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ORIGINAL ARTICLE

Generation of Rainfall Intensity Duration Frequency (IDF) Curves for Ungauged Sites in Arid Region

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Abstract
Objective We developed a method for Intensity Duration Frequency (IDF) curves in ungauged locations in arid region.
Background The arid climate which covers most of Saudi Arabia is typically characterized by large temporal and spatial variations in rainfall distribution. The availability of long-term records of rainfall-runoff series would be useful to better estimate effective rainfall depth. The development process for an IDF curve for a remote, ungauged site is addressed through the use of rainfall record.
Method The analyses focused on the application of two distributions: the Gumbel and Log Pearson III functions combined, to estimate the maximum rainfall for the various return periods in three stations in Al-Madinah region.
Results The empirical intensity frequency equation is used to estimate rainfall intensity for design purposes for the ungauged location. The results of this research contribute to the development of IDF-based design criteria for water projects in ungauged sites located in arid and extreme arid regions.

Keywords IDF curves · Rainfall generation · Ungauged sites · Al-Madinah · Saudi Arabia

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1 Introduction

Rainfall in arid regions is characteristically erratic and random both temporally and spatially, which makes it challenging to develop good water project design. The large areal and temporal rainfall variability is complicated by the dearth of observations in many rainfall and runoff stations located in Saudi Arabia making it necessary to apply empirical and statistical techniques. For most water engineering projects, rainfall intensity analyses, especially IDF curves for the different return periods, are necessary. IDF curves can be developed through the application of appropriate statistical distributions based on the available rainfall record. Better estimation of rainfall depth and intensity, needed for water projects, can be achieved through the availability of long-term records to improve registered storm intensity. The issue of rainfall frequency and the associated IDF curve developments have been evaluated by many researchers for arid regions of the world. The estimated rainfall intensity at different frequencies of return periods for design purposes has been addressed in the literature (e.g., Maidment 1993; Venkata Ramana et al. 2008; Şen 2008; Awadallah et al. 2011; AlHassoun 2011; Elsebaie 2012; El-Sayed 2011; Wayal and Menon 2014).

Other researchers in the fields of hydrology and engineering have developed IDF curves for arid and non-arid regions of the world. For example, Bell (1969) and Chen (1983) derived IDF formulae for certain regions of the United States. Koutsoyiannis et al. (1998) developed a mathematical framework of IDF curves using an efficient parameterization technique. Empirical functions and generalized IDF equations were developed for monsoon areas in Vietnam (Nhat et al. 2006). For ungauged sites, IDF curves have been updated in the eastern United States using rainfall frequency techniques and iso-pluvial maps (Raiford et al. 2007). El-Sayed (2011) derived a set of regional IDE curves using iso-pluvial maps for ungauged sites in the Sinai Peninsula in the northeastern part of Egypt. In Malaysia, the application of IDF curves is extended to ungauged sites using the records from nearby meteorological stations corrected for bias within the typical range (Liew et al. 2014).

Through a consultancy report (Subyani and Al-Ahmadi 2011), regional maps of probable maximum precipitation are developed to estimate flood frequency for Jabal Sayid in the Al-Madinah region. The empirical formula for the IDF curve was further evaluated by Subyani and Al-Amri (2015) using the 43-year record of daily rainfall from the Al-Madinah station (M001). The Gumbel and Log Pearson Type III distributions were applied to estimate the maximum rainfall depth for the different return periods. This approach is suited to the estimate of discharge for the design of flood control structures.

Due to the lack of rainfall intensity data, the design of most drainage structures is based on incorrect rainfall intensity values. Recent devastations caused by flood in various regions of Saudi Arabia have made it imperative to improve this methodology. In ungauged sites, where there are no records of rainfall intensity or climate variables, it is important to generate satisfactory IDF curves for the design of water projects. The objective of this applied research is to use the rainfall records from three stations in Al-Madinah to estimate rainfall intensity and to generate IDF curves of different duration (10–1440 min) for return periods of 5, 10, 25, 50, 100 and 200 years. The IDF parameters of these stations are used to provide regional interpolation to generate rainfall spatial maps. Finally, the regional IDF formula parameters are generated for ungauged sites to estimate rainfall intensity for various return periods and rainfall durations.

2 Methodology

For accurate analysis of IDF curves of extreme rainfall amounts of fixed duration, it is necessary to find the best fit among some theoretical probability distributions. The development of an IDF curve requires implementation of the following steps:

1. Evaluation, selection and processing of the maximum rainfall events.
2. Development of different PDF distributions to select the best fit to the data series.
3. The distribution of best fit provides a mean to estimate rainfall intensity for a given duration for different return periods.

