

Optimized behavior of long-term rainfall for the red sea semi-arid region

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(Received September 10, 2020, Revised June 30, 2021, Accepted July 20, 2021)

Abstract. Precipitation is one of the most significant variables with an impact on the environment, agriculture, as well as the design of any hydraulic infrastructures. The rainfall analysis predicts the highest, average, and minimal values of rainfall that are expected in certain catchments for return periods. The long-term variability of rainfall over the Arbaat watershed was studied at the various stations in a duration (day, month, and year) from 1942 to 2010 rainfall runoff using the Isohyetal Map of the area besides using different plotting position formulae of rainfall ratios. This statistical analysis will offer valuable data for water resource planners for Port Sudan, farmers, and Red Sea Water Corporations engineers (RSSWC) to evaluate the availability of water and create the storage accordingly. From the rainfall-depth analysis outcomes, the rainfall pattern was found to be irregular. Although the historical data was used, the meteorological observation of Suakin, Sinkat, and Arbaat stations was stopped from work. However, Port Sudan station gave reliable results without resorting to precipitation data measured by the satellites. Besides, the outcomes of this study can provide rational guidelines and policy concerning water resources to preserve the health of several ecosystems in the regions of under study.

Keywords: annual rainfall; khor Arbaat; long-term rainfall analysis; monthly rainfall; Red Sea

1. Introduction

Extreme rainfalls frequently leads to drought, severe winds, flash floods, and environmental disruption, including human populations (Easterling *et al.* 2000, Atif *et al.* 2020, Aldrees 2021, Aldrees *et al.* 2021, Chen *et al.* 2021). Therefore, there is great interest in any changes in the frequency and severity of such occurrences. The IPCC has been concluded with a high degree of confidence that the frequency of severe rainfall events would grow in certain regions of the world under global warming (Stocker 2013, Su *et al.* 2020, Liu *et al.* 2021b, Zeng *et al.* 2021). The severity and frequency of extreme weather occurrences typically appears as climate change increases. Moreover, climate change patterns can be utilized as predecessors of changing climate during the historical period (Irizarry-Ortiz *et al.* 2013, Supraja *et al.* 2017, Liu *et al.* 2021a). Therefore, past trend evaluations, particularly for severe situations, are crucial for us (Mackay 2008).

Port Sudan is the Sudan's principal port and the country's most important commercial hub. It's the capital of the Red Sea State located on the coast of the Red Sea. Approximately 1,000,000 people lived in the area in 2010, and the water demand was 120,000 m³/day. For Port Sudan, the Khor Arbaat groundwater basin is the primary source of water supply. Khor Arbaat produces around 45,000 m³ of water per day in normal years, but it can drop to 30,000

m³/day in low raining periods. Domestic water use in the city is limited to 45 liters per cubic meter per day (l/c/d). Khor Arbaat's water sources include wells, base flow, and reservoirs. As a result of the flooding, there are three dams as the Fourth Reservoirs, the Sea Port Corporation and the Upper Gate Dam, which suffer from siltation. For Port Sudan and its residents, the Khor Arbaat watershed is essential. Water resources in Khor Arbaat have been studied in order to ensure a sustainable water supply for the city through the construction of dams (Taha 2016). Across the country, climatic variability is responsible for regional distributions of inter annual rainfall, which are further linked to droughts and catastrophic floods in the region. As a result, the evaluation of severe rainfall events for specified return periods is typically required for the optimal design of urban drainage and infrastructure, as well as for long-term planning. Small changes in variability, rather than a change in the mean, can have a significant impact on the frequency of severe events (Katz *et al.* 1992). Climate change research examined the intensity and more common occurrence of severe rainfall, and public awareness of the problem was enhanced (Bell *et al.* 2018). However, observational datasets, particularly daily data, have not been well examined.

For many applications in the field of water resources management and the construction of hydraulic infrastructures, data is vital for the temporal and geographical distribution of precipitations (Liu *et al.* 2020, Jiang *et al.* 2021a, Li *et al.* 2021b, c, Zhao *et al.* 2021b). Regarding global warming, changes in rainfall patterns and their influence on surface water supplies are, therefore,

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critical climate problems that face the globe (Kumar *et al.* 2010, Goyal 2014, Jiang *et al.* 2021b). Water is a fundamental life source with no substitution that is also used for transportation purposes as a source of power and serves many other useful dedications for domestic consumption, agriculture, and industries (Arvind *et al.* 2017). If all rain fell over a given region, the depth to which the water would accumulate is known as precipitation. So, 1 cm of rainfall over a 1 km² catchment area represents 104 m² water. An open-air rain gauge is made out of a cylindrical vessel that collects the rain (Soliman 2010). This study aims to summarize the importance of rainfall statistical data analysis, such as collecting, describing, graphical data analysis, estimating missing data, check the consistency of precipitation data, probability likelihood of occurrence, and used for Rainfall-Runoff applications. For the design and study of engineering constructions and water supply evaluation, a comprehensive statistical analysis of each region is required. As the primary element in surface runoff, rain analysis is crucial to water resources management. Hydraulic structures are designed based on rainfall analysis. The rainfall analysis predicts the maximum, average, and minimum values of rainfall that are expected in specific catchments for return periods (Rajeevan *et al.* 2008). Sudan has a desert climate in the north and along the Red Sea coast, and a semi-desert or semi-arid climate in the south influenced by the summer monsoon rain (World climate guide, 2020). Regarding the Red Sea climate, the winters are warm around 27/28°C (81/82°F), while summer is stifling, with a combination of humidity and heat. Poor rains occur mostly between October and January. Indeed, the prevailing north-east currents deposit a bit of moisture as precipitation on the coast after passing over the sea in autumn and winter. The rainfall regime of the Red Sea region and the factors influencing its climate is distinctly different from that of the rest of Sudan (El-Tom 1975). While rainfall system is highly controlled by the Inter-Tropical Convergence Zone (ITCZ) and southwesterly winds in Sudan, the presence of the Red Sea Hills and the Red Sea as a large water body is the main influential factors (WMO & FAO, 2016) in the Red Sea area. The total precipitation received at one area during a certain period varies greatly from year to year. The difference relies on the climatic type and the duration of the period considered. The rainfall depth estimations can be produced via a frequency analysis for the specified probability or retroactive periods necessary for the design. After collecting historical data for several years, the data are ranked and assigned plotting positions by estimating probability of exceedance with a model while choosing a distributional assumption and plotting the data in a probability graph; and analyzing the selected distribution. If not suitable, a different distribution should be picked or the data is converted to ensure that the transformed data follows the distribution selected while calculating rainfall depths (XP) that was predicted for specified probabilities or probability plot return period (Dirk 2013, Nookala *et al.* 2015, Miao *et al.* 2019, Lan *et al.* 2021, Li *et al.* 2021a, Zhao *et al.* 2021a). Storm-water management systems are often designed and analyzed based on a hypothetical rainfall

event with a particular return period (T). It should be noted, however, that the return duration of a rainfall event is not equivalent to that of the surface runoff. Since surface-water management systems rely on elements such as moisture conditions in the watershed and location, for example, a dry or semi-arid region's surface-water management systems will be less reliable (Shadeed *et al.* 2007). A particular, severe rainfall of a given length will be relevant in many hydraulic engineering applications, such as those that deal with floods. There are three types of rainfall durations: short duration (less than one hour), intermediate length (between one and 24 hours), and long duration (more than 24 hours) (Viswanadhapalli *et al.* 2017). Suitable for dry and semi-arid areas, short-duration rainfall is the norm. A maximum length of 2 hours is thus advised for storm planning purposes. A frequency study of point rainfall data uses this information. It is usual to utilize annual series of data, which consists of values that occur once a year, such as annual rainfall (Soliman 2010). There are two metrics that indicate normal distribution of rainfall data: kurtosis and skewness. In contrast to a normal distribution, kurtosis indicates data peak or flatness, whereas skewness reflects the degree of symmetry in a data set. This data set follows the normal distribution if these two parameters are zero or close to 0 as stated by Shadeed and Almasri (2007). Estimating the average rainfall over a watershed is highly dependent on the number of rain gauges in the region and how a storm moves through it. $N = 0.73 A^{0.33}$ for arid and semi-arid areas (Soliman 2010). As a result, hydrologists require techniques for converting the point rainfall quantities into the average rainfall quantity over a given area. Numerous approaches including the arithmetic means method, the Thiessen method, and the Isohyetal method can be used to handle this point to area rainfall conservation challenge (Gill 2005). This approach employs topography and other data to get credible predictions of the area's annual rainfall. Isohyets are created on an appropriate base map to generate an isohyetal map, and the average areal rainfall is calculated by averaging the Isohyetal zones (Jain *et al.* 2005). The design of hydraulic infrastructures and water resources management need a frequency study of severe occurrences. The features of these severe occurrences differ. For example, severe rainfall characteristics include quantity, length, number of occurrences per year and inter-arrival time, duration, peak characterization, severity, range, flooding and volume (Li *et al.* 2019). In this paper, the maximum daily rainfall events were analyzed using frequency analysis. The basic goal of the frequency analysis of hydrological data is to find the relation of the magnitude of extreme values to their frequency of occurrence through a probability distribution. In general, studying the extreme hydrological events required choosing the largest or smallest greatest events. However, for rainfall-runoff hydrological modeling and sediment transport prediction, the researchers are more interested in the largest extreme events that have a large probability of creating maximum runoff. Also, the probable maximum rainfall (precipitation, PMP) in the design of some Hydraulic Structures, Flood control structures, and Sediment control structures as Sediment Trapping Basin,

the highest possible rainfall is assumed as the extreme total sediment load. The return period (T) of a design rainfall storm should be based on economic efficiency. In practice, however, the return period (T) is usually selected based on the level of hydraulic structures. Therefore, in this paper, the Gumbel distribution and Weibull Formula were used, which are the most widely used methods in probability distribution functions for extreme values in hydrologic and meteorological studies for prediction of maximum rainfall, flood peak (Soliman 2010, Zhang *et al.* 2016).

