International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

Assessment Of Temperature And Precipitation Characteristics Under Climate Change In Sudan

Karama A Ismail[1]*, Fawzia I Moursy[1], and Mohamed El-Sayed El-Mahdy[1]
[1]Department of Natural Resources, Faculty of African Postgraduate Studies, Cairo University, Egypt
* Correspondence: m_elsayed50@cu.edu.eg;

Abstract

For twenty-five observation stations spread over Sudan, three meteorological variables—monthly rainfall, maximum and minimum temperature values were taken into consideration for the 65 years from 1958 to 2022. Two approaches were used to calculate the Aridity Index (AI), which was based on yearly and seasonal data on temperature and precipitation.to ascertain Sudan's aridity conditions throughout the study period. Also, Standardized Precipitation Index (SPI) which is widely used as a drought meteorological index, to identify drought characteristics including the number of events, frequency, duration, and intensity. In the present study, measuring Sudan's drought aridity is the main objective of this study. Measurements of seasonal, monthly, or the same area's yearly humidity and aridity also have the goal of determining the climatic categorization for the twenty-five stations that are part of this study. Finally, to assist decision-makers in the natural resources sectors, a map representing all aspects of the drought was created, highlighting the areas that were most impacted over the course of the study. Three meteorological drought indexes based on climatic variables were therefore used. Therefore, the Thornthwaite method was used to estimate the monthly/seasonal Aridity Index, and the research area was classified into five distinct categories: Arid conditions (less than 16) were documented at Atbara. AlAtun, Gebeit, Dongola, Dogash, portsudan, AubHamed and wadiHalfa around 65 years, in contrast, semi-arid climatic conditions are identified in the region of Aduragi., Khartoum and Umm Durman during summer Arid conditions were observed for the same stations during winter, spring, and Autumn, and Humid circumstances (16-31), were observed at EdDueim,WadMedani Elfasher ,kosti Elobeid Zallngei,Nyala, Kadogli, Genena and Gadarif stations during summer season. Very humid (≥ 128), recorded at Abu-Na-ama in the summer seasons. De Martonne approach was used to apply the yearly AI. Thus, the results were divided into four main categories: Semi-Arid (-5) at Kosti, Fasher, Wad Madnie, and Kassala stations; Sub-Humid (values -10), represented by Sennar; Very Humid (values are shown by Zellngei, Kadogli, Abu Nama, and Gadarif); and Arid (value5 at Khartoum, ummDurman Aduragi, AlAtun, Gebeit Atbara Dongola, Dogash, portsudan, AubHamed, and WadiHalfa stations. These findings show that drought has been common in the study area and has rapidly moved southward.

Keywords: *Climate Variables, Sudan, Standardized Precipitation Index and Aridity Index*

1. INTRODUCTION

The African Sahel region, which includes Sudan, is famous for going through severe droughts in the 1970s and 1980s (Mohamed and El-Mahdy, 2021a). Drought is considered an environmental calamity and is one of the most frequent occurrences in this region. Meteorologists, Ecologists, agricultural specialists, hydrologists, and geologists have all studied droughts extensively. Droughts, primarily brought on by a drop in precipitation over a prolonged period, such as a season or a year, can occur in almost every climatic zone, even those with high or low rainfall. Low relative humidity, temperature, winds, and the quantity, distribution, and amount of rainfall that happens during harvest seasons are all major contributors to droughts. Between 1967 and 1973 and 1980 and 1984, there were two major droughts, the second is the more serious. During the period 1987, 1989, 1990, 1991, and 1993, there were localized droughts, primarily in western and portions of central Sudan (Elagib et al., 2021). The nation had severe health and nutritional problems, food shortages, and social instability as a result of the drought that lasted from 1985 to 1993. Furthermore, a great number of Africans suffered greatly as a result of drought, which exacerbated malnutrition, land degradation, and epidemics (Mohamed et al., 2023). A significant natural disaster that has affected the world on a global scale, the drought killed between 1974 and 2007 in the Sahel region in 1974 and in Ethiopia/Sudan in 1984, killing 325,000 people (Mera, 2018). According to Mujumdar et al. (2020), droughts are commonly divided into four categories: hydrological, agricultural, meteorological, and socioeconomic. A region experiences a hydrological drought when groundwater and stream flow decline, a

meteorological drought when precipitation declines, an agricultural drought when soil moisture levels fall and the growing season is interrupted, and a socioeconomic drought when environmental factors adversely affect specific facets of human existence. The aridity index is an indicator of climate that can be utilized to track and forecast droughts (Mohamed et al., 2022). However, aridity results from dry, descending air and is frequently observed in regions under continuous anticyclonic circumstances, such as those under subtropical anticyclones (Sahour et al., 2020). The degree of aridity can be gauged using an aridity index, it can be used to locate, identify, or demarcate areas that lack water, which can have a detrimental impact on the effective use of land for activities that support life. Several long-term aridity indices (1971–2000) were assessed in some studies employing climatic indices in order to create a suitable climate classification system for Sudan. Six aridity indices were used to assess Sudan's level of aridity. According to the results, Sudanese climates are best categorized using the Emberger and Eddebba aridity indices. Because it considers the length of the growing season, the (EAI) index was selected (Tabari et al., 2014). Mohmmed et al. (2018) applying the Drought Severity Index (DSI), and the Standardized Precipitation Index (SPI), two meteorological drought indices, to assess and examine the drought situation in Sudan. To categorize how the drought affected Sudan's sorghum yield from 2001 to 2011 and to identify the wet and dry areas of the nation. When the long-term mean for the same period was subtracted from the Tropical Rainfall Measurement Mission (TRMM) rainfall products, Plotting and computation were done on a seasonal basis (July–October), which demonstrated that the dry state varied across the whole Sudan on various time and space scales. Along with the Sudan General Soil Map, which is digitized to generate a GIS database, there are hydrological system studies conducted in the White Nile area, Sudan, utilizing GIS technologies and remote sensing techniques with a resolution of 90 meters. The aridity index was used in the research area, which was one of the arid regions (Mohamed and El-Mahdy, 2021b). A drought impact curve needs to be created for every system and region in order to evaluate the effects of drought on the resilience and resistance of different systems, such as crops, natural vegetation, and water supplies (Todisco et al., 2013). Lastly, they identified the most drought-vulnerable regions in Africa by monitoring and evaluating the effects of the Standard Precipitation Evapotranspiration Index (SPEI). Traditional meteorological indices, which solely showed stations based on drought levels, were employed in the majority of Sudanese studies on drought. Moreover, the majority were reliant on the brief intervals. For the purpose of researching and evaluating future changes in arid environments, such as semi-arid and deserts regions, etc., some studies employed specific places, while others used large areas with various indices. For the long-term period of 1958–2022, the Standardized Precipitation Index (SPI) based on 25 sites was created using a variety of goals and techniques to gauge the levels of humidity and aridity. To determine Sudan's aridity and wet conditions, annual, seasonal, and Monthly rainfall and temperature statistics serve as the foundation for the datasets. Finally, Although prior studies on Sudan have used hydrological and/or agricultural drought methodologies, our findings may be primarily categorized using meteorological drought techniques.

2. MATERIALS AND METHODS

Study area

One of Africa's biggest nations, Sudan occupies an area of roughly 1 860 000 km². and with a population of roughly 5.66 million (2021) World Bank million people (World Population Prospects, Population Division, United Nations) (Simonin et al., 2023). Geographically, the nation is located between latitudes 8.45 and 23.8° N and longitudes 21.49° and 38.24° E. It is bordered by nine nations: Ethiopia and Eritrea in the east, Kenya, Democratic Republic of the Congo, and Uganda the in the south, the Libyan Arab Jamahiriya, the Central African Republic, and Chad in the west, and in the north lays Egypt. The Red Sea borders it on the northeast (Gelaw and Debele, 2024). Except for the Red Sea Hills, Jebel Marra, the Nuba Mountains, and the Ima Tong Hills, the nation is a gently sloping plain.. The eastern and central lacustrine clay accumulations are its primary characteristics dunes in the western and northern part and the red ironstone soils in the south, the stabilized sand (El-Mahdy et al., 2024). The country is traversed by 9000 km of the waterways of the Nile River. These have produced a variety of soil types, and their impact on the hydrologic cycles affects rainfall as well. The nation's water and land resources can be categorized into the five ecosystems listed below (Sherif and Sturchio, 2021): A. More than half of the country is made up of arid and semi-arid environments. The

Red Sea highlands in Eastern Sudan and the Jebel Marra and Meidob Cliffs in Western Sudan are home to montage vegetation, low rainfall savannah, desert, and semi-desert vegetation belts. About 700,000 km2 make up the desert region, whereas 478,000 km2 make up the semi-desert region; B. Balanites aegyptiaca, Acacia mellifera,Acacia seyal, and thorn land, anogeissus, and Combretum hartmannianum are the vegetation belts that make up the clay low-precipitation savannah. About 122,000 km2 make up the entire clay low-precipitation savannah (Higher Council for Environment and Natural Resources, 2003); C. sand Low-precipitation savannah makes up a region of about 83,000 km2, it has Combretum, Acacia Senegal, and vegetation belts; D. There are roughly 14,000 km2 of higher rainfall savannah woodland, that was formerly rainforest, out of the high rainfall zone, approximately 120,000 km2; E. The 85,000 km2 flood ground and the 2,500 km2 occupied by montane vegetation.

With the exception of the Red Sea mountains (22.8 °C) and the high points of Jebel Marra in the west (22.6 °C), the average annual temperature ranges from 26 °C to 32 °C throughout the nation. part, the red ironstone soils in the south, and the stabilized sand dunes in the north and west. The northern portions of central Sudan, which are located within the Atbara, Kassala, and Khartoum, have the hottest regions, with mean annual temperatures of 32 °C. The air temperature drops beyond this area in all directions, especially northwest. Sudan's annual rainfall ranges from almost nothing near the Egyptian border to roughly 200 mm around Khartoum, and up to 700 mm at El Damazin.In areas that experience rainfall, the rainy season lasts only two or three months, with the remainder of the year being essentially dry. Furthermore, the rain typically falls in sporadic showers that vary greatly in time and place. Over the same time period, the average rainfall also decreased. [2]. Traditional farmers' and herders' livelihoods are negatively impacted by declining and unpredictable rainfall, which makes life extremely difficult.

Data

Twenty-five meteorological stations used as focal points to depict Sudan's entire dry region are listed in . The selection of meteorological stations was based on their geographical suitability. These data, which cover 65 years from 1958 to 2022, were gathered from The Global Historical Climate Network Dataset (GHCN). These data include the annual minimum and maximum temperature readings for 25 sites, as well as the monthly rainfall (in millimeters) (Figure 1). The means of the monthly, seasonal, and yearly rainfall and temperature data have been computed, and these mean values will be utilized as input files for the Thormathwite, DeMartonne Aridity Index (AI), and Standardized Precipitation Index (SPI) methodologies.

Methods:

Meteorological data were used in this study. Two important climate variables with the longest historical records and the easiest to observe are temperature and precipitation. These variables serve as empirical systems' cornerstones. One was computed using temperature data and monthly/seasonal rainfall averages. (Tables 1 and 2). The other was calculated using the Thornthwaite Aridity Index approach, which was developed to categorize drought conditions throughout the research region, and average annual rainfall and temperature values. Second, to categorize drought conditions and ascertain the frequency of droughts over the same region, the De Martonne aridity index was computed using the mean annual rainfall and temperature values. Third, the Drinc program used the standardized precipitation index (SPI), which was derived from the computation of mean annual precipitation and mean temperature values.

First method

Thornthwaite developed the Precipitation Effectiveness Index (PEI) in 1931 (Li et al., 2022). When the rate at which water vapor evaporates from the surface of free water is known, the ratio, which is only a measure of precipitation efficiency, achieves its maximum value. All of the Precipitation/Evaporation (P/E) ratios for every month all the year round are added up to create the Index, and any fractions are then subtracted by 10. For stations lacking evaporation data, an extra computation based on mean monthly temperature and precipitation was provided.

$$DI = [12 * 1.65 [\frac{R}{t + 12.2}] 10/9 \quad \text{(Eq. 1)}$$

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

The mean temperature and precipitation dataset averages for the study period from 1958 to 2022 (65-year) were used to find the Drought Index (DI), where R is the rainfall (mm), t is the temperature values (in c^o), and so on. Thornthwaite divided the climatic zones into five classifications based on this index, as shown in Table 2.

