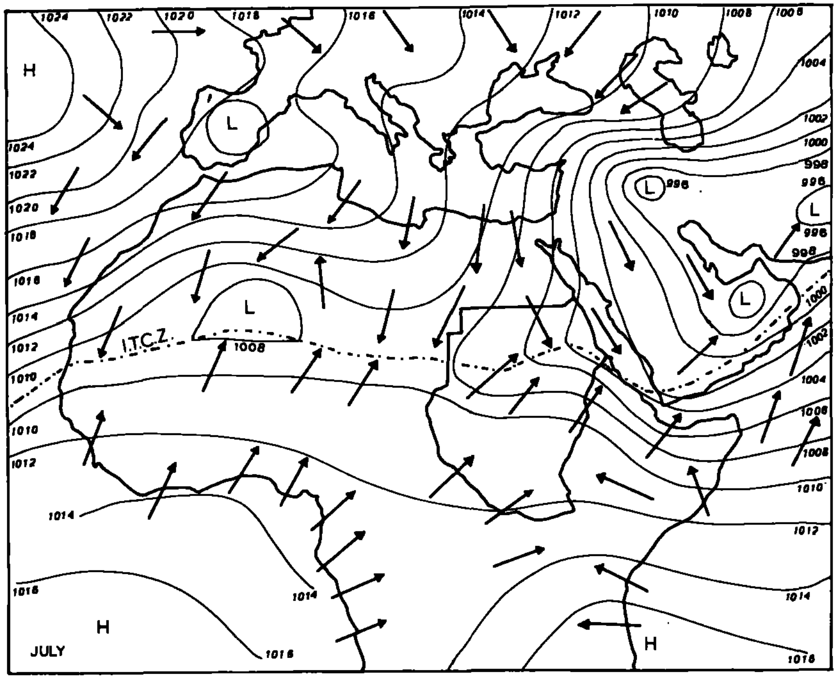


Fig. 4. July Pressure and Wind
(after Bhalotra, 1963)

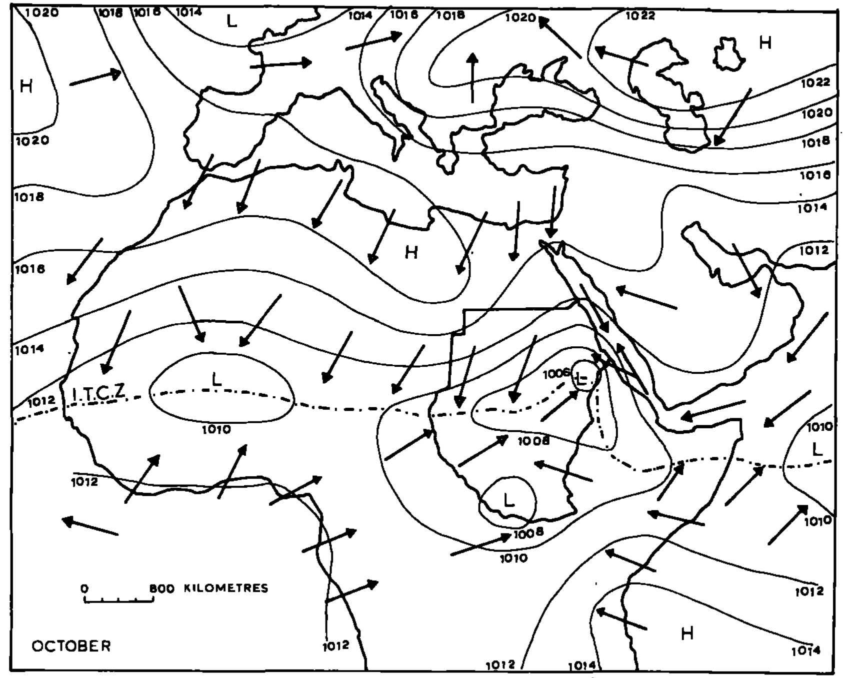


Fig. 5. October Pressure and Wind
(after Bhalotra, 1963)

south westerly current from the Atlantic Ocean causes marked development of heavy rainfall.

(iv) TRANSITIONAL SEASON (RETREATING MONSOON):-

During this season, represented by October the Sahara high has become more prominent and an anticyclonic circulation exists particularly over northwest Africa, Egypt and some parts of northwest Sudan. The Arabian high, on the other hand, starts to develop again and the associated anticyclonic circulation tends to affect Arabia and the adjoining parts of northeastern Sudan. In between the two opposite anticylonic circulations (Arabian and Saharan) a transition zone exists in the Red Sea, between $18^{o}$-$21^{o}$ north, where winds are light variable, pressure is relatively low and air masses of different physical properties from the northern and southern regions of the Red Sea meet. This area therefore becomes favourable for the development of thundery activity. Consequently the coastal area and the neighbouring Red Sea hills get the heaviest rainfall of the year during this season (El-Fandy, 1952).

The I.T.C.Z. during October starts to shift southwards to the area between Khartoum and Kosti over central Sudan (Fig. 5). Along with this, the field of equatorial maritime air also gradually contracts and is confined, generally, to the area south of the I.T.C.Z. As a result, the precipitation in this season is localised in character and the intensity is, usually light to moderate (Mustafa, 1965). However, with the retreat of the I.T.C.Z., the anticyclonic field of dry continental air of Saharan origin spreads southwards and covers most parts of Sudan (Fig. 5).

TEMPERATURE:-

Average monthly isothermal maps are constructed for January, April, July and October to represent the various seasons in the country. These maps are based on temperature data of fifty stations during the period 1931-1960.[1] The locations of such stations are illustrated in Fig. 6 and Appendix I.

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(1) All temperature statistics have been obtained from "Climatological Normals" for fifty stations, published by the Sudan Meteorological Service, (1931-1960).

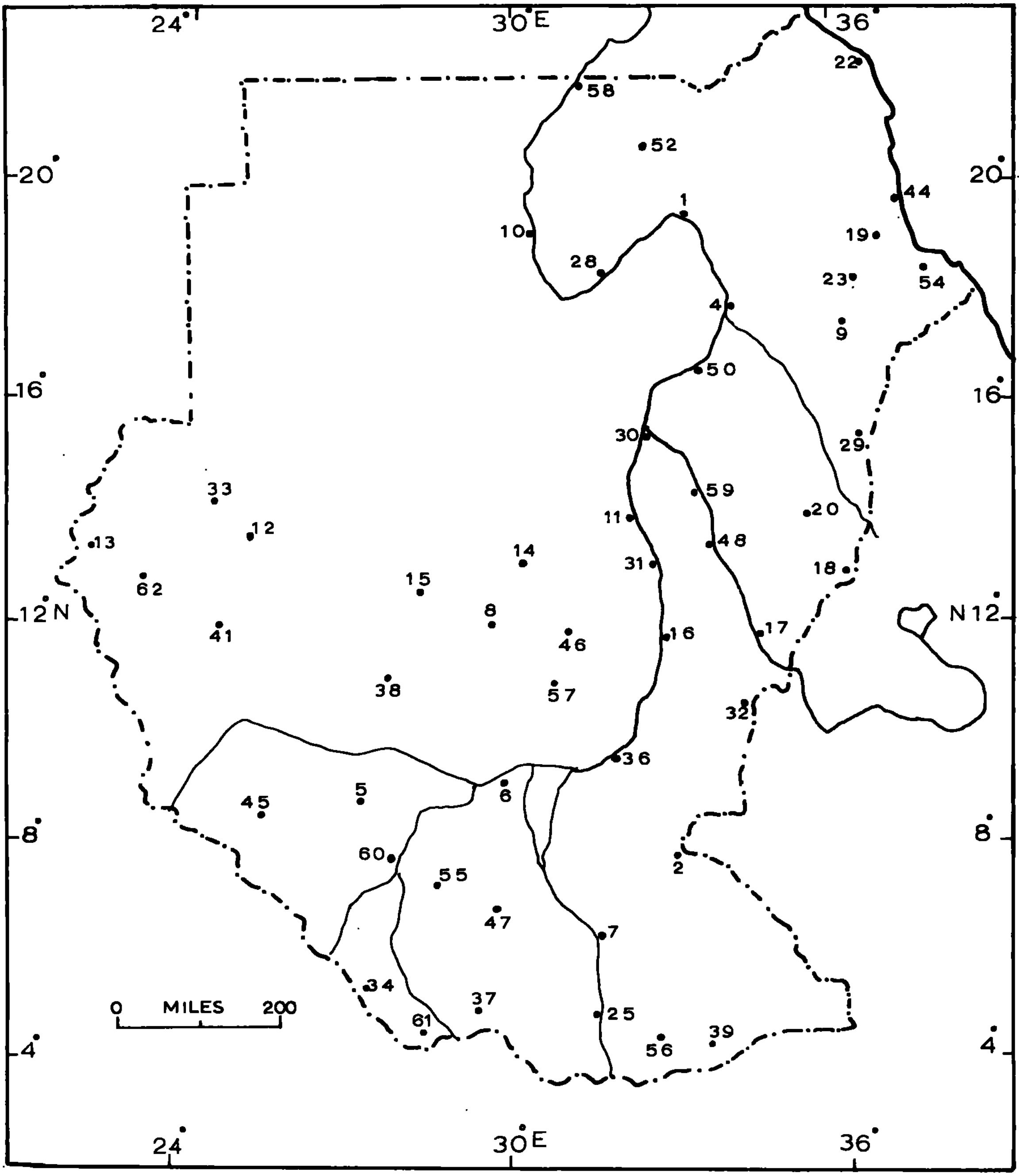
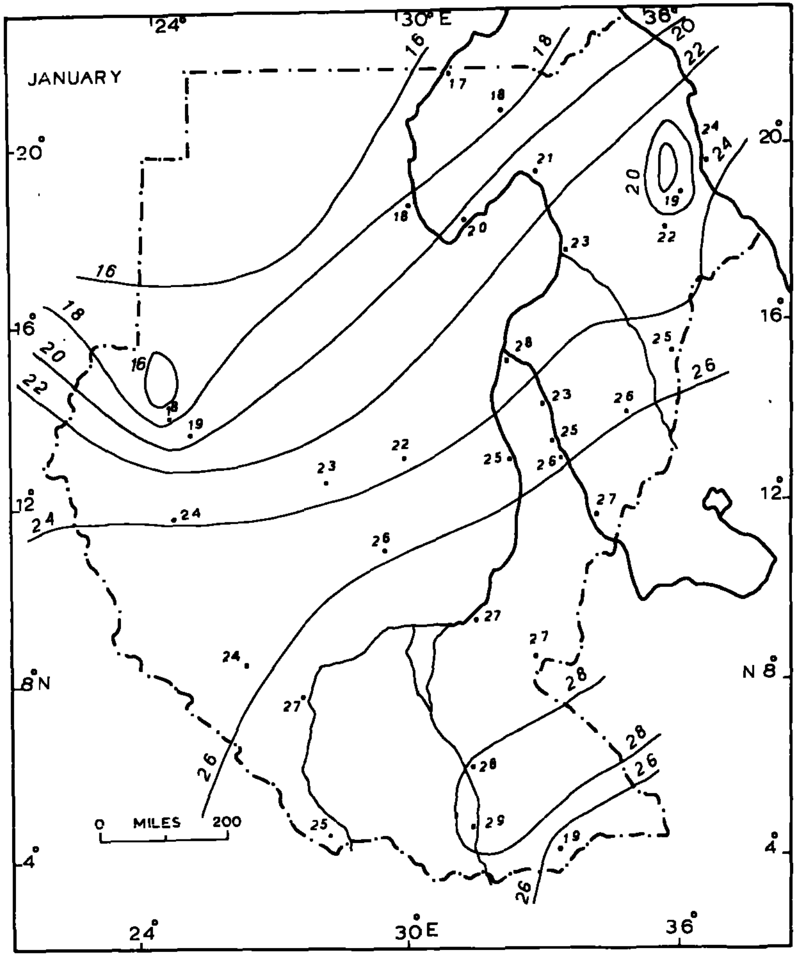



Fig. 6. Location of Met. Stations used for Temperature and Humidity maps (See Appendix I)

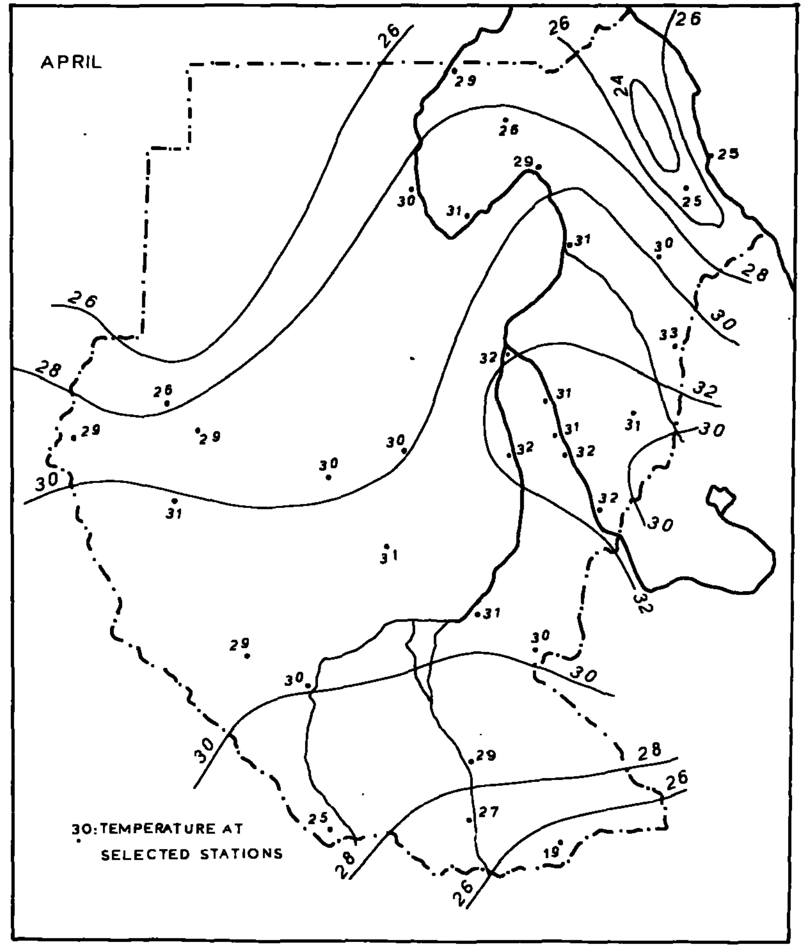
It can be seen that over much of the Sudan plains in winter, represented by January, the temperature increases steadily southwards from 17°C (63°F) at Wadi Halfa in the north to 29°C (84°F) at Juba in the extreme south of the country (Fig. 7). The lower temperatures of northern and central Sudan are, perhaps, due to the influence of the cool dry Saharan air and the cold Polar continental air invading the northern Sudan during this period. To the east, the southern parts of the coastal plain are comparatively warmer owing to the influence of the warm tropical continental air mass of the Arabian anticyclone. South of the line passing through Gedaref, Sennar and Kadugli, temperatures are, generally, higher than the rest of the country, especially in the Nasir-Bor-Juba area and the respective areas around Wau and east of Malakal. The reason for this general rise in temperature is due to the intrusion of the warm moist equatorial air mass or the nearness of the I.T.C.Z. to the extreme south of the country.

In the hot dry season of early summer, represented by April, the position of high temperatures shifts northwards towards the centre and north east of the




SOURCE OF DATA : 'CLIMATOLOGICAL NORMALS'(1931-1960), SUDAN MET. SERVICE, KHARTOUM.

Fig. 7. January Temperature

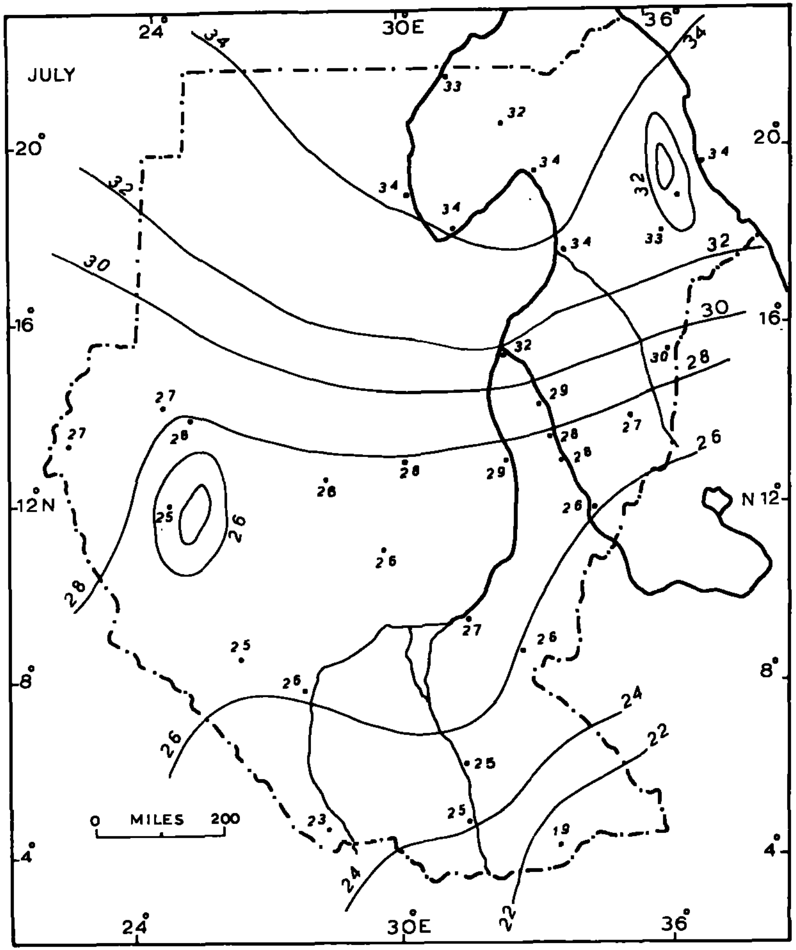



SOURCE OF DATA : SEE FIG. 7

Fig. 8. April Temperature

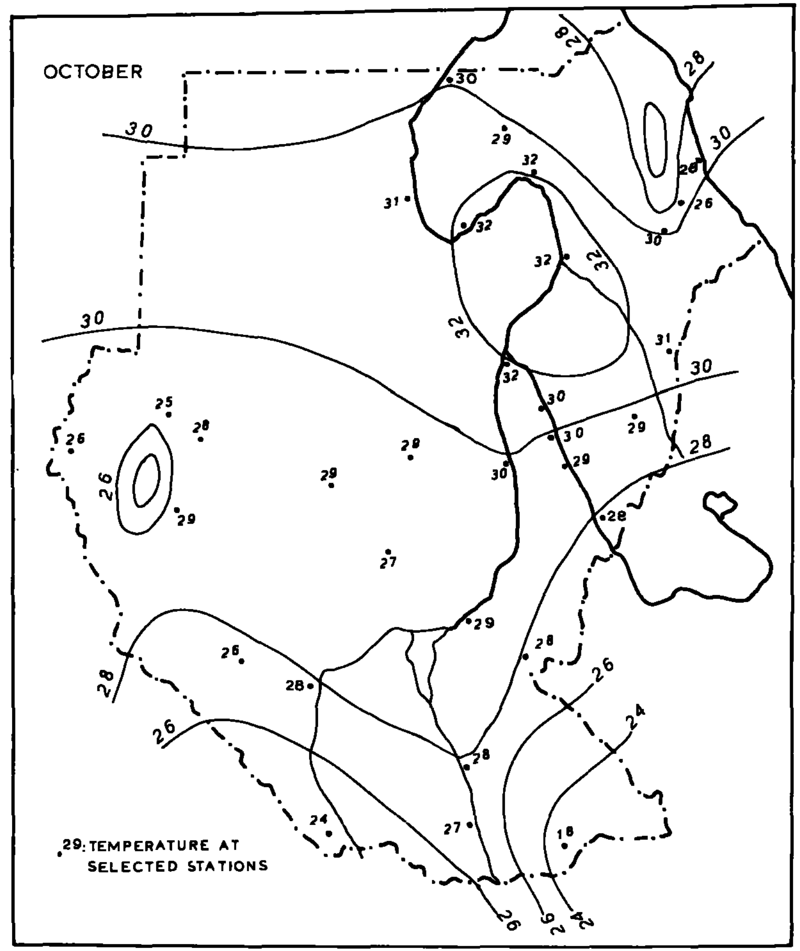
country, following the northward movement of the I.T.C.Z. to latitude 10° to 13° north over eastern Sudan (Fig. 8). The presence of the thermal equator over the north east„ may also be responsible for raising the temperature conditions in these regions. Over the east of central Sudan, north of the convergence zone, night temperatures tend to be almost higher than most other parts in the country. This is, perhaps, the result of moisture on the surface layers which arrives from the Red Sea, under the influence of the thermal low, and therefore restricts radiational coöling during the night (Bhalotra, 1963).

In the rainy season, represented by July, the area of highest temperatures lies over northern Sudan and the lowest temperatures generally occur over the southern portion of the country (Fig. 9). Moving northwards, over the plains, the temperatures increases considerably from about 23°C (73°F) at Yambio, on the southern border, to over 33°C (91°F) at Wadi Halfa in the extreme north. Taking the country as a whole, the average temperature ranges from 22°C (72°F) to 34°C (93.2°F) during this period.




SOURCE OF DATA: SEE FIG.7

Fig. 9. July Temperature




SOURCE OF DATA: SEE FIG.7

Fig. 10. October Temperature

This distribution of temperature is controlled, mainly, by the location of the I.T.C.Z. and the nature of air masses associated with it. In July, the I.T.C.Z. has moved further northwards to the area between Atbara and Abu Hamad (lats. 17-19$^{\circ}$N), and thus gives rise to relatively higher temperatures over this region (Fig. 9). To the south of the I.T.C.Z., lies the moist and relatively cool maritime air mass from the southern hemisphere, and to the north of it exists the dry and hot tropical continental air which produces the relative rise in temperature over northern Sudan.

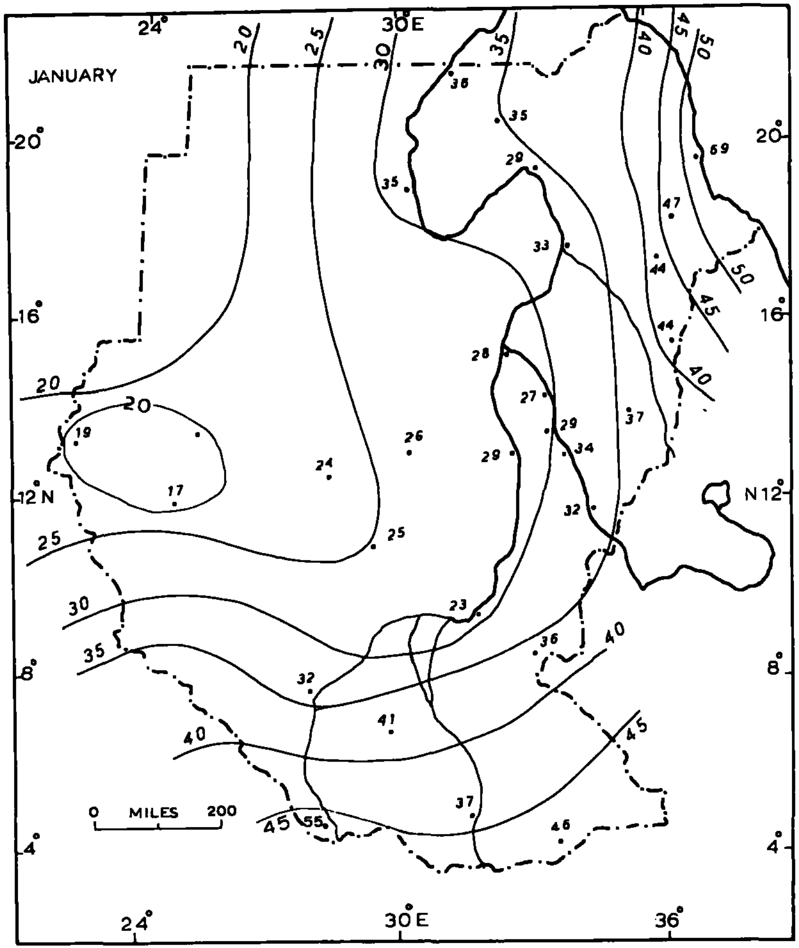
The temperature pattern in the transitional period, between the rainy and winter seasons, may be represented by October (Fig. 10). From this month onwards, the position of high temperatures moves progressively southwards until winter is reached in December. The highest temperatures in October are received in the Atbara-Khartoum area, and lower temperatures are normally registered over west-central Sudan and some parts of southern Sudan. During this period, most of central and northern Sudan lies between 28°C (82°F) and 30°C (86°F), compared with southern Sudan whose temperature ranges, roughly between 26°C (79°F) and 28°C (82°F) (Fig. 10). This variation in the temperature regime can be ascribed directly or indirectly to the air masses and pressure belts prevailing over the country at this time of the year. The Red Sea region for example, is dominated by the Red Sea trough (Bhalotra, 1963) and consequently the Port Sudan area and the adjoining hills have sufficient rains to lower temperature conditions in this season. South of the Red Sea hills, the plains of north east Sudan experience relatively higher temperatures as a result of the prevailing South Arabian air, which is usually hotter and more humid than the Saharan air. In central Sudan the I.T.C.Z. (between Khartoum and Kosti) is responsible, to a great extent, for raising the thermal conditions in this region, and even further to the north of Khartoum. North of the I.T.C.Z., the northern parts of Sudan are affected by the modified polar continental air mass; south of the front are, somewhat, influenced by the equatorial air, prevailing over the southern Sudan.

During the year as a whole, the highest temperatures in the country occur normally in June and July particularly in the area between Atbara and Wadi Halfa. These higher temperatures, however, are closely related to the area of seasonal heat low and the annual oscillations of the Inter-Tropical Convergence Zone. As emphasized by Bhalotra (1963), the lower temperatures of the cool dry season can be mainly ascribed to the passage of cold fronts associated with the Mediterranean depressions or unusual accentuations of the Saharan anticyclone which causes some flow of cooler air from northern latitudes. In the rainy season, an exceptional fall of temperature may occur in association with the passage of thunder squalls or showers or the arrival of fresh monsoon air masses. As shown in the seasonal isothermal maps, temperatures over the Red Sea hills (eastern Sudan) and Jebel Marra region (western Sudan) are slightly reduced by higher altitudes as compared with the adjoining plain lands of the Sudan.

Humidity:-

Seasonal relative humidity maps for January, April, July and October have been constructed from average daily relative humidity at fifty selected stations (Fig. 6). The humidity data are obtained from the "Climatological Normals" for each of these stations during the period (1931-1960).

The main feature of a great part of central and northern Sudan in January, (winter) is its dryness (Fig. 11), while the whole of north west Sudan is extremely dry throughout the cool winter season. Along the Nile valley the mean relative humidity continues to decrease southwards from Wadi Halfa to Malakal and then increases further south. West of the Nile in northern and central Sudan, the humidity tends to increase from north to south over the plain lands. Towards the east of central Sudan it is increasingly higher than other places at the same latitude. Over the Sudan plain, north of Malakal and west of longitude 34$^{o}$ East, the relative humidity is about 35% or less, while west of 30$^{o}$ East, it is generally less than 30% (Fig. 11). Over the area north of Malakal and east of longitude 34$^{o}$ East, the humidity is generally over 35%. South of Malakal, it ranges from about 30% to over 45% in the extreme south of the country.




SOURCE OF DATA: SAMEAS FIG.7

Fig. 11. January Humidity

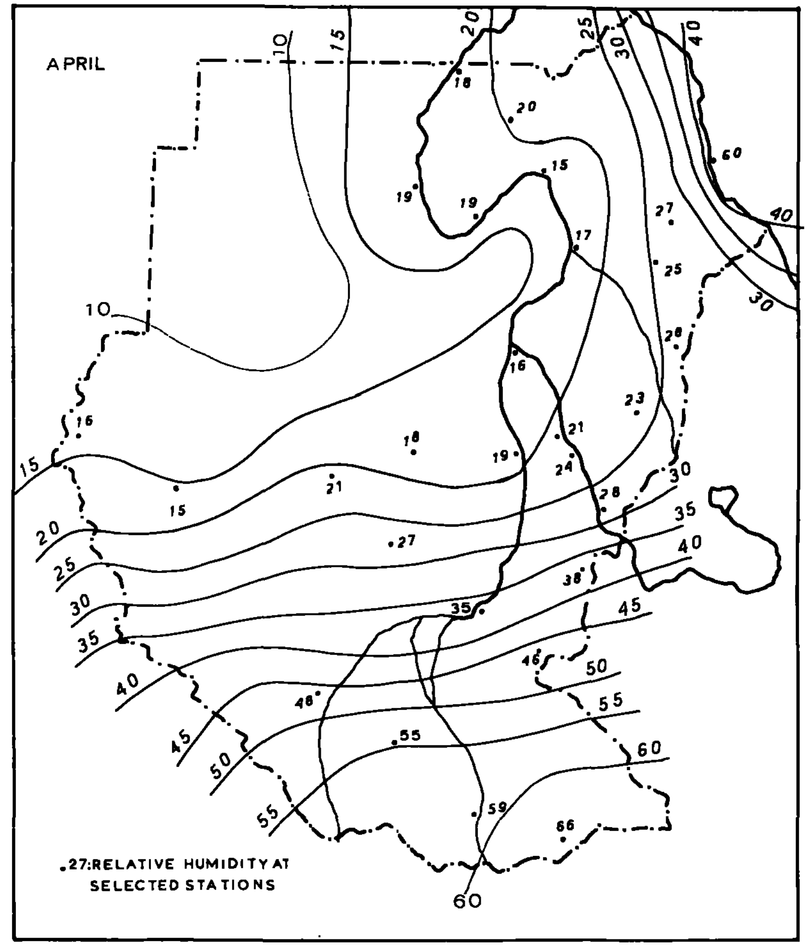



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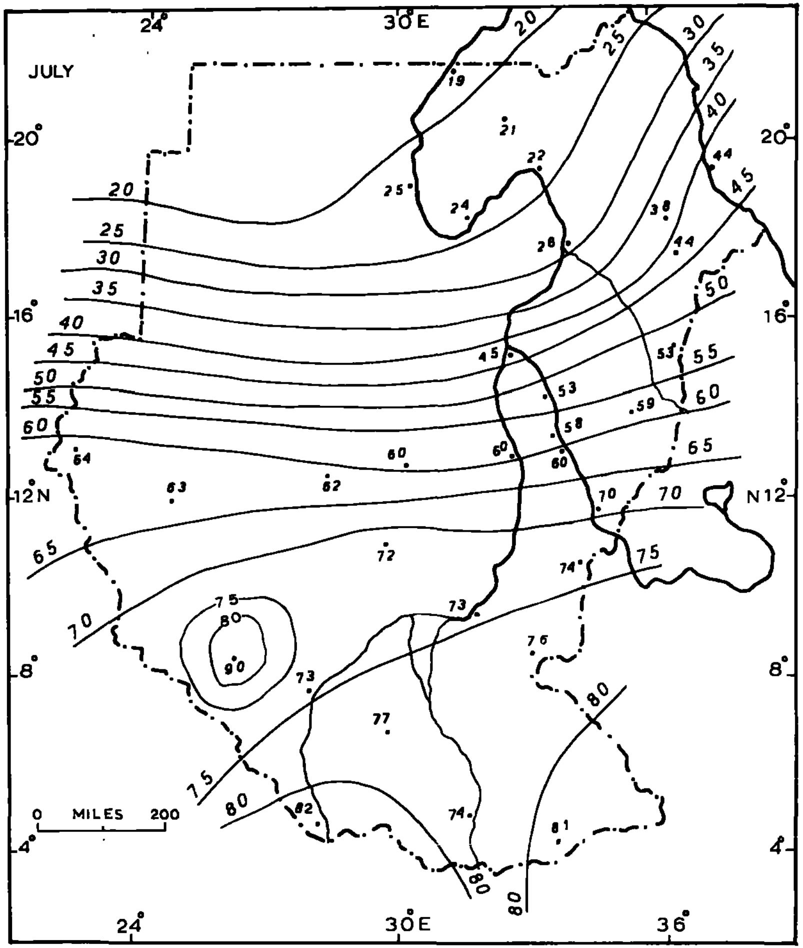
Fig. 12. April Humidity

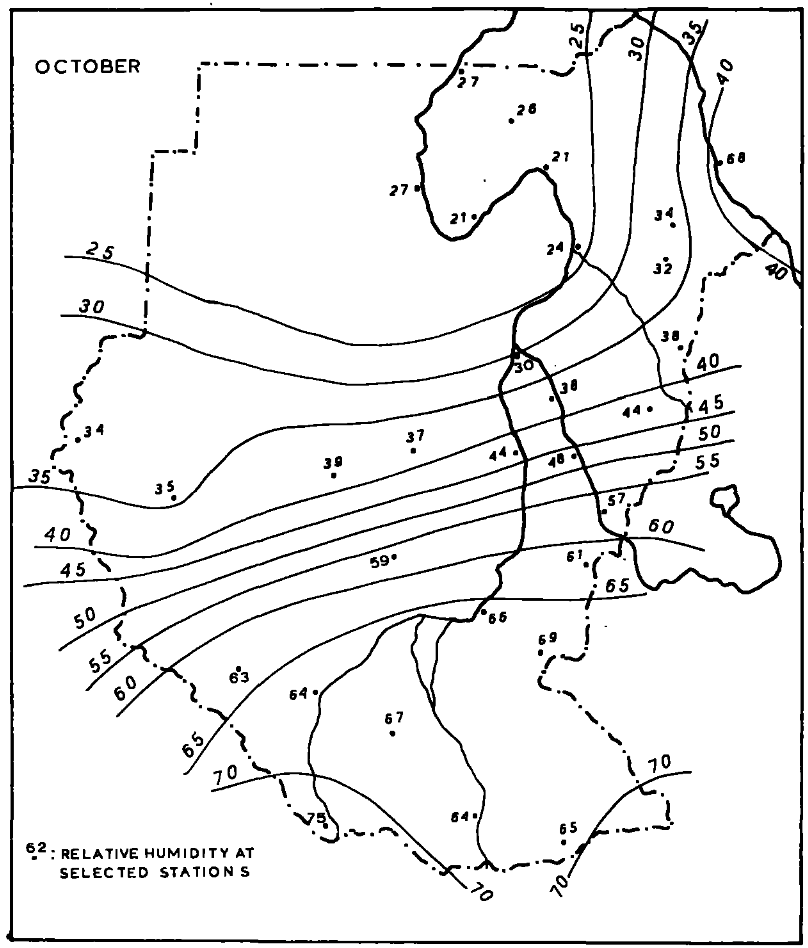
In April (hot dry season), the gradient of relative humidity over the country decreases considerably, as we go north of Malakal, (Fig. 12). West of the Nile, in northern and central Sudan, the humidity decreases towards the north from over 25% in the south of the region, to less than 15% in the dry area of north west Sudan. East of the Nile the humidity increases greatly from 20% to over 40% in the Red Sea region. Along the Nile valley, the relative humidity varies quite inconsistently towards the north or south, but it decreases from 18% at Wadi Halfa to about 16% at Khartoum. South of Khartoum it increases to about 28% at Roseires, on the Blue Nile, and 35% at Malakal on the White Nile. Further south of Malakal which has 40% to 60% can be considered as the most humid part compared with the rest of the country (Fig. 12).

