

Article

Extreme Daily Rainfall Assessment in Arid Environments Through Statistical Modeling

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Abstract

Rainfall is a significant input for several engineering designs such as hydraulic structures, culverts, bridges and ducts, rainfall water sewer, and highway drainage system. The detailed statistical analysis of extreme daily rainfall of each arid environment's region is essential to estimate the relevant input value for designing and analyzing engineering structures and agricultural planning. This paper aims to assess the best-fitting distribution to estimate the design of rainfall depth (XT) and maximum rainfall values for different return periods (2, 10, 25, 50, 100, and 150). This study used extreme daily rainfall historical data collected in period of 1970–2020, collected from four rainfall gauge stations nearby the Wadi Al-Aqiq that are selected for analysis; they are Al Faqir (J109), Umm Al Birak (J112), Madinah Munawara (M001), and Bir Al Mashi (M103). The methodology approved in this paper examined four frequency distributions, namely: GEV (Generalised Extreme Value), Gumbel, Weibull, and Pearson type III to identify the most suitable and extreme storm design depth corresponding to different return periods. The results demonstrate that GEV and Pearson Type 3 produce higher extremes values, while the Weibull method is commonly suggested in the HYFRAN-PLUS MODEL (DSS) for criterion suitability. The findings for the 100-year storm design demonstrate that extreme values generated by the Hyfran-Plus model are higher than the decision support system (DSS). All (DSS) comparative values are less than the maximum historical data from 1970–2020, except the Al Faqir station (DSS), which has a value of 79.6 mm that exceeds the historical maximum of 71 mm. This study will provide advantageous information about the study area for water resources planners, farmers, and urban engineers to assess water availability and create storage.

Keywords: arid environments; wadi alaqiq; extreme daily rainfall; hyfran-plus model; DSS



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1. Introduction

Water is essential to any life process and cannot be substituted. Water is also an energy source and is used for many other valuable purposes for domestic use, agriculture, and industry. Rainfall is an essential natural resource used as a direct/indirect input for meeting the water requirements of crops and indirect input in satisfying the water demands of domestic, commercial, and industrial activities through surface and subsurface storage. The hydrologic characteristics of an arid or semi-arid region are mainly determined by its climate, geology, and geography [1,2]. The climatic factors that establish the hydrologic features of these regions include the amount and distribution of precipitation and the effects of wind, temperature, and humidity on evaporation and evapotranspiration.

Meteorology plays an essential role in hydrologic problems, such as determining probable maximum precipitation conditions for spillway design, forecasting precipitation for reservoir operation, and determining probable maximum winds over water surfaces (used for evaluating the resulting waves in connection with the design of dams and levees). Climate varies greatly, depending on the geography and the season in Saudi Arabia (KSA) [3–5]. A hypothetical rainfall event corresponding to a specified return period (T) is usually the basis for designing and analyzing stormwater management systems. However, the return period (T) of a rainfall event is not equal to the return period of the resulting runoff, and, therefore, the reliability of surface-water management systems will depend on factors such as the antecedent moisture conditions in the catchment and its geographical location; for example, in an arid or semi-arid region [6,7]. In contrast to the single-event design storm approach, a continuous simulation approach is sometimes used. A historical rainfall record is an input to a rainfall–runoff model; the resulting runoff is analyzed to determine the hydrograph corresponding to a given return period. The design storm approach is more widely used in engineering practice than the continuous simulation approach. Design storms can be synthetic or actual (historical), with synthetic storms determined from historical rainfall statistics. Synthetic design storms are characterized by their frequency or return period, duration, depth, temporal distribution, and spatial distribution [8,9]. A hypothetical rainfall in each period is typically the basis for stormwater management systems design and review. However, the return of precipitation is not equal to the return duration for the resulting surface runoff, so the efficiency of the water-surface management systems would depend on factors such as the historical humidity of the catchment and its geographic position; for instance, in a semi-arid and arid region [10]. In West Saudi Arabia, Al-Madinah has normal-to-extremely dry conditions [11]. For describing the rainfall patterns and runoffs in this region as being characterized by extremely high variability in time and space. In this region, exact and continuous meteorological data on hydro are sadly minimal or incomplete. Runoff measurements and continuous large spatial or time precipitation data are challenging, and runoff processes are less predictable and difficult to interpret and model. The studies of rainfall analysis include gathering historical data over enough years. After that, they were primarily based on the classification of data and assignment of plotting positions in the calculation of the likelihood of exceeding by one method. A distribution assumption should be picked, the data should be plotted in a probability plot, and the assurance of the goodness of the distribution should be chosen. Another distribution should be selected in the absence of a suitable distribution, or the data should be transformed to follow the selected distribution [12–14]. Determination of rainfall depths (XPs) can be predicted from the probability plot for selected probabilities or the return time [15]. Probability plotting positions are used to demonstrate annual maximum hydrologic series and estimate the probability of exceedance. The importance of probability plots, which allow a visual assessment of the capability of the fit provided by alternative parametric flood frequency models [16]. Software used to match statistical distributions is HYFRAN-PLUS (Hydrological Frequency Analysis PLUS DSS). It contains a variety of strong, versatile, and easy-to-use mathematical tools that can be used to analyse extreme events statistically. It can also conduct simple analyses of independent and identically distributed (IID) data at any time more broadly. For studying the rainfall analysis as input data to HEC_HMS (Wadi Arbaat_Eastern Sudan), used the maximum rainfall events (the extreme hydrological events, MRE) required to choose the most significant events [17]. However, for rainfall–runoff hydrological modeling and sediment transport prediction, the researchers are more interested in the most significant extreme events with a considerable probability of creating maximum runoff. The return period (T) of a design rainfall should be selected based on economic efficiency. Typical return periods are given in Table 1, although

longer return periods are sometimes used (see Table 2). For example, return periods of 10–30 years in arid and semi-arid regions are commonly used for designing storm sewers in commercial and high-value districts [3]. Local drainage regulations should be reviewed and followed when selecting the return period for a particular project. An implicit assumption in designing drainage systems for a given return period of rainfall is that the return period of the resulting runoff is equal to the return period of the design rainfall. Based on this assumption, the risk of failure of the drainage system is taken to be the same as the exceedance probability of the design rainfall. On the other hand, the engineering designer chooses the return period (T), and Table 1 (ASCE, 1992) [18] may be used as a reference when used in conjunction with local regulations and experience. The return periods commonly used in hydraulic structures design and hydrology studies show that design return periods vary typically from 10 to 100 years, and in world regions where the Probable Maximum Precipitation (PMP) has not been definite, up to 10,000 years. The selection of return period (T) in rainfall analysis depends on different factors, containing: (1) the size of the drainage area, (2) the risk of failure, (3) the importance of the hydraulic structures, and (4) the desired degree of conservatism in the design. The return period (T) is chosen by the hydrologist designer, in consultation with the owner of project, following established practice in a certain country or climatic region. An assessment of risk is paramount to the selection of return period. Table 2 may be used as a guideline when used in conjunction with local regulations and experience [3,18–20].

Table 1. 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: Adapted from ASCE (1992) [18].

Table 2. Guidelines for the selection of return period (T).

No.	Type of Project or Feature	Return Period (Year)
1.	Urban drainage [low risk] (up to 100 ha)	5 to 10
2.	Urban drainage [medium risk] (more than 100 ha)	25–50
3.	Road drainage	25–50
4.	Principal spillways (dams)	25–100
5.	Highway drainage	50–100
6.	Levees [medium risk]	50–100
7.	Urban drainage [high risk] (more than 1000 ha)	50–100
8.	Flood plain development	100
9.	Bridge design (piers)	100–500
10.	Levees [high risk]	200–1000
11.	Emergency spillways (dams)	100 to 10,000 (PMP)
12.	Freeboard hydrograph [for a class (c) dam]	10,000 (PMP)

Source: Victor M. Ponce May 2008 (https://ponce.sdsu.edu/return_period.html, accessed on 6 April 2026).

The Problem Statement of this study includes three crucial points as follows:

(1) Extreme rainfall in arid and semi-arid regions has caused life loss and significant damage to infrastructure, especially in urban areas; (2) Probability and frequency analysis of rainfall data facilitate us to determine the expected rainfall with various chances of occurrence; and (3) Madinah Region is located in an arid–semi arid region. Many of its main urban centers have suffered from intense rainfall, producing flash flood of high frequencies and magnitudes. Therefore, the rainfall frequency analysis using the Hyfran Model is a most important technique for storm water design in this study. This paper aims to understand the concept of storm water patterns, highlight the important of rainfall analysis in water resources management, collect, describe and summarize historical rainfall data, and study the statistical techniques used to summarize and describe a rainfall dataset using the HYFRAN-PLUS model in statistical frequency analysis to determine rainfall depth (X_T) and intensity values for different return periods (T).

2. Data and Methods

The methodology used in this study is descriptive rainfall statistics for maximum daily historical data from 1970 to 2020, as arithmetic mean, standard deviation skewness, and other parameters. The probability analysis of (MDR) events were conduct using Hyfran_plus model (version 2.2), which applies different plotting position and probabilistic methods. This comprehensive analysis joined several distributions, containing Gumbel, Weibull, GEV, Person type III Distributions, and others for maximum daily rainfall events. The flowchart below summarizes the steps of methods in Figure 1.

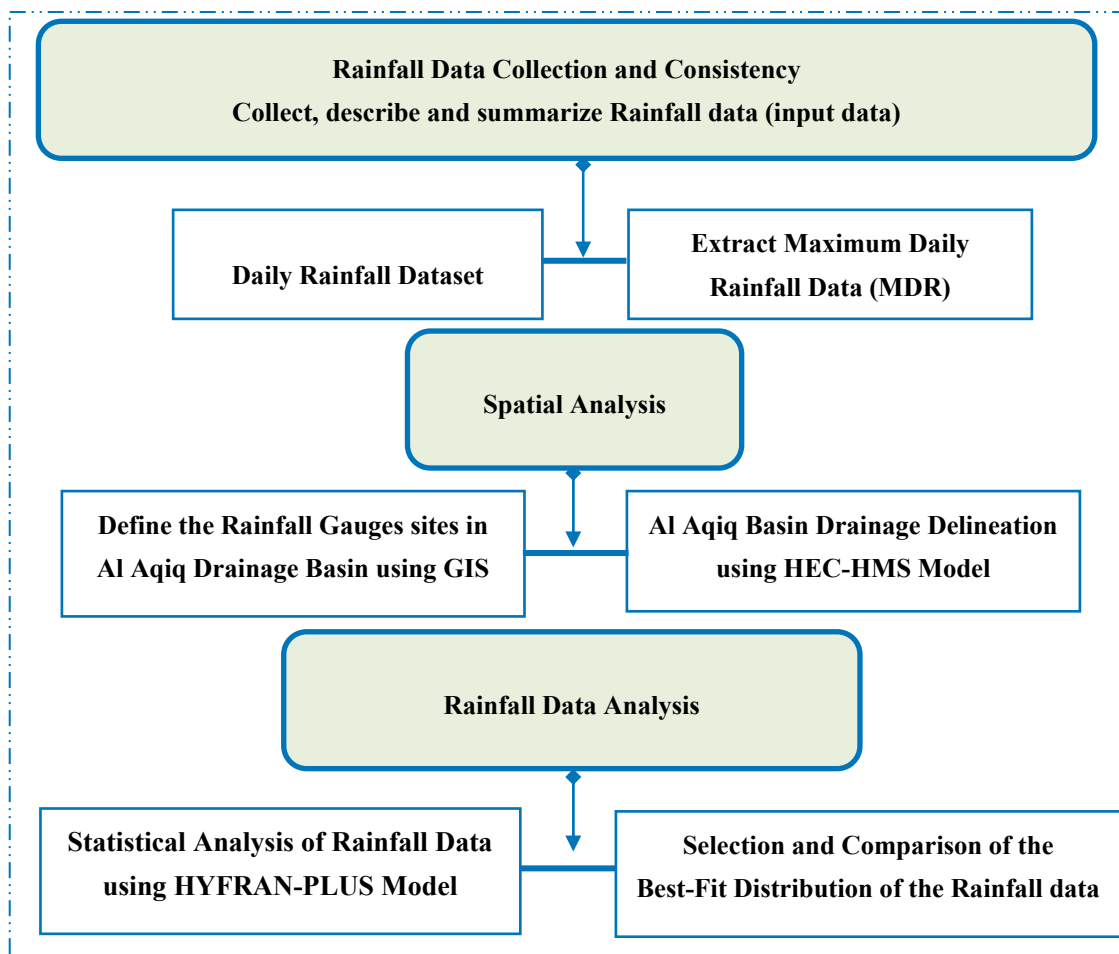


Figure 1. Methodology Flowchart of study.

2.1. Study Area

The present study is carried out for Wadi Alaqiq in Al-Madinah Al-Munawarah of Saudi Arabia, which is bounded in the east, south, and west by the high plateau of Harrat (Basaltic Lava Groups), as shown in Figure 2. It is also bounded in the north and northeast by the mountains of Jabal Uhud, Southwest Jabal Eier. This area is typically hilly with gentle and steeply sloping plains and barren rocks void of significant vegetative growth [21]. Several wadis flow in wadi form towards Al-Madinah through basalt formations and depots of alluvium. These Wadis flow from the northwest side of the city to the south, southeast, and northeast. Wadi Alaqiq, Wadi Alaqoul (known as the Wadi Qanat or Wadi Sayedna Hamzah), Wadi Bat-han, Wadi Mahזור, and Wadi Ranounaa are all located near Madinah.

