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ORIGINAL PAPER

Hydrologic behavior and flood probability for selected arid basins in Makkah area, western Saudi Arabia

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Abstract In arid regions, flash floods often occur as a consequence of excessive rainfall. Occasionally causing major loss of property and life, floods are large events of relatively short duration. Makkah area in western Saudi Arabia is characterized by high rainfall intensity that leads to flash floods. This study quantifies the hydrological characteristics and flood probability of some major wadis in western Saudi Arabia, including Na'man, Fatimah, and Usfan. Flood responses in these wadis vary due to the nature and rainfall distribution within these wadis. Rainfall frequency analysis was performed using selected annual maximums of 24-h rainfall from eight stations located in the area. Two of the most applied methods of statistical distribution, Gumbel's extreme value distribution and log Pearson type III distribution, were applied to maximum daily rainfall data over 26 to 40 years. The Gumbel's model was found to be the best fitting model for identifying and predicting future rainfall occurrence. Rainfall estimations from different return periods were identified. Probable maximum floods of the major wadis studied were also estimated for different return periods, which were extrapolated from the probable maximum precipitation.

Keywords Hydrologic behavior · Flood probability · Maximum 24-h rainfall · Makkah area · Saudi Arabia

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Introduction

Taking place immediately after a heavy short rainstorm, flash floods are one of the most catastrophic phenomena. They are fairly common in arid regions and present a potential hazard to life, personal property, and structures such as small dams, bridges, culverts, wells, and dykes along wadi courses. However, flash floods form rapidly and flow down over watercourses that are nearly or already extremely dry. Flood occurrences are complex since they depend on interactions between many geological and morphological characteristics of the basins, including rock types, elevation, slope, sediments transport, and flood plain area. Moreover, hydrological phenomena, such as rainfall, runoff, evaporation, and surface and groundwater storage (Farquharson et al. 1992; Flerchinger and Cooly 2000; Şen 2004; Nouh 2006) can affect floods. The wadi's course has been negatively affected by man-made objects, such as extending barriers, levees, and farms, that increase the risk for flood behavior. On the contrary, the statistics of extremes have played an important role in engineering the water resource design and management (Katz et al. 2002; Tingsanchali and Karim 2005)

In western Saudi Arabia, flood discharge from the wadi basins that drain toward the Red Sea can become dangerous and threaten coastal cities, towns, villages, and engineering structures. A previous report documented (ACSAD/AFESD/KFAED 1986) that the average surface water flow into the Red Sea zone can be estimated to be about 39.8 m^3/s, of which 27 m^3/s (70%) occurs south of Jeddah, 8.2 m^3/s (21%) north of Jeddah, and the remaining 4.6 m^3/s (9%) around Jeddah city.

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During Hajj season, Makkah area, 1426H (22 January 2005), experienced a heavy rain storm that was described as the worst in 20 years. As a result, 29 people were killed, and 17 were wounded. Flood waters swept cars off roads and destroyed bridges, electrical towers, and communications. Flash floods occurred in some parts of the study area, including Jeddah city in November 2006 and Makkah city in January 2008. Most rainstorms within the study area did not exceed 3 h, and according to rain gauge data, rainfall totals did not exceed 80 mm in this area (Subyani et al. 2009).

Alyamani and Subyani (2001) studied and collected runoff hydrographs and sediments load transport from some major wadis in western Saudi Arabia. Nouh (1988) obtained data from 32 arid catchments from different parts of the Kingdom to derive regional equations for flood estimation. Results from this study indicated that the weighted estimate is more accurate than the estimate of flood through the calibrated regional method.

Nouh (2006) used real data on wadi flood flows from the Arabian Gulf States and Yemen to develop methodologies for predicting annual maximum flow. Three methods were investigated. In the first method, regional curves were developed and used along with the mean annual flood flow, which was estimated from characteristics of the drainage basin, to estimate the flood flows at a particular location within the basin. The second method involved fitting data using different probability distribution functions; the best fit was used for the flood estimate. In the final method, only floods over a certain threshold were considered and modeled.

The main purpose of this study is to analyze the extreme rainfall with an annual maximum of 24 h using Gumbel's type I and log Pearson type III probability distributions to generate the potential maximum flood in some major wadis within Makkah area, namely Na'man, Fatimah, and Usfan, extending between latitudes 21° 00′N and 22° 30′N and longitudes 39° 00′ 40 30′ as shown in Fig. 1.

