RAINFALL DISTRIBUTION AND ITS CHARACTERISTICS IN MAKKAH AL-MUKARRAMAH REGION, SAUDI ARABIA

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(Received 26th Mar 2018; accepted 12th Jun 2018)

Abstract. Defining the characteristics of rainfall distribution is the key for many engineering applications such as road design, flood damage mitigation measures, and planning and management of water resources. Since Makkah Al-Mukarramah area is of utmost importance in Saudi Arabia, studying the characteristics of rainfall distribution is necessary. This research aims at investigating rainfall data to define the best rainfall distributions and its characteristics in the study area via rainfall frequency analysis. Different statistical analyses such as log-normal distribution, normal distribution, extreme value type I distribution, Pearson type III distribution, and log-Pearson type III distribution were preformed on more than 20 stations having annual rainfall data over ten years. The results showed the best probability distributions, and rainfall predictions at various return periods for the study area. 36% of rainfall stations follow three parameters log-normal distribution, 27% of stations follow log-Pearson type III distribution, 14% of stations follow Pearson type III distribution,9% of stations follow GEV distribution,9% of stations follow two parameters log-normal distribution and 5% follow Gumbel Type I.

Keywords: *arid and semiarid zones, frequency analysis, rainfall modelling, stochastic analysis*

Introduction

Rainfall is considered the most important factor in hydrology, and nearly most or all of the natural and unnatural activities depend on rainfall, and rainfall initiates various types of work, like water resource management, agriculture and forestry, flood protection and many other (Mahdavi et al., 2010). Predicted changes in precipitation in the future are needed for studying of the consequences of the climatic changes around the world which represent input to the hydrological cycles. And due to lack of randomization in the meteorological and hydrological data, they can be analyzed statistically using frequency data analysis of rainfall and flood. Due to these reasons, it is easy to use statistical distribution in many studies like those dealing with water structure design, water resources and watershed management and parameter estimation in the hydrological cycle (Subyani, 2011; Mashat and Basset, 2011). One of the essential things is the determination and fitting of the best distribution to the data. The analysis of frequency means relating the ultimate events magnitude to their occurrence frequency by the use of the probability distribution (Chow et al., 1988). Rainfall measurements would enhance the feasibility of flood protection works, and will also lead to successful managing of runoff water, and such data analysis will help in preventing floods and droughts (Bahrawi, 2009). It can also be applied in the management and design of most engineering works that deal with water resources like the design of reservoirs, the control of floods and drainage systems, methods to conserve soil and water. Rainfall data are needed to provide the base for all these types of design works.

Makkah Al-Mukarramah area is one of the most developed areas in Saudi Arabia. The annual average rainfall of Makkah Al-Mukarramah area exceeds 100 mm (Bahrawi et al., 2016). There is an increasing need for water for economic development. Autumn and

DOI: http://dx.doi.org/10.15666/aeer/1604_41294144

winter are the major rainy seasons, and steep terrains of the study area often cause short time of concentration and extremely rapid creation of wadis during the precipitation-runoff process. It results in flash flood dangers. In order to reduce losses arising from these kinds of floods, an appropriate hydrologic design is very important. Rainfalls are not evenly distributed spatially and temporally (Mahdavi et al., 2010). Makkah Al-Mukarramah climate is affected by various air masses from Mediterranean (cyclone type) during winter season to monsoon type in summer season. The mechanisms of the movement of these air masses is explained in details in the literature (Mahdavi et al., 2010; Subyani, 2011; Mashat and Basset, 2011).

This particular research intends to study the rainfall distribution characteristics of the Makkah Al-Mukarramah area, through utilizing various statistical tests of probability distributions such as the normal distribution, log-normal distribution, extreme value type, I distribution, Pearson type III distribution, and log-Pearson type III distribution all these distributions are mentioned as suitable and practical in the literature (Kite, 1977). Rainfall gauging data from stations of Makkah Al-Mukarramah province were used to investigate the fitness of statistical distributions (*Fig. 1*). Twenty-two stations providing annual rainfall data over more than 30 years were chosen in order to execute the frequency analysis (Subyani, 2011). For determination of the best fitting distribution to maximum daily rainfall the Relative residual mean square (RRMS) is used. Shuqiu (1993) suggested in her research, that: “Nearly all rainfall stations at the same region can easily certainly not be characterized simply by only an individual probability distribution, supposing these types of stations to fit to a specific probability distribution and type a cluster.” nearly all the stations in the similar regions categorized a varied cluster in agreement with their probability distributions. In case important characteristics among clusters persisted, such as a particular part of the stations being similar to rainfall characteristics and consequently fit to the exact same probability distribution, these characteristics might result from the stations of a cluster and have a special connection to a particular daily rainfall data. Subyani (2011) used annual maximum rainfalls from 8 rainfall stations in order to obtain rainfall frequency analysis. The author utilized the statistical distribution methods like Gumbel’s extreme value distribution and Log Pearson Type III distribution for maximization of the daily rainfall data over 24-40 years, and he found that the best fitting for prediction of the rainfall occurrence in future is Gumbels model.

The areas with heavy annual rainfall within Saudi Arabia extend along the southwestern Red Sea Coast and North-Eastern coast and then moves over the middle region of the Saud Arabia. Hasanean and Almazroui (2015) mentioned that within Saudi Arabia, the very heavy precipitation areas were along the southwestern coast and the South West to North East inclined precipitation band, which moves over the middle region of Saudi Arabia. However, the annual average rainfall of the Makkah Al-Mukarramah area exceeds about 140 mm mean annual rainfall, generally there is a big gap between rainfalls, which usually has wide uncertainly spatially and temporally (Subyani, 2011; Shuqiu, 1993).

Materials and methods

Study area

Saudi Arabia is divided into 13 districts. Makkah Al-Mukarramah region is one of the most important districts. It has 22 recording rainfall gauges (*Fig. 1*). Makkah Al-Mukarramah region has actually a dry climate with extremely high temperature values during the day, and minimal rainfall that is inconsistent (Mahdavi et al., 2010; Subyani, 2011). There are either wadis during the entire 12 months, or the rain might just occur in the type of one or two abundant outbursts that may cause actual flooding. Data from different sources, which is usually climatological, was provided by the Ministry of Water and Electricity in Saudi Arabia. Spatially, the mountainous area has additional rainfalls compared to the regular area, and the sloping ground would definitely result from the water preservation potential of watershed to decline dramatically (Subyani, 2011). A large portion of rainfalls will become runoff and discharges quickly, causing damage to infrastructure. Types of these sources had a continuous and timely based record (*Table 1*). The rainfall data with valid documentation obtained and examined from these types of gauging stations, considerably increased in the past 20 years. Some other stations either had very few records of daily data or records with total sum of daily data.