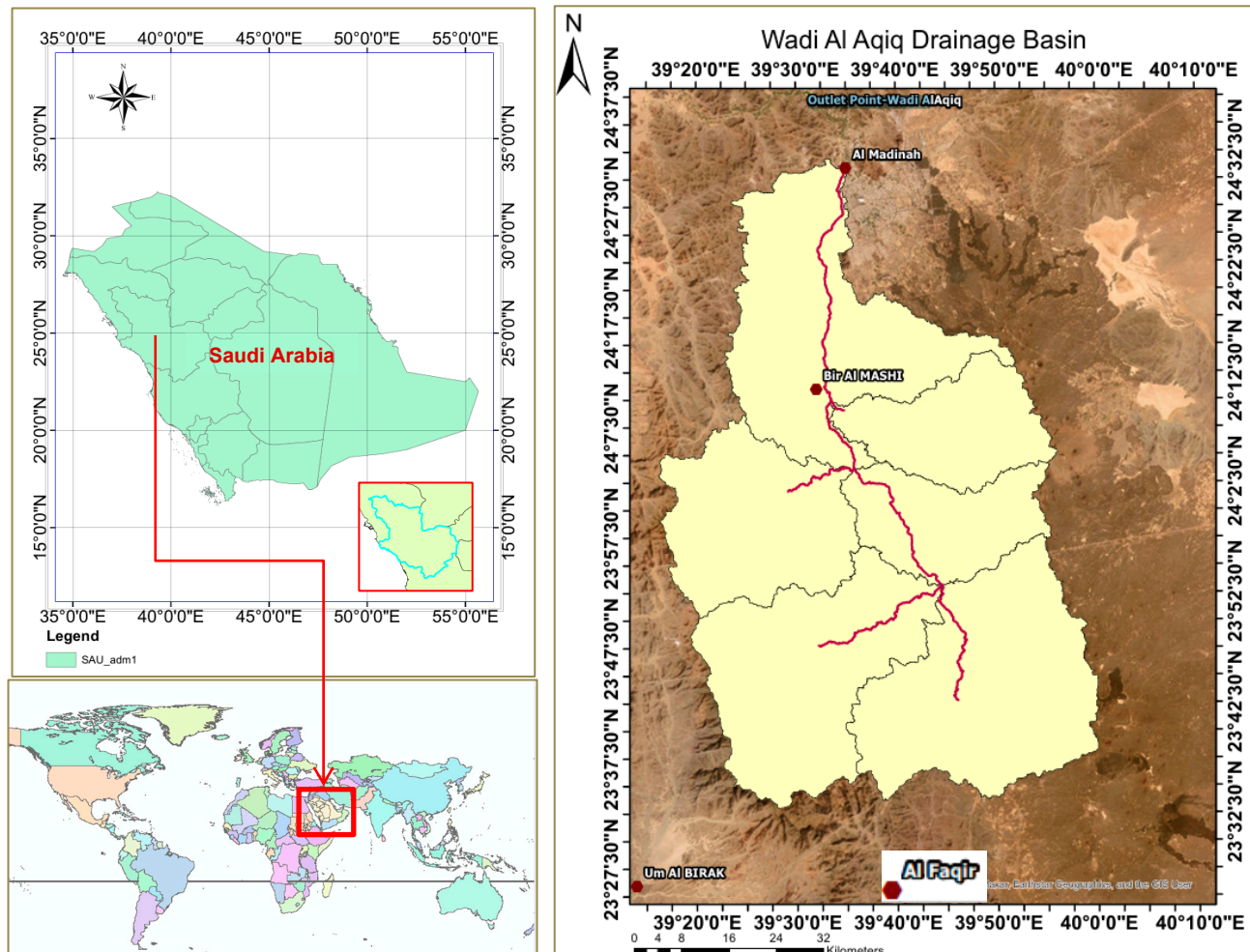


Figure 2. Location map of the study area.

Moreover, Wadi Alaqiq was chosen to implement this study due to the considerable divergence in their topography and climate, and it will be the focus of our study. The study area comprises 5130.8 km² drainage area. It is located within the 39°16'13.2" E, 40°05'8.5" E, 23°32'50.4" N, and 24°31'41.1" N in the western region of KSA. Figure 2 shows the Al Madinah Munawwara region relative to KSA and Wadi Aqiq. The basin area of Wadi Al Aqiq is characterized by an arid climate rainfall pattern with high temporal and spatial variability that takes place primarily during the winter and spring seasons. The seasonal rainfall events are caused by the combination of disturbances from the winter Mediterranean and the Sudan trough, which usually generate extreme rainfall convective events over the Madinah region and its surrounding areas [22–24]. The drainage areas of Wadi Aqiq sub-basins are given in Table 3. Wadi Alaqiq, with a length of 163.2 km, starts

flowing towards AL Madinah from the mountains of Adan, Alsudair, and Alqinainah, located 85 km south of Al-Madinah. Wadi Aqiq takes many names along its course; Naqi in the high stream, and Al Asad Al Hassi between Eir Mountain, Hamra'a, and Aqiq next to Dhou Al Halifa. Many of tributary wadis flow into Wadi Aqiq, like Chaabine, Dhalama, Al Ouch, El Yatama, Dhaf, Malaha, Rym, Naqi', Khanga, Hadha, and Sudayr. In addition, many tributaries feed Wadi Aqiq like Al lihyane, Arar, Nakhal Malha, and Slayem Massaid [25].

Table 3. Drainage areas of Wadi Aqiq sub-basins.

Sub-Basins	Drainage Area (km ²)	Perimeter (km)	Length (km)	%
Al Ishsh	1193.0	251.2	41.8	34%
Ruwawah	527.9	153.6	39.0	15%
Al Yitimah	1037.5	240.9	48.1	29%
Rim	776.1	193.3	37.2	22%
Total (Al Aqiq basin)	3534.5	534.0	108.5	100

The RST (Red Sea Trough) is commonly recognized as one of the dominant synoptic systems responsible for producing extreme rainfall events across Western Saudi Arabia (Arabian Peninsula). It typically forms through the southward extension of a mid-latitude trough along the Red Sea axis, which improves low-level convergence and accelerates the northward conveyance of warm, moisture-laden air from tropical latitudes. This pattern promotes strong atmospheric instability and deep convection, making the RST a frequent driver of heavy rainfall and flash-flood events in the region. Extreme rainfall episodes are most commonly observed during spring from March to May and in fall from September to November, seasons that accord with peak (RST) motion and favorable upper-level dynamical environments. Although the role of the surface oscillation system (RST) as a primary mechanism for heavy rainfall is well established in the scientific literature, any specific quantitative attribution of the frequency of events to the occurrence of the surface oscillation system (RST) must be supported by relevant comprehensive observational or climate studies.

2.2. Rainfall Data Collection

Measurements of rainfall have several methods to determine rainfall depth, including daily known non-recording gauge, or rainfall intensity as short durations (mm/h or mm/min) with known recording gauge. In this paper, daily rainfall data obtained from a non-recording gauge were used. The maximum daily rainfall (MDR) values were extracted using built-in functions within Microsoft Excel. Radar Measurement of rainfall (RMR) and satellite measurement of rainfall (SMR) are most important for identifying the amount of rainfall, but they were not utilized in this study. These modern applications are widely used for cover precipitation over large areas, monitoring the short duration of rainfall duration, flash flood, and global weather and climate changes. One example of satellite measurements is global precipitation measurements (GPM), which provides continuous long-term data records, which are valuable for rainfall patterns [24,26]. The analysis of rainfall data is an essential step to estimate the flood water flowing in the valleys and drainage networks. Rainfall data analysis depends on the data available from meteorological stations around the study area to describe the storm pattern and the total daily cumulative precipitation rate.

2.2.1. Rainfall Gauges in Al-Madinah Al-Munawarah Region (Wadi Al Aqiq)

Four rainfall gauge stations in the locality of the Wadi Alaqiq, namely M001, M103, J109, and J112, as shown in Figure 3, with a record length of more than 30 years, were used in this study. Moreover, the geographical locations and available data of stations around the study area are given in Table 4.

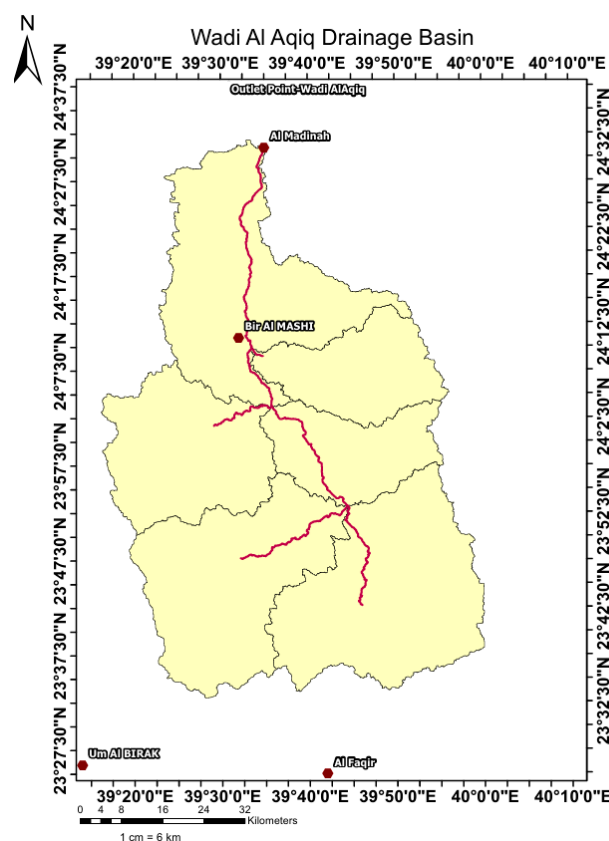


Figure 3. Meteorological Stations in Study Area.

Table 4. Geographical location and available data of stations around the study area.

No.	M. Station	Code No.	Coordinates		Altitude (m)	Data Analysis
			Longitude (°) E	Latitude (°) E		
1	Um Al BIRAK	J112	39°14'	23°26'	210	1970–2020
2	Al Madinah	M00L	39°35'	24°31'	590	1970–2020
3	Bir Al MASHI	M103	39°35'	24°31'	660	1970–2020
4	Al Faqir	J109	39°42'	23°25'	682	1970–2020

2.2.2. Rainfall Data Records

The rainfall data recorded by rain gauges (four meteorological stations) near the study area for different stations of Um Al Birak (J112), Al Madinah Munawwara (M00L), Bir Al Mashi (M103), and Al Faqir (J109) are revealed in Figure 3, and the details of stations shown are Table 4. For this study, the maximum daily rainfall data in studied stations recorded during the period from 1970–2020 are present in Table 5 and Figure 4. All rainfall data, which are daily rainfall data for 24 h, have been gathered from the Ministry of Environmental, Water and Agriculture (MEWA).

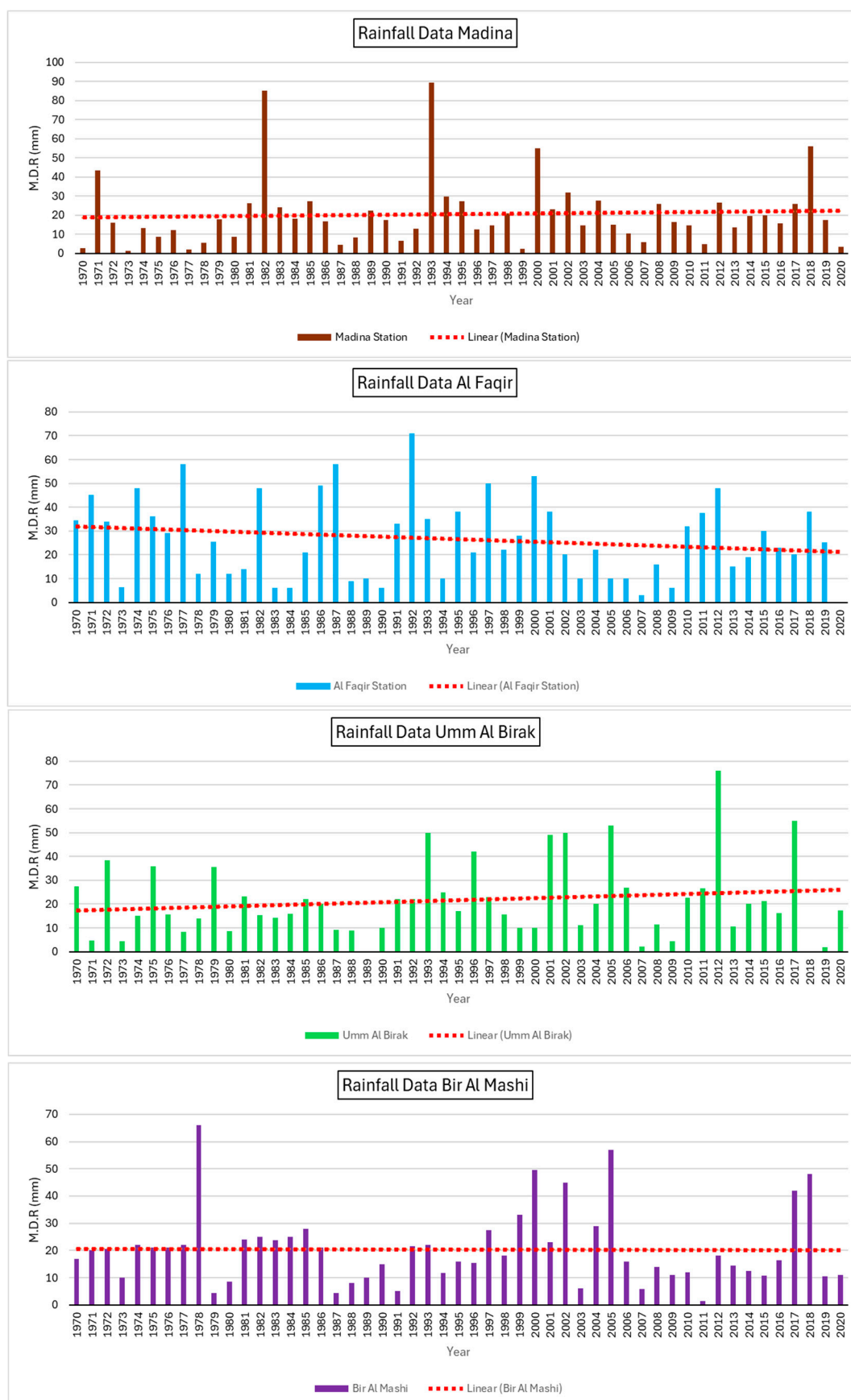


Figure 4. Maximum daily rainfall and trend lines (1970–2020) for Al Madinah, Al Faqir, Um Al BIRAK, Bir Al MASHI, respectively.

Table 5. Maximum Daily Rainfall during the period of 1970–2020 (mm).

Rainfall Data (mm) (1970–2020)									
Year	Al Madinah (M001)	Bir Al Mashi (M103)	Al Faqir (J109)	Um Al Birak (J112)	Year	Al Madinah (M001)	Bir Al Mashi (M103)	Al Faqir (J109)	Um Al Birak (J112)
1970	2.8	16.9	34.5	27.5	1996	12.6	15.5	21	42
1971	43.6	20	45	4.8	1997	14.8	27.5	50	23
1972	16	20.5	34	38.5	1998	21	18	22	15.6
1973	1.4	10	6.3	4.5	1999	2.5	33	28	10
1974	13.4	22	48	15.1	2000	55	49.5	53	10
1975	8.6	21	36	35.8	2001	23.2	23	38	49
1976	12.2	21	29	15.5	2002	32	45	20	50
1977	2	22	58	8.2	2003	14.8	6	10	11
1978	5.4	66	12	14	2004	27.8	29	22	20
1979	17.8	4.3	25.5	35.5	2005	15	57	10	53
1980	8.8	8.6	12	8.5	2006	10.5	16	10	27
1981	26.4	24	14	23.2	2007	6	5.9	3	2.1
1982	85.2	25	48	15.3	2008	26	14	16	11.4
1983	24.2	23.7	6	14.2	2009	16.3	11	6	4.3
1984	18.2	25	6	16	2010	14.8	12	32	22.7
1985	27.4	28	21	22.2	2011	4.7	1.5	37.5	26.6
1986	16.6	21	49	20.1	2012	26.5	18	48	76
1987	4.4	4.3	58	9.2	2013	13.5	14.5	15	10.7
1988	8.2	8	9	9	2014	19.5	12.5	19	20
1989	22.3	10	10	0	2015	20	10.8	30	21.3
1990	17.3	15	6	10	2016	15.7	16.5	23	16.3
1991	6.6	5	33	22	2017	26	42	20	55
1992	12.8	21.5	71	22	2018	56.1	48	38	-
1993	89.6	22	35	50	2019	17.5	10.6	25.2	1.8
1994	29.8	11.6	10	25	2020	3.56	11	0.2	17.2
1995	27.4	16	38	17					

Source: The Ministry of Environment, Water and Agriculture (MEWA, 2020).