2. Methodology

2.1 Study area

2.1.1 Port Sudan city and Khor Arbaat

The study area includes the Port Sudan City and Khor Arbaat (coastal region) located between ($19^{\circ} 39''$) northern latitude and ($37^{\circ} 13''$) longitude (50 km north of Port Sudan town). The study area includes of Port Sudan town, Red Sea State, and Khor Arbaat. When it comes to population, Port Sudan is the state's main urban center, as well as its capital. Red Sea area is a semi desert climate with low precipitations, less than a 100 mm per year. Groundwater resources in the study region are not affected by local rainfall. Port Sudan has a mean annual rainfall of 89 mm, with an average standard deviation of 33 mm, whereas the Red Sea Hills have an average annual rainfall of 100 to 150 mm. As a result, the station-based total rainfall with daily temporal resolution was utilized to investigate the frequency and severity of rainfall extremes together with the contribution of severe events to the total rainfall amounts. The daily rainfall time series data for the 42-year period 1978–2019 was used to calculate extreme rainfall indexes. The most reliable approach to assess the frequency and trend of severe rainfall occurrences is to use daily rainfall data. Time is divided into two equal periods, and the trend for each half period is calculated together with the decadal trends. The frequency of rainy days at each station was tallied for different threshold values, such as 1, 5, and up to 50 mm with intervals of 5 mm. We classify severe rainfall events in this study based on daily cumulative rainfall. It is described as "An occurrence with at least one day of cumulative rainfall equal to or over a certain threshold." As a result of the regression equation and F-test, the rainfall trends and their significant levels were computed. Mann–Kendall (MK) test with the MK statistic and S test statistic are to obtain the slope and significance. The return time period of precipitation is defined as the expected time period over which an exceptional event is not occurring on average. This period is usually modified for practical applications like 2 years, 5 years, 10 years, 25 years, 50 years or 100 years, or 0.50, 0.20, 0.10. The risk thresholds are 0.04, 0.02, or 0.01. As a technique, severe events are supposed to occur independently from one another, thus the probability distribution function (PDF) gives a scientific framework. Three separate techniques are available, including threshold selection, threshold extremes and annual maxima in a way that number of years is equal



Fig. 1 Red Sea state map, OCHA

to the extreme events' numbers over the threshold level. There are no reliable evaluations that can be made until the frequency of daily rainfall over a lengthy time-series is examined. The gamma distribution is used to examine the daily total rainfall time-series. Different return times are used at each site to annually estimate wet season, and dry season maximum rainfall during the 42-year period. As a result of the annual extreme time-series statistical distribution, the return periods are determined for each station. The threshold is determined with percentile values for severe occurrences that contribute to the total precipitation. First, the daily interruption of the precipitation is derived for the 90, 95 and 99th percentiles. Later, the rainfall ratio at the 90th, 95th, and 99th percentiles are compared with the thresholds of ≥ 10 mm up to ≥ 30 mm with intervals of 1 mm at each station the entire country. The severe event threshold is defined as the percentile-based rainfall comparable to the threshold-based rainfall. Finally, the contribution to total precipitation of severe events at several locations is calculated to determine to what degree extreme events are contributing to total precipitation over certain climates. Fig. 1 shows the Red Sea State Map, OCHA.

2.1.2 Topography & geographical features of Khor Arbaat

Geomorphologically, the region of research belongs to the coastal lowlands of the Red Sea. Along the coastline, there are primarily marine reservoirs, but the inward side is dominated by a deposit of mainland facets bounded by the

Red Sea Hills. The latter is deposited by a large Wadi system which drained the Red Sea Hills and debouched onto the coastline producing a range of fans and deltas, made up of gravels, sand, silts and clay. The Red Sea coastal plain ranges in breadth from around 56 km in the South near Tawkar up to roughly 25 km towards the Egyptian border. The coastal plain is dry and barren. There are a number of Khors systems in this area come from the Red Sea Hills and are the region's primary water. For example, the higher gate of Khor Arbaat drains a catchment area of roughly 4200 km² into the alluvial basin of the lower gate (450 meters wide). Averagely, a minimum of 43 mm annual rain is fallen recording about 7mm mean raining for the red Sea area. Khor Arbaat have a greater potential for the surface water development considering the Khor watershed 9180 –249 million cubic meters and different estimates of surface outflow (32 million cubic meters) (Taha 2016). There are a number of factors that make Red Sea State unique: its relative remoteness and hard topography, its highly variable rainfall system with frequent periods of drought, its tiny cultivate land, as well as its low population. Khor Arbaat is the largest water source near Port Sudan, which is located in the central Red Sea State and bounded by lat. 19°00" N to 20°00" N and long 36°30"E to 37°15"E. Khor Arbaat floods heavily in the summer and winter, yet the water is wasted. The Wadi has an inlet (upper gate) and outlet (lower gate). The length between upper gate (Upper Gate Dam 1) and lower gate (Fourth Reservoir, Dam 2) is about 14.55 km, as well as the middle gate (about 0.5 to 1 kilometers). As a result, Port Sudan's city center is 8 m above the sea level with 181 m elevation at the upper gate and 110 m at the lower gate. Fig. 2 shows rainfall for Semi-Arid Region in Wadi Arbaat-Eastern Sudan. Fig. 3 indicates the groundwater balance in the Khor Arbaat basin, Red Sea State. The methodology used in this research is descriptive rainfall statistics for annual and monthly historical data (Arithmetic Mean, Standard deviation Skewness, and others parameter). The frequency analysis of rainfall and probability analysis used plotting position and probabilistic methods, following the Gumbel distribution and Weibull Formulas (Eq. (1) and Eq. (2)), for daily rainfall events. On the other hand, the study also analyzed and extracted the average areal rainfall distribution using GIS technique and the optimal number of

rainfall gauges suitable for the Arbaat watershed area.

In this study, the Weibull formula (Eq. (1)) was applied for frequency analysis of rainfall (the probability of occurrence of an event whose magnitude is equivalent to or above a specified magnitude X is denoted by P), as follow:

$$P = \frac{m}{N+1}, T = \frac{N+1}{m} \quad (1)$$

where P is the probability of rainfall equaled or exceeded, T is the return period (recurrence interval is give as: $T = 1/P$), m is the order number ($m = 1,2,3,4 \dots N$), in the last event $m = N =$ number of years on record, and N is the sample size