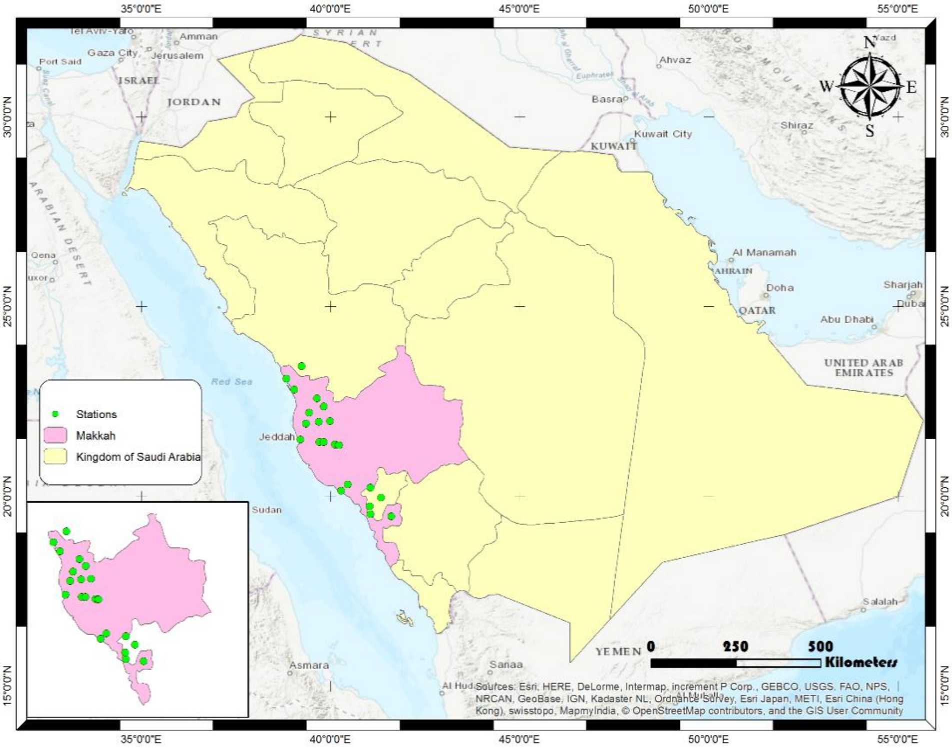


Figure 1. *Stations in the Kingdom of Saudi Arabia and Makkah Al-Mukarramah Region*

Data

Saudi Arabia has an arid environment characterized by extreme heat during the day, abrupt drop in temperature at night. Rainfall in the region of Makkah Al-Mukarramah is low and erratic. *Figure 2* shows the average monthly rainfall depth for the rainfall stations in the study area from (1966 to 2013). The figure shows that the spatial variation of rainfall is influenced by the topographic features. The rainfall depth increases with the elevation (which is called the orographic effect). The orographic rainfall is due to the mechanical raising of the clouds over mountain boundaries (Linsley et al., 1982). The stations near the coastal zone receive less rainfall in comparison with the stations in mountainous areas. (see e.g. station J108, J111, J134, J140 at coastal plain, and stations J113, J116, J131, J137 at the mountains). It is obvious from *Figure 2* that most rainfall occurs in October, November, December and January (winter season), and out of the winter season there is a lot of rainfall in March and April. May, June, July, August and September have low rainfall. There is no specific pattern spatially and temporally in every region. This behaviour is evident from *Figure 2* since in every month there is a high variation of rainfall depth in all stations.

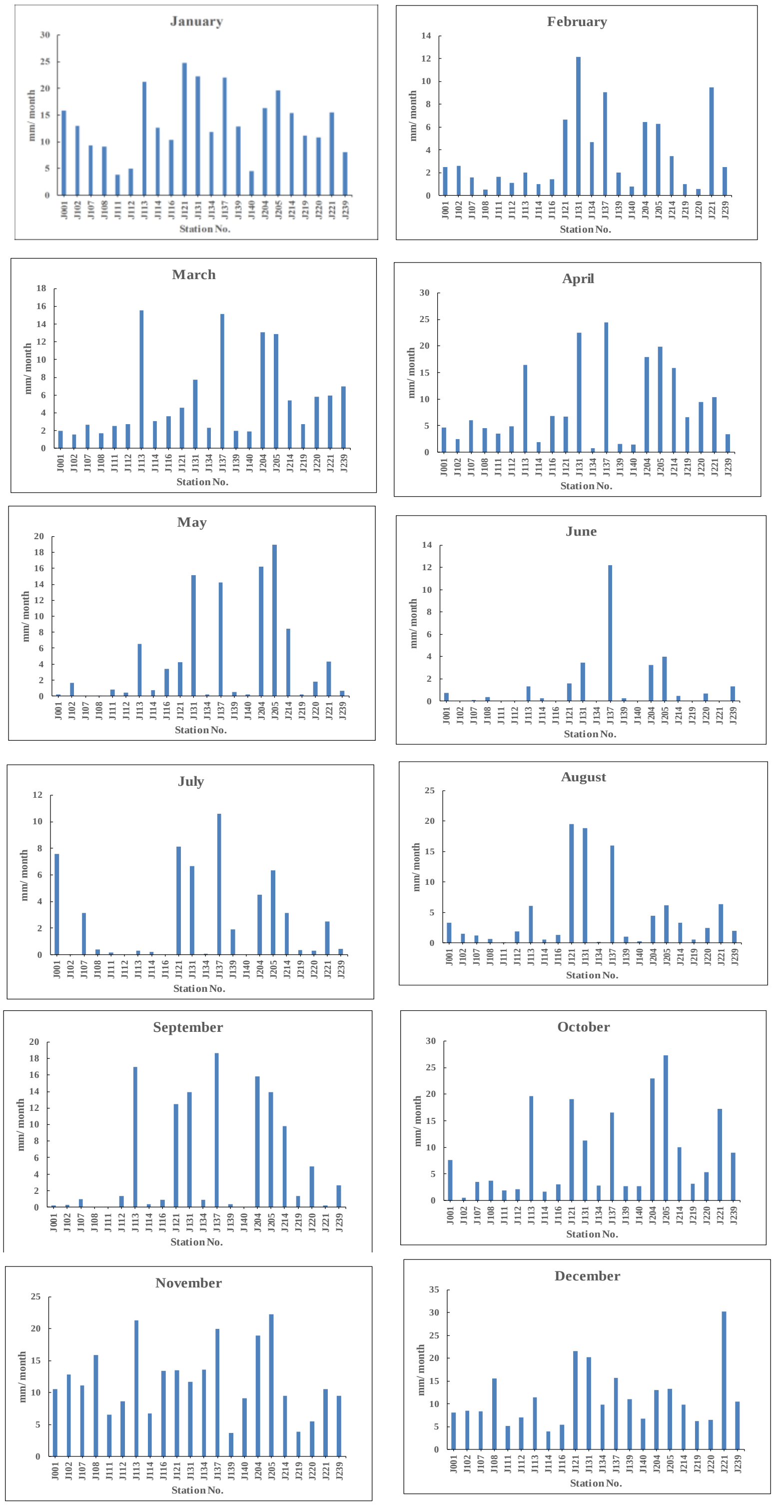


Figure 2. *Average monthly rainfall depth*

Continuous rainfall data were collected from 1966 to 2013, from the rainfall gauge network that covers the Makkah Al-Mukarramah region. The data collected for each station includes the station number, station symbol, years of records, coordinates, and number of storms (*Table 1, Fig. 3*). Maximum daily rainfall, storms are collected from the 22 stations covering the study area (*Table 1*). *Figure 3* shows samples of time series for maximum daily rainfall data at some stations in the study area. The figures show high variations in the rainfall data over the station history. Some years show no rainfall.