Table 1: Specification of meteorological station

serial no	WMO CODE.	Station Name	Latitude	longitude	Altitude
1	62810	Kadugli	11° 00`N	29° 43`E	499m
2	62790	Nyala	12° 04`N	24° 53`E	674m
3	62795	Abu Na-ama	12° 44`N	34° 08`E	445m
4	62780	Zallngei	12° 89`N	23° 47`E	905m
5	62771	El Obeid	13° 10`N	30° 14`E	575m
6	62772	Kosti	13° 10`N	32° 40`E	382m
7	62770	Geneina	13° 29`N	22° 27`E	805m
8	62762	Sennar	13° 33`N	33° 37`E	418m
9	62760	El Fasher	13° 38`N	25° 20`E	730m
10	62750	Ed Dueim	13° 59`N	32° 20`E	379m
11	62752	Al qadarif	14° 02`N	35° 24`E	599m
12	62751	Wad Medani	14° 23`N	33° 29`E	408m
13		Aduragi	15° 02`N	26° 35`E	474m
14	62730	Kassala	15° 28`N	36° 24`E	501m
15	62721	Khartoum	15° 36`N	32° 33`E	389m
16		Umm Durman	15° 64`N	32° 47`E	382m
17	62680	Atbara	17° 68`N	34° 02`E	348m
18		AL Atrun	18° 18N`	26° 64`E	348m
19	62661	Gebeit	18° 57`N	36° 51`E	797m
20	62650	Dongola	19° 10`N	30° 29`E	228m
21		Dagash	19° 13`N	33° 39`E	335m
22	62641	Port Sudan	19° 35`N	37° 13`E	3m
23	62640	Abu Hamed	19° 52`N	33° 31`E	314m
24		Laqiya Arbain	20° 06`N	28° 02`E	458m
25	62600	Wadi Halfa	21° 50`N	31° 18`E	160m

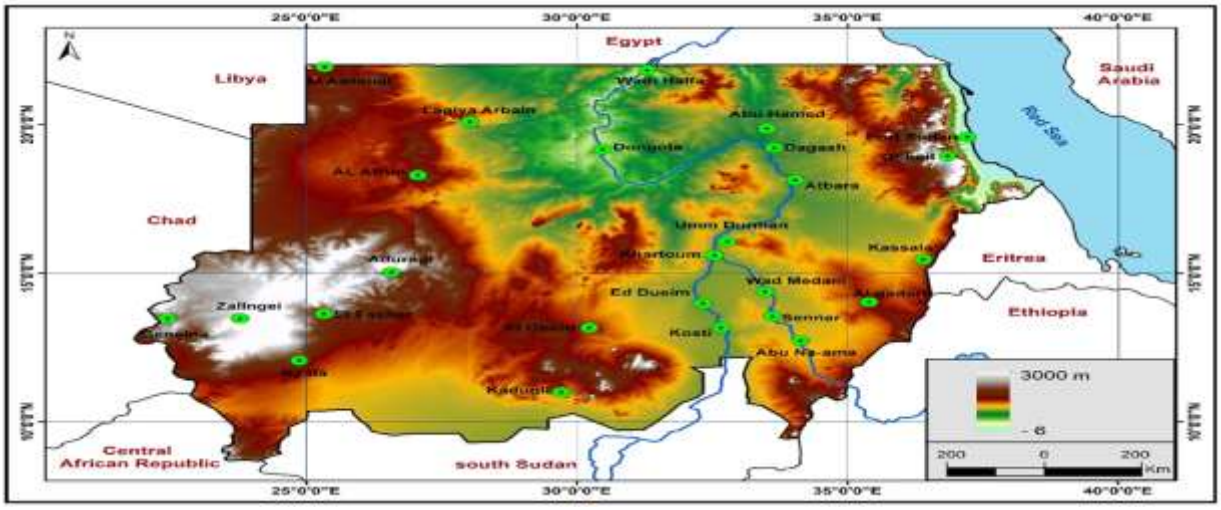


Figure 1: Map showing the location of the study area of Sudan

Table 2: classes of DI (Paltineanu et al., 2007)

DI Value	Climate Class
<16	Arid
16-31	Semiarid
63-32	Sub-humid
64-127	Humid
>128	Very humid

Second method

that is One of the standard methods for classifying climates, the De Martonne aridity index approach is employed in the majority of climatology projects, especially those involving the building of dams and other agricultural practices. Equation (2) presents the foundation of this approach (Tabari et al., 2014).

$$AI = [(p / T+10)] \quad \text{(Eq.2)}$$

where:

P: is the mean annual rainfall in mm

T: is the mean annual temperature in ^{o}C

Thus, for the years 1958 to 2022, Additionally, nine meteorological locations provided mean annual rainfall and temperature data. De Martonne's aridity index, which was determined for each station using equation. Table 3 shows the classes of Aridity Index. De Martonne's categorization and index values were established in 1928.

Table 3: classes of Aridity Index (Pellicone et al., 2019)

Aridity Index Value	Climate Class
5	Arid
5-12	Semiarid
12-20	Dry sub – humid
20-30	Moist sub-humid
30-60	Humid
> = 60	Wet

Third method

For the purposes of calculating Deciles and SPI (Table 4), Programmed of Drinc (GSG) to compute RDI, potential evapotranspiration (PET) is used as output data and annual or monthly precipitation is used as input data. Alternatively, the Thornthwaite method can be used to calculate PET using temperature data. Keep in mind that data must be accessible for at least 30 years in order to get reliable results. Enhancing the input and output is necessary to improve the software's interface. The files are in spreadsheet format for Microsoft Excel. Guide to Getting Started 5 for computations on a seasonal basis (monthly, 3-months, 6-months, or annually) for the computation of the yearly indices, data that may be yearly or monthly, and file format samples (monthly and annual datasets) Monthly information is required for every additional time step. When dealing with monthly data sets, the software might automatically determine the data's location and disregard any additional information present in the file. The months of the water year (October through September or September through August) should be identified on a line in the file format, with at least the first letter of each month. The data for each water year is grouped in lines beneath the corresponding year month. yearly information. In the File Management Window (menu>Data>File Management), the data files are selected. This window defines the potential evapotranspiration (PET) files, the beginning year, the water year period, and the DrinC number of years in the dataset. The cell containing the value for the first year should also be included if the data is collected annually.

Table 4: Drought category classification (McKee et al., Tsakiris et al., 2007)

SPI value	Classification
2.0 or more	Extremely wet

1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry

3. RESULTS AND DISCUSSIONS

Mean annual, seasonal, and monthly temperature and rainfall values:

The mean seasonal and monthly rainfall quantity (in mm) varied from station to station and was displayed in Table 5. As Figure 3 illustrates, the highest rainfall season in Sudan occurs in the summer, specifically in June, July, and August. However, it might occasionally extend until September. (Figure 4). Rainfall is often unrestricted throughout the summer months in the region, with August seeing the highest amounts. The rainy season begin in the middle of June and lasts until October. The season lasts one to two months in the North. (Aduragi, Khartoum, Ummdurman, Atbara, AlAtun, Dongola, Dagash, AbuHamed, Laqiya Arbain, and WadiHalfa) to six months in Kadogli station, with a slight variation for some Sudanese stations in the south, and four months in Gadarif station, the middle of Sudan stations shows a small variation, where the season lasts precisely four months (Table 5). Furthermore, Nicholson (1986) noted that rather than changes in the start or length of the rainy season, variations in the Sahel rainfall are typically associated with changes in the intensity of the rainy season. Thus, rainfall mechanisms moving from south to north, linked to a surface feature known as the Inter-Tropical Convergence Zone (ITCZ), are what cause the start of the rainy season. In the summer months of the Northern Hemisphere, this zone "follows the sun" by traveling northward, whereas in the summer months of the Southern Hemisphere, it moves southward (Nicholson, 2018). The southwest monsoon (wet) flows from the Atlantic Ocean and the northeasterly (dry) wind from the Sahara converge to form the ITCZ over Sudan (Nicholson, 2013). Additionally, figure (2) depicts the average rainfall in this region over a 65-year period. Thus, Zallngei station in the west had the greatest average (223.4 mm), followed by Elobeid in the south (201 mm) and Al Qadarif in the east (200.8 mm), On the other hand, WadiHalfa (2.8 mm) and Port Sudan (4.9 mm) in the north had the lowest averages. With the exception of December–January, which is considered the winter season and has a predominately northeasterly wind, which causes low temperatures in the north, temperatures did not significantly change with the seasons at any location Table 6. Table 7displayed the mean annual rainfall for the entire study period. In 1980, all stations recorded a significant quantity of rainfall, with slight variances from the south to the north. However, at several stations, mostly in the northern part of Sudan, drought was seen in 1984, 1990, and 2012. Over a 65-year period, the Atbara station to Wadi Halfa station records the least quantity of rainfall. The mean annual temperature readings for the study area were shown in Table 8, and it was evident that there was little difference across stations and years. Accordingly, based on mean temperature and mean rainfall, instead of four distinct seasons, the three geographical regions can be divided into three (Elagib and Elhag, 2011): (1) The southern region, which includes Kadogli, Abu Na-ama, Zallngei, El Obaied, Geneina Ed Dueim, and Alqadarif, is hot in March and April, wet in June and October, and dry in December and February; (2) The central region, which includes Nyala, Kosti, Sennar, El Fasser, and Wad Medani, is hot from March to May, wet from July to September, and dry from November to December to February; (3) The northern region, which includes Aduragi, Kassala, Khartoum, Umm Durman Atbara, AlAtrun, Gebeit, Dongola, Dogash, Port Sudan, Abu Hamed, Laqiya Arbain, and Wadi Halfa, is hot (March, April-June, October), wet (August), and dry (November, December–February) (see Table 5 and Table 6 for more information).

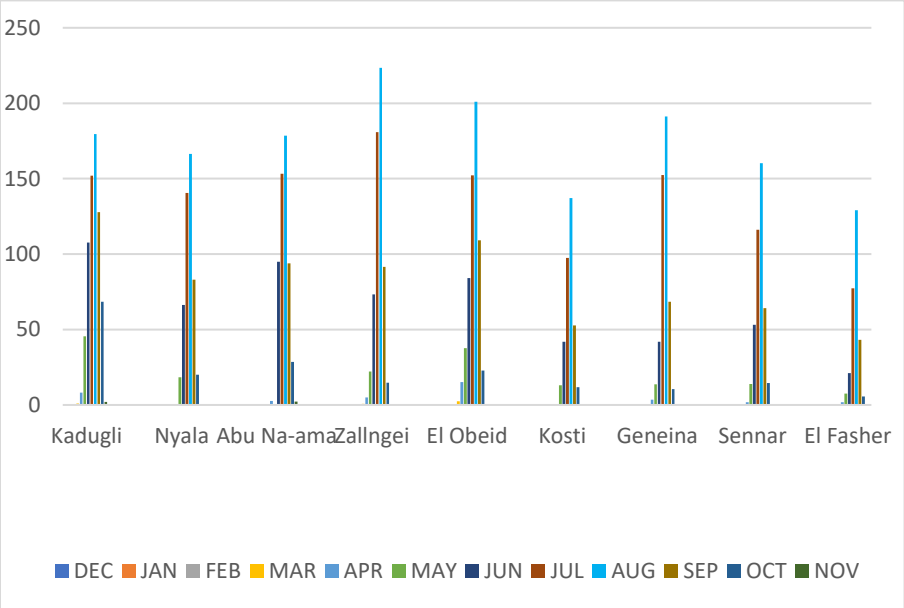
Table 5: Seasonal and monthly rainfall (mm) (1958 – 2022)

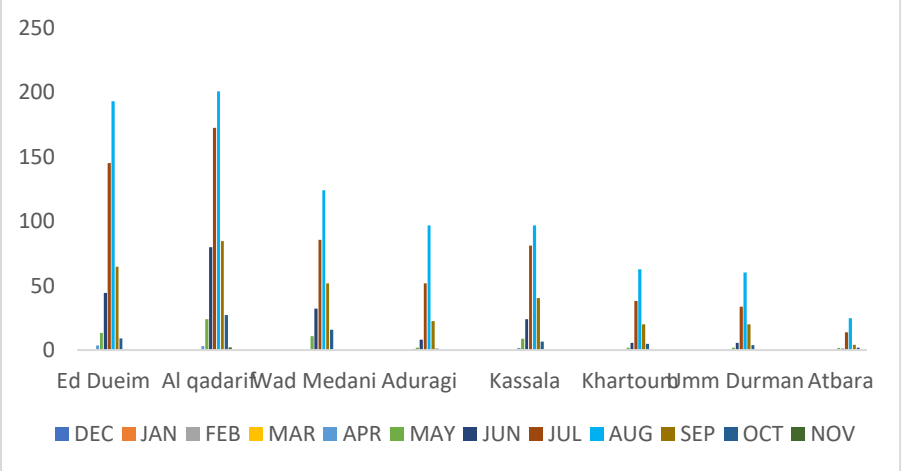
Station	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
	Winter			Spring			Summer			Autumn		
Kadugli	0	0	0.1	0.9	8.2	45.4	107.6	151.9	179.6	127.8	68.3	2.1
	0.1			54.5			439.0			198.1		

