



Rainfall Intensity–Duration–Frequency (IDF) Curves: Effects of Uncertainty on Flood Protection and Runoff Quantification in Southwestern Saudi Arabia

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Abstract

Southwestern Saudi Arabia experiences occasional flash floods, possibly due to an inadequate understanding of rainfall and runoff and a lack of infrastructure. Several studies have investigated rainfall intensity, duration, and runoff, while the infrastructure is not adequate to avoid floods. One possibility for the lack of adequate infrastructure might be the limitations in handling rainfall data. In this study, rainfall intensity–duration–frequency (IDF) curves were developed using the Gumbel distribution for five areas (Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait) in southwestern Saudi Arabia. Four methods of calculating depth–duration relationships were applied. The 25-year daily maximum rainfall data were converted into hourly and sub-hourly data using these methods. The methods showed considerable variability in the IDF relationships, which may influence the essential protective measures against floods and runoff collection. The log-Pearson Type III (LPT III) distribution and RainyDay were also used to develop the 24-h IDF curves. The results show that Gumbel and LPT III can be used in regions with a lack of sub-daily rainfall data, while RainyDay can be used with caution in regions with no rainfall data. This study observed significant variability in the storage capacity requirements in different areas. The effects of methodological variability can be minimized by long-term monitoring of data, calibrating the methods using these data, and constructing watersheds to store the wide ranges of runoff. The areas showed significant differences in IDF curves, emphasizing the need for studying smaller areas rather than the entire region. A better understanding of the variability in IDF relationships may assist in controlling flash floods and maximizing runoff storage.

Keywords IDF curve · Rainfall depth–duration conversion · The southwestern region of Saudi Arabia · Flash floods · Methodological limitations

1 Introduction

The Kingdom of Saudi Arabia has low average annual rainfall with a few extreme precipitation events per year, which are occasionally responsible for the loss of lives and properties. The intense rainfall in 2009, 2011, and 2013 created flash floods, which were responsible for the death of 100, 10, and 7 people, respectively, in the southwestern region of the country [1–3]. In Saudi Arabia, the source of surface water is seasonal rainfall. In the northern region, annual

rainfall varies between 70 and 200 mm (long-term average = 70.1 mm/year), while in the south, 500 mm/year of rainfall (long-term average = 265 mm/year) is not unlikely [4].

In 2012, a total of 449 dams collected and recharged approximately 2.02 billion cubic meters (BCM) of runoff [5], which is a significant increase from 2009's collection of 1.4 BCM of runoff using 302 dams [6]. Despite the increase in collected runoff, the occurrences of flash floods and excess runoff almost every year indicate the vulnerability of the southwestern region. Understanding the rainfall–runoff relationship may assist in strategic planning to reduce such vulnerability and maximize runoff collection. The southwestern region is mostly mountainous and is likely to generate surface runoff within a few minutes to a few hours [7, 8] after rainfall. Research to date has indicated the need for water resource augmentation through rainwater collection

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and conservation as a partial solution to the water crisis problem [6, 9]. Runoff collection and rainwater harvesting in semiarid and arid countries were reported to be economically feasible [10–12].

Intensity–duration–frequency (IDF) relationships have first become available in 1932 [13]. Hershfield [14] developed rainfall contour maps to determine rainfall design depths for various return periods and durations. Bell [15] proposed a generalized IDF formula using the 1-h, 10-year rainfall depths, P_1^{10} , as an index. Chen [16] developed a generalized IDF formula for the USA using three base rainfall depths: the 1-h, 10-year rainfall depths, P_1^{10} ; the 24-h, 10-year rainfall depths, P_{24}^{10} ; and the 1-h, 100-year rainfall depths, P_1^{100} . Kothiyari and Garde [17] presented a relationship between rainfall intensity and the 24-h, 2-year rainfall depths, P_{24}^2 , for India. Using depth–duration–frequency (DDF) relationships, Al-Shaikh [18] recommended dividing Saudi Arabia into six regions to analyze rainfall data, with the southwestern region playing the most important role in the context of flood protection and runoff collection [4]. Al-Dokhayel [19] estimated rainfall DDF relationships for various return periods in Qassim, Saudi Arabia. Elsebaie [20] developed IDF relationships for Najran and Hafr Al-Batin in Saudi Arabia. They applied the Gumbel and log-Pearson Type III (LPT III) distributions. Ewea [21] developed IDF curves for the Makkah Al Mukarramah region and found that the optimal distribution for the Makkah region is the Gumbel Type I distribution. Al-Hassoun [22] presented an IDF relationship for Riyadh, Saudi Arabia, and noted a similarity between the Gumbel and LPT III methods. Such a similarity might be attributed to the consistently low rainfall in the Riyadh region. Awadallah et al. [23] presented a methodology for developing an IDF relationship through the joint use of limited ground data and Tropical Rainfall Measuring Mission (TRMM) satellite data. A methodology for obtaining the ratio between daily and sub-hourly rainfall was developed. Al-Subyani et al. [24] investigated the effects of topography, seasonal variability, and aridity on rainfall variability in the western region of Saudi Arabia.

Al-Zahrani et al. [9] investigated the spatiotemporal variability in rainfall in this region and the generation of surface runoff under a variable set of coefficients. Ewea et al. [25] developed IDF curves for Saudi Arabia based on measured rainfall in 28 meteorological stations and storm durations ranging from 10 min to 24 h. Abdeen et al. [26] investigated the distribution of the maximum daily rainfall in Saudi Arabia and concluded that the best model was the log-Pearson Type III distribution. Zainudini et al. [27] developed an IDF relationship using the ground station data from Sistan and Balochistan covering the borders of Iran, Pakistan, Afghanistan, and Oman. Jaleel and Farawn [28] developed an IDF curve for Basrah city, Iraq. The authors derived the sub-hourly data from the daily data using the

Indian Meteorological Department (IMD) method [29]. Nhat et al. [30] developed IDF curves for seven stations in the monsoon area of Vietnam and proposed a generalized IDF formula using the base rainfall depth and base return period for the Red River Delta of Vietnam. Solaiman and Simonovic [31] developed probability-based IDF curves under climate change conditions for London, Ontario, Canada. Agarwal and Suchithra [32] used log-normal, normal, and Gumbel (EV-I) distributions to develop IDF curves for Krishna District, India.

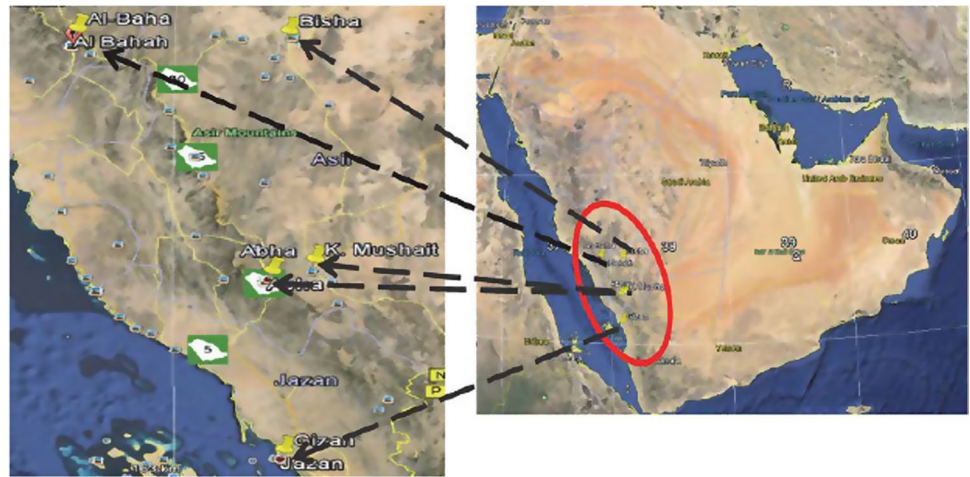
The availability of IDF relationships is important to better plan for flash floods and runoff collection. The literature on the development of IDF curves for various regions using different approaches is abundant. However, IDF curves were reported only for a few cities in the southwestern region of Saudi Arabia, and a comprehensive representation of this region using IDF relationships is scarce [20, 33]. Furthermore, the topography of the region is variable, so the region needs to be divided into smaller areas for a better estimation of IDF relationships. Since rainfall data are available on a daily basis and sub-hourly data are required to develop IDF relationships, several approaches are taken to obtain sub-hourly data from daily data. In this study, five areas with relatively high rainfall (Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait) were selected from the southwestern region of Saudi Arabia. The 25-year daily maximum rainfall data were converted into hourly and sub-hourly data using four methods. IDF curves were developed for each area using these methods, and the results were compared. The parameters for the IDF curves were estimated. The ranges of storage capacities to minimize flood occurrences were assessed. The advantages of IDF curves and their methodological limitations were discussed.