During the rainy season in July, the relative humidity over the Sudan increases from less than 20% in the dry north to over 80% in the moist parts of southern Sudan (Fig. 13). In central Sudan, west of the White Nile (between latitudes 12$^{\circ}$ and 15$^{\circ}$ north) the humidity




SOURCE OF DATA: SAME AS FIG.7

Fig. 13. July Humidity




SOURCE OF DATA: SAME AS FIG.7

Fig. 14. October Humidity

tends to increase slightly westwards, being 60% at El Obeid, 62% at Ennahud, 63% at Nyala and 64% at El Genina in the western border. Most of the Sudan plains north of Khartoum, except for the coastal plain and eastern Sudan are dry compared with central and southern Sudan (Fig. 13). Along the Nile basin, the humidity steadily decreases northwards from 73% at Malakal to 19% at Wadi Halfa in the extreme north.

In October, the relative humidity is also increasing southwards over the country. It ranges from about 25% in the north to over 70% in the south west of Sudan (Fig. 14). Over the Nile basin, however, it decreases considerably from 66% at Malakal to less than 25% at Karima, and then slightly increases further northwards along the river Nile. During this period north west Sudan is the driest part in the country, while the southern Sudan is mostly humid, particularly in the area of the Sudd region.

It may be observed from the foregoing seasonal maps that the relative humidity is exceptionally high over the following areas:

(i) In the cultivated area of the Gezira, between the Blue and White Niles, as illustrated by October map.

(ii) Along the Ethiopian foothills, in eastern Sudan, particularly during the monsoon season.

(iii) In the Red Sea hills and the coastal plain owing to the maritime influence of the Red Sea.

(iv) Over the Jebel Marra region, because of larger rainfall in the area and the existence of vegetation.

(v) Along the Nile valley owing to the effect of the Nile and the cultivation on its banks.

CLOUDINESS:-

The average daily clouds data extracted from the "Sudan Climatological Normals" for forty stations reveal that, with the exception of the coastal area which receives 3 to 4 Oktas, the country is usually free from low or medium clouds during the dry season. Nevertheless, Bhalotra (1963) indicated that some altocumulus clouds sometimes appear over the northern parts of the country in association with the passage of cold fronts. "In isolated cases, thundery activities over the Ethiopian hills may cause medium clouds over the area south of latitude 10$^{o}$ north, and an unusual northward movement of the I.T.C.Z. may induce some clouding over the extreme south of the country" (Bhalotra, 1963).

In the rainy season, however, there is little cloud in the area north of latitude 20° north. To the south, the cloudiness increases as far as latitude 10° north, and south of it. The area covered by Malakal-Rumbek-Tong seems to have the largest mean of daily cloud cover (Sudan Climatological Normals, 1931-1960). The area south of latitude 10° north, has usually a large cover of altocumulus clouds in the mornings, but tend to decrease rapidly in the early afternoon. Cumuliform clouds often develop south of the I.T.C.Z. owing to intense insolation and strong convection; medium clouds may appear as well, due to occasional incursions of the moist south easterly stream from the Indian Ocean (Ireland, 1948).

SUNSHINE:-

Sunshine records have been taken from Bhalotra's publication "Meteorology of the Sudan" issued in 1963. The mean day duration of bright sunshine hours for the various months is illustrated by (Table 1) for a number of selected stations in the Sudan. The data is based on the records of the Cambell-Stokes sunshine recorders installed at these stations. The figures in brackets indicate the mean duration of sunshine expressed as a percentage of the maximum bright sunshine possible at each station, assuming that the sky is perfectly clear and there is nothing in the atmosphere to reduce solar radiation.

Table 1

Mean duration of bright sunshine (Hours)

| Station | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wadi Halfa | 10.1 | 10.3 | 10.3 | 10.7 | 11.3 | 11.8 | 11.7 | 11.1 | 10.7 | 10.6 | 10.4 | 9.9 | 10.7 |
| | (92) | (90) | (85) | (85) | (86) | (88) | (88) | (87) | (87) | (91) | (94) | (92) | (88) |
| Atbara | 10.7 | 10.5 | 10.3 | 11.5 | 11.1 | 9.8 | 8.8 | 9.1 | 10.1 | 10.7 | 10.7 | 10.5 | 10.3 |
| | (96) | (91) | (85) | (93) | (86) | (75) | (67) | (72) | (83) | (91) | (95) | (95) | (86) |
| Khartoum | 10.6 | 10.6 | 10.4 | 10.7 | 10.0 | 9.8 | 8.4 | 8.6 | 9.3 | 10.3 | 10.8 | 10.5 | 10.0 |
| | (94) | (91) | (87) | (86) | (77) | (75) | (65) | (68) | (76) | (87) | (95) | (92) | (83) |
| Kassala | 10.0 | 10.2 | 10.0 | 10.7 | 10.4 | 9.9 | 7.9 | 7.7 | 9.6 | 10.3 | 10.3 | 10.1 | 9.8 |
| | (89) | (88) | (83) | (85) | (81) | (76) | (62) | (61) | (79) | (86) | (90) | (90) | (81) |
| W/Medani | 10.6 | 10.6 | 10.5 | 10.6 | 9.9 | 9.6 | 7.7 | 7.7 | 8.9 | 10.0 | 10.7 | 10.5 | 9.8 |
| | (93) | (91) | (87) | (85) | (77) | (74) | (60) | (61) | (73) | (85) | (93) | (93) | (81) |
| El Obeid | 10.4 | 10.5 | 9.8 | 10.1 | 10.1 | 8.2 | 6.8 | 6.8 | 8.1 | 9.6 | 10.7 | 10.6 | 9.3 |
| | (91) | (89) | (82) | (81) | (78) | (64) | (52) | (54) | (66) | (81) | (93) | (93) | (77) |
| Kosti | 10.5 | 10.2 | 10.1 | 10.1 | 10.1 | 8.1 | 7.0 | 6.9 | 8.3 | 9.7 | 10.6 | 10.3 | 9.3 |
| | (92) | (88) | (86) | (82) | (79) | (62) | (54) | (55) | (69) | (82) | (92) | (91) | (77) |
| El Fasher | 10.3 | 10.8 | 10.0 | 10.2 | 10.2 | 9.1 | 7.5 | 7.6 | 8.8 | 10.2 | 10.9 | 9.8 | 9.6 |
| | (88) | (92) | (82) | (82) | (80) | (71) | (58) | (60) | (72) | (86) | (95) | (90) | (80) |
| El Genina | 10.3 | 10.7 | 10.3 | 9.4 | 10.1 | 9.1 | 7.3 | 6.3 | 8.5 | 10.2 | 10.8 | 10.6 | 9.5 |
| | (91) | (92) | (82) | (77) | (80) | (70) | (56) | (50) | (76) | (86) | (94) | (93) | (79) |
| En Nahud | 10.0 | 10.2 | 9.4 | 10.7 | 10.5 | 8.4 | 7.3 | 7.1 | 8.3 | 9.3 | 10.8 | 10.6 | 9.4 |
| | (88) | (89) | (78) | (86) | (83) | (66) | (57) | (56) | (69) | (79) | (93) | (93) | (78) |
| Tozi | 10.2 | 10.2 | 10.4 | 9.7 | 9.9 | 7.4 | 6.2 | 6.3 | 7.3 | 8.8 | 10.1 | 10.4 | 8.9 |
| | (89) | (86) | (84) | (79) | (78) | (54) | (48) | (50) | (60) | (75) | (86) | (92) | (73) |
| Malakal | 9.9 | 9.2 | 8.9 | 8.1 | 7.8 | 5.2 | 5.0 | 5.4 | 5.9 | 7.3 | 9.5 | 9.8 | 7.7 |
| | (86) | (79) | (74) | (66) | (62) | (41) | (40) | (43) | (48) | (61) | (81) | (84) | (64) |
| Wau | 9.6 | 9.1 | 8.3 | 7.3 | 8.2 | 7.1 | 5.6 | 6.3 | 6.8 | 7.1 | 9.0 | 9.6 | 7.8 |
| | (82) | (76) | (69) | (64) | (66) | (56) | (45) | (51) | (55) | (60) | (76) | (84) | (65) |
| Juba | 9.2 | 8.1 | 7.3 | 6.7 | 7.8 | 7.4 | 6.1 | 6.7 | 7.8 | 7.8 | 8.0 | 8.9 | 7.7 |
| | (77) | (67) | (60) | (55) | (63) | (60) | (49) | (55) | (64) | (65) | (67) | (75) | (63) |
| Port Sudan | 7.0 | 7.9 | 8.5 | 10.2 | 10.8 | 10.2 | 9.7 | 9.7 | 10.0 | 9.9 | 8.3 | 6.7 | 9.1 |
| | (62) | (69) | (71) | (81) | (84) | (87) | (74) | (77) | (80) | (84) | (74) | (61) | (75) |

Source: "Met. of Sudan" Bhalotra (1963), Memoir No. 6, p. 32.

Taking the year as a whole, the average daily duration of sunshine decreases southwards from 10.7 hours at Wadi Halfa to 7.7 hours at Malakal (Table 1). South of Malakal there is little variation and average sunshine hours are nearly the same as Malakal. In the dry season, represented by January, the duration of sunshine increases southwards to about latitude 17° north and then decreases further south to Juba. The latitudinal variation of mean daily sunshine is small during this dry period; the maximum duration being 10.7 hours at Atbara (Latitude 17° 42' north) and the minimum (9.2 hours) at Juba (Latitude 4° 52' north). Over eastern Sudan, the coastal area, represented by Port Sudan, experiences the minimum sunshine ever recorded in January. The low value at this station is almost equivalent to 62% of the maximum possible sunshine. During the rainy season (July) the mean daily duration of sunshine is largest at Wadi Halfa (11.7 hours), which is outside the belt of tropical rains, and lowest at Malakal (5 hours) which lies within the belt (Table 1).

SURFACE WIND SPEED:-

The mean monthly run of wind seems to be quite low for most of the selected stations at the various localities in the country (Table 2). Along the Nile valley, at stations north of latitude 15$^{\circ}$ north, the mean wind speed is 8 to 10 m.p.h., at stations between 15$^{\circ}$ north and 9$^{\circ}$ north it is between 6 to 8 m.p.h., and at places further south it is less than 4 m.p.h. The lowest wind speeds are recorded in the extreme south of the country, particularly in the belt of equatorial calms.

Table 2

Mean Monthly Speed of Surface Wind (m.p.h.)

| Station | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oc. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wadi Halfa | 9.0 | 10.2 | 10.4 | 11.0 | 10.3 | 9.6 | 7.8 | 8.3 | 9.8 | 9.6 | 8.4 | 7.8 |
| Karima | 7.7 | 10.2 | 10.6 | 9.4 | 8.4 | 8.5 | 8.0 | 6.6 | 8.0 | 8.4 | 9.2 | 9.0 |
| Atbara | 9.5 | 9.6 | 9.1 | 8.3 | 7.4 | 5.6 | 6.4 | 7.2 | 5.6 | 5.4 | 7.7 | 7.6 |
| Khartoum | 10.9 | 11.4 | 10.2 | 9.8 | 10.4 | 10.4 | 11.0 | 10.4 | 7.8 | 7.7 | 9.2 | 9.8 |
| Kassala | 3.7 | 4.0 | 4.0 | 3.4 | 3.4 | 4.6 | 5.4 | 4.6 | 4.1 | 2.8 | 2.6 | 3.1 |
| W/Medani | 8.5 | 10.0 | 8.4 | 8.2 | 8.5 | 11.9 | 11.5 | 8.5 | 7.3 | 5.2 | 6.6 | 7.7 |
| El Obeid | 9.6 | 10.4 | 8.5 | 7.6 | 7.2 | 8.5 | 8.4 | 7.1 | 5.8 | 6.4 | 7.9 | 7.7 |
| El Fasher | 5.4 | 6.7 | 7.2 | 5.9 | 6.4 | 5.5 | 5.5 | 3.7 | 3.1 | 4.6 | 4.9 | 4.8 |
| El Genina | 8.5 | 10.1 | 7.3 | 6.2 | 5.6 | 5.4 | 5.0 | 3.8 | 3.5 | 5.3 | 6.6 | 6.8 |
| Kosti | 7.6 | 7.6 | 6.4 | 5.4 | 6.5 | 8.8 | 8.4 | 6.5 | 5.5 | 4.9 | 6.5 | 7.4 |
| Malakal | 9.4 | 10.2 | 7.0 | 6.1 | 6.1 | 5.9 | 2.9 | 5.0 | 3.7 | 3.7 | 4.4 | 7.0 |
| Juba | 3.4 | 3.2 | 4.0 | 4.0 | 3.4 | 2.5 | 2.3 | 2.4 | 2.3 | 2.4 | 2.6 | 2.8 |
| Port Sudan | 10.4 | 10.2 | 8.8 | 9.5 | 8.0 | 7.6 | 8.0 | 7.6 | 7.1 | 6.6 | 8.4 | 9.2 |

Source: "Met. of Sudan" Bhalotra (1963) - Sudan Met. Service, Memoir No. 6. pp. 101-113.

<u>AVERAGE ANNUAL RAINFALL</u>:-

Generally, the mean annual rainfall decreases steadily from south to north. It ranges between 1512 mms. received at Yambio (latitude $4^{\circ}$ $34^{-}$ north) in the extreme south and 3mms. received at Wadi Halfa (lat. $21^{\circ}$ $50^{-}$ north) in the extreme north. The annual isohyets run smoothly from south west to north east, but they show a tendency to run further north in the eastern part of the country (Fig. 15). This is, perhaps, due to the influence of the Abyssinian plateau which helps to extend the rains further north. The run of isohyets nearly parallel to the Ethiopian border indicates the part played by the Ethiopian hills in extending the rainfall westwards over the Sudan plains. The excess of rainfall over the north eastern parts is partly due to the thundery activities that build up along the Ethiopian foothills, and partly due to the orientation of the I.T.C.Z. over the north east Sudan (El Tom, 1966). The location of Kassala (latitude $15^{\circ}$ $28^{-}$ north), close to the Ethiopian hills is highly responsible for

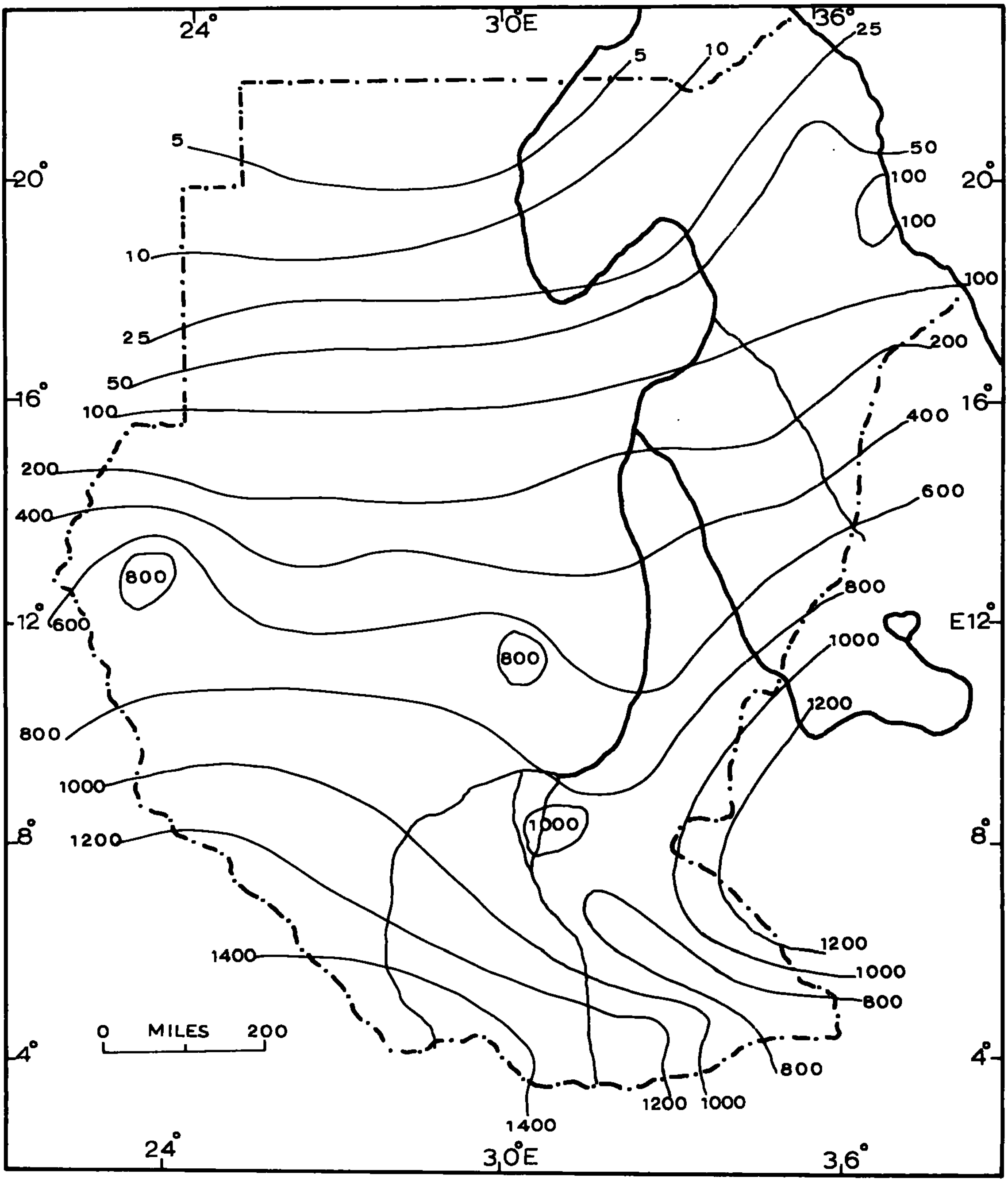



Fig. 15. Average Annual Rainfall (after Bhalotra, 1963)

giving it an annual rainfall of (341 mm.) which is more than twice the annual rainfall of Khartoum (164 mm.) at the same latitude. The influence of relief on precipitation is also shown by the Nuba Mountains, Jebel Marra region, and the Red Sea hills where the rainfall tends to be larger than that of the adjoining plains to these upland areas (Fig. 15).

However, there are two regional exceptions which do not fit to the general rainfall pattern of Sudan. The south eastern parts of the clay plain and the eastern extremity of the Iron Stone plateau (southern Sudan) receive an annual rainfall which is scanty for their latitude. While Yambio in the centre of the plateau receives 1512 mm., Torit further east in the same latitude receives 994 mm., and Kapoeta, still further east and slightly more north receives 776 mm. This shows that rainfall tends to decrease eastwards in this part of the country.

The second regional exception is to be found in the Red Sea coast and part of the Red Sea hills which receive both summer and winter rains. The south westerlies bring summer showers to Port Sudan (lat. $19^{\circ}$ $35^{-}$ north) and even to places to the north of it (El Tom, 1967). The winter showers which are more important generally fall between mid October and the end of February. From the two rainfall regimes, the coastal plain and the Red Sea hills have an annual rainfall ranging from 60 to 150 mm., which is higher than the adjoining plains.

The duration and intensity of the rainy season vary according to the location and latitude of the place. In the extreme south at Juba (lat. $4^{\circ}$ $52^{-}$ north) the rainy season lasts for 9 months (March to November); at Malakal (lat. $9^{\circ}$ $33^{-}$ north) it extends for 7 months (April to October); at Khartoum (lat. $15^{\circ}$ $36^{-}$ north) for 3 months (July to Sept.) and at Wadi Halfa (lat. $21^{\circ}$ $50^{-}$ north) in the extreme north, there is no practical rainy season.

Features of topography and some climatic elements like temperature, humidity, rainfall, clouds, sunshine and surface-wind speed are outlined in this chapter, in order to provide some background for the study of relationships between measured and estimated evaporation as discussed later. These factors may also exert some influence upon the regional distribution of measured evaporation which will be dealt with in chapter 4.

## Chapter Two

## METHODS OF MEASURED AND ESTIMATED EVAPORATION IN SUDAN

In most countries the study of evaporation has been a neglected part of climatology. It was only in the 1930's that climatologists began to show greater interest in the subject, whilst an important postwar development was the publication of Thornthwaite's articles on water balance (Thornthwaite, 1948a, 1948b). In recent years workers have produced reliable figures for measured and actual evaporation (Penman 1946, 1948) and (Pasquill, 1950).

Davies (1966) defined water losses to the air as the total evaporation from open water surfaces and bare ground, together with evapotranspiration from vegetation. He emphasized that the process requires a supply of energy to bring about the change of state from water to water vapour (590 gram calories are required to evaporate 10 mm of water) and a transport mechanism to carry the vapour into the atmosphere. Net radiation and advection are the main energy sources, and atmospheric turbulence provides the transport mechanism. According to Thornthwaite and Mather (1955), evaporation represents an important mass transfer from ground to atmosphere, the reverse of precipitation in the hydrologic cycle. It is also an important agency of energy transfer, since vast amounts of heat are required to bring evaporation about, and are then transferred to the air with the vapour as latent heat.

The rate of evaporation is defined as the amount of water lost by evaporation from a unit area of surface in unit time (London Met. Office, 1956).[(1)] It has been suggested in this reference that the following factors affect the evaporation rate, sometimes indirectly, from any natural surface: (i) wind at the surface, (ii) humidity of the air at the surface, (iii) temperature of the air at the surface, (iv) temperature of the evaporating surface, (v) amount of moisture in the surface available for evaporation, and (vi) nature of the surface.

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(1) Handbook of Meteorological Instruments, Part 1, 1956, H.M.S.O., London

Thornthwaite and others have found that the influences caused by non-climatic factors are small in comparison with the effect of climate upon evaporation, Thornthwaite and Mather (1951, 1954); Penman, (1956). Thornthwaite (1955) also indicated that the size of evaporating surface is of much less significance in humid climates than in sub-humid and arid climates.

MEASUREMENT OF EVAPORATION:-

The actual measurement of evaporation is much more difficult than the measurement of precipitation, and reliable absolute values of the loss from the surface of the earth over areas of any appreciable size have not yet been obtained (London Met. Office, 1956).[1] The instruments used for direct measurements of evaporation in the Sudan are, the Piche evaporimeter and the Class 'A' U.S. Weather Bureau pan. In the Sudan, evaporation values, in millimetres, are recorded from these instruments twice daily at 08 a.m. and 2.0 p.m. (Sudan local time). The total of the two readings of each instrument gives the daily Piche and Pan evaporation at any particular station in the country.

(1) See footnote on p. 31.

PICHE EVAPORIMETER:-

The Piche evaporimeter is exposed in a standard Sudanese screen. The base of this screen is one metre above the ground level. This screen is made of wood, with a double roof, and double louvres on its four sides. It has two doors; one on the north side and the other on the south side. These doors are used in turn each season according to whether the sun is south or north of the station (Wahab, 1955).

The Piche instrument is designed to indicate in a simple and convenient manner the amount of evaporation which takes place from a wet paper surface. It is more often used in hot dry climates where knowledge of the rate of evaporation is of importance for the conservation of water. It consists of a cylindrical glass tube 14 mm. outside diameter. This paper is kept in position by means of a brass ring and spring clip. The surface of the clip in contact with the paper is of the same diameter as the tube itself and is provided with a small central hole to enable the filter disc to be perforated if desired. The evaporating surface of the paper is 11 square centimetres (Fig. 16).[1]

(1) Met. Instruments (1963) p. 10 - C.F. Casella & Co. Ltd., Regent House, Britannia Walk, London, N.1.

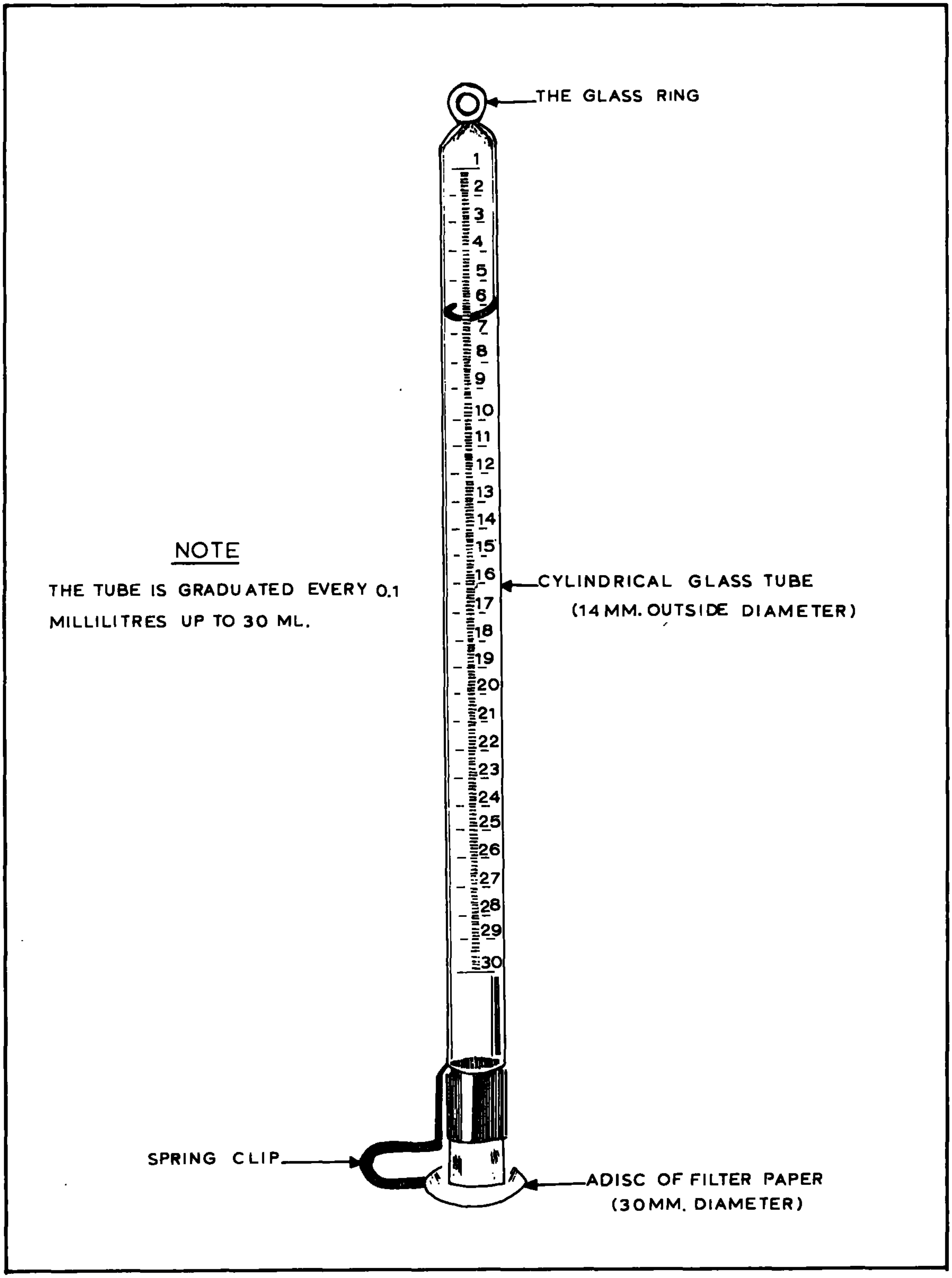


Fig. 16. Piche Evaporimeter

The instrument is filled with distilled water, the paper and clip placed in position, and the whole inverted and suspended from the glass ring provided at the closed end. Both sides of the saturated paper protruding from the edges of the tube and clip thus form the evaporating surface. The alteration in level of the water in the tube indicates the amount of evaporation which takes place between consecutive readings.

This type of evaporimeter is very sensitive to wind speed, and in making observations in different places similar exposures must be used (London, Met. Office, 1956).[1] Thornthwaite (1954), on the other hand, indicated that evaporation from the small evaporating surface of the Piche (11 sq. cm.) is unlikely to raise the air humidity, which may cause a reciprocal effect on the Piche values. As a result a very large energy supply used for evaporation may come from the surrounding air.

The Piche evaporimeter is probably the most convenient and widely used instrument purporting to measure the evaporating potential of the atmosphere. It has been shown by Prescott and Stirk (1951) and Rosenan (1951)

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(1) See footnote on p. 31.

that evaporation from the instrument is a function of the saturation vapour-pressure deficit and velocity of the air. However, both a physical study of the instrument (De Vreis and Venema 1954), and empirical attempts to correlate readings from it with measurements of potential evapotranspiration (Stanhill 1961) have shown that the instrument is only partially suitable for this purpose.

CLASS 'A' PAN:-

This instrument is the standard United States Weather Bureau pan, and the details of its construction and support are shown in figure 17. The pan is set up on timbers as shown. The size of the timbers is not important, but the bottom of the pan should be six inches above ground level, and there should be free contact with the atmosphere over approximately one-half of its area (Halcrow, 1962).

The pan should be emptied and inspected for leaks and rust spots at the end of each month, and it should then be cleaned to keep it free from sediment, scum and oil films.

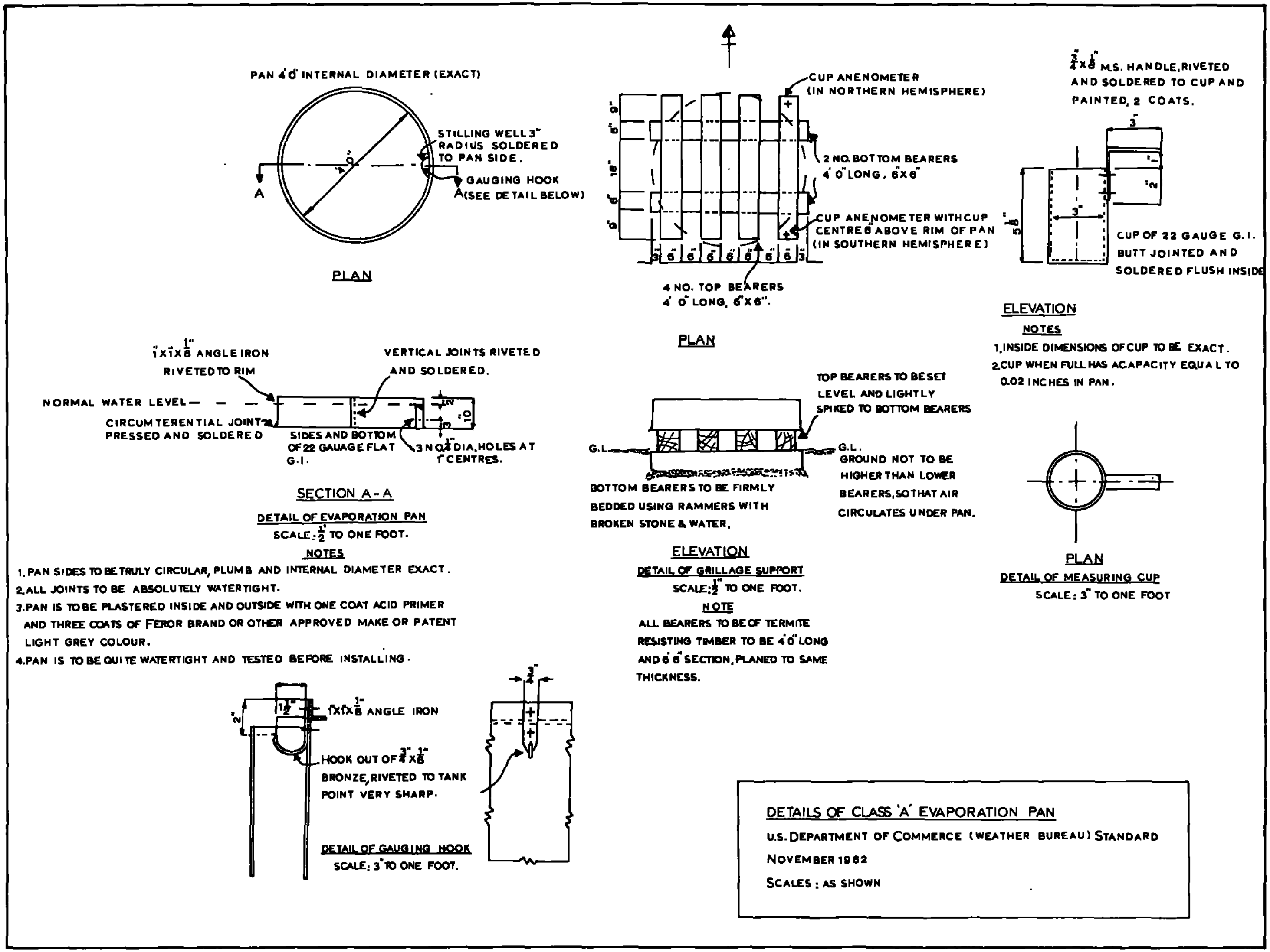


Fig. 17. Class 'A' pan Evaporimeter

The water surface should normally be level with the point of the hook gauge. To make an observation the water level is brought back to the point of the gauge either by filling from a measuring cup, or if rainfall has exceeded evaporation, removing water with the cup. The number of cupfulls of water added or subtracted are entered in a special measurement sheet and reduced to the equivalent depth of water (Halcrow, 1962). The plan shows a cup which has a capacity equal to a depth of 0.02 inches in the pan. In fact any sort of cup will do, provided it is calibrated in terms of depth of water in the pan.

The pan may evaporate two gallons of water on a summer day in a dry situation. Solar radiation contributes an important share of the energy for evaporation, the amount depending on the turbidity of the water and on the albedo of the pan which varies greatly with type, age and condition of the material used. Additional energy for evaporation is available from the air. The amount of water evaporated from the pan will do little to modify the moisture content of the air. But, immediately over the water surface the humidity is raised, the moisture gradient reduced, and the evaporation impeded. The extent of this influence depends on the rate at which fresh air passes across the evaporating surface from outside, (Thornthwaite, 1954).