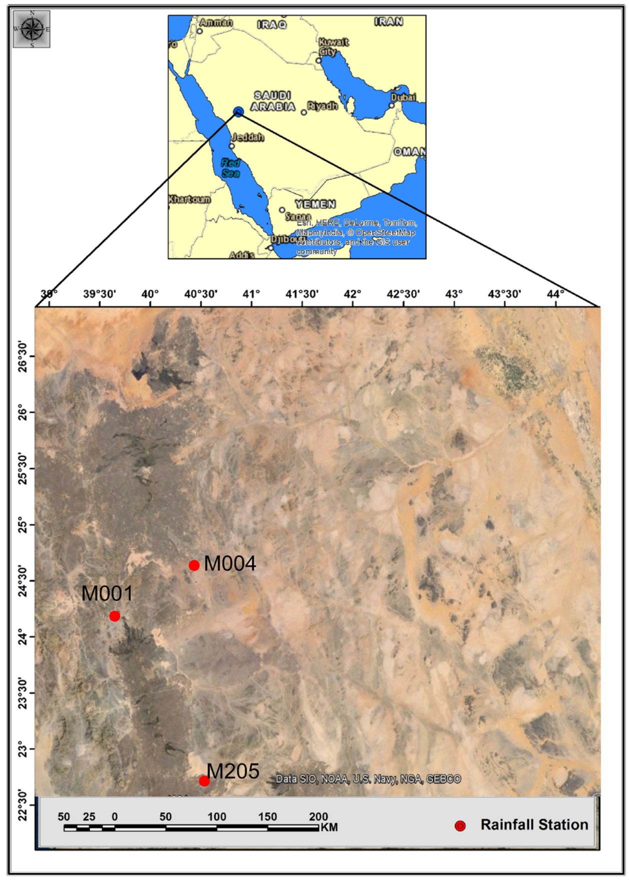


Fig. 1 Location map of the study area

Two common frequency analysis techniques were used in this study to develop the relationship between rainfall intensity and return period (for any duration). The selected distributions are Gumbel and Log Pearson III (Millington et al. 2011).

3 Gumbel Probability Distribution

Gumbel distribution is type I of general extreme value (EVI) with shape parameter equal to zero. This distribution is one of the most widely used in arid regions to estimate the maximum rainfall depth for different return periods. The probability density function (PDF) of this distribution takes the form of:

$$p = 1 - e^{-e^{-y}}. \quad (1)$$

where the symbol p designates the probability of a given value being equal to or exceeding 1 and y is the reduced varieties usually estimated from a statistical table (Subramanya 1994; Aksoy 2000). The rainfall depth for different rainfall durations and frequencies can be estimated by the following equation:

Table 1 Storm rainfall records for Al-Madinah Station (M001)

Date	M10	M20	M30	H1	H2	H3	H6	H12	H24	Storm time (h)
1972	5	8.4	9.8	15.6	16	16	16	16	16	1.1
1973	0.6	0.6	1.4	1.4	1.4	1.4	1.4	1.4	1.4	0.5
1974	4.9	5.7	6.3	7.4	13.2	17.7	22	22.8	22.8	7
1975	1	1.6	2.4	4.2	6.5	6.5	8.6	8.6	8.6	5.8
1976	1.6	2	2.6	3.6	4.4	5	7.4	9.8	9.8	10.1
1977	1.6	2.6	2.6	3	3.6	3.6	3.6	3.6	3.6	1.3
1978	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	0.3
1979	5.6	6.2	8	10.8	14	14.6	16	17.8	17.8	11
1980	0.9	1.5	2.3	2.6	2.6	2.8	2.8	2.8	2.8	2.1
1981	12.4	17	17	17.5	22.8	22.8	26.4	26.4	26.4	4
1982	9.4	11.4	14.8	18.8	33.2	35	49.8	66.8	85.2	17
1983	7.8	12.6	14.8	20.6	24.2	24.2	24.2	24.2	24.2	1.92
1984	3.8	4.2	4.8	6.8	11.2	11.4	11.8	18	18.2	12.33
1985	10.2	10.6	10.6	15.6	15.8	16.4	24.6	27.4	27.4	6.33
1986	5	8.8	10	11.8	11.8	16.2	16.6	16.6	16.6	3.33
1992	8.4	10	11.4	11.8	12.8	12.8	12.8	12.8	12.8	2
1993	5.6	6.8	8	14.6	25.6	33.8	55.2	73.3	89.6	18.5
1994	11.4	14.6	15.2	18	29.4	29.4	29.8	29.8	29.8	3.5
1995	5.6	6.6	6.6	8.4	12.2	12.6	13.8	27.4	27.4	12
1997	1.4	2.2	3	6.2	9	10.4	12.6	12.6	12.6	6
1999	5.2	8.4	8.6	9.8	16.6	17	22.2	35.8	35.8	12
2001	5.2	7.2	8.8	10.6	13.2	13.2	15.4	21.2	23.2	12
Mean	5.4	7.0	7.9	10.2	13.9	14.9	18.1	21.8	23.5	6.8
Median	5.2	6.7	8.0	10.2	13.0	13.9	15.7	17.9	18.0	5.9
Std	3.4	4.4	4.6	5.7	8.5	9.3	13.4	17.8	22.2	
Skew	0.4	0.5	0.4	0.2	0.6	0.7	1.4	1.7	2.2	
CV	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.9	

Table 2 Parameters estimation of Gumbel and LP III distributions for M001

Gumbel dist. Log Pearson III dist									
Duration	σ	μ	K–S test	χ^2 test	α	β	γ	K–S test	χ^2 test
M10	3.42	4.11	0.148	0.686	5.9	−0.36	3.63	0.178	0.645
M20	4.88	5.4	0.096	0.721	5.83	−0.37	3.96	0.094	0.126
M30	4.49	6.2	0.110	0.18	24.43	−0.15	5.71	0.126	0.032
H1	5.3	7.92	0.072	1.15	6.86	−0.28	4.12	0.069	0.230
H2	6.77	9.87	0.089	0.41	4.47	−0.38	4.06	0.106	0.236
H3	7.36	10.46	0.110	0.46	4.29	−0.39	4.12	0.13	1.160
H6	10.67	11.05	0.175	2.06	7.8	−0.31	4.99	0.15	9.67
H12	14.3	13.1	0.130	1.01	5.53	−0.35	5.34	0.11	0.002
H24	17.8	12.8	0.180	3.61	13.07	−0.27	6.34	0.131	0.226

$$P_T = \bar{P} + K_T \sigma_P \quad (2)$$

where P_T represents the rainfall depth (mm) for any rainfall duration and any given return period, $\overline{P}$ and σ_P represent, respectively, the mean rainfall depth (mm) and standard deviation for a given rainfall duration and return period, K_T is the Gumbel frequency factor for a given return period and given standard deviation. K_T is estimated by the following equation (Chow et al. 1988):