2 Methodology

2.1 Data Collection and Study Area

The southwestern region of Saudi Arabia is mountainous, with elevations of up to 2000 m above the mean sea level. The region is located within the subtropical climate zone and receives the highest rainfall in the country [4, 34]. It is under the influence of a relatively moist southeasterly stream of monsoon air [34]. The periods of March–May and July–August are the main rainy seasons, due to an increase in rainfall along the leeward side of the mountains and the Red Sea Coast. The location of the study areas is shown in Fig. 1. The study region is divided into five areas: Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait, which are covered by rain gauges of the Ministry of Water and Electricity (MOWE). In this study, the daily rainfall data for 25 years

Fig. 1 Study area (southwestern region of Saudi Arabia)



(1985–2009) were obtained from MOWE. A detailed summary of the data is available in Al-Zahrani et al. [9].

2.2 Rainfall Depth–Duration Relationship

In developing the IDF curves, it is necessary to obtain the maximum rainfall for specific durations (e.g., 5, 10, 15, 20, 30 min) in each year of the historical dataset. However, obtaining such data for a longer period is difficult, particularly in areas with low rainfall, scattered shower events, and mountainous topography. Accurate estimation is challenging particularly in areas with sparse observations and regions with complex terrain [35], such as the southwestern region of Saudi Arabia. Although measuring precipitation by rain gauges provides the most accurate data, there are limitations associated with the spatial and temporal resolution [36]. As a result, several researchers have become interested in using indirect remotely sensed estimate (RSE) data, such as radar and satellite data, as they provide fine-scale information [37–41]. Al-Areeq et al. [42] developed a method that can be used to adjust global precipitation measurements (GPM) based on daily rain gauge observations to obtain highly accurate spatial and temporal rainfall data, which can be used as a substitute for the lack of data. Past studies have used several approaches to obtain sub-hourly data from daily and hourly rainfall data, and the rainfall depth-to-duration ratio can be obtained using several methods:

2.2.1 Method 1

In the USA, Hershfield [14] recommended using the following ratios of the 1-h rainfall to the rainfall of 5, 10, 15, and 30 min for the same return period: 0.29, 0.45, 0.57, and 0.79, respectively. Using 15 years of data from 15 stations covering South Africa, Reich [43] found similar ratios between the 1-h rainfall and the 5-, 10-, 15-, and 30-min rainfall. The author hypothesized that the ratios of Hershfield [14] might

be applicable to the whole world. However, in an Australian study, Al-Khalaf [44] reported ratios of 0.3, 0.57, 0.78, and 1.24 for 5, 15, 30, and 120 min of rainfall, respectively, while Saad [45] reported similar ratios using rainfall data from 40 continuous rainfall recorders in Jordan. The World Meteorological Organization (WMO) provided similar ratios to those of Hershfield [14] to obtain the sub-hourly rainfall depth from the hourly rainfall depth [46]. In Canada, Solaiman and Simonovic [31] used these ratios in developing probability-based IDF curves under variable climatic conditions.

The Indian Meteorological Department (IMD) developed the following relationship between the daily rainfall data and the hourly rainfall data:

$$P_t = P_{24} (t/24)^{1/3} \quad (1)$$

where P_t = estimated precipitation depth (mm) for the duration of t hours, P_{24} = daily precipitation depth (mm), and t = time duration (h) for which the precipitation depth is required (e.g., 1, 2, 4, 6, 12 h).

Using Eq. (1), the rainfall depth can be obtained for 1 h from the daily rainfall data. The sub-hourly rainfall depth can be estimated using the abovementioned Hershfield ratios. If the rainfall occurs in thunderstorms, the duration is likely to be much lower. The southwestern region of Saudi Arabia is mountainous, and rainfall is often accompanied by thunderstorms, lasting for 1/2 h to less than 2 h [20, 34]. In such a scenario, the ratio between 1-h and 24-h rainfall typically varies in the range of 0.5–0.6 [45]. As an example, evidence of Sanaa, Yemen, can be provided [45]. In 1972–1974, the hourly maximum rainfall depths around Sanaa (Yemen) were 39, 27, and 16 mm in Dhahran, Mind, and Dhab, respectively. However, the maximum daily rainfall depth for the past 30 years was reported to be 65 mm, with a ratio of the hourly maximum to the daily maximum of approximately 0.6 [45]. Since Eq. (1) was developed for wet regions, it was

not used in this study to avoid high uncertainty. Also, Eq. (1) gives a ratio between 1-h and 24-h rainfall of around 0.35, which is much lower than the values reported in Wheater et al. [47], Saad [45], and Al-Khalaf [44] and lower than the value that we found (0.65) when we analyzed the 7-year sub-daily rainfall data for one station located in Dhamar, Yemen. Therefore, the ratios of Hershfield [14] were used to obtain the sub-hourly depths, and a ratio between 1-h and 24-h rainfall of 0.6 was used to determine the hourly rainfall depth. Since the ratios proposed by Hershfield were used to obtain the sub-hourly rainfall depth from the hourly rainfall depth, the lack of hourly rainfall data for the study area might have affected the performance of this method.

2.2.2 Method 2

Wheater et al. [47] provided ratios for shorter durations using the daily rainfall data in the southwestern region of Saudi Arabia. The rainfall data were mainly from short-duration storm events in a day [20, 34]. Wheater et al. [47] recommended using the following ratios of the 1-day rainfall to the rainfall of 10 min, 30 min, 1 h, 2 h, and 6 h: 0.33, 0.56, 0.68, 0.79, and 0.92, respectively. This method analyzed the historical rainfall patterns in this region and thus might be more representative.

2.2.3 Method 3

Al-Khalaf [44] developed rainfall depth–duration relationships for eight regions of Saudi Arabia. For the southwestern region, the following relationship was obtained:

$$\frac{P_T^t}{P_T^{60}} = 0.1935 t^{0.3904} \quad (2)$$

where P_T^t = rainfall depth for duration t (minutes) with return period T (years), P_T^{60} = rainfall depth for 60 min with return period T , and t = required duration in minutes for rainfall depth. Using Eq. (2), rainfall depth-to-duration ratios were obtained.

The developed relationships were not used by other researchers to investigate the relationships' uncertainty, perhaps because the relationships were not published in a journal paper.

2.2.4 Method 4

Bell [15] developed ratios of the rainfall depths of any short duration to the rainfall depth of 24 h. The ratios from Bell [15] are much lower than those from Wheater et al. [47], with the data from the latter study representing the historical rainfall in the southwestern region of Saudi Arabia. Al-Khalaf [44] noted that the ratios of Bell [15] might not be representative of the conditions in the southwestern region of Saudi Arabia. The ratios of the four methods are shown in Table 1.

2.3 IDF Curve Development

2.3.1 Gumbel Distribution

The IDF curves can be developed using frequency analysis. The extreme value Type I (Gumbel) distribution is widely used in developing IDF curves. Elsebaie [20] used the Gumbel and LPT III distributions to develop IDF curves for two cities in Saudi Arabia. This study did not find a significant difference between the Gumbel and the LPT III distribution. The extreme value distribution is recommended as the best one for fitting the series of annual rainfall maxima [48]. Several studies around the world have recommended using the Gumbel distribution to develop IDF curves [28, 31, 49, 50]. If the annual maxima are available for 20 years or more, the Gumbel distribution has been recommended in many past studies [51]. In the absence of data, the Gumbel distribution can be used to reach a higher level of safety by obtaining higher intensities for shorter durations [48]. This method calculates the rainfall with return periods of 2, 5, 10, 25, 50, and 100 years. The rainfall depth for any duration (e.g., 5, 10, 30 min) with a specific return period can be obtained as follows:

$$P_T = P_{\text{avg}} + K_T S \quad (3)$$

$$S = \left[\frac{1}{n-1} \sum_{i=1}^n (P_i - P_{\text{avg}})^2 \right]^{1/2} \quad (4)$$

$$K_T = -\frac{\sqrt{6}}{\pi} \left[0.5772 + \ln \left[\ln \left[\frac{T}{T-1} \right] \right] \right] \quad (5)$$

Table 1 Rainfall ratios for shorter durations

Duration (D _i)	5 min	10 min	15 min	20 min	30 min	1 h	2 h	6 h	1 day	Ratio base
Hershfield (1961)	0.29	0.45	0.57	–	0.79	1	–	–	–	Shorter duration to 1 h
Wheater et al. (1989)	–	0.33	–	–	0.56	0.68	0.79	0.92	1	Shorter duration to 1 day
Al-Khalaf (1997)	0.36	0.48	0.56	–	0.73	1	–	–	–	Shorter duration to 1 h
Bell (1969)	0.13	0.2	–	0.28	0.34	0.44	0.57	0.75	1	Shorter duration to 1 day



where P_T = frequency of rainfall for any duration with a return period of T years (mm), P_{avg} = average of rainfall data corresponding to that duration (mm), S = standard deviation of the data series (mm), K_T = Gumbel frequency factor, P_i = rainfall value for this duration in the i th year (mm), and T = return period (years).