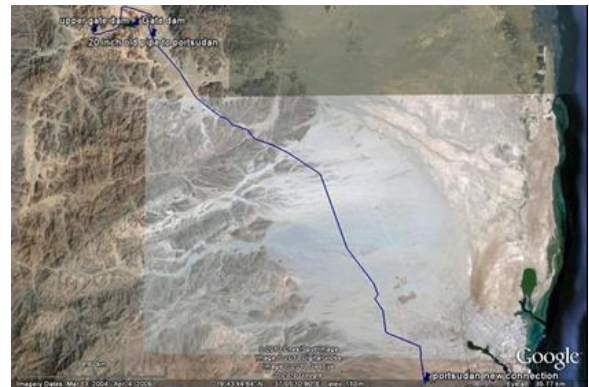


Fig. 2 Rainfall for semi-arid region in Wadi Arbaat-Eastern Sudan

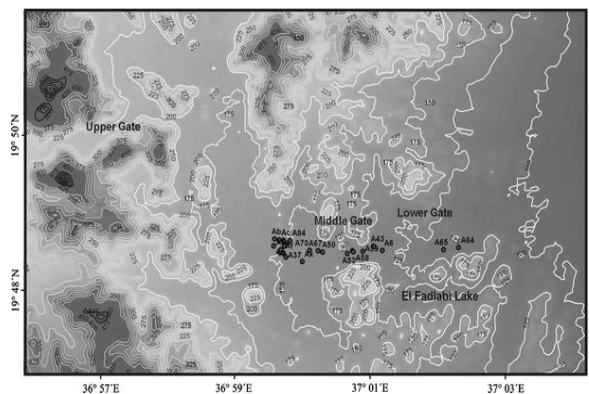


Fig. 3 Groundwater balance in the Khor Arbaat basin, Red Sea State

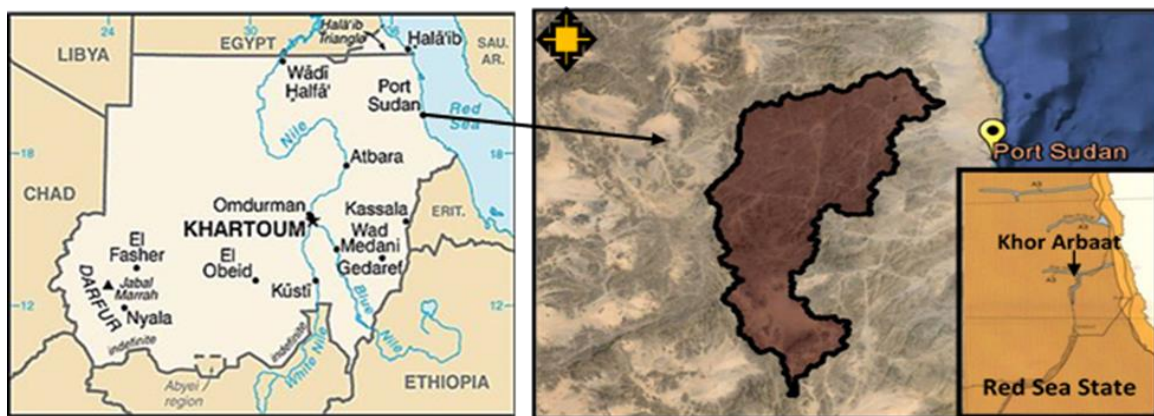


Fig. 4 Location map of the study area

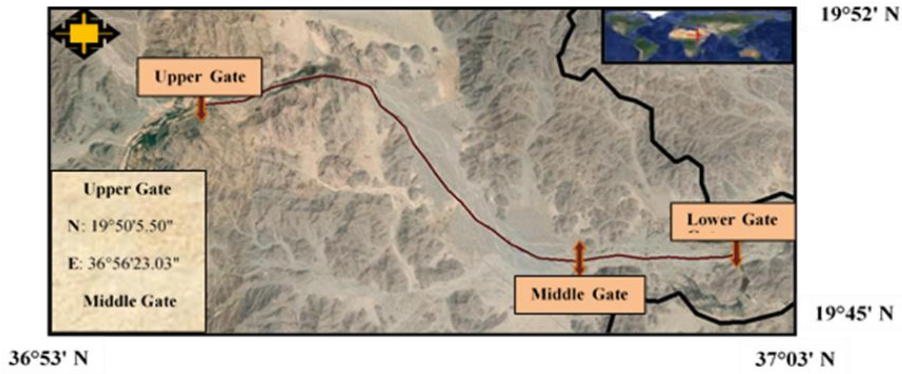


Fig. 5 Khor Arbaat, upper gate, middle gate, and lower gate area

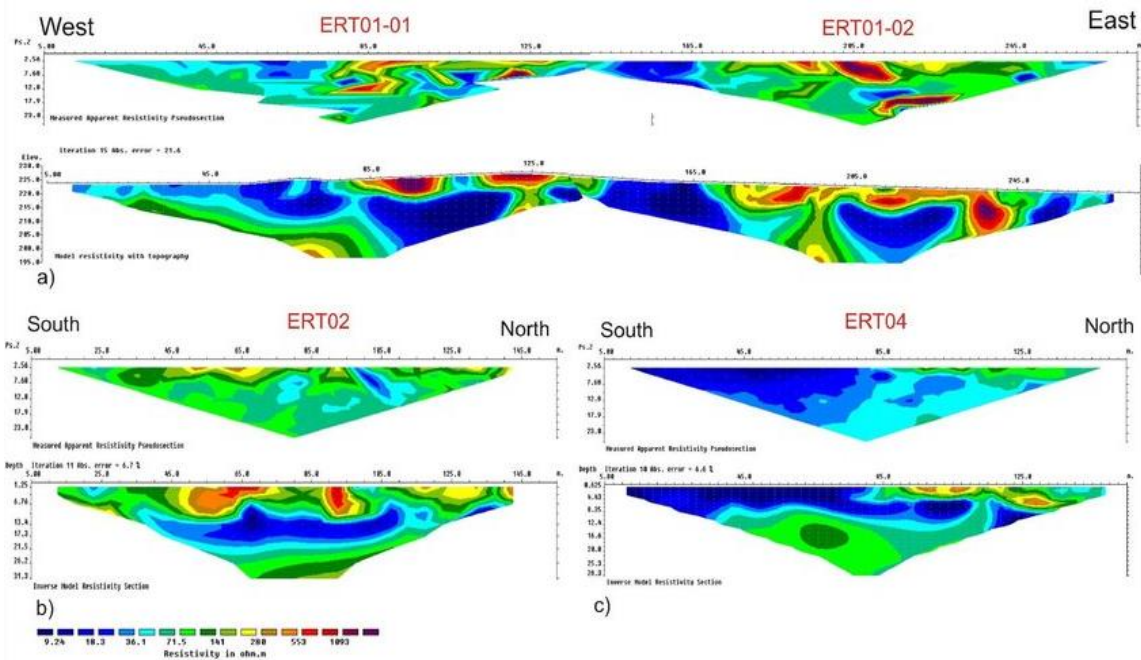


Fig. 6 Different degrees of flooding, a) ERT01 in an elevated area close to the Nile, b) ERT02 in low lying area suffering flooding, c) ERT03 in farm area much affected (to the degree of collapse)

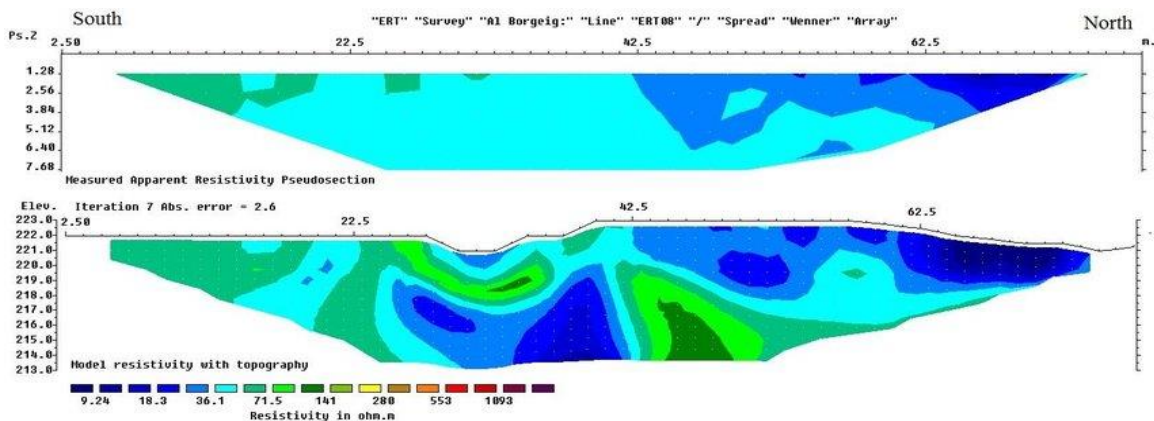


Fig. 7 ERT08 results showing various groundwater floodings in farm area

(number of record). Fig. 4 shows the location map of the study area, also Fig. 5 shows Khor Arbaat, upper gate, middle gate, and lower gate area. Besides, the Gumbel's equation (Eq. (2)) was used to estimate the rainfall magnitude

corresponding to a given return period based on a maximum daily rainfall (Annual series), as follow:

$$X_T = \bar{x} + K_T \sigma_p \quad (2)$$



Fig. 8 Location of ERT06 and ERT07, topographically high farm area and low lying settlement area

Table 1 The geographical location of the station around the study area

No.	M. Station	Code No.	Coordinates		Altitude (m)	Data Period
			Longitude (°) E	Latitude (°) N		
1.	Arbaat	80015	36°58'06.1"	19°50'25.8"	181	1942-1988
2.	Port Sudan	80021	37°13'6.63"	19°36'28.75"	5	1942- 2010
3.	Sinkat	80022	36°49'58.05"	18°50'12.64"	900	1920 - 1973
4.	Suakin	80023	37°20'00.00"	19°06'00. 00"	0	1901 - 1973
5.	Gebeit Mines	80017	36°20'0.00"	21° 7'30.00"	570	1943 - 1981

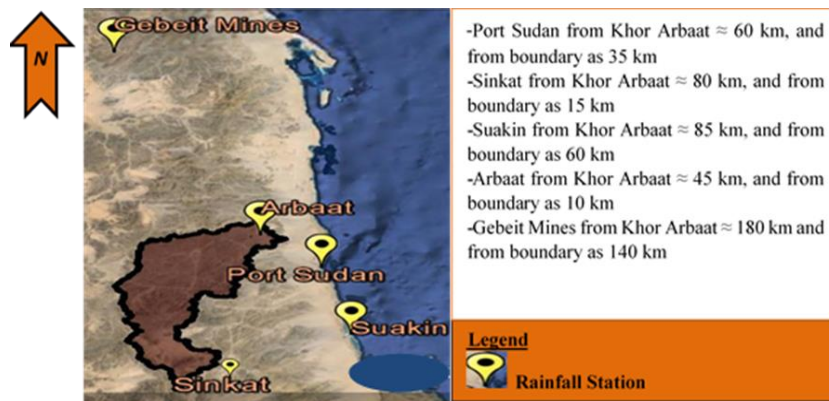


Fig. 9 Meteorological stations in the study area

where \bar{x} the mean of maximum rainfall data, σ_p is the standard deviation of maximum rainfall data, and K_T is the frequency factor that expressed as Type 1 Distribution and calculated by Eq. (3), as follow:

$$K_T = -\frac{\sqrt{6}}{\pi} \left(0.5772 + \ln \left(\ln \frac{T}{T-1} \right) \right) \quad (3)$$

2.2 Data collection

The rainfall-depth data applied in this research were gained from Sudan Meteorological Authority (SOM). The Gauges - stations are a standard weather station that most climatic record data are verified, analyzing daily rainfall-depth for over 30 years to establish a long-term climatology (Aldabagh *et al.* 1982). Data was maintained in a spreadsheet using Excel and Origin-Pro. After data collection, statistical analysis was carried out at different periods (day,

month, and year) for 68 years (1942-2010). Fig. 6 shows ERT results showing various degrees of flooding, a) ERT01 in an elevated area close to the Nile, b) ERT02 in low lying area suffering flooding, c) ERT03 in farm area much affected (to the degree of collapse). Wenner array was used, spacing, 5 m It was interpreted that a resistive (90-500 Ω -m) surface layer corresponding to the streambed sediments. A relatively conductive (10-30 Ω -m) middle layer corresponding to mud-clay soils. Fig. 7 shows ERT08 outcomes including various groundwater floodings in the farm area. Fig. 8 shows the location of ERT06 and ERT07, topographically high farm area and low lying settlement area. In this figure, Two-dimensional (2-D) electrical resistivity tomography can create a more accurate subsurface model since the resistivity varies both vertically and horizontally along the survey line (Loke 2000). The inversion program uses the conventional least-squares optimization technique and the Res2Dinv algorithm to calculate the apparent resistivity values (Loke *et al.* 2003).