2.2.3. Frequency Analysis of Rainfall (Plotting Positions)

Many plotting position formulas are available. This paper used four more commonly ones, as given in Table 6. Adamowski [3,8,21] has shown that all these formulas can be expressed in general form:

$$P_m = \frac{m - a}{N + b} \quad (1)$$

where a and b are constants, P_m is the probability of the exceedance of the m th observation, and m is the rank of N ordered observations (in decreasing order), such as

$$P_{m=1} > P_{m=2} > \dots P_{m=N} \quad (2)$$

Table 6. Common Plotting-Position Formulas More Frequently Used.

No.	Plotting-Position Method	Formula for Probability of Exceedance, P_m	a	b	Return Period
1.	Hazen	$P_m = \frac{m-0.5}{N}$	0.5	0.0	$P_m = \frac{N}{m-0.5}$
2.	Gumbel	$P_m = \frac{m-0.5}{N}$	0.5	0.0	$P_m = \frac{N}{m-0.5}$
3.	California	$P_m = \frac{m}{N}$	0.0	0.0	$T = \frac{N}{m}$
4.	Weibull	$P_m = \frac{m}{N+1}$	0.0	1.0	$T = \frac{N+1}{m}$
5.	Beard	$P_m = \frac{m-0.31}{N+0.38}$	0.31	0.38	$P_m = \frac{N+0.38}{m-0.31}$
6.	Chegodayev	$P_m = \frac{m-0.3}{N+0.4}$	0.3	0.4	$P_m = \frac{N+0.4}{m-0.3}$
7.	Blom	$P_m = \frac{m-0.375}{N+0.25}$	0.375	0.25	$P_m = \frac{N+0.25}{m-0.375}$
8.	Gringorten	$P_m = \frac{m-0.44}{N+0.12}$	0.44	0.12	$P_m = \frac{N+0.12}{m-0.44}$
9.	Cunnane	$P_m = \frac{m-0.4}{N+0.2}$	0.4	0.2	$P_m = \frac{N+0.2}{m-0.4}$
10.	Adamowski	$P_m = \frac{m-0.25}{N+0.5}$	0.25	0.5	$P_m = \frac{N+0.5}{m-0.25}$

These formulas are selected based on the target distribution, environment, and desired bias features. For hydrological extremes, especially rainfall and flood frequency analysis, the Weibull, Gumbel, Gringorten, and Cunnane formulas are often preferred due to their ability to handle skewed and heavy-tailed distributions. These distributions are selected based on their performance in describing the characteristics of extreme events and the desired bias characteristics of the analysis. Six precipitation probability distributions in Quebec, (Canada), focusing on their effectiveness in replicating observed precipitation statistics and hydrological responses. Results showed more parameterized distributions yielded better performance, with mixed exponential distribution being most effective for hydrological modeling [27–29].

2.3. Hyfran and HYFRAN_PLUS MODEL

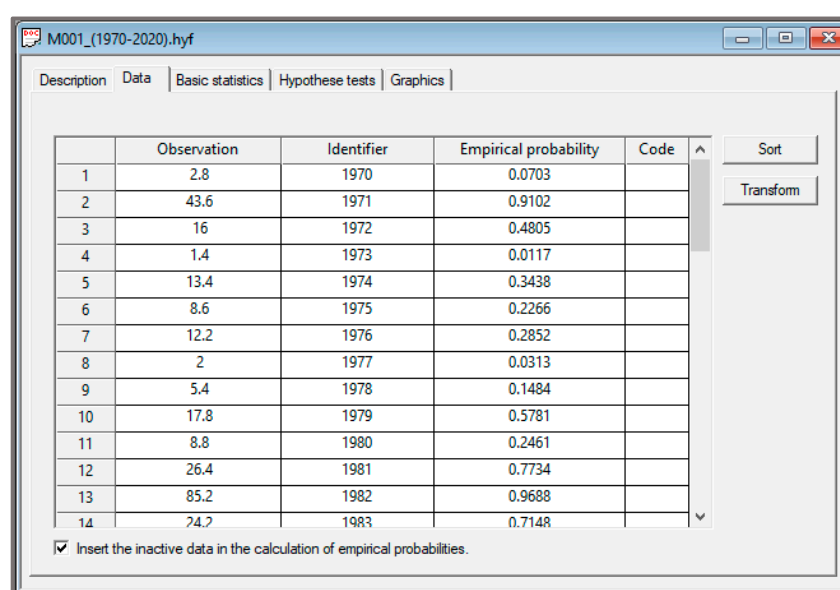
HYFRAN-PLUS is software that allows fitting several statistical distributions for data samples. It includes several powerful and flexible mathematical tools that can be used for the statistical analysis of extreme events.

HYFRAN and HYFRAN-PLUS are commercial standalone software products authored by a group of researchers at INRS University, Canada, designed initially for hydrological frequency analysis but now marketed more generally as software for fitting many distributions with different tail weights to data using a wide range of estimation methods. HYFRAN-PLUS contains a Decision Support System (DSS), which includes graphical diagnostics to enable the user to choose between different models. The main advantage of HYFRAN and HYFRAN-PLUS is the provision of an easy-to-use interface for those with little computational experience [30,31].

In addition, HYFRAN-PLUS (Hydrological Frequency Analysis PLUS) for Windows is software that allows fitting several statistical distributions to a data sample. INRS-Eau has developed this software with the collaboration of Hydro-Québec Hydraulic Service (Department Hydrology) in the framework of Hydro-Québec/CRSNG statistical hydrology Chair located at INRS-Eau: Commercial standalone software products. HYFRAN-PLUS (Hydrological Frequency Analysis) Description is a software used to fit statistical distributions. It includes several powerful, flexible, user-friendly mathematical tools that can be used for the statistical analysis of extreme events. Therefore, based on the suitability of this software, the analysis of the recorded data was carried out by using Hyfran and Hyfran_plus model.

2.3.1. Rainfall Data Represent on Hyfran-Plus Model

In this study, the annual maximum rainfall depth, the maximum daily rainfall intensity, and the intensity rainfall data were used as input data in the Hyfran-plus model. HYFRAN-PLUS comes with a spreadsheet that allows to enter and view data. Each line corresponds to an observation and is divided into four columns as shown in Figure 5, which are (i) Observation: the numerical value of each observation must be entered in this column; (ii) Identifier: you can assign a sequential number to each observation, if one wants to put a date, it should generally be entered in the format YYYY-MM-DD; however, the user can leave out the day and month and enter only the year (YYYY); (iii) Plotting Position (PP): the PP (Empirical probability) associated with each observation is automatically calculated and displayed in this column, using the formula specified in the description page of the project; (iv) Code: this column can be used to add only a single character in order to codify some observations; for example, add “M” for manually measured data and “R” for revised data.



	Observation	Identifier	Empirical probability	Code
1	2.8	1970	0.0703	
2	43.6	1971	0.9102	
3	16	1972	0.4805	
4	1.4	1973	0.0117	
5	13.4	1974	0.3438	
6	8.6	1975	0.2266	
7	12.2	1976	0.2852	
8	2	1977	0.0313	
9	5.4	1978	0.1484	
10	17.8	1979	0.5781	
11	8.8	1980	0.2461	
12	26.4	1981	0.7734	
13	85.2	1982	0.9688	
14	24.2	1983	0.7148	

☒ Insert the inactive data in the calculation of empirical probabilities.

Figure 5. Rainfall Data Exportation in the Hyfran-plus software (Al Madinah Munawwara Project).

Dealing with Zero and Negative Rainfall Data in Hyfran-Plus Analysis.

In rainfall frequency analysis using Hyfran Plus, researchers must carefully handle zero or negative values in the dataset to ensure statistical validity. Two approaches are commonly adopted: (A) Data Exclusion: If zero values constitute less than 10% of the total dataset, such as in the case of Um Al Birak (J112) rainfall station, they may be excluded, provided this does not compromise the representativeness of the data. (B) Value Adjustment: Alternatively, zero values can be replaced with a minimal positive value; for example, (0.1) to sustain continuity in the rainfall dataset and allow for suitable statistical distribution fitting. On the other hand, in Um Al Birak (J112) rainfall station, a single missing rainfall value in 2018 was handled by excluding that year from the dataset through listwise deletion. As this missing value accounts for less than 2% of the total record, its exclusion has a negligible impact on the frequency analysis.

2.3.2. Rainfall Data Output of Hyfran-Plus Model

Rainfall data output or results of the Hyfran-plus model appeared as follows:

(i) Fitting results:

(a) The return period, where P is the probability of exceedance, following Equation (3):

$$T = \frac{1}{P} \quad (3)$$

(b) The probability of non-exceedance, as given in Equation (2):

$$q = 1 - P \quad (4)$$

(c) The value of the corresponding quantile X_T , the standard deviation of the quantile σ_{XT} .

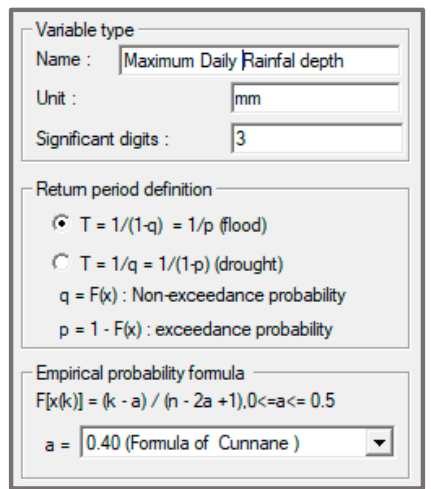
(d) The confidence interval CI of the quantile to a specified level of confidence.

(e) Equation (5) present the empirical probability formula used in Hyfran_plus Model

$$F[x(k)] = \frac{(k - a)}{(n - 2a + 1)} \rightarrow 0 \leq a \leq 0.5 \quad (5)$$

where the value of parameter (a) varies depending on the fitted distribution method. In the Hyfran model, this value is illustrated in Table 7 below.

Table 7. Value of (a) according to distribution Formulas.

Rang in Model	Value of (a) According to Distribution	Interface in Model
1.	0.0 (Formula of Weibull)	 The screenshot shows the Hyfran-Plus model interface. It has three main sections: 'Variable type' with fields for Name (Maximum Daily Rainfal depth), Unit (mm), and Significant digits (3); 'Return period definition' with radio buttons for flood (selected) and drought, and definitions for q and p; and 'Empirical probability formula' showing the formula F[x(k)] = (k - a) / (n - 2a + 1) and a dropdown menu for 'a' set to 0.40 (Formula of Cunnane).
2.	0.10	
3.	0.20	
4.	0.30 (Formula of Chegodayev)	
5.	0.40 (Formula of Cunnane)	
6.	0.44 (Formula of Gringorten)	
7.	0.5 (Formula of Hazen)	

(ii) Graphic results:

It is appropriate to analyse the adequacy of a fitting through graphical representation. HYFRAN PLUS allows for viewing of the fitting on Normal or Gumbel probability paper. As revealed in Figure 6, by default, the graph shows the sample data, the theoretical curve of the fitting (red line), and the confidence interval (blue lines), whose level is specified in the "Results" tab and the legend.

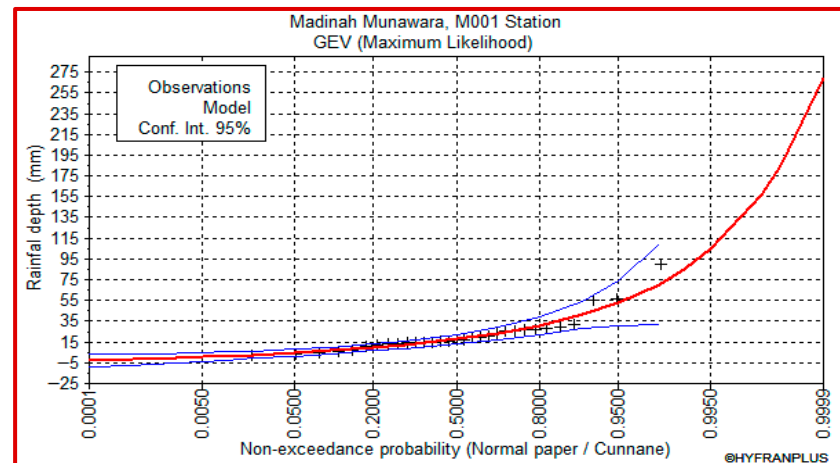


Figure 6. Typical graphical illustration of the GEV distribution fit to the dataset.

2.3.3. HYFRAN—PLUS Plotting Position Methods

Table 8 presents the available statistical distributions in HYFRAN-PLUS software to fit rainfall data sets that are independent, homogenous, and stationary. The various distributions integrated within the Hyfran-plus Model are specifically designed to adapt the characteristics of rainfall data. Therefore, four common frequency analysis methods were used in this study to develop the relationship between rainfall (depth and intensity) and return period (T). The selected distributions are Gumbel, Weibull, Generalized Extreme Value (GEV), and Pearson type 3 (PIII). These methods are famous plotting position methods.

Table 8. Available statistical distributions in HYFRAN-PLUS software, 2013.

No.	Statistical Distribution
1.	Exponential (E)
2.	Generalized Pareto (GP)
3.	Generalized Extreme Value (GEV)
4.	Gumbel
5.	Weibull
6.	Halphen
7.	Normal
8.	Lognormal
9.	Lognormal (3 parameters)
10.	Gamma
11.	Generalized Gamma (GG)
12.	Inverse Gamma (IG)
13.	Pearson type 3 (P3)
14.	Log Pearson Type 3 (LP3)

2.4. Rainfall Analysis and Results Using Hyfran—Plus Model

The statistical analysis of rainfall data aims to determine the maximum rainfall values for a certain period for different return periods, using different statistical distributions. Due to the available rainfall data of daily readings (24 h), the statistical analysis of the rainfall data will be the maximum daily rainfall depth for different return periods. HYFRAN-PLUS (Hydrological Frequency Analysis PLUS) for Windows is software that allows fitting several statistical distributions to a data sample. The Hyfran model is one of the most widely used

probability distribution functions for extreme values in hydrologic and meteorological studies to predict maximum rainfall and flood peaks. The estimation of maximum rainfall is essential for water project designs. The survey carried out studies and statistical analysis of the rainfall data to assume the depth of the daily rainfall corresponding to the storm design of different return periods. For this purpose, the Hyfran-plus model was used in this study. Moreover, the rainfall data input in Hyfran-plus represents maximum daily rainfall data from 1970–2020, as shown in Table 5 and Figure 4.

3. Results and Discussions

In this study, frequency analysis of maximum daily rainfall was conducted for the selected stations: Um Al Birak (J112), Al Madinah Munawwara (M00L), Bir Al Mashi (M103), and Al Faqir (J109) using the Hyfran-Plus model. The analysis aimed to predict the design values of rainfall depth (XT) for Wadi Alaqiq, corresponding to the several return periods (T) (5, 10, 25, 50 and 100), using various statistical distributions and assessing their temporal variability across the study area. Moreover, other concepts have been explained regarding the probability versus the risk analysis.