Station	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
	Winter			Spring			Summer			Autumn		
Nyala	0	0	0	0	0.0	18.4	66.3	140.5	166.5	83.1	20.1	0.0
	0			18.4			373.3			103.2		
AbuNa-ama	0	0	0.1	0.4	2.6	0.1	94.9	153.2	178.6	93.8	28.5	2.2
	0.1			3.0			426.7			124.6		
Zallngei	0	0	0	0.8	4.9	22.1	73.2	180.8	223.4	91.5	14.8	0
	0			27.7			477.5			106.3		
ElObeid	0	0	0	2.4	15.2	37.6	84.2	152.2	201.0	109.1	22.8	0
	0			55.2			437.4			132.0		
Kosti	0	0	0	0	0.1	13.0	41.8	97.5	137.2	52.8	11.7	0
	0			13.0			276.4			64.6		
Geneina	0	0	0	0	3.5	13.6	41.9	152.5	191.3	68.5	10.5	0
	0			17.1			385.8			79.0		
Sennar	0	0	0	0	1.9	13.8	53.2	116.1	160.2	64.2	14.6	0
	0			15.8			329.4			78.8		
ElFasher	0	0	0	0	1.7	7.5	21.2	77.4	129.0	43.2	5.6	0
	0			9.2			227.5			48.9		
EdDueim	0	0	0	0	3.7	13.4	44.3	145.3	193.3	64.7	9.0	0
	0			17.2			383.0			73.7		
Alqadarif	0	0	0	0.1	3.2	24.0	80.0	172.7	200.8	84.5	27.3	2.0
	0			27.3			453.5			113.8		
WadMedani	0	0	0	0	0	10.7	32.2	85.7	124.0	51.8	15.7	0.0
	0			11			241.9			67.6		
Aduragi	0	0	0	0	0.9	1.9	8.0	51.9	96.8	22.4	1.2	0.0
	0			2.7			156.7			23.6		
Kassala	0	0	0	0	1.7	8.9	24.1	81.1	96.7	40.5	6.6	0.2
	0			10.6			201.9			47.2		
Khartoum	0	0	0	0	0	1.9	5.5	38.1	62.8	20.0	4.8	0.0
	0			2			106.4			24.8		
UmmDurman	0	0	0	0	0	1.9	5.5	33.7	60.3	19.9	3.8	0.0
	0			2			99.5			23.8		
Atbara	0	0	0	0	0	1.5	1.1	13.7	24.6	4.2	1.9	0.0
	0			2			39.4			6.1		
ALAtrun	0	0	0	0	0	0	0.0	8.6	25.9	0.9	0	0.0
	0			0			34.4			1		
Gebeit	2.2	0.6	3.6	0	2.6	6.8	2.7	19.1	36.7	6.6	7.4	6.6
	6.4			9.4			58.6			20.5		

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

Station	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
	Winter			Spring			Summer			Autumn		
Dongola	0	0	0	0	0	0	0	3.9	9.9	0.1	0	0.0
	0			0			13.8			0		
Dagash	0	0	0	0	0	0.2	0	4.9	11.2	1.3	0.3	0.0
	0			0			16.1			1.5		
PortSudan	2.73	0.9	14.8	0.9	1.7	1.1	0	3.2	4.9	0	10.5	22.3
	18.4			3.7			8.1			32.8		
AbuHamed	0	0	0	0	0	0.1	0	4.9	11.7	0.7	0.1	0
	0			0			16.6			0.9		
LaqiyaArbain	0	0	0	0	0	0	0	2.1	10.1	0.1	0	0
	0			0			12.2			0		
WadiHalfa	0	0	0	0	0	0	0	0	2.8	0	0	0
	0			0			2.8			0		





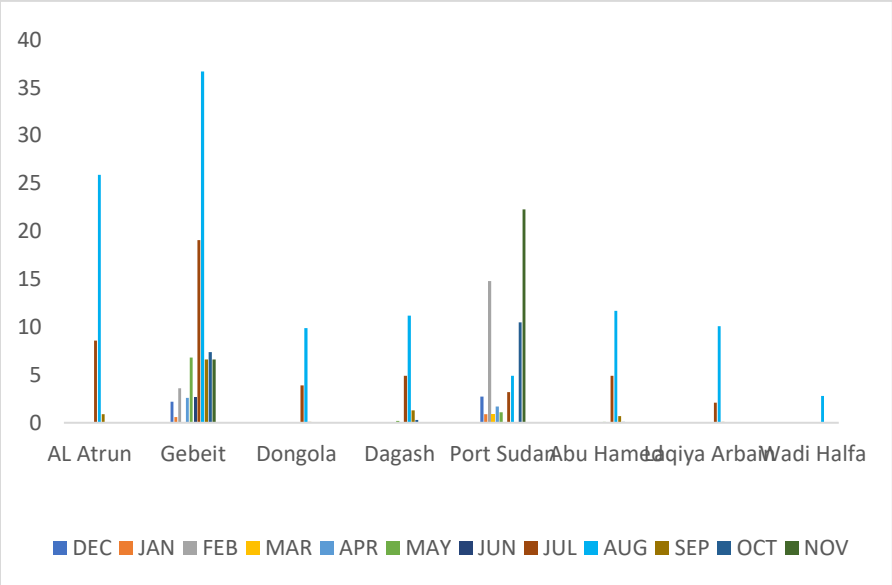


Figure 2: Monthly rainfall (mm) (1958 – 2022)

Table 6: Seasonal and monthly temperature (C°) (1958 – 2022)

Station	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
	Winter			Spring			Summer			Autumn		
Kadugli	26.1	28.1	31.0	32.4	31.9	28.8	27.0	26.0	26.5	27.8	28.1	27.0
	28.4			31.0			26.5			27.6		
Nyala	22.3	24.3	27.7	29.7	30.2	29.0	27.2	25.8	26.4	27.2	25.5	22.8
	24.8			29.6			26.5			25.2		
Abu namaa	25.8	27.5	30.4	32.1	32.0	30.0	27.6	26.4	27.2	28.8	28.2	25.9
	27.9			31.4			27.1			27.6		
zallngei	21.0	23.0	26.1	28.2	29.2	28.3	25.8	24.4	25.3	25.6	23.2	21.0
	23.4			28.5			25.2			23.2		
El Obeid	24.7	27.3	30.6	32.5	32.5	30.4	28.0	26.5	27.5	29.4	28.2	25.4
	27.5			31.8			27.3			27.7		
kosti	24.0	25.7	29.3	32.0	32.8	31.3	29.0	27.2	28.5	29.6	27.8	25.7
	26.4			32.0			28.2			27.7		
geneina	21.5	23.7	26.9	29.3	30.5	29.6	27.2	25.7	26.8	26.7	24.3	22.0
	24.1			29.8			26.6			24.3		
sennar	24.0	25.9	29.2	31.8	33.2	31.6	29.0	27.6	28.4	29.8	27.9	25.7
	26.4			32.2			28.3			27.8		
El Fasher	19.7	21.7	25.5	28.3	30.0	30.3	28.6	27.0	27.9	27.2	23.3	20.2
	22.3			29.5			27.8			23.6		
Ed Dueim	20.5	22.4	25.6	28.2	29.5	29.0	26.6	25.0	25.9	25.9	23.1	20.9
	22.9			28.9			25.8			23.3		
Al qadarif	23.3	24.7	27.1	28.5	28.0	26.2	23.3	23.6	24.1	26.1	25.5	24.0
	25.0			27.6			23.7			25.2		
Wad Medani	23.7	25.5	28.8	31.3	32.9	32.3	29.9	28.2	29.4	29.7	27.6	25.3
	26.0			32.2			29.2			27.5		
Adurargi	19.0	20.7	24.5	27.9	29.6	30.0	28.5	26.8	27.7	27.0	22.9	19.7
	21.4			29.2			27.7			23.2		
Kasala	25.1	26.3	29.3	32.2	33.7	32.7	30.1	28.8	29.6	31.1	29.5	26.6
	26.9			32.9			29.5			29.1		

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

Station	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
	Winter			Spring			Summer			Autumn		
Khartom	23.1	24.8	28.2	31.1	33.0	33.6	32.0	30.8	31.7	31.3	27.6	24.4
	25.3			32.6			31.5			27.8		
Umm Durman	22.9	24.7	28.1	31.1	33.2	33.8	32.1	31.0	31.9	31.4	27.7	24.3
	25.3			32.7			31.7			27.8		
Atbara	22.0	23.6	27.2	30.6	33.8	35.1	34.1	33.3	33.7	31.8	27.2	23.7
	24.3			33.2			33.7			27.6		
AL Atrun	17.2	19.1	23.1	27.4	30.0	31.6	30.8	30.0	28.9	26.7	22.0	18.4
	19.8			29.7			29.9			22.4		
gebeit	19.2	19.8	22.1	25.0	28.3	30.9	30.9	30.7	30.0	26.2	23.1	20.9
	20.4			28.1			30.5			23.4		
Dongola	17.7	19.6	24.1	28.9	32.4	34.2	34.3	34.3	33.6	30.2	23.6	19.2
	20.5			31.8			34.1			24.3		
Dagash	20.1	22.2	25.2	30.1	33.8	35.2	34.6	34.7	34.7	31.8	26.5	22.0
	22.5			33.0			34.7			26.8		
Port Sudan	23.3	23.3	24.6	26.9	29.9	32.4	34.1	34.2	32.2	29.6	27.6	25.0
	23.7			29.7			33.5			27.4		
Abu Hamad	20.1	22.1	25.0	30.1	33.8	35.5	34.7	34.8	34.9	31.8	26.3	21.9
	22.4			33.1			34.8			26.7		
laqiya A rbain	16.4	18.3	22.6	27.0	30.1	32.4	32.0	31.7	30.0	27.1	21.7	17.7
	19.1			29.8			31.3			22.2		
Wadi Halfa	16.5	18.3	22.8	27.5	31.2	33.4	33.3	33.4	32.1	28.9	22.8	18.2
	19.2			30.7			32.9			23.3		

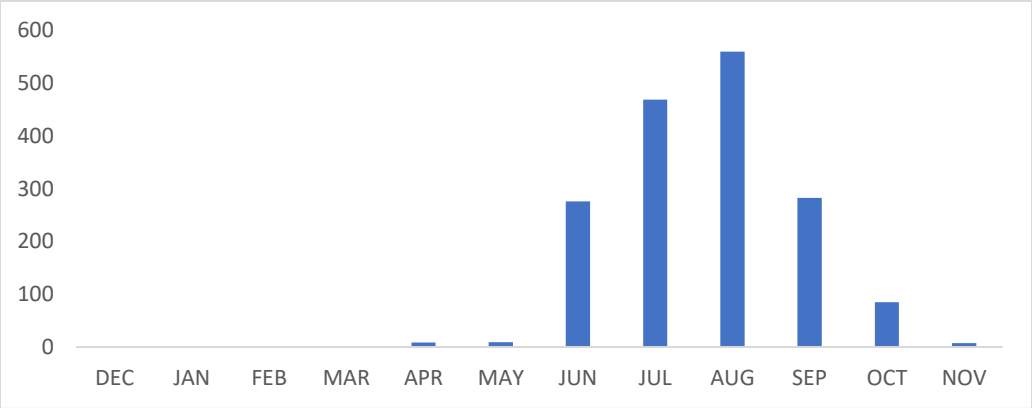


Figure 3: Monthly rainfall for the period 1958-2022

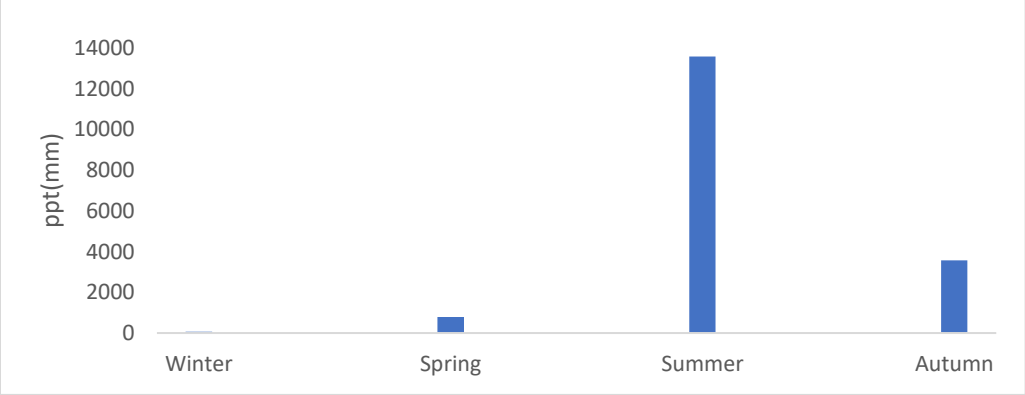


Figure 4: the four seasons rainfall for the period (1958-2022)

Thornthwaite Method for seasonal and monthly aridity

Sudan is mostly composed of arid and semi-arid regions with very few locations that are moist. Initially, Köppen classified a warm desert climate (BWh) for a significant portion of this region, a warm semi-arid climate (BSh) for a smaller portion, and a tropical savannah climate (Aw) for a few isolated tiny parts, mostly along the South Sudan border. Finding the wet and dry indicators is crucial in Sudan's arid and semi-arid regions. This will be accomplished by analyzing monthly and seasonal rainfall and temperature data from 25 sites over a 65-year period (1958–2022) using the Aridity Index. According to a number of studies (UNEP, 1992; Minoru Gamo et al. 2013, the monthly aridity index over the research area was shown in Table (9) and was comparable to those categories when evaluated using the Thornthwaite method. This study uses artificial intelligence to classify data into five categories: Humid (64–127), Sub-humid (32–63), Semi-arid (16–31), Arid (<16), and Very Humid (128≤). Although the Atlas World categorization gives arid regions a value of ($0.05 \leq AI < 0.20$), the values of arid regions in this study are less than 16. Notable aspects of drier conditions on a monthly basis throughout the research period Occasionally, this dry spell lasted up to a whole year. in,Atbara,ALAtrun,Gebeit,Dongola,Dagash,Port Sudan,Abu Hamed,Laqiya Arbain,WadiHalfa stations, so far, to 10 months in Khartoum, Umm Durman, and Aduragi stations, and 9 months in Kassala, Wad Medani, and Ed Dueim El Fasher stations. Additionally, Gedarif, Sennar, Geneina, Kosti Abu Na-ama, and Zallngei stations have recorded eight dry months, while El Obeid and Nyala stations have recorded seven dry months from December through April and November, sometimes reaching Kadugli four months in, even though it was recorded for the highest average rainfall during the study period (figure 2).