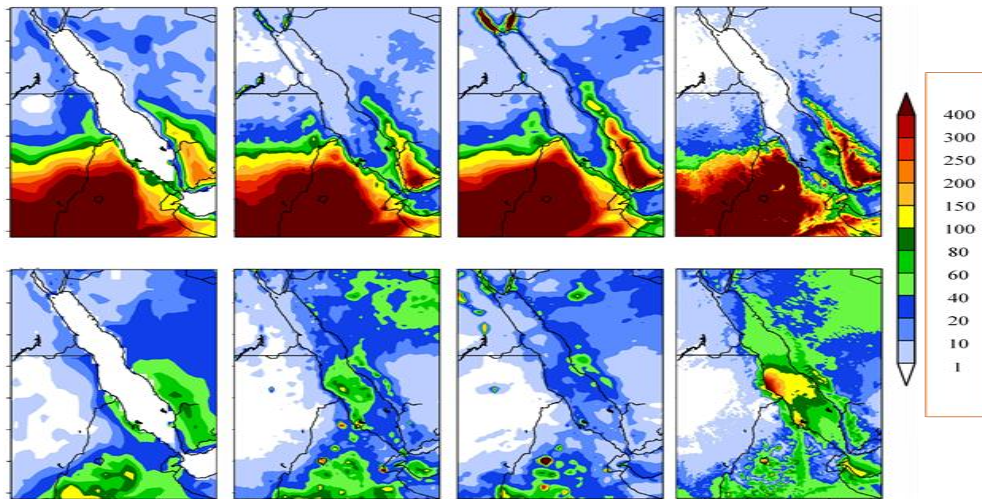


Fig. 10 The total seasonal rainfall (mm) for summer (top panel) and winter (bottom panel) seasons

Table 2 Rainfall zones for Red sea state

Area	Rainy Season
Coastal Eritrea to Khor Arbaat delta	November to January
Coastal Khor Arbaat delta to north boundaries	October
Mountain and coastal northern Red Sea Hills	November
Mountain Northwest	July to August
Mountain Interior southwest	July to September

2.3 Meteorological stations rainfall

The rainfall data recorded by Rain-Gauges (5 meteorological stations) near the study area, Port Sudan, Arbaat, Gebeit Mines, Suakin, and Sinkat, and the details of stations are shown in Table 1 beside their locations in Fig. 9.

2.4 Rainfall season in Red Sea state

There are two rainy seasons in the Red Sea region. Summer rain comes from July to September, such as in the most parts of Sudan by the inter-tropical convergence zones come from the south-west direction (these rainfalls measured by Sinkat station). The winter rains from October to January caused by the monsoon emerging through the Red Sea. These rainfalls are measured by Port Sudan, Suakin, and Arbaat stations. Besides, El-Tom (1975) distinguishes five precipitation zones in Red Sea State; two periods of rainfall can be distinguished: November to January and July to September (Table 2). Fig. 9 shows the Meteorological stations in the study area. Figure 10 shows the total seasonal rainfall (mm) for summer (top panel) and winter (bottom panel) seasons (Yesubabu *et al.* 2016).

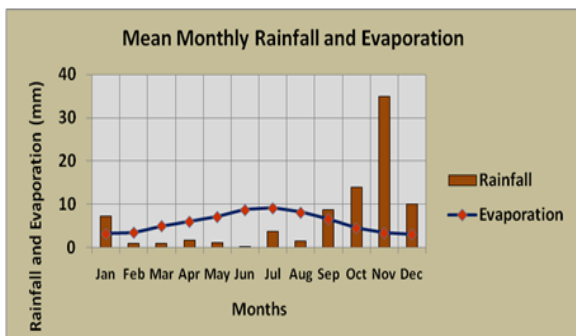


Fig. 11 Monthly average rainfall and evaporation rates in the study area (mean monthly rainfalls over Arbaat watershed (1942 – 2010))

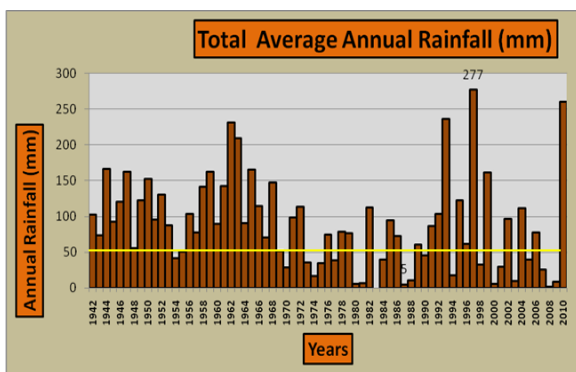


Fig. 12 The annual average precipitation in Study Area for the period (1942 – 2010), with an indication of the average rainfall (yellow horizontal line)

2.4.1 Annual and monthly rainfall

From the meteorological data, the annual average total amount of rainfall in the study area in both summer and winter rains shows a relatively wide range of variation from 1940 to the end of 2000 (Table 3). The coastal area (low land, 2-5 m AMSL) received mainly winter rains such as the Port Sudan area that was rarely affected by the summer rains. Also, it is recognized that the rain intensity decreases from the south to the north direction. The high land, such as Gebeit (795 m AMSL) and Sinkat (900 m AMSL) is mainly affected by the summer rains from July to September, adding that the winter rain in this area is negligible. Some mountainous ridges like Erkwit received summer and winter rains. Fig. 11 shows the monthly average rainfall and evaporation rates in the study area, and Fig. 12 represents the total average annual rainfall recorded in the study area

Table 3 Annual rainfall in the study area (average areal, mm)

Year	Rainfall (mm)	Year	Rainfall (mm)	Year	Rainfall (mm)
1942	103	1965	165	1988	11
1943	74	1966	115	1989	61
1944	166	1967	71	1990	46
1945	93	1968	148	1991	87
1946	121	1969	52	1992	104
1947	162	1970	29	1993	236
1948	56	1971	99	1994	18
1949	123	1972	114	1995	123
1950	152	1973	36	1996	62
1951	96	1974	17	1997	277
1952	131	1975	35	1998	33
1953	88	1976	75	1999	161
1954	42	1977	39	2000	6
1955	51	1978	79	2001	30
1956	104	1979	77	2002	97
1957	76	1980	6	2003	10
1958	142	1981	7	2004	112
1959	162	1982	113	2005	40
1960	90	1983		2006	78
1961	143	1984	40	2007	26
1962	231	1985	95	2008	2
1963	209	1986	73	2009	9
1964	91	1987	5	2010	260
Mean	93.5				
Max	277				
Min	2				
S.D	64				

Statistical Data

for the period 1942-2000. Besides, the average annual rainfall data are given in Table 3.

Fig. 12 shows the plot of total annual rainfall observed in Khor Arbaat Area from 1942 – 2010 period. The annual raining ratio differs between 5, 2 mm (1987, 2008) to 277 mm (1997). The average rainfall and standard deviation are 100 mm and 79 mm in 68 years, respectively. The average shows the normal amount of rainfall in the area, comparing climatic regions and providing the idea of the departure of annual rainfall from the normal. Also, we used the average annual rainfall for estimating the total amount of precipitation. Besides, GIS software was used for calculating the annual amount of precipitation in a million cubic meters in each of the nearest meteorological stations. Therefore, the total amount of precipitation in the study area (4387 Km²) is about 420*106 m³.

3. Results and discussion

The first step in hydrological analysis and study of Khor Arbaat watershed includes analysis of rainfall data to obtain

the maximum monthly flow of the Khor. This encompasses the statistical analysis of rainfall data on daily, monthly, and annual bases, as well as the estimation of areal rainfall of Arbaat watershed. In this study, considering the processing and analysis of hydrological and hydro-meteorological data by using statistical methods, standard deviation, median, mean, kurtosis coefficients, and skewness, minimum and maximum values of the variable were analyzed.

3.1 Rainfall gauging stations

Rainfall analysis starts with collecting the available rainfall data from the surrounding gauging stations of Khor Arbaat watershed as one of the difficult challenges in this study. The existing rainfall gauging stations in the Red Sea State suffer from lack of data for several years. Thus, this study has mainly focus on long term rainfall data from the surrounding rainfall gauging stations. Four (4) rainfall stations surrounding the Arbaat watershed were selected as Port Sudan, Arbaat, Sinkat, and Suakin. The Gebiet Mines station has been selected only to complete the process of spatial analysis of rainfall in the Arbaat watershed using GIS.

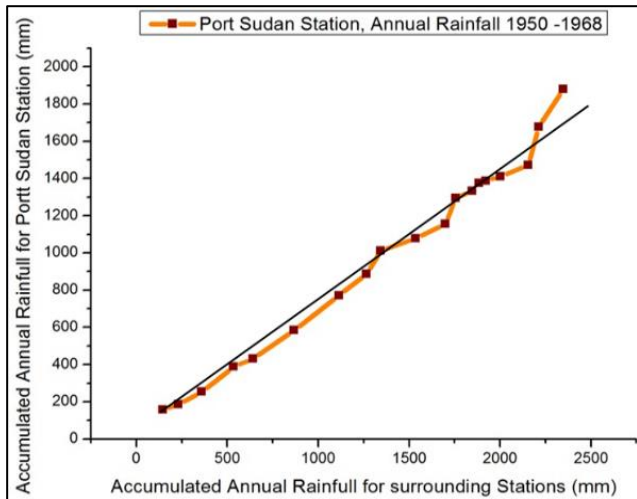


Fig. 13 The double mass curve for the stations surrounding Arbaat watershed

3.2 Optimum number of Arbaat rain gauge stations

There is a clear correlation between the density of rain gauges within a catchment, and the geographical features of a storm that occurs inside the watershed when it comes to estimating the mean. In the study area, the existing stations on study area are not enough for determining the average areal rainfall precisely if we look at the area of Khor Arbaat (4200 square kilometers), and the least recorded number stations as 12 gauges. Hence, the area of Khor Arbaat needs eight stations beside the existing gauges.