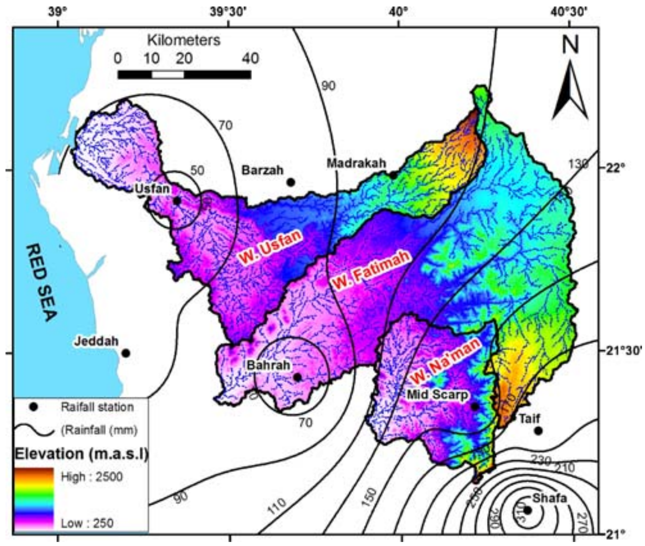

Fig. 1 Map showing the isohyetal lines of annual rainfall and main basins in the study area

Hydrology

Climate conditions over the study area play an important role in defining the hydraulic response of the watersheds existing in that region. The most important factor affecting the hydraulic behavior of the wadi basins is rainfall. Its duration, intensity, distribution, and return periods are major influences. This climate pattern can be described by considering various air masses that affect rainfall distribution. The study area possesses different physiographic and topographic features. In particular, Harrat is predominantly arid and hot, while the Red Sea coast is semiarid yet hot in the summer. The mountainous regions exhibit cooler winters and high incident radiation.

The climate in Makkah area can be described by considering the various air masses that affect rainfall distribution over the area. The climate is a combination of Mediterranean (cyclonic system), which moves in from the north during winter and monsoonal from the southwest in the summer. The Hijaz Escarpment altitude is the major factor controlling the quantity and pattern of rainfall. How these air masses and rainfall patterns influence the Kingdom was discussed and mapped previously (Şen 1983; Alyamani and Şen 1992; Subyani 2004; Nouh 2006).

Due to the different morphological units in the study area, which encompassed Tihamah, foothills, and mountains, the climatological stations were combined based on whether its location was related to one of these three morphological units. Average rainfall and temperature data are summarized in Table 1. This table shows high variation in mean rainfall between the coastal and mountainous areas. Temperatures in the foothills were only slightly different from those in the coastal area, but differed greatly from the mountains.

Assessment of the long-term average annual rainfall depth in the study area from 1970 to 2005 demonstrates that the spatial variation of rainfall is influenced by topography (Fig. 1). The orographic effect states that annual rainfall increases with elevation. Generally, the eastern part of the wadi catchments received considerably more rainfall with an average of more than 220 mm per year near the Hijaz Escarpment as compared to the lower (western) part of the wadi, which received an average of less than 100 mm per year near the Red Sea coast (Tihamah). Overall, rainfall tended to be more regular in the highlands than the coastal plain.

Table 1 Average rainfall and temperature for main morphological units in the study area

Morphological units	Rainfall (mm/year)			Temperature (ºC)		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Coastal area	17	50	100	24	32	39
Foothill area	103	170	230	22	29	34
Mountain area	70	325	650	16	22	28

Methodology

Rainfall frequency curves

Rainfall frequency analysis is a statistical tool applied in the study of random hydrological variables such as the annual maximum rainfall. Two types of uncertainty exist in statistical analyses with random variables. The first is associated with the randomness of future rainfall events, and the second is an estimation of suitable relative frequency. The distribution of rainfall events is estimated by fitting a probability density function to the observed data. The cumulative density function represents all values less than or greater than the value of the random variable. The different types of statistical distributions and probability density functions will be fitted to the historical data. This procedure is typically called rainfall frequency analysis, which can be carried out through graphical or analytical methods.

Two analytical methods of statistical distribution, Gumbel's extreme value distribution (EV1) and log Pearson type III, were applied on maximum daily rainfall data collected from eight stations located in and around wadi basins. Obtained from the 2007 Ministry of Water and Electricity report, the data covered a period up to 40 years (1960–2007). However, not all stations covered the same time interval, but the different climate conditions in the study area were well represented.

A series of annual maximum daily values was constructed and ranked in descending order of magnitude. The recurrence interval corresponding to the rank was computed using the Weibull plotting formula as

$$P = m/n + 1 \qquad \textit{and} \qquad T_r = n + 1/m \tag{1}$$

where n is the number of years on record, and m represents the event rank in order of magnitude. P and T_r indicate the probability and return period or frequency, respectively.