## ESTIMATE OF OPEN-WATER EVAPORATION (EO) AND POTENTIAL EVAPOTRANSPIRATION (PE):-

In the Sudan, direct measurements of (EO) is scarce within most meteorological networks, while (PE) has not been satisfactorily measured by transpirometers or evaporation pans. As a result, there has been this attempt to compute these parameters from more readily available climatological data. Two methods for computing the water loss, have been applied to the Sudan; that of Thornthwaite's potential evapotranspiration (1948) and Penman's open-water evaporation (1948) derived respectively in the United States and Great Britain.

## THORNTHWAITE'S METHOD OF (PE):-

Thornthwaite's concept of potential evapotranspiration (PE) and a method for its computation appeared first in 1943 and reappeared in 1948 as the basis for a classification of climates. According to Thornthwaite and Mather (1955) the term "Potential evapotranspiration" was defined as the amount of water which will be lost from a moist soil surface completely covered with vegetation. However, this term may be purely hypothetical when applied to arid areas or areas with a marked dry season as in the case of Sudan where there is a deficiency of water.

For the computation of potential evapotranspiration, Thornthwaite uses mean temperature as a basis, but he adjusts the values according to the length of day, that is, the number of possible sunshine hours. He recognizes the decisive role of insolation by stressing a strong correlation between insolation and mean air temperature (Thornthwaite, 1948). From a practical viewpoint his formula has the important advantage that it can be used for all stations in the Sudan for which temperature records exist. But it should be realized that the air temperature represents only a small part of the energy exchange in the process of evaporation (Oguntoyinbo 1966).

The basic Thornthwaite (1948) formula used in computing the (PE) is of the form:

$$e = 1.6\ (10t/I)^a$$ where,

e = the monthly (PE),

t = the monthly mean temperature in $^{o}C$,

I = the annual heat index, being the sum of monthly heat indices,

i = $(t/5)^{1.514}$,

a = $0.000000675I^3 - 0.0000771I^2 + 0.01792I + 0.49239$

The formula gives unadjusted rates of potential evapotranspiration. Since the number of days in a month ranges from 28 to 31 (nearly 11 percent) and the number of hours in the day between sunrise and sunset, when evapotranspiration principally takes place, varies with the season and with latitude, it becomes necessary to reduce or increase the unadjusted rates by a factor that varies with the month and with latitude (Thornthwaite 1954).

When Thornthwaite (1954) later reviewed the formula he criticised it by stating that, "this mathematical development is far from satisfactory. It is empirical, and the general equation does not accord with the newly developed law of growth. Furthermore, the equation is completely lacking in mathematical elegance. It is very complicated and without nomograms and tables as computing aids would be quite unworkable".

In order to determine potential evapotranspiration, mean monthly values of temperature must be available, and the latitude of the station must be known. Three steps are involved in the computation, and all three are accomplished by means of nomograms and tables (Thornthwaite, 1948, Appendix 1).

The first step is to obtain the heat index, I. Table 3 gives monthly values of i corresponding to monthly mean temperatures. Summation of the 12 monthly values gives the index, I.

Table 3

| TC° | .0 | .1 | .2 | .3 | .4 | .5 | .6 | .7 | .8 | .9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 15 | 5.28 | 5.33 | 5.38 | 5.44 | 5.49 | 5.55 | 5.60 | 5.65 | 5.71 | 5.76 |
| 16 | 5.82 | 5.87 | 5.93 | 5.98 | 6.04 | 6.10 | 6.15 | 6.21 | 6.26 | 6.32 |
| 17 | 6.38 | 6.44 | 6.49 | 6.55 | 6.61 | 6.66 | 6.72 | 6.78 | 6.84 | 6.90 |
| 18 | 6.95 | 7.01 | 7.07 | 7.13 | 7.19 | 7.25 | 7.31 | 7.37 | 7.43 | 7.49 |
| 19 | 7.55 | 7.61 | 7.67 | 7.73 | 7.79 | 7.85 | 7.91 | 7.97 | 8.03 | 8.10 |
| 20 | 8.16 | 8.22 | 8.28 | 8.34 | 8.41 | 8.47 | 8.53 | 8.59 | 8.66 | 8.72 |
| 21 | 8.78 | 8.85 | 8.91 | 8.97 | 9.94 | 9.10 | 9.17 | 9.23 | 9.29 | 9.36 |
| 22 | 9.42 | 9.49 | 9.55 | 9.62 | 9.68 | 9.75 | 9.82 | 9.88 | 9.95 | 10.01 |
| 23 | 10.08 | 10.15 | 10.21 | 10.28 | 10.35 | 10.41 | 10.48 | 10.55 | 10.62 | 10.68 |
| 24 | 10.75 | 10.82 | 10.89 | 10.95 | 11.02 | 11.09 | 11.16 | 11.23 | 11.30 | 11.37 |
| 25 | 11.44 | 11.50 | 11.57 | 11.64 | 11.71 | 11.78 | 11.85 | 11.92 | 11.99 | 12.06 |
| 26 | 12.13 | 12.21 | 12.28 | 12.35 | 12.42 | 12.49 | 12.56 | 12.63 | 12.70 | 12.78 |
| 27 | 12.85 | 12.92 | 12.99 | 13.07 | 13.14 | 13.21 | 13.28 | 13.36 | 13.49 | 13.50 |
| 28 | 13.58 | 13.65 | 13.72 | 13.80 | 13.87 | 13.94 | 14.02 | 14.09 | 14.17 | 14.24 |
| 29 | 14.32 | 14.39 | 14.47 | 14.54 | 14.62 | 14.69 | 14.77 | 14.84 | 14.92 | 14.99 |
| 30 | 15.08 | 15.15 | 15.22 | 15.30 | 15.38 | 15.45 | 15.53 | 15.61 | 15.68 | 15.76 |
| 31 | 15.84 | 15.92 | 15.99 | 16.07 | 16.15 | 16.23 | 16.30 | 16.38 | 16.46 | 16.54 |
| 32 | 16.62 | 16.70 | 16.78 | 16.85 | 16.93 | 17.01 | 17.09 | 17.17 | 17.25 | 17.33 |
| 33 | 17.41 | 17.49 | 17.57 | 17.65 | 17.73 | 17.81 | 17.89 | 17.97 | 18.06 | 18.13 |
| 34 | 18.22 | 18.30 | 18.38 | 18.46 | 18.54 | 18.62 | 18.70 | 18.79 | 18.87 | 18.95 |
| 35 | 19.03 | 19.11 | 19.20 | 19.28 | 19.36 | 19.45 | 19.53 | 19.61 | 19.69 | 19.78 |

Source: Geog. Rev. Vol. 38, No. 1, 1948, Appendix 1, p. 92.

The next step is to determine unadjusted values of potential evapotranspiration from the nomogram (Fig. 18) which is similar to Thornthwaite's nomogram in figure 13 (Thornthwaite, 1948, Appendix I). Since there is a linear relation between the logarithm of temperature and the logarithm of unadjusted (PE), straight lines on the nomogram define the relationship. All lines pass through the point of convergence at $t = 26.5^{\circ}C$ and PE = 13.5 cm. The slope of the line is determined by the heat index of the station. For example, the heat index of Khartoum (lat. $15^{\circ}$ $36^{-}$ north) is 179, and the line ruled on the nomogram represents the relationship between potential evapotranspiration and temperature at that place (Fig. 18). At mean temperature of $25.1^{\circ}C$ the unadjusted potential evapotranspiration is 9.66 centimetres. Knowing the index (I) of the station, one sets a straight edge in the appropriate position on the nomogram and reads potential evapotranspiration to the given mean temperature of the month. This nomogram is used only when temperature is $26.5^{\circ}C$ or less. For temperatures above $26.5^{\circ}C$, a special nomogram has been

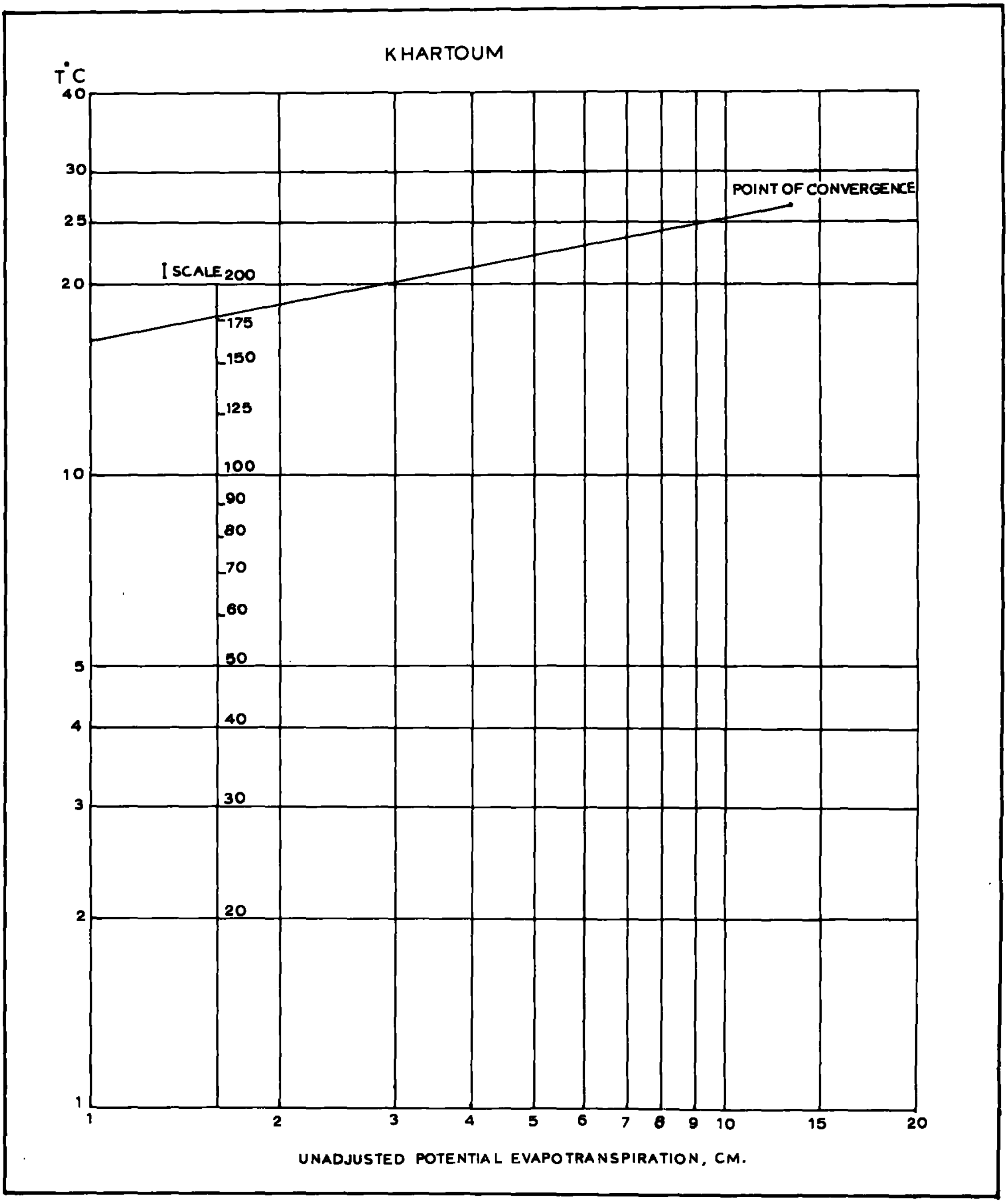


Fig. 18. Nomogram of Unadjusted (PE) Temperature <26.5°C

constructed on a larger scale graph paper from which accurate computation of potential evapotranspiration can be made (Fig. 19). Twelve values are obtained for the 12 months. These are unadjusted values for months of 30 days of 12 hours each.

Finally the values of (PE) are adjusted for a month length. Table 4 gives correction factors by which the unadjusted (PE) of each month must be multiplied. The corrections are the appropriate ones for the latitude of the station. Potential evapotranspiration is in centimetres. Summation of the 12 monthly values gives annual potential evapotranspiration.

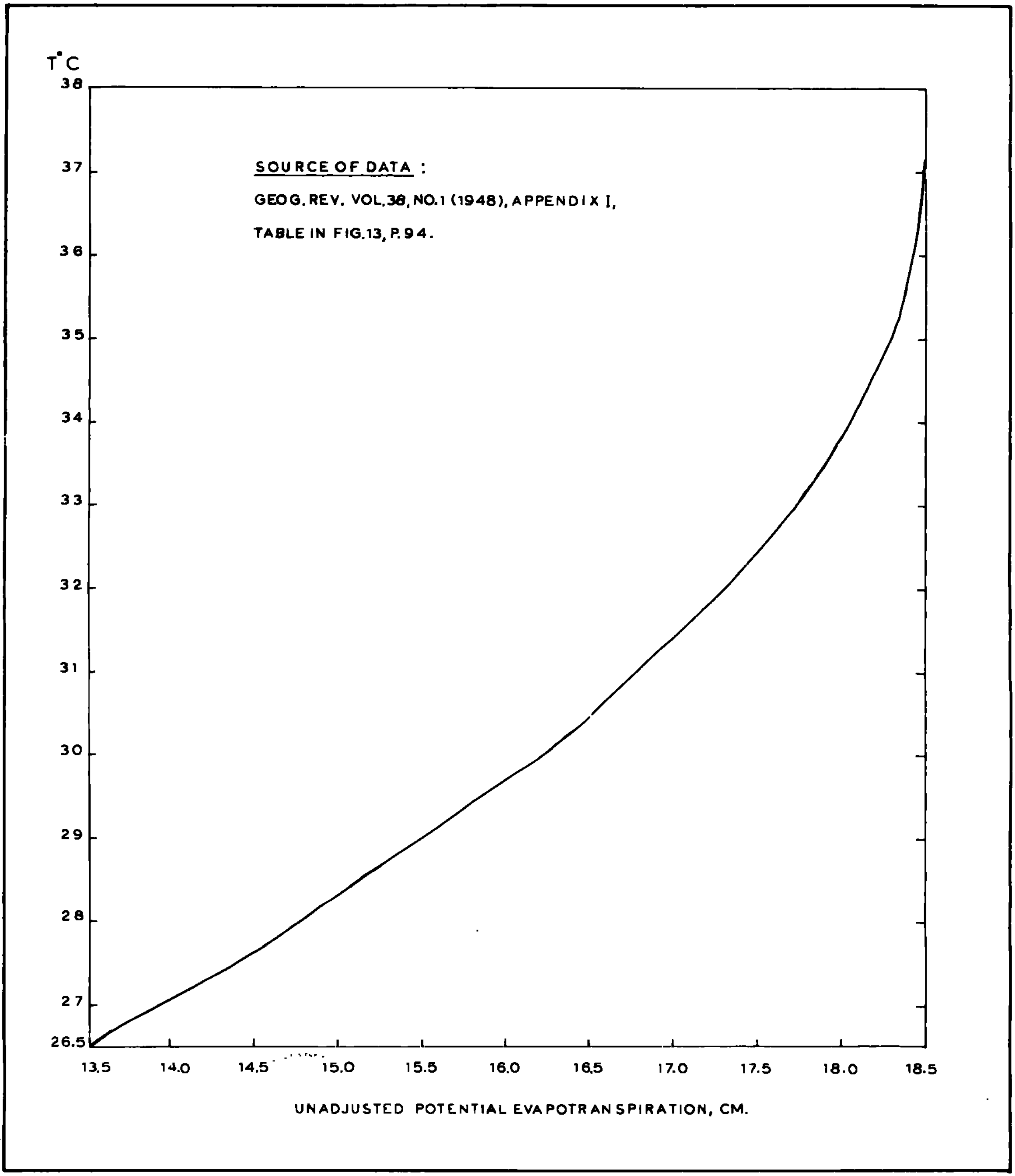


Fig. 19. Nomogram of Unadjusted (PE) for Temperature > 26.5°C

The computations for Khartoum follow:-

| Item | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T C° | 22.2 | 24.1 | 30.2 | 31.7 | 34.6 | 34.5 | 31.9 | 30.0 | 31.1 | 32.9 | 30.0 | 25.5 | - |
| i | 9.55 | 11.50 | 15.22 | 16.38 | 18.70 | 18.62 | 16.54 | 15.07 | 15.92 | 17.33 | 15.07 | 11.78 | 181.68 |
| Unadj. PE | 5.08 | 9.66 | 16.35 | 17.20 | 18.20 | 18.18 | 17.27 | 16.21 | 16.87 | 17.69 | 16.21 | 10.64 | - |
| Adj. PE | 4.93 | 8.79 | 16.84 | 17.85 | 20.2 | 19.63 | 19.34 | 17.51 | 17.21 | 17.87 | 15.40 | 10.32 | 15.49 |



Table 4

| N. Lat.° | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.04 | 0.94 | 1.04 | 1.01 | 1.04 | 1.01 | 1.04 | 1.04 | 1.01 | 1.04 | 1.01 | 1.04 |
| 5 | 1.02 | 0.93 | 1.03 | 1.02 | 1.06 | 1.03 | 1.06 | 1.05 | 1.01 | 1.03 | 0.99 | 1.02 |
| 10 | 1.00 | 0.91 | 1.03 | 1.03 | 1.08 | 1.06 | 1.08 | 1.07 | 1.02 | 1.02 | 0.98 | 0.99 |
| 15 | 0.97 | 0.91 | 1.03 | 1.04 | 1.11 | 1.08 | 1.12 | 1.08 | 1.02 | 1.01 | 0.95 | 0.97 |
| 20 | 0.95 | 0.90 | 1.03 | 1.05 | 1.13 | 1.11 | 1.14 | 1.11 | 1.02 | 1.00 | 0.93 | 0.94 |
| 25 | 0.93 | 0.89 | 1.03 | 1.06 | 1.15 | 1.14 | 1.17 | 1.12 | 1.02 | 0.99 | 0.91 | 0.91 |

Source: Geog. Rev. Vol. 38, No. 1, 1948, Appendix I, p. 93.

PENMAN'S FORMULA OF (EO):-

The formula derived by Penman (1948) from experimental work at Rothamstead in England gives evaporation (EO) from open-water surfaces in millimetres per day. In Penman's formula, the value of evaporation is calculated from the combined heat balance and aerodynamic equations, utilizing measurements of air temperature, humidity, run of wind and the number of bright sunshine hours. As the Sudan possesses a net work of stations which measure these parameters, the application of the formula is, somewhat, feasible. However, the formula was slightly modified by Berry (1964) in order to be programmed and evaluated easily by electronic computers. Thus the formula may be defined by:

$$Eo = Ea + H \qquad (1)$$

$$Ea = d_7(e_a - e_d)\,(d_8 + u_2/100) \times \frac{0.27}{0.27 + \Delta} \qquad (2)$$

$$H = \left\{ d_o\, R_A(d_1 + d_2\, {}^n/N) - \sigma Ta^4\, (d_3 - d_4\sqrt{e_d})\,(d_5 + d_6\, {}^n/N) \right\} \times \frac{\Delta}{0.27 + \Delta} \qquad (3)$$

where,

ea = saturation vapour pressure (mm of mercury) at mean air temperature,

$e_d$ = mean vapour pressure,

$u_2$ = mean run of wind at a height of 2m. (miles/day),

$R_A$ = theoretical total daily radiation at the surface assuming a completely transparent atmosphere (in mm evaporation equivalent),

$^n/N$ = actual/possible duration of bright sunshine,

$\sigma T_a^4$ = theoretical black-body radiation at the mean air temperature, $Ta^oK$,

$\Delta$ = slope of vapour-pressure curve at mean air temperature (mm Hg/$^oF$),

Eo = theoretical evaporation for an open-water surface (mm/day).

The values of the constants ($d_o$ to $d_8$) in the computer programme for evaluating the formula are: $d_o = 0.94$, $d_1 = 0.17$, $d_2 = 0.62$, $d_3 = 0.56$, $d_4 = 0.09$, $d_5 = 0.10$, $d_6 = 0.90$, $d_7 = 0.35$, $d_8 = 0.50$, and up to five extra sets of values of the nine constants may be included in any run of data (Berry, 1964). These constants, however, are empirical and are open to revision, (Penman, 1956) and (Monteith, 1961).

The evaluation of (Eo) by the Penman equation, therefore, depends primarily on standard meteorological data as measured at weather stations. The only elements in equations (2), and (3) which are not directly recorded at Sudanese stations are: saturation vapour pressure (ea), the slope of the vapour-pressure curve at mean air temperature ($\Delta$), theoretical total daily radiation (RA) and theoretical black-body radiation ($\sigma T_a^4$). Hence the quantities of these elements have been calculated from special tables and graphs.[1] Whilst the values of mean vapour pressure ($e_d$), mean run of wind ($u_2$) and actual/possible duration of sunshine ($^n/N$) are prepared from actual climatological data taken from "Sudan Annual Met. Reports" (1959-1966).[2] For the magnitude of ($\Delta$) a special nomogram has been drawn, from which the values (mm Hg/F$^o$) can be read off quite easily (Fig. 20).

After evaluating the measured and estimated elements of the Penman equation, then the mean daily (Eo) was computed accordingly for selected Sudanese stations, at the Computer Unit of Durham University.

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(1) Smithsonian Meteorological Tables - Sixth revised edition, prepared by R.J. List (1951), Washington D.C., p. 355, 413, 419.

(2) Annual Meteorological Reports which contain summaries of meteorological and rainfall observations made at Sudanese stations during the period (1959-1966) - published at Khartoum Met. Office (H.Q.), Sudan Met. Service.

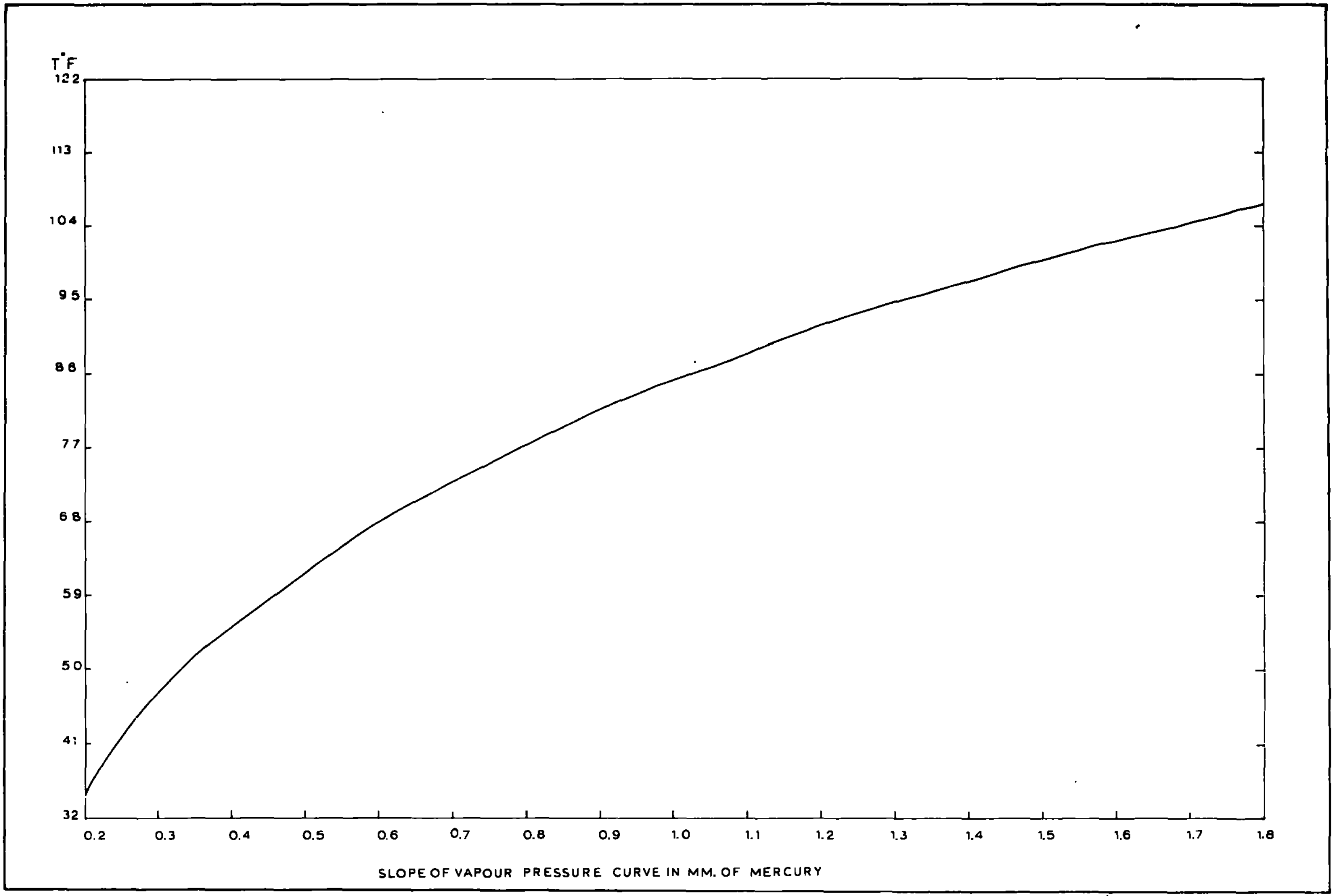


Fig. 20. Nomogram for the slope of vapour pressure curve in mm. of Mercury

From the foregoing discussion of the water loss estimates in the Sudan, it is noted that Penman's formula of (Eo) was physically sounder than Thornthwaite's method of potential evapotranspiration. Both Thornthwaite's and Penman's formulae were first developed for use within monthly averages, but, because that of Penman has a greater physical basis, it was found to give reasonable estimates of daily evaporation under certain climatic conditions in the Sudan. Nevertheless, the formula is of more restricted application than Thornthwaite's, because it is more complex and requires some climatic parameters which have not been measured yet at Sudanese meteorological stations.

# Chapter Three

## COMPARATIVE STUDY OF MEASURED AND ESTIMATED EVAPORATION

In this chapter some effort has been made to compare Class 'A' pan evaporation with that of the Piche evaporimeter, at selected stations, in order to study the relationships between the measured values of these instruments, and to determine, perhaps, the general seasonal pattern of the water loss under various climatic conditions in Sudan. Then, the Class 'A' pan and Piche values are correlated with Penman's open-water evaporation and Thornthwaite's potential evapotranspiration results, by means of statistical methods to investigate some possible agreement or relationship between the measured and computed values at representative stations in the country.

### DATA USED:-

The evaporation data analysed and discussed in this chapter are prepared from measured and calculated values at eight selected stations (Fig. 21).

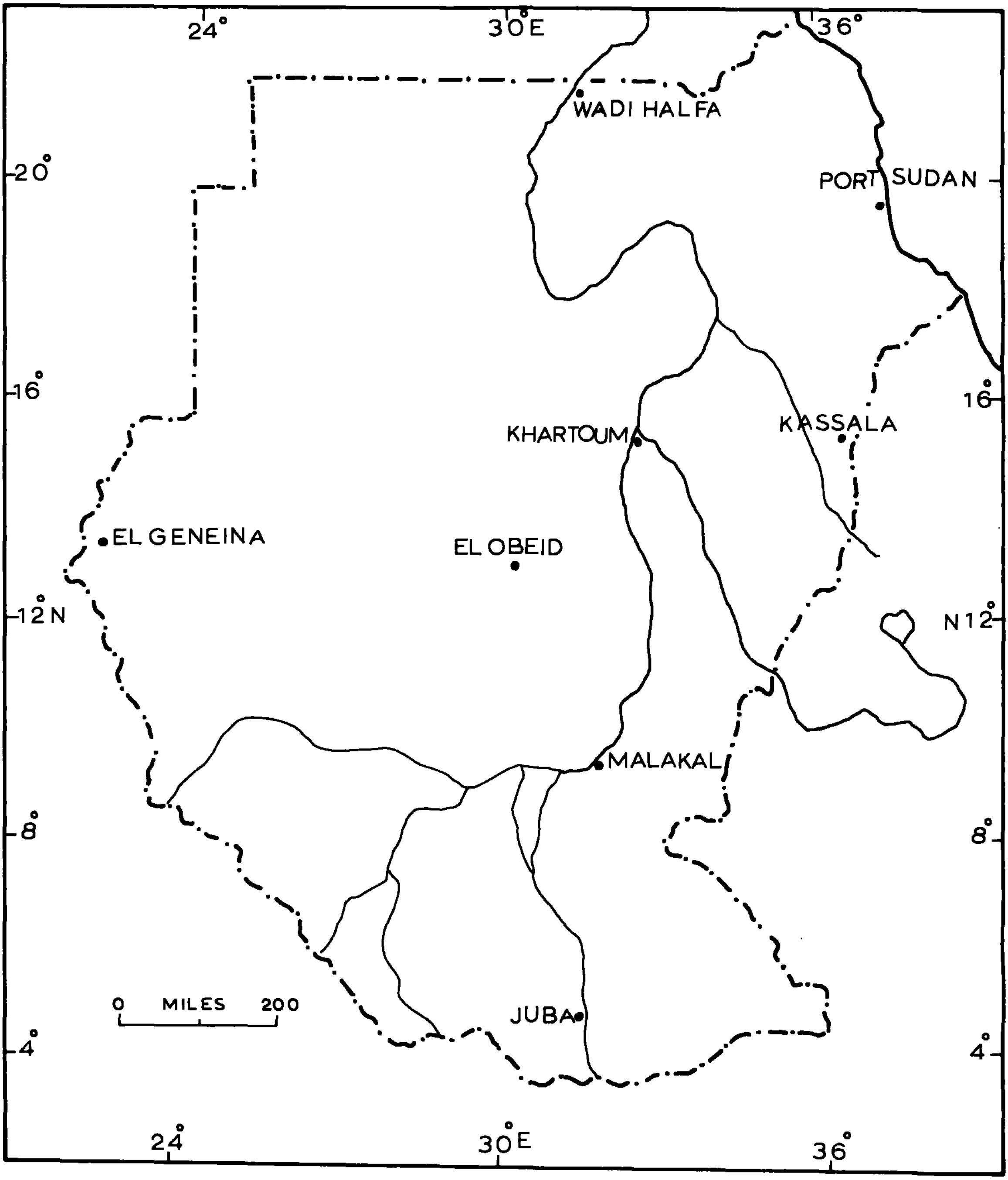


Fig. 21. Location of Met. Stations Used for Comparative Study between Measured and Estimated Evaporation

MEASURED VALUES:-

Average daily Class 'A' pan and Piche evaporation records were obtained mainly from two sources of data: (1) from "Sudan Annual Met. Reports (1959-1962)" and (2) from monthly and annual "Climatological Summaries" for the years (1963-1966).(1) From these available sources individual as well as mean monthly and annual Class 'A' pan evaporation (Appendix II, Tables 1-8), and Piche values (Appendix III, Tables 9-16) have been calculated from an eight year period 1959-1966 for eight selected stations.(2)

CALCULATED VALUES:-

From individual monthly and yearly (PE) values, computed by Thornthwaite's method (1948), during the period (1959-1966) mean monthly and annual values have been averaged for eight selected stations (App. IV, Tables 17-24).(3) Whilst average annual and monthly

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(1) Non-published annual and monthly summaries of climatological data compiled from observation files at the Sudan stations during the period 1963-1966 - Sudan Met. H.Q. at Khartoum.

(2) Mean monthly and annual Piche and Class 'A' pan evaporation are included at the end of each table in Appendices (II-III) for eight selected stations during the period (1959-1966).

(3) Mean monthly and annual Thornthwaite potential evapotranspiration values are included at the end of tables (17-24) in Appendix IV.

(Eo) values have been calculated from the individual annual and monthly (Eo) results computed from Penman's formula (1948) during (1959-1966) and for the same representative stations (App. V, Tables 25-32).[1]

As mentioned above, eight meteorological stations (Fig. 21) were selected to represent the relationships between the Class 'A' pan and Piche evaporation, on the one hand, and then between the measured and computed evaporation on the other hand, for different climatic conditions in the country. These stations have been chosen because they are the only ones that possess complete Piche and Class 'A' pan evaporation records plus other climatic values required for the computational procedure of the water loss during the whole period (1959-1966). The only stations which are exceptional to this eight years period are Kassala and Wadi Halfa. The former station does not possess Class 'A' pan records before January 1962 (Appendix II, Table 3).

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(1) Mean monthly and annual Penman evaporation results are included in tables (25-32) of Appendix V.

All records at Wadi Halfa are limited to the period (1959-1963), since the station was closed in August 1964 when it was overflooded by the Nile waters after the construction of the Aswan High Dam in Egypt.

However, both the measured and computed evaporation data at the selected stations have been confined mainly to an eight years period (1959-1966) as illustrated in appendices (II-V). The choice of this period is based on three main reasons: firstly, before January 1959 Class 'A' pan evaporation, and sunshine records (for Penman's formula) were not available for most of the selected stations, secondly the ([illegible]-1967) data was not released as yet, because it has to be rechecked (at Khartoum Met. Office) for accuracy and reliability; and finally, because the aim of this work was to present a comparative study between observed and estimated evaporation, the study period should be rather uniform for all stations and methods.

## A COMPARISON OF CLASS 'A' PAN AND PICHE EVAPORATION

### (i) AVERAGE ANNUAL CLASS'A' PAN AND PICHE EVAPORATION

It can be seen from figure 22 that the mean annual Piche values are slightly less than the corresponding

Class 'A' pan figures for all stations except Wadi Halfa, where the Piche evaporation exceeds that of the water pan. However, the differences between annual values of both instruments, tend to be rather small as illustrated by the Piche to Class 'A' pan ratios in Table 5.