3.3 Consistency of rainfall records (preparation of data)

For reliable findings, the quality of the incoming data must be considered. In this case, the rainfall data is considered as the main input for the hydrological cycle. Regarding the hardship of getting high quality rainfall data for long term, the collected rainfall data was checked by applying the consistency analysis. The missing data were estimated from the surrounding rainfall stations using Eq. (4), and consistency analysis was applied.

$$R_g = \frac{1}{n} \sum_{i=1}^{i=n} \left(\frac{AR_g}{AR_i} R_i \right) \rightarrow 1$$

- AR = the annual mean of raining
 - (g) = at the missing station
 - (n) = or in the nearby stations
- (4)

Checking the inconsistency of rainfall record was investigated using the double mass curve technique. The accumulated rainfall at a specific station and the accumulated values of the other stations were computed for the period 1950-1968 (18 years). Fig. 13 presents the data for the selected rainfall stations.

3.4 Annual rainfall

Annual rainfall data were analyzed for selected stations surrounding the Arbaat watershed for the hydrological years

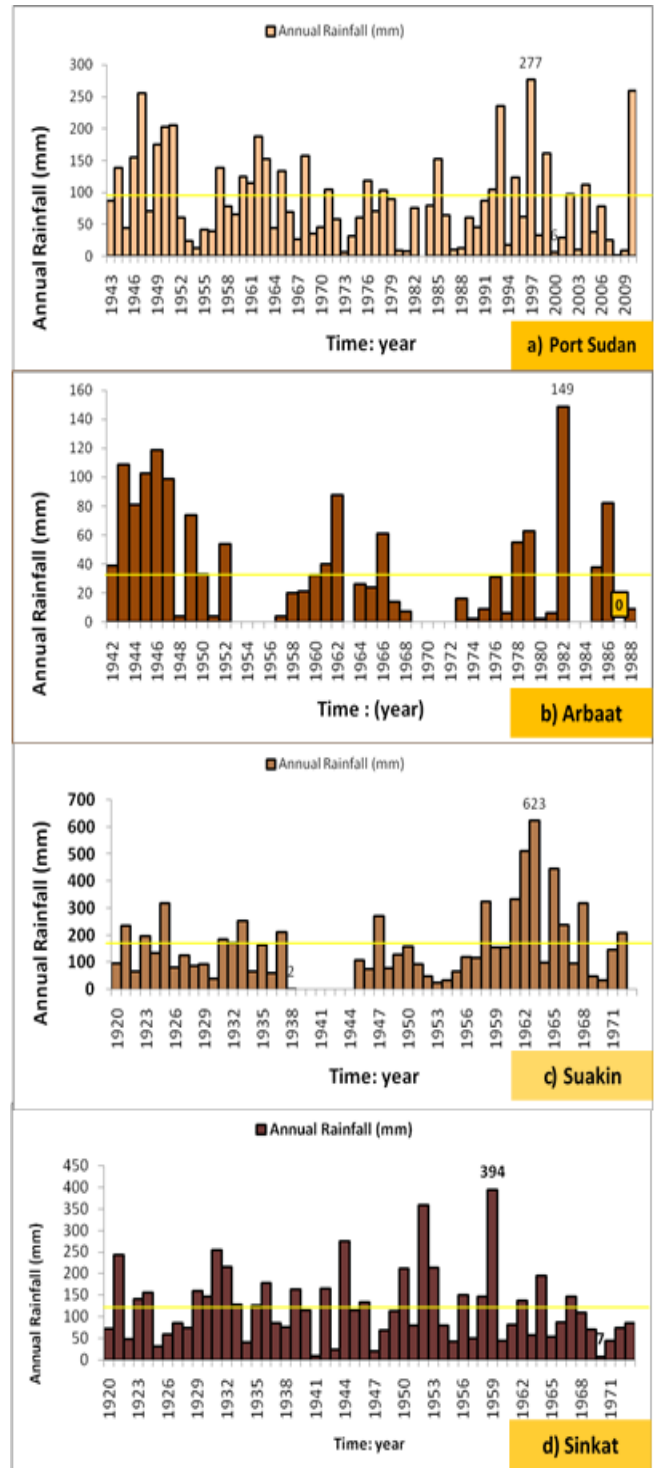


Fig. 14 The annual rainfall time series for a) Port Sudan, b) Arbaat, c) Sinkat, and d) Suakin, with the indication of average rainfall (yellow horizontal line)

from 1943 to 2010. Since one of the main distinctive features of arid and semi-arid areas is the temporal variability of rainfall, a statistical analysis was conducted on the available data, including the median, mean, standard deviation, kurtosis, skewness, as well as maximal and minimal rainfall records. Table 5 shows the statistical analysis results of the annual rainfall data for various stations.

Table 4 The total amount of precipitation in the study area

Basin	Area (Km ²)	Meteorological Station	Annual Precipitation (mm)	Total volume (10 ⁶ m ³)
Arbaat	4387	Arbaat, Port Sudan, Gebeit & Sinkat	100	440

Table 5 Descriptive statistical analysis of annual rainfall data for the selected stations

Stations	Port Sudan	Arbaat	Suakin	Sinkat
Parameter (mm)				
Mean	85.4	36.3	158.1	119.7
Median	69.5	16	123.5	98.5
S. Deviation	68.9	39	130.1	81.8
Skewness	0.97	1.25	0.1	1.3
Kurtosis	0.4	0.71	3.1	2.1
Maximum	277	149	623	404
Minimum	1.4	2	2	10

Table 6 Statistical summary of monthly rainfall data (Port Sudan station, 1942-2010)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	5.5	0.55	0.47	5.3	1.2	0.40	5.9	1.6	0.18	15.1	39.8	15.9
Median	0	0	0	0	0	0	0	0	0	3	16.5	3
Max	84	16	24	193	19	7	51	21	10	240	178	142
Min	0	0	0	0	0	0	0	0	0	0	0	0
S.D	15.1	2.4	3.2	26.5	3.8	1.5	12	3.7	1.32	35.2	48.6	29.7
Skew	3.6	5.5	7.5	6.7	3.8	3.74	2.7	3.4	7.5	5.1	1.4	2.8
Kurt	14.2	32.8	56.4	47.3	14.1	13.1	6.9	13.5	57	31.0	1.0	8.1

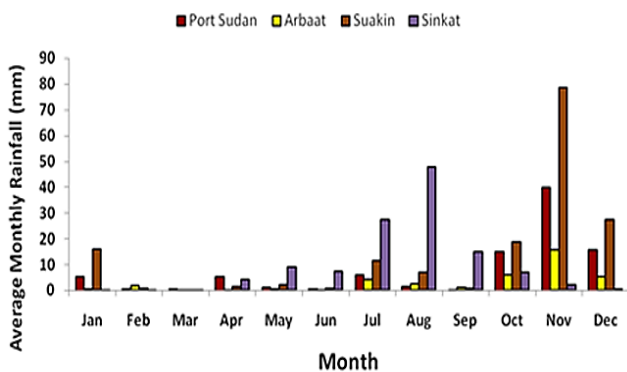


Fig. 15 Average monthly rainfall distribution

This shows that the Standard Deviation value is near to the mean, and this reflects the variability of the annual data during the long term analysis. Regarding the significant difference(s) between the maximum and minimum rainfall-records, the maximum values were recorded in the rainy year of 1963, while the minimum values were recorded in the dry year of 2008 in four stations. However, from Table 5, the two parameters values for four gaging stations are positive that indicates the distribution is skewed to the right and has a peak distribution at each rainfall station. The annual time series for the selected stations are depicted in Fig. 14. There is a significant variation in the rainfall pattern for the four stations during the last (40 years). This indicates that the amount of rainfall oscillates from one

period to another. The values of long term rainfall mean for the Port Sudan, Arbaat, Suakin, and Sinkat stations are (85.4, 36.3, 158.1, and 119.7 mm), respectively. It can be seen that the rainfall mean of Arbaat is smaller than that of Port Sudan, Suakin, and Sinkat, also, in Port Sudan, the rainfall mean is smaller than Suakin and Sinkat gauging stations.

3.5 Monthly rainfall

Monthly rainfall records were analyzed for Port Sudan, Arbaat, Suakin, and Sinkat stations, and the results are displayed in Table 6. It is observed that the distribution of monthly data of rainfall has positive kurtosis and skewness values. Besides, median values in all cases are lower than mean, indicating that the majority of the months had only light rainfall punctuated with a few high values. In addition, Fig. 15 presents the average monthly rainfall for the four gauging stations during the hydrological years of 1943-2010. Rainfall is concentrated in two rainy seasons as summer (June – September) and winter (November – January). The other months are relatively dry with zero rainfall.