Using the four methods of obtaining rainfall depth-to-duration ratios, the annual maxima for different durations (e.g., 5, 10, 15, 30 min) were calculated from the yearly maximum daily rainfall data (Table 2). The average, standard deviation, and frequency factor for return periods of 2, 5, 10, 25, 50, and 100 years were calculated (Eqs. 4–5) for each duration (e.g., 5, 10., 15, 30 min). Using these values in Eq. (3), the frequency of rainfall depth (P_T) was predicted. The rainfall depth frequencies (P_T) were divided by the corresponding durations to obtain the rainfall intensities. The rainfall intensities for different durations with return periods of 2, 5, 10, 25, 50, and 100 years were plotted against the rainfall durations to obtain the IDF curves.

Table 2 The original data on daily maximum rainfall for 25 years in the southwestern region of Saudi Arabia (mm)

Rank	Abha	Al-Baha	Bisha	Gizan	Khamis Mushait
1	119.9	129.3	39.5	90	99.2
2	106.2	63.5	35.9	67.2	59.7
3	88.6	56.3	34.5	67.1	56.3
4	61.1	50.1	33	66	44
5	56	49.2	31.9	61.6	40.7
6	55.9	46.8	31.8	60.1	40
7	48.1	46.8	31.7	50	39.5
8	45.5	40	31.5	48	39.1
9	41.5	32	29.8	47	37.1
10	40.9	30.5	28.7	43	36
11	39.1	28.9	27.2	42.3	33.2
12	35.7	27	22.3	40.2	29.6
13	34.9	27	21.5	38	28.5
14	32.2	27	18.8	36	28.3
15	31	26.2	17.5	31.6	27.2
16	28.6	25.7	16	30	26.2
17	28.5	23.6	15.8	29.2	25
18	24.4	23	13.7	29	22.7
19	24.1	20.5	12.9	26.2	21.8
20	24	15.7	12.7	25	20.9
21	23	12.4	12.6	23.5	20.2
22	17.5	10.4	12.2	19.1	18.4
23	17	10	10.2	17	18
24	16.4	10	10.1	15	13.9
25	10	5.2	8.7	14	7.2

2.3.2 Log-Pearson Type III (LPT III) Distribution

The daily maximum rainfall for the southwestern region of Saudi Arabia is shown in Table 2. These data were used to estimate the frequency of the daily rainfall over the catchment using the log-Pearson Type III distribution (LPT III) [52]. Nhat et al. [30] used the LPT III distribution to develop an IDF curve for Vietnam. Computing the logarithms of the data is required for the LPT III distribution, and then the mean, skewness coefficient (K), and standard deviation of these logarithms can be estimated. The K coefficients were estimated for different return periods based on the K coefficient that was used. The values of the K coefficient were used together with the standard deviations and means to estimate the rainfall frequency values.

2.3.3 RainyDay

RainyDay [53] is a Python-based platform that uses the stochastic storm transposition (SST) method with rainfall remote sensing data to generate large numbers of realistic extreme rainfall scenarios based on relatively short records by transposing observed historical storm events over any given watershed. Accordingly, the extreme rainfall statistics for a specific region can be examined to develop a hazard model by using these rainfall scenarios. Wright et al. [54] mentioned that the SST method, which effectively lengthens the extreme rainfall record by temporal resampling and spatial transposition of observed rainstorms, is simply trading space with time.

2.4 IDF Equation Development

The IDF equations represent the relationships among rainfall intensity, duration, and return period. The IDF equation can be presented as

$$I = \frac{CT^m}{t^n} \tag{6}$$

where I = rainfall intensity (mm/h); T = return period (years); t = rainfall duration (minutes); and C , m , and n are parameters. Using the logarithmic function, Eq. (6) can be expressed as

$$\log I = \log (CT^m) - n \log t \tag{7}$$

For a particular return period (T), $CT^m = (K)$ is constant. The $\log (I)$ versus $\log (t)$ plot for a specific return period results in a straight line for Eq. (7), from which the value of n (slope) and the intercept ($\log (K)$) are obtained. For each return period, the values of $\log (K)$ and n are obtained. The average of the values of n represents the

parameter n , while the intercepts ($\log(K)$) can be represented as

$$\log K = \log(C) + m \log T \tag{8}$$

The $\log(K)$ versus $\log(T)$ plot results in a straight line, from which the values of the intercept ($\log(C)$) and the slope (m) are obtained. The values of C , m , and n are substituted in Eq. (6) to obtain the IDF equations. Further details on determining the parameters of the IDF curves can be found in the literature [20, 33, 48].

3 Results and Discussion

3.1 IDF Curves

The IDF curves were developed for five areas (Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait) in the southwestern region of Saudi Arabia using the Gumbel distribution, the LPT III distribution, and RainyDay.

3.1.1 Gumbel Distribution

Four methods for obtaining the rainfall depth–duration relationships and the Gumbel frequency factor were used. The IDF curves for Abha are presented in Fig. 2, while the IDF curves for the other areas are discussed when the different return periods are compared. For all methods, the log–log plots of the IDF curves showed a nearly perfect linear relationship (Fig. 2). In the Abha region, Al-Anazi and Elsebaie [33] also presented such a relationship in the log–log plot of IDF curves using the Gumbel method.

In Abha, the rainfall intensity for a duration of 10 min with a return period of 2 years varies in the range of 45.5–75.0 mm/h. For the same duration with a return period of 50 years, the rainfall varies in the range of 152.1–250.9 mm/h, while for a return period of 100 years, the rainfall varies in the range of 173.2–285.7 mm/h (Fig. 2). The minimum and maximum rainfall intensities corresponding to the different rainfall durations are presented in Table 3. In these areas, the rainfall intensities for a duration of 10 min with return periods of 50 and 100 years vary in the ranges of 62.9–259.9 and 70.4–285.7 mm/h, respectively (Table 3), indicating that the application of a single IDF curve to the entire southwestern region may not be representative. It is advisable to understand the rainfall characteristics in each

Fig. 2 IDF curves for Abha with return periods of 2, 5, 10, 25, 50, and 100 years using Gumbel frequency distributions

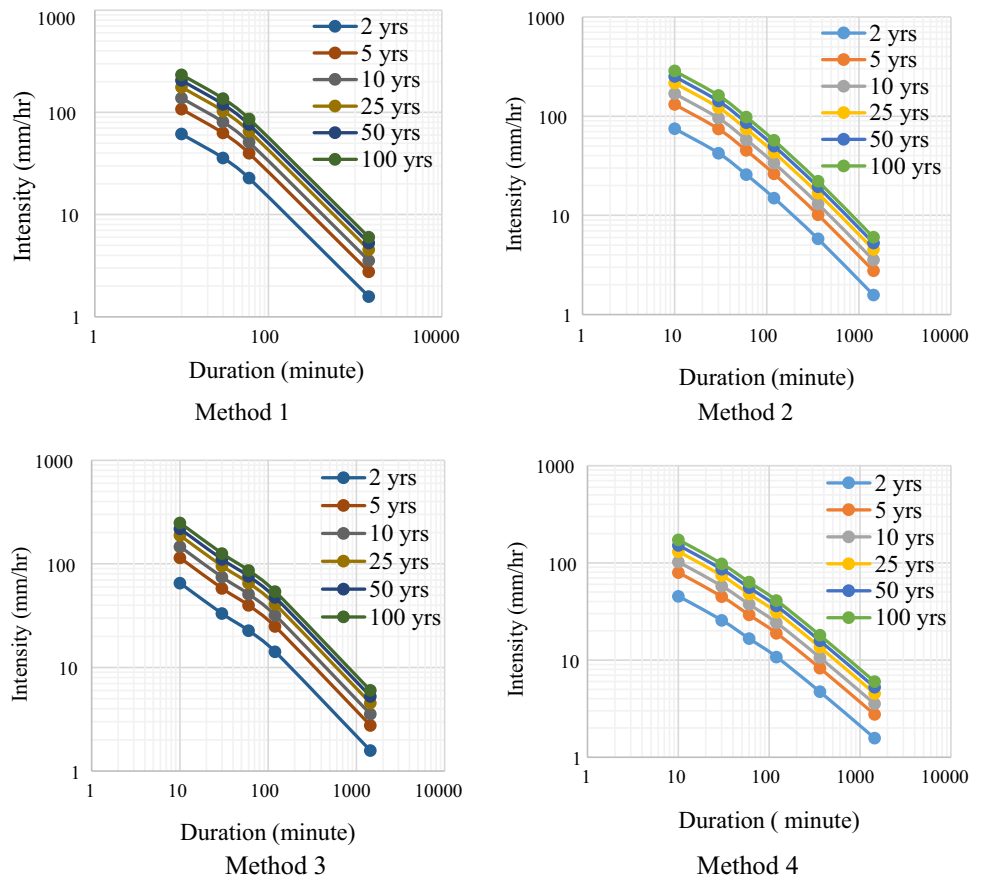


Table 3 Minimum and maximum rainfall intensities (mm/h) for specific durations at different return periods