Table 5

| Station | Piche/Pan |
|---|---|
| Wadi Halfa | 1.1 |
| Port Sudan | 0.76 |
| Kassala | 0.85 |
| Khartoum | 0.91 |
| El Obeid | 0.89 |
| El Genina | 0.92 |
| Malakal | 0.84 |
| Juba | 0.68 |

Source of data: Mean annual values, (Appendices II and III)

From the same figure 22 it can be seen that the Piche curve tends to approximate rather closely with the Class 'A' pan's, but making varying discrepancies from one place to another. Nevertheless, both curves

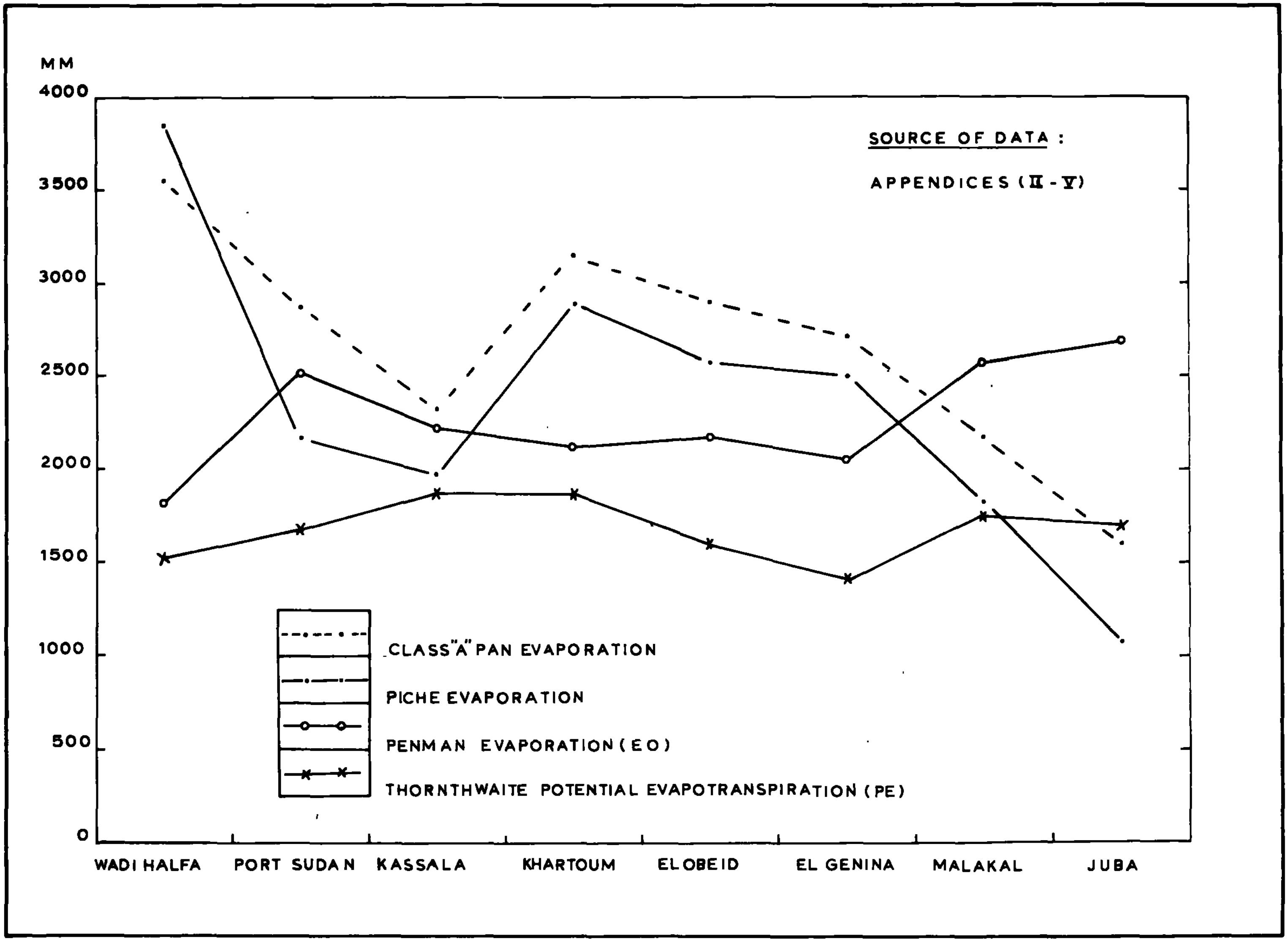



Fig. 22. Graph for Average Annual Measured and Estimated Evaporation at selected stations (1959-1966)

generally fluctuate in a similar manner. From maximum values at Wadi Halfa (northern Sudan) they fall towards Kassala (east-central Sudan) from which they rise towards Khartoum (Central Sudan). From Khartoum, the measured curves slope gently downwards towards Genina (west-central Sudan), then they drop progressively to minimum values at Juba in southern Sudan. Although the maximum annual values of the two instruments are recorded at Wadi Halfa, and the minimum values at Juba, yet the difference between maximum and minimum Piche evaporation (2766mm.) is much greater than that of the Class 'A' pan which is only 1952 mm. (App. III, Tables 9 and 16) and (App. II, Tables 1 and 8).

(ii) AVERAGE MONTHLY PICHE AND CLASS 'A' PAN EVAPORATION:-

Figure 23 indicates that the mean monthly pan evaporation for the various stations is generally higher than that of the Piche for most months of the year. The only exception to this is to be found at Wadi Halfa where the Piche values are slightly more than the Class 'A' pan results for the greater part of the year. This may possibly be attributed to the extremely arid conditions of hot temperatures and high wind speed experienced at this station. Since the Piche evaporimeter is known to be sensitive to air movement it is possible that the prevalence of hot winds may lead to abnormally high measurements at Wadi Halfa.

The amount by which the Class 'A' pan evaporation exceeds the Piche value, on a seasonal or monthly basis, is not uniform at any station or from one station to another (Fig. 23). Yet it seems that the numerical differences, though small, between the Class 'A' pan and Piche values increase in the rainy season or wet periods and decrease, to some extent, during the dry season. Thus, in the rainy months (July to September) the differences increase at (Kassala, Khartoum, Obeid, Malakal and Juba) and also decrease at (Genina, Obeid, Khartoum and Kassala) during the dry season from November to March (Fig. 23). These differences between the two instruments might be further illustrated by mean monthly Piche to Class 'A' pan ratios at each of the selected stations (Table 6).

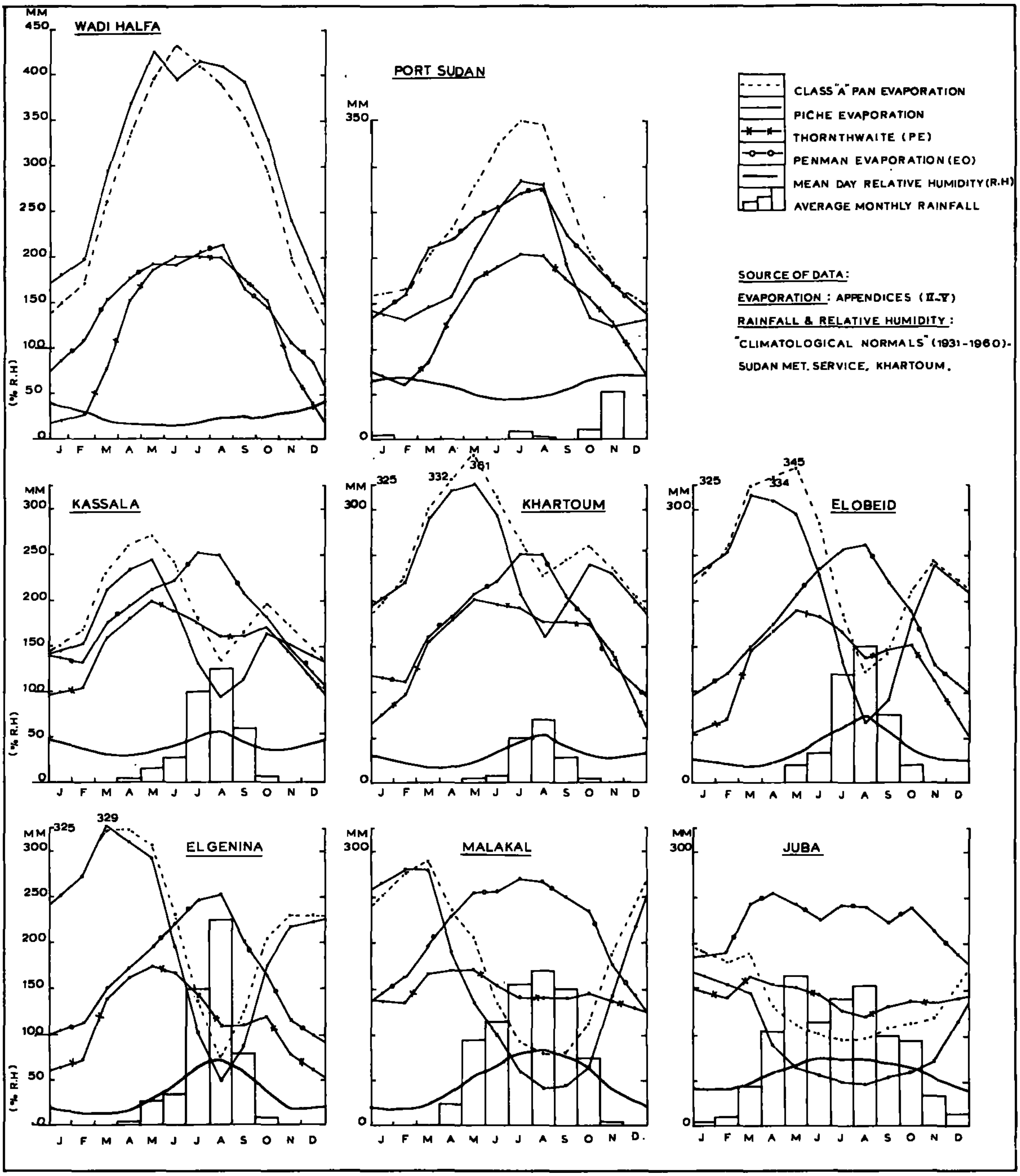



Fig. 23. Graph for Average Monthly Measured and Estimated Evaporation at selected stations (1959-1966)

## Table 6

## Monthly Piche/Class 'A' pan Evaporation Ratios

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W/Halfa | 1.20 | 1.20 | 1.10 | 1.10 | 1.10 | 0.91 | 1.00 | 1.00 | 1.10 | 1.10 | 1.20 | 1.20 |
| Port Sudan | 0.87 | 0.81 | 0.72 | 0.67 | 0.75 | 0.78 | 0.81 | 0.80 | 0.71 | 0.66 | 0.74 | 0.83 |
| Kassala | 0.97 | 0.91 | 0.92 | 0.91 | 0.91 | 0.81 | 0.74 | 0.61 | 0.68 | 0.83 | 0.88 | 0.95 |
| Khartoum | 1.00 | 0.98 | 0.97 | 0.96 | 0.91 | 0.93 | 0.78 | 0.70 | 0.80 | 0.93 | 0.99 | 0.98 |
| El Obeid | 1.00 | 0.99 | 0.97 | 0.93 | 0.86 | 0.81 | 0.72 | 0.56 | 0.64 | 0.86 | 1.00 | 1.00 |
| El Genina | 1.00 | 1.00 | 1.00 | 0.95 | 0.95 | 0.85 | 0.75 | 0.68 | 0.69 | 0.85 | 0.94 | 0.97 |
| Malakal | 1.00 | 1.00 | 0.96 | 0.82 | 0.66 | 0.74 | 0.63 | 0.54 | 0.58 | 0.58 | 0.76 | 0.90 |
| Juba | 0.86 | 0.86 | 0.78 | 0.67 | 0.57 | 0.55 | 0.53 | 0.49 | 0.51 | 0.54 | 0.61 | 0.74 |

Source of data: Mean monthly values (Appendices II and III)

It is perhaps, difficult to account fully for the differences between the measured values of Piche and Class 'A' pan evaporimeters situated at the same site or locality. On the other hand, since the water pans and Piche evaporimeters vary from one another in size, shape, material, exposure and operation, they will be influenced differently by the various climatic factors like winds, solar radiation, air temperature, and humidity. This is likely to result in different evaporation values. As indicated by Thornthwaite (1954) the higher water loss from the Class 'A' pan, compared with the Piche, may be attributed to the effect of heat transfer through the pan wall from the surrounding environment. During the hot dry season, especially when the ground around the pan is lacking in moisture, a great proportion of radiant energy received at the ground surface is used in warming the air. If this air is then blown over the pan which has a lower temperature, there will be energy transfer from the air to its evaporating surface, and thus will increase the evaporation rate relative to the Piche. Also a considerable amount of radiant energy will be intercepted by the walls of the pan.

During the rainy season, the pan evaporation is often much higher than the Piche values and the discrepancy can be rather large. This may be partially due to the effects of rain splash and blow out from the evaporating surface of the pan during the tropical storms; whilst the Piche evaporating surface will not be affected by such splash out. This phenomenon has been noted by Gilchrist (1961) in Nigeria, and by Kohler (1952) in the "Lake Hefner study".

Nevertheless, the two instruments seem to react in a similar fashion during the wet or dry periods. The measured evaporation is higher during the hot dry summer where temperatures are high and relative humidities are lowest; whilst in the rainy season the temperature conditions are cooler and the humidities are relatively high, which lead to lower evaporation values. Moreover, the mean monthly Piche and pan evaporation curves appear to follow quite identical trends and show similar fluctuations during the year for most of the individual stations (Fig. 23). This close agreement between the two instruments, makes it rather tempting to suggest that the Piche and Class 'A' pan give reliable values of the water loss parameter under various climatic conditions in the Sudan.

THORNTHWAITE (PE) AND MEASURED EVAPORATION

(i) AVERAGE ANNUAL (PE) AND MEASURED EVAPORATION:-

As illustrated in figure 22 the mean annual (PE) is lower than the measured evaporation for all stations except Juba where the (PE) is about one and a half as much as Piche and almost equal to the pan evaporation. At Malakal and Kassala stations Thornthwaite estimates are almost similar to the measured values (Fig. 22). But, on the other hand, the (PE) is found to be seriously below the measured values at Wadi Halfa and El Genina where it is 60% less than the Piche at the former, and almost half the measured amount at the latter station.

(ii) AVERAGE MONTHLY (PE) AND MEASURED EVAPORATION:-

It can be seen from figure (23) that the mean monthly computed Thornthwaite (PE) is, generally, low compared with the observed pan and Piche evaporation during the dry season and slightly larger than the measured water loss during the rainy season. This pattern can be observed for many stations under various climatic environments and is particularly apparent at Kassala, El Obeid, El Genina and Malakal. The exception to this trend is found at Wadi Halfa where the (PE) is suppressed below the measured evaporation throughout the year (Fig. 23).

However, the relatively high measured evaporation of the dry season, may be directly attributed to climatic factors prevailing over the country. During this season, most of Sudan experiences scanty or nil rainfall, and almost clear skies help to give a large duration of sunshine hours. The winds tend to be dry and relatively high for most of the dry season. As a result of these factors and, perhaps, some local microclimatic environments including inadequate "buffer zones" may add to the evaporating capacity and energy of the air to pick up more moisture from land and water surfaces. Water pans and Piche evaporimeters, however, tend to react more readily to these evaporating conditions by giving higher values in comparison with Thornthwaite's (PE) which is computed solely on the basis of air temperature and length of day and does not show any response to other influential factors.

With the onset of the rainy season, whose duration and intensity vary from one place to another, there are plenty of clouds which restrict the intensity of solar radiation and reduce the amount of bright sunshine hours. The atmospheric humidity is often quite high and temperature conditions are slightly low, especially during rain periods. As a result, the Piche and pan records tend to be much reduced during this season. But since the mean air temperature is, perhaps, altered less than moisture or humidity terms which may suppress the observed evaporation, the (PE) seems to give larger figures than the actual measured values (Fig. 23).

The monthly and seasonal differences between the measured water loss and computed (PE) can be best detected from monthly ratios illustrated in Table 7 and Table 8. The average ratio of the twelve months at each station is also included in the tables.

## Table 7

## Thornthwaite (PE)/Piche ratios

| Station | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Ave. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wadi Halfa | 0.13 | 0.14 | 0.26 | 0.42 | 0.44 | 0.50 | 0.49 | 0.49 | 0.44 | 0.46 | 0.32 | 0.22 | 0.36 |
| Port Sudan | 0.51 | 0.46 | 0.59 | 0.86 | 0.83 | 0.75 | 0.72 | 0.73 | 0.93 | 1.10 | 1.00 | 0.69 | 0.76 |
| Kassala | 0.70 | 0.68 | 0.75 | 0.76 | 0.81 | 0.97 | 1.30 | 1.70 | 1.50 | 1.00 | 0.97 | 0.83 | 0.99 |
| Khartoum | 0.37 | 0.43 | 0.54 | 0.56 | 0.62 | 0.67 | 0.93 | 1.10 | 0.91 | 0.73 | 0.62 | 0.45 | 0.66 |
| El Obeid | 0.26 | 0.29 | 0.46 | 0.54 | 0.64 | 0.80 | 1.20 | 2.00 | 1.60 | 0.85 | 0.47 | 0.32 | 0.79 |
| El Genina | 0.26 | 0.26 | 0.43 | 0.52 | 0.60 | 0.85 | 1.40 | 2.2 | 1.30 | 0.68 | 0.37 | 0.28 | 0.76 |
| Malakal | 0.52 | 0.48 | 0.60 | 0.90 | 1.30 | 1.50 | 2.40 | 3.2 | 3.00 | 2.20 | 0.96 | 0.59 | 1.50 |
| Juba | 0.90 | 0.92 | 1.10 | 1.70 | 2.40 | 2.50 | 2.50 | 2.6 | 2.40 | 2.30 | 1.90 | 1.20 | 1.90 |

Source: Mean monthly values (Appendix III and Appendix IV)

## Table 8

## Thornthwaite (PE)/Class 'A' pan ratios

| Station | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Ave. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wadi Halfa | 0.16 | 0.16 | 0.30 | 0.46 | 0.48 | 0.46 | 0.50 | 0.51 | 0.49 | 0.52 | 0.39 | 0.26 | 0.39 |
| Port Sudan | 0.44 | 0.37 | 0.42 | 0.58 | 0.62 | 0.58 | 0.58 | 0.58 | 0.66 | 0.76 | 0.77 | 0.57 | 0.58 |
| Kassala | 0.68 | 0.62 | 0.69 | 0.69 | 0.74 | 0.79 | 0.99 | 1.00 | 0.99 | 0.86 | 0.85 | 0.79 | 0.81 |
| Khartoum | 0.37 | 0.42 | 0.52 | 0.54 | 0.56 | 0.63 | 0.73 | 0.78 | 0.73 | 0.68 | 0.61 | 0.44 | 0.58 |
| El Obeid | 0.26 | 0.28 | 0.44 | 0.50 | 0.55 | 0.64 | 0.89 | 1.10 | 1.00 | 0.73 | 0.47 | 0.32 | 0.60 |
| El Genina | 0.26 | 0.26 | 0.43 | 0.50 | 0.57 | 0.72 | 1.00 | 1.50 | 0.90 | 0.58 | 0.35 | 0.27 | 0.61 |
| Malakal | 0.54 | 0.50 | 0.58 | 0.73 | 0.84 | 1.10 | 1.50 | 1.80 | 1.70 | 1.30 | 0.73 | 0.54 | 0.98 |
| Juba | 0.77 | 0.79 | 0.87 | 1.20 | 1.30 | 1.40 | 1.30 | 1.30 | .120 | 1.20 | 1.10 | 0.92 | 1.10 |

Source: Mean monthly values (Appendix II and Appendix IV)

The principal feature shown by these tables (7 & 8) is the notable variation of ratios at any station and from one station to the other. The average ratios show that Thornthwaite's (PE) is low at arid stations such as Wadi Halfa where the Piche evaporation tends to be over three times the (PE), and the Class 'A' pan's is almost more than double the computed value. In most humid localities, the average ratio shows that Thornthwaite's (PE) seems to be similar to the pan evaporation as in the case of Malakal and Juba (Table 8). But the (PE) is about one and a half times as much as the Piche evaporation in the former and almost double the Piche value at the latter station (Table 7). At central Sudanese stations, the average ratio of the (PE) to the Piche ranges between 0.66 and 0.99 (Table 7) as opposed to the PE/Class 'A' pan mean ratios that vary from 0.58 at Khartoum to 0.81 at Kassala (Table 8).

If we consider the seasonal or monthly patterns of measured evaporation as compared to the computed (PE) at the selected stations, we find interesting variations and fluctuations (Fig. 23). In the first place, the minimum or maximum values of the (PE) and observed water loss are not the same or coincident for most of the stations. Secondly, the seasonal trends of the measured and computed curves are, generally, not the same for many places. The relation between the (PE) and measured evaporation at Wadi Halfa in northern Sudan is not found at other stations. At this station, although the (PE) and measured curves show the same rhythm, the potential evapotranspiration is consistently lower than the observed values and creates a serious discrepancy, particularly in the period March-October. This suggests an important difference between Thornthwaite's (PE) and measured evaporation at the station of Wadi Halfa (Fig. 23). At Port Sudan which experiences a peculiar climate of summer and winter rainfall, similar fluctuations are noted between the (PE) and Class 'A' pan results. The values increase steadily from January to July and then fall steeply towards December. The Piche curve follows the same pattern, but it tends to deviate slightly below the (PE) curve during the moist winter months of October and November. (Fig. 23)

In central Sudan, represented by Kassala, El Obeid and El Genina, the (PE) and measured curves are inclined to behave in a similar manner, that is different from other stations. In general, the computed potential evapotranspiration and measured water loss increase during late winter and the hot dry summer, and start to descend at the onset of the rains where the Piche and Class 'A' pan curves reach their minimum limits. But at the end of the rainy season, the curves rise again and then progressively go down in the cool dry season. The disparity which results between the(PE) and measured values at these three stations is often higher in the dry periods than the wet season as illustrated by figure 23.

At Malakal and Juba (southern Sudan) the (PE) diminishes slightly in the wet season as compared with the measured water loss which shows a considerable fall during this season. But the (PE) and measured curves seem to follow similar trends and fluctuations for the greater part of the year, except in the relatively cool dry season (November-December) where the curves diverge, since the measured water loss sharply increases upwards, and the (PE) gently slopes downwards until the end of the year (Fig. 23).

It can be generalized then, from figure 23 that the mean monthly measured evaporation and estimated (PE) show discrepancies both in the individual monthly values as well as the seasonal phases of the year. The greatest discrepancy occurs during the months of the dry season where the (PE) is considerably less than the measured evaporation. When the hot dry summer progresses towards the wet season the discrepancies tend to be less, and often an excess of computed (PE) over measured evaporation occurs. Despite the larger differences between them, the curves of the measured water loss sometimes bear a marked resemblance to the estimated potential evapotranspiration. But, nevertheless, the monthly and seasonal fluctuations in the measured evaporation are very large as compared with the (PE) which displays only very limited variations. As a result the difference between maximum and minimum measured figures at any place is large in comparison with the smaller range of Thornthwaite's extreme values. This is , probably, attributed to the empirical nature of Thornthwaite's (PE) which is basically calculated from mean monthly temperature and length of day which show only very limited variations in the tropical climate of the Sudan, whose greater part lies only 15$^{\circ}$ north of the equator. Whilst, the greater fluctuations in the measured evaporation might be ascribed, as mentioned earlier, to the greater sensitivity of evaporimeters.

## PENMAN (EO) AND MEASURED EVAPORATION

### (i) AVERAGE ANNUAL (EO) AND MEASURED EVAPORATION:-

From figure 22 it can be seen that the mean annual Penman (EO) largely exceeds the measured evaporation at Malakal and Juba. At Juba, the (EO) is, roughly, more than twice the Piche and almost one and a half as much as the Class 'A' pan values. But the computed evaporation is lower than the measured at other stations in this figure. However, at Port Sudan and Kassala, the Penman evaporation is found to be intermediate between the Piche and Class 'A' pan evaporation. It may also be observed from the figure, that the Penman's curve seems to follow the same rhythm as that of Thornthwaite's, but the former tends to approximate more closely to the measured curves than the latter (Fig. 22).

(ii) AVERAGE MONTHLY PENMAN (EO) AND MEASURED EVAPORATION:-

At most stations in figure 23 it is evident that the mean monthly Penman open-water evaporation (EO) is low during the season of high measured water loss, and relatively high during lower values of observed evaporation. In other words, the Penman formula tends to provide larger results than the Class 'A' pan or Piche evaporation in the wet season, and as the dry weather approaches, the values of computed (EO) are increasingly diminished in comparison with the measured water loss. However, the subsequent disparities between the measured values and estimated (EO) figures are quite remarkable for most of the selected stations in figure 23. These differences between the measured and computed are illustrated in tables 9 and 10 which indicate the degree of correlation by dividing mean monthly (EO) by the corresponding pan or Piche figures. The average ratio of the twelve months is also included for each station in the tables.

Table 9

Penman (EO)/Piche ratios

| Station | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Ave. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wadi Halfa | 0.47 | 0.55 | 0.52 | 0.48 | 0.45 | 0.49 | 0.50 | 0.52 | 0.42 | 0.44 | 0.45 | 0.47 | 0.48 |
| Port Sudan | 1.00 | 1.20 | 1.40 | 1.40 | 1.20 | 1.00 | 0.96 | 0.99 | 1.20 | 1.50 | 1.30 | 1.20 | 1.20 |
| Kassala | 0.95 | 0.87 | 0.82 | 0.83 | 0.87 | 1.10 | 1.90 | 2.60 | 1.90 | 1.10 | 0.98 | 0.88 | 1.20 |
| Khartoum | 0.56 | 0.50 | 0.55 | 0.58 | 0.63 | 0.75 | 1.20 | 1.60 | 1.10 | 0.75 | 0.56 | 0.54 | 0.78 |
| El Obeid | 0.45 | 0.47 | 0.47 | 0.57 | 0.70 | 1.00 | 1.90 | 3.90 | 2.40 | 1.10 | 0.54 | 0.50 | 1.20 |
| El Genina | 0.41 | 0.41 | 0.46 | 0.56 | 0.66 | 1.10 | 2.40 | 5.1 | 2.30 | 0.94 | 0.54 | 0.45 | 1.30 |
| Malakal | 0.55 | 0.58 | 0.69 | 1.20 | 1.90 | 2.50 | 4.60 | 6.2 | 5.40 | 3.50 | 1.20 | 0.66 | 2.40 |
| Juba | 1.10 | 1.20 | 1.60 | 2.90 | 3.80 | 3.90 | 4.70 | 5.00 | 3.90 | 3.90 | 2.90 | 1.70 | 3.10 |

Source: Mean monthly values (Appendix III and Appendix V)

## Table 10

### Penman (EO)/Class'A' pan ratios

| Station | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Ave. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wadi Halfa | 0.57 | 0.63 | 0.59 | 0.53 | 0.49 | 0.45 | 0.50 | 0.54 | 0.47 | 0.50 | 0.54 | 0.56 | 0.53 |
| Port Sudan | 0.89 | 0.97 | 1.00 | 0.94 | 0.87 | 0.79 | 0.78 | 0.80 | 0.83 | 0.97 | 0.99 | 0.96 | 0.89 |
| Kassala | 0.93 | 0.79 | 0.76 | 0.75 | 0.79 | 0.92 | 1.40 | 1.60 | 1.30 | 0.92 | 0.86 | 0.84 | 0.98 |
| Khartoum | 0.57 | 0.49 | 0.53 | 0.55 | 0.58 | 0.70 | 0.96 | 1.10 | 0.84 | 0.69 | 0.56 | 0.53 | 0.68 |
| El Obeid | 0.46 | 0.47 | 0.46 | 0.53 | 0.60 | 0.83 | 1.40 | 2.20 | 1.50 | 0.90 | 0.54 | 0.50 | 0.87 |
| El Genina | 0.42 | 0.41 | 0.46 | 0.53 | 0.63 | 0.96 | 1.80 | 3.40 | 1.60 | 0.80 | 0.51 | 0.44 | 0.99 |
| Malakal | 0.57 | 0.60 | 0.67 | 0.98 | 1.20 | 1.90 | 2.90 | 3.40 | 3.10 | 2.10 | 0.94 | 0.60 | 1.60 |
| Juba | 0.98 | 1.10 | 1.30 | 1.90 | 2.10 | 2.20 | 2.50 | 2.40 | 2.00 | 2.10 | 1.80 | 1.20 | 1.80 |

Source: Mean monthly values (Appendix II and Appendix V)

The above ratios (of EO to measured evaporation) which vary seasonally and monthly may also emphasize the tendency of Penman's formula for computing low evaporation during the dry periods and very high values in the more wet humid months as illustrated in figure 23.

The same figure 23 also reveals the varying discrepancies between the (EO) and measured curves during different parts of the year. The seasonal fluctuations of both the (EO) and measured evaporation seem to display different trends for various stations in the figure. In the extreme dry northern Sudan represented by Wadi Halfa, the (EO) is consistently less than the measured values under the very arid conditions, and for most of the seasons the discrepancy is seriously high. Here the minimum values of the (EO) and measured evaporation appear to be in the same seasons, whilst the maximum values occur in the dry period (May-August). But the general behaviour of Penman's curve follows a similar pattern to that of the Piche and Class 'A' pan. In the relatively more humid north east Sudan at Port Sudan, the (EO) is generally greater than the Piche evaporation for most of the wet season, and tends to be below the

Piche's during the less humid period (July-August). Nevertheless, the (EO) approximates closely with the pan evaporation for most of the period (October-March) where the measured values are equal to or in excess of the Penman estimates. For the rest of the year, the (EO) is inclined to diverge clearly from the high pan evaporation and lead to the subsequent large discrepancy. But, on the whole, the (EO) curve tends to fluctuate between the Piche and Class 'A' pan curves. At Kassala (eastern Sudan) the (EO) curve parallels rather closely the Piche and pan evaporation in the dry periods, but for most of the wet season, it moves away from the measured curves and creates a larger discrepancy than in the dry summer or winter periods.

At Khartoum and El Obeid (Central Sudan) Penman's evaporation is likely to behave in a similar fashion to the measured water loss during periods of droughts (Fig. 23). It tends to reflect the measured curves, i.e. it rises in the same direction during the transitional period (between the cool dry winter and hot wet summer) and then decreases in accordance with the measured values in the winter season. During the wet season the (EO) curve is inclined to make a larger discrepancy at El Obeid where the measured water loss appears highly exaggerated, and relatively less discrepancy occurs at Khartoum where it tends to approximate with the observed values. At El Genina (western Sudan), although the (EO) and measured curves follow the same pattern of fluctuations like other stations in central Sudan, the gap between the computed and measured is quite large since the (EO) fails to provide for the sharp decrease of observed evaporation in the rainy season and the relative increase during the dry season.

At the remaining stations Juba and Malakal (southern Sudan), the (EO) curve is likely to accord with the measured evaporation in the winter period (December-February) at the former, but it is less than the measured water loss at the latter station during this period (Fig. 23). In the wet season at Juba, the computed (EO) does not show any sympathy or logical agreement with the measured water loss since it seriously exaggerates the Piche and pan evaporation during almost all the rainy months. At Malakal, the (EO) curve crosses the measured curves at the onset of the rains and recrosses them during late autumn where it descends steeply towards the month of December (Fig. 23).

From Figure 23 it may also be deduced that the monthly and seasonal fluctuations in the measured evaporation are very large compared with the computed (EO) which shows relatively less variations throughout the year. This is, perhaps, a result of the fact that the evaporating surfaces of the instruments are more sensitive to the changes of weather in the Sudan than the Penman's (EO) which is calculated from interrelated meteorological data that seem to give more conservative values than the actual measured water loss.

The foregoing discussions, however, emphasize that in most cases Penman's evaporation is less than that of the Piche or Class 'A' pan throughout the dry season. Whilst in most of the rainy season, the formula provides larger results than the observed water loss and the disparities are often considerable. This serious exaggeration of the computed (EO) during the rainy season is difficult to explain since Penman's equation does not show any response to the wet humid conditions in the country. As a result the application of Penman's formula, which was initially derived from temperate weather data at Rothamstead (England), appears unsuitable for Sudanese tropical humid conditions where the computed values have highly exceeded the measured results. Nevertheless, the formula could be of immense value if an effort was made to modify some elements in the equation or apply some correction factors in order to make the formula somewhat, accurate and perhaps reliable. This can only be achieved through some intensive experimental work, the time of which is, unfortunately, not permitted during the limited period of this research.

## REGRESSION ANALYSES OF AVERAGE MONTHLY MEASURED AND ESTIMATED EVAPORATION:

Mean monthly measured water loss from the Class 'A' pan and Piche evaporimeter has been plotted against Thornthwaite's potential evapotranspiration and Penman's open-water evaporation for representative Sudanese meteorological stations (Figs. 24, 25, 26 and 27). All units of measured and estimated evaporation are in millimetres per month. The relationship between the mean monthly measured and estimated quantities is shown by fitted lines calculated by the method of least squares for the eight years data (1959-1966) in Appendices II, III, IV and V. In obtaining the regression line by calculation, the idea is to ensure that the sum of squares of the difference of the individual values from the line is at an absolute minimum. It may be visualized as being akin to ensuring that the variance of the individual values in relation to the regression line is the smallest value it can possibly be (Gregory, 1963). The position and slope of this line has been calculated according to the method given by Gregory (1963). The formula for the regression line requires the correlation coefficient, the average and standard deviation values for the two sets of data, i.e. the measured and computed evaporation. The formula to be used is written as follows:

$$a - \bar{a} = r \cdot \frac{\sigma a}{\sigma b} \cdot (b - \bar{b}),$$

in which the value a is unknown and the value b is known. In other words, the unknown value (a) differs from the average of its set of data ($\bar{a}$) by the same amount as the known value (b) differs from its average ($\bar{b}$), modified by (i) the ratio of the two standard deviations, which express the overall spread of values about their respective averages and (ii) the correlation coefficient, which expresses the degree of actual relationship unit by unit.

For each station in figures (24, 25, 26 and 27) a regression equation has been set up for each pair of estimated and measured evaporation, and the correlation coefficient (r) is also indicated to show the statistical significance of the relationship between the observed and calculated water loss. However, in all such cases there is always the possibility that the coefficient obtained could have occurred "by chance" i.e. that its significance is suspect because of the probability of a chance occurrence. Therefore, the correlation coefficient at each of the selected stations was tested to see the percentage probability that this coefficient could have occurred by chance. The magnitude of these significance levels in every case (Figs. 24-27) has been obtained from a special graph prepared by Gregory (1963). If the percentage probability was 0.1% that means the correlation coefficient is highly significant; and it can be also considered as statistically significant even between the 1% and 5% level.