3.1. Descriptive Statistical Analysis of Rainfall

The statistical analysis of the annual maximum rainfall data for Wadi al-Aqiq covered the period from 1970 to 2020. A total of 51 observations were recorded, representing yearly heavy rainfall. Therefore, the resulting annual maximum values for each station consist of 51 values for stations M001, M103, and J109, and 50 values for station J112. The basic statistics include nine parameter outlines in relation to the data (No. of Data (Observations), including minimum, maximum, average, median, standard deviation, coefficient of variation, skewness, and kurtosis coefficient. The descriptive statistical analysis (Basic Statistics) of maximum daily rainfall (1970–2020) for four rainfall stations is shown in Table 9. Figure 7 below shows that the summary of the basic statistics of the rainfall stations: (a) maximum and minimum of the daily extreme events rainfall, (b) the average and SD, and (c) the skewness (CS) and (Ck) kurtosis c coefficients. Figure 5 illustrates the maximum daily rainfall and corresponding trend lines from 1970 to 2020 for Al Madinah, Al Faqir, Um Al Birak, and Bir Al Mashi, respectively.

Table 9. Basic Statistics of maximum rainfall data for Wadi al-Aqiq (1970–2020).

Descriptive	Rainfall Depth (mm)			
	Al Madinah (M001)	Bir Al Mashi (M103)	Al Faqir (J109)	Um Al Birak (J112)
No. of Data (Observations)	51	51	51	51
Minimum	1.40	1.50	0.200	0.00
Maximum	89.6	66.0	71.0	76.0
Average	20.5	20.4	26.5	21.2
Standard Deviation (S.D)	18.1	13.7	17.0	16.1
Median	16.3	18.0	23.0	17.0
Coefficient of variation (C_V)	0.882	0.670	0.641	0.761
Skewness Coefficient (C_S)	2.29	1.48	0.530	1.31
Kurtosis Coefficient (C_K)	8.23	4.81	2.37	4.32

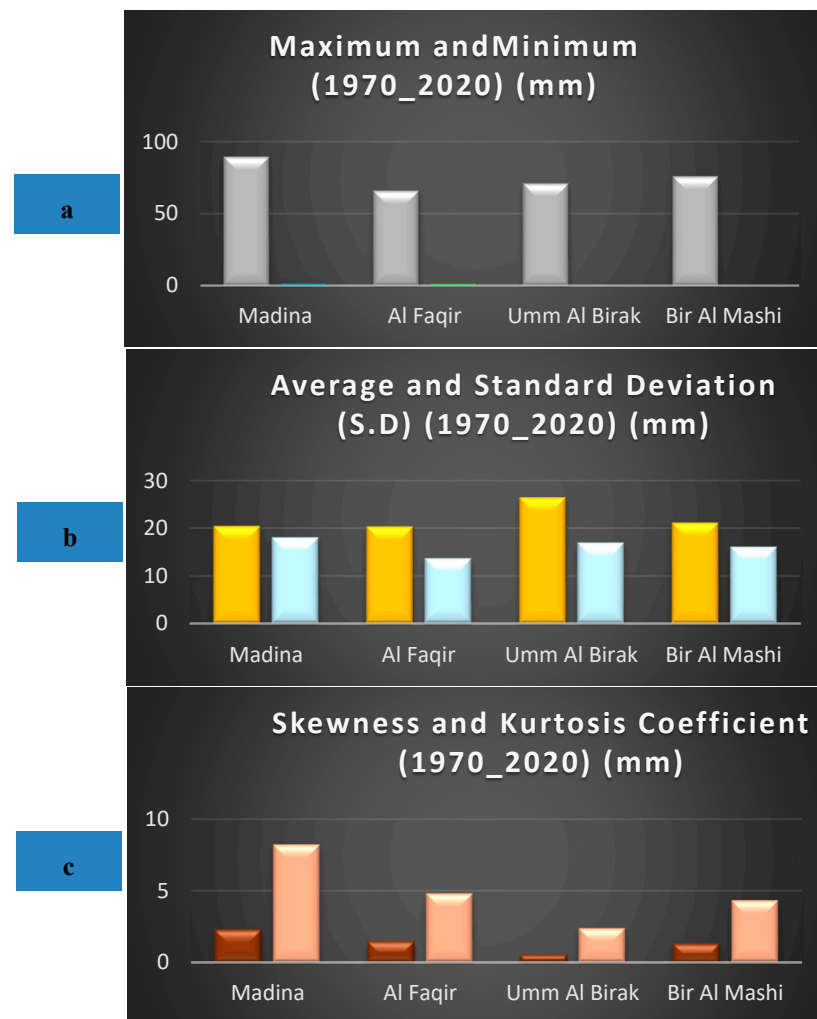


Figure 7. Summary of the basic statistics of the rainfall stations. (a) Maximum, minimum and of extreme rainfall data. (b) Average and standard deviation. (c) Skewness and kurtosis.

Homogeneity Tests

Several methods can be used to detect abrupt changes such as the standard normal homogeneity test (SNHT). Pettitt's test for homogeneity was employed to detect change points in the time series of monthly, seasonal, and annual precipitation records. [31,32]. These tests are conducted for four stations in the study area, which present consistent annual rainfall series at a 5% significance level, as confirmed by the Pettitt test and the SNHT test. This observation supports the use of the entire recording period (1970–2020), accounting for the missing 2018 value for Umm Birak station (J112) for the analysis of fixed outliers. The results confirm the absence of statistically significant abrupt changes (such as those resulting from land-use change, station relocation, or climate shifts) in the annual rainfall series, justifying the application of the annual extreme values method to estimate the return period.

The Annual Maximum Rainfall (AM) method was selected instead from the Threshold Overshoot (POT) method because significant rainfall events are a primary contributor to flood risk and infrastructure strain in arid drainage basins. Accurate assessment of rainfall is crucial for the design of hydraulic structures, stormwater drainage systems, and flood protection due to the large spatial and temporal variability of rainfall. The AM method, which takes out the annual maximum value, makes a data series that is almost independent and evenly spread out. This is in line with the stability hypothesis that homogeneity tests support. The AM method is also commonly used in regional infrastructure design

standards, which makes it easier to compare with current guidelines. It has a 51-year data record, so it can give stable and accurate estimates of return periods that are important for engineering (like events that happen every 25, 50, or 100 years). However, the Threshold Overshoot method is more accurate in terms of time.

3.2. Madinah Munawarah (M001)

The maximum daily rainfall during the period of 1970–2020 for the Madinah Munawarah (M001) station, as shown in Figure 8, was used to analyse the rainfall data using the Hyfran-plus model. Table 9 and Figure 7 represent the minimum and maximum rainfall values observed during this period, which were 1.4 mm in 1973 and 89.6 mm in 1993, respectively, indicating considerable variability in extreme rainfall events in the dataset. The Hyfran-plus model conducts several processes and hypotheses for observation data and shows whether these variables are dependent or independent. Then, the relation between maximum rainfall depth (MDR) versus Non-exceedance probability ($q = 1 - p$) is drawn in Figure 9. For the rainfall data analysis, various statistical distributions methods such as GEV, Gumbel, Weibull, and Pearson Type-3 were used and denoted in Figure 10a–d, and the outputs of each method were compared and illustrated in Figure 10. Table 10 also presents the return period–rainfall depth using different methods for the M001 station.

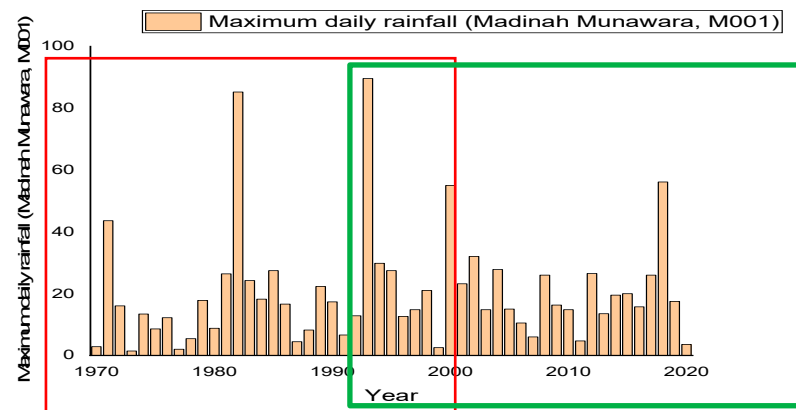


Figure 8. Maximum Daily Rainfall Madinah Munawarah (1970–2020).

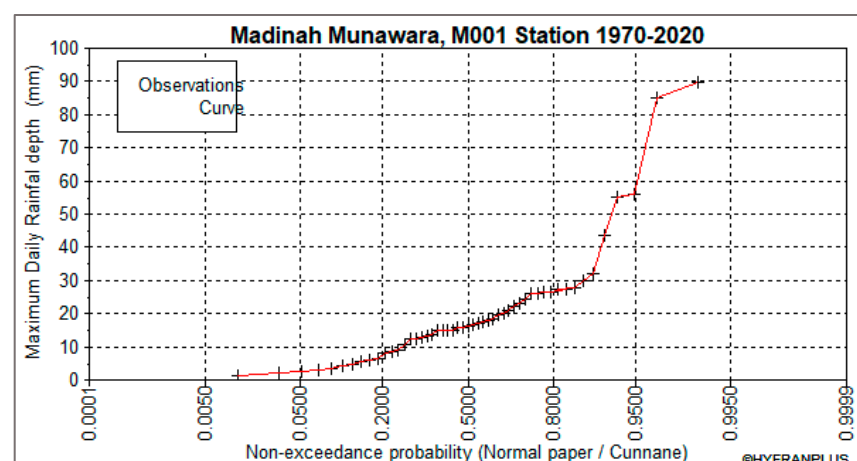


Figure 9. Rainfall versus Non-exceedance probability in (Madinah, M001).

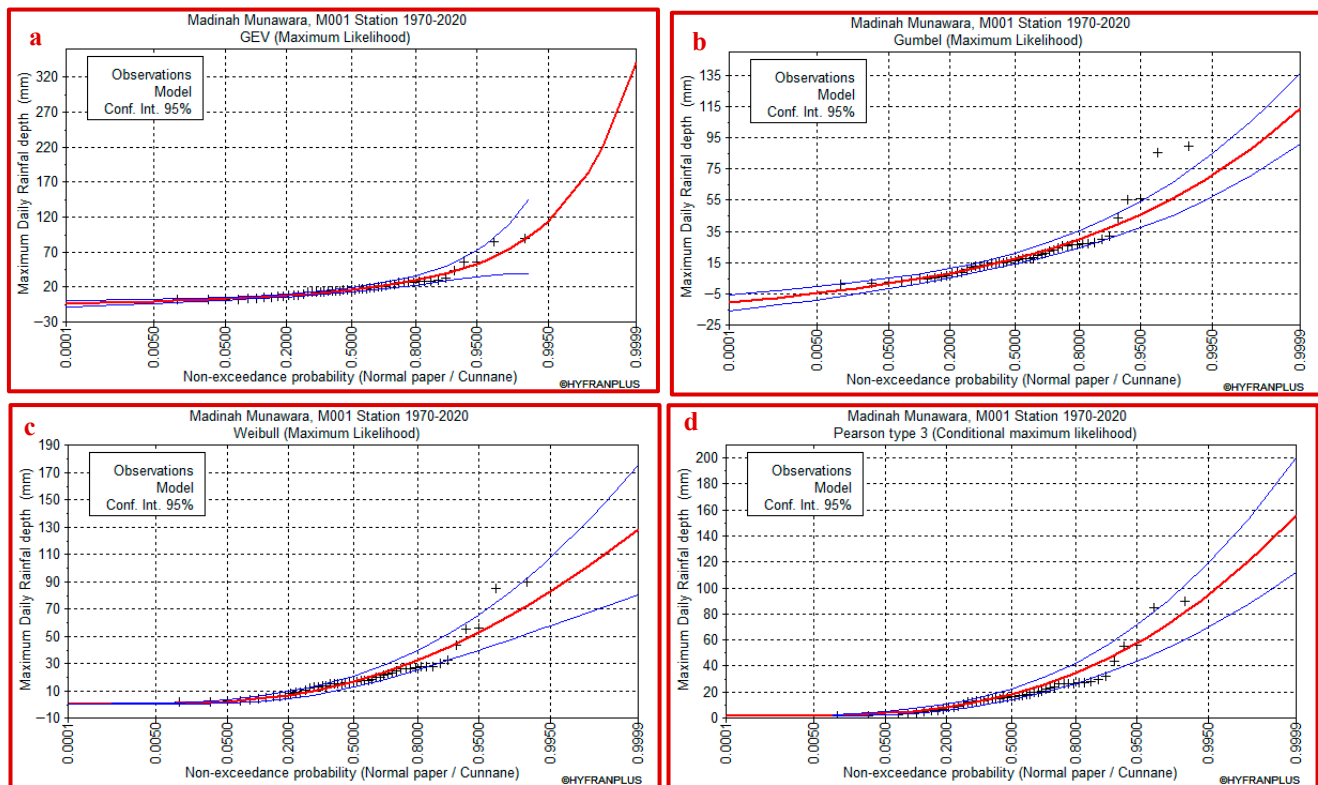


Figure 10. Statistical Distributions Methods using different methods (Madinah, M001) (a) GEV, (b) Gumbel, (c) Weibull, and (d) Pearson Type-3.

Table 10. Results of Rainfall depth (mm) versus return period (year) (Madinah, M001) using four statistical distributions methods.

Return Period (T, Years)	Rainfall Depth (mm)			
	GEV (Maximum Likelihood)	Gumbel (Maximum Likelihood)	Weibull (Maximum Likelihood)	Person Type 3 (Maximum Likelihood)
2	15.8	17.4	16.6	17.9
5	29.2	29.8	32.3	34.4
10	40.3	37.9	42.8	46.2
25	57.7	48.2	55.7	61.3
50	73.6	55.9	65.0	72.5
100	92.2	63.5	73.9	83.6
150	105	67.9	79.0	90.1

Figure 10 explain four probability plots of annual maximum daily rainfall recorded at rainfall station (M001) from 1970 to 2020. The horizontal axis represents the non-exceedance probability (q) using the cunnane plotting position, while the vertical axis shows the corresponding maximum daily rainfall (XT) in mm. The charts contain three main elements; the black crosses represent the observed annual maximum daily rainfall values (mm). The red curve shows the four distribution methods fitted using Maximum Likelihood Estimation, the four plotting position methods widely used were extreme in rainfall and flood frequency analysis, and infrastructure design describes the expected relationship between rainfall depth and its probability of occurrence. Surrounding this Hyfran-plus model, the two blue curves form the 95% confidence interval, illustrating the uncertainty in the fitted

distribution where a narrow band indicates high confidence in the model's predictions, while a wider band reflects greater uncertainty. Finally, these charts generated by the Hyfran-plus model is a visualization investigation to show what distribution method is the best one. Figures 11 and 12 describes the comparison between four statistical distributions at the M001 station to determine the best one that is suitable.