T_r	T_d	2 yrs		5 yrs		10 yrs		25 yrs		50 yrs		100 yrs	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Abha	10	45.5	75.0	79.6	131.4	102.3	168.8	130.9	215.9	152.1	250.9	173.2	285.7
	30	25.8	42.4	45.1	74.3	58.0	95.5	74.2	122.2	86.2	142.0	98.1	161.6
	60	16.7	25.8	29.2	45.1	37.5	58.0	48.0	74.2	55.8	86.2	63.5	98.1
	120	10.8	15.0	18.9	26.2	24.3	33.7	31.1	43.1	36.1	50.1	41.1	57.0
Al-Baha	10	35.6	58.8	67.1	110.8	88.0	145.2	114.4	188.8	134.0	221.1	153.4	253.1
	30	20.2	33.2	38.1	62.7	49.9	82.2	64.8	106.8	75.9	125.0	86.9	143.2
	60	13.1	20.2	24.6	38.1	32.3	49.9	42.0	64.8	49.1	75.9	56.2	86.9
	120	8.5	11.7	16.0	22.1	20.9	29.0	27.2	37.7	31.8	44.1	36.4	50.5
Bisha	10	25.2	41.5	37.3	61.5	45.3	74.7	55.4	91.5	62.9	103.9	70.4	116.2
	30	14.3	23.5	21.1	34.8	25.7	42.3	31.4	51.7	35.7	58.8	39.9	65.7
	60	9.2	14.3	13.7	21.1	16.6	25.7	20.3	31.4	23.1	35.7	25.8	39.9
	120	6.0	8.3	8.9	12.3	10.8	14.9	13.2	18.2	15.0	20.7	16.7	23.2
Gizan	10	45.3	74.7	69.5	114.8	85.6	141.3	106.0	174.8	121.0	199.7	136.0	224.4
	30	25.6	42.2	39.4	64.9	48.5	79.9	60.0	98.9	68.6	113.0	77.1	126.9
	60	16.6	25.6	25.5	39.4	31.4	48.5	38.9	60.0	44.4	68.6	49.9	77.1
	120	10.8	14.9	16.5	22.9	20.3	28.2	25.2	34.9	28.7	39.8	32.3	44.8
Khamis Mushait	10	36.6	60.5	59.6	98.4	74.9	123.5	94.1	155.3	108.4	178.8	122.6	202.2
	30	20.8	34.2	33.8	55.7	42.4	69.9	53.3	87.8	61.4	101.2	69.5	114.4
	60	13.4	20.8	21.9	33.8	27.5	42.4	34.5	53.3	39.7	61.4	44.9	69.5
	120	8.7	12.1	14.2	19.6	17.8	24.6	22.4	31.0	25.7	35.7	29.1	40.3

T_r : return period (year); T_d : Rainfall duration (minute); Min: Minimum (mm); Max: Maximum.

Table 4 Maximum daily rainfall(mm) for different return periods using the Gumbel distribution

Tr	Abha	Al-Baha	Bisha	Gizan	Khamis Mushait
2	37.9	29.7	21.0	37.7	30.5
5	66.4	56.0	31.1	58.0	49.7
10	85.2	73.3	37.7	71.4	62.4
25	109.1	95.3	46.2	88.3	78.4
50	126.7	111.6	52.5	100.9	90.3
100	144.3	127.8	58.7	113.3	102.1

area separately for the implementation of infrastructural projects. The maximum daily rainfall values for return periods between 2 and 100 years are shown in Table 4.

3.1.1.1 LPT III Figure 3 shows the frequency distribution, fitted to the LPT III distribution, of the rainfall data of the southwestern region of Saudi Arabia. Table 5 shows the maximum daily rainfall values for return periods between 2 and 100 years.

3.1.2 RainyDay

RainyDay was used to generate IDF results for a 24-h duration for the southwestern region of Saudi Arabia (Table 6)

using rainfall data from the TRMM Multi-satellite Precipitation Analysis (TMPA) [55].

3.1.3 Comparison of 24-h IDF Curves

The 24-h IDF curves generated using the Gumbel distribution were compared with those generated using the LPT III distribution and RainyDay for the TMPA rainfall datasets for the southwestern region of Saudi Arabia (Fig. 4). Moreover, the 24-h IDF curves developed for Abha by the three above-mentioned techniques were compared with those generated by Ewea et al. [25], which are regarded as a reference for comparison. For Abha, the results show a relatively good agreement between Gumbel, LPT III, and Ewea et al. [25], but the RainyDay results show an underestimation for the low return periods and a good agreement between Gumbel, LPT III, and Ewea et al. [25] for the high return periods (Table 7). For Al-Baha, the results show a relatively good agreement between Gumbel and LPT III, while RainyDay shows an underestimation for the low return periods and an overestimation for the high return periods. The IDF results of Bisha show a good agreement between the results obtained by Gumbel and LPT III and the minimum values obtained by RainyDay for all return periods. The Ewea et al. [25] results show an overestimation compared with the Gumbel, LPT III, and RainyDay results for all return periods except the

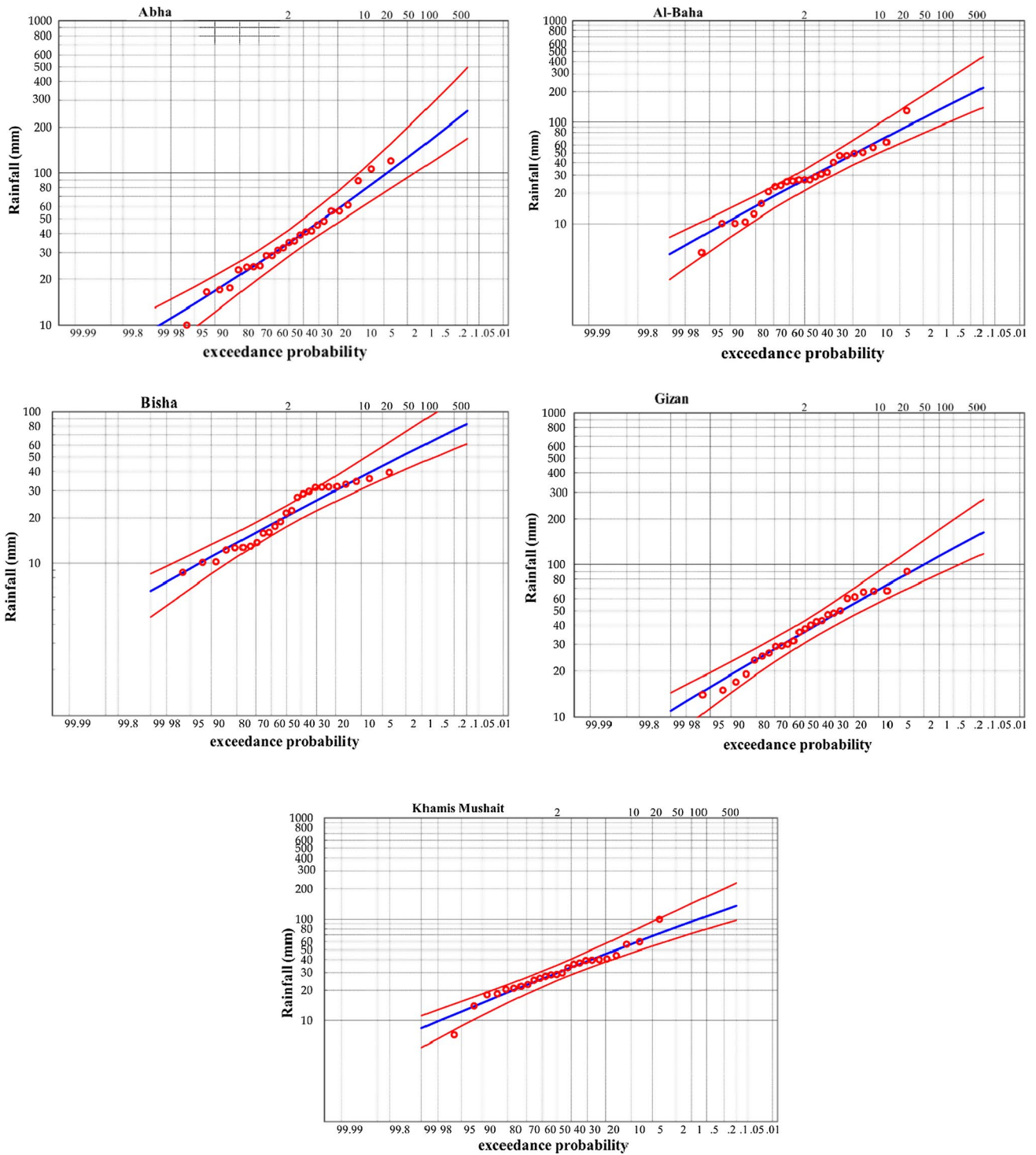


Fig. 3 Fitted log-Pearson Type III distribution for different sub-regions

100-year return period. This may be attributed to the mismatch in spatial resolution between the rain gages (approximately 0.1 m²) and the remote sensing data (approximately 625 km² for TMPA) [53]. The Gizan IDF results show a good agreement between Gumbel and LPT III, but the

RainyDay results show an underestimation for the low return periods and an overestimation for the high return periods. The results in Fig. 4 for Khamis Mushait show a relatively good agreement between Gumbel, LPT III, and RainyDay. In this study, the Gumbel and LPT III distributions, which are

Table 5 Maximum daily rainfall (mm) for different return periods using the LPT III distribution

Tr	Abha	Al-Baha	Bisha	Gizan	Khamis Mushait
2	35	26.9	20.4	36.4	29.6
5	57.8	48.3	30.2	55.4	45.6
10	76.4	65.3	37.0	68.7	56.8
25	103.2	89.8	45.7	86.2	71.7
50	126.1	110.1	52.4	99.7	83.1
100	151.3	132.1	59.1	113.5	94.7

suiting for extreme value events such as erratic rainfall in arid regions, showed a good agreement. Regarding the existing literature, Al-Shaikh [18] found that LPT III and Gumbel yielded similar IDF values in some regions of Saudi Arabia. Also, similar findings were observed by Al-Hassoun [22] in the Riyadh region. Subyani and Al-Amri [56] mentioned no remarkable differences between LPT III and Gumbel in Al-Madinah city, western Saudi Arabia. However, Elsebaie [20] noticed that the Gumbel distribution yielded larger rainfall intensity estimates than the LPT III distribution.