In May, 25 stations in western Sudan from Nayala, Abu Nama, Zallngei, and Alqadarif stations strongly suggest semi-arid conditions. The remaining study stations had one month in semi-arid conditions, and Umm Durman's stations had two months. Early April marks the beginning of the rainy season in southern Sudan as a result of the moist southwesterly winds reaching the area; by August, the winds have reached the northern borders. For this reason, throughout the summer (JJA), all stations aside from Atbara, that suffered from semi-arid conditions are humid or extremely humid. However, due to the influence of a dry northeasterly wind, all stations experience nearly dry conditions during the winter. Only in a small region in northeastern Sudan, where breezes from the Mediterranean occasionally deliver modest rainfall, can the country get rain during this time of year. But in the fall, three of these stations Nyala, Zallngei, Al Qadarif and El Obeid are categorized as semi-arid. Due to the moisture conditions caused by the ITCZ's southern excursion, 12 stations mostly close to the south border as well as Aduragi and Kassala in the central region have exceptionally humid conditions during the summer that are classified as humid or sub-humid. The length of the more humid season is evident. In this location, the four wettest seasons can be identified as follows: July and August (Gdarif, Kadugli); August and July (Nyala, El Obaied, Geneina, and Ed Dueim); April through November (Abu Na-ama); and July (Zallngei).Umm Durman, Atbara, AL Atrun, Dongola, Dagash, Port Sudan, Abu Hamed, Laqiya Arbain, and Wadi Halfa are all characterized by extreme drought event, where there may occasionally be eleven dry months and the climate does not meet the requirement of being more humid than the arid and semi-arid classes. Tables 9 and 10 show the differences between El Gadarif, Kadogli, and Genena, where summer humid has increased recently.

Table 7: Thornthwaite drought monthly index (DI)

station	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Kadugli	0	0	2.62	0.46	4.03	22.64	57.776	85.35	103.36	72.58	37.55	1.15
	D	D	D	D	D	SD	SH	H	H	H	SH	D
Nyala	0	0	0.000926	0.194904	1.35	0.05	50.64299	85.44	103.39	53.46	15.89	1.31
	D	D	D	D	D	D	SH	H	H	SH	D	D
Abu Na-ama	0	0	0.051178	11.86919	82.72	3.13	3217.207	5502.83	6607.98	3405.75	993.92	79.58
	D	D	D	D	H	D	SH	VH	VH	VH	VH	H

Zallngei	0	0	0.000961	0.434871	2.68	11.73	39.78846	104.83	134.47	53.63	8.62	0.00
	D	D	D	D	D	D	SH	H	VH	SH	D	D
El Obeid	0	0	0	1.231118	7.46	18.54	43.53256	83.36	114.32	60.44	12.07	0.00
	D	D	D	D	D	SD	SH	H	H	SH	D	D
Kosti	0	0	0.002676	0	0.04	6.34	21.11628	52.11	76.52	28.55	6.18	0.03
	D	D	D	D	D	D	SD	SH	H	SD	D	D
Geneina	0	0	0.000942	0	1.84	7.04	22.07304	85.24	111.00	38.67	5.93	0.00
	D	D	D	D	D	D	SD	H	H	SH	D	D
Sennar	0	0	0	0	0.97	6.71	26.70604	61.93	88.59	34.77	7.62	0.00
	D	D	D	D	D	D	SD	SH	H	H	D	D
El Fasher	0	0.001061	0.000999	0	0.93	3.89	10.98182	41.69	72.46	23.69	3.15	0.00
	D	D	D	D	D	D	D	SH	H	SD	D	D
Ed Dueim	0	0	0.000978	0	2.04	7.08	23.67947	82.30	114.47	37.39	5.20	0.00
	D	D	D	D	D	D	SD	H	H	SH	D	D
Al qadarif	0	0	0.023834	0.068074	1.71	13.13	45.85364	106.94	123.44	51.27	15.67	1.18
	D	D	D	D	D	D	SH	H	H	H	D	D
Wad Medani	0	0	0	0	0.00	5.23	15.91025	44.81	67.45	27.40	8.26	0.03
	D	D	D	D	D	D	D	SH	H	SD	D	D
Aduragi	0	0	0.001028	0	0.47	0.98	4.170844	28.09	54.62	12.32	0.69	0.00
	D	D	D	D	D	D	D	SD	SH	D	D	D
Kassala	0	0	0	0	0.83	4.26	11.77838	42.18	51.94	21.30	3.33	0.11
	D	D	D	D	D	D	D	SH	SH	SD	D	D
Khartoum	0	0.00096	0	0	0.00	0.92	2.646176	18.97	32.14	10.03	2.42	0.00
	D	D	D	D	D	D	D	SD	SH	D	D	D
Umm Durman	0	0	0	0	0.00	0.91	2.629811	16.74	30.70	9.94	1.92	0.01
	D	D	D	D	D	D	D	SD	SD	D	D	D
Atbara	0	0	0	0	0.00	0.71	0.515105	6.51	11.88	2.00	0.95	0.00
	D	D	D	D	D	D	D	D	D	D	D	D
AL Atrun	0	0	0.001083	0	0.00	0.00	0	4.38	13.48	0.49	0.00	0.00
	D	D	D	D	D	D	D	D	D	D	D	D
Gebeit	1.5	0.392727	2.468037	0.000987	1.55	3.70	1.391409	9.77	18.81	3.43	4.24	4.08
	D	D	D	D	D	D	D	D	SD	D	D	D
Dongola	0	0	0.001063	0	0.00	0.00	0	1.85	4.69	0.03	0.00	0.00

	D	D	D	D	D	D	D	D	D	D	D	D
Dagash	0	0	0	0	0.00	0.09	0	2.29	5.27	0.60	0.13	0.00
	D	D	D	D	D	D	D	D	D	D	D	D
Port Sudan	1.6	0.530936	9.183863	0.545083	0.96	0.58	0	1.52	2.35	0.00	5.52	12.35
	D	D	D	D	D	D	D	D	D	D	D	D
Abu Hamed	0	0	0	0	0.00	0.05	0	2.29	5.50	0.35	0.06	0.00
	D	D	D	D	D	D	D	D	D	D	D	D
Laqiya Arbain	0.01	0	0.001108	0	0.00	0.00	0	1.04	5.05	0.04	0.00	0.00
	D	D	D	D	D	D	D	D	D	D	D	D
Wadi Halfa	0.00	0	0	0	0.00	0.00	0	0.00	1.37	0.00	0.00	0.00
	D	D	D	D	D	D	D	D	D	D	D	D

H = HUMID, SH = SUB HUMID, SD= SEMI ARID, SD= SEMI ARID, D= ARID

Table 8: Thormathwite drought seasonal index

Station	Winter	Spring	Summer	Autumn
Kadugli	0.9	9.04	82.16	37.09
	D	D	H	SH
Nyala	0	0.53	79.82	23.56
	D	D	H	SD
Abu Na-ama	0	32.57	5109.34	1493.09
	D	SH	VH	VH
Zallngei	0	4.95	93.03	20.75
	D	D	H	SD
El Obeid	0	9.08	80.40	24.17
	D	D	H	SD
Kosti	0	2.13	49.91	11.59
	D	D	SH	D
Geneina	0	2.96	72.77	14.87
	D	D	H	D
Sennar	0	2.56	59.08	14.13
	D	D	SH	D
El Fasher	0	1.61	41.71	8.95
	D	D	SH	D
Ed Dueim	0	3.04	73.48	14.20
	D	D	H	D
Al qadarif	0	4.97	92.08	22.71
	D	D	H	SD
Wad Medani	0	1.74	42.72	11.89
	D	D	SH	D
Aduragi	0	0.48	28.96	4.34
	D	D	SD	D
Kassala	0	1.70	35.30	8.25
	D	D	SH	D
Khartoum	0	0.31	17.92	4.15
	D	D	SD	D

Station	Winter	Spring	Summer	Autumn
Umm Durman	0	0.30	16.69	3.96
	D	D	SD	D
Atbara	0	0.24	6.30	0.99
	D	D	D	D
AL Atrun	0	0	5.95	0.16
	D	D	D	D
Gebeit	1.4	1.75	9.99	3.92
	D	D	D	D
Dongola	0	0	2.18	0.01
	D	D	D	D
Dagash	0	0.03	2.52	0.24
	D	D	D	D
Port Sudan	4	0.70	1.29	5.95
	D	D	D	D
Abu Hamed	0	0.02	2.60	0.14
	D	D	D	D
Laqiya Arbain	0	0	2.03	0.01
	D	D	D	D
Wadi Halfa	0	0	0.46	0
	D	D	D	D

At least 12 stations in the area, which endured drought annually; during the study period, Atbara was less impacted by drought in 1959, from 1961 to 1967, and in 1988. The stations in Khartoum and Umm Durman were less affected by drought in 1988 and 1996. Overall, there were 64 and 65 years, respectively, when drought often plagued Khartoum and Atbara. Furthermore, Fasher and Kassala, among other stations, had semi-arid conditions for the duration of the study, with coefficients ranging from 5 to less than 10. Table (7) and figure (4) made it abundantly evident that the highest rainfall totals for the previous eight years were recorded, with values ranging from 898.2 to 938.3 mm/year. Kadogli Station in southern Sudan is classified as extremely humid because of the precipitation quantities seen there. Ten of the twenty-five stations, including Aduragi, Khartoum, Durman, and Atbara, had dry conditions in 2003 and 2004 (see table 11). Between 2003 and 2017, the Khartoum station was regularly hit by dry conditions; In contrast, Genena, Kosti, and Obaied were classified as having subhumid weather; the outliers were Kadogli in the south and Gadarif in the east, which had exceptionally humid circumstances. Accordingly, the eastern area of Sudan experienced above-average rainy weather in 2003, whereas the central Sudanese regions of Darfur and Kordofan experienced dry circumstances in 2004 (Khalid M. et al (2018). A strong relation was found in several studies between high average temperatures and drought. For instance, 2010 was deemed the warmest year on record for the period of 1958 to 2022, with a maximum temperature of 31.4 °C in some locations and an average of 29.1 °C. As a result, a continuous increase in temperature, from 23.4 °C to 31.4 °C, was also noted between 1961 and 2010. Figure 6 shows the study area's aridity and more humid conditions. Over the past 65 years, the region's extreme droughts have become more frequent and widespread, which has caused the northernmost areas of the region—such as Khartoum and Umm Durman—to shift from the arid to the hyper-arid zones. Furthermore, Elagib (2009) notes that the drought conditions have grown increasingly erratic and unpredictable. Despite the relatively different circumstances that developed in the semi-arid regions of central Sudan's east and southeast, namely Kassala in the east.

The Annual Aridity using De Martonne Method

The outcomes of using the De Martonne index annually to identify the research area's more humid years and aridity frequencies during the study period (1958–2022) were shown in Table (11). If we narrow down to specific years, we find that, for twenty-five stations, For 25 stations for the entire time, 1958 was the wettest year. As proof, consider the extreme drought that struck the same region in 1983–84, which was the worst

period for Sudan. overall was compared to the lowest rainfall average—20 mm reported in Wadi-Halfa. The greatest rainfall average recorded at Kadugli station was 938.3 mm. While 1990 appeared to be nearly dry during the research period, six sites also showed signs of dryness in 1997. Rainfall was recorded in Gadarif in 1981 and 1986, having respective average measurements of about 317.1 mm and 313.1 mm. Additionally, nine stations—El Obaied, Genena, Sennar, El Fasher, EdDueim, and Zellngei—were categorized as sub-humid with a value between 20 and 30, while ten stations—Kadugli and Gadarif—were reported as extremely humid with a value of ≥ 30.WadMedani and Kosti, Abu Na-ama. However, rather than being extremely humid in this study, 1990 and 1991 were among the driest years, according to Elagib (2009), primarily in Gadarif station.