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

The K_T values for the different return periods (T_r) 5, 10, 25, 50, 100 and 200 years are estimated from Eq. (3) as $K_5 = 0.72$, $K_{10} = 1.3$, $K_{25} = 2.04$, $K_{50} = 2.59$,

Table 3 Return period rainfall amount (mm) for M001 station using the Gumbel method

Time (years)	M10	M20	M30	H1	H2	H3	H6	H12	H24
5	9.17	12.64	13.43	15.78	19.89	21.35	26.84	34.25	39.14
10	11.68	16.22	17.12	19.68	24.86	26.74	34.67	44.74	52.19
25	14.86	20.75	21.78	24.61	31.13	33.56	44.56	57.98	68.68
50	17.21	24.11	25.24	28.26	35.79	38.62	51.9	67.81	80.92
100	19.55	27.44	28.67	31.89	40.41	43.64	59.18	77.57	93.07
200	21.88	30.76	32.09	35.50	45.01	48.64	66.44	87.29	105.17

Table 4 Return period rainfall rate (mm/h) for M001 station using the Gumbel method

Time (years)	M10	M20	M30	H1	H2	H3	H6	H12	H24
5	55.07	37.92	26.86	15.78	9.95	7.12	4.47	2.85	1.63
10	70.14	48.67	34.24	19.68	12.43	8.91	5.78	3.73	2.17
25	89.17	62.25	43.56	24.61	15.57	11.19	7.43	4.83	2.86
50	103.30	72.32	50.48	28.26	17.89	12.87	8.65	5.65	3.37
100	117.31	82.32	57.35	31.89	20.20	14.55	9.86	6.46	3.88
200	131.28	92.28	64.19	35.50	22.51	16.21	11.07	7.27	4.38

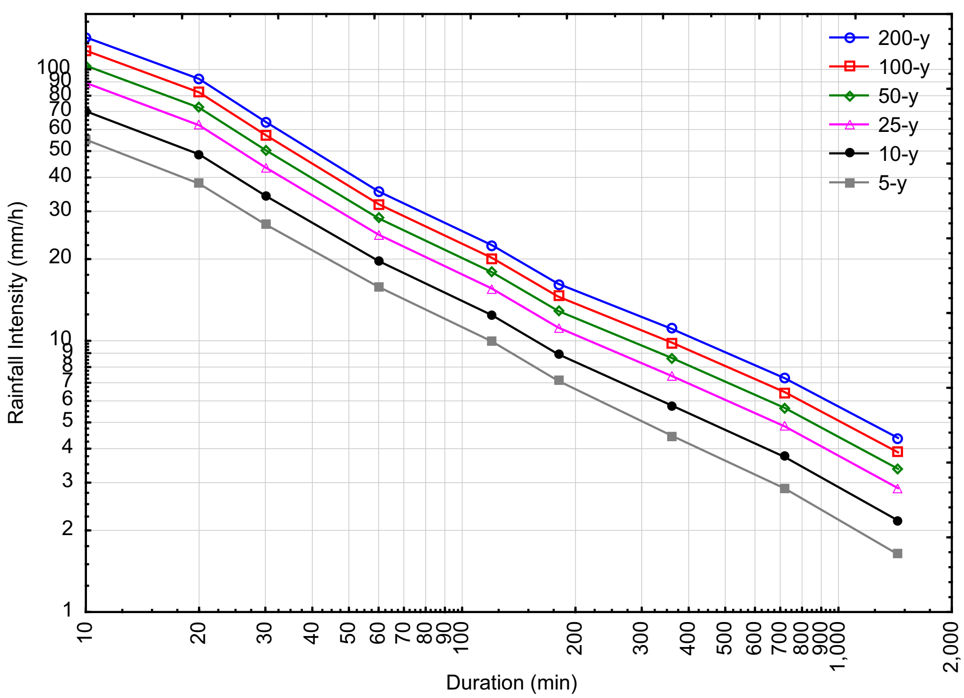


Fig. 2 IDF curves for Al-Madinah station M001 (Gumbel method)

$K_{100} = 3.14$ and $K_{200} = 3.68$. The rainfall intensity I_T (mm/h) for return period T_r is estimated by the following equation

$$I_T = \frac{P_T}{t_d} \quad (4)$$

where t_d is the duration in hours (1/6, 1/3, 1/2, 1, 2, 3, 6, 12, 24 h).