3.2 Effects on Rainfall Intensity Predictions

Table 3 shows wide ranges of rainfall intensities in different methods. The predicted rainfall intensities also vary considerably among different areas. For a specific duration, Bisha has the lowest intensities, while Abha has the highest intensities (Table 3). To explain the variability among different methods and areas, the IDF curves with a return period of 100 years were plotted (Fig. 5). In Abha, the rainfall intensities for a 10-min event are 233.7, 285.7, 249.3, and 173.2 mm/h for Method 1, Method 2, Method 3, and Method 4, respectively (Fig. 5). In Al-Baha, these values are 207.1, 253.1, 220.9, and 153.4 mm/h, respectively. The rainfall intensities in Abha are 13% higher than the rainfall intensities in Al-Baha. In Bisha, the rainfall intensities for the same duration are 95.1, 116.2, 101.4, and 70.4 mm/h, respectively. In Gizan, these intensities are 183.6, 224.4, 195.8, and 136 mm/h, respectively, while in Khamis Mushait, these

values are 165.5, 202.2, 176.5, and 122.6 mm/h, respectively. The rainfall intensities in Bisha were only 41% of the rainfall intensities in Abha. The variability in rainfall intensities among these areas might have implications for planning flood protection and runoff storage infrastructure.

Comparing the different methods shows that Method 4 resulted in the lowest intensities and Method 2 in the highest intensities. For a 10-min rainfall event, Methods 1–3 had 35%, 65%, and 44% higher intensities than Method 4, respectively. The ratio of the rainfall intensities for different durations is presented in Fig. 6. For all short-duration rainfall events with a return period of 100 years, Method 2 has the highest intensities (Fig. 6). The intensities for a 10-min duration in Method 1, Method 3, and Method 4 are 81.8%, 87.3%, and 60.6% of Method 2, respectively (Fig. 6). For a 30-min event, the intensities were 84.6%, 78.2%, and 60.7% of Method 2, respectively, while for a 60-min event, these were 88.2%, 88.2%, and 64.7% of Method 2, respectively. In the case of a duration of 120 min, Method 3 and Method 4 have 94.9% and 72.2% of the intensities in Method 2, respectively, while Method 1 does not have an intensity for a 120-min duration. Notice that Method 4 underestimated the rainfall intensities, which confirms what was noted by Al-Khalaf [44]. Awadallah and Younan [57] found that Bell ratios (Method 4) are suitable for representing rainfall patterns for rainfall durations of less than 2 h in arid regions. The other three methods gave similar results, which could be attributed to the fact that Method 2 and Method 3 were developed for Saudi Arabia, while Method 1 can be used for the whole world.

3.3 Equations of IDF Curves

A total of 20 IDF Eqs. (5 areas × 4 methods) were developed. The parameters for the IDF curves are shown in Table 8. The value of *m* is constant for an area, while *C* and *n* are variable (Table 8). For Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait, the values of *C* in Methods 1–4 are in the ranges of 194.2–442.19, 153.56–349.66, 106.13–241.66, 191.25–435.49, and 155.42–353.92, respectively. For these areas, the values of *m* and *n* are in the ranges of

Table 6 Minimum, mean, and maximum 24-h duration rainfall (mm) for different return periods using RainyDay with TMPA rainfall data

Tr	Abha			Al-Baha			Bisha			Gizan			Khamis Mushait		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
2	8.5	14.9	20.8	8.5	14.9	20.8	8.2	12.0	16.8	6.1	11.4	18.4	6.5	10.7	16.6
5	27.0	33.7	43.4	27.0	33.7	43.4	21.3	28.9	39.2	22.6	30.6	47.0	20.3	29.9	41.9
10	36.0	45.9	56.8	36.0	45.9	56.8	29.4	42.1	57.6	32.9	44.4	60.8	32.4	44.0	60.6
20	41.6	59.0	77.1	41.6	59.0	77.1	39.1	55.2	78.0	43.1	59.5	87.2	40.8	57.1	78.0
50	53.3	81.1	129.4	53.3	81.1	129.4	47.8	80.3	212.5	49.2	80.9	129.6	52.0	76.7	127.4
100	62.0	98.7	148.8	62.0	98.7	148.8	53.8	107.7	245.7	59.5	108.3	250.5	55.6	107.0	250.5

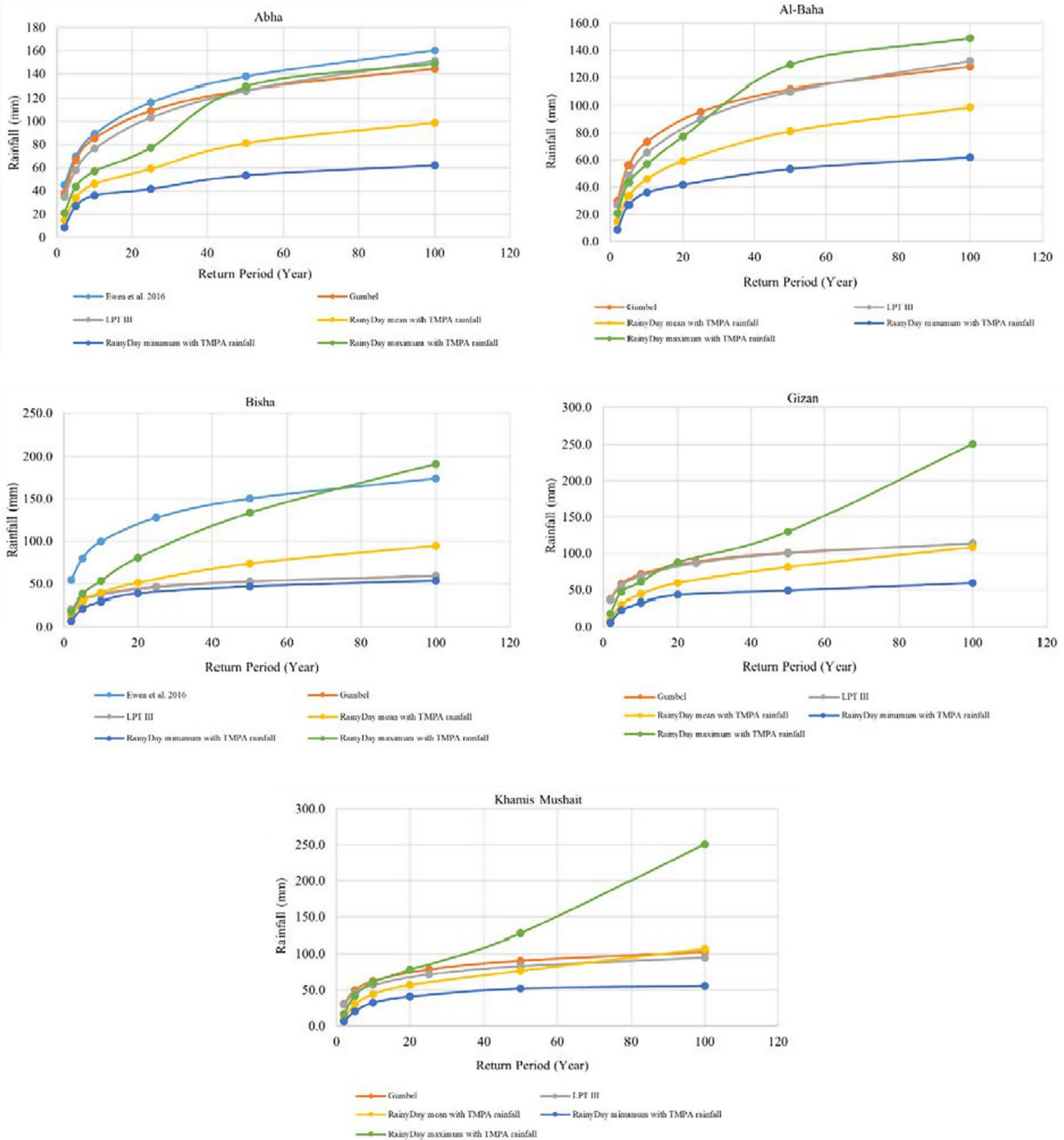


Fig. 4 Comparison of 24-h IDF curves from Ewea et al. (2017), Gumbel, LPT III, and RainyDay using TMPA data for different sub-regions with return periods of 2, 5, 10, 25, 50, and 100 years

0.2545–0.3551 and 0.681–0.788, respectively. The parameters (C, m, n) for Abha are comparable to those obtained by some past studies. Using three frequency factors, Al-Anazi and Elsebaie [33] predicted $C, m,$ and n for Abha to be in the ranges of 287.42–369.82, 0.142–0.307, and 0.608–0.613, respectively. The parameters for the IDF curves in other

areas could not be compared due to the limited number of past studies in these areas.