Gumbel's method

This method is one of the most widely used probability density function (pdf) then calculating extreme values in hydrological and meteorological studies for the prediction of such meteorological factors as flood peak, maximum rainfall, and maximum wind speed. According to Gumbel, a flood is the largest of the 365 daily flows, and the annual series of flood flows constitutes a series of flow values. This probability density function is given by

$$p = 1 - e^{-e^{-y}} \tag{2}$$

where p is the probability of a given flow being equal or exceeded, and y is the reduced variate as a function of probability from ready tables (Subramanya 1994). In addition,

$$x = \bar{x} + k\sigma_x \tag{3}$$

where $\bar{x}$ is the mean of the data series, and σ_x is its standard deviation, $k = 0.7797y–0.45$.

Log Pearson type III

Karl Pearson developed a system of 12 pdfs that approximate all forms of single-peak statistical distributions. The system includes three main and nine transition pdfs. The log Pearson type III pdf is particularly useful for hydrological analysis because the skew parameter enables sample fitting where other pdfs fail. The log Pearson type III frequency curve is characterized by three parameters. The mean represents the average ordinate, the standard deviation represents the slope of the straight line on probability paper, and the skew coefficient represents the degree of curvature. However, this technique is mainly based on the use of log-transformed data. The following equations have been used previously (Viessman and Lewis, 1996; Wanielista et al. 1997; Saf 2005).

$$\overline{\log x} = \frac{\sum \log x}{n} \tag{4}$$

$$\sigma_{\log x} = \sqrt{\sum \left(\log x - \overline{\log x}\right)^2 / (n-1)} \tag{5}$$

$$G = n \sum \left(\log x - \overline{\log x}\right)^3 \Big/ (n-1)(n-2)(\sigma \log x)^3 \tag{6}$$

The value of x for any recurrence interval is calculated by

$$\log x = \overline{\log x} + k\sigma_{\log x} \tag{7}$$

In the equations listed above, n is equals the number yearly records, $\sigma_{\log x}$ is the standard deviation of the transformed data, G represents the skew coefficient, $\overline{\log x}$ is the mean of the transformed data, and k is a frequency factor which is a function of the recurrence interval (T) and the coefficient of skew (G). In addition, $k=f(G, T)$ and can be found in ready tables (Subramanya 1994). When the skew equals zero, the pdf becomes a two-parameter equation that is identical to a log-normal pdf.

After obtaining rainfall values using the two methods described above for different return periods, the chi-square test was performed to calculate the “goodness of fit” and enable graphical comparison.

Probable maximum precipitation

When designing major structures such as dams and highways, researchers prefer to keep the failure probability as low as possible to prevent loss of human life and property damage. The use of maximum possible precipitation (PMP) can be expected at any given location. The spatial and temporal context of the upper limit of rainfall quantity is incorporated into the definition of PMP, which is defined by the World Meteorological Organization as “theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year.” Therefore, statistical analysis of maximum precipitation PMP of a specific return period can be estimated as

$$\mathrm{PMP} = \overline{p} + K_T\sigma_x \tag{8}$$

where $\overline{p}$ is the mean annual maximum rainfall, σ_x is the series standard deviation, and K_T is a frequency factor that depends on the distribution type, number of recorded years (or return periods). The latter variable can be estimated from published ready tables (Subramanya 1994; Wanielista et al. 1997).

Probable maximum flood

Flood events with maximum rainfall are called probable maximum floods (PMFs), or the maximum water flow in a drainage area that would be expected from a PMP event. Calculation of the PMF begins by obtaining an estimate of the PMP. The PMF is useful in designing major structures such as dams, culverts, and other hydraulic structures. High-hazard dams whose failure would result in the loss of lives and property are required to contain 100% of a PMF without water overflowing the dam. Not all catchment areas with the same PMP possess the same magnitude of PMF because different areas vary in their morphometric characteristics, including the slope, drainage density, shape, size, vegetation, and geology. All of these factors affect runoff patterns and the discharge of floodwaters in a catchment area. In general, a basin discharge is a function of climatic and watershed characteristics (Cech 2005).