3.6 Daily rainfall

The available daily rainfall records in Port Sudan, Arbaat, Suakin, and Sinkat stations are presented only in 24-hour rainfall depths with no details for storms

Table 7 Descriptive statistics of maximum daily rainfall data (monthly, time series)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port Sudan, 1943-2000												
Mean	3.74	0.51	0.39	4.3	1.0	0.37	4.8	1.4	0.18	10.7	21.2	9.375
Max	38	16	19	138	18	7	47	21	10	163	111	106
S.D	9.2	2.4	2.5	19.5	3.2	1.9	9.1	3.5	1.3	24.2	26.0	17.5
Arbaat, 1942-1988												
Mean	0.35	0.83	0.1	0.13	0.4	3.23	0.05	2.13	1.16	4.82	9.03	3.6
Max	6	33	3	4	8	27	2	17	36	31	81	42
S.D	1.3	5.22	0.5	0.65	1.4	67	0.31	4.5	5.88	9.289	16.4	8.36
Suakin, 1943-1973												
Mean	6.6	0.8	0.2	1.4	2.5	0.4	9.15	3.2	0.04	10.6	32.4	17
Max	90	10	4	18	71	5	43	15	1	99	96	92
S.D	17.9	2.3	0.8	3.6	13.4	1.1	13.2	5.2	0.2	26.6	31.2	21.9
Sinkat, 1943- 1973												
Mean	0.22	0	0.29	4.2	7.4	3.1	14.7	20.8	7.9	5.8	2.8	0.52
Max	6	0	6	32	27	26	82	101	61	61	17	14
S.D	1.2	0	1.2	8.6	8.8	5.8	18.5	23.6	11.9	13.2	5.5	2.6

- zero case → (rainy day)
- non –zero cases→ (non- rainy day)

occurrence, such as duration, intensity, and distribution. Statistical analysis for the daily rainfall data was carried out considering the maximum values of daily rainfall (Table 7). There is a great difference between the mean values of zero case and non –zero cases. The maximum daily rainfall depth is recorded 163 mm in Port Sudan station, while the minimum value is recorded 0.1 mm in Port Sudan (non-zero cases) during the analysis period.

3.6.1 Areal rainfall

Point values (mm) are used to express the precipitation occurrences recorded by four gauges. Hydrologists need techniques for converting point rainfall amounts into average rainfall amounts across a given region in order to calculate the areal rainfall mean values for a watershed area. In this research, the arithmetic means and Isohyetal method were used to convert the point rainfall to areal rainfall for Khor Arbaat watershed in the following sections.

3.6.1.1 Arithmetic means method

Arithmetic method is used to figure out the rainfall of a region. There’s a lot of formulas involved in calculating the average of the rainfall depth. This approach works well if the gages are evenly distributed throughout the region and the individual gage values do not deviate considerably from the mean measurement. The average depth of precipitation over a Khor Arbaat drainage basin was calculated by using the equation of the arithmetic mean method (Eq. (5)).

$$P_{av} = \sum_{i=1}^{i=n} P_i \tag{5}$$

The average areal rainfall computed by annual data of four gauging stations equals to 93.5 mm. Although the Arithmetic mean method gives a poor indication rainfall ratio especially in arid and semi-arid regions, it has been

used here due to lack of adequate meteorological data seen in other meteorological data analysis methods.

3.6.1.2 Isohyetal rainfall method

In this research, the GIS application and tools were used to create Isohyetal Map for Arbaat watershed. A GIS shapefile includes the isohyets lines for the area of interest. By using the GIS analysis tools, a clip was done to the Arbaat Watershed to obtain its Isohyetal map, as shown in Fig. 16. Later, the data was analyzed in Excel program to estimate the areal rainfall using the Average areal rainfall following the Eq. (6) (Table 8).

$$P_{av} = \frac{\sum_{i=1}^i A_i P_i}{\sum A_i} \tag{6}$$

3.6.2 spatial distribution of rainfall

The geographic information system can be used to study the characteristics of rainfall. In this research, the Inverse Distance Weighted (IDW) model was used for obtaining the rainfall surface depth at locations with no rain-gauges using data from nearby rain-gauges. This is to create an Isohyetal Map of Arbaat watershed (contour rainfall map) from a limited number of measurement stations such as Port Sudan, Sinkat, Suakin, Arbaat, and Gebit Mining on the watershed area and to determine the areas represented between each Isohyet of Isohyetal Map for estimation the areal rainfall. From Fig. 16, it can be seen that for the IDW spatial rainfall analysis of Arbaat watershed, the rainfall is concentrated in the southern direction.

3.7 Maximum rainfall events

In general, studying the extreme hydrological events requires choosing the largest or smallest events. However,

Table 8 Average areal rainfall of Arbaat watershed using the Isohyetal method

Zone No.	Isohyetal Zone	Area (Ai, km ²)	Rainfall (Pi, mm)	Ai*Pi (km ² /mm)
1	158-133	255	145.5	37102.5
2	133 - 116	457	124.5	56896.5
3	116 - 104	425	110	46750
4	104 - 92	425	98	41650
5	92 - 81	475	86.5	41087.5
6	81 - 69	650	75	48750
7	69 - 58	600	63.5	38100
8	58 - 47	725	52.5	38062.5
9	47 - 36	375	41.5	15562.5
Total		4387		363961.5
Average areal rainfall (mm/year)			83	

Table 9 Khor Arbaat catchment area maximum rainfall during (1944-2000)

Max daily rainfall (mm)							
Port Sudan		Sinkat		Arbaat		Suakin	
Date	Rainfall	Date	Rainfall	Date	Rainfall	Date	Rainfall
30/11/1949	104	31/7/1944	82	10/11/1946	53	27/11/1947	84
20/12/1950	106	8/8/1952	101	21/12/1982	81	29/10/1958	50
6/11/1951	74	12/8/1953	71	-	-	24/12/1958	50
21/11/1957	111	24/10/1959	61	-	-	30/11/1961	85
30/11/1961	56	12/9/1959	61	-	-	29/11/1962	95
9/11/1962	51	17/8/1962	51	-	-	8/1/1963	90
20/11/1975	60	16/8/1967	51	-	-	27/11/1965	95
20/12/1978	56	-	-	-	-	30/10/1966	98
16/10/1979	58	-	-	-	-	20/11/1968	84
17/4/1993	138	-	-	-	-	28/10/1972	99
27/10/1997	163	-	-	-	-	-	-

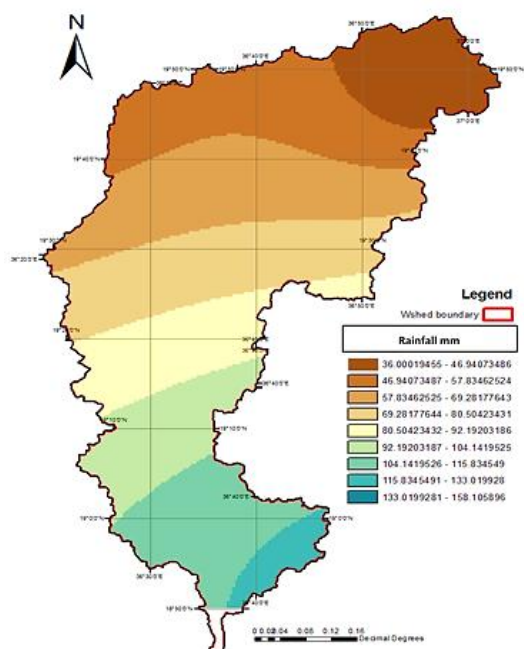


Fig. 16 Isohyetal map for Arbaat watershed

for rainfall-runoff hydrological modeling and sediment transport prediction, the researchers are more interested in the largest extreme events including large probability of creating maximum runoff. Also, the probable highest rainfall (precipitation, PMP) in the design of some Hydraulic Structures, Flood control structures, and Sediment control structures (as Sediment Trapping Basin), the highest possible rainfall could be assumed as the extreme total sediment load. Table 9 shows the maximum daily rainfall for Port Sudan, Arbaat Suakin, and Sinkat stations. Moreover, the maximum daily rainfall events were analyzed using frequency analysis. When analyzing hydrological data, the major goal is to correlate extreme results with their frequency by using probability distributions.

3.7.1 Depth-duration-frequency-Intensity of Arbaat rainfall

Considering many hydraulic structures like those involved in floods (Sediment Trapping Basin), the probability high rainfall in a certain period of time could be important. In general, the rainfall duration is divided into

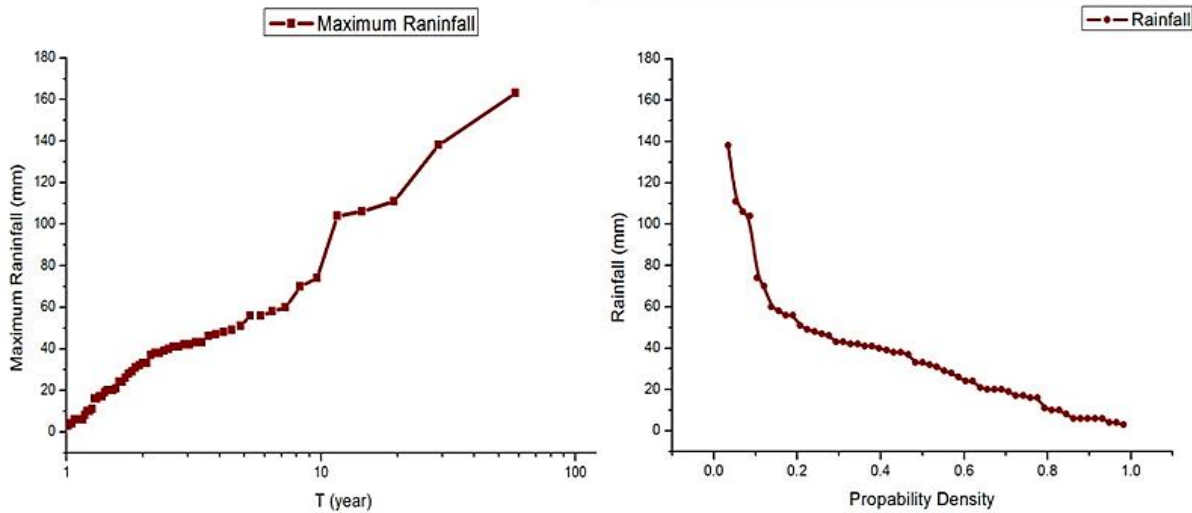


Fig. 17 Gumbel distribution for maximum daily rainfall data (PMP, T, P)

Table 10 Typical return periods (T)

Land Use Minor Drainage System	Design Storm Return Period (Years)
Residential	2-5
High-value general commercial area	2-10
Airports (terminals, roads, aprons)	2-10
High-value downtown business areas	2-10
Major drainage-system elements	Up to 100 years

Source: Adopted from ASCE (1992)

three groups: 1) Short Duration (1 minute - 1 or 2 hr.), Intermediate Duration (1 to 24 hrs.), and Long Duration (more than 24 hrs.). Maximum 2 hours is recommended for arid and semi-arid regions, such as Arbaat Area, having short-duration rainfall. The Depth – Duration – Frequency (DDF) relationships have an essential effect on this study to estimate the peak discharge (Q_{peak}) with Rainfall-Runoff Models like HEC-HMS. Unfortunately, in the study area, only 24-hour rainfall data are available. Thus, the comprehensive hydrological study of the Arbaat Valley is seen to either take a uniform precipitation distribution over the total storm duration leading to an underestimation of peak discharges or to assume the rainfall depth record for each storm by duration 120 minute (2 hours). In this research, the Gumbel distribution was used for all frequency analysis for consistency.