Table 1. *Stations used in the current study*

Station number	**Station name**	**Record**		**Number of storms**	**Coordinate**	
		From	**To**		**Lat. (N)**	**Long. (E)**
J001	MUDAYLIF	1966	1998	27	19°31'47.46"	41° 3'4.32"
J102	BAHRAH	1966	2011	40	21°25'58.94"	39°42'4.45"
J107	GHUMAYQAH	1966	2012	34	20°18'59.24"	40°27'4.38"
J108	LITH	1966	2011	40	20° 8'59.29"	40°16'52.38"
J111	MASTURAH	1966	2008	38	23° 5'58.49"	38°50'4.54"
J112	UMM AL BIRAK	1964	2012	39	23°25'58.39"	39°14'4.53"
J113	FARRAIN	1966	2005	38	21°21'58.94"	40° 7'4.44"
J114	MAKKAH	1967	2013	20	21°25'58.93"	39°49'4.46"
J116	SHABAH	1966	2012	37	22°34'58.61"	39°38'4.48"
J121	HAJRAH	1966	2007	37	20°13'47.25"	41° 3'4.34"
J131	FAYJAH	1970	2012	39	19°28'11.46"	41°36'4.28"
J134	JEDDAH	1970	2012	38	21°29'58.93"	39°12'4.49"
J137	HASAN AL HABS	1966	2005	35	19°58'11.32"	41°19'52.32"
J139	WADI DDQAH	1967	2011	28	19°43'59.40"	41° 2'4.31"
J140	RABIQH	1966	2012	32	22°48'58.57"	39° 2'4.52"
J204	KURR	1966	2005	39	21°20'58.95"	40°12'4.42"
J205	MID SCARP	1966	2005	40	21°20'58.95"	40°13'4.43"
J214	MADRAKAH	1966	2006	40	21°58'58.77"	39°59'4.44"
J219	AIN AZIZIYAH	1970	2006	36	22°11'58.73"	39°25'52.49"
J220	MIDHAH	1966	2011	40	22°22'10.67"	39°49'16.47"
J221	USF AN	1971	2006	30	21°54'58.81"	39°21'4.49"
J239	BARZAH	1976	2011	32	21°57'58.79"	39°41'4.46"

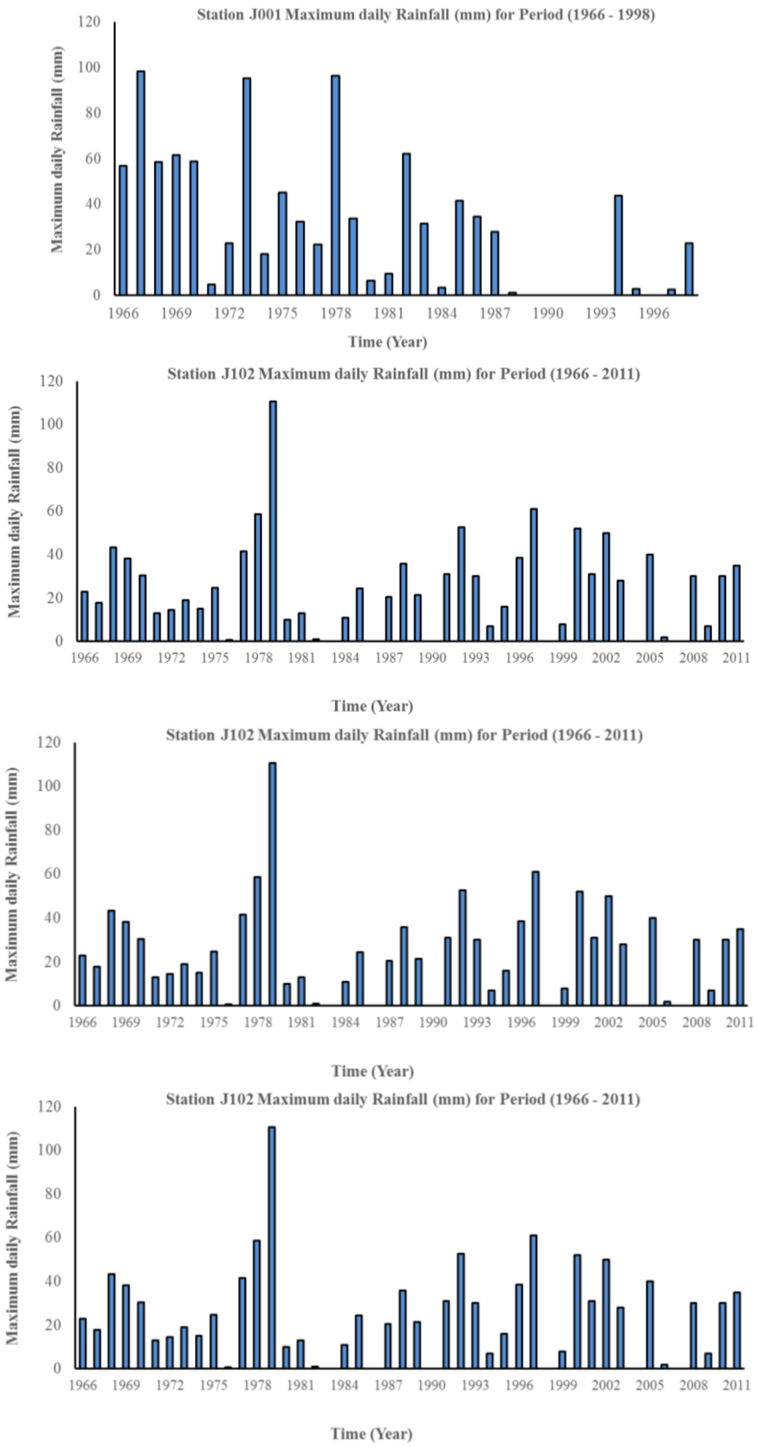


***Figure 3.** Sample of maximum daily rainfall depth time series of some stations, namely J001, J102 and J108*

Research method

Frequency analysis

Hydrologic Frequency Analysis is the method used for evaluation of the probability of the hydrologic events, which are averaged out in statistical viewpoints, either greater than or of a specific magnitude within a certain area, that will occur within a certain period. The frequency analysis methods used in this study are as follows.