4 Log Pearson Distribution (LP III)

LP III distribution depends on three parameters. It is widely applied due to the fact that its skew parameter allows a better fit to data series where other distributions fail. The graphical ordinate of the distribution is represented by the mean values, the slope of the fitted curve by the standard deviation and the degree of curvature by the skew

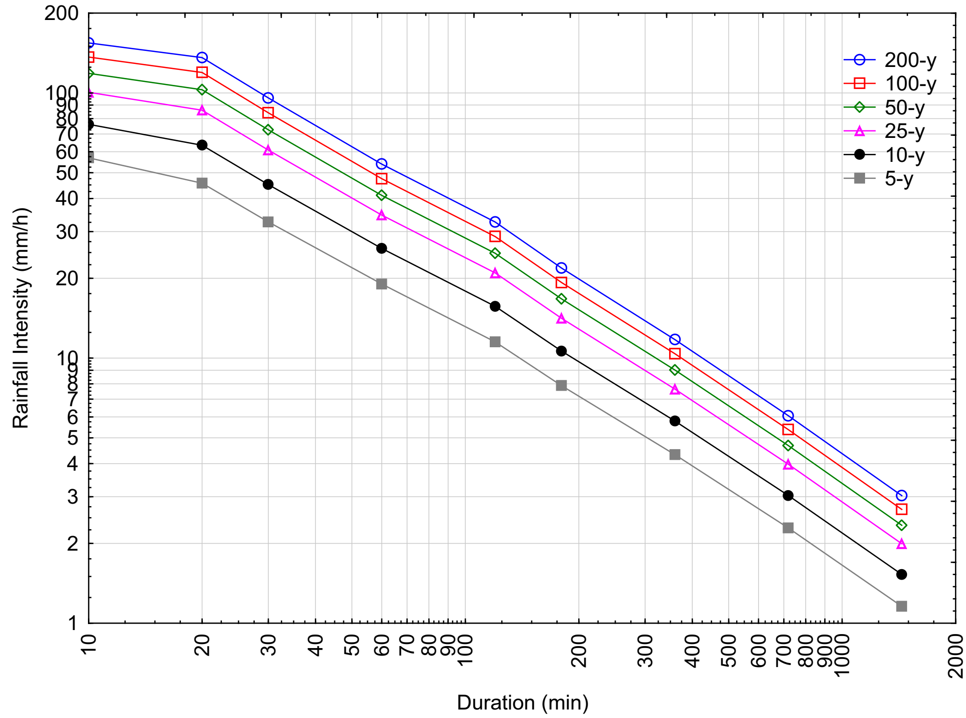


Fig. 3 IDF curves for the Al-Al-Henakyyah station M004 (Gumbel method)

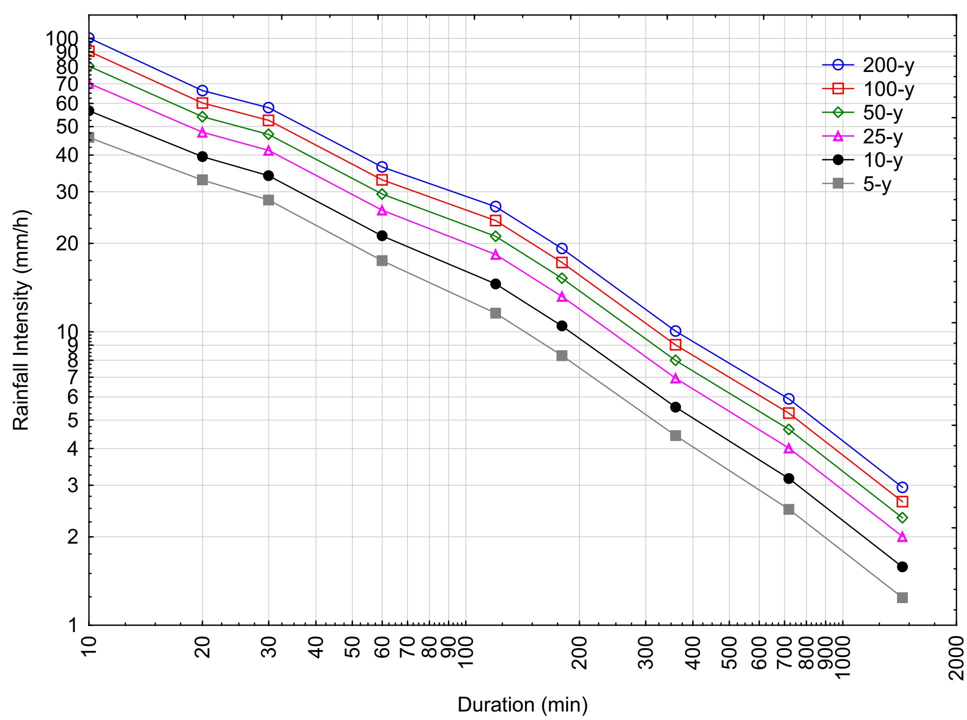


Fig. 4 IDF curves for Safinah station M205 (Gumbel Method)

coefficient. The log transformation of data takes the form (Viessman and Lewis 1996; Saf 2005):

$$\overline{\log x} = \frac{\sum \log x}{n} \quad (5)$$

$$\sigma_{\log x} = \sqrt{\sum \left(\log x - \overline{\log x}\right)^2 / (n-1)} \quad (6)$$

$$G = n \sum \left(\log x - \overline{\log x}\right)^3 / (n-1)(n-2)(\sigma \log x)^3 \quad (7)$$

Table 5 The parameters of the Kimijima equations as IDF curves for three stations

Return period (years)	M001 station			M004 station			M205 station		
	A	*B*	*E*	*A*	*B*	*e*	*A*	*B*	*E*
200	1732.3	0.89	5.26	15046.6	1.26	76.81	712.3	0.69	2.25
100	1519.2	0.89	5.10	12495.3	1.24	71.64	689.6	0.71	2.63
50	1306.2	0.88	4.90	9991.6	1.23	65.31	671.3	0.72	3.15
25	1093.9	0.88	4.66	7575.3	1.21	57.60	658.8	0.74	3.91
10	811.4	0.86	4.22	4524.7	1.16	43.85	666.2	0.79	5.71
5	593.2	0.84	3.72	2419.8	1.09	29.49	709.0	0.84	8.61

The following expression is used for x in any recurrence interval.

$$\log x = \overline{\log x} + k\sigma_{\log x} \quad (8)$$

Assessment of the criteria for the distribution of best fit can be done through the χ^2 and Kolmogorov–Smirnov (K–S) tests in combination with visual evaluation of the graphical representation.