3.7.2 Gumbel's distribution

The calculation of maximum-rainfall is essential for the computing peak of discharge and sediment load. For this purpose, the Gumbel method was used in this study. The daily maximum rainfall events for the study area (Table 9) was found to be the suitable probability distribution for extreme value Type 1. The relation between the annual maximum rainfall, X_T , and the corresponding return period T, for Arbaat watershed area, is given by Gumbel equation (Eq. 7) as (PMP):

$$X_T = 38.4 + 32.9 \left(-\ln \left(\ln \frac{T}{T-1} \right) \right) \quad (7)$$

In this study, the return periods (T) of 10,20,50,80, and 100 years were used, according to the typical return periods of land use and drainage system (Table 10) developed by ASCE 1992. In addition, following the Eqs. (2) and (3), Gumbel's application was used to define the rainfall magnitude corresponding to a given return period on the basis of a maximum daily rainfall. The Gumbel extreme value frequency factors of $K_{10} = 1.3$, $K_{20} = 1.9$, $K_{50} = 2.6$, $K_{80} = 2.96$, $K_{100} = 3.1$ were applied. It was observed that the estimated return periods for maximum daily rainfall events of over 123.7 mm and 141.5 mm exceed 50 and 100 years, respectively. As shown in Fig. 17, the value of maximum rainfall depth $p^2_{100} = 141.6$ mm/day was found, by extending the curve based on the Gumbel Distribution for Maximum Daily Rainfall Data (PMP, T, P). Weibull and Gumbel are empirical methods known as plotting positions. Table 11 displays the plotting position for maximum daily rainfall for the Port Sudan station. Port Sudan gauge stations have been adopted as a rainfall value to be used in this study. Because it is the maximum value after comparing it with the rain values of the other gauge stations such as Sinkat, Suakin, and Arbaat stations.

Fig. 18 shows the rain flow counting of signal and Fig. 19 shows rain flow pointing. Fig. 20 shows spatial distribution of rainfall (mm). According to the obtained results given in Table 12, it was found that the return period of 100 years has provided the rainfall value of 141.6 millimeters, which is almost the same as the obtained value of 141.6-mm by PMP. Therefore, this value can be approved

Table 11 Plotting position for maximum daily rainfall (Port Sudan station)

Year	Max daily R.F (mm)	m	Sort data	$P = m / (N+1)$	$T = 1/P$
12/7/1943	47	1	163	0.017241379	58
16/11/1944	49	2	138	0.034482759	29
29/10/1945	11	3	111	0.051724138	19.333333
12/11/1946	40	4	106	0.068965517	14.5
27/11/1947	70	5	104	0.086206897	11.6
22/10/1948	17	6	74	0.103448276	9.6666667
30/11/1949	104	7	70	0.120689655	8.2857143
20/12/1950	106	8	60	0.137931034	7.25
6/11/1951	74	9	58	0.155172414	6.4444444
25/12/1952	20	10	56	0.172413793	5.8
30/7/1953	6	11	56	0.189655172	5.2727273
6/8/1954	6	12	51	0.206896552	4.8333333
21/11/1955	8	13	49	0.224137931	4.4615385
28/7/1956	20	14	48	0.24137931	4.1428571
21/11/1957	111	15	47	0.25862069	3.8666667
4/11/1958	19	16	46	0.275862069	3.625
15/12/1959	20	17	43	0.293103448	3.4117647
5/12/1960	42	18	43	0.310344828	3.2222222
30/11/1961	56	19	42	0.327586207	3.0526316
9/11/1962	51	20	42	0.344827586	2.9
20/1/1963	38	21	41	0.362068966	2.7619048
27/12/1964	21	22	41	0.379310345	2.6363636
27/11/1965	39	23	40	0.396551724	2.5217391
3/11/1966	31	24	39	0.413793103	2.4166667
1/12/1967	10	25	38	0.431034483	2.32
17/4/1968	32	26	38	0.448275862	2.2307692
19/2/1969	16	27	37	0.465517241	2.1481481
31/12/1970	28	28	33	0.482758621	2.0714286
1/1/1971	33	29	33	0.5	2
28/10/1972	33	30	32	0.517241379	1.9333333
26/11/1973	4	31	31	0.534482759	1.8709677
18/7/1974	17	32	29	0.551724138	1.8125
20/11/1975	60	33	28	0.568965517	1.7575758
2/11/1976	42	34	26	0.586206897	1.7058824
18/10/1977	43	35	24	0.603448276	1.6571429
20/12/1978	56	36	24	0.620689655	1.6111111
16/10/1979	58	37	21	0.637931034	1.5675676
9/12/1980	6	38	20	0.655172414	1.5263158
3/11/1981	3	39	20	0.672413793	1.4871795
21/11/1982	46	40	20	0.689655172	1.45
12/10/1984	43	41	19	0.706896552	1.4146341
18/11/1985	24	42	17	0.724137931	1.3809524
1/1/1986	26	43	17	0.74137931	1.3488372
17/10/1987	10	44	16	0.75862069	1.3181818
10/11/1988	6	45	16	0.775862069	1.2888889
18/10/1989	16	46	11	0.793103448	1.2608696

Table 11 Continued

Year	Max daily R.F (mm)	m	Sort data	$P = m / (N+1)$	$T = 1/P$
27/11/1990	29	47	10	0.810344828	1.2340426
7/4/1991	48	48	10	0.827586207	1.2083333
1/11/1992	38	49	8	0.844827586	1.1836735
17/4/1993	138	50	6	0.862068966	1.16
8/1/1994	6	51	6	0.879310345	1.1372549
19/11/1995	41	52	6	0.896551724	1.1153846
17/11/1996	41	53	6	0.913793103	1.0943396
27/10/1997	163	54	6	0.931034483	1.0740741
12/7/1998	24	55	4	0.948275862	1.0545455
18/12/1999	37	56	4	0.965517241	1.0357143
17/4/2000	4	57	3	0.982758621	1.0175439

N = 57 years, Av = 38.4 mm, Std = 32.9, and PMP = 141.6 mm

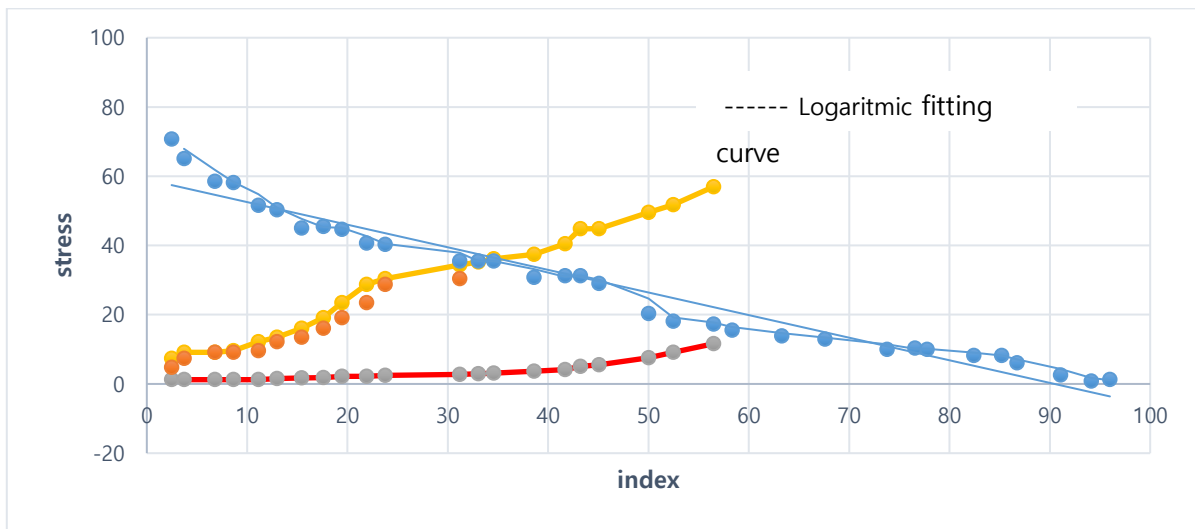


Fig. 18 Rain flow counting of signal

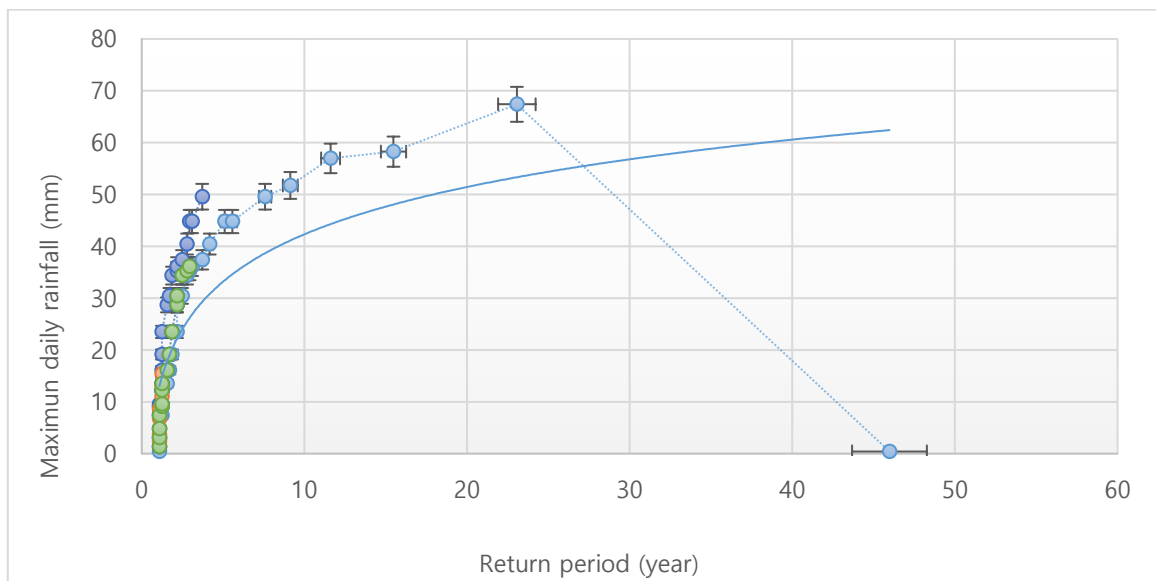


Fig. 19 Rain flow pointing

Table 12 Maximum daily rainfall corresponding return period (T)