In arid regions, such as the area investigated in this research, runoff gauging records and measurements are unavailable. As a result, several methods have been developed to estimate the flood volume with PMFs for different return periods and discharges. These estimations require information such as mean annual rainfall, PMPs with different return periods, and runoff coefficients. Şen and Subai’ (2002) presented basic calculations of floods and sediment amounts that are necessary for determining dam sites and construction in the southwest region of Saudi Arabia. This was accomplished by calculating the mean of the runoff coefficient, C_R, for the catchment of four gauged streams located in the southwest region of Saudi Arabia. They found that the C_R value ranged from 0.048 to 0.078. The relationship between log C_R and log A (catchment area) was a straight line in the form of

$$C_R = A^{-0.359} \tag{9}$$

This equation was used to estimate the runoff coefficient, C_R, for ungauged catchments wadis in the study area as well as the runoff volume of wadis (Şen 2008).

Results and discussion

Eight stations located in and around wadi basins were selected for this study (Fig. 1). The DISTRIB program (Wanielista et al. 1997) was used to analyze the maximum daily rainfall (24 h) data and fit the data series to the log Pearson type III and Gumbel (EV1) pdfs. A plot of each pdf on log probability paper, as well as the statistical parameters of the data series, is shown in Fig. 2. The chi-square test comparing computed values with observed values was carried out to identify the best fit method. Visual inspection revealed that Gumbel’s pdf produced the best fit in most of cases.

Shafa station, which received the maximum amount of rainfall, is located along the mountainous edge. The data series collected from Shafa station had the longest record (40 years) and lowest coefficient of variation and skew. In contrast, the data series from Usfan represented the shortest time period (24 years) with the maximum coefficient of variation and skew. Data from other stations reside in between Shafa and Usfan (Fig. 2). These variations are due to high rainfall variation in the area.