According to Conway (2000), El Gadarif's observations are in line with the Ethiopian highlands' recovery to greater humidity levels in the 1990s. Every year, more than 600 mm of rain falls somewhere in East Central Sudan. In the meantime, soil evaporation is prevented in this area since the majority of the rainfall occurs in the late afternoon or during the colder part of the day. The fact that Gadarif state is one of the most productive rain-fed agricultural regions in central Sudan may be one factor contributing to the effectiveness of rainfall (Elhag and Sulieman, 2017).

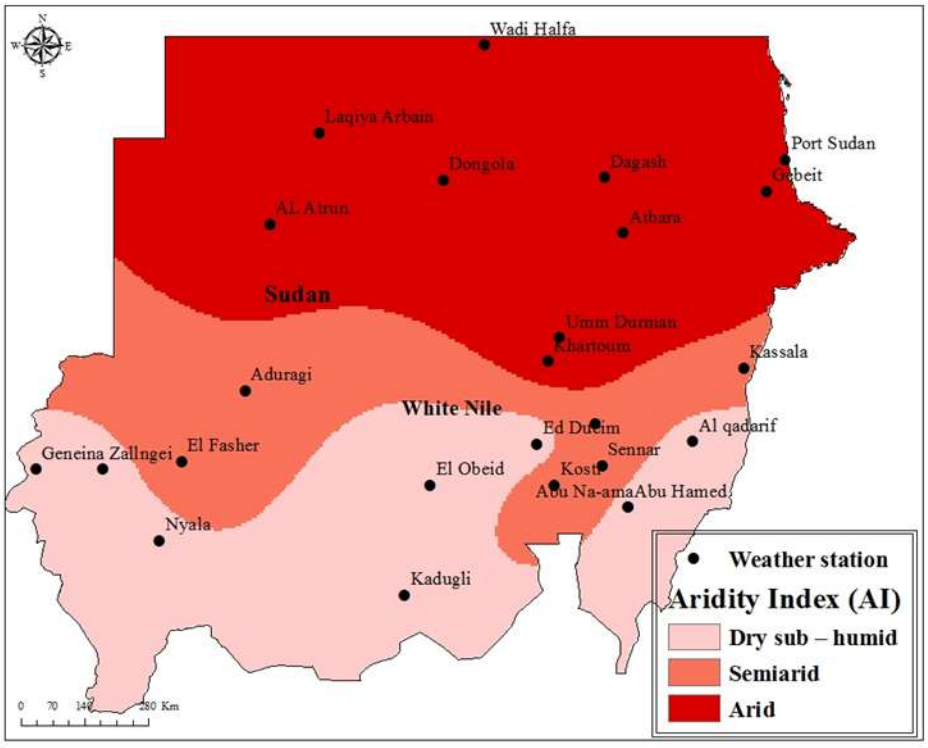


Figure 5: De Martonne Aridity Index (AI) classification for (1958-2022)

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

Table 9: Aridity Index (AI) classification according to De Martonne

Year	Kadugli	Nyala	Abu Na-ama	Zallngei	El Obeid	Kosti	Geneina	Sennar	El Fasher	Ed Dueim	Al qadarif	Wad Medani	Aduragi	Kassala	Khartoum	Umm	Atbara	AL Atrun	Gebeit	Dongola	Dagash	Port Sudan	Abu Hamed	Laqiya	Wadi Halfa
1958	18.46	16.6	17.8	19.9	27.99	13.04	15.53	14.86	9.47	15.83	18.62	11.19	6.50	8.21	4.35	4.00	2.49	1.46	1.21	0.67	0.86	1.86	0.83	0.39	0.00
1959	20.75	14.7	15.5	18.0	18.57	13.54	14.40	15.55	10.00	14.28	19.40	14.19	6.86	9.19	7.08	6.84	2.44	3.59	2.12	1.35	1.29	2.67	1.33	1.17	0.09
1960	17.89	15.4	16.2	19.9	18.10	8.14	14.94	11.35	9.26	15.15	16.02	8.02	5.90	5.89	1.73	1.63	0.48	0.17	0.53	0.00	0.15	0.65	0.08	0.00	0.00
1961	20.64	15.7	18.0	22.3	20.39	12.78	18.52	12.22	9.87	18.38	18.93	10.03	6.63	8.74	6.91	6.41	2.56	1.60	7.30	0.87	0.97	3.46	0.99	0.74	0.29
1962	21.75	16.5	18.9	20.5	21.90	12.00	17.01	13.26	10.79	16.78	17.13	11.59	7.16	7.58	5.80	5.38	1.89	4.11	3.25	1.55	1.30	4.50	1.49	2.24	0.55
1963	21.72	19.2	16.8	24.6	17.38	10.67	17.35	12.80	10.74	17.98	19.58	10.19	6.02	5.85	3.50	3.29	0.55	0.17	1.19	0.02	0.05	1.98	0.03	0.00	0.00
1964	24.46	16.4	17.6	22.8	23.99	11.57	20.78	13.91	11.07	20.56	19.92	11.79	7.77	11.20	7.30	6.95	2.38	0.84	6.54	0.58	1.48	2.86	1.53	0.29	0.06
1965	20.39	15.1	17.5	19.5	22.04	10.74	13.73	13.19	9.88	14.33	18.09	10.65	6.76	7.05	4.60	4.12	1.99	5.38	3.28	1.80	1.30	3.18	1.41	2.52	0.56
1966	16.84	15.9	15.3	18.6	17.49	8.86	13.80	10.34	9.31	14.30	16.10	7.72	5.31	5.75	3.67	3.63	0.58	1.42	2.59	0.41	0.12	2.82	0.14	0.54	0.23
1967	19.38	16.9	17.1	20.2	19.00	11.13	12.98	15.98	9.11	14.19	18.12	14.10	5.66	5.69	6.40	6.20	1.80	3.95	4.88	1.45	0.75	1.70	0.78	1.73	0.53
1968	16.14	17.5	16.4	23.1	18.27	9.96	15.66	12.66	10.04	16.79	17.09	9.55	6.08	7.92	5.06	4.90	2.14	0.83	6.93	0.42	0.67	2.69	0.66	0.21	0.00
1969	16.42	15.2	15.0	18.6	18.59	8.19	14.57	9.82	7.95	14.28	14.93	6.73	4.70	6.03	2.14	1.96	0.56	0.16	1.44	0.02	0.16	1.41	0.14	0.00	0.00
1970	16.25	15.8	13.4	18.0	13.23	8.68	12.62	10.45	10.11	13.03	15.69	8.56	6.33	6.38	3.13	2.89	2.08	0.70	2.11	0.33	1.02	1.42	1.02	0.16	0.00

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

Year	Kadugli	Nyala	Abu Na-ama	Zallngei	El Obeid	Kosti	Geneina	Sennar	El Fasher	Ed Dueim	Al qadarif	Wad Medani	Aduragi	Kassala	Khartoum	Umm	Atbara	AL Atrun	Gebeit	Dongola	Dagash	Port Sudan	Abu Hamed	Laqiya	Wadi Halfa
1971	16.41	13.5	14.7	0.0	13.31	9.92	13.50	12.87	9.18	14.37	18.93	10.09	5.75	8.11	3.55	3.30	0.66	1.25	3.45	0.40	0.37	1.71	0.32	0.37	0.03
1972	16.84	12.8	15.1	16.4	14.96	9.39	11.28	11.90	5.83	11.51	17.98	8.68	3.90	7.27	3.43	3.27	1.35	0.16	3.55	0.06	0.21	1.74	0.15	0.01	0.00
1973	13.31	12.1	14.5	13.3	14.08	8.60	8.33	10.58	5.88	8.69	16.18	6.60	3.49	6.10	2.74	2.53	0.70	0.16	0.98	0.05	0.24	0.47	0.22	0.01	0.00
1974	19.26	15.7	15.1	17.7	16.32	8.90	13.35	10.53	10.24	13.76	20.67	6.58	6.82	9.22	2.46	2.27	1.29	0.30	2.16	0.21	0.40	0.78	0.33	0.09	0.01
1975	16.98	13.8	16.7	17.8	15.83	11.65	12.67	13.19	7.74	13.73	19.26	9.10	5.55	7.09	2.87	2.75	1.63	0.39	3.81	0.17	0.32	1.27	0.27	0.09	0.01
1976	15.76	13.3	14.2	15.9	18.74	9.48	11.03	11.08	6.91	11.40	17.95	7.66	3.94	7.57	3.46	3.38	1.36	0.16	2.03	0.03	0.18	2.96	0.13	0.00	0.00
1977	20.78	13.1	13.4	16.0	14.62	9.23	12.70	10.47	7.60	12.86	16.82	7.57	5.20	6.06	3.13	2.97	1.25	1.84	1.19	0.69	1.02	0.66	1.08	0.47	0.04
1978	23.16	16.2	14.4	20.2	17.33	10.08	15.39	13.34	8.36	15.57	18.28	10.39	5.41	8.40	4.85	4.58	2.08	0.89	4.29	0.79	0.94	2.18	0.88	0.40	0.01
1979	17.60	13.3	13.3	17.3	15.12	7.57	13.06	10.19	6.89	12.95	17.87	7.60	4.42	7.57	3.31	3.33	1.26	0.98	6.39	0.36	0.56	1.82	0.47	0.30	0.03
1980	16.59	15.3	13.3	17.1	14.32	10.49	12.79	10.17	8.14	12.50	18.71	8.22	5.45	8.16	3.39	3.11	1.19	0.35	0.78	0.18	0.51	0.52	0.49	0.05	0.00
1981	23.88	12.3	14.6	15.0	13.45	7.48	11.18	9.56	6.93	11.20	18.68	7.20	4.23	7.13	3.05	2.77	0.60	0.16	1.02	0.02	0.09	0.98	0.06	0.00	0.00
1982	13.47	10.4	11.4	13.1	15.68	6.55	9.58	7.43	5.85	10.09	15.81	5.75	4.16	5.76	2.47	2.30	0.47	0.17	1.53	0.02	0.09	2.87	0.07	0.00	0.00
1983	15.14	9.8	11.4	13.0	10.88	7.12	9.01	7.70	5.82	10.14	13.82	4.75	4.28	5.47	1.56	1.48	0.43	0.18	0.38	0.01	0.02	0.38	0.01	0.00	0.00
1984	11.15	6.1	8.5	8.2	12.30	2.77	7.94	4.56	3.26	6.53	9.30	2.79	1.85	2.62	0.40	0.35	0.06	0.15	0.69	0.00	0.01	1.22	0.00	0.00	0.00

Year	Kadugli	Nyala	Abu Na-ama	Zallngei	El Obeid	Kosti	Geneina	Sennar	El Fasher	Ed Dueim	Al qadarif	Wad Medani	Aduragi	Kassala	Khartoum	Umm	Atbara	AL Atrun	Gebeit	Dongola	Dagash	Port Sudan	Abu Hamed	Laqiya	Wadi Halfa
1985	15.49	11.6	11.4	15.1	13.88	7.64	13.35	9.92	6.12	12.35	16.97	8.42	3.98	6.04	1.94	1.76	0.56	0.17	2.01	0.01	0.05	2.94	0.03	0.00	0.00
1986	17.89	9.6	13.0	13.8	13.62	7.86	11.25	9.38	6.61	11.43	13.96	6.41	4.50	6.50	2.35	2.13	0.85	0.17	0.92	0.17	0.27	1.25	0.23	0.07	0.02
1987	13.42	8.8	12.0	10.8	12.94	7.41	8.04	9.00	6.28	8.70	13.64	6.93	4.06	4.70	2.57	2.41	1.36	0.17	1.02	0.15	0.70	1.07	0.72	0.03	0.03
1988	18.02	16.5	16.5	22.4	16.57	9.70	17.57	11.86	10.14	17.67	19.72	10.29	6.70	9.38	8.79	8.64	2.57	3.48	3.18	1.28	0.76	0.75	0.75	1.39	0.49
1989	19.38	14.2	16.7	16.8	12.34	9.19	12.40	11.76	6.63	12.48	19.59	7.92	3.62	5.48	1.91	1.78	0.98	0.16	1.77	0.05	0.47	1.66	0.45	0.01	0.02
1990	13.09	9.1	10.7	10.7	13.74	5.22	8.45	5.89	4.28	7.75	8.67	3.26	2.38	1.92	0.69	0.61	0.15	0.15	0.65	0.00	0.01	0.82	0.01	0.00	0.00
1991	18.43	14.1	12.5	18.7	18.17	8.64	14.73	8.97	8.14	14.64	14.48	5.42	5.71	3.95	1.52	1.36	0.31	0.17	0.94	0.04	0.16	0.83	0.14	0.01	0.00
1992	16.89	11.4	11.9	15.2	17.35	7.01	12.32	9.40	7.55	12.56	17.50	7.40	5.86	8.24	3.33	3.21	1.03	4.27	4.71	1.12	0.25	2.66	0.25	1.27	0.05
1993	18.18	10.6	19.3	13.1	13.42	11.21	9.95	13.40	5.56	9.94	20.60	9.42	3.33	6.28	3.69	3.48	0.58	1.14	1.37	0.27	0.10	1.08	0.06	0.30	0.01
1994	18.20	16.1	15.2	22.0	20.74	10.07	17.10	11.56	11.01	17.88	17.11	8.85	7.11	6.68	4.54	4.35	1.87	4.77	4.31	1.35	1.09	1.34	1.13	0.95	0.03
1995	23.12	11.9	12.7	17.4	15.61	8.24	13.38	11.66	7.98	13.45	17.20	10.22	5.42	7.87	5.03	4.65	1.79	0.17	2.91	0.06	0.70	2.77	0.65	0.00	0.02
1996	17.07	12.1	14.0	13.6	14.32	9.15	8.92	11.43	5.83	9.20	16.71	8.59	3.77	4.97	3.26	3.00	0.39	0.16	1.19	0.01	0.04	1.20	0.02	0.00	0.00
1997	19.08	12.9	14.6	16.4	13.64	7.80	13.04	9.76	5.96	12.65	16.05	7.89	4.35	6.10	3.37	3.14	1.46	0.83	2.50	0.33	0.23	1.97	0.20	0.23	0.01
1998	20.97	15.5	17.0	20.6	17.08	10.02	15.29	12.08	12.19	16.50	17.82	9.81	8.20	7.27	3.90	3.64	0.84	1.49	6.77	0.38	0.34	1.02	0.26	0.40	0.02