5 Application and results

5.1 IDF curves for Al-Madinah region

The development of the IDF curves was achieved using three records of rainfall intensity for the Al-Madinah region from: the Al-Madinah station (M001), the Al-Al-Henakyyah station (M004) and the Safinah station (M2005) (Fig. 1) with a record length of 22, 14 and 18 years, respectively. The data were made available by the Hydrology Division of the Ministry of Water and Electricity (2015). For example, 22 years of rainfall intensity records are listed for station M001 in Table 1. However, the application of Gumbel and LP III distributions with K–S and χ^2 tests for goodness of fit for station M001 indicates that there is no major difference between them as shown in Table 2. However, as the climate change report (IPCC 2007) indicates that it is more judicious to choose the high-risk scenario and the corresponding numerical value for any design work. Analyses suggest that the Gumbel provides a better fit than the LP III.

The application of Eqs. 2 and 4 to the data from station M001 produced the outcome of the analyses for the generation of IDF curves as shown in Tables 3 and 4 which show the rainfall depths (mm) and rainfall intensities (mm/h), respectively. The information in Table 4 for station M001 is applied to generate the IDF curves on double logarithmic paper and are presented in Fig. 2 for return periods of 5, 10, 25, 50, 100, and 200 years using the Gumbel approach.

Similar calculations are performed on rainfall intensity data from the M004 and M205 stations, where the statistical tests (K–S and χ^2) do not show a significantly big difference between them. The best fit was achieved by the Gumbel PDF. The IDF curves of the Gumbel distribution are presented on double logarithmic paper in Figs. 3 and 4 for M004 and M205, respectively.

Comparison of the IDF curves at the three stations clearly indicates that the most uncertain results are at station M004 with rainfall of 154 mm/h for a 10 min duration and a 200-year return period. This station has the lowest number of recordings (14 events only) and has the highest variation among all stations. In addition, the IDF curves are not parallel to each other as they would be ideally, and, therefore, it is recommended to adapt the IDF curves from this station through further calculation for any future project concerning water-related problems in the region. By taking into consideration the Gumbel PDF based IDF curves, one can design any water structure to protect it against future risk in the ungauged sites depending on the expected life of the construction.

5.2 Empirical IDF Formulation for Ungauged Site

The IDF application is based on empirical equations correlating the maximum rainfall intensity, rainfall duration and frequency of occurrence of a given rainfall event. There are several widely used alternatives for practical hydrology applications. For example, for Jabal Sayid (JS), an ungauged site located southeast of Al-Madinah city, where a record of rainfall intensity is not available; the general form of the Kimijima equation is used to estimate the rainfall intensity to duration relationship (Chow et al. 1988). Three stations with IDF curves are located around the JS area. The typical IDF relationship for a given intensity and specific return period in the special case of the generalized formula from the Kimijima equation can be estimated by the following equation:

$$i = \frac{\mathrm{a}}{d^b + e} \quad (9)$$

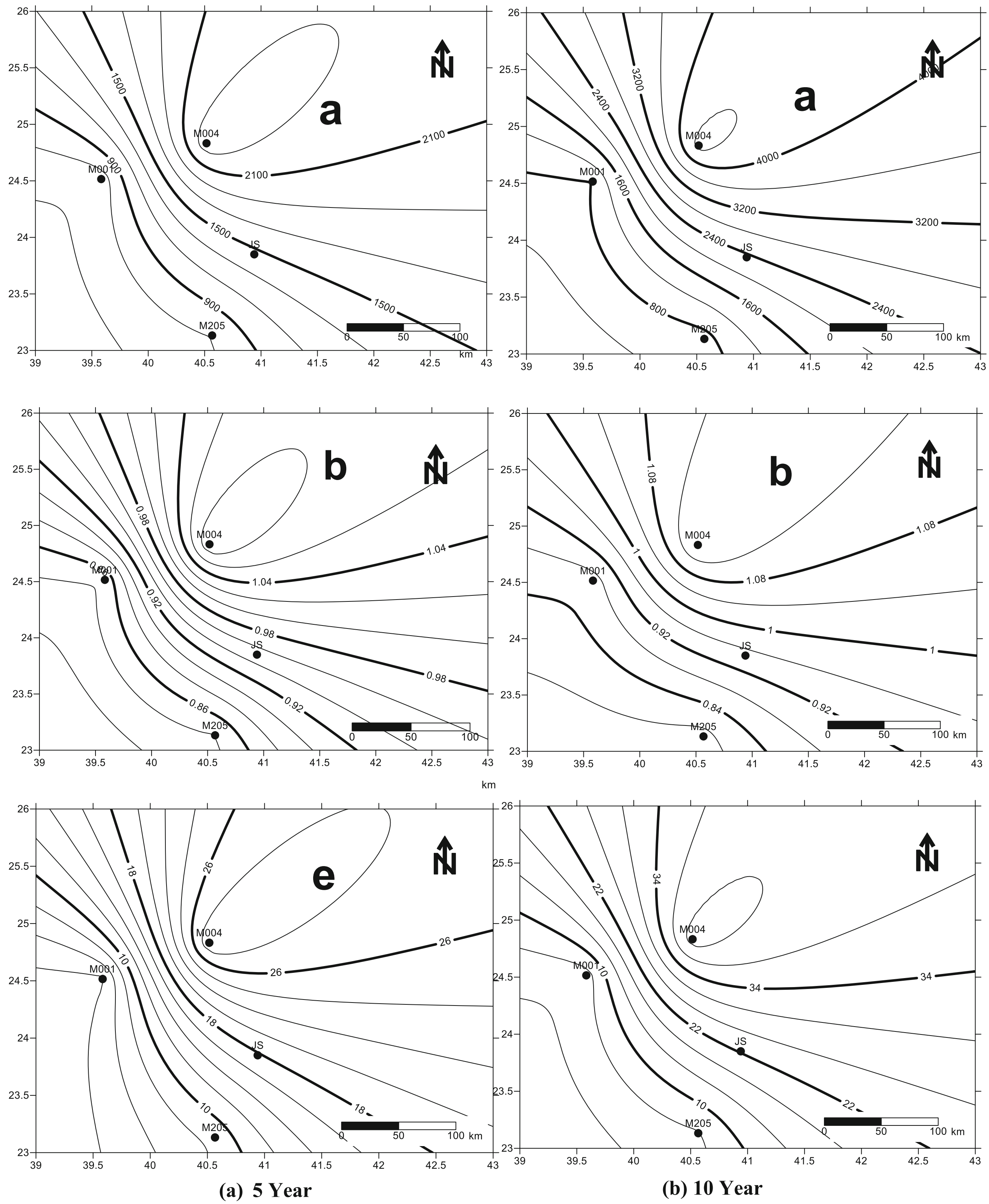
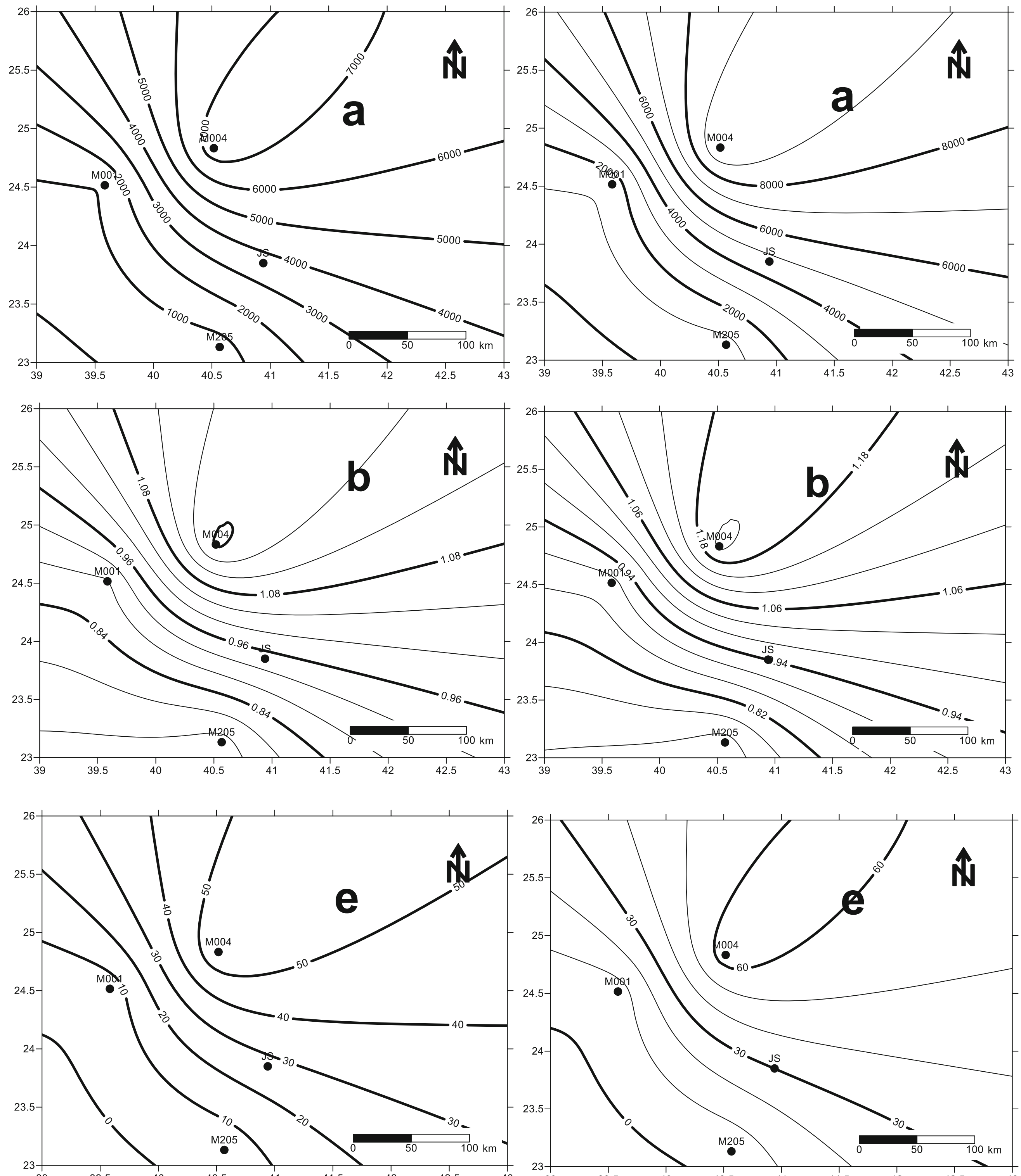