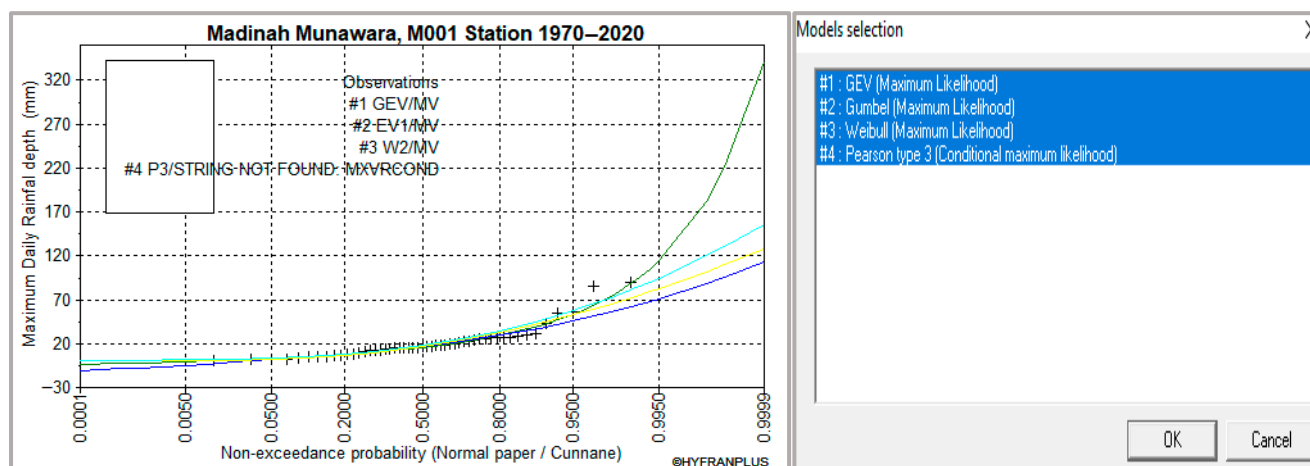


Figure 11. Comparison between statistical distributions at M001 station.

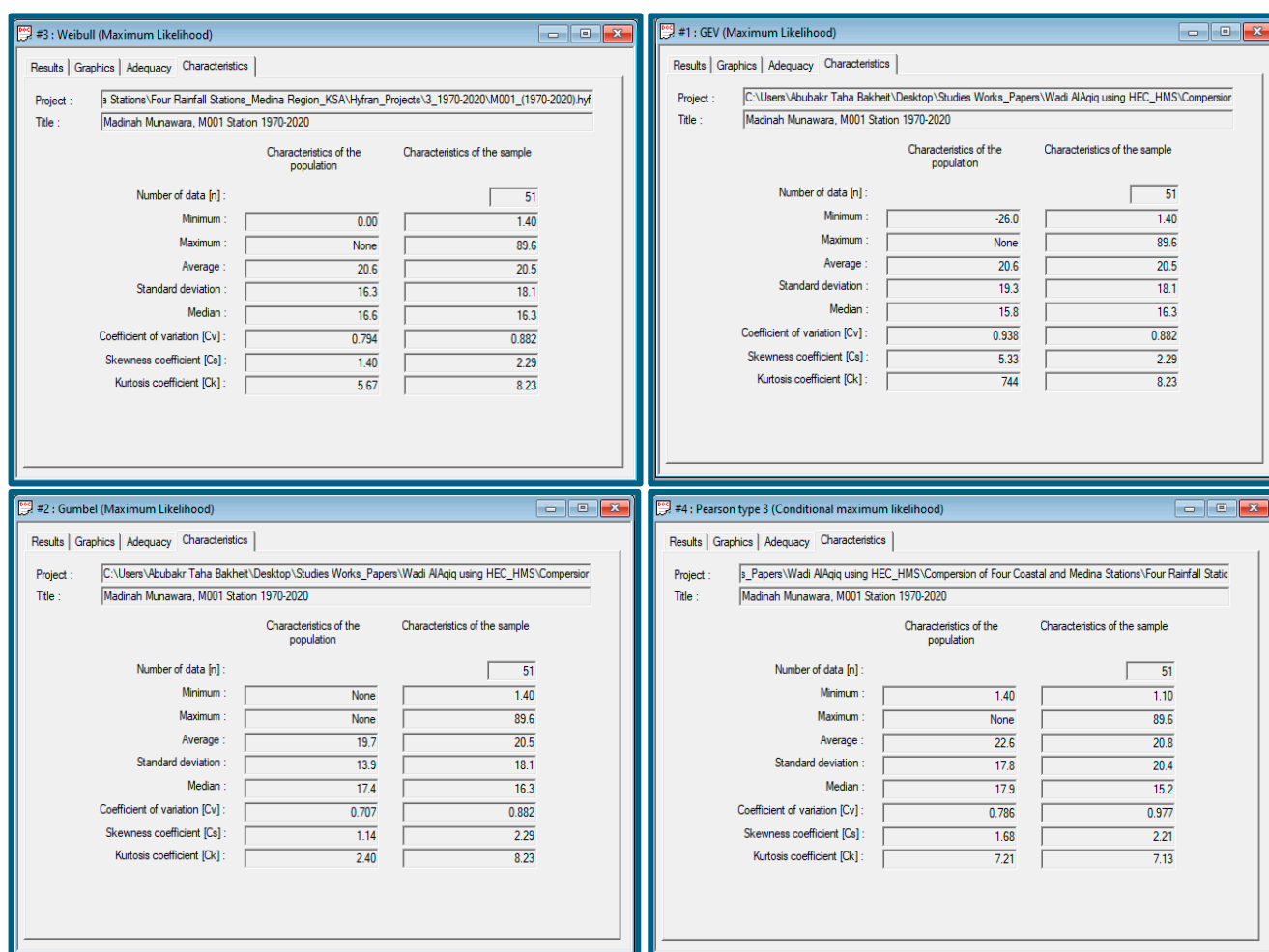


Figure 12. Descriptive Statistical Comparison between statistical distributions at M001 station.

3.3. Bir Al Mashi (M103)

The rainfall data of Bir Al Mashi (M103) station, as shown in Figures 13 and 14, were used to analyse the rainfall data using the Hyfran-plus model. Also, the fundamental statistics of the series of maximum daily rainfall for M103 station in the period of 1970–2020 are given in Table 9 and indicate that the minimum and maximum rainfall values observed during this period were 1.5 mm in 2011 and 66 mm in 1978, respectively. For this station, different statistical distributions methods of GEV, Gumbel, Weibull, Lognormal, and Pearson Type-3 were used, and the obtained results were compared, as shown in Figure 15a–d. The descriptive statistical comparison between distributions methods at M103 station (see Figure 16) illustrates significant variations. Similarly, in steps in model running, the previous station (M001), comparing the obtained statistical results showed the maximum depth of daily rainfall for different return periods Figure 17 and Table 11.

Table 11. Results of Rainfall depth (mm) versus return period (year) (Bir Al Mashi, M103) using four statistical distributions methods.

Return Period (T, Years)	Rainfall Depth (mm)			
	GEV (Maximum Likelihood)	Gumbel (Maximum Likelihood)	Weibull (Maximum Likelihood)	Person Type 3 (Maximum Likelihood)
2	17.3	18.0	18.2	17.6
5	28.7	28.8	30.7	29.9
10	37.2	36.0	38.4	38.0
25	49.4	45.0	47.3	48.1
50	59.4	51.7	53.5	55.4
100	70.4	58.4	59.2	62.6
150	77.3	62.3	62.4	66.7

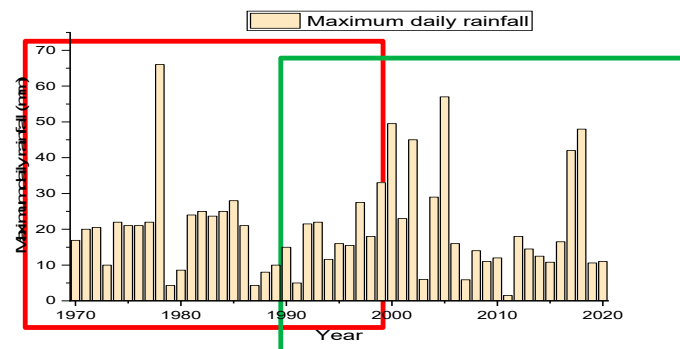


Figure 13. Maximum Daily Rainfall Bir Al Mashi Station (1970–2020).

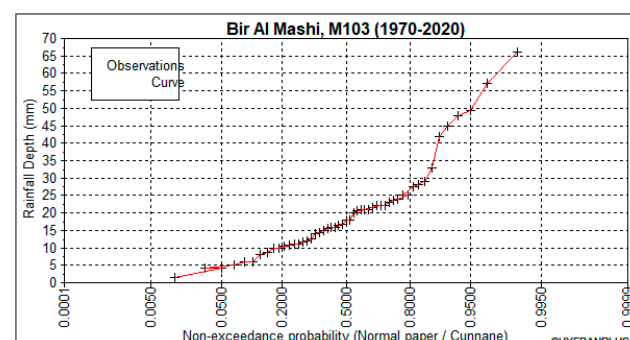


Figure 14. Rainfall versus non-exceedance probability in (Bir Al Mashi, M003).

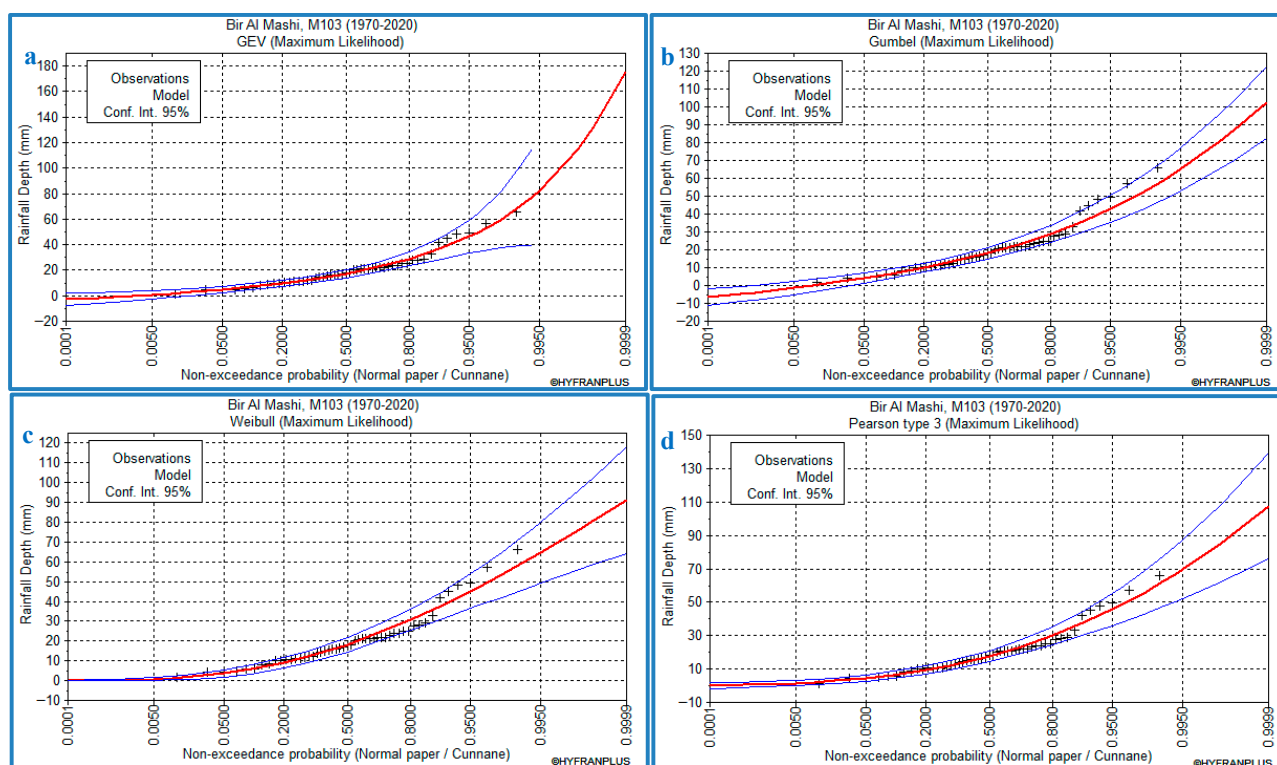


Figure 15. Statistical Distributions Methods using different methods (Bir Al Mashi, M003) (a) GEV, (b) Gumbel, (c) Weibull, and (d) Pearson Type-3 method.

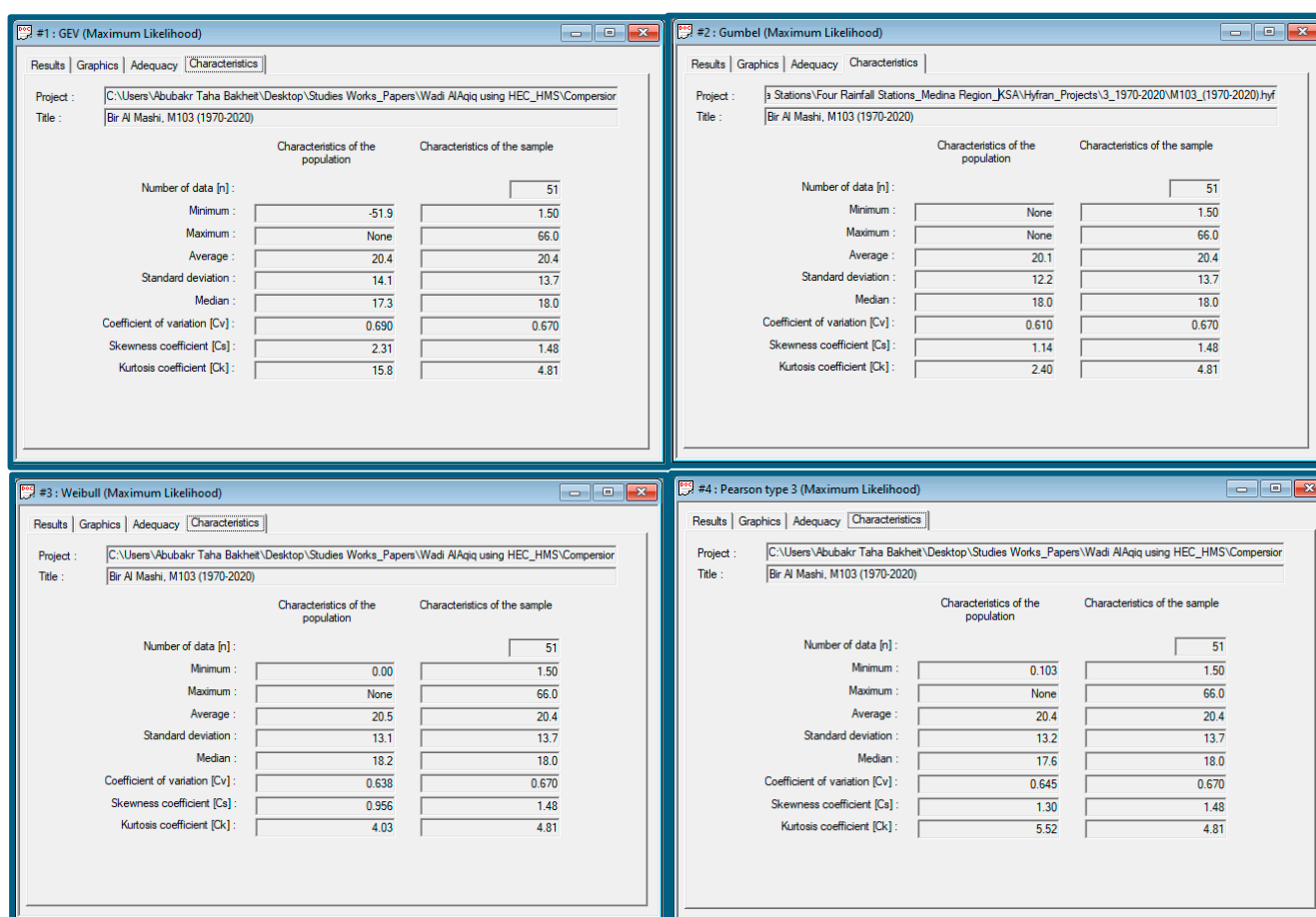


Figure 16. Descriptive Statistical Comparison between statistical distributions at M003 station.