THORNTHWAITE'S (PE) AND PICHE EVAPORATION:-

In Figure 24, despite the serious discrepancy between the Piche and Thornthwaite's (PE) there is a close positive correlation between the two at Wadi Halfa ($r = 0.96$) and Port Sudan ($r = 0.82$). This is also indicated by the close fit of the points along the lines. At other stations, the lower value of correlation coefficient (below 0.50) reveals a poor relationship between the two sets of data. This is probably a result of the sudden and sharp decrease of the Piche values from the (PE) during the rainy months or the irregular differences between the measured and computed values at dry periods. At Kassala ($r = 0.45$), Khartoum ($r = 0.41$) and Juba ($r = 0.42$) the points seem to scatter along the regression line in the dry season, but tend to disperse across it during the rainy season when Thornthwaite's (PE) starts overestimating the Piche evaporation. For the rest of the stations in the

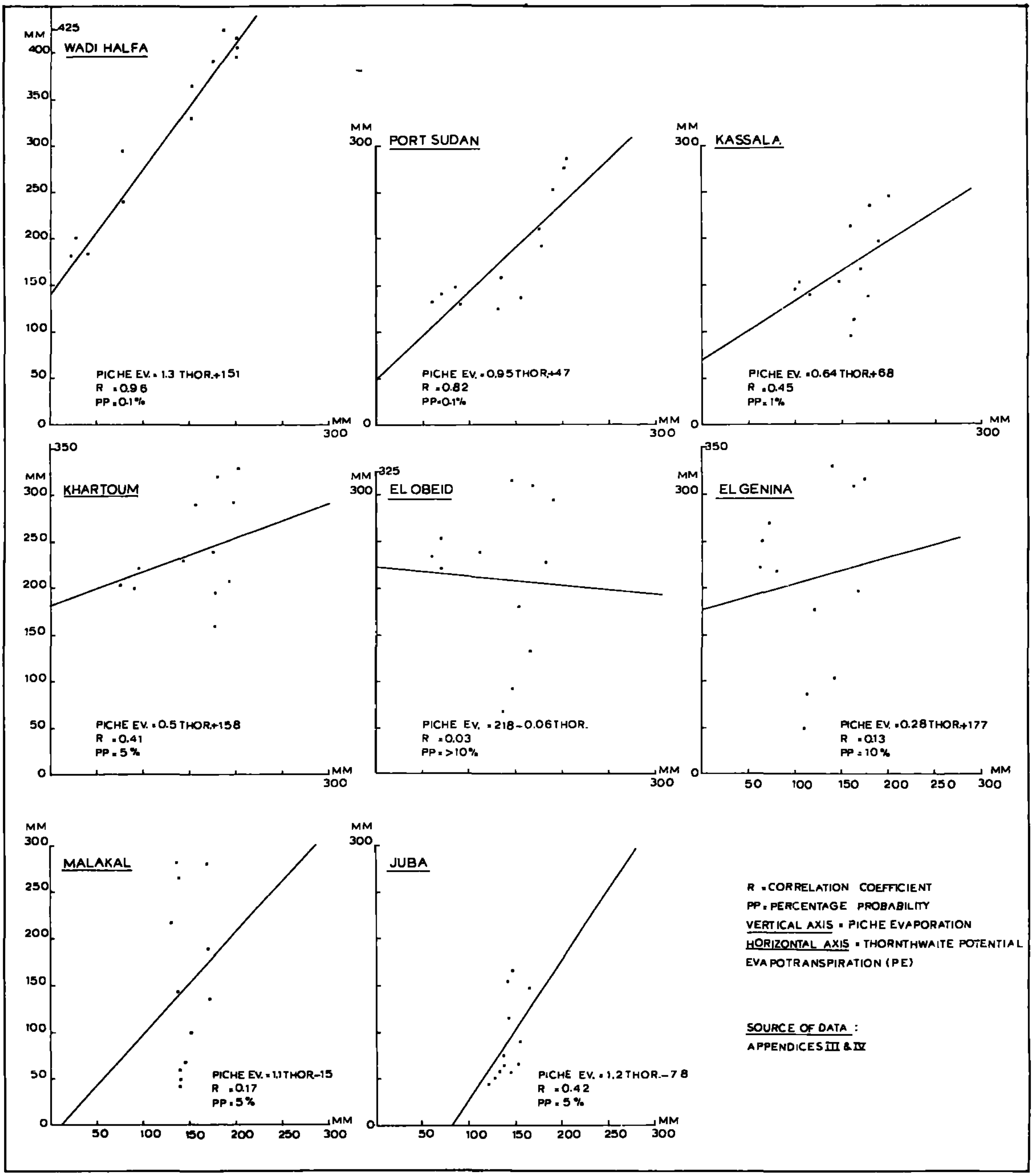



Fig. 24. Relation between Thornthwaite's (PE) and Piche Evaporation

figure, the correlation is quite unreliable since the correlation coefficients are low as indicated by the wide scatter of points.

## THORNTHWAITE'S (PE) AND PAN EVAPORATION:-

The mean monthly Thornthwaite's (PE) is also plotted against the values measured by Class 'A' pan to see if there is any possible agreement at the selected stations (Fig. 25). The figure illustrates that the (PE) highly relates to the pan evaporation for a number of stations in northern and central Sudan such as Wadi Halfa, Port Sudan, Kassala and Khartoum where the correlation coefficient ranges between 0.70 and 0.98. This is possibly owing to some seasonal harmony of (PE) fluctuations with the Class 'A' pan evaporation under arid and semi-arid conditions. The rest of the stations display surprisingly poor agreement as demonstrated by the low correlation coefficient (less than 0.50) and the large scatter of points on both sides of the regression lines. At Malakal and Juba, however, the points seem to disperse vertically along the lines,

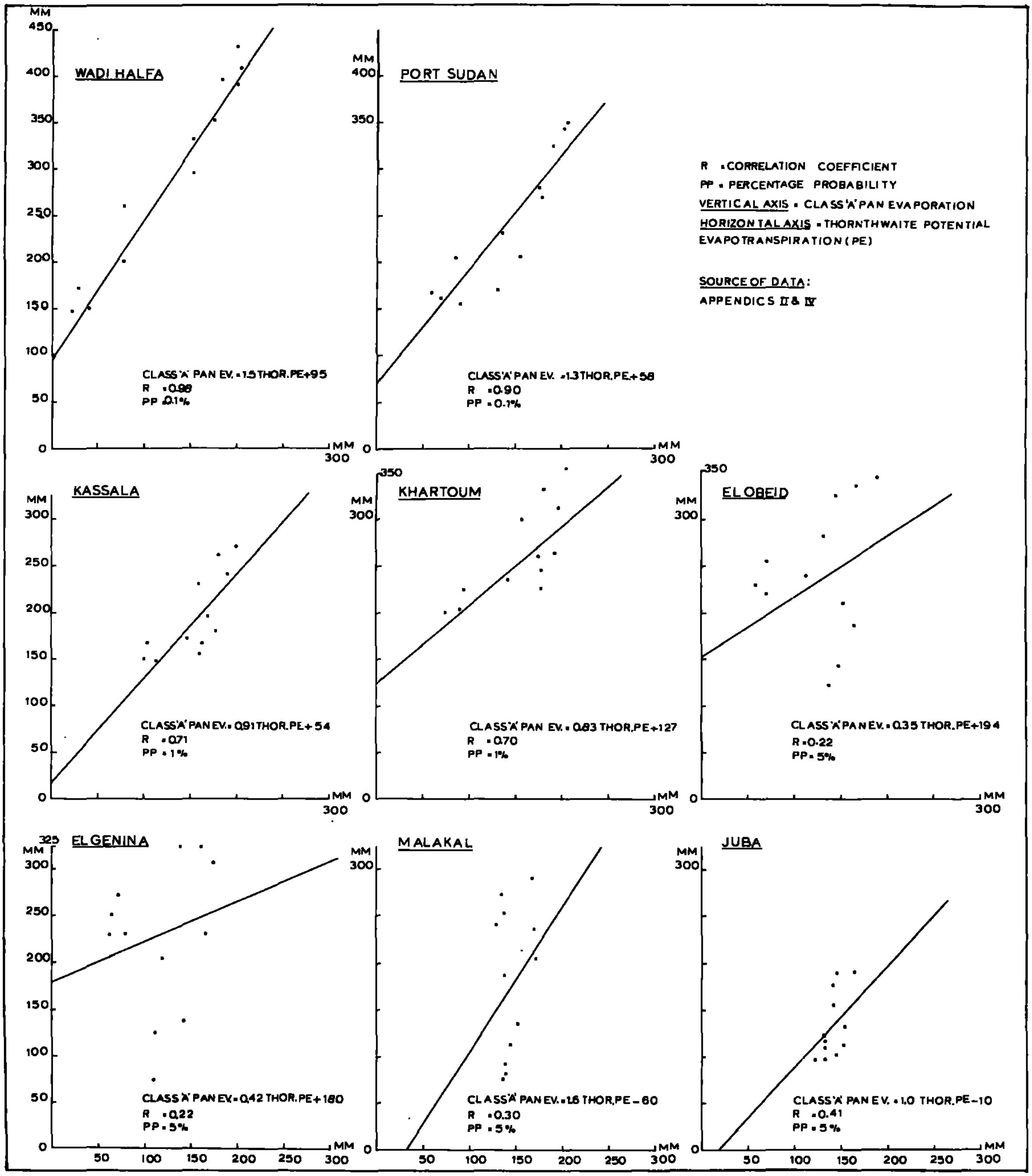



Fig. 25. Relation between Thornthwaite's (PE) and Class 'A' pan Evaporation

though they are relatively wide spread at the former and more concentrated at the latter station. This general disagreement at some stations is, perhaps, owing to the serious discrepancy between the (PE) and pan evaporation in the dry season and the relative contraction of the Class 'A' pan values in the wet season where high humidities are responsible for suppressing the pan evaporation below the level of Thornthwaite's potential evapotranspiration. Other factors such as inadequate buffer area and local microclimatic effects might help to give evaporation values which may lead to the poor correlation between Thornthwaite's (PE) and Class 'A' pan.

PENMAN'S (EO) AND PICHE EVAPORATION:-

In figure 26 a part from Wadi Halfa ($r = 0.94$) and Port Sudan ($r = 0.91$) where the Penman formula discloses a seasonal bias similar to the Piche values, there is only a poor correlation for the remaining stations. At Kassala ($r = 0.01$) and Khartoum ($r = 0.07$) the agreement is very poor and does not indicate any statistical importance particularly in the former station

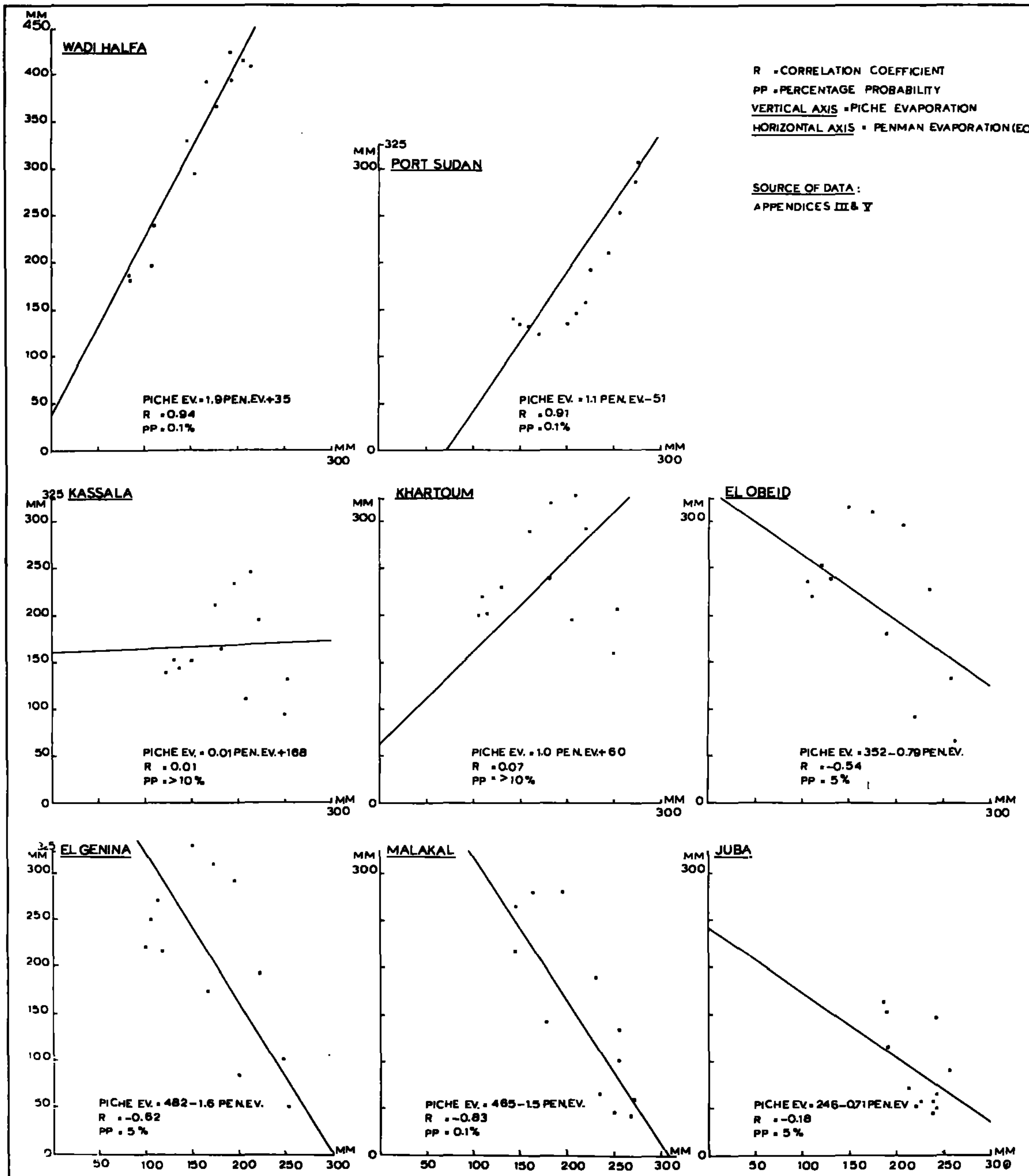



Fig. 26. Relation between Penman's (EO) and Piche Evaporation

where the regression line tends to be almost horizontal. The stations, El Obeid, El Genina, Malakal and Juba, on the other hand, show up a very surprising correlation which is negative and as a result the regression lines rise from right to left as shown in figure 26.

PENMAN (EO) AND PAN EVAPORATION:-

It can be visualized from figure 27 that, despite the large discrepancy between Penman and Class 'A' pan evaporation, the measured water loss agrees very well with the computed (EO) at Wadi Halfa and Port Sudan. The relationship at these stations is indicated by the high correlation coefficient (0.97). This can be attributed to the marked resemblance of seasonal fluctuations between the pan evaporation and the calculated water loss of Penman (EO). At Kassala (r = 0.35) and Khartoum (r = 0.42), though the relation is positive yet it is rather poor since the correlation coefficient is under 0.50 (Fig. 27). But it is likely that for both stations the points scatter in a similar pattern, that is, in each case they tend to isolate into two groups below the line and a third group above it, leaving

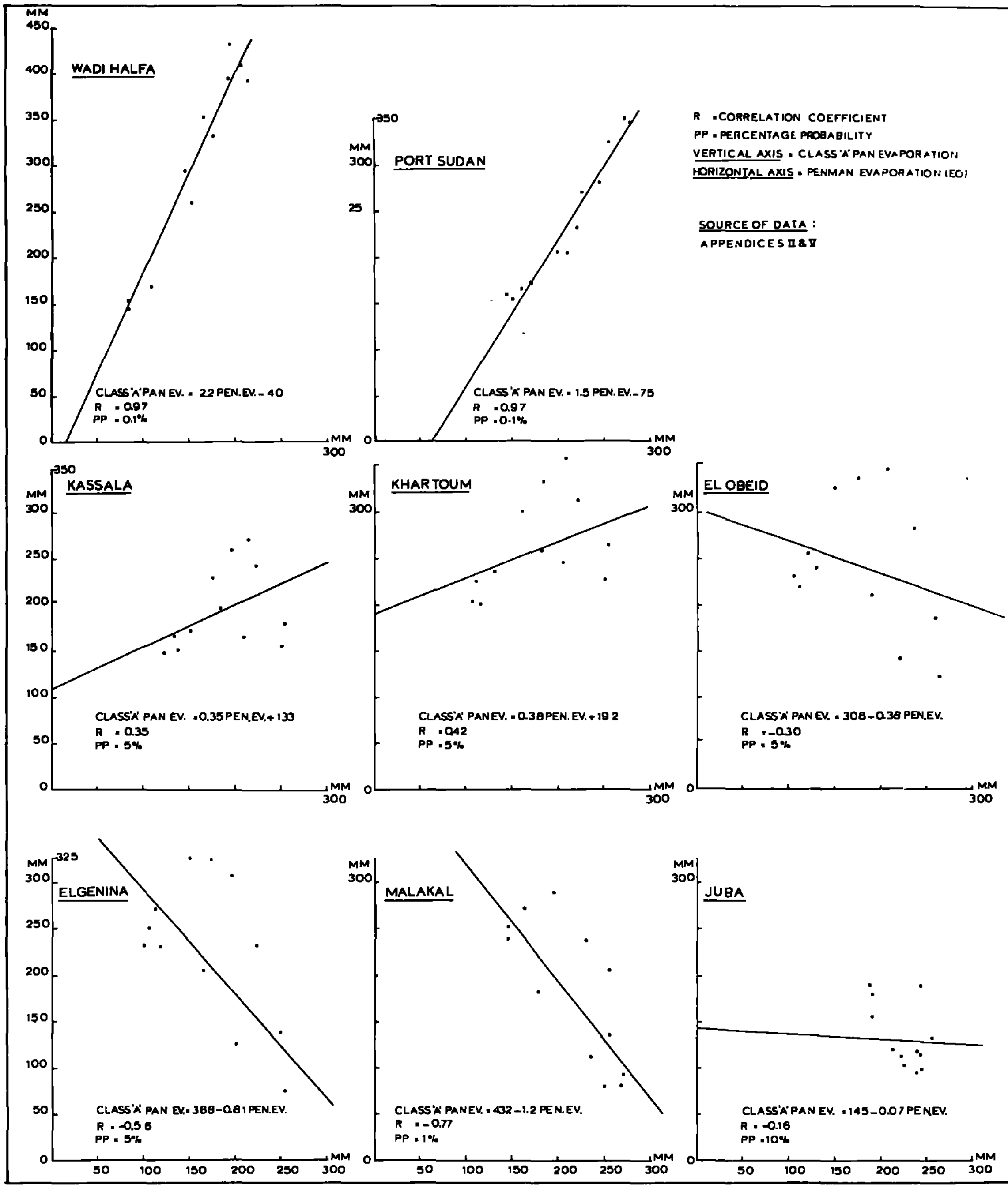



Fig. 27. Relation between Penman's (EO) and Class 'A' pan Evaporation

only a few points falling closely along the line of regression. For the remaining stations in the figure, the relationship is not positive as indicated by the negative correlation coefficients. This negative relationship is, relatively, high at El Genina (r = -0.56) and Malakal (r = -0.77) and the points show large scatter along and on both sides of the regression lines. But where the negative relationship is poor at El Obeid (r = -0.30) and Juba (r = -0.16) the points, however, tend to disperse vertically and thus, sometimes, disregard the fitted lines.

In some cases, however, no close agreement between the water pan and Penman evaporation was obtained. The negative or poor correlations might be subject to the criticisms outlined earlier for the Penman equation and the Class 'A' pan evaporimeter. It might be suggested that the overall deficiencies of these correlations may be traced to the exaggerated measured pan evaporation in the dry periods, and the Penman (EO) which results in excessive values during the rainy season. However, this unusual lack of sympathy between the measured evaporation and computed (EO) seems to be confined to the more humid conditions of southern Sudan.

THORNTHWAITE'S (PE) AND PENMAN'S (EO):-

After this brief comparative study of measured and computed evaporation, it may be desirable to investigate also the possible relationship between Thornthwaite's (PE) and Penman's (EO) in order to draw some conclusions on the merits and drawbacks of each method. It may be observed from figure 23 that Penman's (EO) gives continuously larger values than Thornthwaite's (PE) for most selected stations in the country. During the dry season, when humidities are lowest, the differences between the estimated values are relatively small; whilst in the wet season, the differences are large when humidities are highest. Hence, the (EO) and (PE) curves seem to accord quite well in the dry season. But in the rainy season Penman's evaporation overestimates Thornthwaite's potential evapotranspiration and results in the subsequent large disparities (Fig. 23).

However, Penman's formula is out of phase under moist humid conditions. The values seem very high, whilst Thornthwaite's method gives almost intermediate values between the (EO) and measured evaporation under such climatic conditions. But, on the other hand, the computed evaporation and potential evapotranspiration tend to give reasonable estimates with some degree of accuracy in some arid and semi-arid regions in Sudan. The sound explanation to these features however, must await further collection of data, as the present record is only available for a few stations and for only a restricted data-period.

# Chapter Four

## REGIONAL DISTRIBUTION OF EVAPORATION OVER THE SUDAN

It has been found in the third chapter that the differences in actual evaporation values of the Piche evaporimeter and Class 'A' pan are very small for various regions in the country. This may also be illustrated by the following: (1) The mean annual values of the two instruments show very close agreement (Fig. 22) and similar trends in the monthly as well as seasonal phases of the curves (Fig. 23). (2) The monthly ratios of Piche to Class 'A' pan are always high for the eight selected stations in various climatic regions (Table 6). (3) Hence the correlation coefficients and percentage probabilities of these coefficients as estimated for eight representative stations reveal good relationships between the mean monthly Piche and Class 'A' pan evaporation (Table 11). It can be seen from this table that the percentage probability these coefficients could have occurred by chance is only 0.1% for seven stations. In other words these coefficients are highly significant.

Table 11

| Station | Correlation Coefficient | Percentage Probability |
| --- | --- | --- |
| Wadi Halfa (N. Sudan) | 0.75 | 1% |
| Port Sudan (NE Sudan) | 0.98 | 0.1% |
| Khartoum (North-central Sudan) | 0.90 | 0.1% |
| Kassala (E. Sudan) | 0.93 | 0.1% |
| Obeid (Central Sudan) | 0.96 | 0.1% |
| Genina (W. Sudan) | 0.99 | 0.1% |
| Malakal (S. Sudan) | 0.98 | 0.1% |
| Juba (S. Sudan) | 0.99 | 0.1% |

Source: Mean monthly values (Appendix II and Appendix III)

For the study of evaporation distribution over the entire country the Piche readings have been preferably chosen rather than the Class 'A' pan. This is mainly because the water pans are confined to a few major stations, which makes it rather difficult to construct reliable isoline maps or give a realistic picture of the water loss distribution over the Sudan. Whilst the Piche evaporimeter is more widespread at climatological stations in the country.

Sixty two stations for which Piche evaporation is available were utilized in constructing the evaporation maps (Fig. 28) and Appendix I. These stations are dispersed over most of the Sudan, except for the inhospitable mountainous areas and desert regions.

The evaporation maps in this chapter were based on average annual and monthly values calculated from the mean daily Piche readings during the period (1931-1960). These Piche values were obtained from "Climatological Normals" available from the Sudan Meteorological Headquarters in Khartoum. Other climatic elements like temperature, humidity, clouds and rainfall which are, more or less, related to evaporation distribution are also estimated for the period (1931-1960) from the same source of data.

Although averages do not represent the conditions prevailing for every month or specific year, they are a short cut to a general appraisal of the water loss over a certain period of years. Isoline patterns were constructed to fit the data. In areas where evaporation

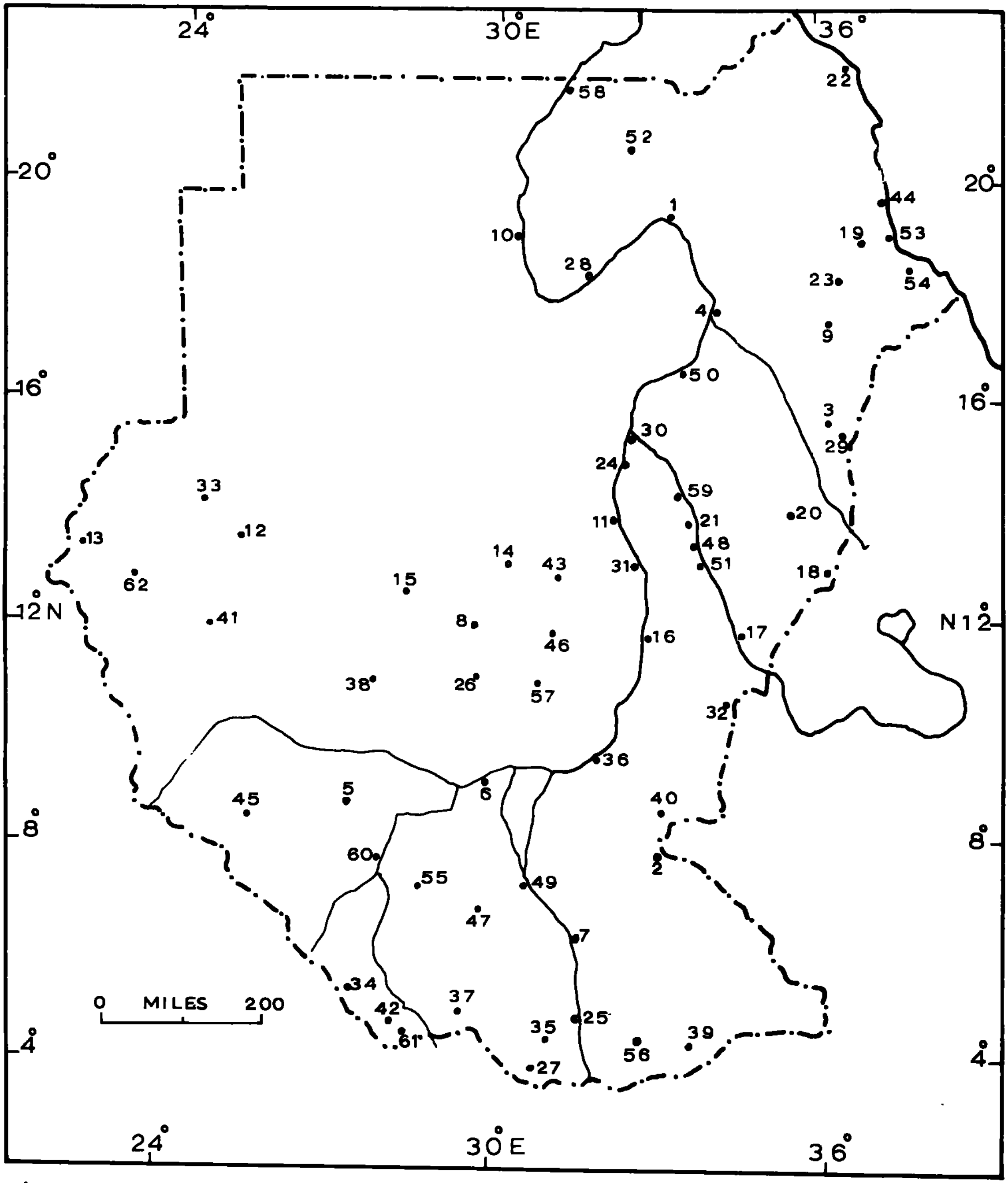
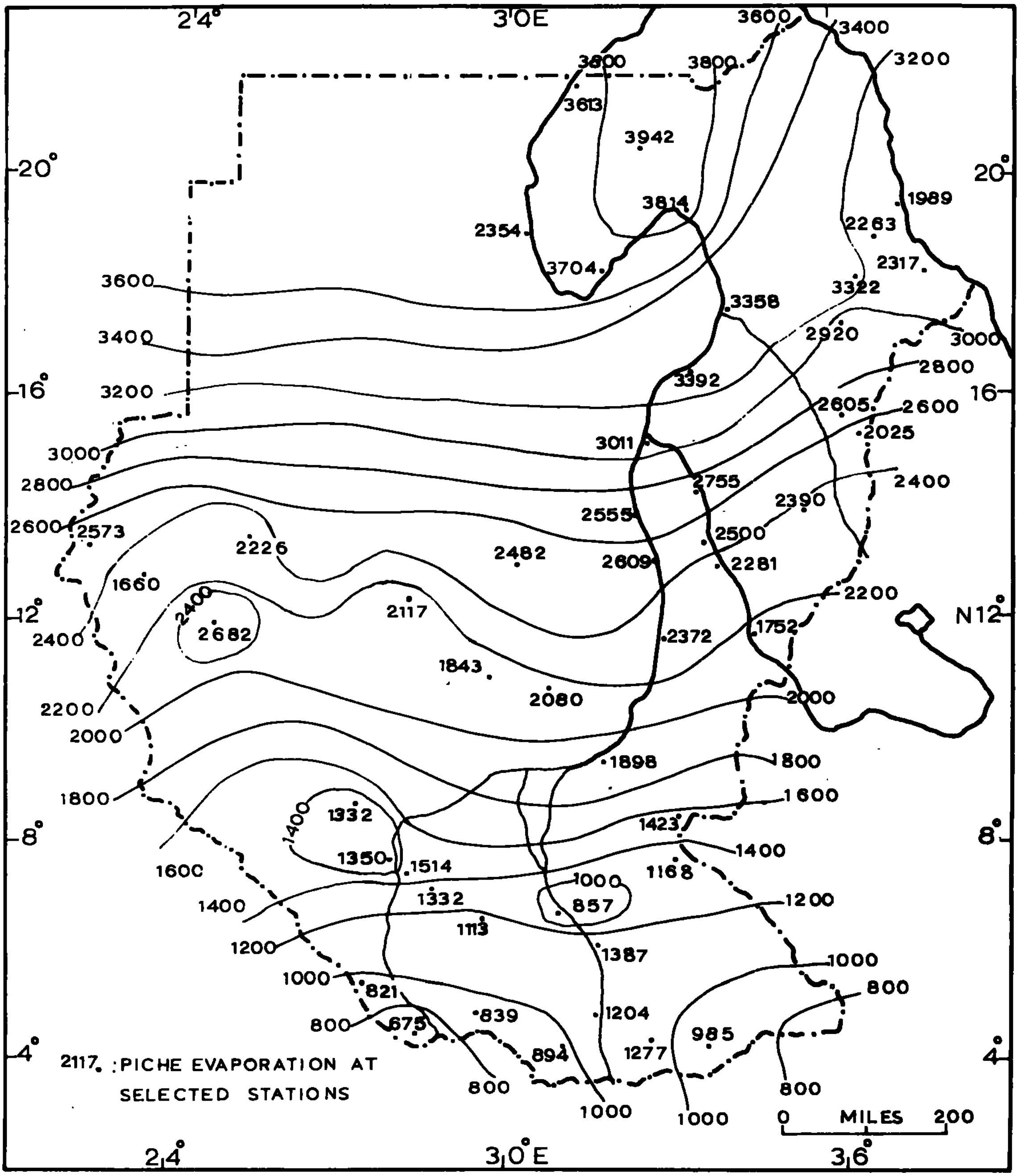



Fig. 28. Location of Piche Stations (See Appendix I)

data were limted or unavailable as in the highest parts of the country, interpolation of the isolines was guided by the relief pattern.

DISTRIBUTION OF AVERAGE ANNUAL PICHE EVAPORATION:-

The distribution of annual Piche evaporation tends to be fairly simple over most of Sudan (Fig. 29). The actual values reveal a steady decrease from 3942 mm at Station No. 6 in the vicinity of the northern border to about 675 mm recorded at Yambio in southern Sudan. The isolines tend to run rather smoothly from east to west over most of the country. This general pattern of isolines is interrupted by some relief irregularities localised mainly at the Jebel Marra region, the Red Sea hills, the Nuba Mountains and the Imatong Mountains. This is mainly because, at higher elevations, cloudiness often increases and the actual number of sunshine hours is relatively less than at low land areas. Also at higher altitudes temperatures fall (0.6°C per 100 metres), humidity often increases and, as a result, evaporation is reduced with height. Hence, the regions of marked relief will be dealt with separately in order to




SOURCE OF DATA : "CLIMATOLOGICAL NORMALS" 1931-1960, KHARTOUM MET. OFFICE - SUDAN.

Fig. 29. Average Annual Piche Evaporation Distribution

illustrate, perhaps, the role played by elevation upon the areal distribution of annual evaporation.

The relatively smooth east-west alignment of annual isolines is broken over the Jebel Marra region. Here the isolines show a tendency to run parallel to the contours, which appears to indicate the influence of elevation in this region. Unfortunately, there are no stations which measure evaporation on the summits of Jebel Marra. Nevertheless, the location of some stations away from the highest core of Jebel Marra, but on rather elevated ground, may illustrate the role of the Marra range on the annual distribution of the water loss. South west of the core, Zalingi (900 metres above sea level) registers an annual evaporation of 1660 mm which is about 40% less than the annual value of 2682 mm at Nyala (655 metres above sea level) situated further in the lowland plains to the south of Jebel Marra region. To the north of the highest part of the Jebel at Kutum, which is located on an altitude of 1160 metres, there is an annual evaporation of 2171 mm, which apparently contrasts with the annual amount of 2573 mm at El Genina (805 metres above sea level) west of the Jebel Marra region.

The topographic influences on evaporation may also be observed in the region of the Nuba mountains in southern Kordufan. This area is represented by two stations, since they are the only ones which measure evaporation. Kadugli (500 metres above sea level) lies within the hilly part of the region and has an annual evaporation of 1843 mm. On the other hand, Tozi (400 metres above sea level), which is situated on the adjoining plains, gives a value of 2080 mm., thus making a difference of 237 mm. more than the former upland station.

Over eastern Sudan, the Red Sea hills also show some indication of decreased evaporation over high altitudes as shown in figure (29). The lack of evaporation measurements in the Red Sea hills makes it rather difficult to investigate in detail the effect of altitude on the distribution of the water loss in this portion of the country. However, from the information available at Gebiet, which lies in the Red Sea hills, and Haiya, which is located at the foot of the western slopes of the Red Sea mountains, something of this effect can be seen. At Gebiet (797 metres above sea level) the annual evaporation (2263 mm) is only 68% of the total average year (3322 mm.) recorded at Haiya which is 643 metres above sea level. Further southwards from the Red Sea hills, Derudeb (509 metres above sea level) gives an annual value of 2920 mm.which is 657 mm. more than the actual value of Gebiet which is rather higher.

Another feature imposed by relief on the general distribution of annual evaporation is to be observed in the Imatong Mountains of southern Sudan which rise to a height of 3350 metres above sea level. This region like other Sudanese upland areas, is formed mainly of inselbergs of varying altitudes, separated by lower plain lands. Again evaporation stations are scarce but at Nagishot (1979 metres above sea level) the annual evaporation is reduced to 985 mm. in comparison with Torit (1277 mm.) which lies almost on the same latitude west of the Imatong mountains, but on an altitude of 625 metres above sea level.