The parameters in Table 8 predicted reasonable rainfall intensities in all areas (Table 9). For example, in Abha, the rainfall intensities of a duration of 10 min with a return period of 100 years were predicted to be 258.4, 324.5,

Table 7 Comparison of IDF curves from Ewea et al. (2016), Gumbel, LPT III, and RainyDay using TMPA rainfall datasets for 24-h durations for Abha

Tr	Ewea et al. 2016	Gumbel	LPT III	Rainyday			Error (%)		
				Minrain	Meanrain	Maxrain	Gumbel	LPT III	Rainyday
2	44.9	37.9	35	8.5	14.9	20.8	15.6	22.0	53.7
5	69.5	66.4	57.8	27	33.7	43.4	4.5	16.8	37.6
10	89.1	85.2	76.4	36	45.9	56.8	4.4	14.3	36.3
20	109.6	–	–	41.6	59	77.1	–	–	29.6
25	116.3	109.1	103.2	–	–	–	6.2	11.3	–
50	137.9	126.7	126.1	53.3	81.1	129.4	8.1	8.6	6.2
100	160.3	144.3	151.3	62	98.7	148.8	10.0	5.6	7.2

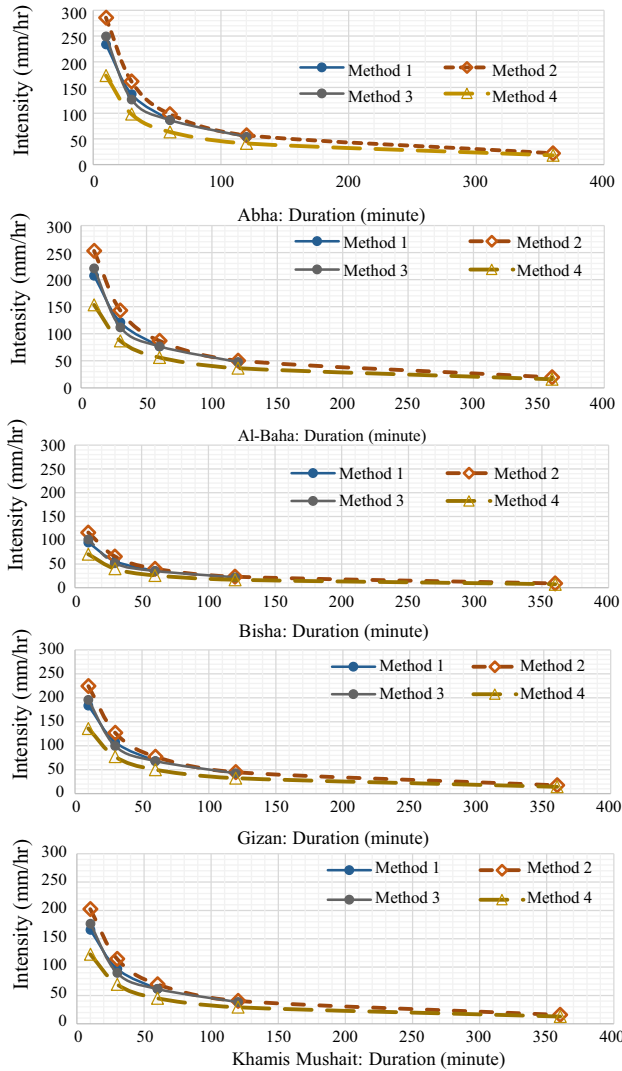


Fig. 5 IDF curves for different sub-regions with return period of 100 years

268.3, and 182.3 mm/h for Methods 1–4, respectively. The rainfall intensities that were used for estimating the parameters are 233.7, 285.7, 249.3, and 173.2 mm/h for Methods 1–4, respectively, indicating that the model predictions are

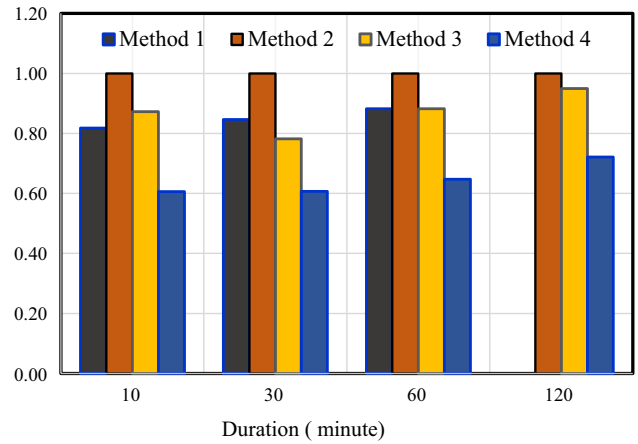


Fig. 6 Ratio of rainfall intensities in different methods of depth–duration calculation

Table 8 Parameters for the IDF curves in different methods

Sub-area	Parameter	Method 1	Method 2	Method 3	Method 4
Abha	C	328.57	442.19	338.83	194.20
	m	0.3268	0.3268	0.3268	0.3268
	n	0.758	0.788	0.755	0.681
Al-Baha	C	259.81	349.66	267.94	153.56
	m	0.3551	0.3551	0.3551	0.3551
	n	0.758	0.788	0.755	0.681
Bisha	C	179.56	241.66	185.17	106.13
	m	0.2545	0.2545	0.2545	0.2545
	n	0.758	0.788	0.755	0.681
Gizan	C	323.59	435.49	333.70	191.25
	m	0.2713	0.2713	0.2713	0.2713
	n	0.758	0.788	0.755	0.681
Khamsi Mushait	C	262.97	353.92	271.19	155.42
	m	0.2966	0.2966	0.2966	0.2966
	n	0.758	0.788	0.755	0.681

Equation of IDF curve: $I = CT^m/t^n$, I =rainfall intensity (mm/h); T =return period (years); t =rainfall duration (minute); C, m, n are the parameters

Table 9 Modeled and estimated rainfall intensities(mm/h) for a duration of 10 min with a return period of 100 years

Sub-region		Method 1	Method 2	Method 3	Method 4
Abha	Modelled	258.4	324.5	268.3	182.3
	Original	233.7	285.7	249.3	173.1
Al-Baha	Modelled	232.7	292.3	241.7	164.2
	Original	207.1	253.1	220.9	153.4
Bisha	Modelled	101.2	127.1	105.1	71.4
	Original	95.0	116.2	101.4	70.4
Gizan	Modelled	197.1	247.5	204.6	139.1
	Original	183.6	224.4	195.8	136.0
Khamis Mushait	Modelled	179.9	226.0	186.8	127.0
	Original	165.5	202.2	176.5	122.6

5.3–13.6% higher than the input data. Overall, the rainfall intensities predicted by the equations (Table 8) for Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait are 5.3–13.6%, 7.1–15.5%, 1.4–9.4%, 2.2–10.3%, and 3.6–11.8% higher than the rainfall intensities used for predicting the parameters. Relatively consistent outputs of the IDF equations indicate that representative values of rainfall intensities may be obtained by using these equations. It can be concluded that Method 4 showed the worst performance and that Method 2 showed the best performance for all regions. The methods yielded different outcomes because Method 2 used the historical data of rainfall in the southwestern region of Saudi Arabia, while Method 4 used the historical data of other regions. Thus, Method 4 might not be an appropriate method for the conditions of the southwestern region of Saudi Arabia, as reported by Al-Khalaf [44]. However, the parameters should be further validated using additional hourly and sub-hourly rainfall data for better performance.

3.4 Implications for Flood Protection and Runoff Storage

IDF curves have many applications, including designing storm sewer systems, as well as flood protection and runoff storage through dams and watersheds. The four methods of predicting rainfall depth–duration ratios have shown wide ranges of intensities for shorter durations. Furthermore, the areas show significant differences. In the case of a 10-min

rainfall event, the IDF ordinates for Method 1, Method 2, and Method 3 are 35%, 65%, and 44% higher than the ordinates of Method 4, respectively. For a 30-min event, the ordinates are 39%, 65%, and 29% higher than those of Method 4, respectively. Designing hydraulic structures using the IDF relationship of Method 4 may not be adequate, while the application of the IDF relationship of Method 2 may involve significant costs. However, the data of Method 2 represented the historical trends of the southwestern region of Saudi Arabia [47].