Fig. 5 Parameter spatial distribution contour maps from the Kimijima equation for: **a** 5-year return period, **b** 10-year return period



(a) 25 Year (b) 50 Year

Fig. 6 Parameter spatial distribution contour maps from the Kimijima equation for: **a** 25-year return period, **b** 50-year return period

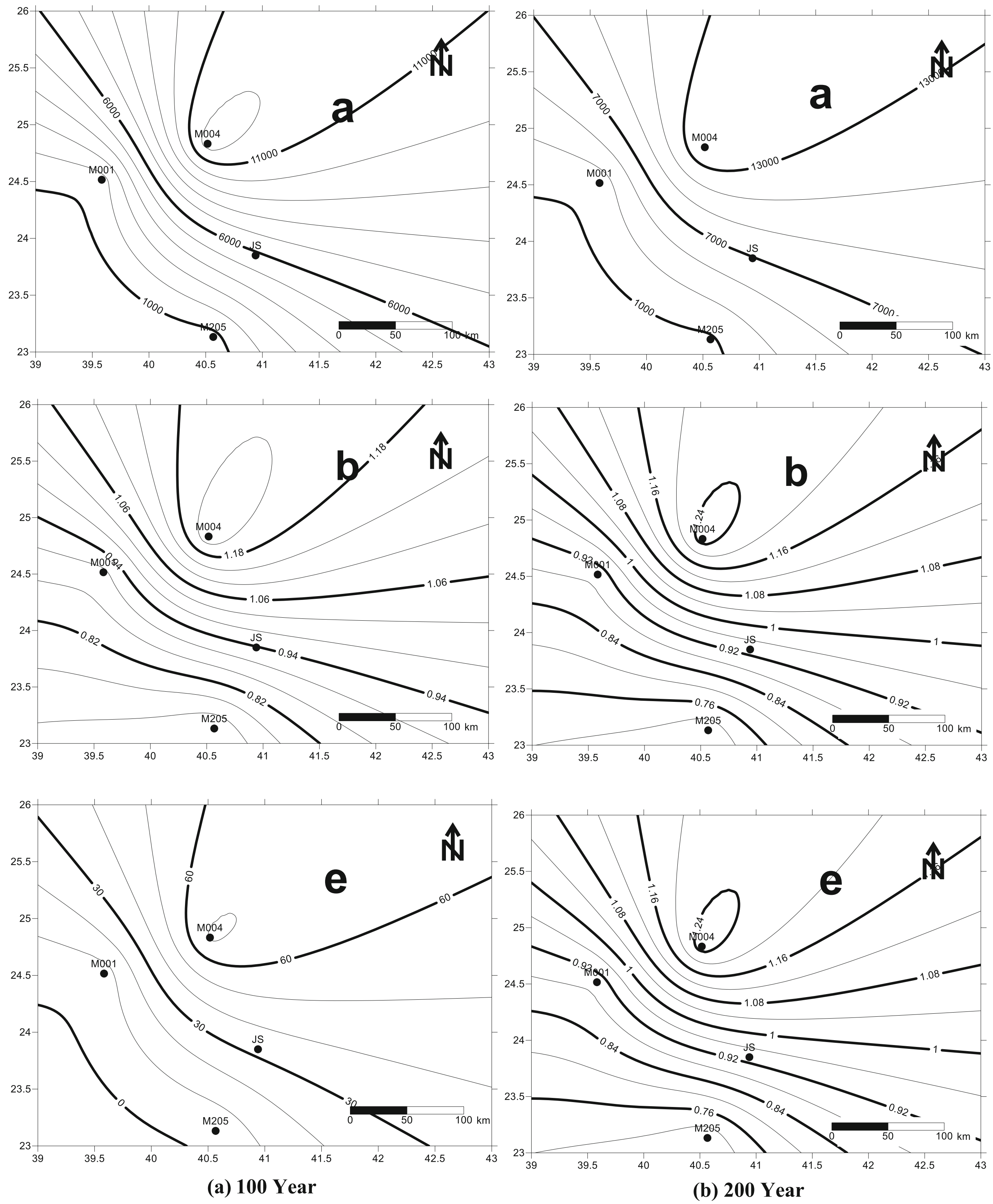


Fig. 7 Parameter spatial distribution contour maps from the Kimijima equation for: **a** 100-year return period, **b** 200-year return period

Table 6 The parameters of JS location using the Kimijima equation

Return period (years)	*A*	*B*	*E*
5	1400	0.95	18
10	2300	0.95	23
25	3650	0.94	27.3
50	4750	0.94	30
100	5800	0.94	33
200	6800	0.93	36

where i represents the design rainfall intensity (mm/h), d is the duration (min), and a, b, and e are coefficients which vary depending on geographic variations and return periods.