The equation (*Eq. 1*) of frequency analysis is

$$Q_T = M + K_T S \qquad \text{(Eq.1)}$$

where Q_T is the hydrologic quantity (rainfall depth in the current study) with the return period T; M is the mean of hydrological data; S is the standard deviation of hydrological data; and K_T is the frequency factor, a function of the return period and probability distribution Kite (1977) has calculated K_T for the Gumbel distribution for the lognormal distribution and for the gamma distribution. The followings are short descriptions of the probability distributions used in the analysis:

Two-parameter lognormal distribution (LN2)

The lognormal distribution is used at a larger stage for the analysis of environmental extremes. The probability density function of the two-parameter lognormal distribution is calculated as *Equation 2:*

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left\{ -\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2 \right\} \qquad \text{(Eq.2)}$$

μ is a location parameter, and σ is a scale parameter.

The magnitude of the event with return period T = 1/p can be estimated from *Equation 3:*

$$\ln x_T = \mu + \sigma Z_p \qquad \text{(Eq.3)}$$

where Z_p is the standard normal variate with exceedance probability p.

Three-parameter lognormal distribution (LN3)

The three-parameter lognormal distribution which is in fact the two-parameter distribution is represented as *Equation 4:*

$$f(x) = \frac{1}{(x - x_0)\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{\ln(x - x_0) - \mu}{\sigma}\right)^2\right\} \qquad \text{(Eq.4)}$$

μ is the location parameter and ð is the scale parameter, while X_0 controls the shape of the distribution.

The event magnitude for the return period T = 1/p is calculated according to *Equation 5:*

$$\ln(x_T - x_0) = \mu + \sigma Z_p \qquad \text{(Eq.5)}$$

where z_p is the standard normal variate with exceedance probability p.

Pearson Type III distribution (P3)

The Pearson Type III distribution is one of a large family of probability distributions developed by Pearson (Price and Harrison, 1975). Both the exponential and gamma distributions are special cases of the Pearson Type III distribution.

The distribution function is (*Eq. 6*):

$$f(x)=\frac{(x-x_0)^{\gamma-1}\exp\left\{\frac{-(x-x_0)}{\beta}\right\}}{\beta^{\gamma}\,\Gamma(\gamma)} \tag{Eq.6}$$

The X_0 which constitutes a lower bound controls locations, β controls the scale and γ controls the shape. And due to difficulty in calculating the magnitude of the event with return period T using hand calculation, the best and simplest way is to make estimations of the T-year event from the means of the sample, the standard deviation and a factor K_T (*Eq. 6*)

$$x_T=\bar{x}+\sigma K_T \tag{Eq.7}$$

The factor K_T varies with return period T and sample skewness γ, and can be read from tables (Tables 9-2 and 13-4 in Mahdavi et al., 2010, for example).

Log-Pearson Type III distribution (LP3)

Log-Pearson Type III distribution is in fact refers to Pearson Type III distribution, and it is represented as *Equation 8:*

$$f(x)=\frac{\ln(x-x_0)^{\gamma-1}\exp\left\{\frac{-\ln(x-x_0)}{\beta}\right\}}{\beta^{\gamma}\,\Gamma(\gamma)} \tag{Eq.8}$$

The X_0 which constitutes a lower bound controls location, β controls the scale and γ controls the shape. And the best and simplest way is to make estimations of the T-year event from Pearson Type III distribution.

Generalized extreme value distribution (GEV)

The generalized extreme-value (GEV) distribution was introduced by Jenkinson (1955, 1969) and Mahdavi et al. (2010) initiated the distribution based on the, Generalized Extreme Value (GEV) for annual rainfall data, and thus brought together a number of distributions into Gumbel's value, and thus the function is (*Eq. 9*):

$$F(x) = \exp\text{-}\,[1-k(\frac{x-u}{\alpha})\,]^{1/k} \tag{Eq.9}$$

and the magnitude with Gumbel reduced variate y can be determined from *Equation 10:*

$$x = u + \alpha\left(\frac{1 - e^{-ky}}{k}\right) \qquad \text{(Eq.10)}$$

$$\text{where} \quad u + \frac{\alpha}{k} \le x < \infty \quad \text{if } k < 0$$

$$-\infty < x \le u + \frac{\alpha}{k} \quad \text{if } k > 0$$

µ and α represent parameters, a location parameter and a scale parameter, and K represents the shape of the distribution. When K becomes zero the general extreme value will be reduced to extreme value 1 distribution, and when K becomes negative then the general extreme value will be type 2 without an upper limit, and when K is positive then the general extreme value becomes 3 with an upper limit of µ + α/k.

Results and discussions

It was indicated from the relative frequency distribution that Log Pearson type III distribution initiated the best probability distribution (Mahdavi et al., 2010). *Figure 4* shows the annual average rainfall depth of the stations in the study area. It is obvious that there is high variation between the different stations (minimum is 10 mm and maximum 45 mm) the highest annual rainfall depth is observed in station J205 and lowest rainfall station is J140. The standard deviation rainfall of the stations is shown in *Figure 5*.

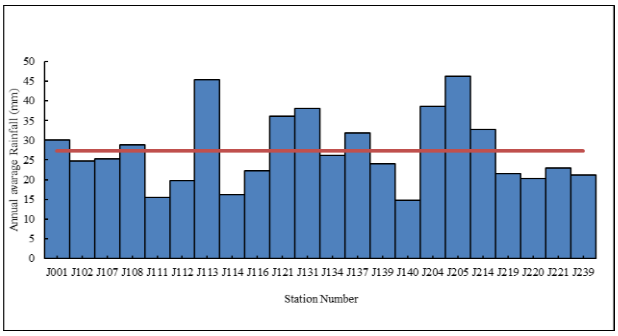


Figure 4. *Annual average rainfall depth of the stations in the study area*

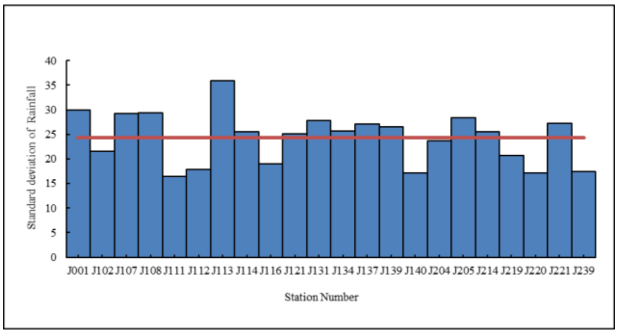


Figure 5. *Standard deviation of the rainfall depth of the stations in the study area*

The relationship between the annual average rainfall depth and the distance from the sea shown in *Figure 6*, as the distance from the sea increases the rainfall depth increases. A trend line is made to describe the relationship. Similarly, *Figure 7* shows a relationship between the annual average rainfall depth and the elevation of the stations from the sea. As the elevation increases the rainfall depth increases. The trend line is made to describe the relationship.