Further assessment was performed with respect to the need for runoff storage capacity. The areas of Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait are approximately 50, 12,000, 19,200, 13,000, and 500 km², respectively, while their topography is quite different. For a 30-min rainfall event with a 100-year return period, the ranges of the rainfall intensities in these areas are 98.1–161.6, 86.9–143.2, 39.9–65.7, 77.1–126.9, and 69.5–114.4 mm/h, respectively. In similar geological areas, past studies used runoff coefficients in the range of 0.05–0.65 [9]. For an area in the southwestern region of Saudi Arabia, Nouh [58] reported runoff coefficients in the range of 0.133–0.185. Sen and Al-Suba [59] estimated runoff coefficients for Tihama in the Asir region in the range of 0.05–0.22. In mountainous areas, some studies showed that the runoff coefficient might reach 0.65 [60]. For demonstration purposes, average runoff coefficients of 0.10–0.50 were assumed for each area, and the ranges of storage capacities are shown in Table 10. Note that these values are somewhat arbitrary and can be updated in future research. For a runoff coefficient of 0.1, the storage capacity requirements for Methods 1–4 were in the ranges of 0.25–0.4, 52.0–86.0, 38.3–63.1, 50.1–82.5, and 1.9–2.9 million cubic meters (MCM) for Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait, respectively. For a runoff coefficient of 0.5, these values were 1.2–2.0, 259.8–429.6, 191.5–315.4, 250.6–412.4, and 8.7–14.3 MCM, respectively (Table 6). For a coefficient of 0.5, the upper bounds of the storage capacities were 0.79, 169.8, 123.8, 161.9, and 5.6 MCM higher than the lower bounds in these areas. Note that Method 2 showed the highest runoff, while Method 4 showed the lowest runoff. To provide adequate flood protection and maximize runoff collection, the methodological uncertainties need to be incorporated into frequency infrastructural designs. Furthermore, appropriate locations

Table 10 Generation of surface runoff (million cubic meters) under various scenarios in different areas for a duration of 30 min with a return period of 100 years

Sub-region	C=0.1	C=0.2	C=0.3	C=0.4	C=0.5
Abha	0.25–0.4	0.5–0.8	0.74–1.2	1.0–1.6	1.2–2.0
Al-Baha	52.0–86.0	103.9–171.8	155.9–257.8	207.9–343.7	259.8–429.6
Bisha	38.3–63.1	76.6–126.1	114.9–189.2	153.2–252.3	151.5315.4
Gizan	50.1–82.5	100.2–165.0	150.4–247.5	200.5–330	250.6–412.4
Khamis Mushait	1.9–2.9	3.5–5.7	5.2–8.6	7.0–11.4	8.7–14.3

for water infrastructures (e.g., watershed, dam) need to be identified to minimize property damage and maximize runoff storage.

In Saudi Arabia, occurrences of flash floods are likely. Such events are often linked to the loss of lives and properties. Furthermore, due to inadequate infrastructure, surface runoff is often lost. Therefore, additional flood protection and/or runoff collection systems might be needed in Saudi Arabia. The methodological variability might play an important role in the selection of design criteria and constraints for flood protection and/or runoff collection systems. With a better understanding of the IDF relationship in a relatively small area, flood protection and runoff collection capabilities can be improved. As there is a serious need for collecting runoff from rainfall events, the availability of such water infrastructures can be of great importance. By incorporating uncertainty to account for the methodological variation, appropriate measures can be adopted for runoff collection and systematic recharge into groundwater aquifers. Future studies may focus on identifying the appropriate locations using advanced modeling tools (e.g., WMS software).

4 Conclusions

This study developed IDF curves for five areas (Abha, Al-Baha, Bisha, Gizan, and Khamis Mushait) in the southwestern region of Saudi Arabia. Four methods of obtaining rainfall depth-to-duration ratios were applied to predict the rainfall depth for sub-hourly durations. The Gumbel frequency factor was used to develop IDF curves with return periods of 2, 5, 10, 25, 50, and 100 years. The four types of IDF curves demonstrate significant variability, indicating methodological uncertainties. Furthermore, the application of any method needs appropriate calibration for an area. Lack of calibration may result in an erroneous IDF relationship, which may compromise the safety of flood protection. By long-term monitoring of rainfall data and calibrating the models using these data, IDF relationships can be improved in the future. The developed IDF relationships using the Gumbel frequency factor based on the proposed four methods were compared with the relationships developed by using the LPT III distribution and RainyDay, and it was found that Gumbel and LPT III were similar to each other, while RainyDay mostly underestimated the low return period.

Based on our findings, it appears that Method 2 provides the highest values of rainfall intensities for shorter durations, while Method 4 provides the lowest intensities. This is because the ratios obtained based on Method 4 are much lower than those estimated by Method 2. Furthermore, the data used in Method 2 were representative of the historical pattern of rainfall in the southwestern region

of Saudi Arabia. From the flood protection point of view, Method 2 might be the better method to use. However, a better understanding of the topography, soil properties, and rainfall events is required for planning and implementing infrastructural projects. Gumbel and LPT III can be used to develop IDF curves when sub-daily rainfall data are scarce, while RainyDay can be used with caution in regions with no rainfall data. Also, IDF curves representing smaller areas than the entire southwestern region are needed to implement cost-effective and protective infrastructures. Significant variability was observed among different areas. For example, if the IDF curves for Bisha are used for Abha, the designed infrastructure may not provide adequate protection against flash floods and runoff storage in Abha. Conversely, if the IDF curves for Abha are used for Bisha, the cost of infrastructure may become unnecessarily high.

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References

1. BBC News: Flood deaths in Saudi Arabia rise to around 100. <http://news.bbc.co.uk/2/hi/8384832.stm>
2. CNN World (Cable News Network) (2011). http://articles.cnn.com/2011-01-29/world/saudia.arabia.flooding_1_jeddah-rain-water-rescue-operations?_s=PM:WORLD
3. Arab News: Flash flood fury leaves 7 dead in south. Published in Arab News on Monday, 5 August 2013. (2013). <https://www.arabnews.com/news/460295>
4. FAO (Food and Agriculture Organization): Irrigation in the Middle East Region in Figures. Food and Agriculture Organization of the United Nations. FAO Water Reports 34, Rome (2009)
5. MOWE (Ministry of Water and Electricity): Annual Report, Riyadh, Saudi Arabia. <http://www.mowe.gov.sa/ENIndex.aspx>
6. MOEP (The Ministry of Economy and Planning): The ninth development plan (2010–2014), The Kingdom of Saudi Arabia (2010)
7. Dawod, G.M.; Mirza, M.N.: GIS-based estimation of flood hazard impacts on road network in Makkah city, Saudi Arabia. *Environ. Earth Sci.* **67**(8), 2205–2215 (2012)
8. Abdelkarim, A.; Gaber, A.F.D.: Flood risk assessment of the Wadi Nu'man Basin, Mecca, Saudi Arabia (During the Period, 1988–2019) based on the integration of geomatics and hydraulic modeling: a case study. *Water* **11**(9), 1887 (2019)
9. Al-Zahrani, M.; Chowdhury, S.; Abo-Monasar, A.: Augmentation of surface water sources from spatially distributed rainfall in Saudi Arabia. *J. Water Reuse Desalin.* **5**(3), 391–406 (2015)
10. Evenari, M.: Ancient agriculture in the negev. *Science* **133**, 976–986 (1961)
11. Yuan, T.; Fengmin, L.; Puhai, L.; Yuan, T.; Fengmin, L.; Puhai, L.: Economic analysis of rainwater harvesting and irrigation methods, with an example from China. *Agric. Water Manag.* **60**(3), 217–226 (2003)
12. Sivanappan, R.K.: Rainwater harvesting techniques. *Rainwater Harvest. water Manag.* **14**, 10–15 (2006)
13. Bernard, M.M.: Formulas for rainfall intensities of long duration. *Trans. Am. Soc. Civ. Eng.* **96**(1), 592–606 (1932)