The Kimijima parameters for rainfall stations M001, M004 and M205 are presented in Table 5. The IDF parameters of these stations are used to provide regional interpolation to generate spatial distribution maps as shown in Figs. 5, 6 and 7 using the Kriging method of best unbiased linear estimation (Isaaks and Srivastava 1989; Subyani 2004). From these maps, it is easy to find the value of parameters with various return periods for any ungauged location within the region. The IDF curves can be generated using the corresponding parameters for a given return period of rainfall intensities.

Table 6 shows the parameters of the JS location which are estimated from the information presented in Figs. 5, 6 and 7 for different return periods. From the Kimijima equation estimation, the rainfall IDF curves for return periods of 10, 25, 50, 100 and 200 years are presented in Fig. 8 using information from Table 7.

Jabal Sayid site is expected to experience high rainfall intensities with a high return period and high duration compared to other stations. However, the highest elevation point in the JS area at 900 m above sea level and local conditions such as air movement, topographic effects, and the rain type are expected to play a role in rainfall intensity.

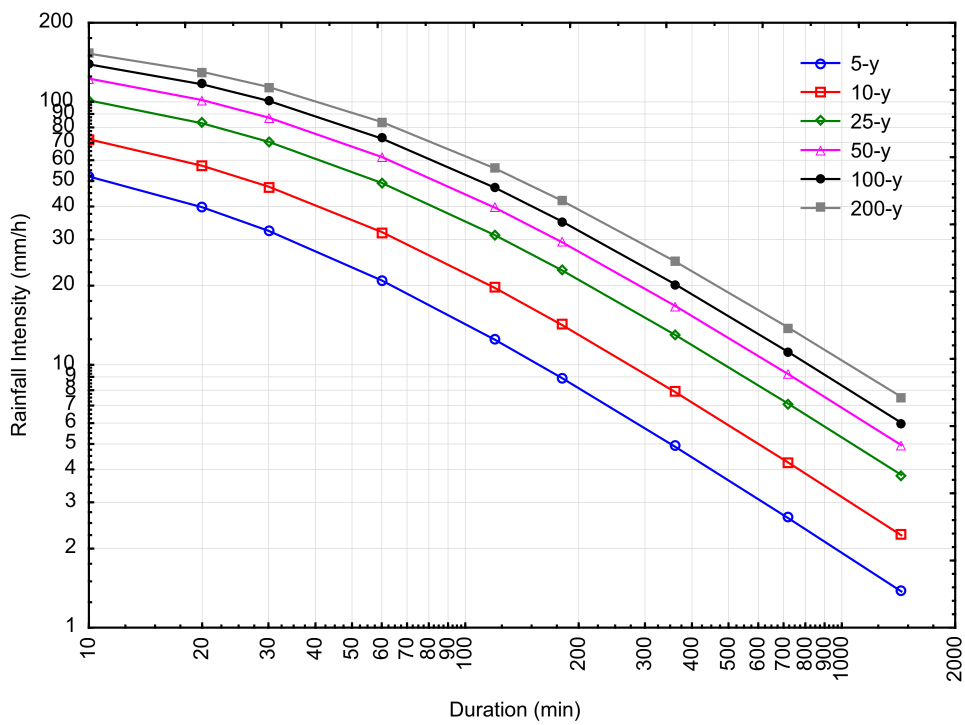


Fig. 8 Rainfall IDF curves for Jabal Sayid

Table 7 Return period rainfall rate (mm/h) for JS (ungauged location) using parameter spatial distribution contour maps

Time (years)	M10	M20	M30	H1	H2	H3	H6	H12	H24
5	52.02	39.75	32.33	20.93	12.45	8.93	4.89	2.61	1.37
10	72.07	57.19	47.61	31.99	19.58	14.21	7.90	4.25	2.25
25	101.36	82.94	70.51	49.17	31.11	22.94	13.03	7.12	3.81
50	122.71	101.69	87.22	61.74	39.57	29.35	16.79	9.22	4.94
100	139.06	116.68	100.94	72.56	47.14	35.19	20.29	11.19	6.02
200	152.77	130.23	114.01	83.90	55.82	42.20	24.78	13.87	7.54

Therefore, it is recommended to presume a possible increase in rainfall depth and intensity for the design of water structures, land use and drainage basin management and operation.

6 Conclusions

Intensity–duration–frequency (IDF) curves are basic information resources for hydrologists and engineers involved in water project design. Historical records of rainfall intensity are produced from three main meteorological stations in the Al-Madinah region (M001, M004 and M205) using the best probability distribution function approaches. On the basis of the PDF results, relevant IDF curves of different durations 10, 20, 30, 60, 120 180, 720 and 1440 min are derived with the corresponding return periods 5, 10, 25, 50, 100 and 200 years. The Kimijima parameters for the M001, M004 and M205 stations are used to arrive at a regional interpolation needed to generate spatial distribution maps. The information from spatial distribution maps is used to estimate the IDF curve parameters at ungauged locations (e.g., Jabal Sayid) to estimate rainfall intensity for various return periods and rainfall durations. This study can be applied to ungauged locations within the study area for any water resource project design. Additionally, one can observe that the duration of intense rainfall is approximately 1–3 h, which is the most critical time for possible flood magnitude calculations. This approach can be applied to other arid regions and recommended under certain circumstances such as homogeneity of rainfall intensity data record and topographic and geographic features of the stations. However, this research makes a significant contribution to arid areas, which suffer from the lack of rainfall intensity records, important information to design suitable water projects, especially with the prevailing state of climate variability. However, the use of climate model data for the long-term design of water projects under different scenarios needs to be explored further.

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