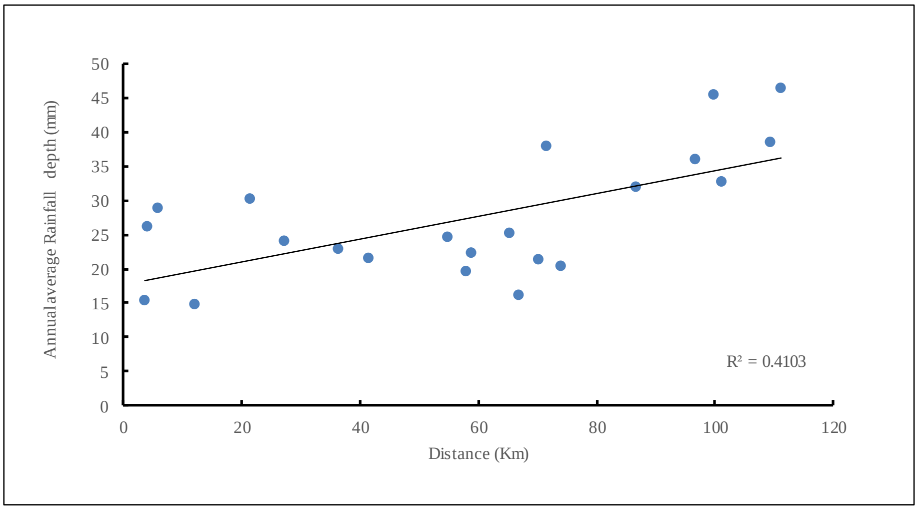


***Figure 6.** Distance versus annual average rainfall depth*

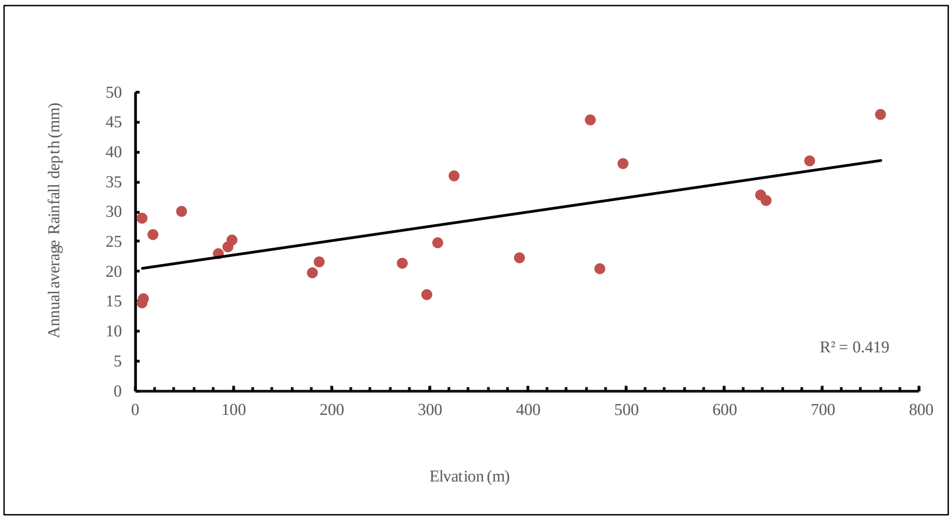


***Figure 7.** Elevation versus annual average rainfall depth*

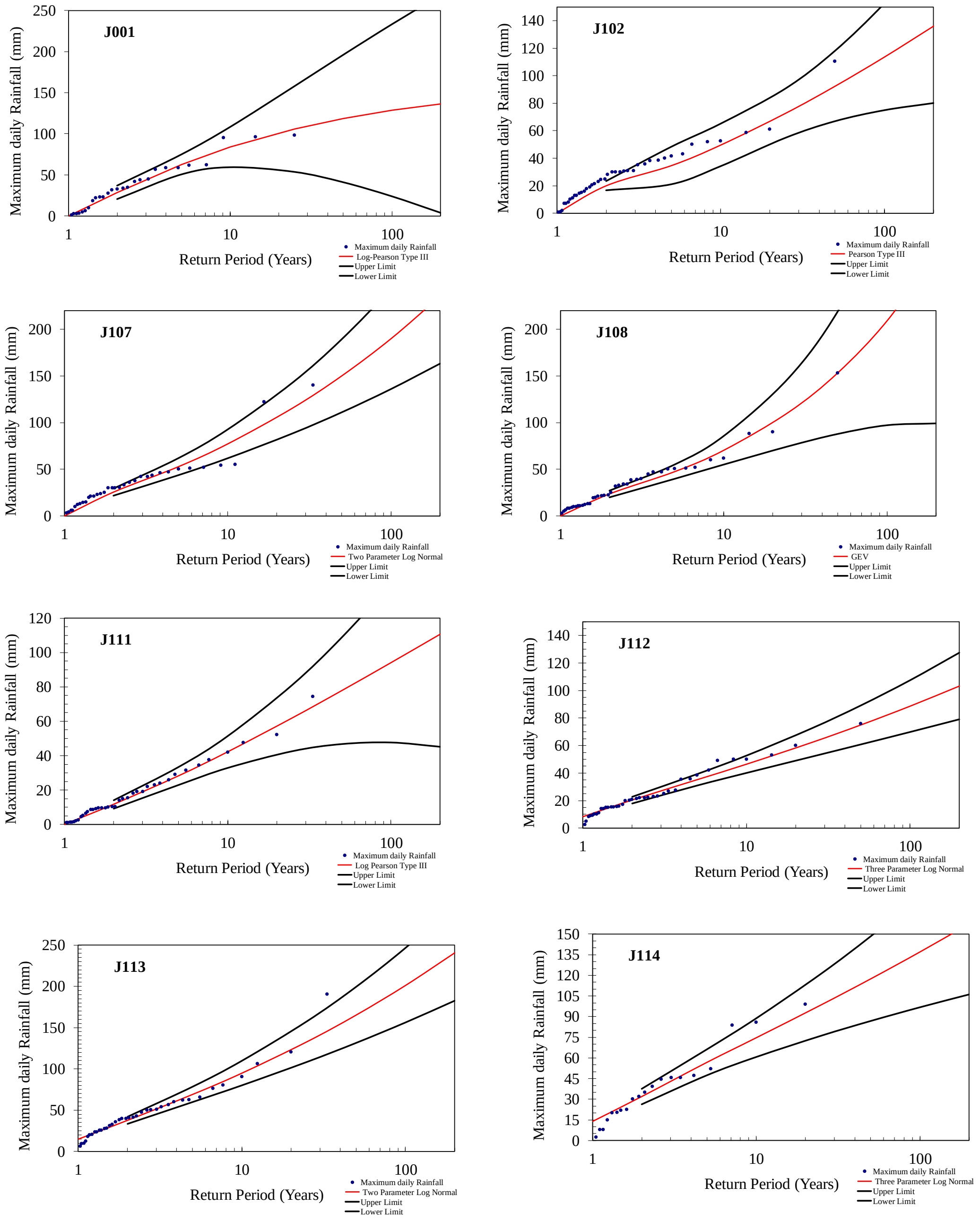
Frequency analysis

In order to determine common characteristic rainfall distribution of the study area frequency analysis is applied using various distributions, of which, three parameters log-normal distribution, two parameters log-normal distribution, log Pearson type III distribution, Pearson type III distribution, and Gumbel extreme value distribution, with rainfall data recorded through 22 stations over 30 years. Results showed that the 3 par log-normal distribution