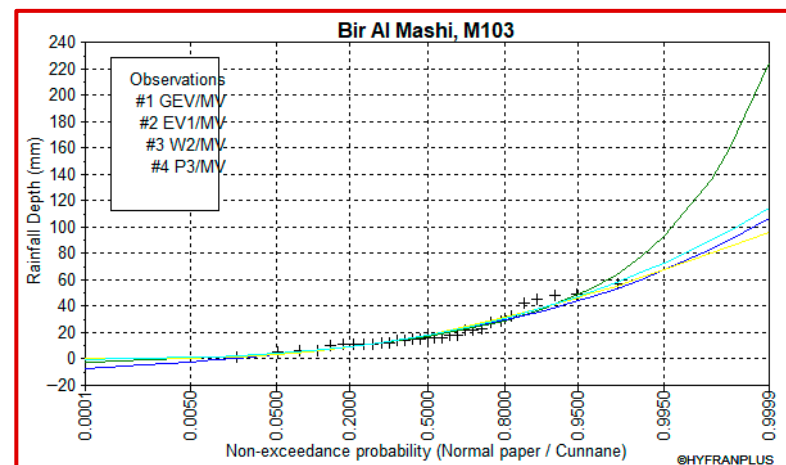


Figure 17. Comparison between statistical distributions at M103 station.

3.4. Al Faqir (J109)

Al Faqir, J109 rainfall gauge station is one of the four climatological and rainfall gathering stations used in this study, which is located in the Madinah Munawarah region, Saudi Arabia Kingdom. This station is part of a network designed to monitor and collect rainfall data within the Wadi Al-Aqiq drainage basin. Figure 18 shows the rainfall data of the Al Faqir (J109) station for the period of 1970–2020, which were used to achieve a statistical analysis of the rainfall data using the Hyfran-plus model. In addition, the fundamental statistics of the time series of maximum daily rainfall for the Al Faqir (J109) station in the period of 1970–2020 are given in Table 9. The minimum and maximum rainfall values observed during this period were 0.2 mm in 2020 and 71 mm in 1992, respectively. Figure 19 illustrates maximum daily rainfall depth beside non-exceedance probability in this station. The statistical distributions methods of GEV, Gumbel, Weibull, Lognormal, and Pearson Type-3 were applied, and the results of Hyfran model plus were showed and compared and illustrated in Figures 20–22 and Table 12 to determine the maximum depth of daily rainfall for different return periods (2, 5, 10, 25, 50, 100, and 150).

Table 12. Results of Rainfall depth (mm) versus return period (year) (Al Faqir, J109) using four statistical distributions methods.

Return Period (T, Years)	Rainfall Depth (mm)			
	GEV (Maximum Likelihood)	Gumbel (Maximum Likelihood)	Weibull (Maximum Likelihood)	Person Type 3 (Maximum Likelihood)
2	23.8	23.5	23.0	22.8
5	39.1	39.3	39.9	39.6
10	48.9	49.7	50.5	50.8
25	60.9	62.9	62.9	64.5
50	69.5	72.7	71.5	74.4
100	78.0	82.4	79.6	84.1
150	82.8	88.0	84.1	89.6

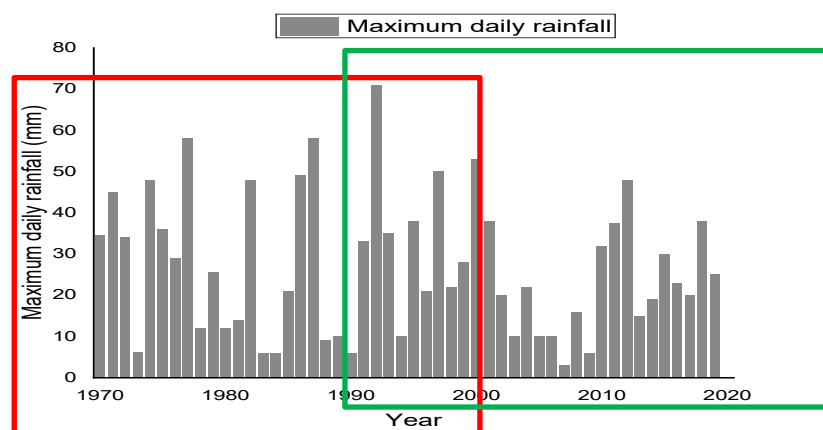


Figure 18. Maximum Daily Rainfall Al Faqir, J109 Station (1970–2020).

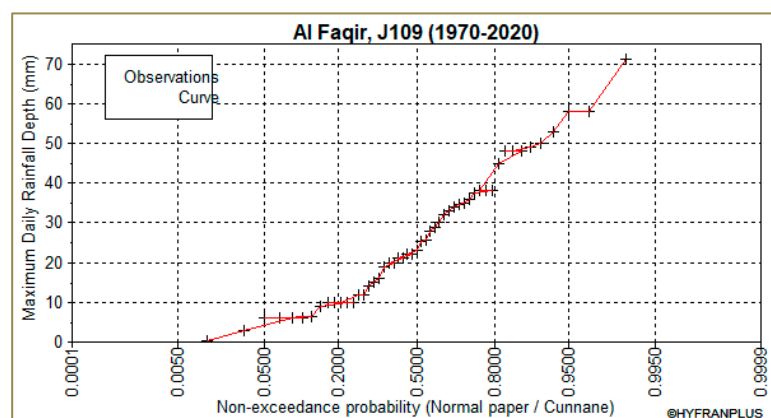


Figure 19. Rainfall versus Non-exceedance probability in (Al Faqir, J109).

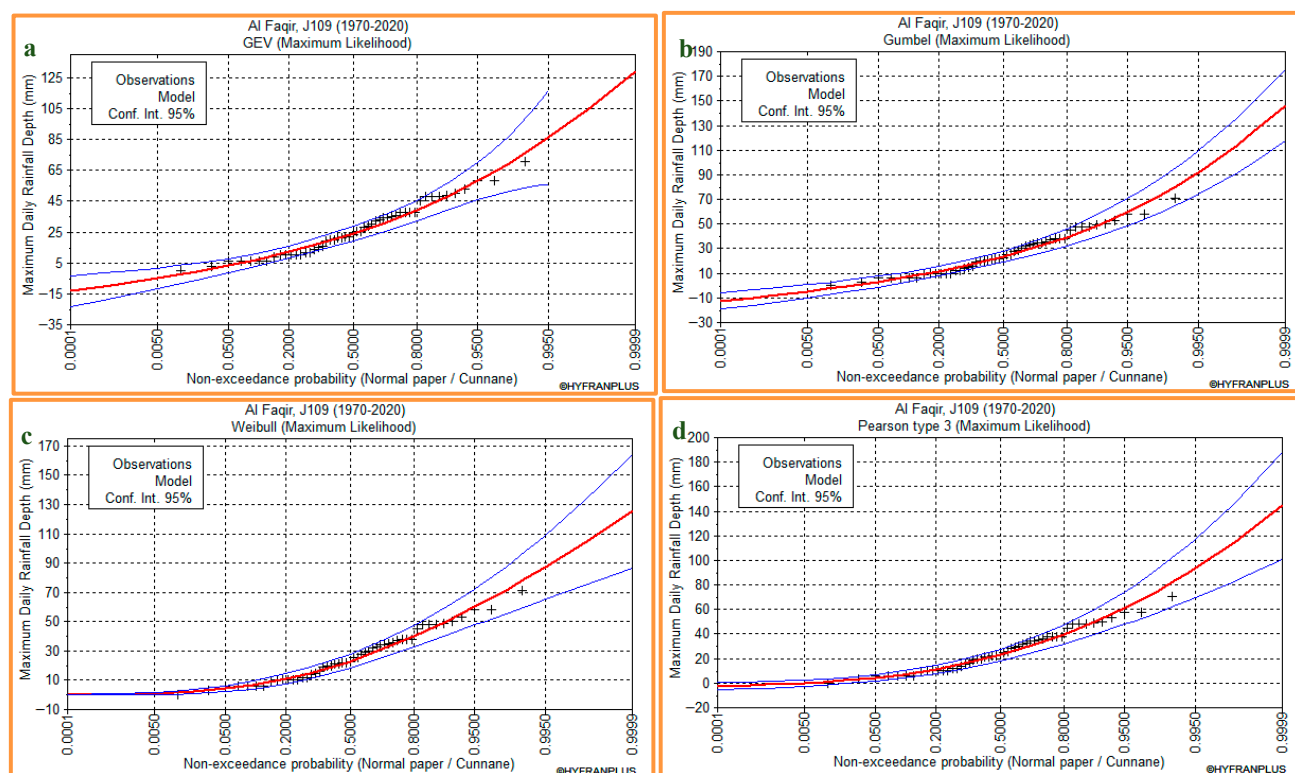


Figure 20. Statistical Distribution (Al Faqir, J109) using the different methods, (a) GEV, (b) Gumbel, (c) Weibull, and (d) Pearson Type-3 method.

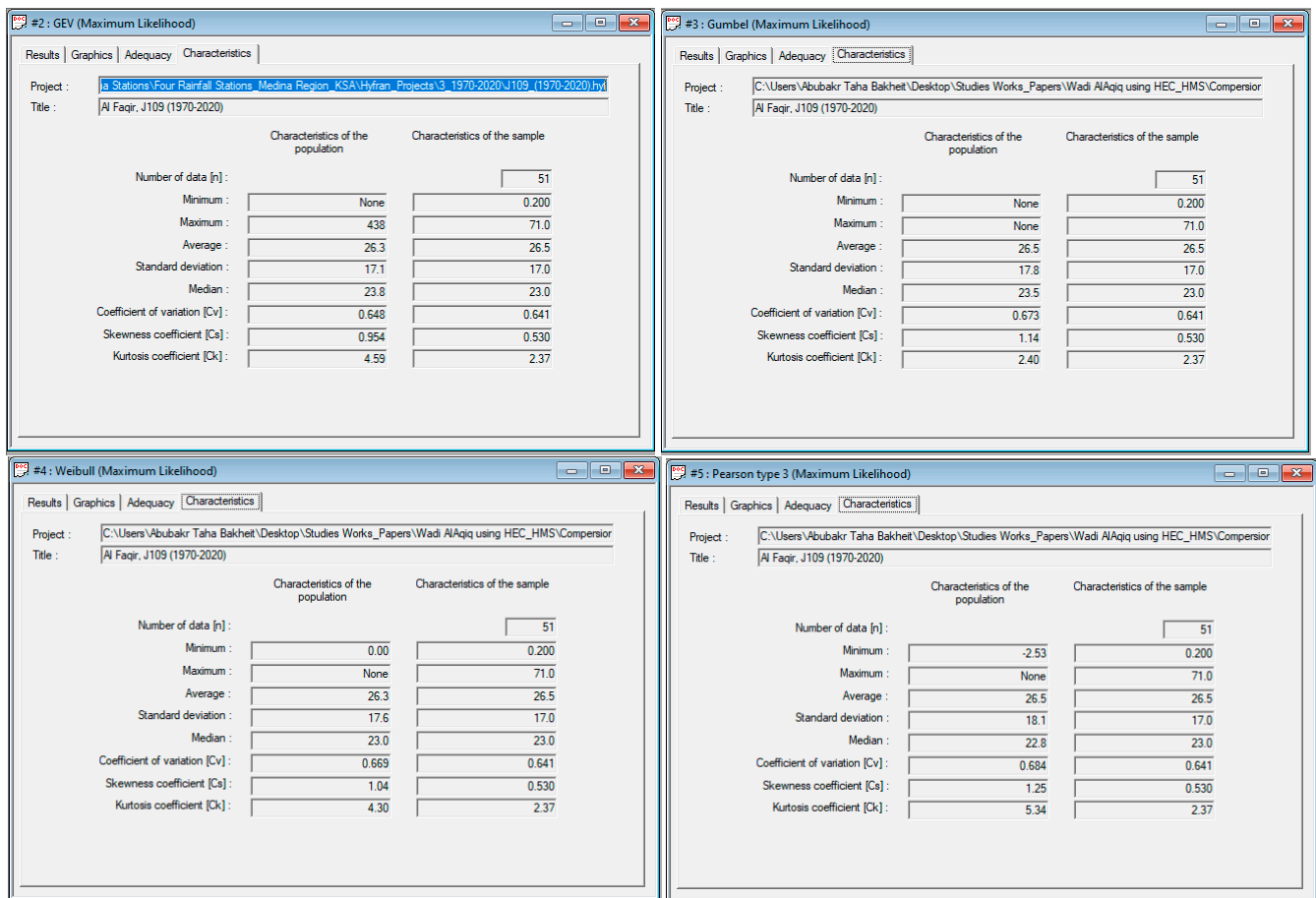


Figure 21. Descriptive Statistical Comparison between statistical distributions at J109 station.

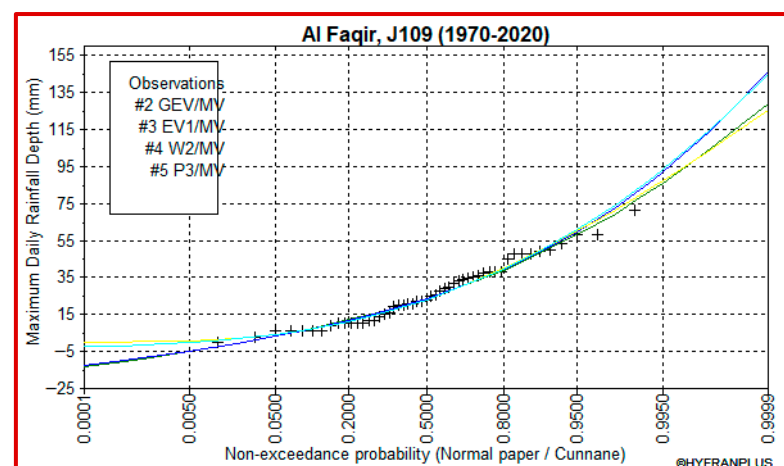


Figure 22. Comparison between statistical distributions at (Al Faqir, J109) station.

3.5. Umm Al Birak (J112)

The rainfall data of the Umm Al Birak (J112) station revealed in Figure 23 were used to analyze the rainfall data using the Hyfran-plus model. Also, the fundamental statistics of the time series of maximum daily rainfall for Umm Al Birak (J112) station in the period of 1970–2020 are given in Table 9. The minimum and maximum rainfall values observed during this period were 0.0 mm in 1989 and 76 mm in 2012, respectively. Based on Figure 23 and Table 9, after 1990, the temporal variability in the Umm Al Birak rainfall data is more pronounced, with several years exhibiting high records compared to earlier years. The record includes several extreme years, including 1993 (50 mm), 2001 (49 mm), 2002 (50 mm),

2005 (53 mm), 2012 (76 mm), and 2017 (55 mm), even though the 1970–1990 period had moderate rainfall. Despite the Umm Al Birak rainfall station's generally arid climate, these peaks show a shift toward more intense rainfall events and represent some of the highest values in the entire dataset.