Return Period (T, years)	Maximum Rainfall (mm)			
	Port Sudan	Arbaat	Suakin	Sinkat
10	81.3	38.8	86.3	62.1
20	99.8	48.4	103.2	74.5
50	123.7	60.6	125.11	90.7
80	135.4	66.8	136.3	98.9
100	141.6	69.8	141.5	102.8
Gumbel's value distribution	Average = 38.4 mm S.D = 32.9mm N = 57	Average = 16.9 mm S.D = 16.7 mm N = 32	Average = 46.9 mm S.D = 30.1 mm N = 29	Average = 33.1mm S.D = 22.2mm N = 32



Fig. 20 Spatial distribution of rainfall (mm)

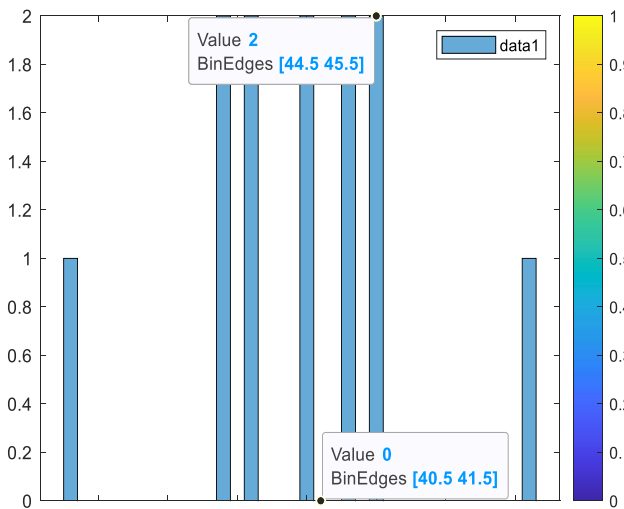


Fig. 21 The error distribution of selected annual rainfall data

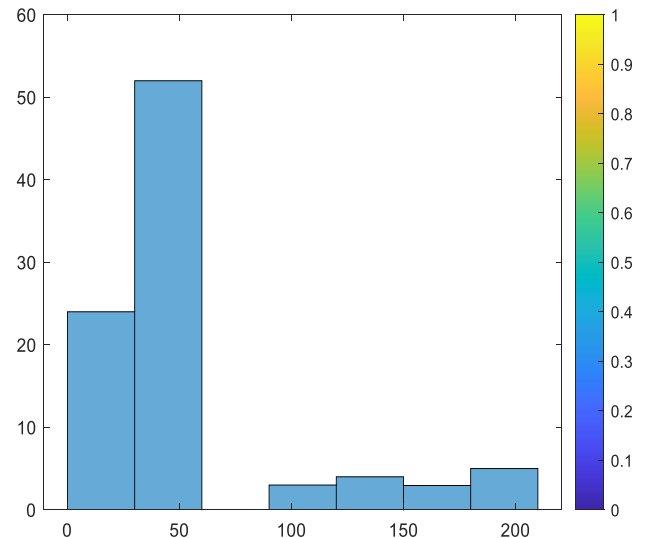


Fig. 22 The error distribution of selected monthly rainfall data

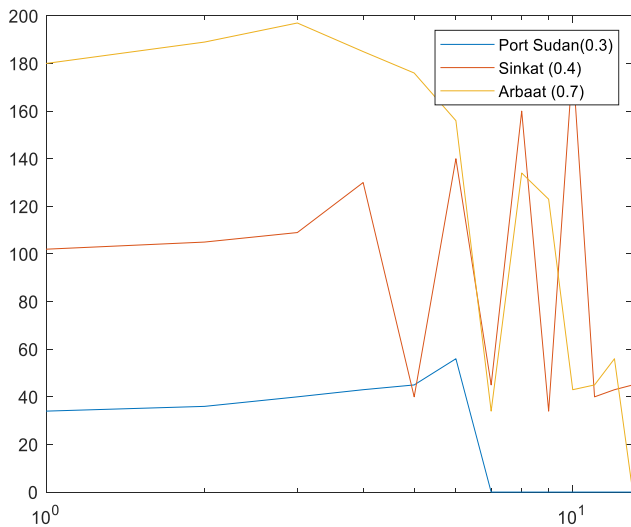


Fig. 23 The rainfall ratio plot of three station in 10 years

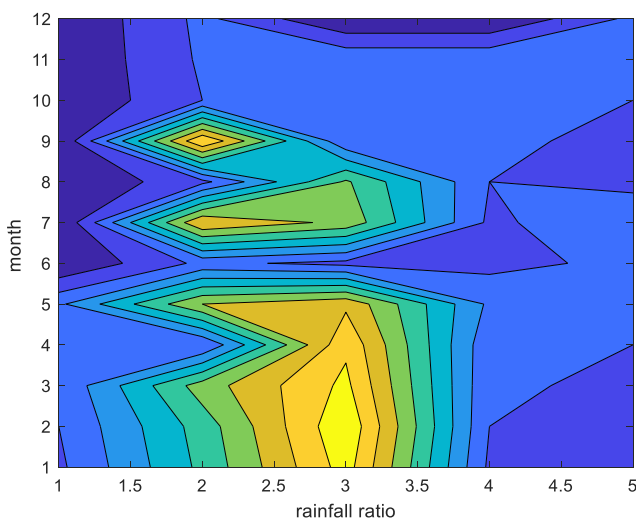


Fig. 24 Rainfall intensity plot during the 10 years (1990-2000) in three station (Port Sudan, Arbaat, and Sinkat stations) (blue = low rain, yellow = high rain)

for Rainfall-Runoff models as the only value in extracting the discharge hydrograph. Fig. 21 shows the error distribution of selected annual rainfall data, while Fig. 22 is the error distribution of selected monthly rainfall data. Fig. 23 indicates the rainfall plot of three station in 10 years, and Fig. 24 is the rainfall intensity plot during a year in three station (Port Sudan, Arbaat, and Sinkat stations) (blue = low, yellow = high rain).

4. Conclusions

Water resources in Red Sea State –Sudan are scarce. This is because, geographically, Eastern Sudan is located in arid to semi-arid region. Daily, monthly and annually rainfall data for three gauging stations surrounding Arbaat Watershed Area (Port Sudan, Arbaat, and Sinkat stations) were critically studied and analyzed. In this study, for Meteorological data analysis, Micro-soft Excel and

Origin_Pro_8.0 were used. The following results are drawn:

- Based on the obtained results of the selected rainfall data, the annual variations of rainfall are high with an average value of 93.54 mm, a maximum of 272 mm, and a minimum of 2 mm. Rainfall is variable in both spatial and period. Its gradient is very steep westward towards the Red Sea Mountain. The average annual areal rainfall over Arbaat watershed is about 93.5 mm estimated using the Isohyetal map for the watershed area.

- Precipitation in the Red Sea State occurs in two seasons, summer and winter. Summer rainfall (July to September) occurs roughly 80 percent of the annual rainfall happens from June to September. In this study, the extreme daily depths are defined through a frequency analysis, and the computed 24-hour extreme depth across the design storm duration is distributed through Gumbel distribution Type 1.

- DDF relationships have an essential effect on this study to estimate peak discharge (Q_{peak}) with Rainfall-Runoff Models (HEC-HMS, HEC-RAS, WMS). In this study, only 24-hour rainfall data are available. Alternatively, assume the rainfall depth record for each storm by the duration of 120 minutes (2 hours). For consistency, the Gumbel distribution was adopted for all frequency analysis in this study.

- This distribution gives a large amount of rainfall storm 113.9 mm in average values of stations and 141.6 as the maximum value of Port Sudan Station with return period 100. In general, studying the extreme hydrological events required choosing the largest or smallest greatest events. However, for rainfall-runoff hydrological modeling and sediment transport prediction, the researchers are more interested in the largest extreme events that have a large probability of creating maximum runoff.

- In addition, the highest rainfall in the design of some Hydraulic Structures, Flood control structures, and Sediment control structures such as Sediment Trapping Basin, the maximum possible rainfall that could be assumed as the extreme total sediment load.

Acknowledgments

The authors would like to thank Deanship of Scientific Research at Prince Sattam Bin Abdulaziz University to support this study, and also would like to thank the Sudanese Meteorological Organization (SMO) for providing the basic hydro-climatic data and Red Sea State Water Corporation (RSSWC) for providing some data about the study area.

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