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

Year	Kadugli	Nyala	Abu Na-ama	Zallngei	El Obeid	Kosti	Geneina	Sennar	El Fasher	Ed Dueim	Al qadarif	Wad Medani	Aduragi	Kassala	Khartoum	Umm	Atbara	AL Atrun	Gebeit	Dongola	Dagash	Port Sudan	Abu Hamed	Laqiya	Wadi Halfa
1999	21.88	17.1	16.9	20.0	15.81	11.16	14.45	13.29	10.27	15.11	22.99	10.79	6.72	9.68	4.80	4.58	3.23	1.28	2.16	0.54	1.06	1.09	0.95	0.31	0.02
2000	15.26	16.9	15.0	16.7	12.76	9.18	10.25	10.68	9.26	11.68	17.46	7.36	5.44	6.09	1.84	1.64	0.16	0.59	1.77	0.15	0.03	2.03	0.03	0.12	0.00
2001	22.29	11.9	13.6	16.6	14.36	8.38	13.13	10.12	7.07	13.29	16.80	8.25	4.40	7.04	3.49	3.18	0.45	0.16	0.90	0.01	0.04	2.01	0.02	0.00	0.00
2002	19.59	10.8	12.6	14.4	14.31	8.54	11.97	9.99	6.48	11.61	17.25	7.97	4.48	6.38	2.70	2.49	0.45	1.07	1.19	0.28	0.25	2.57	0.25	0.29	0.02
2003	16.77	18.0	15.5	21.3	19.96	10.61	16.37	12.92	7.57	16.27	21.98	11.31	4.54	10.09	5.05	4.81	2.68	0.89	3.94	0.73	0.77	0.67	0.76	0.58	0.20
2004	14.96	13.1	12.6	16.0	13.62	7.15	12.55	8.52	5.65	12.21	13.86	6.40	3.14	4.80	2.68	2.50	0.38	0.16	1.18	0.01	0.04	2.60	0.03	0.00	0.00
2005	18.22	13.7	13.1	21.4	19.13	8.53	17.63	9.29	10.22	17.53	16.44	6.87	6.82	8.30	3.12	2.92	1.47	1.68	3.95	0.59	0.31	0.69	0.28	0.45	0.00
2006	19.24	15.5	14.8	18.3	14.22	10.13	13.24	11.29	9.08	13.82	19.00	9.01	6.08	7.78	3.33	3.19	0.94	0.16	2.45	0.11	0.78	1.61	0.82	0.02	0.04
2007	24.07	14.7	19.6	18.9	17.52	15.03	14.81	16.40	9.94	15.18	19.98	11.36	8.02	8.32	5.11	4.94	1.89	0.24	8.07	0.38	0.80	1.10	0.80	0.12	0.04
2008	17.30	15.8	16.0	17.2	16.55	8.94	11.81	10.64	7.47	12.28	16.00	7.19	4.25	5.39	2.39	2.19	0.39	0.15	0.67	0.01	0.05	0.05	0.03	0.00	0.00
2009	14.04	10.1	12.7	13.8	16.02	7.70	11.86	8.78	5.10	11.35	13.00	6.44	3.59	3.94	3.05	2.81	0.54	0.16	0.33	0.04	0.28	0.22	0.29	0.00	0.01
2010	20.27	14.8	16.7	20.0	15.61	9.47	16.10	11.20	8.35	15.74	18.03	8.16	5.17	6.44	2.72	2.50	0.93	1.96	5.05	0.82	0.77	0.98	0.85	1.19	0.52
2011	16.88	12.9	10.9	17.1	14.52	7.06	14.03	7.68	7.39	13.68	11.92	5.59	5.20	4.05	1.97	1.80	0.70	0.17	0.67	0.01	0.06	0.58	0.04	0.00	0.00
2012	18.38	16.5	15.1	27.4	18.26	9.62	24.07	11.27	10.70	23.06	15.30	7.98	7.28	3.69	2.90	2.60	0.20	0.27	0.72	0.05	0.03	1.30	0.03	0.04	0.00

Year	Kadugli	Nyala	Abu Na-ama	Zallngei	El Obeid	Kosti	Geneina	Sennar	El Fasher	Ed Dueim	Al qadarif	Wad Medani	Aduragi	Kassala	Khartoum	Umm	Atbara	AL Atrun	Gebeit	Dongola	Dagash	Port Sudan	Abu Hamed	Laqiya	Wadi Halfa
2013	16.81	17.5	13.2	19.4	16.82	9.85	13.11	10.57	9.71	14.00	14.54	7.80	6.27	5.79	3.18	3.07	2.11	1.26	8.11	0.64	1.11	1.46	1.20	1.06	0.54
2014	22.31	13.6	16.9	19.6	16.18	11.27	16.42	13.33	9.57	16.34	21.42	10.39	6.45	8.00	4.38	4.03	0.93	2.10	3.61	0.67	0.30	1.37	0.29	0.59	0.02
2015	18.18	13.3	13.1	17.2	18.21	7.56	14.33	8.81	6.85	13.90	14.19	5.41	4.26	6.18	2.32	2.29	2.16	0.16	1.89	0.06	0.29	1.96	0.20	0.01	0.00
2016	20.35	12.3	14.6	14.0	18.81	6.55	10.58	10.18	6.88	9.87	18.05	7.97	3.48	6.72	1.94	1.77	0.30	0.62	1.40	0.11	0.03	1.39	0.03	0.19	0.01
2017	19.92	11.6	15.0	14.9	17.73	9.98	11.46	11.40	6.53	11.12	15.98	8.33	3.43	5.03	3.18	2.94	0.93	0.76	2.02	0.24	0.35	1.99	0.36	0.13	0.04
2018	21.98	16.6	17.7	20.5	17.67	10.24	15.15	12.64	9.82	16.08	22.12	10.14	7.42	9.63	4.25	4.03	1.93	0.82	5.50	0.42	0.67	3.94	0.67	0.33	0.05
2019	14.54	8.6	9.3	11.6	11.31	5.71	9.54	8.06	5.03	9.76	13.44	5.47	2.35	5.12	2.26	2.16	1.30	0.34	2.31	0.11	0.24	1.21	0.21	0.11	0.28
2020	14.41	10.5	10.5	18.5	12.84	11.50	13.50	13.05	9.58	13.45	15.31	9.79	7.87	4.33	1.85	1.58	0.85	1.15	1.96	0.23	0.45	1.07	0.66	0.39	0.05
2021	10.66	8.2	8.1	12.5	10.36	4.79	9.21	6.15	4.76	8.29	8.54	3.31	1.76	3.15	1.35	1.19	0.58	0.20	1.85	0.22	0.47	1.00	0.42	0.04	0.10
2022	13.91	11.0	11.4	14.8	15.62	11.33	11.40	11.84	5.64	11.47	16.34	7.66	3.75	4.25	1.99	1.59	0.66	0.28	2.15	0.06	0.27	1.58	0.25	0.15	0.01
average	18.04	13.66	14.44	17.16	16.24	9.20	13.33	10.99	7.99	13.47	16.92	8.29	5.19	6.58	3.40	3.19	1.19	1.01	2.67	0.37	0.46	1.64	0.45	0.35	0.08

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

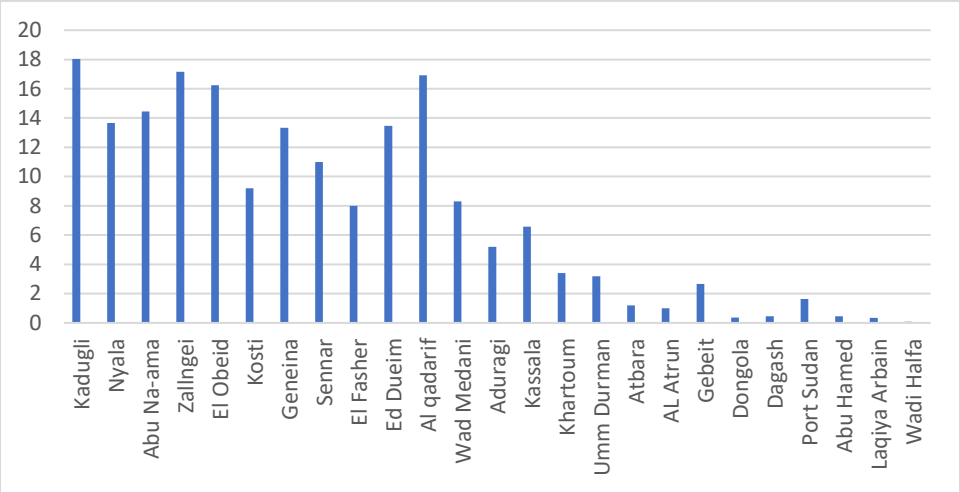


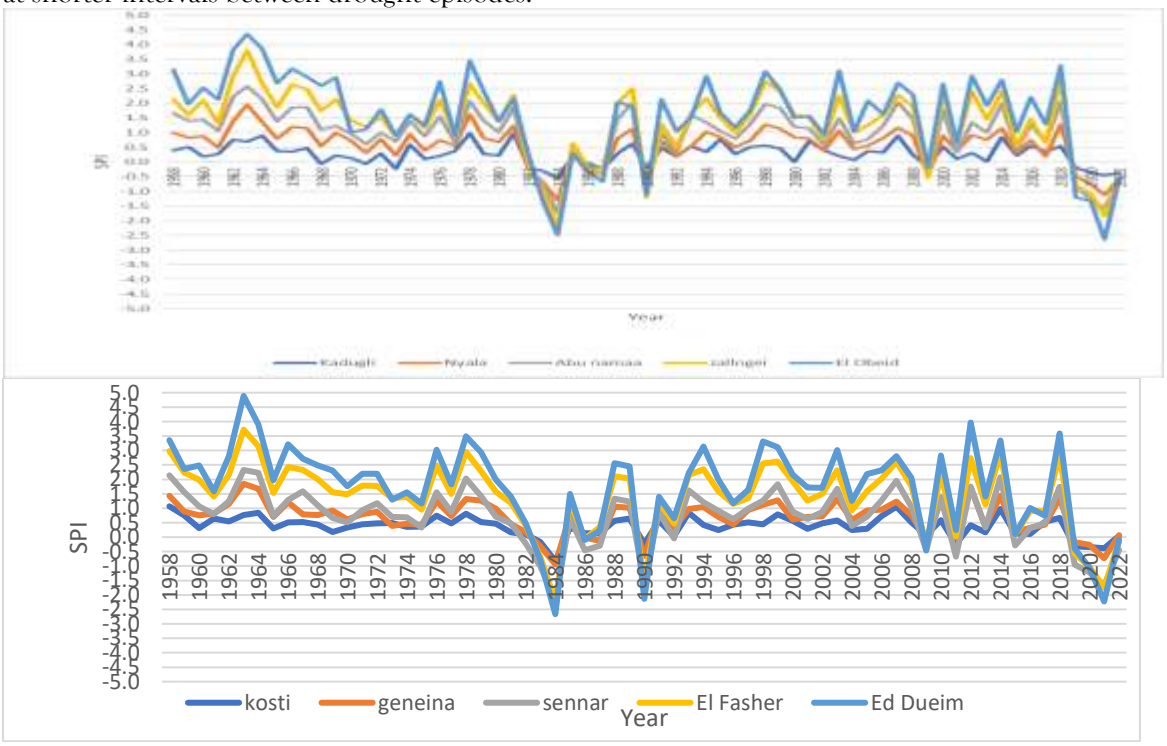
Figure 6**: station Rainfall (1958-2022)**

Figure 7 Annual mean Aridity Index for study area in period 1958-2022

Standardized Precipitation Index (SPI)