Apart from the influence of relief, other factors such as temperature, humidity, rainfall, clouds, sunshine and wind-speed may also affect directly or indirectly the general distribution of evaporation over the whole country. But, since the detailed influence of such factors is beyond the scope of this work, the country has been divided into four main regions (Fig. 30) by taking into consideration the general distribution of mean monthly temperature, humidity and average annual rainfall. These regions may be defined roughly as follows:

(1) Region (I): Northern Sudan between latitudes $16^{o}$-$22^{o}$ north and longitudes $24^{o}$-$36^{o}$ east.

(2) Region (II): The coastal plain and part of the Red Sea hills immediately beyond the Red Sea littoral.

(3) Region (III): Central Sudan between latitudes $10^{o}$-$16^{o}$ north and longitudes $22^{o}$-$36^{o}$ east.

(4) Region (IV): Southern Sudan.

Each of these four regions will be examined individually in an attempt to show the relationship between evaporation distribution and the various influential factors during the average year.

REGION (I)

This region may be represented by four stations: Wadi Halfa, Karima and Atbara along the eastern bank of the Nile, and Station No. 6 situated in the desert, east

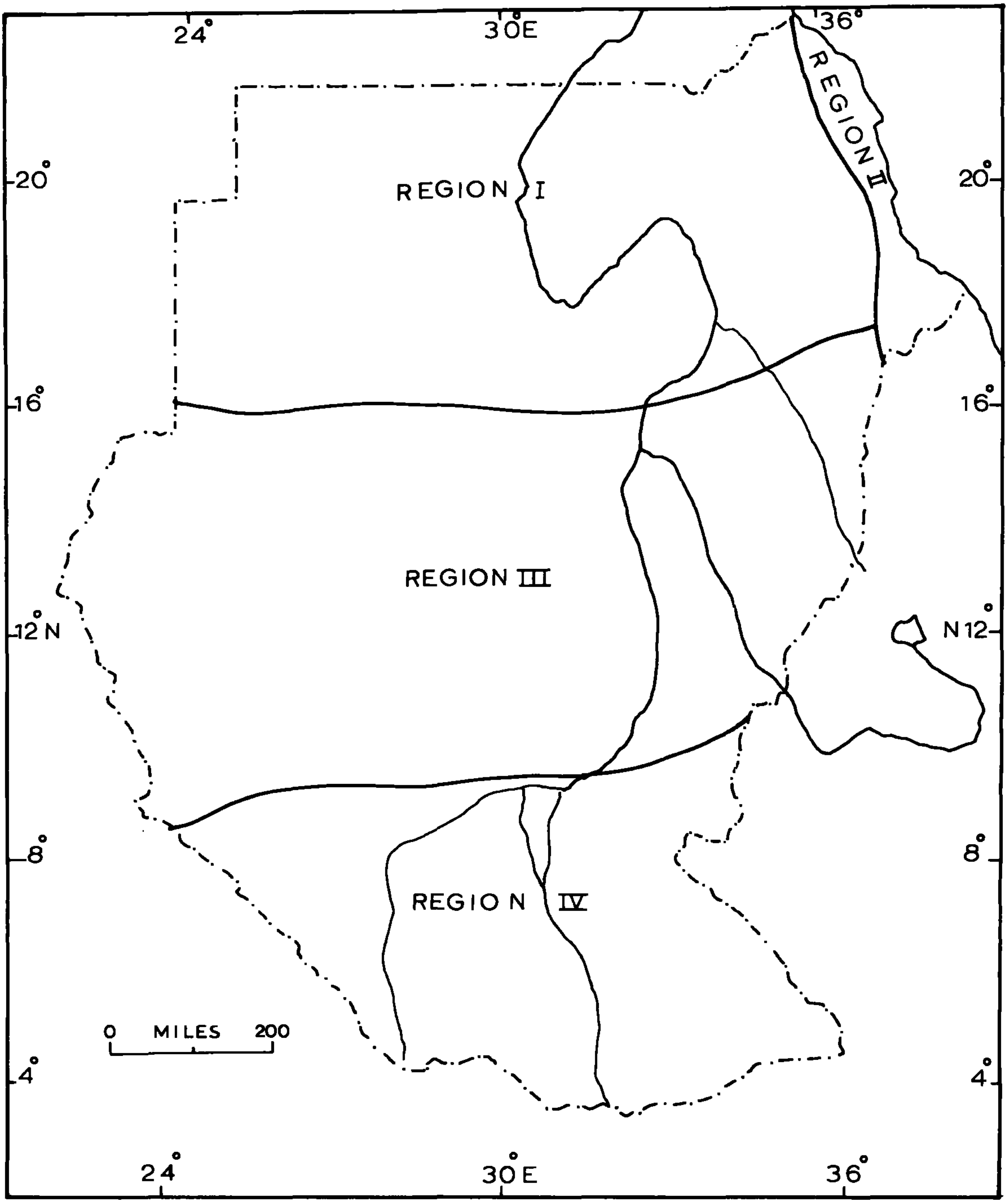



Fig. 30. Four Regions of Evaporation Distribution

of the Nile (Fig. 30). The hot dry desert, west of the Nile, is not represented since it is devoid of meteorological stations. The region as a whole, generally, experiences extremely hot dry conditions with scanty or sometimes absent rainfall and cloud amount (Table 12).

Table 12[1]

| Station | Temperature °C | Mean day R. Humidity | Mean day clouds (Oktas) | Mean annual rainfall mm | Mean annual evaporation mm |
|---|---|---|---|---|---|
| Station No. 6 | 26.4 | 21% | 0.65 | 7.0 | 3942 |
| Wadi Halfa | 26.1 | 24.7% | 1.10 | 3.0 | 3613 |
| Karima | 29.2 | 25.5% | 1.30 | 38 | 3704 |
| Atbara | 30.0 | 26.3% | 1.60 | 72 | 3358 |

Away from the Nile in the eastern desert, Station No. 6 registers the maximum evaporation value (3942 mm) in the whole country. To the north west of this station Wadi Halfa gives a lower annual value of 3613 mm. (Table 12). This difference within a short distance between the two stations may indicate either some effect imposed by the Nile to increase the humidity, or possibly the

(1) Data of tables (12-16) are compiled from, "Climatological normals" - Khartoum Met. Office - Sudan.

vegetation cover on its banks might provide some shelter from the high northerly winds. South of Karima the evaporation gradually decreases towards Atbara with the general increase of clouds, humidity and rainfall amounts (Table 12) which tend to suppress the evaporative capacity of the atmosphere to some degree.

REGION II:-

Along the coastal area the representative station (Port Sudan) shows a considerable contrast in evaporation amount with the inland stations of Region I. This is, perhaps, due to the influence of maritime air masses that may cause some cloud development and bring an increase of humidity to reduce the evaporation values along the coast. The Red Sea breeze - the diurnal movement of air from the sea to the land, caused by differential heating (Moore, 1966) - may also exert some influence on the water loss values over the coastal plain. During the day, the greater heating of the land causes the air to ascend, and relatively moist air from the Red Sea moves in to take its place. As a result, along the Red Sea coast, the humidity tends to be high and the evaporation is reduced. This reduced evaporation over the coast can be illustrated if we compare the annual value at Port Sudan (on the coast) with that of Abu Hamad, on the same latitude but about 250 miles inland from the Red Sea. It has been found that Port Sudan has an average evaporation of 1989 mm. which is almost 48% less than the actual figure at Abu Hamad station (Table 13). South of Port Sudan, Tokar (25 miles from the sea) gives an average value of 2317 mm; west of Tokar, on the same parallel, Haiya has 3322 mm. and further westwards on a similar latitude Atbara has 3358 mm. This also might show that the annual evaporation increases with distance from the coast as a result of the combined effects of lower humidities, clearer skies and greater temperatures at these inland stations (Table 13).

Table 13

| Station | Temperature °C | Mean day R. Humidity | Mean day clouds (oktas) | Mean annual rainfall mm | Mean annual evaporation mm |
|---|---|---|---|---|---|
| Port Sudan | 28.6 | 63% | 2.8 | 110 | 1989 |
| Abu Hamad | 29.3 | 21.7% | 1.7 | 17 | 3814 |
| Tokar | 28.3 | 53% | 3.2 | 88 | 3317 |
| Haiya | 29.9 | 36.5% | 1.7 | 89 | 3322 |
| Atbara | 30.0 | 23% | 1.6 | 72 | 3358 |

REGION III:-

The distribution of annual evaporation in this region is likely to follow a pattern contrary to the rainfall regime experienced over some parts of central Sudan. This feature may be illustrated by comparing annual evaporation values with the corresponding rainfall figures received at contrasting stations such as Gedarif, ED Duem and Kutum which have annual rains of 614 mm., 340mm. and 320 mm. respectively. These three stations lie on almost the same latitude. In the extreme east Gedaref has an annual evaporation of 2390 mm., whilst Ed Duem in the centre has a mean annual evaporation of 2555 mm., and Kutum in the west has a mean annual value of 2171 mm. Further north of Gedaref, at Kassala near the eastern border (341 mm. of rainfall), there is a mean annual evaporation of 2025 mm. On the other hand Khartoum (164 mm. of rainfall) on the same latitude west of Kassala, registers an annual evaporation of 3011 mm., which is equivalent to about 1.5 times as much as the evaporation at Kassala. This general east-west increase in annual evaporation can probably be related to the declining rainfall further westwards over these particular areas of central Sudan.

Another feature of the evaporation distribution in this region is observed along the Blue Nile where the annual results show very remarkable variations of the following order. At Wadi Medani (lat. $14^{\circ}$ 24' north) the annual value is 2755 mm., at Sennar (lat. $13^{\circ}$ 33' north) it is 2500 mm., at Singa (lat. $13^{\circ}$ 09' north) it is 2281 mm. These stations reveal a rapid decrease of mean annual evaporation southwards following the increase in cloud amount and the rise in rainfall and mean relative humidity (Table 14).

Table 14

| Station | Mean day clouds (oktas) | Mean day R. Humidity | Mean annual Rainfall mm | Mean annual evaporation mm |
|---|---|---|---|---|
| Wad Medani | 2.3 | 33.7% | 373 | 2755 |
| Sennar | 2.6 | 38.5% | 481 | 2500 |
| Singa | 2.7 | 43.0% | 588 | 2281 |
| Roseries | 3.0 | 47.7% | 776 | 1752 |

Further west of the Blue Nile and along the White Nile, the annual evaporation also tends to display a reverse pattern to the rainfall distribution. Here the average annual rainfall increases from about 406 mm. at

Kosti (lat. $13^{0}$ $10^{-}$ north) to over 525 mm. at Renk (lat. $11^{0}$ $45^{-}$ north) situated further southwards along the eastern bank of the White Nile. However, the annual evaporation diminishes from 2609 mm. at the former to about 2372 mm. at the latter station.

REGION IV:

This region is one of the most humid parts of the country, and it experiences a very long wet season (seven to nine months) and a rather short dry season (three to five months). Part of this region is occupied by the "Sudd region", which is an extensive area lying approximately between latitudes $5^{o}$-$10^{o}$ north and longitudes $30^{o}$-$40^{o}$ East. This Sudd region (represented by Shambe) is relatively more humid than the adjoining lands south of Malakal and east of $32^{o}$ East (represented by Akobo) and west of $30^{o}$ East (represented by Tonj). Although these three representative stations lie on nearly the same latitude as well as altitude, there is a marked difference between them with respect to the average annual evaporation. To the east of the Sudd region, Akobo has a mean annual evaporation of 1168 mm., Shambe in the centre has 857 mm., and Tonj in the west of the region has a mean annual value of 1514 mm. (Table 15). Although Shambe receives the least rainfall and cloud amounts and the highest temperatures, it gives the lowest evaporation value in comparison with Tonj and Akobo. This can be ascribed to the more humid conditions at Shambe compared with the other two stations (Table 15). Unfortunately, the low density meteorological network within or outside the Sudd region, as well as the unavailability of Piche records for many of the existing stations makes it rather difficult to proceed with further analyses in this respect.

Table 15

| Station | Lat. N | Altitude (metres) | Temp, (°C) | Mean day R. Humidity | Mean day clouds (oktas) | Mean annual Rainfall (mm) | Mean annual Evaporation (mm) |
|---|---|---|---|---|---|---|---|
| Akobo | 7° 47' | 400 | 27.5 | 58.5% | 5.0 | 784 | 1168 |
| Shambe | 7° 07' | 405 | 28.1 | 77% | 4.8 | 736 | 857 |
| Tonj | 7° 16' | 433 | 26.9 | 54.5% | 6.0 | 1014 | 1514 |

For the area just south of latitude 5° north, the evaporation distribution seems to be influenced by the Trade winds (SW and SE), which tend to distort the general east-west pattern of isolines over southern Sudan (Fig. 29). These Trade winds cause clouds and heavy rainfall for most of the year. The temperatures are somewhat reduced and the humidities are considerably increased under such moist conditions. As a result, the potential water loss is suppressed over this part of southern Sudan. Hence, if the area south of latitude 5° north is represented by Yambio, Loka and Torit, which lie almost on the same latitude (Table 16), contrasts in the average annual evaporation are evident. In the west Yambio has a mean annual evaporation of 675 mm., Loka in the centre has 894 mm. and Torit in the east has an annual value of 1277 mm. This eastward evaporation increase can be associated, to some extent, with the relative decrease in mean annual rainfall, cloudiness and relative humidities together with the increasing temperatures from Yambio to Torit (Table 16).

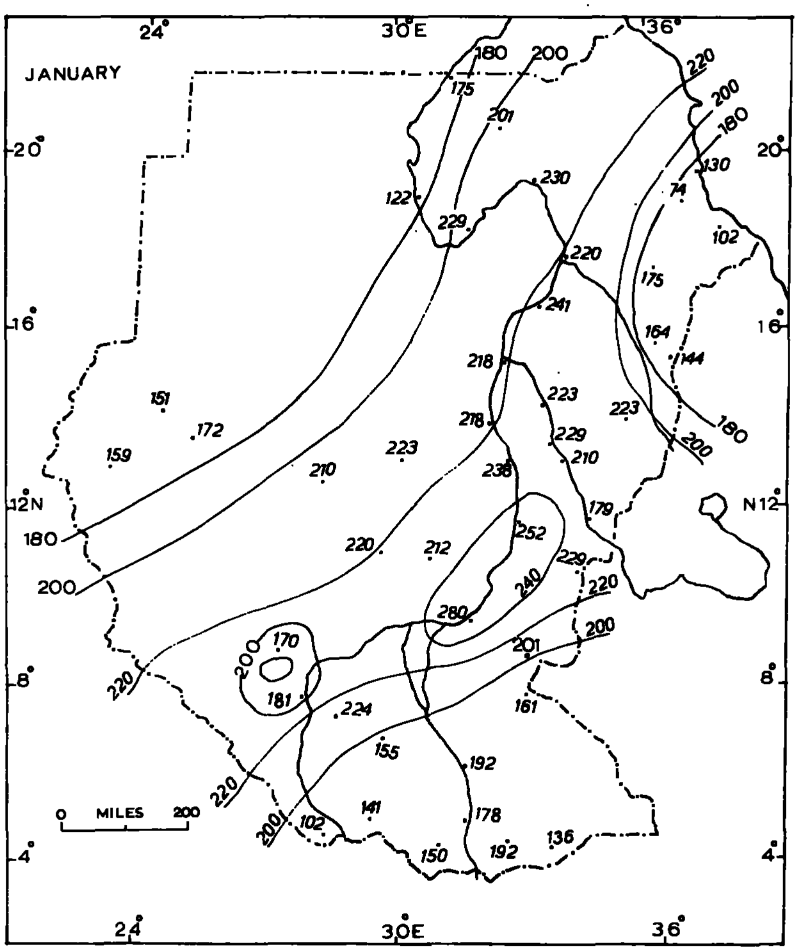
Table 16

| Station | Lat. N | Temp. °C | Mean day R. Humidity | Mean day clouds (oktas) | Mean annual Rainfall (mm) | Mean annual Evaporation (mm) |
|---|---|---|---|---|---|---|
| Yambio | $4^{\circ}$ 34' | 24.6 | 70% | 5.1 | 1512 | 675 |
| Loka | $4^{\circ}$ 15' | 25.0 | 65% | 4.5 | 1284 | 894 |
| Torit | $4^{\circ}$ 25' | 26.9 | 56% | 3.9 | 994 | 1277 |

Further inland, north of Yambio and west of $30^{\circ}$ east, the south west Trades start to lose some moisture and as a result the cloud amount, rainfall and humidity tend to decrease, whilst temperatures seem to rise in comparison with the southern border. The annual evaporation, therefore, is inclined to increase from 675 mm. at Yambio (Lat. $4^{\circ}$ 34' north) to 1332 mm. at Busseri (lat. $7^{\circ}$north) and it increases further northward at Aweil (lat. $9^{\circ}$ north), which has an annual value of 1350 mm.

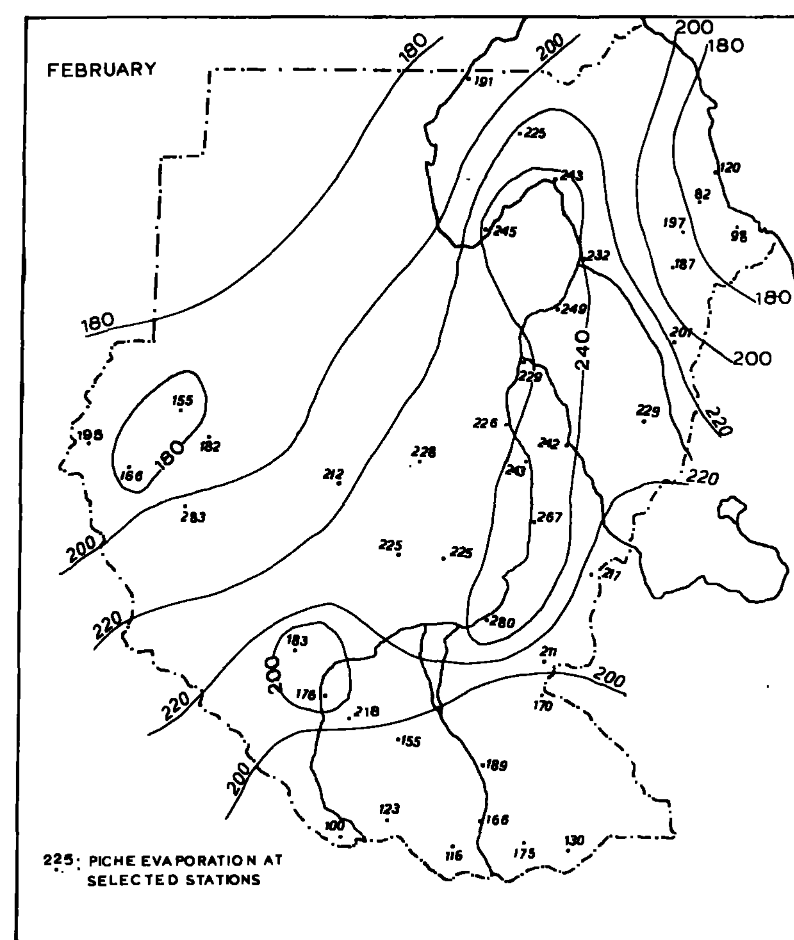
DISTRIBUTION OF AVERAGE MONTHLY AND SEASONAL PICHE EVAPORATION:-

In January and February which represent the cool dry winter (under 50 mm. of rainfall), the Piche evaporation generally decreases from central Sudan towards northern Sudan, north of latitude $20^{\circ}$ north, and southern Sudan, south of latitude $8^{\circ}$ north (Figs. 31 and 32). This decline of evaporation towards the north and south may be closely related to the gradual decrease of temperature over the north (Fig. 7) and the relative increase of humidity over southern Sudan (Fig. 11) during the winter season. But in the western half of northern Sudan the




SOURCE OF DATA: SAME AS FIG. 29

Fig. 31. January Piche Evaporation Distribution



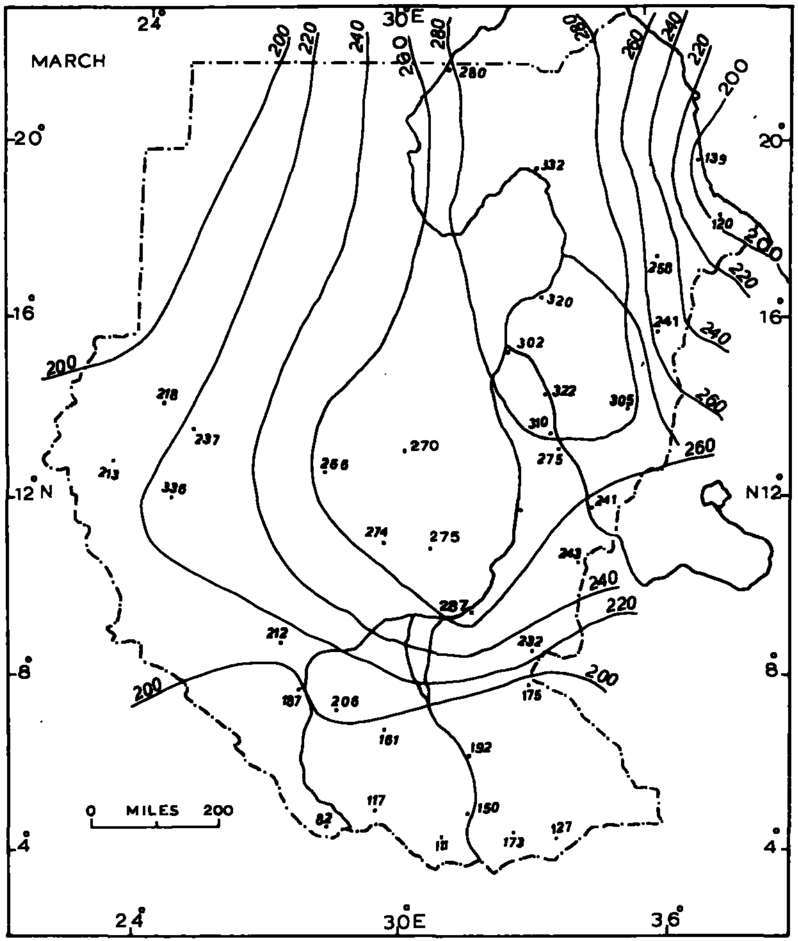

SOURCE OF DATA: SAME AS FIG. 29

Fig. 32. February Piche Evaporation Distribution

evaporation tends to decrease towards the north west under lower temperature conditions during the invasion of cool dry Saharan air to the northern border of the country. In the Red Sea region, which receives 50 to 100 mm. of rain in January, the evaporation tends to decrease eastwards as a result of higher humidities and cloudiness over the hills and the coastal area. To the south of the Red Sea hills, the adjoining plains have relatively more evaporation owing to the warming effect of tropical continental air masses of the Arabian anticyclone. South of latitude $8^{o}$ north, the evaporation (under 200 mm.) decreases southwards towards the southern border of the country. This is the only portion of the Sudan (except the Red Sea region) which receives a little rain of over 50 mm., and higher humidities of more than 40% (Fig. 11). The area of highest evaporation (over 240 mm.) during the two winter months, is localized mainly along the Malakal-Renk region in January (Fig. 31) but extends further north as far as the latitude of Abu Hamad in February (Fig 32). Most of this area is considered to be fairly dry and with relatively high temperatures during the winter season (Fig. 7).

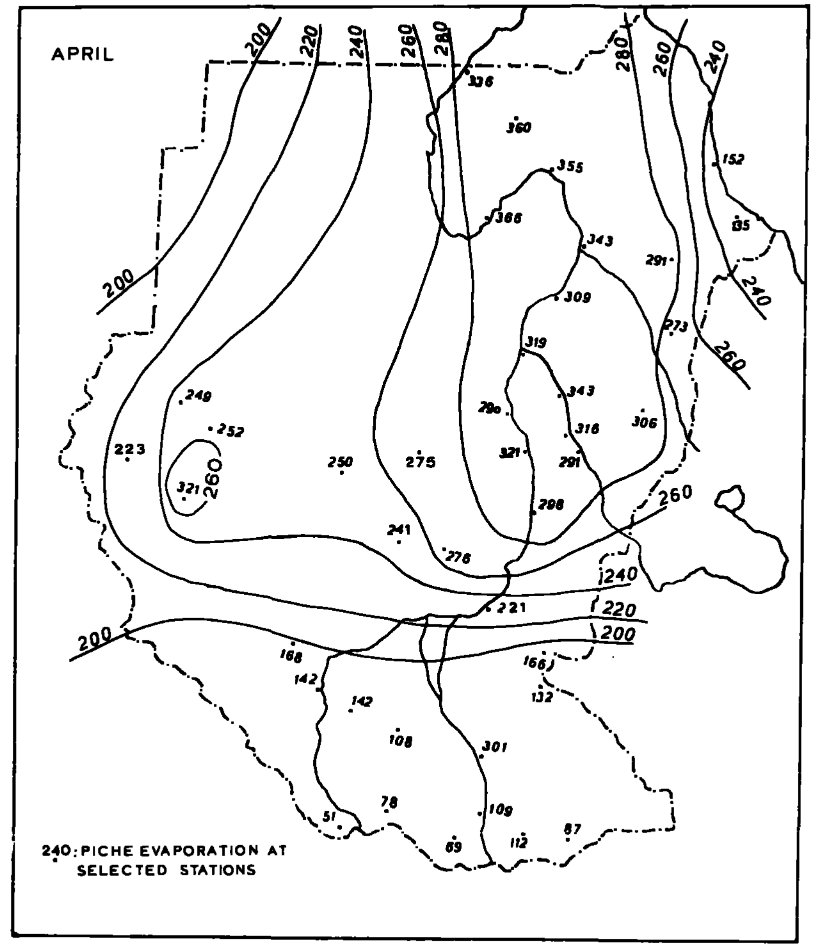
By March, the country is still mostly dry (less than 50 mm. of rainfall) except for the extreme south (50-100 mm.) and south east which receives over 100 mm. of rains in this month. The region of highest evaporation (over 280 mm.) shifts northwards to the area located roughly between latitudes $13^{\circ}$-$22^{\circ}$ north and longitudes $32^{\circ}$-$35^{\circ}$ east in northern and central Sudan (Fig. 33.). Away from this region, evaporation decreases considerably from over 280 mm., to less than 200 mm. in the remaining parts of the country, particularly in southern Sudan.

April represents the transitional period between the winter and rainy seasons. In this month, the region of highest evaporation (over 280 mm.) has expanded considerably from its previous position in March towards the eastern parts of northern and central Sudan, and also westwards as far as longitude $31^{\circ}$ East. Its southern extent is delimited by Renk beyond latitude $12^{\circ}$ north (Fig. 34). This region coincides roughly with the region of high temperatures and dry conditions (under 50 mm. of rainfall) in the month of April. To the east of this region (over the Red Sea zone) the temperatures decrease



SOURCE OF DATA: SAME AS FIG.29

Fig. 33. March Piche Evaporation Distribution



SOURCE OF DATA: SAME AS FIG.29

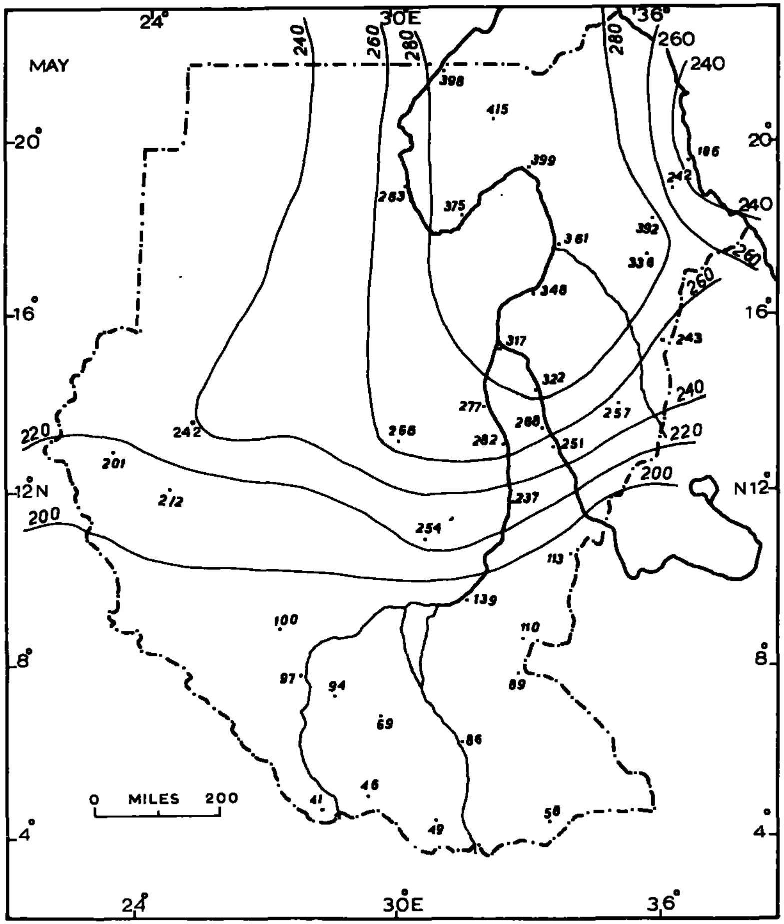
Fig. 34. April Piche Evaporation Distribution

from 28°C in the plains west of the Red Sea hills to less than 26°C over the coastal area (Fig. 8), and the humidities increase from 25% to 40% (Fig. 12). As a result, the evaporation values tend to decrease accordingly towards the Red Sea coast as represented by Port Sudan, which has only 152 mm. of evaporation during this month. West of longitude 32° east in northern and central Sudan, the evaporation tends to decrease westwards as illustrated by figure 34. This general evaporation decrease towards the east and west during this month, however, may be ascribed to relatively lower temperature conditions in these parts of the country (Fig. 8).

South of latitude 10° north the evaporation decreases from over 240 mm. to less than 100 mm. in the extreme south represented by Loka (69 mm.) and Yambio (51 mm.). This substantial reduction of evaporation opportunity in southern Sudan is mainly attributed to cooler temperatures (Fig. 8) and higher humidities (Fig. 12) in comparison with other parts of the country. Also over most of southern Sudan, April can be regarded as a cloudy and wet month (50-200 mm. of rainfall), compared with the vast area north of latitude 8° north.

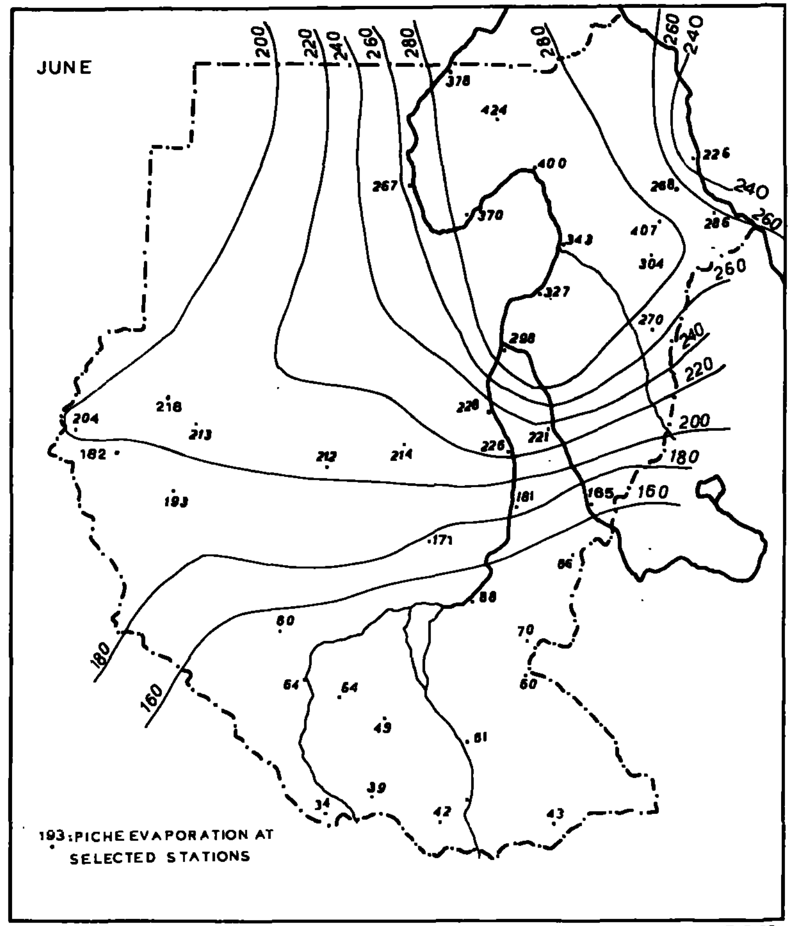
During May most of northern and central Sudan (north of latitude 14° north) has the highest evaporation values, especially over the area east of 31° East, which experiences rather hot and arid conditions (rainfall under 50 mm.). Between latitudes 14° north and 10° north the evaporation generally diminishes southwards from over 240 mm. to about 200 mm. (Fig. 35). South of latitude 10° north, all the stations receive between 100 mm. and 200 mm. of rain, which may produce more humid conditions over this part of the country. As a result in southern Sudan (south of latitude 10° north) the evaporation declines from almost 200 mm. to less than 60 mm. near the border as represented by Nagishot and Maridi, which have evaporation values of 58 mm. and 46 mm. respectively.