14. Hershfield, D.M.: Estimating the probable maximum precipitation. *J. Hydraul. Div.* **87**(5), 99–116 (1961)
15. Bell, F.C.: Generalized rainfall duration frequency relationships. *J. Hydraul. Div., ASCE* **95**(1), 311–327 (1969)
16. Chen, C.: Rainfall Intensity-Duration-Frequency Formulas. *J. Hydraul. Eng.* **109**(12), 1603–1621 (1983)
17. Kothiyari, U.C.; Garde, R.J.: Rainfall intensity-duration-frequency formula for India. *J. Hydraul. Eng.* **118**(2), 323–336 (1992)
18. Al-Shaikh, A.: Rainfall frequency studies for Saudi Arabia. M.S. Thesis, Civ. Eng. Dep. King Saud Univ. Riyadh, Saudi Arab. (1985)
19. Al-Dokhayel, A. A.: Regional rainfall frequency analysis for Qasim. Civ. Eng. Dep. King Saud Univ. Riyadh, Saudi Arab (1986)
20. Elsebaie, I.H.: Developing rainfall intensity–duration–frequency relationship for two regions in Saudi Arabia. *J. King Saud Univ. - Eng. Sci.* **24**(2), 131–140 (2012)
21. Ewea, H.A.; Elfeki, A.M.; Bahrawi, J.A.; Al-amri, N.S.: Modeling of IDF curves for stormwater design in Makkah Al Mukarramah region, The Kingdom of Saudi Arabia. *Open Geosci.* **10**(1), 954–969 (2018)
22. AlHassoun, S.A.: Developing an empirical formulae to estimate rainfall intensity in Riyadh region. *J. King Saud Univ. - Eng. Sci.* **23**(2), 81–88 (2011)
23. Awadallah, A.G.; ElGamal, M.; ElMostafa, A.; ElBadry, H.: Developing intensity-duration-frequency curves in scarce data region: an approach using regional analysis and satellite data. *Engineering* **03**(03), 215–226 (2011)
24. Subyani, A.M.; Al-Modayan, A.A.; Al-Ahmadi, F.S.: Topographic, seasonal and aridity influences on rainfall variability in Western Saudi Arabia. *J. Environ. Hydrol.* **18**, 1–11 (2010)
25. Ewea, H.A.; Elfeki, A.M.; Al-Amri, N.S.: Development of intensity–duration–frequency curves for the Kingdom of Saudi Arabia. *Geomat. Nat. Hazards Risk* **8**(2), 570–584 (2017)
26. Abdeen, W.M.; Awadallah, A.G.; Hassan, N.A.: Investigating regional distribution for maximum daily rainfall in arid regions: case study in Saudi Arabia. *Arab. J. Geosci.* **13**(13), 1–18 (2020)
27. Agri, P.J.; Zainudini, M.A.; Marriott, M.J.; Mirjat, M.S.; Chandio, A.S.: Establishing intensity duration frequency curves for Sistan and Balochistan provinces of Iran. *Agric. Eng. Vet. Sci.* **27**(2), 115–124 (2011)
28. Jalee, L.A.; Farawn, M.A.: Developing rainfall intensity-duration-frequency relationship for Basrah City. *Kufa J. Eng.* **5**(1), 105–112 (2014)
29. Rathnam, E.; Jayakumar, V.K.; Cunnane, C.: Runoff computation in a data scarce environment for urban stormwater management. A case study. *J-Global* **29**(Theme B), 446–454 (2001)
30. Nhat, L.; Tachikawa, Y.; Takara, K.: Establishment of intensity–duration–frequency Curves for Precipitation in the Monsoon Area of Vietnam. *Annu. Disas. Prev. Res. Inst., Kyoto Univ.* **49**(B) (2006)
31. Solaiman, T.A.; Simonovic, S.P.: Development of probability based intensity-duration-frequency curves under climate change (2011)
32. Suchithra, A. S.; Agarwal, S.: IDF curve generation for historical rainfall events. In: *Proceeding of National Conference on Emerging Trends in Civil Engineering* (2020)
33. Al-anazi, K.; Ibrahim, H.: Development of intensity-duration-frequency relationships for Abha City in Saudi Arabia. *Int. J. Comput. Eng. Res.* **10**(3), 58–65 (2013)
34. Subyani, A.M.: Geostatistical study of annual and seasonal mean rainfall patterns in southwest Saudi Arabia/Distribution géostatistique de la pluie moyenne annuelle et saisonnière dans le Sud-Ouest de l'Arabie Saoudite. *Hydrol. Sci. J.* **49**(5), 49 (2009)
35. S. Moazami and M. R. Najafi, "A comprehensive evaluation of GPM-IMERG V06 and MRMS with hourly ground-based precipitation observations across Canada," *J. Hydrol.*, vol. 594, p. 125929, 2021.
36. Villarini, G.; Krajewski, W.F.: Empirically-based modeling of spatial sampling uncertainties associated with rainfall measurements by rain gauges. *Adv. Water Resour.* **31**(7), 1015–1023 (2008)
37. Al-Areeq, A.M.; Al-Zahrani, M.A.; Sharif, H.O.: The performance of physically based and conceptual hydrologic models: a case study for makkah watershed, Saudi Arabia. *Water (Switzerland)* **13**(8), 1098 (2021)
38. Bhuiyan, M.A.E.; Yang, F.; Biswas, N.K.; Rahat, S.H.; Neelam, T.J.: Machine learning-based error modeling to improve GPM IMERG precipitation product over the brahmaputra River Basin. *Forecasting* **2**(3), 248–266 (2020)
39. Sakib, S.; Ghebreyesus, D.; Sharif, H.O.: Performance evaluation of imerg gpm products during tropical storm imelda. *Atmosphere (Basel)* **12**(6), 687 (2021)
40. Omranian, E.; Sharif, H.O.: Evaluation of the global precipitation measurement (GPM) satellite rainfall products over the lower Colorado River Basin, Texas. *J. Am. Water Resour. Assoc.* **54**(4), 882–898 (2018)
41. Sunilkumar, K.; Yatagai, A.; Masuda, M.: Preliminary evaluation of GPM-IMERG rainfall estimates over three distinct climate zones with APHRODITE. *Earth Space Sci.* **6**(8), 1321–1335 (2019)
42. Al-Areeq, A.M.; Al-Zahrani, M.A.; Sharif, H.O.: "Physically-based, distributed hydrologic model for Makkah watershed using GPM satellite rainfall and ground rainfall stations." *Geomatics Nat. Hazards Risk* **12**(1), 1234–1257 (2021)
43. Reich, B.M.: Short-duration rainfall-intensity estimates and other design aids for regions of sparse data. *J. Hydrol.* **1**(1), 3–28 (1963)
44. Al-Khalaf, H.: Predicting short-duration, high-intensity rainfall in Saudi Arabia. M.S. Thesis, Fac. Coll. Grad. Stud. King Fahad Univ. Pet. Miner. Dhahran. (1997)
45. Saad, A.Y.: *Manual of Applied Hydrology for Dams*, 1st edn. Ministry Of Agriculture & Irrigation, Yemen (2003)
46. MTO: Ministry of Transportation of Ontario Drainage Management Manual. Drainage and Hydrology Section, Transportation Engineering Branch, and Quality Standards Division, Ministry of Transportation of Ontario, Ottawa, Ontario, Canada (1997)
47. Wheeler, H.S.; Laurentis, P.; Hamilton, G.S.: Design rainfall characteristics for South-West Saudi Arabia. *Proc. Inst. Civ. Eng.* **87**(4), 517–538 (1989)
48. Ahmed, Z.; Rao, D.; Reddy, K.; Raj, E.: Rainfall intensity variation for observed data and derived data: a case study of Imphal. *ARPN J. Eng. Appl. Sci.* **11**(7), 1506–1513 (2012)
49. NRC (National Research Council): *Committee on Techniques for Estimating Probabilities of Extreme Floods, Estimating Probabilities of Extreme Floods, Methods and Recommended Research*. National Academy Press, Washington D.C. (1988). <https://nrc.canada.ca/en>
50. Raiford, J.P.; Aziz, N.M.; Khan, A.A.; Powell, D.N.: Rainfall depth-duration-frequency relationships for SC related papers rainfall depth-duration-frequency relationships for South Carolina, North Carolina, and Georgia. *Am. J. Environ. Sci.* **3**(2), 78–84 (2007)
51. Manley, R.: BELL'S FORMULA = A REAPPRAISAL. VIII' *Journées Hydrol.*, pp. 121–131 (1992)
52. Te Chow, V.: A general formula for hydrologic frequency analysis. *Trans. Am. Geophys. Union* **32**(2), 231 (1951)
53. Wright, D.B.; Mantilla, R.; Peters-lidard, C.D.: A remote sensing-based tool for assessing rainfall-driven hazards. *Environ. Model. Softw.* **90**, 34–54 (2017)
54. Wright, D.B.; Smith, J.A.; Villarini, G.; Baeck, M.L.: Estimating the frequency of extreme rainfall using weather radar and stochastic storm transposition. *J. Hydrol.* **488**, 150–165 (2013)



55. Huffman, G.J.; Adler Bolvin, R.F.; Nelkin, E. J.: The TRMM multi-satellite precipitation analysis (TMPA). *Satellite Rainfall Applications for Surface Hydrology*, pp. 3–22. Springer, Dordrecht (2010)
56. Subyani, A.M.; Al-Amri, N.S.: IDF curves and daily rainfall generation for Al-Madinah city, western Saudi Arabia. *Arab. J. Geosci.* **8**(12), 11107–11119 (2015)
57. Awadallah, A.G.; Younan, N.S.: Conservative design rainfall distribution for application in arid regions with sparse data. *J. Arid Environ.* **79**, 66–75 (2012)
58. Nouh, M.: A comparison of three methods for regional flood frequency analysis in Saudi Arabia. *Adv. Water Resour.* **10**, 212–219 (1987)
59. Şen , Z.; Al-Suba'i, K.: Hydrological considerations for dam siting in arid regions: a Saudi Arabian study. *Hydrol. Sci. J.* **47**(2), 173–186 (2002)
60. Holko, L.; Kostka, Z.: Impact of landuse on runoff in mountain catchments of different scales. *Soil Water Res* **3**(3), 113–120 (2008)