The findings showed how the Standardized Precipitation Index (SPI) varied across 25 stations. Kadugli had the highest edge, reaching a maximum value of 2.00 in 2007. Wadi Halfa had the lowest edge, with a value of only -2.10 in 1962, 1967, 1988, and 2013, although there was convergence amongst other stations (Figure

7). The rainfall amount, which recorded the highest value (during the entire period) in Kadugli (938.3 mm) in 2007 and the lowest value (20) in Wadi Halfa (2013), is the reason for this finding, which is typical of AI results in time and location. This conclusion is supported by the rainfall amount figure (8), which displayed the relationship between monthly rainfall and SPI, with August seeing the highest SPI occurrence in the rainy moths. The annual Standardized Precipitation Index (SPI) at the 25 stations is rising over time, according to Figure 9. All of the study area's focal points showed signs of improving drought conditions. In Kadugli, Nyala, Abu Nama, and Elobied, roughly 70% of the time period was classified as near normal; in Elfasher station, the percentage was roughly 56%. Additionally, Figure 9 showed that approximately 16% of the graph's points fell into the moderately wet zone for 25 stations, with some points in the severe wet zone for Kassala and Wadmedni and in the extreme wet zone for Eldouim, Elobied, and Elfasher. However, extreme dry zone conditions only happened once in Eldouim in 1984, while they were severe in Kassala and Wadmedni in 1990 and Elfasher in 1983. Comparable findings from SPI's 1941–1970 analysis for Sudan's arid and semi-arid regions. The fact that the extremely and severely wet classes experienced wet conditions for a number of years was evident. Only one case was severe during the June–August drought, while the majority were mild. The wet cases, however, were almost always mild and infrequently moderate. As per the analysis of long-term data (1941-2004) from 25 stations in semi-arid areas (El Fasher, Elobied, Port Sudan) and arid areas (Atbara, Dagasha, Dongola, Laqiya Arbain, and Wadi Halfa), "SPI analysis showed that severe drought has occurred during 1984, 1990, 1991whereas only certain regions of the region were impacted by the droughts in 1972, 1983, and 2000. Additionally, it was mentioned that a study of the standardized precipitation index (SPI) time series for Sudan's arid and semi-arid regions from 1941 to 2010 (using data from 25 stations spread throughout the region) revealed that drought has become more likely in the last 40 years and that it occurs at shorter intervals between drought episodes.



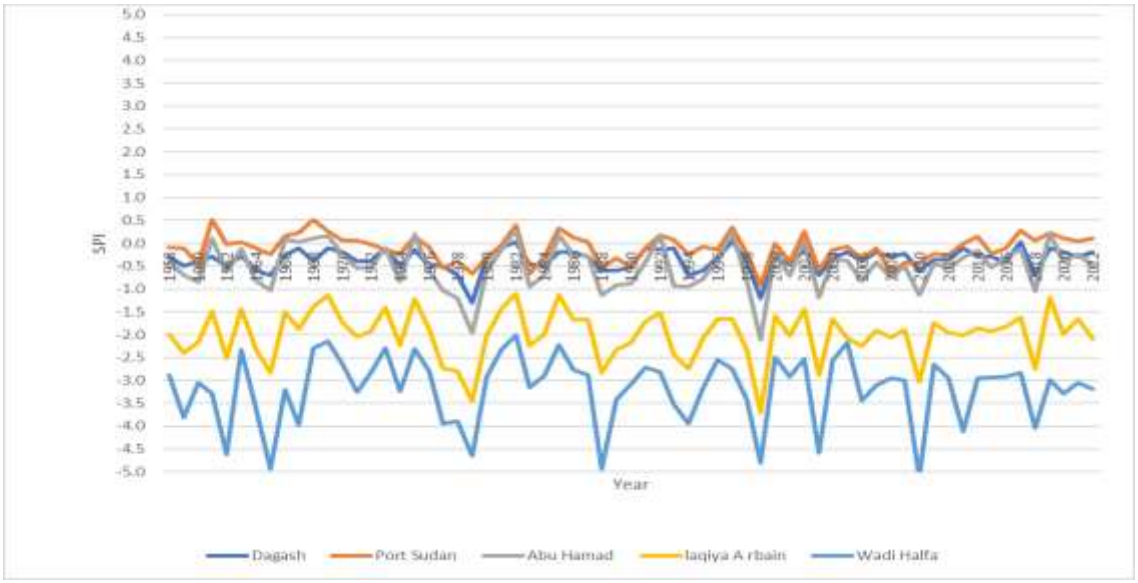
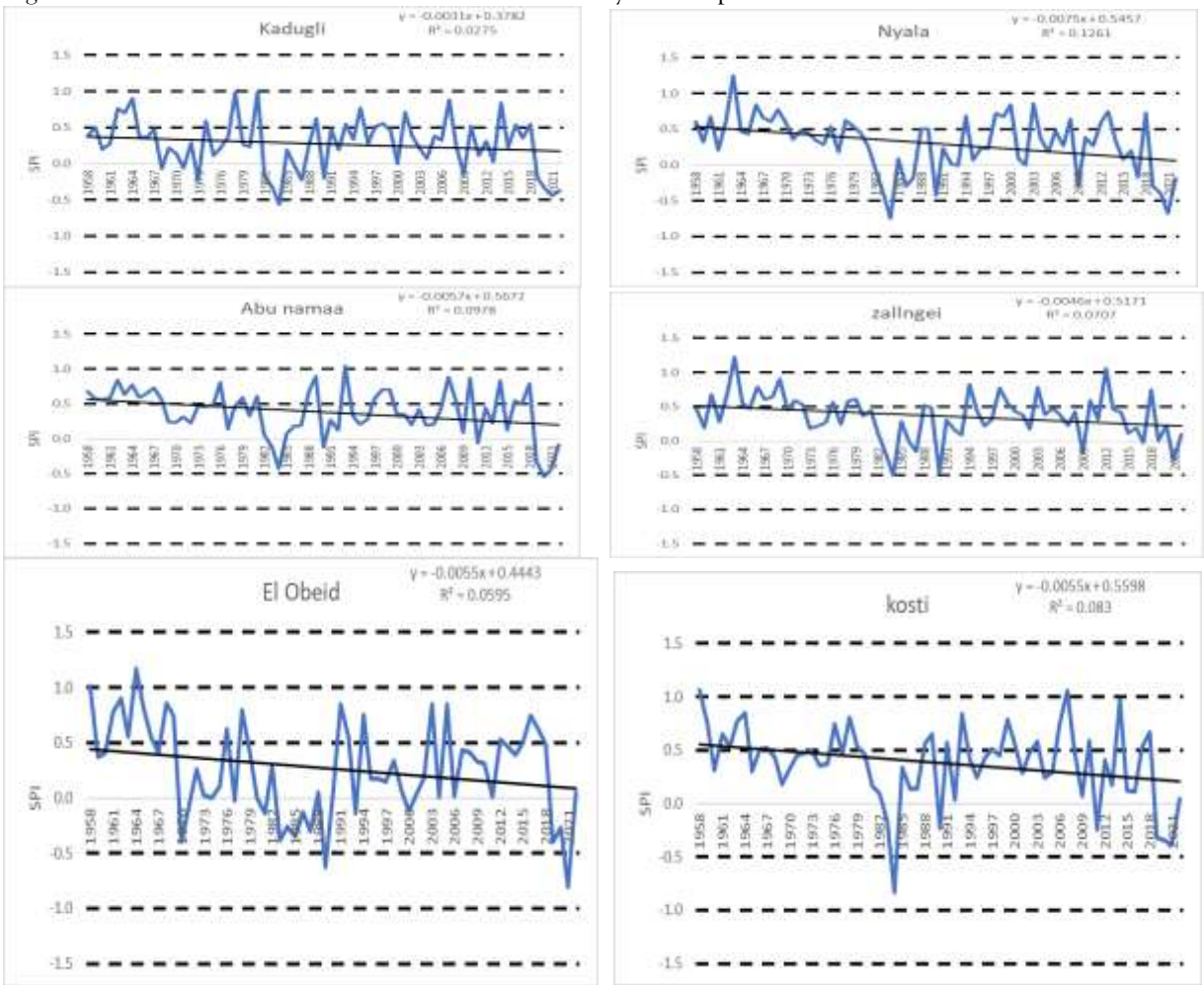
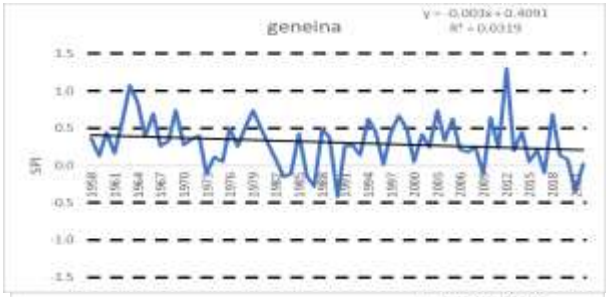
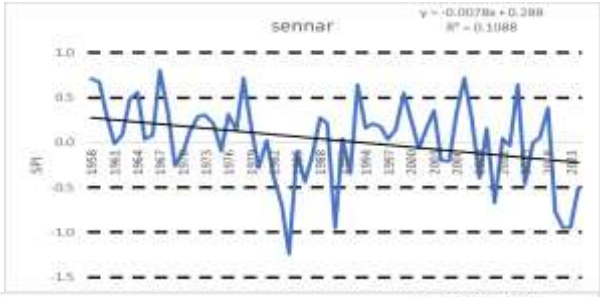


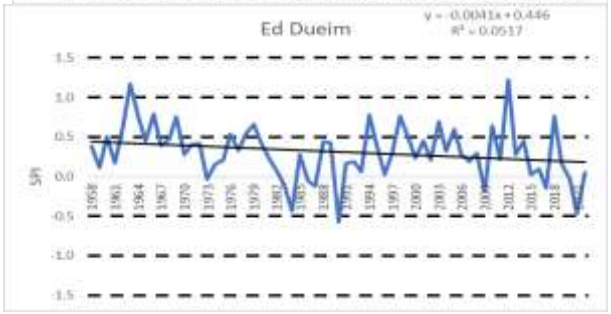
Figure 8: Annual mean SPI of the stations in the study area in period 1958-2022

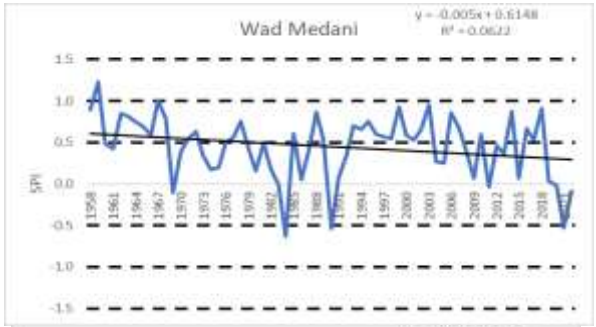


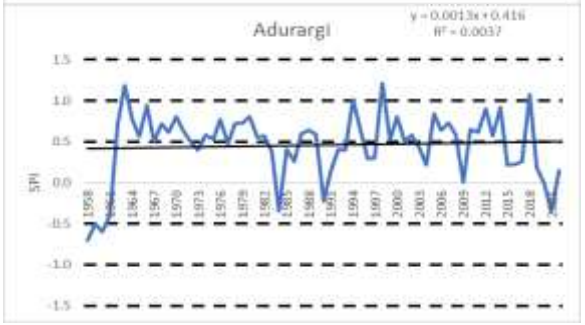
International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s,2025
https://theaspd.com/index.php