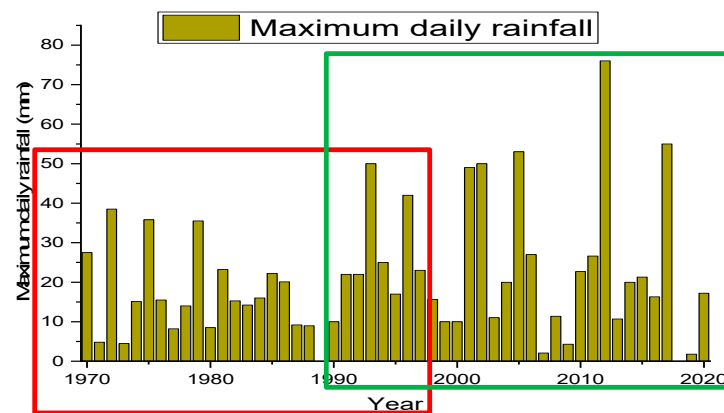


Figure 23. Maximum Daily Rainfall Umm Al Birak, J112 (1970–2020).

Climate assessments for the Arabian Peninsula and Saudi Arabia show increasing rainfall variability, more frequent short, intense storms, and an overall rise in extreme precipitation events, even as total annual rainfall remains stable or decrease. These changes are linked to regional warming, increased atmospheric moisture, and shifts in large-scale circulation patterns that influence the area's climate. Saudi Arabia is facing increasing rainfall variability; rainfall has become more irregular, characterized by longer dry periods and short, intense rainfall events. This pattern and situation of rainfall is related to wider climate-change trends affecting the Arabian Peninsula and also shows that the climate system is changing and may lead to more storms in Saudi Arabia [33–35]. Figure 24 explain rainfall design depth versus non_exceedance probability in Umm Al Birak, J112 rainfall station.

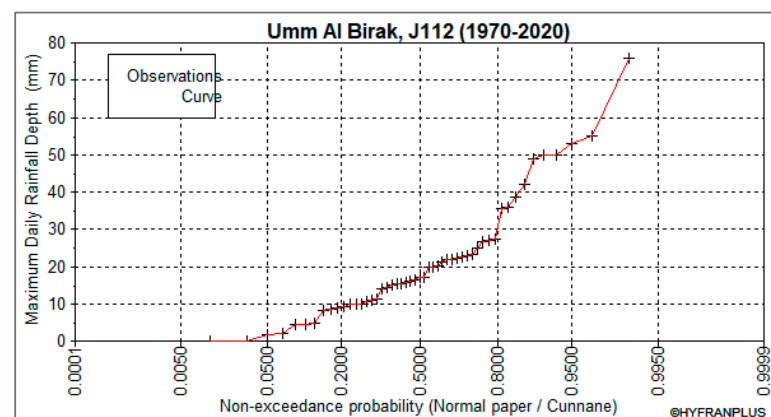


Figure 24. Rainfall versus Non _ exceedance probability in (Umm Al Birak, J112).

The statistical distribution methods of GEV, Gumbel, Weibull, Lognormal, and Pearson Type-3 were used to analyses the given data and outputs were plotted and illustrated in Figures 25–28; Table 13 shows the rainfall depth results for various return periods for the Umm Al Birak station.

In the 1989 and 2018 rainfall dataset on Umm Al Birak, a zero-rainfall value and (N/A → Not Available Data) were recorded. In Hyfran-plus model, two statistical distribution methods (GEV and Gumbel) were able to include these zero and N/A values in the analysis. However, other methods such as Weibull and Pearson Type III generated error messages

through the analysis model, indicating mismatch with zero and N/A values. The study evaluated two results with and without zero value in rainfall dataset presented in Table 13 and Figures 26 and 27.

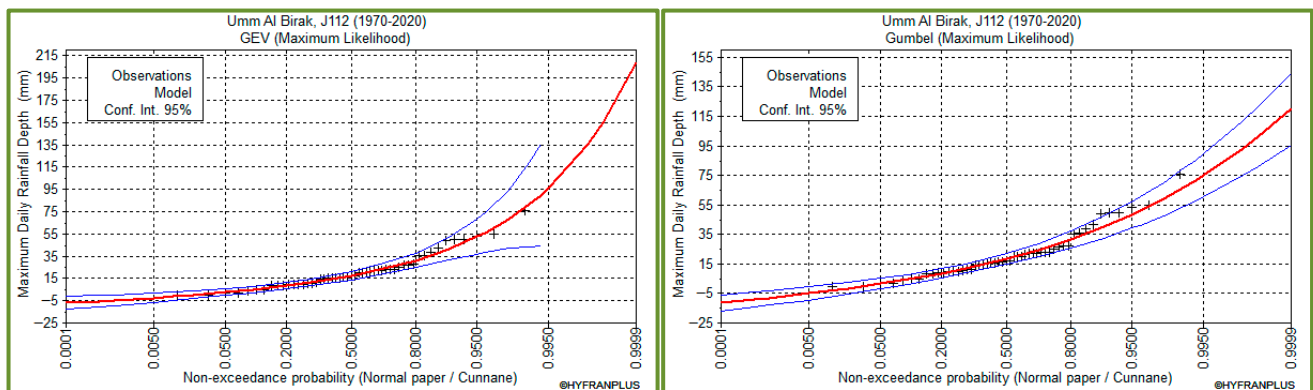


Figure 25. Statistical Distribution (Umm Al Birak, J112) using GEV and Gumbel statistical methods with Zero and N/A values.

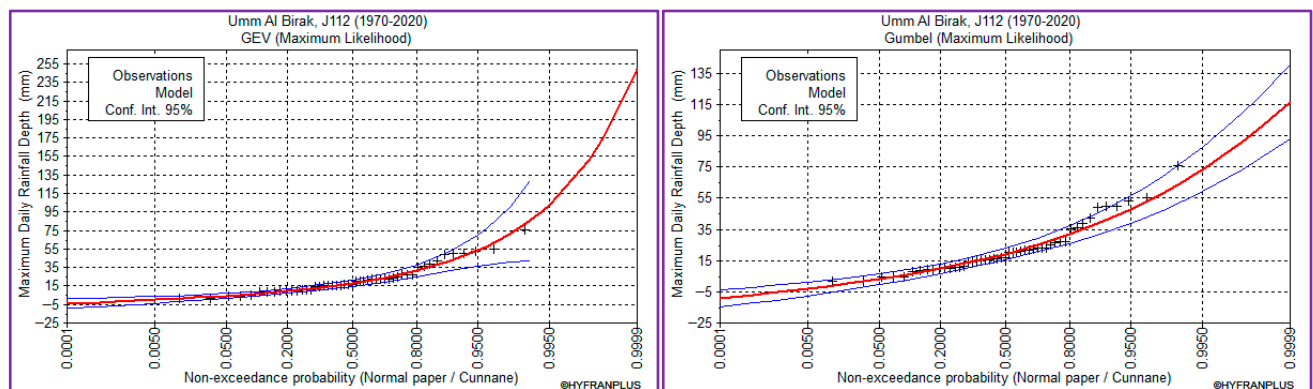


Figure 26. Statistical Distribution (Umm Al Birak, J112) using GEV and Gumbel statistical methods without Zero and N/A values. statistical methods without zero value.

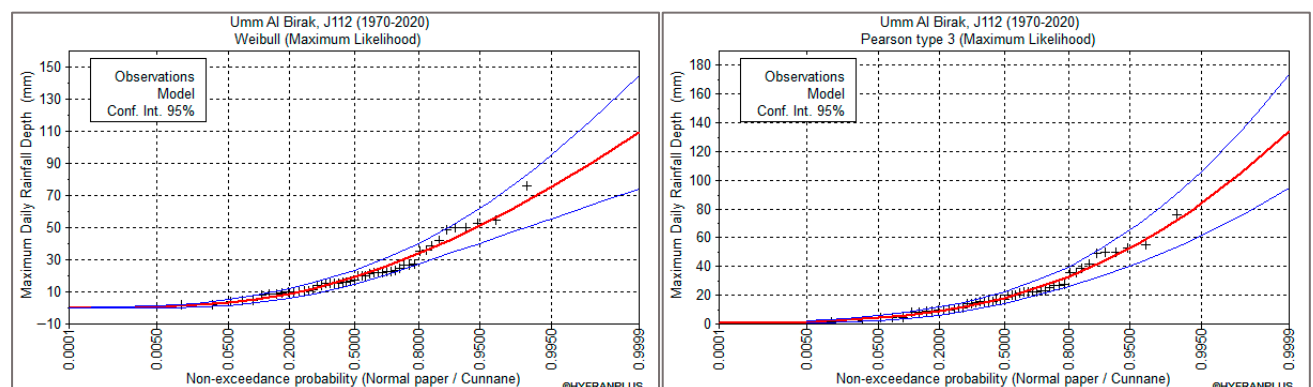


Figure 27. Statistical Distribution (Umm Al Birak, J112) using Weibull and Pearson Type III statistical methods without Zero and N/A values. Statistical methods without zero value.

From Table 13, excluding zero rainfall values in extreme rainfall values, statistical frequency analysis mostly leads to higher rainfall depth design (X_T) estimates across different return periods (T), with the effect more definite in the GEV method, particularly at longer return periods; for example, 89.9 mm vs. 95.2 mm. Although the Gumbel distribution method illustrates a similar tendency, its response is less consistent, as seen at return period 50 year, where the estimate slightly decreases when the zero is excluded (40.0 mm

to 39.9 mm), indicating sensitivity in Hyfran-plus model fitting. Including zero values tends to reduce the tail behaviour, resulting in lower extremes, and GEV appears more sensitive to this than Gumbel. For hydrological study and infrastructures design, excluding zero values may be appropriate when they represent non-rainfall events rather than actual rainfall measurements.

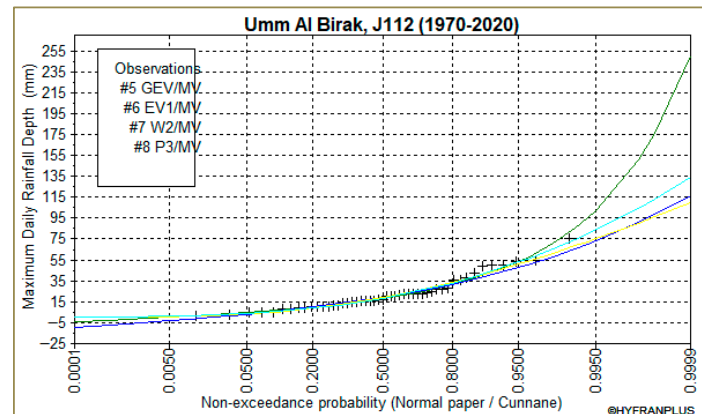


Figure 28. Comparison between statistical distributions at (Umm Al Birak, J112) station.

Table 13. Results of Rainfall depth (mm) versus return period (year) (Umm Al Birak, J112) using four statistical distributions methods.

Return Period (T, Years)	Rainfall Depth (mm)					
	GEV (Maximum Likelihood)		Gumbel (Maximum Likelihood)		Weibull (Maximum Likelihood)	Person Type 3 (Maximum Likelihood)
	With Zero Value	Without Zero Value	With Zero Value	Without Zero Value		
2	17.4	18.0	18.3	19.2	19.1	18.2
5	31.2	31.4	31.4	31.7	33.7	33.0
10	41.5	41.9	40.0	39.9	42.9	43.1
25	56.1	57.3	50.9	50.4	53.8	56.0
50	68.3	70.6	59.0	58.1	61.4	65.4
100	81.5	85.6	67.0	65.8	68.5	74.7
150	89.9	95.2	71.7	70.3	72.5	80.1

3.6. Summary Statistics Distribution of the Rainfall Stations Model Results

Figures 29 and 30 and Tables 14 and 15 presents the estimated rainfall depths (mm) corresponding to a 100-year return period for four rainfall stations in study area Al Madinah (M001), Bir Al Mashi (M103), Al Faqir (J109), and Um Al Birak (J112) based on the four criteria comparatives maximum rainfall (mm) in rainfall dataset from (1970–2020), decision support system from model for suitable statistical distribution (DSS), maximum rainfall depth generate using Hyfran-plus Model (extreme statistical distribution values), results of HYFRAN-PLUS MODEL using the GEV method dataset (1960–1990) and (1990–2020). [21] In arid environments and regions, rainfall is extremely variable temporally and spatially, requiring statistical frequency analysis to determine design rainfall depth (XT) for various return periods (T). A study in the Wadi Alaqiq watershed in Madinah Munawarah region in the Kingdom of Saudi Arabia, using over 40 years of data and applying L-moments and the Anderson-Darling test, identified generalized logistic and extreme value distributions as best fits, supporting flood analysis and climate trend evaluation. The effects of various

rainfall analysis methods using two rainfall gauges near Wadi Arbaat in Eastern Sudan: Port Sudan (80021) and Arbaat (80015) (1942–2010) from the HYFRAN-PLUS MODEL [36]. This analysis presented that the Generalized Extreme Value (GEV) was the best-fit statistical distribution for maximum daily rainfall. The Hyfran-plus model (integrated with modeling software HEC-RAS, HEC-HMS) is comprehensive software for rainfall, flood frequency analysis, and hydrological risk assessment using probability distributions such as Gumbel, Log-Normal, Pearson Type III, and Weibull [21,24,36–40]. Table 14 shows rainfall depths for four stations, M001, M003, J109, and J112, over a 100-year period that was studied in two datasets: (1960–1990) and (1990–2020). Temporal variability, with Al Madinah suffering a slight decrease and Bir Al Mashi and Al Faqir facing decreases in storm design. In contrast, Um Al Birak demonstrates a substantial increase from 46.5 mm to 97.2 mm [37]. This highlights the need for local hydrological assessments for infrastructure planning and climate adaption.