is the best probability distribution, occupying 36% of the total number of stations (as shown in *Figure 8a, b, c* and *Table 2*).

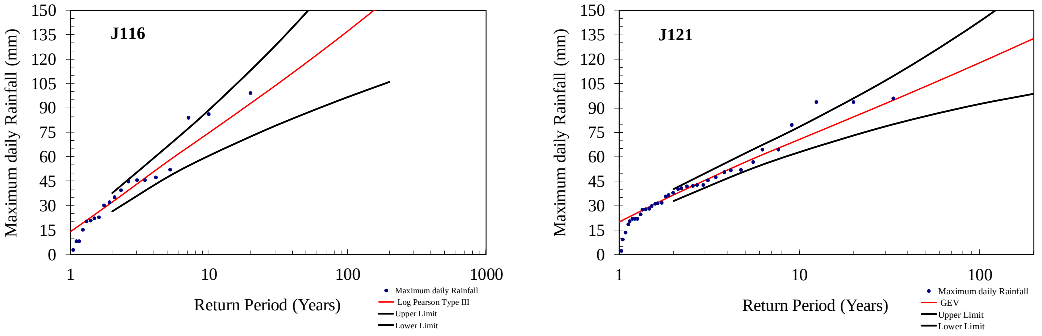
The best distributions were chosen dependent on the root-mean-square error measure, RMSE (Mahdavi et al., 2010). RMSE values for the different distributions explain the mean inconsistency between the predictable value and the measured one. *Table 2.* shows the best fitting distributions depending upon the minimum RMSE as given by italicization in the table. The best probability distribution is presented in *Figure 8a, b, c.*

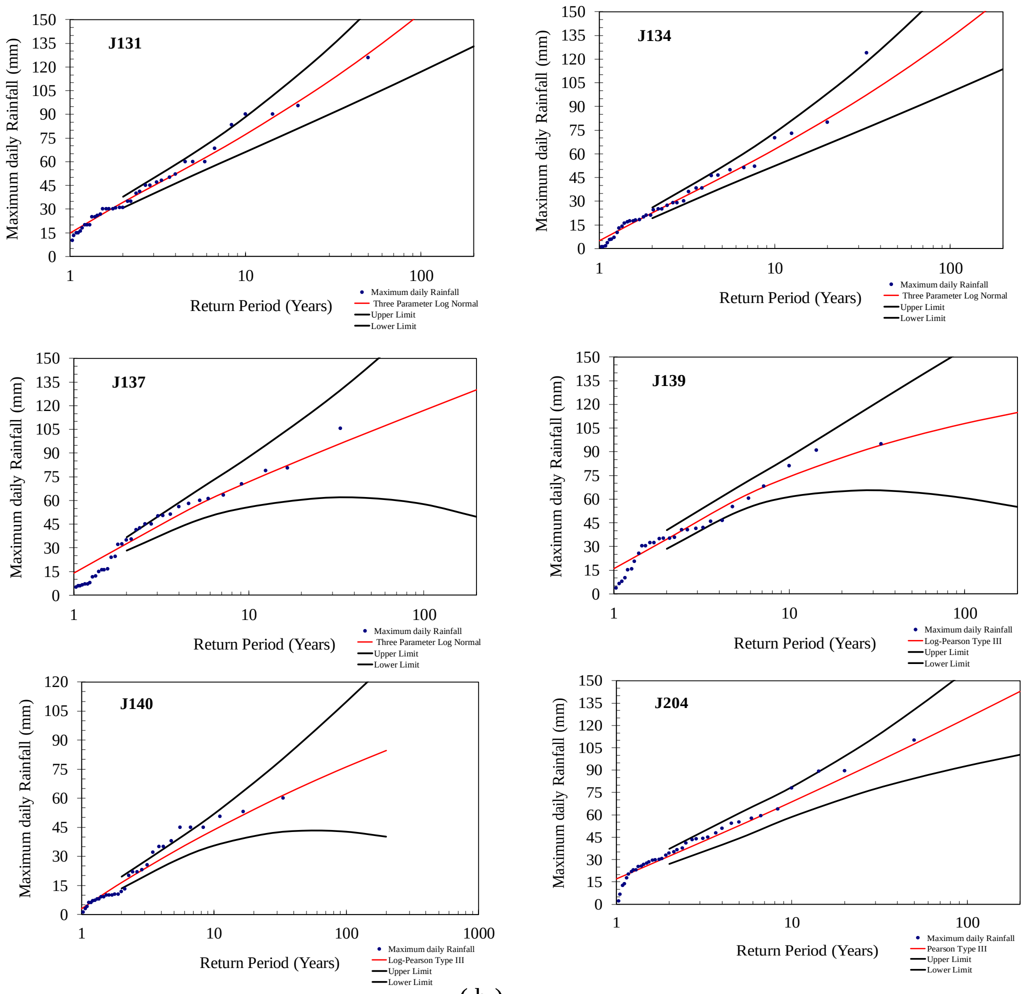
Table 2. *Root-mean-square error (RMSE) for all stations at different distributions*