By the month of June most of the country is under the 200 mm. evaporation isoline as shown in figure 36. North of the 200 mm. isoline the evaporation seems to rise sharply towards northern Sudan. Over the western part of northern Sudan, it decreases from over 280 mm. at 31° east to less than 200 mm. along the western




SOURCE OF DATA: SAME AS FIG.29

Fig. 35. May Piche Evaporation Distribution

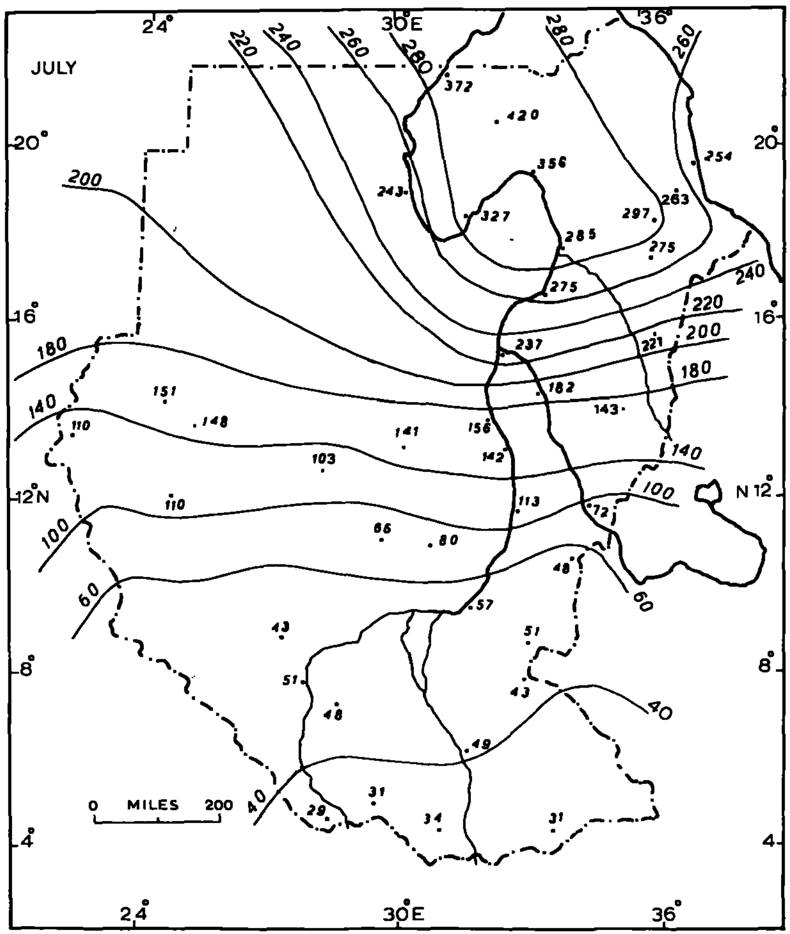



SOURCE OF DATA: SAME AS FIG.29

Fig. 36. June Piche Evaporation Distribution

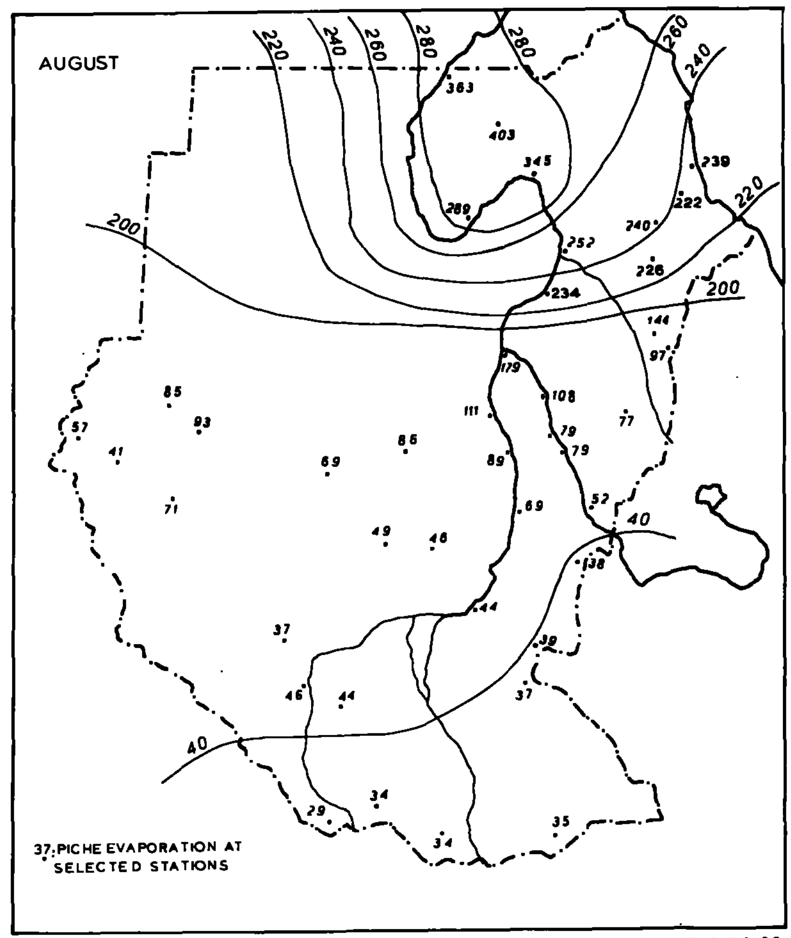
frontier. East of northern Sudan it also decreases from 280 mm. east of the Nile, to less than 240 mm. along the Red Sea coast. South of the 200 mm. isoline the evaporation decreases gradually to less than 40 mm. in the extreme south of the country (Fig. 36). This can be illustrated by the case of Maridi, which has an evaporation of 39 mm. and Yambio which has 34 mm. in June.

In July, which represents the rainy season that covers the whole country, most of the Sudan experiences lower evaporation values of under 200 mm. (Fig. 37). But, north of latitude 16$^{o}$ north, the evaporation starts to increase towards the Atbara-Karima-station No. 6 area in the dry northern Sudan where the values go beyond 280 mm.(Fig.37). This area coincides roughly with the area of highest temperatures of 34$^{o}$C (Fig. 9) and relative humidities which are less than 30% (Fig. 13). Taking the whole country, with special reference to the Nile basin, the evaporation generally diminishes considerably from north to south. This feature can be illustrated by these cases: Wadi Halfa (lat. 21$^{o}$ 50$^{-}$ north) which




SOURCE OF DATA: SAME AS FIG.29

Fig. 37. July Piche Evaporation Distribution




SOURCE OF DATA: SAME AS FIG.29

Fig. 38. August Piche Evaporation Distribution

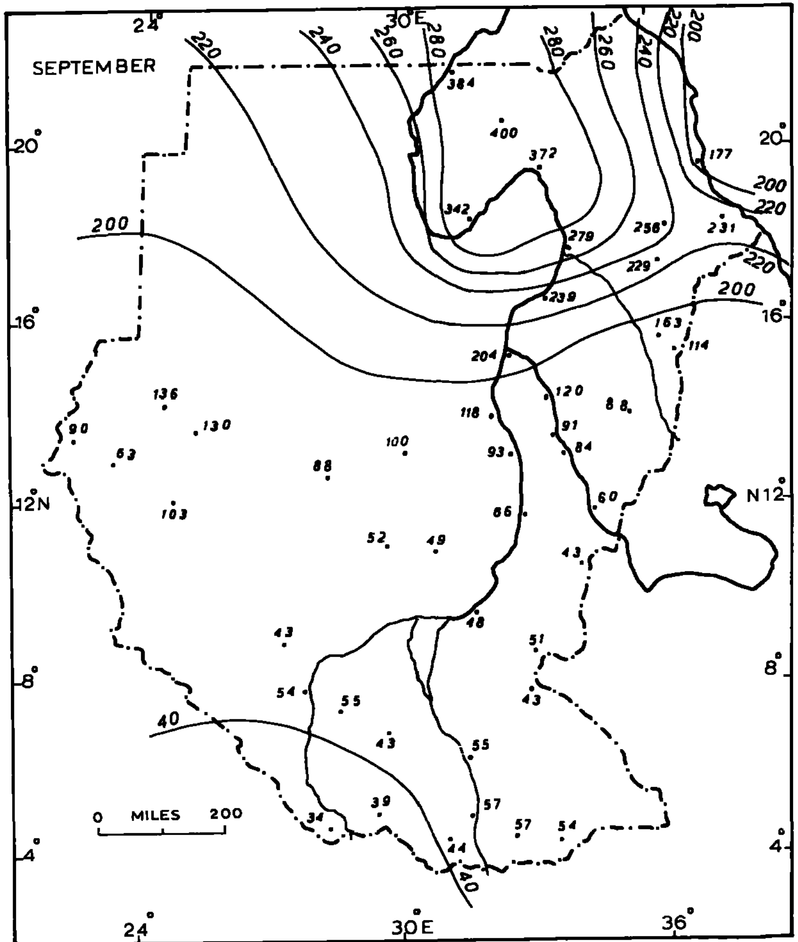
has 372 mm., Khartoum (lat. $15^{\circ}$ 36' north) has 237 mm. Kosti (lat. $13^{\circ}$ 10' north) has 142 mm., Malakal (lat. $9^{\circ}$ 33' north) has 57 mm. and Loka (lat. $4^{\circ}$ 15' north) in the extreme south registers only 34 mm. in this month. The temperatures in July also decrease considerably from 33°C at Wadi Halfa in the north to 23°C at Yambio in the south (Fig. 9), whilst relative humidity, on the other hand, increases from about 20% in the dry north to over 80% in southern Sudan (Fig. 13).

Over central Sudan (west of the White Nile) the evaporation in July tends to decline westwards owing to cooler temperatures (Fig. 9) and higher humidities (Fig. 13) together with larger rainfall over western Sudan. This case can be illustrated by the stations Kosti, En Nahud and Zalingi which lie almost on the same latitude. Kosti, which is located along the western bank of the White Nile, has an evaporation of 142 mm., En Nahud in the centre has 103 mm. and Zalingi in the extreme western Sudan has only 69 mm. in this month. Whilst east of the Blue Nile, evaporation varies from 237 mm. at Khartoum to 141 mm. at Kassala, in the same latitude but lying near the eastern border of the country.

This eastwards reduction in evaporation, illustrated by these two stations, may indicate also the influence of humid conditions (Fig 13) and higher rainfall that occurs in eastern Sudan particularly after the commencement of Trade winds during the rainy season.

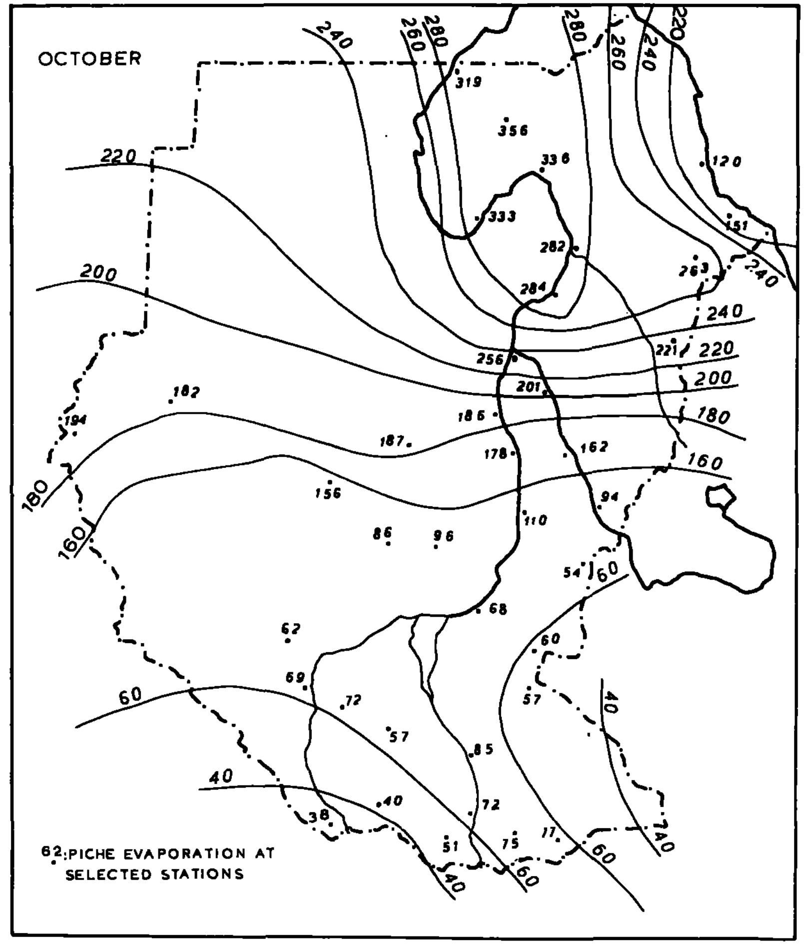
The evaporation distribution in August, the rainiest month, seems to follow a similar pattern to July conditions. But in this month, the evaporation isolines shift from their July position even further north across the country. In northern Sudan (north of latitude 16° north), evaporation increases rapidly from about 200 mm. to over 280 mm. in the Wadi Halfa-Karima-Abu Hamad area, which experiences relatively high temperatures and dry conditions in August. But the evaporation tends to diminish towards the west and east of this area (Fig. 38). South of latitude 16° north, the largest sector of the country lies almost under the 200 mm. isoline in this month, and, further south of this isoline, evaporation decreases to less than 40 mm. over the southern border of Sudan.

In September northern Sudan still has the highest evaporation compared with the rest of the country (Fig. 39). But the values steadily decrease from this area towards cooler conditions in the west (under 220 mm.) and more humid conditions in the coastal area, represented



SOURCE OF DATA: SAME AS FIG.29

Fig. 39. September Piche Evaporation Distribution



SOURCE OF DATA: SAME AS FIG.29

Fig. 40. October Piche Evaporation Distribution

by Port Sudan which registers 177 mm. during this month of September. From the area of highest evaporation, the values tend to decrease southwards, thus following the rapid retreat of the rainy season towards the southern frontier.

Following the end of the rains in September, the month of October may represent the hot dry spell (October-November) which is experienced between the rainy season and cool dry winter. By October the evaporation decreases from over 280 mm. in the north to less than 60 mm. in the extreme south of the country (Fig. 40). Over most of northern Sudan, which is arid and less humid (under 30%) in this month (Fig. 14), the actual evaporation values are often above the 240 mm. isoline. Over the centre of northern Sudan, Station No. 6, Abu Hamad, and Karima give the respective figures of 365 mm., 336 mm. and 333 mm. which are considered to be the highest values recorded in this month, (Fig. 40). The possible reason for such high values is the higher temperatures of 30$^{o}$ to 32$^{o}$C (Fig. 10) and the larger number of sunshine hours plus high wind speeds which may add to the magnitude of evaporation in this region. The coastal area, on the other hand, seems to contrast sharply with the zone of highest evaporation. This coastal area is influenced by the moist air drawn in from over the Red Sea and its humidity therefore, rises to over 40% (Fig. 14). As a result evaporation tends to be lower over the coastal plain as compared with the inland areas on the same latitude. This can be illustrated by the case of Port Sudan (on the coast) which registers 120 mm. which is less than half the amount recorded at Abu Hamad (336 mm.) at the same latitude but further inland.

Over central Sudan, the water loss in October ranges from more than 200 mm. about latitude 15° north to less than 160 mm. southwards along latitude 12° north (Fig. 40). In this part of the country, the evaporation isolines tend to run roughly from east to west over the lowland plains. This regular run of isolines is broken mainly at the Nuba mountains whose relatively higher rainfall (over 100 mm.)(1) and lower temperature conditions help to suppress the values of evaporation. This case can be demonstrated by Kadugli, on the mountains,

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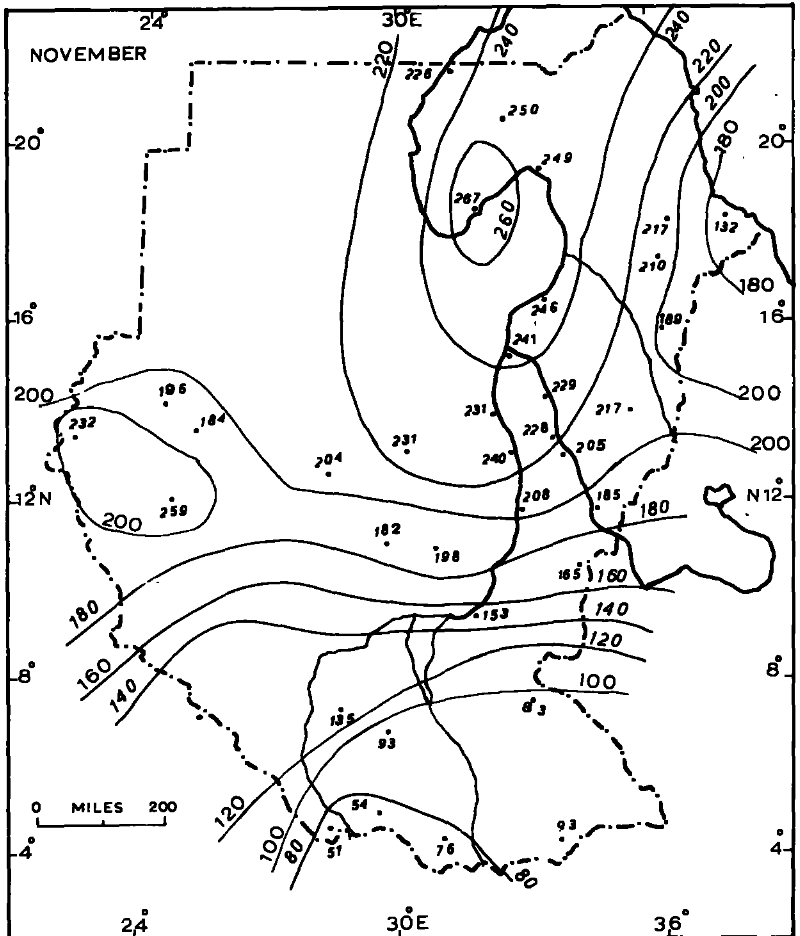
(1) "Some Aspects of the Annual and Monthly Rainfall over the Sudan" - M.A. Thesis by M.A. El-Tom (1966), Geography Department of Durham University.

which gives a lower evaporation value (86 mm.) than Tozi (96 mm.) almost on the same latitude but located in the adjoining plains. Further west of the Nuba mountains, the Jebel Marra region displays similar influences on the isolines and evaporation values. Over Jebel Marra, Kutum and Zalingi register evaporation of 182 mm. and 111 mm. respectively in October, which is comparatively less than Fasher (198 mm.) east of the Jebel, and Nyala (193 mm.) to the south west of the highest core of the Jebel Marra region.

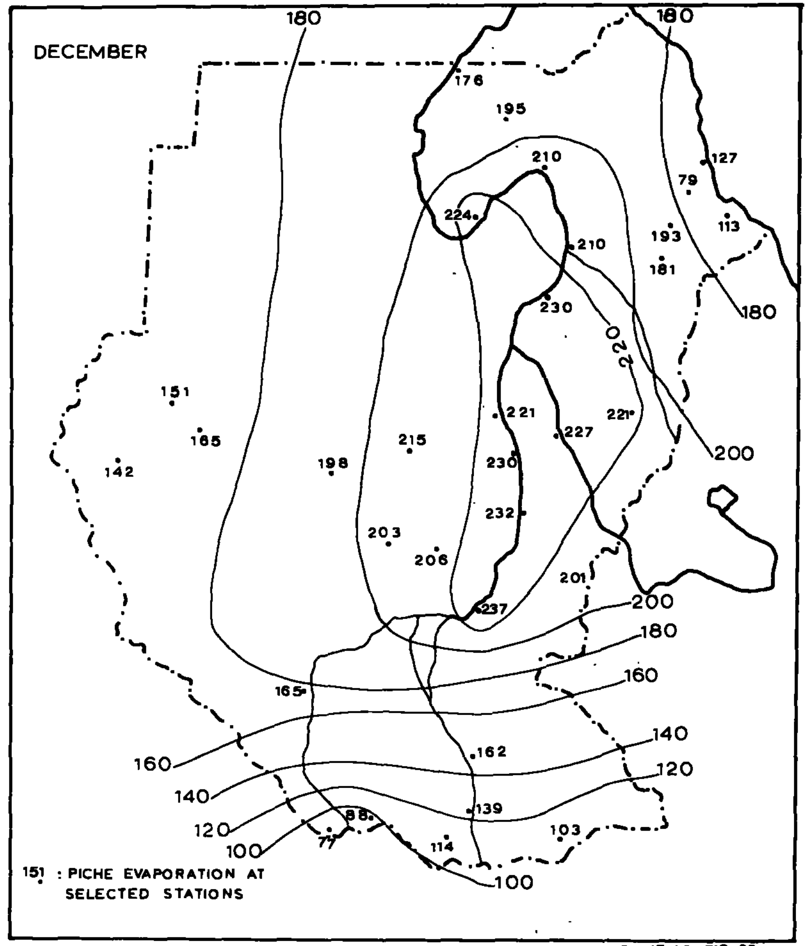
Figure 40 also reveals that south of the isoline 160 mm., the evaporation decreases considerably southwards to less than 40 mm. in the extreme south western and south eastern parts of the country.

The conditions in October are continued into November, but, during the latter month, the 200 mm. isoline seems to divide the country into two similar parts. In the southern part evaporation ranges from over 200 mm. to less than 80 mm. (Fig. 41). North of the isoline, the evaporation increases to over 260 mm. as illustrated in figure (41). By November the highest evaporation (over 260 mm.) is confined to the area




SOURCE OF DATA: SAME AS FIG.29

Fig. 41. November Piche Evaporation Distribution




SOURCE OF DATA: SAME AS FIG. 29

Fig. 42. December Piche Evaporation Distribution

around Karima, which experiences relatively high temperatures and dry conditions in this month. Outside this area the evaporation values progressively decline to less than 200 mm. where the weather conditions are comparatively more humid or less hot during this part of the year.

In December, which represents early winter, the water loss is lower over the entire country as compared to November. The region of highest evaporation (over 220 mm.) extends to the south as far as Malakal (Fig. 42). From this area, the values diminish towards northern, western and eastern Sudan where climatic conditions are likely to be cooler during December. Along the Nile valley, on the other hand, the water loss tends to rise steadily from Wadi Halfa to Malakal in accordance with the decrease in the relative humidity from 38% at the former in the north to 27% at the latter station in the south. This can be illustrated by the values of the following selected stations: at Wadi Halfa (lat. 21° 50' north) December evaporation is 176 mm., at Atbara (lat.17° 42' north) it is 210 mm., at Kosti (Lat. 13° 10' north) it is 230 mm. and at Malakal (lat. 9° 33' north) it is 237 mm. South of Malakal, where the humidity is higher, evaporation values are somewhat reduced below the 200 mm. isoline. In the extreme south west, which is relatively more humid and wet (rainfall is 50-100 mm.) the water loss is even less than 100 mm. in this month of December (Fig. 42).

However, it can be seen from the foregoing discussion of evaporation maps that, in some cases, the monthly isolines seem to behave in a similar manner to the annual isolines and run roughly along latitudes from east to west. This pattern, however, is only slightly influenced by topographic factors.

## CONCLUSION

It has been shown that the measured evaporation from Piche evaporimeters tends to agree fairly closely with the Class 'A' pan values at certain selected stations in the Sudan. Both the Piche and Class 'A' pan evaporimeters respond to climatic factors prevailing in different parts of the year, but the exact effect that individual factors have on such instruments is not clearly known. In view of the seasonal climatic rhythm over the Sudan, it has been found that the measured water loss shows fluctuations in sympathy with the contrasts between the wet and dry seasons. On the other hand, there seem to be some anomalies to this pattern which are difficult to explain.

In addition to responding to broad climatic factors, each of these instruments is affected by conditions of local exposure. In order to permit a comparison of the observations from installations in different regions in the Sudan, it is important that such evaporimeters be maintained so that the differences which are noted from one station to another can be definitely ascribed to climatic differences as opposed to differences in operating procedure or local exposure.

It has been emphasized that average annual calculated potential evapotranspiration is lower than the Piche and Class 'A' pan evaporation for all representative stations in northern and central Sudan, whilst in the extreme south, the computed (PE) is found to be greater than the measured values. In monthly terms, the (PE) is generally less than the observed evaporation during the dry season, and slightly larger than the measured water loss during the rainy season for most selected stations. As a result of these contrasts, the mean monthly measured evaporation and estimated (PE) show descrepancies both in the individual monthly values as well as the seasonal phases of the year. The greatest discrepancy occurs in the dry season but tends to be relatively less marked during the wet season. Despite these differences, the measured curves bear a marked resemblance to that of potential evapotranspiration for most selected stations. Nevertheless, the actual water loss displays larger fluctuations as compared to the (PE).

Although Thornthwaite's method has been applied satisfactorily for some climatic regions in the world it is perhaps unsuitable under certain Sudanese climatic conditions especially those with very marked variations in the humidity and rainfall regimes. One of the countries where Thornthwaite's method was found to be rather unsatisfactory was Nigeria. Garnier (1956) found that it underestimated measured evapotranspiration during the dry season at Samaru in Northern Nigeria. He attributed the disparity between measured and computed (PE) to the effects of an extremely dry atmosphere.

The Penman formula, however, tends to provide larger values than the Class 'A' pan or Piche evaporimeter in the wet season, whilst in the dry season the (EO) is below the measured evaporation. This suggests the tendency of Penman's equation to overestimate in relative terms the measured evaporation in the wet season and underestimate it during the dry season. Over southern Sudan, on the other hand, the measured evaporation indicates that the tendency for the Penman formula to underestimate during the dry months is less anomalous than the overestimation in the wet months. This interrelationship between the measured evaporation and computed (EO) was also illustrated by mean monthly ratios between the two over the country. The monthly and seasonal fluctuations in the measured evaporation, as indicated in the text, are rather large compared with the computed (EO) which reveals relatively smaller variations throughout the year.

The lack of sympathy between the Penman formula and measured evaporation, on the other hand, is more difficult to explain. The causes of possible errors in measured evaporation have been discussed in the text. In the case of the formula, it may be that the approximations which have been made concerning, in particular, sunshine values for radiation may be inadequate for the climatic regime of the Sudan. It would be interesting to have a check on some of these values if net radiation data becomes available in the future.

The method of regression analyses applied in the text was utilised to detect, perhaps, the possible correlation between the calculated and measured water loss at selected Sudanese stations. It has been illustrated that the former tends to indicate very high positive correlation with the latter under arid conditions particularly in the northern parts of the country.

But, surprisingly, the degree of correlation between the two seems to lose its statistical value under the more humid conditions of southern Sudan.

But, despite the drawbacks and disadvantages of the Penman and Thornthwaite formulae, they may estimate the water loss from meteorological data with some degree of accuracy. For practical purposes in the country, the (PE) seems preferable to (EO) owing to the simplicity of calculating the former for every station where the measurement of air temperature is made. Fortunately some apparently satisfying estimates of both the (EO) and (PE) were obtained for arid and semi-arid regions in the country where the problem of water loss to the atmosphere is most crucial.

The distribution of average annual and monthly Piche evaporation is partly controlled by topographic features in the country. There is in the Sudan a general decrease of evaporation with increasing elevation particularly over the Nuba mountains, Jebel Marra region and the Red Sea hills.

However, climatic elements such as temperature, humidity, rainfall, cloudiness, sunshine and wind exert the dominant influence on the distribution of

Piche evaporation during the different seasons of the year. Maximum evaporation is almost coincident with the dry season and, with the progress of this season towards the rainy season, the values tend to decline accordingly. Other factors which might affect the actual water loss distribution such as soil types, soil moisture conditions, and vegetation have not been fully discussed.

It remains for future investigations to deal with more localised aspects of water loss and their relationships with the overall water balance in selected areas. Then maximum benefits could be obtained from the available water resources, which are in great demand for human and animal consumption as well as agricultural development in many parts of the Sudan.

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Table of Appendices

## Appendix I

## Index of the Stations used in this work

1. Abu Hamad
2. Akobo
3. Aroma
4. Atbara
5. Aweil
6. Bentu
7. Bor
8. Dalleng
9. Derudeb
10. Dongola
11. Ed Duem
12. El Fasher
13. El Genina
14. El Obeid
15. En Nahud
16. Er Renk
17. Er Roseires
18. Gallabat
19. Gebeit
20. Gedaref
21. Hag Abdalla
22. Halaib
23. Haiya
24. Jebel Aulia
25. Juba
26. Kadugli
27. Kagelu
28. Karima
29. Kassala
30. Khartoum
21. Kosti
32. Kurmuk
33. Kutum
34. Liyubu
35. Loka
36. Malakal
37. Maridi
38. Muglad
39. Nagishot
40. Nasir
41. Nyala
42. Nzara
43. Om Ruwaba
44. Port Sudan
45. Raga
46. Rashad
47. Rumbek
48. Sennar
49. Shambi
50. Shendi
51. Singa
52. Station No. 6
53. Suakin
54. Tokar
55. Tonj
56. Torit
57. Tozi
58. Wadi Halfa
59. Wad Medani
60. Wau
61. Yambio
62. Zalingi

# Appendix II

## Monthly and Annual Class 'A' Pan Evaporation (mm.)

### Table 1

### Wadi Halfa

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nove. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 137 | 161 | 247 | 334 | 419 | 441 | 402 | 404 | 367 | 309 | 206 | 164 | 3591 |
| 1960 | 157 | 188 | 250 | 358 | 377 | 436 | 414 | 387 | 367 | 287 | 178 | 167 | 3566 |
| 1961 | 144 | 155 | 255 | 315 | 399 | 446 | 402 | 389 | 339 | 301 | 201 | 158 | 3504 |
| 1962 | 137 | 173 | 296 | 332 | 402 | 446 | 407 | 407 | 348 | 279 | 218 | 142 | 3587 |
| 1963 | 171 | 185 | 266 | 308 | 391 | 421 | 416 | 381 | 353 | 305 | 194 | 141 | 3532 |
| 1964 | 136 | 167 | 252 | 353 | 381 | 407 | 413 | - | - | - | - | - | - |
| Mean | 147 | 171 | 261 | 333 | 394 | 432 | 409 | 392 | 353 | 294 | 200 | 151 | 3556 |

### Table 2

### Port Sudan

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 174 | 181 | 203 | 225 | 260 | 318 | 318 | 318 | 256 | 208 | 178 | 137 | 2776 |
| 1960 | 176 | 139 | 206 | 223 | 272 | 320 | 362 | 326 | 263 | 193 | 185 | 105 | 2770 |
| 1961 | 174 | 188 | 211 | 232 | 294 | 344 | 358 | 362 | 280 | 191 | 197 | 157 | 2988 |
| 1962 | 164 | 153 | 198 | 261 | 287 | 318 | 360 | 360 | 277 | 193 | 130 | 154 | 2855 |
| 1963 | 127 | 147 | 203 | 208 | 256 | 310 | 330 | 372 | 258 | 203 | 170 | 173 | 2757 |
| 1964 | 178 | 167 | 200 | 244 | 303 | 322 | 359 | 347 | 289 | 227 | 187 | 183 | 3006 |
| 1965 | 149 | 163 | 217 | 246 | 303 | 336 | 361 | 347 | 274 | 227 | 151 | 171 | 2945 |
| 1966 | 149 | 188 | 203 | 229 | 278 | 324 | 352 | 357 | 274 | 207 | 165 | 165 | 2891 |
| Mean | 161 | 165 | 205 | 233 | 281 | 324 | 350 | 348 | 271 | 206 | 170 | 155 | 2873 |

Table 3

Kassala

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1962 | 130 | 166 | 235 | 237 | 272 | 235 | 162 | 118 | 147 | 191 | 171 | 140 | 2204 |
| 1963 | 161 | 172 | 237 | 244 | 252 | 244 | 212 | 185 | 191 | 227 | 168 | 154 | 2447 |
| 1964 | 151 | 163 | 237 | 291 | 308 | 248 | 134 | 112 | 149 | 188 | 187 | 146 | 2314 |
| 1965 | 154 | 176 | 222 | 265 | 252 | 244 | 178 | 158 | 170 | 188 | 168 | 149 | 2324 |
| 1966 | 151 | 158 | 225 | 260 | 262 | 239 | 217 | 200 | 163 | 198 | 173 | 146 | 2393 |
| Mean | 148 | 167 | 231 | 259 | 269 | 242 | 180 | 155 | 164 | 198 | 173 | 147 | 2336 |

Table 4

Khartoum

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 191 | 201 | 279 | 306 | 326 | 289 | 240 | 149 | 194 | 237 | 209 | 171 | 2792 |
| 1960 | 179 | 204 | 257 | 296 | 336 | 284 | 267 | 267 | 220 | 208 | 225 | 184 | 2927 |
| 1961 | 203 | 215 | 277 | 306 | 358 | 265 | 176 | 164 | 223 | 240 | 204 | 174 | 2805 |
| 1962 | 179 | 204 | 267 | 310 | 331 | 273 | 225 | 191 | 190 | 213 | 182 | 184 | 2749 |
| 1963 | 180 | 196 | 290 | 338 | 349 | 369 | 320 | 303 | 277 | 283 | 258 | 212 | 3375 |
| 1964 | 227 | 255 | 345 | 346 | 349 | 303 | 266 | 200 | 255 | 283 | 260 | 217 | 3306 |
| 1965 | 241 | 293 | 369 | 410 | 467 | 402 | 354 | 315 | 334 | 345 | 296 | 269 | 4095 |
| 1966 | 205 | 232 | 312 | 341 | 369 | 322 | 266 | 234 | 255 | 271 | 239 | 210 | 3256 |
| Mean | 201 | 225 | 300 | 332 | 361 | 313 | 264 | 228 | 244 | 260 | 234 | 203 | 3163 |

Table 5

El Obeid

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 228 | 246 | 338 | 337 | 333 | 294 | 193 | 115 | 149 | 230 | 249 | 220 | 2932 |
| 1960 | 232 | 252 | 304 | 334 | 353 | 304 | 218 | 164 | 154 | 191 | 268 | 240 | 3014 |
| 1961 | 260 | 288 | 362 | 353 | 389 | 268 | 147 | 125 | 159 | 240 | 251 | 223 | 3065 |
| 1962 | 225 | 248 | 306 | 348 | 345 | 251 | 211 | 96 | 111 | 186 | 201 | 220 | 2748 |
| 1963 | 220 | 240 | 318 | 279 | 283 | 255 | 188 | 129 | 139 | 205 | 248 | 207 | 2711 |
| 1964 | 220 | 249 | 330 | 341 | 367 | 308 | 141 | 116 | 146 | 190 | 227 | 205 | 2840 |
| 1965 | 237 | 267 | 323 | 343 | 394 | 310 | 212 | 116 | 149 | 229 | 234 | 225 | 3039 |
| 1966 | 229 | 249 | 310 | 334 | 298 | 277 | 178 | 114 | 139 | 210 | 232 | 214 | 2784 |
| Mean | 231 | 255 | 324 | 334 | 345 | 283 | 186 | 122 | 143 | 210 | 239 | 219 | 2891 |