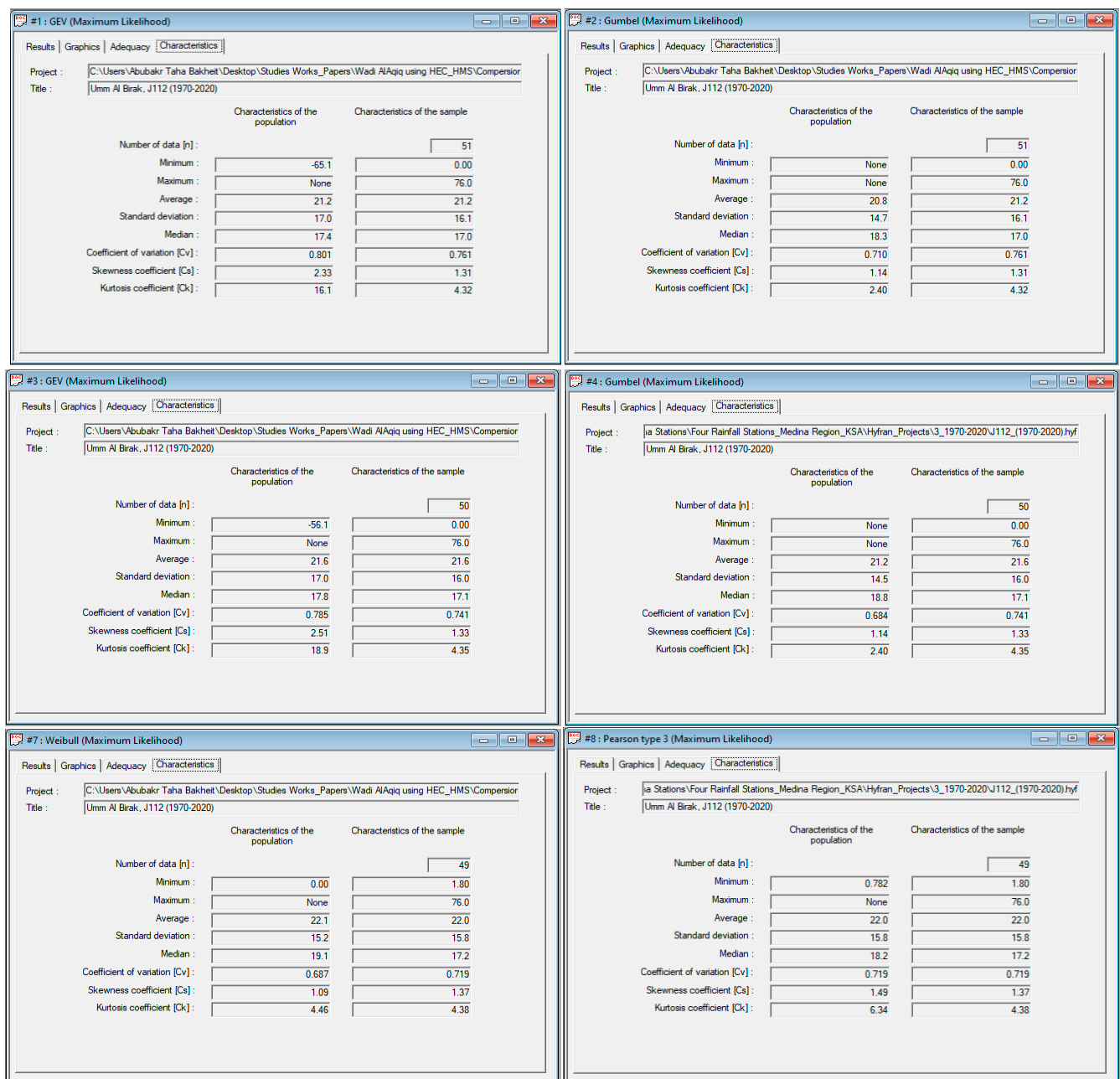


Figure 29. Descriptive Statistical comparison between statistical distributions at J112 station.

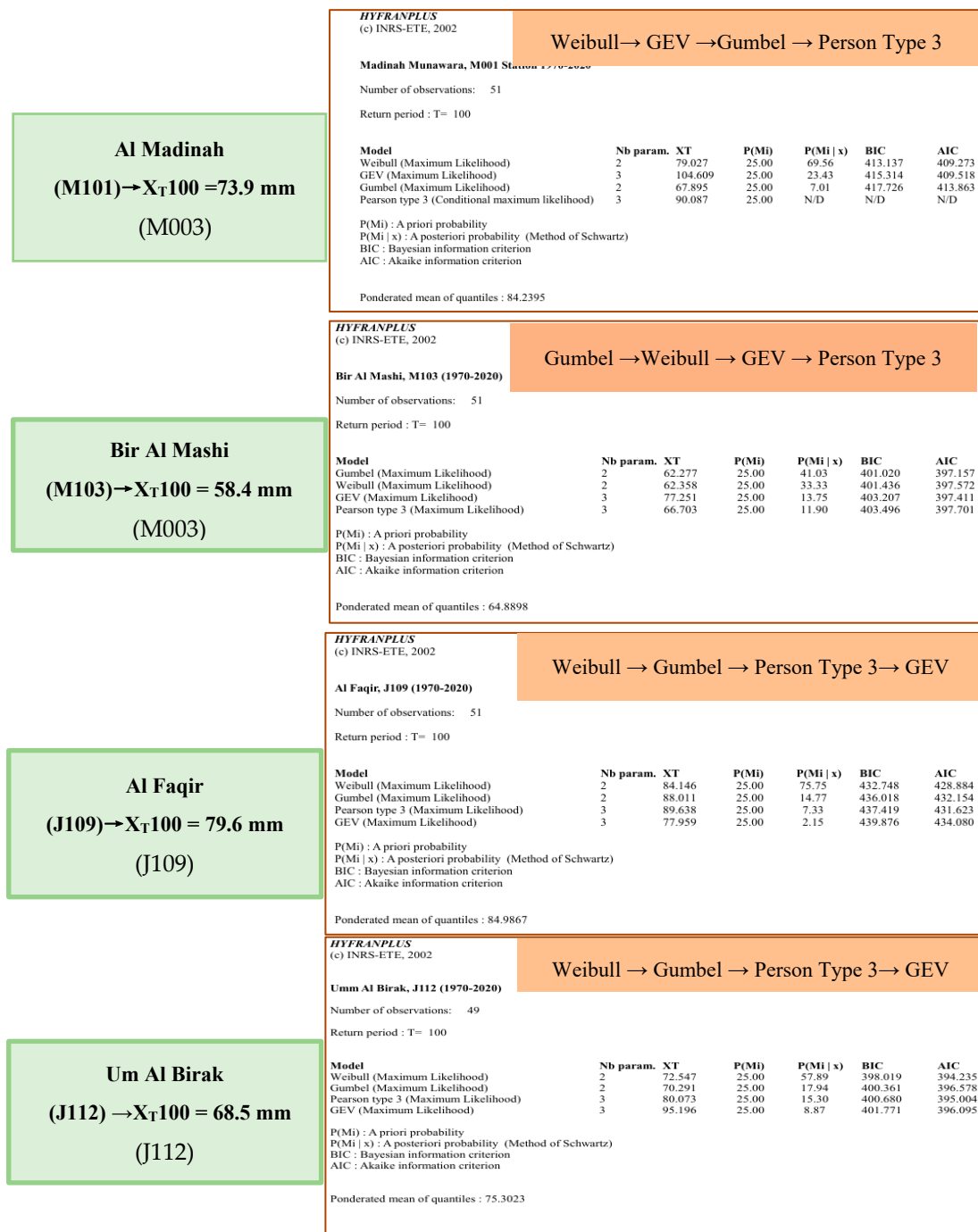


Figure 30. Comparison criteria of the distribution according to Hyfran-plus model decision support system (DSS).

Table 14. Results of Rainfall depth (mm) versus return period (100 year) for Stations (M001, M103, J109, and J112)—two dataset (1960–1990) and (1990–2020) [24].

Return Period (T, Years)	Rainfall Depth (mm)							
	Al Madinah (M001)		Bir Al Mashi (M103)		Al Faqir (J109)		Um Al Birak (J112)	
	1960–1990	1990–2020	1960–1990	1990–2020	1960–1990	1990–2020	1960–1990	1990–2020
100	94.6	86.2	82.9	77.7	84.0	73.8	46.5	97.2

Table 15. Maximum rainfall depth corresponding to return period of 100 years for the effective stations around Study Area based on the four criteria.

Station	Maximum Rainfall (mm) in Dataset (1970–2020) (mm)	Rainfall Design (mm) → Suitable Statistical Distribution in Model (DSS) (mm)	Maximum Rainfall Depth Generate Using Model → (Extreme Statistical Distribution (mm)	GEV Method Dataset (1960–1990)	GEV Method Dataset (1990–2020)
Madinah Munawarah (M001)	89.6	73.9 → Weibull	92.2 → GEV	94.6	86.2
Bir Al Mashhi (M003)	66.0	58.4 → Gumbel	70.4 → GEV	82.9	77.7
Al Faqir (J109)	71.0	79.6 → Weibull	84.1 → Pearson Type 3	84.0	73.8
Umm Al Birak (J112)	76.0	68.5 → Weibull	85.6 → GEV	46.5	97.2

Comparison criteria of the four distributions (Weibull, GEV, Gumbel, and Person Type 3) according to the Hyfran-plus model decision support system (DSS) are reviewed in Figure 30.

3.6.1. AIC and BIC Good Fitness Comparison Criteria

Goodness-of-fit test is used to determine the best model between the statistical plotting distributions tested in rainfall feature. A couple of goodness-of-fit tests have been conducted, such as AIC, BIC tests, along with the Hyfran-plus model for choosing the best probability distribution. Akaike information criterion (AIC) is a fined technique based on in-sample fit to estimate the likelihood of a model to predict/estimate the future values [41]. Bayesian information criterion (BIC) is another criterion for model selection that measures the trade-off between model fit and complexity of the model. A lower AIC or BIC value indicates a better fit. A good model is the one that has minimum AIC among all the other models [42,43].

Equations (4) and (5) are used to estimate the AIC and BIC of a model:

Bayesian Information Criterion (BIC)

$$\text{BIC} = -2 \log(L) + 2 K \log(n) \quad (6)$$

Akaike Information Criterion (AIC)

$$\text{AIC} = -2 \log(L) + 2 K \quad (7)$$

where: L is the likelihood, K is the number of parameters, and n is the sample size.

Table 15 explains the four station scenarios examined: Umm Al Birak (J112) station showed the extreme demonstrated rainfall depth design (XT) corresponding to return period (T = 100 year) in the dataset of 97.2 mm, while the pattern from 1990–2020 showed an extensive increase in extreme rainfall events compared to its earlier GEV estimate of 46.5 mm. M001 station consistently indicated high values, with the highest GEV estimate of 94.6 mm in the 1960–1990 dataset; however, the shift to Weibull plotting method in the extreme model 73.9 mm highlights the influence of Model (DSS) distribution selection. Al Faqir (J109) rainfall stations presented strong alignment and similarity between maximum rainfall depth generated using Model (1970–2020) and scenario of extreme statistical distribution (ESD) 84.1 mm, as well as results using GEV method from 1960–1990, which showed values in previous data of 84.0 mm and (DSS) of model 79.6 mm, but a decline to 71.0 mm

in the recent period maximum rainfall in dataset (1970–2020) suggests temporal variability. Bir Al Mashri (M003) maintained moderate rainfall depths, with a significant increase from the Gumbel statistical distribution of 58.4 mm to the GEV estimate of 82.9 mm (1960–1990); this recommends that the chosen extreme distribution may be underestimated.

For statistical distribution suitability in HYFRAN-PLUS MODEL, Weibull is commonly selected in (DSS) but Generalized Extreme Value distribution (GEV) and Pearson Type 3 produce higher extremes values, reinforcing their relevance for design under climate variability. To compare between Hyfran-plus model versus DSS for 100-Year Storm Design: In all rainfall gauge stations, mostly the Hyfran-Plus model produced rainfall depths using extreme value distributions (GEV and Pearson Type 3) that are higher than the decision support system (DSS) values, indicating that the DSS may be conservative or based on less extreme assumptions. Moreover, all (DSS)-generated values are less than the historical values in the maximum rainfall dataset recorded in the period 1970–2020, except Al Faqir station (DSS), which has a value of 79.6 mm that exceeds the historical maximum of 71 mm, which may reflect a precautionary design approach.

3.6.2. Uncertainty Analysis for Madinah (M001) Station 100-Year Return Period

The 100-year GEV estimate is taken as 94.6 mm from the 1960–1990 period, which represents the most conservative (highest) estimate among the available values.

As shown in Table 16, the estimated 100-year rainfall depth is 94.6 mm, with a 95% confidence that the true value lies between 79.5 mm and 112.8 mm. The alternative GEV estimates (full period and 1990–2020) fall within the 95% confidence interval of the 1960–1990 estimate, indicating that the differences between sub-periods are not statistically significant. The observed maximum of 89.6 mm falls well within the 95% confidence interval (79.5–112.8 mm), confirming that the fitted distribution adequately captures the extreme event observed during the study period. The Weibull-based 100-year estimate (85.8 mm) falls within the GEV confidence interval (79.5–112.8 mm), indicating that the difference between the two distributions is not statistically significant at the 5% level for this station. The quantified uncertainty range of $\pm 17.6\%$ provides a strong basis for risk-informed engineering design and water resource planning. The extreme rainfall estimates developed from the GEV distribution in the Hyfran-plus model should be interpreted within the context of the region's dominant atmospheric processes. Extreme events in Western Saudi Arabia are primarily driven by the interaction of tropical moisture sources with mid-latitude disturbances, particularly through the activation of the Red Sea Trough (RST) and the presence of upper-level cut-off lows [44,45]. The GEV distribution's ability to capture heavy upper-tail behavior aligns with the convective nature of these events, where rainfall intensities can substantially exceed historical maxima when multiple synoptic conditions align favorably.

Table 16. Results for 100-Year Return Period Quantile Estimate with Confidence Interval.

Return Period	GEV Estimate (mm)	95% Confidence Interval (mm)	Uncertainty Range
100 year	94.6	79.5–112.8	$\pm 17.6\%$

4. Conclusions

Rainfall analysis using historical data collected from available gauges involves examining rainfall trends and patterns at a higher temporal resolution than traditional daily or monthly, or even yearly, data. This study used extreme daily rainfall data in period of 1970–2020, collected from rainfall gauges. Four rainfall stations in the vicinity of the Wadi Alaqiq, namely: M001, M103, J109 and J112, with a record length of 51 years, were used in

the analyses. Rainfall frequency analysis was performed on the available data gathering from the Ministry of Environment, Water and Agriculture (MEWA). This paper discusses methods for comparing statistical distributions to select the most fitting one for modeling to use the design storm depth in simulation and modeling rainfall runoff, specifically in arid and semi-arid regions. Rainfall data analysis is an essential information resource for hydrologists and engineers involved in water project designs. The use of high-resolution rainfall data in understanding the complexities of hydrological process dynamics and describing them comprehensively and accurately is becoming increasingly apparent. This study was conducted using the most common and famous model (Hyfran-plus). The theoretical frequency distributions for the historical dataset from 1970–2020, namely GEV, Gumbel, Weibull, and Pearson type III, were used. GEV (Generalised Extreme Value) is the best plotting position method analysis for Madinah Munawarah, Umm Al Birak, and Bir Al MASHI stations, but the Pearson Type 3 method is the best distribution for Al Faqir station. The study tried to highlight on four scenarios for the return period of 100 years as comparative, such as maximum rainfall values in historical data (1970–2020) in 51 years, extreme values model generated, (DSS) Model proposed, and extreme values generated in previous study using two sets of historical data (1960–1990) and (1990–2020) to develop a comprehensive vision for select the best fit storm design in the Wadi Alaqiq drainage basin. This study focused on frequency rainfall analysis in Al Madinah Al Munwwarah and Wadi Al-Aqiq located in arid and semi-arid areas, which can be used to improve flash flood estimating using several software, such as HEC-HMS, to simulate the rainfall and runoff, hydraulic structures, dams, culverts, design of urban drainage systems, and water resource planning and management. The comparison of four statistical distributions at the stations shows that distribution choice strongly affects design rainfall depth (XT), especially for higher return periods (T). Although estimates are similar for short return periods, such as 2, 5, and 10 years, they diverge significantly beyond 50 years, emphasizing the need to match the distribution to infrastructure risk. Pearson Type III provides the highest values and is best for critical, long-life structures. Gumbel and Weibull propose moderate estimates suitable for urban and rural drainage, respectively, whereas GEV gives the lowest values and suits low-risk or preliminary assessments. This highlights the importance of a station-specific, purpose-driven approach. Moreover, high-frequency rainfall data can help water engineers to learn more about how climate change is affecting rainfall patterns. The quantified uncertainty ranges ($\pm 17.6\%$ for the 100-year event) reflect the inherent variability in the recurrence of these complex atmospheric configurations.

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