Stations	Distribution type					
	Gumbel type I	**GEV**	**Two-parameter log-normal**	**3-par log-normal**	**Pearson type III**	**Log-Pearson type III**
J001	9.49	9.78	13.13	9.43	9.96	**7.32**
J102	12.84	12.03	10.40	11.73	**9.34**	18.21
J107	20.78	19.47	**14.00**	18.71	17.84	19.61
J108	20.69	**6.23**	7.65	8.29	14.68	11.73
J111	5.39	3.07	6.28	3.68	4.19	**1.29**
J112	4.49	2.64	3.71	**2.26**	3.28	3.40
J113	14.44	12.58	**7.93**	11.99	10.81	12.94
J114	7.57	7.23	8.67	**6.44**	7.50	6.50
J116	4.50	3.92	5.78	3.77	3.77	**3.27**
J121	7.42	**7.08**	7.71	7.12	7.10	13.97
J131	10.14	7.34	7.15	**6.35**	8.02	6.47
J134	8.40	7.10	9.56	**5.39**	6.97	5.92
J137	2.32	2.38	5.73	**2.29**	3.05	3.58
J139	5.85	5.91	7.28	5.63	6.12	**4.18**
J140	5.17	5.82	6.87	5.38	5.08	**5.04**
J204	6.60	4.65	5.48	4.81	**4.64**	16.13
J205	4.66	4.96	6.78	**4.55**	4.68	23.90
J214	11.78	8.73	9.65	**8.41**	8.83	17.35
J219	8.65	7.59	10.21	**6.70**	7.87	7.13
J220	2.74	2.78	4.01	**2.62**	2.91	7.86
J221	11.20	**3.58**	4.63	4.78	8.25	6.72
J239	3.14	2.94	4.67	2.84	3.01	**1.69**

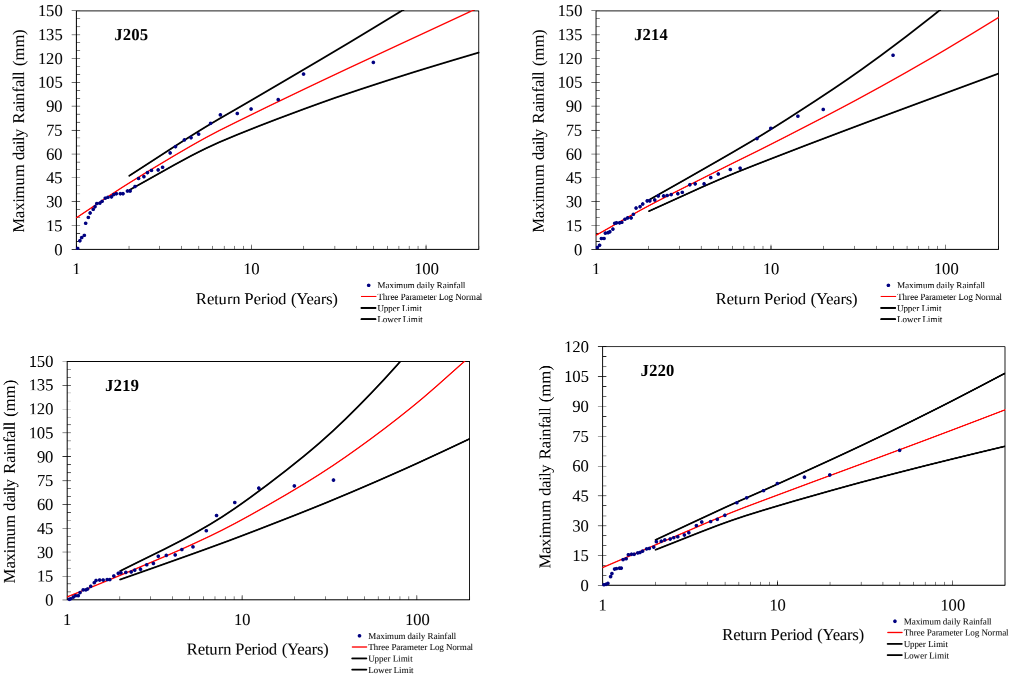

J001
Maximum daily Rainfall (mm)
0
50
100
150
200
250
1
10
100
Return Period (Years)
Maximum daily Rainfall
Log-Pearson Type III
Upper Limit
Lower Limit
J102
Maximum daily Rainfall (mm)
0
20
40
60
80
100
120
140
1
10
100
Return Period (Years)
Maximum daily Rainfall
Pearson Type III
Upper Limit
Lower Limit
J107
Maximum daily Rainfall (mm)
0
50
100
150
200
1
10
100
Return Period (Years)
Maximum daily Rainfall
Two Parameter Log Normal
Upper Limit
Lower Limit
J108
Maximum daily Rainfall (mm)
0
50
100
150
200
1
10
100
Return Period (Years)
Maximum daily Rainfall
GEV
Upper Limit
Lower Limit
J111
Maximum daily Rainfall (mm)
0
20
40
60
80
100
120
1
10
100
Return Period (Years)
Maximum daily Rainfall
Log Pearson Type III
Upper Limit
Lower Limit
J112
Maximum daily Rainfall (mm)
0
20
40
60
80
100
120
140
1
10
100
Return Period (Years)
Maximum daily Rainfall
Three Parameter Log Normal
Upper Limit
Lower Limit
J113
Maximum daily Rainfall (mm)
0
50
100
150
200
250
1
10
100
Return Period (Years)
Maximum daily Rainfall
Two Parameter Log Normal
Upper Limit
Lower Limit
J114
Maximum daily Rainfall (mm)
0
15
30
45
60
75
90
105
120
135
150
1
10
100
Return Period (Years)
Maximum daily Rainfall
Three Parameter Log Normal
Upper Limit
Lower Limit

(a)


J116
Maximum daily Rainfall (mm)
0
15
30
45
60
75
90
105
120
135
150
1
10
100
1000
Return Period (Years)
Maximum daily Rainfall
Log Pearson Type III
Upper Limit
Lower Limit
J121
Maximum daily Rainfall (mm)
0
15
30
45
60
75
90
105
120
135
150
1
10
100
Return Period (Years)
Maximum daily Rainfall
GEV
Upper Limit
Lower Limit



(b)



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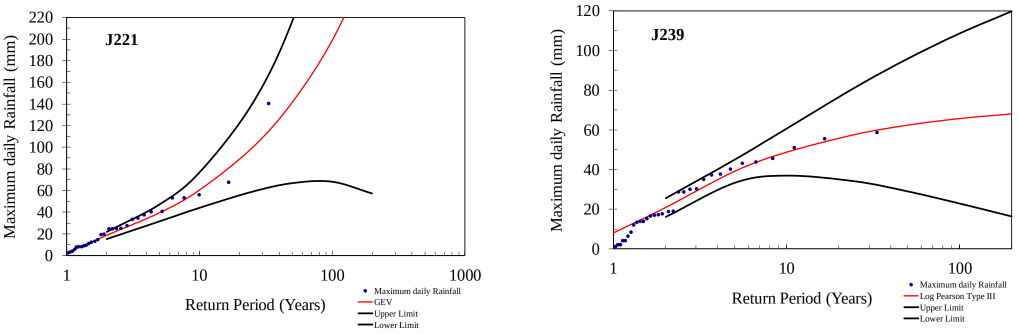

(c)

Figure 8. *(a, b, c) Rainfall depth, frequency analysis at the stations in the study area based on the best probability distribution assigned from Table 2 and the corresponding confidence interval*

Table 3 shows the maximum and minimum values of the expected rainfall depth for study area under different return periods. The table shows that the variation between the minimum, and maximum is very high depending on the location of the stations where the stations over the mountain area have high expected rainfall depth. However, stations at low plain area have low expected rainfall depth. The eastern part of the study area has no stations. Therefore, the contouring extrapolated values for these areas which need to be validated by ground stations. It is recommended to have extra rainfall stations in this area to get more reliable mapping. *Table 4* shows the percentage of each distribution of the rainfall stations. The table shows that 36% of the rainfall stations follow three parameters log-normal distribution, 27% of the stations follow log-Pearson type III distribution, 14% of the stations follow Pearson type III distribution, 9% of the stations follow GEV distribution, 9% of the stations follow two parameters log-normal distribution and 5% follow Gumbel Type I.