Table 6

El Genina

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 257 | 291 | 334 | 339 | 294 | 308 | 191 | 98 | 119 | 230 | 223 | 240 | 2924 |
| 1960 | 257 | 285 | 325 | 320 | 318 | 265 | 120 | 93 | 116 | 208 | 235 | 227 | 2769 |
| 1961 | 279 | 321 | 387 | 377 | 384 | 237 | 91 | 47 | 121 | 220 | 244 | 203 | 2911 |
| 1962 | 235 | 268 | 289 | 320 | 289 | 213 | 137 | 47 | 83 | 193 | 206 | 238 | 2518 |
| 1963 | 232 | 243 | 293 | 265 | 232 | 237 | 146 | 82 | 144 | 154 | 203 | 192 | 2423 |
| 1964 | 220 | 222 | 263 | 296 | 310 | 241 | 122 | 67 | 146 | 207 | 225 | 222 | 2541 |
| 1965 | 239 | 236 | 315 | 341 | 327 | 201 | 129 | 73 | 149 | 234 | 282 | 281 | 2807 |
| 1966 | 283 | 318 | 391 | 336 | 298 | 146 | 168 | 85 | 127 | 200 | 232 | 227 | 2811 |
| Mean | 250 | 273 | 325 | 324 | 307 | 231 | 138 | 74 | 126 | 206 | 231 | 229 | 2713 |

Table 7

Malakal

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 263 | 280 | 299 | 238 | 213 | 164 | 110 | 76 | 88 | 135 | 190 | 255 | 2311 |
| 1960 | 291 | 283 | 333 | 211 | 191 | 142 | 118 | 83 | 78 | 113 | 225 | 235 | 2303 |
| 1961 | 260 | 299 | 316 | 258 | 277 | 140 | 86 | 76 | 81 | 91 | 145 | 193 | 2222 |
| 1962 | 238 | 257 | 247 | 246 | 201 | 154 | 98 | 98 | 90 | 113 | 119 | 203 | 2064 |
| 1963 | 229 | 267 | 281 | 218 | 158 | 99 | 80 | 82 | 94 | 131 | 149 | 232 | 2020 |
| 1964 | 254 | 282 | 308 | 229 | 180 | 130 | 75 | 67 | 61 | 85 | 163 | 212 | 2046 |
| 1965 | 239 | 243 | 263 | 237 | 212 | 125 | 90 | 73 | 68 | 129 | 331 | 357 | 2367 |
| 1966 | 241 | 267 | 281 | 237 | 205 | 127 | 85 | 78 | 78 | 109 | 180 | 239 | 2127 |
| Mean | 252 | 272 | 291 | 234 | 205 | 135 | 93 | 79 | 80 | 113 | 188 | 241 | 2182 |

Table 8

Juba

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 216 | 197 | 242 | 201 | 103 | 107 | 105 | 105 | 107 | 81 | 116 | 159 | 1739 |
| 1960 | 186 | 190 | 191 | 128 | 125 | 109 | 96 | 91 | 116 | 120 | 133 | 167 | 1652 |
| 1961 | 193 | 166 | 218 | 135 | 135 | 107 | 88 | 82 | 109 | 98 | 78 | 142 | 1552 |
| 1962 | 162 | 190 | 149 | 116 | 86 | 95 | 88 | 88 | 88 | 113 | 133 | 167 | 1475 |
| 1963 | 185 | 150 | 190 | 104 | 102 | 99 | 85 | 88 | 125 | 149 | 94 | 134 | 1505 |
| 1964 | 192 | 188 | 178 | 116 | 107 | 92 | 82 | 100 | 97 | 109 | 161 | 158 | 1580 |
| 1965 | 192 | 180 | 190 | 132 | 127 | 113 | 139 | 131 | 132 | 122 | 130 | 165 | 1753 |
| 1966 | 205 | 178 | 154 | 135 | 122 | 99 | 94 | 97 | 109 | 116 | 116 | 151 | 1576 |
| Mean | 191 | 180 | 189 | 133 | 113 | 103 | 97 | 98 | 110 | 114 | 120 | 155 | 1604 |

Appendix III

Monthly and Annual Piche Evaporation (mm)

Table 9

Wadi Halfa

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 165 | 180 | 289 | 393 | 460 | 399 | 393 | 407 | 405 | 341 | 243 | 190 | 3865 |
| 1960 | 175 | 212 | 261 | 376 | 390 | 394 | 416 | 416 | 397 | 314 | 214 | 207 | 3772 |
| 1961 | 196 | 180 | 289 | 333 | 424 | 418 | 413 | 407 | 369 | 341 | 249 | 179 | 3798 |
| 1962 | 172 | 222 | 351 | 387 | 454 | 381 | 430 | 423 | 381 | 311 | 255 | 179 | 3946 |
| 1963 | 203 | 207 | 302 | 336 | 415 | 409 | 421 | 423 | 418 | 345 | 234 | 165 | 3878 |
| 1964 | 162 | 184 | 285 | 385 | 412 | 373 | 412 | - | - | - | - | - | - |
| Mean | 179 | 198 | 296 | 368 | 425 | 395 | 414 | 410 | 393 | 330 | 240 | 182 | 3851 |

Table 10

Port Sudan

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 170 | 172 | 150 | 156 | 206 | 247 | 258 | 275 | 184 | 147 | 138 | 105 | 2208 |
| 1960 | 153 | 106 | 148 | 141 | 192 | 256 | 269 | 260 | 186 | 130 | 138 | 80 | 2059 |
| 1961 | 142 | 168 | 159 | 157 | 226 | 264 | 314 | 330 | 204 | 124 | 153 | 144 | 2385 |
| 1962 | 153 | 114 | 137 | 178 | 237 | 277 | 330 | 297 | 207 | 122 | 93 | 114 | 2259 |
| 1963 | 96 | 106 | 151 | 135 | 182 | 238 | 275 | 268 | 165 | 134 | 130 | 155 | 2035 |
| 1964 | 179 | 144 | 142 | 171 | 243 | 241 | 269 | 274 | 210 | 137 | 135 | 158 | 2303 |
| 1965 | 119 | 110 | 136 | 172 | 215 | 249 | 272 | 248 | 187 | 155 | 100 | 134 | 2097 |
| 1966 | 113 | 147 | 153 | 153 | 181 | 253 | 291 | 283 | 193 | 133 | 121 | 142 | 2163 |
| Mean | 140 | 133 | 147 | 157 | 210 | 253 | 284 | 279 | 192 | 135 | 126 | 129 | 2188 |

## Table 11

### Kassala

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 153 | 152 | 230 | 249 | 265 | 225 | 128 | 75 | 93 | 148 | 160 | 148 | 2026 |
| 1960 | 158 | 148 | 209 | 231 | 213 | 181 | 144 | 125 | 103 | 158 | 150 | 165 | 1985 |
| 1961 | 153 | 151 | 207 | 226 | 275 | 198 | 91 | 68 | 106 | 164 | 145 | 124 | 1908 |
| 1962 | 133 | 170 | 230 | 235 | 251 | 193 | 136 | 88 | 106 | 172 | 153 | 139 | 2006 |
| 1963 | 148 | 154 | 217 | 232 | 215 | 202 | 155 | 122 | 141 | 204 | 142 | 142 | 2074 |
| 1964 | 139 | 147 | 212 | 258 | 263 | 198 | 96 | 66 | 108 | 150 | 169 | 133 | 1939 |
| 1965 | 144 | 154 | 195 | 232 | 255 | 193 | 153 | 97 | 121 | 153 | 147 | 130 | 1974 |
| 1966 | 133 | 145 | 210 | 222 | 223 | 181 | 167 | 119 | 115 | 168 | 151 | 134 | 1968 |
| Mean | 145 | 152 | 213 | 235 | 245 | 196 | 133 | 95 | 112 | 164 | 152 | 139 | 1985 |

## Table 12

### Khartoum

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 206 | 210 | 306 | 346 | 375 | 313 | 224 | 113 | 175 | 254 | 228 | 186 | 2936 |
| 1960 | 198 | 226 | 277 | 313 | 342 | 309 | 260 | 255 | 229 | 238 | 247 | 204 | 3098 |
| 1961 | 215 | 217 | 277 | 307 | 328 | 286 | 151 | 120 | 219 | 249 | 226 | 187 | 2782 |
| 1962 | 196 | 219 | 280 | 318 | 306 | 280 | 218 | 164 | 162 | 223 | 202 | 210 | 2778 |
| 1963 | 182 | 200 | 286 | 316 | 288 | 315 | 240 | 199 | 210 | 255 | 265 | 207 | 2963 |
| 1964 | 217 | 245 | 322 | 325 | 320 | 273 | 151 | 88 | 157 | 212 | 217 | 178 | 2705 |
| 1965 | 209 | 232 | 289 | 325 | 343 | 291 | 229 | 192 | 220 | 269 | 244 | 223 | 3066 |
| 1966 | 203 | 222 | 292 | 315 | 327 | 271 | 184 | 142 | 184 | 234 | 225 | 199 | 2798 |
| Mean | 203 | 221 | 291 | 320 | 328 | 292 | 207 | 159 | 194 | 241 | 231 | 199 | 2890 |

Table 13

El Obeid

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 244 | 240 | 327 | 330 | 305 | 261 | 153 | 66 | 102 | 210 | 253 | 226 | 2717 |
| 1960 | 241 | 267 | 311 | 304 | 310 | 247 | 165 | 105 | 106 | 158 | 277 | 244 | 2735 |
| 1961 | 257 | 268 | 328 | 322 | 320 | 214 | 105 | 57 | 115 | 229 | 262 | 224 | 2701 |
| 1962 | 229 | 256 | 303 | 342 | 308 | 207 | 144 | 54 | 70 | 150 | 192 | 230 | 2485 |
| 1963 | 218 | 238 | 314 | 261 | 235 | 192 | 108 | 77 | 87 | 178 | 261 | 220 | 2389 |
| 1964 | 227 | 246 | 334 | 318 | 319 | 231 | 96 | 40 | 81 | 145 | 213 | 193 | 2443 |
| 1965 | 227 | 254 | 302 | 301 | 334 | 256 | 170 | 83 | 91 | 198 | 243 | 220 | 2679 |
| 1966 | 229 | 249 | 306 | 294 | 240 | 219 | 124 | 62 | 88 | 179 | 234 | 217 | 2441 |
| Mean | 234 | 252 | 315 | 309 | 296 | 228 | 133 | 68 | 92 | 180 | 241 | 221 | 2573 |

Table 14

El Genina

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 249 | 284 | 330 | 342 | 280 | 204 | 151 | 54 | 72 | 209 | 220 | 254 | 2649 |
| 1960 | 288 | 306 | 334 | 318 | 310 | 259 | 103 | 72 | 90 | 184 | 247 | 235 | 2746 |
| 1961 | 289 | 301 | 367 | 336 | 364 | 204 | 72 | 38 | 94 | 204 | 229 | 209 | 2707 |
| 1962 | 227 | 257 | 282 | 325 | 279 | 193 | 125 | 44 | 70 | 165 | 198 | 229 | 2394 |
| 1963 | 226 | 268 | 361 | 261 | 218 | 199 | 63 | 41 | 67 | 122 | 207 | 203 | 2236 |
| 1964 | 248 | 254 | 303 | 300 | 302 | 204 | 71 | 32 | 82 | 164 | 196 | 199 | 2355 |
| 1965 | 232 | 233 | 317 | 292 | 350 | 186 | 99 | 54 | 109 | 189 | 232 | 240 | 2533 |
| 1966 | 255 | 287 | 339 | 303 | 243 | 120 | 141 | 65 | 112 | 168 | 211 | 215 | 2459 |
| Mean | 251 | 273 | 329 | 309 | 293 | 196 | 103 | 50 | 87 | 175 | 217 | 223 | 2509 |

Table 15

Malakal

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 294 | 323 | 331 | 241 | 148 | 126 | 88 | 54 | 79 | 71 | 151 | 240 | 2146 |
| 1960 | 297 | 266 | 323 | 174 | 153 | 118 | 82 | 49 | 40 | 60 | 186 | 198 | 1946 |
| 1961 | 266 | 310 | 303 | 234 | 210 | 109 | 49 | 34 | 37 | 54 | 115 | 198 | 1919 |
| 1962 | 254 | 263 | 229 | 193 | 133 | 94 | 62 | 46 | 43 | 62 | 102 | 203 | 1684 |
| 1963 | 230 | 242 | 285 | 175 | 100 | 66 | 46 | 38 | 45 | 82 | 121 | 230 | 1660 |
| 1964 | 261 | 278 | 302 | 178 | 120 | 94 | 40 | 41 | 41 | 54 | 148 | 213 | 1770 |
| 1965 | 234 | 256 | 244 | 195 | 159 | 103 | 58 | 46 | 48 | 83 | 190 | 244 | 1860 |
| 1966 | 279 | 301 | 227 | 138 | 66 | 93 | 51 | 40 | 42 | 66 | 132 | 217 | 1652 |
| Mean | 264 | 278 | 280 | 191 | 136 | 100 | 59 | 43 | 46 | 66 | 143 | 217 | 1829 |

Table 16

Juba

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 210 | 184 | 198 | 136 | 63 | 58 | 57 | 44 | 54 | 63 | 79 | 122 | 1268 |
| 1960 | 178 | 158 | 156 | 84 | 66 | 76 | 52 | 46 | 64 | 62 | 91 | 144 | 1177 |
| 1961 | 178 | 161 | 182 | 106 | 83 | 70 | 55 | 41 | 51 | 49 | 39 | 106 | 1121 |
| 1962 | 134 | 169 | 111 | 78 | 52 | 52 | 46 | 43 | 45 | 58 | 76 | 106 | 970 |
| 1963 | 127 | 116 | 141 | 64 | 52 | 46 | 41 | 55 | 76 | 93 | 67 | 100 | 978 |
| 1964 | 162 | 148 | 137 | 82 | 65 | 43 | 43 | 44 | 46 | 54 | 97 | 110 | 1031 |
| 1965 | 165 | 152 | 151 | 84 | 69 | 60 | 68 | 62 | 61 | 51 | 66 | 124 | 1113 |
| 1966 | 172 | 148 | 114 | 79 | 65 | 54 | 49 | 49 | 55 | 60 | 69 | 108 | 1022 |
| Mean | 165 | 154 | 148 | 89 | 64 | 57 | 51 | 48 | 56 | 61 | 73 | 115 | 1085 |

# Appendix IV

## Monthly and Annual Thornthwaite Potential Evapotranspiration (mm)

### Table 17

### Wadi Halfa

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 18 | 14 | 68 | 152 | 196 | 198 | 200 | 199 | 169 | 137 | 69 | 32 | 1452 |
| 1960 | 22 | 37 | 67 | 157 | 185 | 195 | 201 | 195 | 175 | 165 | 70 | 79 | 1548 |
| 1961 | 28 | 15 | 50 | 143 | 182 | 204 | 203 | 199 | 158 | 139 | 51 | 22 | 1394 |
| 1962 | 14 | 29 | 139 | 144 | 187 | 200 | 204 | 203 | 174 | 162 | 128 | 30 | 1614 |
| 1963 | 38 | 43 | 66 | 160 | 195 | 202 | 205 | 200 | 180 | 164 | 69 | 35 | 1557 |
| 1964 | 15 | 21 | 76 | 160 | 180 | 195 | 203 | - | - | - | - | - | - |
| Mean | 23 | 27 | 78 | 153 | 188 | 199 | 203 | 200 | 174 | 153 | 77 | 40 | 1513 |

### Table 18

### Port Sudan

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 72 | 46 | 68 | 144 | 183 | 192 | 204 | 203 | 173 | 153 | 129 | 88 | 1655 |
| 1960 | 62 | 70 | 74 | 138 | 183 | 193 | 207 | 200 | 177 | 158 | 138 | 112 | 1712 |
| 1961 | 89 | 53 | 78 | 138 | 174 | 196 | 208 | 205 | 172 | 153 | 130 | 71 | 1667 |
| 1962 | 62 | 64 | 96 | 138 | 174 | 193 | 208 | 205 | 180 | 154 | 129 | 99 | 1702 |
| 1963 | 82 | 80 | 89 | 139 | 174 | 195 | 206 | 203 | 179 | 150 | 130 | 89 | 1716 |
| 1964 | 57 | 56 | 95 | 142 | 164 | 161 | 195 | 202 | 188 | 149 | 126 | 70 | 1605 |
| 1965 | 59 | 61 | 95 | 102 | 165 | 188 | 202 | 203 | 175 | 160 | 130 | 85 | 1625 |
| 1966 | 82 | 54 | 91 | 142 | 175 | 194 | 205 | 202 | 180 | 160 | 134 | 94 | 1713 |
| Mean | 71 | 61 | 86 | 135 | 174 | 189 | 204 | 203 | 178 | 155 | 131 | 89 | 1674 |

## Table 19

### Kassala

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 81 | 76 | 151 | 185 | 199 | 193 | 176 | 153 | 156 | 168 | 150 | 131 | 1819 |
| 1960 | 94 | 130 | 146 | 184 | 194 | 190 | 182 | 175 | 162 | 171 | 145 | 146 | 1919 |
| 1961 | 138 | 104 | 159 | 176 | 201 | 189 | 162 | 148 | 164 | 169 | 142 | 81 | 1833 |
| 1962 | 81 | 124 | 169 | 178 | 200 | 191 | 180 | 156 | 159 | 170 | 150 | 131 | 1889 |
| 1963 | 135 | 128 | 164 | 177 | 198 | 191 | 184 | 170 | 172 | 176 | 149 | 119 | 1963 |
| 1964 | 89 | 86 | 161 | 182 | 200 | 190 | 166 | 150 | 156 | 164 | 142 | 76 | 1762 |
| 1965 | 76 | 111 | 163 | 173 | 199 | 193 | 185 | 161 | 167 | 168 | 147 | 123 | 1866 |
| 1966 | 110 | 71 | 159 | 178 | 202 | 189 | 190 | 173 | 170 | 172 | 151 | 123 | 1888 |
| Mean | 101 | 104 | 159 | 179 | 199 | 191 | 178 | 161 | 163 | 170 | 147 | 116 | 1867 |

## Table 20

### Khartoum

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 62 | 46 | 149 | 182 | 203 | 198 | 193 | 163 | 170 | 172 | 145 | 94 | 1777 |
| 1960 | 56 | 125 | 147 | 184 | 200 | 198 | 198 | 192 | 179 | 178 | 138 | 141 | 1936 |
| 1961 | 107 | 133 | 150 | 175 | 202 | 196 | 177 | 169 | 176 | 172 | 130 | 51 | 1838 |
| 1962 | 49 | 88 | 168 | 179 | 202 | 196 | 193 | 175 | 172 | 179 | 154 | 103 | 1858 |
| 1963 | 119 | 126 | 155 | 180 | 202 | 198 | 195 | 187 | 182 | 178 | 146 | 87 | 1955 |
| 1964 | 54 | 67 | 161 | 183 | 201 | 197 | 181 | 162 | 174 | 174 | 140 | 62 | 1756 |
| 1965 | 68 | 111 | 164 | 175 | 200 | 197 | 196 | 181 | 182 | 172 | 140 | 83 | 1869 |
| 1966 | 83 | 64 | 163 | 182 | 204 | 198 | 204 | 185 | 183 | 181 | 152 | 94 | 1893 |
| Mean | 75 | 95 | 157 | 180 | 202 | 197 | 192 | 177 | 177 | 176 | 143 | 89 | 1860 |

Table 21

El Obeid

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 56 | 48 | 136 | 169 | 192 | 184 | 168 | 138 | 144 | 148 | 125 | 70 | 1578 |
| 1960 | 54 | 96 | 138 | 173 | 189 | 184 | 170 | 157 | 152 | 159 | 104 | 128 | 1704 |
| 1961 | 79 | 51 | 137 | 165 | 191 | 178 | 152 | 133 | 144 | 148 | 87 | 45 | 1510 |
| 1962 | 43 | 74 | 156 | 165 | 190 | 177 | 169 | 128 | 142 | 156 | 133 | 76 | 1609 |
| 1963 | 78 | 91 | 140 | 165 | 192 | 185 | 168 | 146 | 149 | 157 | 116 | 67 | 1652 |
| 1964 | 49 | 63 | 148 | 171 | 190 | 183 | 151 | 119 | 142 | 147 | 105 | 49 | 1517 |
| 1965 | 57 | 84 | 150 | 163 | 186 | 184 | 172 | 132 | 146 | 147 | 95 | 57 | 1573 |
| 1966 | 65 | 61 | 146 | 168 | 192 | 177 | 180 | 153 | 162 | 162 | 135 | 71 | 1672 |
| Mean | 60 | 71 | 144 | 167 | 190 | 182 | 166 | 138 | 148 | 153 | 113 | 70 | 1602 |



Table 22

El Genina

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 67 | 69 | 144 | 162 | 182 | 172 | 163 | 122 | 108 | 107 | 88 | 63 | 1447 |
| 1960 | 61 | 84 | 145 | 169 | 178 | 174 | 138 | 128 | 121 | 129 | 88 | 91 | 1506 |
| 1961 | 84 | 61 | 136 | 166 | 180 | 166 | 113 | 99 | 116 | 102 | 60 | 42 | 1325 |
| 1962 | 45 | 71 | 146 | 156 | 173 | 164 | 155 | 103 | 112 | 133 | 90 | 75 | 1423 |
| 1963 | 65 | 91 | 140 | 160 | 175 | 173 | 132 | 108 | 125 | 132 | 80 | 56 | 1437 |
| 1964 | 65 | 71 | 143 | 157 | 176 | 171 | 123 | 84 | 75 | 93 | 69 | 47 | 1274 |
| 1965 | 62 | 66 | 135 | 160 | 169 | 160 | 147 | 113 | 120 | 119 | 80 | 58 | 1389 |
| 1966 | 71 | 66 | 141 | 165 | 178 | 158 | 164 | 132 | 130 | 136 | 87 | 65 | 1493 |
| Mean | 65 | 72 | 141 | 162 | 176 | 167 | 142 | 111 | 113 | 119 | 80 | 62 | 1412 |

Table 23

Malakal

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 140 | 127 | 170 | 174 | 170 | 158 | 151 | 138 | 136 | 144 | 141 | 135 | 1784 |
| 1960 | 135 | 144 | 168 | 166 | 173 | 153 | 147 | 146 | 136 | 146 | 134 | 153 | 1801 |
| 1961 | 151 | 135 | 161 | 178 | 193 | 156 | 132 | 127 | 140 | 141 | 129 | 93 | 1736 |
| 1962 | 110 | 135 | 172 | 175 | 172 | 154 | 144 | 139 | 139 | 148 | 141 | 136 | 1765 |
| 1963 | 146 | 140 | 168 | 173 | 166 | 149 | 141 | 144 | 145 | 152 | 139 | 137 | 1800 |
| 1964 | 136 | 132 | 172 | 172 | 172 | 153 | 122 | 131 | 134 | 139 | 138 | 112 | 1713 |
| 1965 | 131 | 138 | 169 | 169 | 179 | 157 | 147 | 140 | 144 | 147 | 141 | 134 | 1796 |
| 1966 | 144 | 131 | 164 | 164 | 156 | 139 | 141 | 144 | 139 | 144 | 137 | 130 | 1733 |
| Mean | 137 | 135 | 168 | 171 | 173 | 152 | 141 | 139 | 139 | 145 | 138 | 129 | 1766 |

Table 24

Juba

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 158 | 141 | 168 | 163 | 152 | 142 | 131 | 115 | 133 | 141 | 138 | 145 | 1727 |
| 1960 | 149 | 150 | 165 | 149 | 150 | 180 | 125 | 129 | 133 | 142 | 143 | 156 | 1771 |
| 1961 | 160 | 137 | 164 | 159 | 159 | 143 | 116 | 110 | 125 | 122 | 108 | 112 | 1615 |
| 1962 | 112 | 138 | 157 | 148 | 140 | 133 | 126 | 120 | 124 | 141 | 142 | 144 | 1625 |
| 1963 | 149 | 140 | 160 | 145 | 148 | 140 | 120 | 128 | 145 | 152 | 137 | 144 | 1708 |
| 1964 | 152 | 143 | 170 | 156 | 155 | 135 | 129 | 116 | 123 | 126 | 141 | 141 | 1687 |
| 1965 | 148 | 143 | 172 | 156 | 155 | 141 | 146 | 138 | 138 | 139 | 139 | 144 | 1759 |
| 1966 | 159 | 142 | 159 | 153 | 159 | 148 | 120 | 128 | 132 | 144 | 144 | 149 | 1737 |
| Mean | 148 | 142 | 164 | 154 | 152 | 145 | 127 | 123 | 132 | 138 | 137 | 142 | 1704 |

## Appendix V

### Penman Monthly and Annual Evaporation (mms.)

### Table 25

### Wadi Halfa

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 84 | 101 | 158 | 183 | 192 | 195 | 202 | 217 | 162 | 146 | 108 | 84 | 1832 |
| 1960 | 81 | 112 | 152 | 183 | 198 | 198 | 202 | 198 | 171 | 152 | 108 | 99 | 1854 |
| 1961 | 90 | 104 | 143 | 171 | 183 | 195 | 205 | 211 | 159 | 140 | 99 | 78 | 1778 |
| 1962 | 84 | 112 | 161 | 174 | 202 | 198 | 208 | 223 | 165 | 143 | 111 | 81 | 1862 |
| 1963 | 84 | 112 | 149 | 171 | 189 | 189 | 202 | 208 | 168 | 152 | 111 | 84 | 1735 |
| 1964 | 81 | 106 | 152 | 171 | 192 | 195 | 211 | - | - | - | - | - | - |
| Mean | 84 | 108 | 153 | 176 | 193 | 193 | 205 | 213 | 165 | 146 | 107 | 85 | 1812 |

### Table 26

### Port Sudan

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 140 | 151 | 195 | 225 | 248 | 261 | 295 | 279 | 225 | 195 | 171 | 149 | 2534 |
| 1960 | 133 | 174 | 208 | 216 | 254 | 249 | 269 | 270 | 231 | 205 | 174 | 152 | 2535 |
| 1961 | 161 | 168 | 198 | 216 | 236 | 258 | 298 | 285 | 219 | 195 | 165 | 133 | 2532 |
| 1962 | 127 | 154 | 208 | 216 | 245 | 258 | 270 | 276 | 222 | 198 | 168 | 127 | 2469 |
| 1963 | 149 | 160 | 205 | 225 | 248 | 255 | 276 | 276 | 231 | 198 | 171 | 195 | 2589 |
| 1964 | 140 | 168 | 198 | 216 | 245 | 258 | 245 | 282 | 225 | 195 | 165 | 146 | 2483 |
| 1965 | 140 | 151 | 202 | 216 | 236 | 240 | 263 | 279 | 228 | 205 | 171 | 149 | 2480 |
| 1966 | 152 | 157 | 260 | 219 | 239 | 261 | 257 | 276 | 228 | 198 | 165 | 143 | 2555 |
| Mean | 143 | 160 | 209 | 219 | 244 | 255 | 272 | 278 | 226 | 199 | 169 | 149 | 2522 |

Table 27

Kassala

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 127 | 126 | 171 | 207 | 217 | 219 | 267 | 260 | 213 | 186 | 144 | 121 | 2258 |
| 1960 | 124 | 140 | 167 | 198 | 214 | 222 | 245 | 239 | 207 | 183 | 144 | 127 | 2210 |
| 1961 | 202 | 143 | 192 | 195 | 211 | 228 | 264 | 254 | 210 | 186 | 168 | 118 | 2371 |
| 1962 | 127 | 126 | 174 | 189 | 211 | 219 | 248 | 257 | 207 | 177 | 147 | 127 | 2209 |
| 1963 | 130 | 129 | 171 | 201 | 214 | 222 | 248 | 251 | 207 | 186 | 150 | 121 | 2230 |
| 1964 | 124 | 134 | 171 | 198 | 217 | 225 | 260 | 245 | 201 | 183 | 144 | 121 | 2223 |
| 1965 | 133 | 134 | 180 | 183 | 205 | 222 | 245 | 251 | 207 | 183 | 150 | 121 | 2214 |
| 1966 | 133 | 126 | 177 | 192 | 205 | 222 | 245 | 248 | 210 | 180 | 144 | 124 | 2206 |
| Mean | 138 | 132 | 175 | 195 | 212 | 222 | 253 | 251 | 208 | 183 | 149 | 123 | 2240 |

Table 28

Khartoum

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 112 | 106 | 152 | 186 | 245 | 219 | 248 | 254 | 201 | 174 | 129 | 112 | 2138 |
| 1960 | 109 | 118 | 152 | 189 | 198 | 219 | 251 | 236 | 204 | 183 | 123 | 121 | 2103 |
| 1961 | 121 | 112 | 164 | 165 | 195 | 231 | 276 | 251 | 192 | 174 | 129 | 99 | 2109 |
| 1962 | 109 | 112 | 171 | 189 | 208 | 228 | 257 | 254 | 216 | 189 | 138 | 105 | 2176 |
| 1963 | 115 | 106 | 149 | 183 | 211 | 204 | 251 | 254 | 204 | 171 | 129 | 109 | 2086 |
| 1964 | 109 | 112 | 155 | 186 | 198 | 213 | 236 | 236 | 201 | 183 | 126 | 112 | 2067 |
| 1965 | 118 | 106 | 155 | 165 | 192 | 219 | 254 | 257 | 198 | 183 | 129 | 99 | 2075 |
| 1966 | 115 | 115 | 171 | 192 | 214 | 222 | 251 | 254 | 213 | 183 | 135 | 109 | 2174 |
| Mean | 114 | 111 | 159 | 182 | 208 | 219 | 253 | 250 | 204 | 180 | 130 | 108 | 2116 |

Table 29

El Obeid

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 109 | 115 | 146 | 189 | 220 | 240 | 267 | 260 | 222 | 180 | 132 | 112 | 2192 |
| 1960 | 102 | 123 | 143 | 186 | 192 | 231 | 248 | 251 | 216 | 198 | 120 | 115 | 2125 |
| 1961 | 115 | 120 | 155 | 168 | 198 | 240 | 264 | 316 | 213 | 180 | 120 | 105 | 2194 |
| 1962 | 99 | 123 | 164 | 159 | 205 | 234 | 254 | 257 | 222 | 198 | 138 | 109 | 2162 |
| 1963 | 102 | 112 | 143 | 183 | 220 | 234 | 264 | 257 | 225 | 189 | 132 | 112 | 2173 |
| 1964 | 102 | 120 | 136 | 183 | 211 | 234 | 251 | 251 | 213 | 195 | 126 | 115 | 2137 |
| 1965 | 112 | 115 | 152 | 168 | 195 | 243 | 254 | 254 | 216 | 180 | 126 | 105 | 2120 |
| 1966 | 109 | 126 | 155 | 168 | 217 | 234 | 251 | 257 | 228 | 192 | 138 | 109 | 2184 |
| Mean | 106 | 119 | 149 | 176 | 207 | 236 | 257 | 263 | 219 | 189 | 129 | 110 | 2161 |

Table 30

El Genina

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 102 | 112 | 146 | 177 | 198 | 216 | 245 | 257 | 213 | 152 | 114 | 99 | 2031 |
| 1960 | 112 | 112 | 146 | 174 | 202 | 231 | 254 | 251 | 213 | 177 | 123 | 112 | 2107 |
| 1961 | 105 | 112 | 146 | 171 | 171 | 219 | 251 | 260 | 201 | 158 | 108 | 93 | 1995 |
| 1962 | 96 | 115 | 164 | 168 | 202 | 231 | 242 | 242 | 225 | 171 | 129 | 105 | 2090 |
| 1963 | 99 | 112 | 149 | 171 | 202 | 210 | 242 | 251 | 213 | 164 | 117 | 96 | 2026 |
| 1964 | 115 | 112 | 152 | 171 | 195 | 231 | 257 | 264 | 135 | 164 | 120 | 105 | 2021 |
| 1965 | 99 | 106 | 149 | 171 | 167 | 219 | 245 | 251 | 198 | 158 | 111 | 96 | 1970 |
| 1966 | 102 | 118 | 155 | 174 | 211 | 219 | 236 | 251 | 213 | 177 | 123 | 99 | 2078 |
| Mean | 104 | 112 | 151 | 172 | 194 | 222 | 247 | 253 | 201 | 165 | 118 | 101 | 2040 |

Table 31

Malakal

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 146 | 160 | 189 | 237 | 267 | 255 | 264 | 260 | 243 | 233 | 174 | 146 | 2574 |
| 1960 | 143 | 174 | 183 | 243 | 251 | 267 | 276 | 273 | 255 | 236 | 162 | 158 | 2621 |
| 1961 | 152 | 165 | 195 | 222 | 242 | 249 | 267 | 273 | 264 | 239 | 177 | 136 | 2581 |
| 1962 | 133 | 157 | 214 | 222 | 264 | 246 | 270 | 264 | 252 | 229 | 192 | 143 | 2586 |
| 1963 | 140 | 146 | 186 | 231 | 260 | 252 | 270 | 270 | 237 | 223 | 186 | 143 | 2544 |
| 1964 | 143 | 168 | 183 | 237 | 260 | 249 | 270 | 264 | 249 | 236 | 165 | 149 | 2573 |
| 1965 | 152 | 160 | 192 | 219 | 236 | 261 | 270 | 264 | 246 | 239 | 171 | 136 | 2546 |
| 1966 | 146 | 165 | 208 | 228 | 251 | 255 | 264 | 264 | 249 | 239 | 189 | 143 | 2601 |
| Mean | 144 | 162 | 194 | 230 | 254 | 254 | 269 | 267 | 249 | 234 | 177 | 144 | 2578 |

Table 32

Juba

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1959 | 192 | 179 | 236 | 246 | 245 | 222 | 236 | 239 | 222 | 242 | 210 | 189 | 2658 |
| 1960 | 189 | 207 | 251 | 261 | 239 | 237 | 242 | 242 | 228 | 239 | 204 | 195 | 2734 |
| 1961 | 192 | 188 | 233 | 255 | 245 | 234 | 245 | 248 | 222 | 242 | 234 | 183 | 2721 |
| 1962 | 183 | 174 | 251 | 255 | 242 | 225 | 242 | 236 | 225 | 239 | 210 | 192 | 2674 |
| 1963 | 189 | 196 | 236 | 255 | 242 | 222 | 248 | 239 | 213 | 236 | 219 | 198 | 2693 |
| 1964 | 189 | 202 | 254 | 264 | 248 | 225 | 248 | 242 | 225 | 239 | 195 | 186 | 2717 |
| 1965 | 180 | 174 | 233 | 246 | 242 | 225 | 233 | 239 | 216 | 245 | 210 | 186 | 2629 |
| 1966 | 189 | 193 | 251 | 255 | 233 | 216 | 242 | 236 | 225 | 239 | 210 | 189 | 2678 |
| Mean | 188 | 189 | 243 | 255 | 242 | 226 | 242 | 240 | 222 | 240 | 212 | 190 | 2688 |