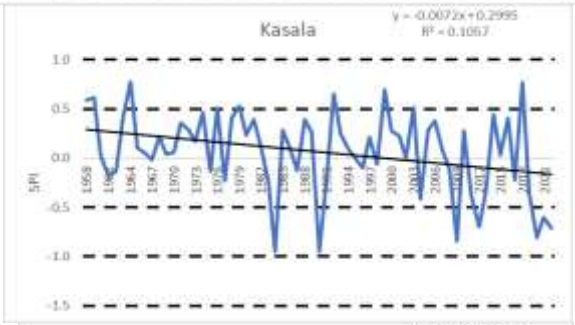


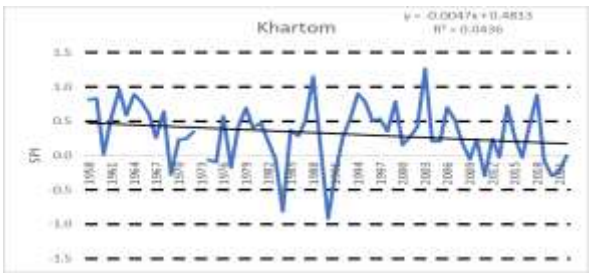


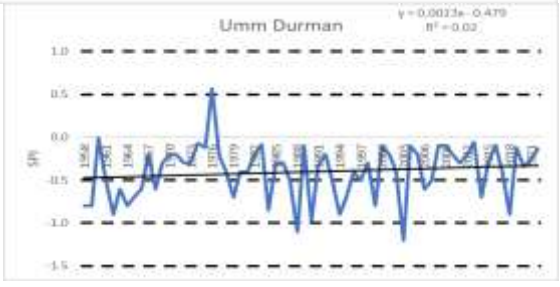












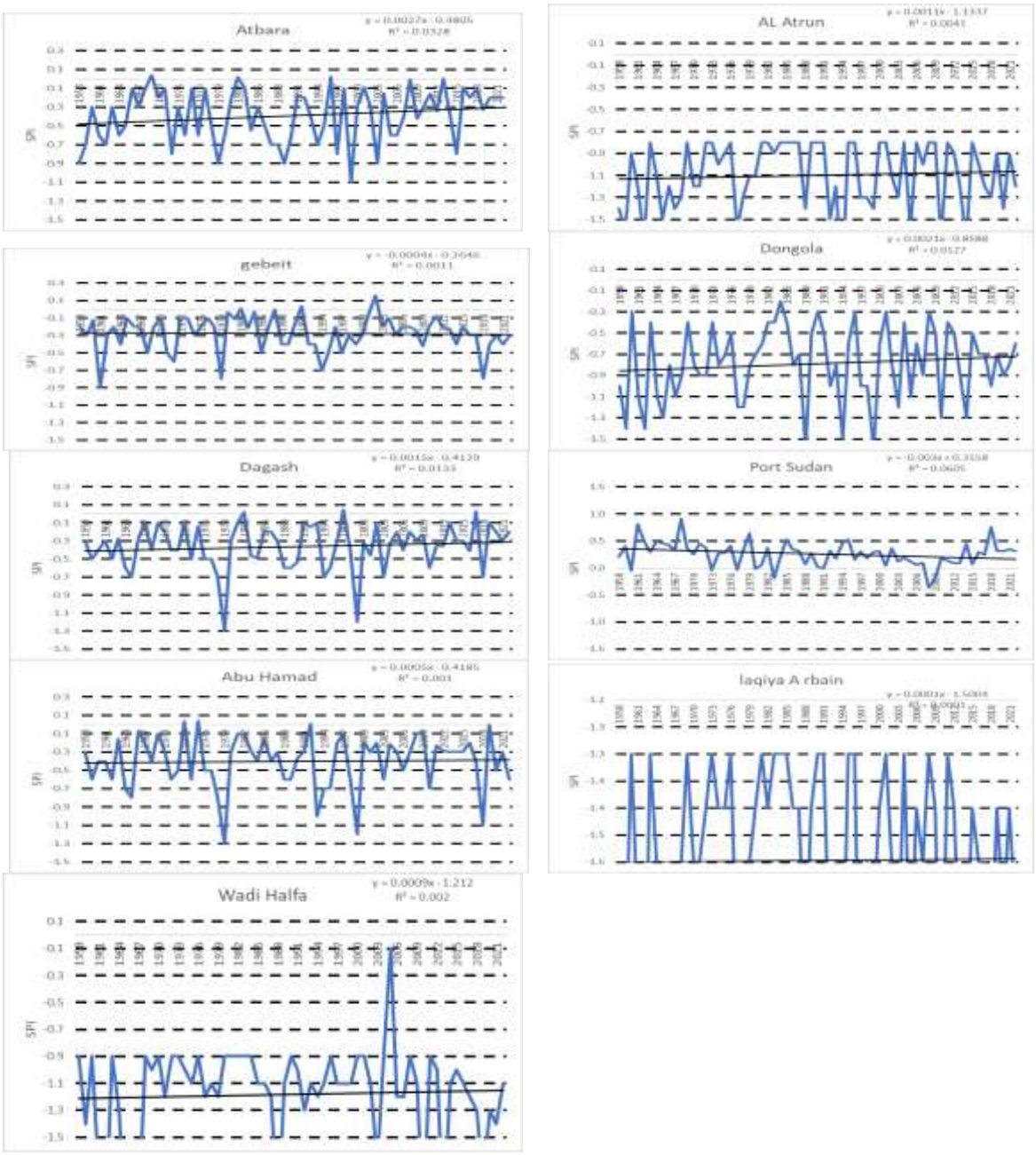


Figure 9: Standardized Precipitation Index trend in stations of the study area in the period 1958-2022

4. CONCLUSION

Five categories—arid, semi-arid, sub-humid, and humid—were created from the results of the three meteorological indices, which were based on monthly, seasonal, and annual rainfall and temperature measurements. For example, the values of the monthly/seasonal aridity index were different from those of the annual aridity index. These values were shown as follows at the annual aridity index: > 16 for arid versus < 5, 16-31 for semi-arid versus -5, 32-63 for sub-humid versus -10, 64-127 for humid versus -20, and ≥ 128 for very humid versus ≥ 30. The most affected locations were displayed in Figure 9, which includes stations in the Northern region that are categorized as desert for 65 years, such as Adurgi, Khartoum, Ummdurman, Dongola, Dagash, and Atbara. On the other hand, stations in the Central region, such as Fasher, Obaied,

and Kassala, experienced semi-arid conditions for the duration of the study period, whereas Kosti experienced moderately humid conditions. Additionally, over the course of the 65 years, extremely humid conditions predominated at stations in the southern region, mainly Kadugli and Gadarif in the east; Genena, on the other hand, was depicted as having sub-humid conditions. Furthermore, the research area stations that displayed an increase in the spatial extent of drought, which was linked to changes in temperature and precipitation, were displayed in figure (9). Previous research revealed that the amount of rainfall in Sudan as a whole was below average in 2010; as a result, the amount of rainfall fluctuated annually (Khalid M. et al. 2018). Additionally, the characteristics of the drought varied both regionally and temporally throughout Sudan in terms of severity. The overall regional climate system controlled the pattern of rainfall, which was a consequence of climate change. As a result, there has been a shift in the climate from hyper-arid to semi-arid, as shown by the fact that six of the 25 sites have had arid or semi-arid conditions for 65 years. Around the same time as El Niño 2009–10, which was deemed to be of moderate strength, several African nations were impacted, including Sierra Leone, Sudan, Kenya, Somalia, and Ethiopia experienced the worst droughts. in thirty years. Between 1966 and 2019, there was a consistent decrease in seasonal rainfall in July and August of between 81 and 95.8 mm. According to this study, the wet season is getting shorter as a result. For instance, at Fasher Station, rather than July, August, and September, the rainy season only lasts through August. According to Le Barbé and Lebel (1997), the precipitation deficit in West Africa during the dry periods was mostly caused by a lack of rainfall events throughout the rainy season. As a result, throughout July and August, rainfall has decreased by roughly 3.2 to 4.9 mm per month over the Sahel region. Physical and human factors, such as overgrazing and deforestation on marginal lands that has resulted in desertification and changes in the surrounding ocean temperature, are some of the variables impacting drought over the study area. In addition to decreasing monsoon rains and raising ocean temperatures in the south and Indian oceans, climate change has also decreased or altered the predictability of rainfall. It is highly advised that the drought conditions in Sudan be taken into account using various meteorological indexes over a minimum of 100 years. Hydrological modeling of the area using the available historical and predicted climate data should be developed.

REFERENCES:

- CONWAY, D. 2000. The climate and hydrology of the Upper Blue Nile River. *The Geographical Journal,* 166, 49-62.
- EL-MAHDY, M. E.-S., ABDEL-MONSEF, M., ABO-ELELLA, S. & SHAHBA, M. 2024. Impact of climate change on the water resources of the Atbara River using novel hydrological models. *Water Science and Technology,* 89, 1419-1440.
- ELAGIB, N. A. 2009. Assessment of drought across central Sudan using UNEP dryness ratio. *Hydrology Research,* 40, 481-494.
- ELAGIB, N. A. & ELHAG, M. M. 2011. Major climate indicators of ongoing drought in Sudan. *Journal of Hydrology,* 409, 612-625.
- ELAGIB, N. A., ZAYED, I. S. A., SAAD, S. A. G., MAHMOOD, M. I., BASHEER, M. & FINK, A. H. 2021. Debilitating floods in the Sahel are becoming frequent. *Journal of Hydrology,* 599, 126362.
- ELHAG, M. M. & SULIEMAN, H. M. 2017. Rainfall erosivity, land-use and land-cover change analysis for Gadarif region, Sudan. *International Journal of Water Resources and Arid Environments,* 6, 252-260.
- GELAW, A. & DEBELE, M. 2024. International water conventions, the exploitation of trans-boundary rivers and the Nile water dispute among Ethiopia, Sudan and Egypt. *Heliyon,* 10.
- LE BARBÉ, L. & LEBEL, T. 1997. Rainfall climatology of the HAPEX-Sahel region during the years 1950–1990. *Journal of hydrology,* 188, 43-73.
- LI, Y., QIN, Y. & RONG, P. 2022. Evolution of potential evapotranspiration and its sensitivity to climate change based on the Thornthwaite, Hargreaves, and Penman–Monteith equation in environmental sensitive areas of China. *Atmospheric Research,* 273, 106178.
- MCKEE, T. B., DOESKEN, N. J. & KLEIST, J. The relationship of drought frequency and duration to time scales. 1993. Boston, 179-183.
- MERA, G. A. 2018. Drought and its impacts in Ethiopia. *Weather and Climate Extremes,* 22, 24-35.

- MOHAMED, M. A. & EL-MAHDY, M. E.-S. 2021a. Impact of sunspot activity on the rainfall patterns over Eastern Africa: a case study of Sudan and South Sudan. *Journal of Water and Climate Change,* 12, 2104-2124.
- MOHAMED, M. A., EL AFANDI, G. S. & EL-MAHDY, M. E.-S. 2022. Impact of climate change on rainfall variability in the Blue Nile basin. *Alexandria Engineering Journal,* 61, 3265-3275.
- MOHAMED, M. A. E.-H., MOURSY, F. I., DARRAG, M. H. & EL-MAHDY, M. E.-S. 2023. Assessment of long-term trends and mapping of drought events in Tunisia. *Scientific African,* 21, e01766.
- MOHAMED, M. A. H. & EL-MAHDY, M. E. S. 2021b. Evaluation of climate change impact on extreme temperature variability in the Blue Nile Basin, Ethiopia. *Geosci. Instrum. Method. Data Syst.,* 10, 45-54.
- MOHMMED, A., ZHANG, K., KABENGE, M., KEESSTRA, S., CERDÀ, A., REUBEN, M., ELBASHIER, M. M. A., DALSON, T. & ALI, A. A. S. 2018. Analysis of drought and vulnerability in the North Darfur region of Sudan. *Land Degradation & Development,* 29, 4424-4438.
- MUJUMDAR, M., BHASKAR, P., RAMARAO, M. V. S., UPPARA, U., GOSWAMI, M., BORGAONKAR, H., CHAKRABORTY, S., RAM, S., MISHRA, V., RAJEEVAN, M. & NIYOGI, D. 2020. Droughts and Floods. *In:* KRISHNAN, R., SANJAY, J., GNANASEELAN, C., MUJUMDAR, M., KULKARNI, A. & CHAKRABORTY, S. (eds.) *Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MoES), Government of India.* Singapore: Springer Singapore.
- NICHOLSON, S. E. 1986. The spatial coherence of African rainfall anomalies: Interhemispheric teleconnections. *Journal of Applied Meteorology and Climatology,* 25, 1365-1381.
- PALTINEANU, C., MIHAILESCU, I. F., SECELEANU, I., DRAGOTA, C. & VASENCIUC, F. 2007. Using aridity indices to describe some climate and soil features in Eastern Europe: a Romanian case study. *Theoretical and Applied Climatology,* 90, 263-274.
- PELLICONE, G., CALOIERO, T. & GUAGLIARDI, I. 2019. The De Martonne aridity index in Calabria (Southern Italy). *Journal of Maps,* 15, 788-796.
- SAHOUR, H., VAZIFEDAN, M. & ALSHEHRI, F. 2020. Aridity trends in the Middle East and adjacent areas. *Theoretical and Applied Climatology,* 142, 1039-1054.
- SHERIF, M. I. & STURCHIO, N. C. 2021. Elevated radium levels in Nubian Aquifer groundwater of Northeastern Africa. *Scientific Reports,* 11, 78.
- SIMONIN, V., VAGHEFI, S. A., ABDELGADIR, Z. M., ELTAYEB, D., SIDAHMED, M. A. M., MONET, J.-P. & RAY, N. 2023. Present and Future Drinking Water Security and Its Impacts on Maternities: A Multi-Scale Assessment of Sudan. *International Journal of Environmental Research and Public Health* [Online], 20.
- TABARI, H., HOSSEINZADEH TALAEE, P., MOUSAVI NADOUSHANI, S. S., WILLEMS, P. & MARCHETTO, A. 2014. A survey of temperature and precipitation based aridity indices in Iran. *Quaternary International,* 345, 158-166.
- TODISCO, F., MANNOCCHI, F. & VERGNI, L. 2013. Severity–duration–frequency curves in the mitigation of drought impact: an agricultural case study. *Natural Hazards,* 65, 1863-1881.
- TSAKIRIS, G., PANGALOU, D. & VANGELIS, H. 2007. Regional Drought Assessment Based on the Reconnaissance Drought Index (RDI). *Water Resources Management,* 21, 821-833.