Table 3. *Expected maximum and minimum rainfall depth for Makkah Al-Mukarramah region at different return periods*

Return period years	Minimum rainfall depth (mm)	Maximum rainfall (mm)
5	27.08	69.17
10	42.41	94.91
25	57.47	132.98
50	62.41	165.36
100	65.76	208.85
200	68.1	282.15

Table 4. *The percentage of the best distributions over Makkah Al-Mukarramah region from all stations*

Distribution type	% per all stations
Gumbel type I	5%
GEV	9%
Two-parameter log-normal	9%
Three parameters log-normal	36%
Pearson type III	14%
Log-pearson type III	27%

Moreover, *Figure 9* displays a color contour map of the expected rainfall depth at different return periods from 2 to 200 years over Makkah Al-Mukarramah region. The maps show the locations of expected high and low rainfall depth in the region. This can be useful in the flood analysis in these areas. Locations of maximum rainfall have a high risk of flooding while locations of minimum rainfall have a low risk of flooding.

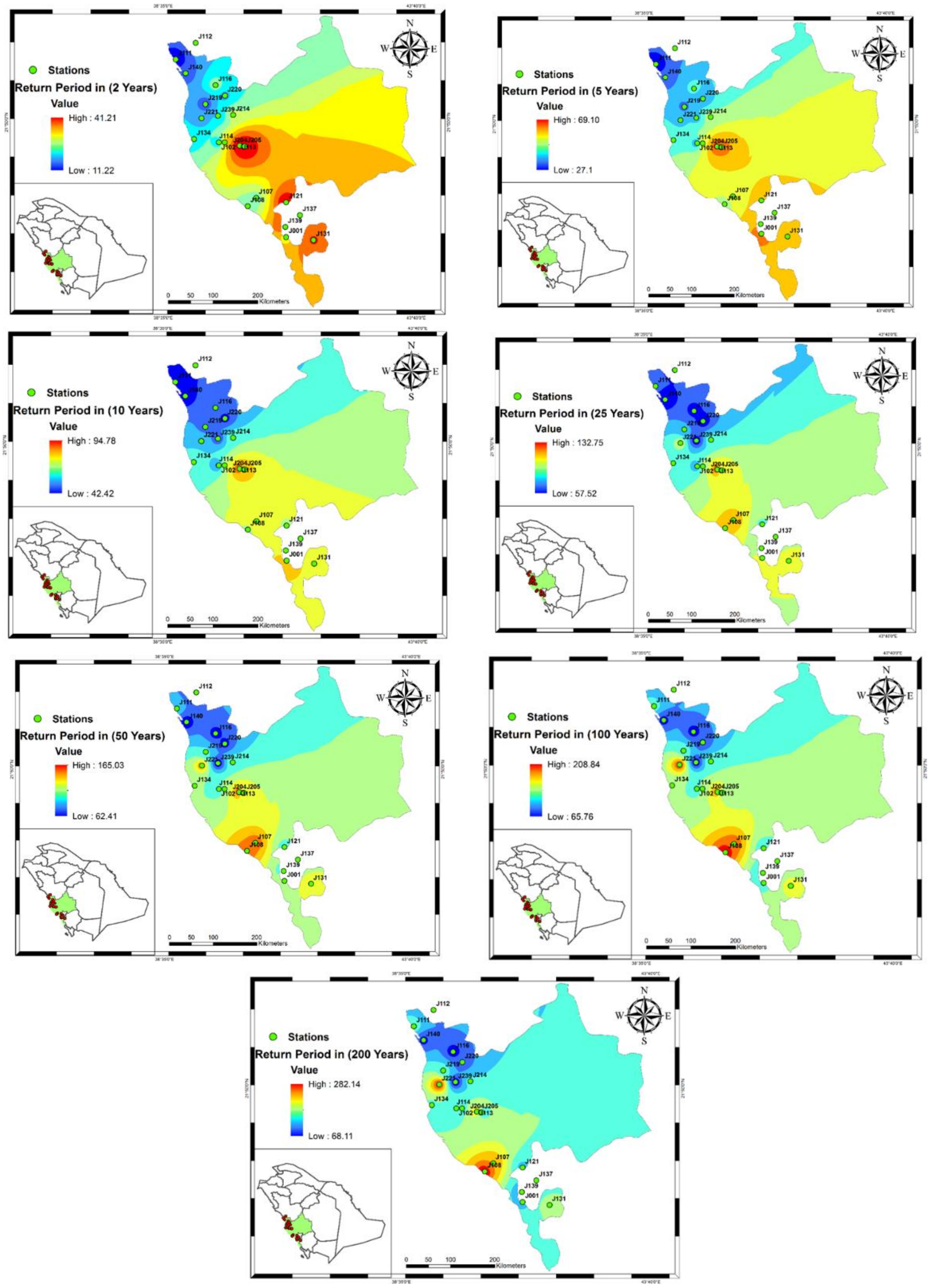

Figure 9. *Mapping rainfall depth for different return periods (5, 10, 25, 50, 100, 200 years) over Makkah Al-Mukarramah region*

Conclusion

From the results of five frequency distributions applied in this study, it is suggested that the best frequency distribution obtained for Makkah Al-Mukarramah area is the three Parameter Log-Normal distribution, which occupies 36% of the total number of stations, followed by the log-Pearson Type III and Pearson type III distribution which accounts for 27% and 14% of the total station number, respectively. From the results of the frequency analysis, three Parameter Log-Normal distribution is the primary distribution pattern for this study site. By increasing the number of years and data and employing different methods for the analysis, it is believed that more accurate results could be obtained. Outcomes revealed that the three Parameter Log-Normal distribution, conducted the best in the probability distribution, fitting 36% of the total station data.

Acknowledgements. This article was funded by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah. The authors, therefore, acknowledge with thanks DSR for technical and financial support. The authors would also like to thank Professor Hatem and lecturer Mr. Anis Chaabani for helping in GIS maps and our technicians Mr. Abdullah Al-Maliki and Mr. Abdalaziz Al-Bishri for their assistance.

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