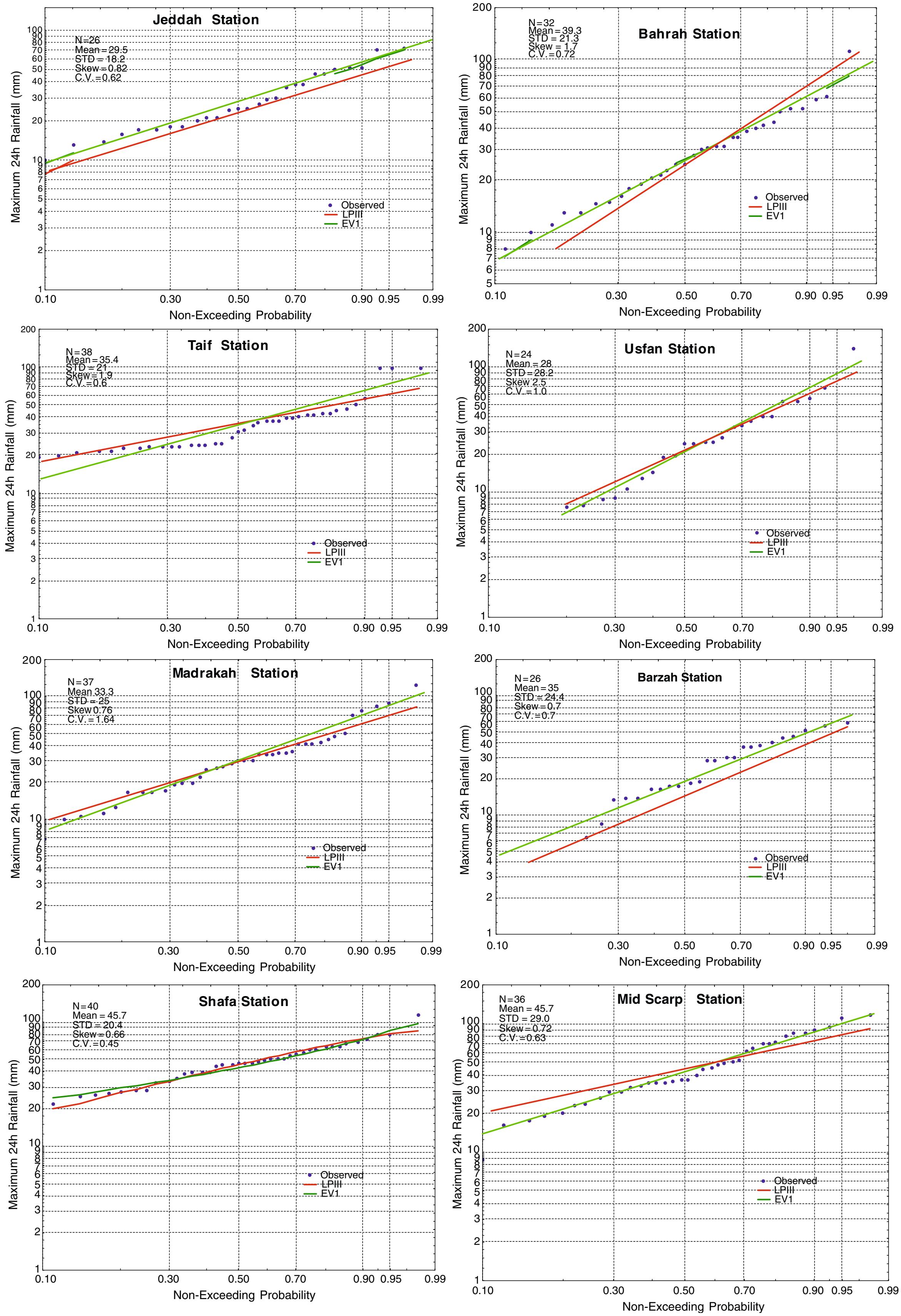

Fig. 2 Annual maximum daily rainfall and probability plot

Table 2 Prediction (millimeter) for Gumbel pdf for selected return periods (in years) based on 24-h duration data

ID	Site	Probability Return period (year)	0.995 200	0.99 100	0.98 50	0.96 25	0.9 10	0.8 5	0.667 3	0.5 2
J102	Bahrah		108.8	97.2	85.5	73.8	57.9	45.4	35.5	26.5
J134	Jeddah		98.9	88.7	78.5	68.3	54.4	43.5	34.8	27.0
J214	Madrakah		123.5	110.2	96.9	83.6	65.5	51.2	39.9	29.7
J221	Usfan		136.6	120.7	104.8	88.7	67.1	49.9	36.3	24.1
J239	Barzah		130.9	117.8	103.4	89.2	69.6	54.7	42.5	31.6
TA109	Shaffa		121.5	110.4	99.3	88.1	72.9	60.9	51.4	42.9
TA206	Taif		111.3	100.2	89.0	77.8	62.6	50.6	41.1	32.5
J205	Mid Scarp		151.1	135.7	120.2	104.6	83.5	66.9	53.7	41.7

Table 2 shows the prediction for a 24-h duration along with those for 2-, 3-, 5-, 10-, 25-, 50-, 100-, and 200-year return periods according to Gumbel's pdf. The Gumbel pdf overestimates high return periods (e.g., 100 and 200 years) and does not fit well in the higher probability range compared to maximum real data, especially with short records (e.g., Usfan and Barzah stations). In addition, variations in rainfall are also important factors affecting its prediction.

Figure 3 shows the comparison between maximum observed rainfalls and different return periods. Stations can be grouped into three categories: mountainous stations (e.g., Taif, Shaffa, and Mid Scarp), which show a strong relationship between the maximum observed rainfall and the predicted value over a 100-year return period; medium elevation stations (e.g., Madrakah, Usfan, and Bahrah) which exhibit a strong correlation between maximum observed rainfall and the predicted 200-year return period; finally, coastal or low elevation stations (e.g., Jeddah and Barzah) which display a strong correlation between the maximum observed rainfall and a 25-year return period. These differences may be due to different rainfall mechanisms, rainfall variability, topography, and the availability of short-term records.

The regional observed annual maximum rainfall over a 24-h period is shown in Fig. 4. This figure illustrates inconsistency in storms due to the topography of the study area, which is normal in arid regions. PMP values were estimated using the Gumbel distribution over a 50-year return period (Fig. 5). This data demonstrates an increase in rainfall from the southeast to the northwest (i.e., from 100 to 50 mm). In addition, Fig. 6 lists the PMP estimates for a 100-year return period, which also indicates a southeast to northwest increase (i.e., from 120 to 60 mm). These figures can be helpful when planning different structural designs.

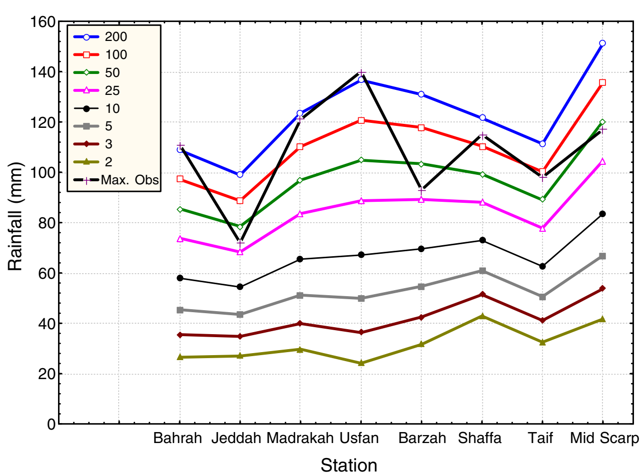

Fig. 3 Comparison of maximum observed and different return period of rainfall

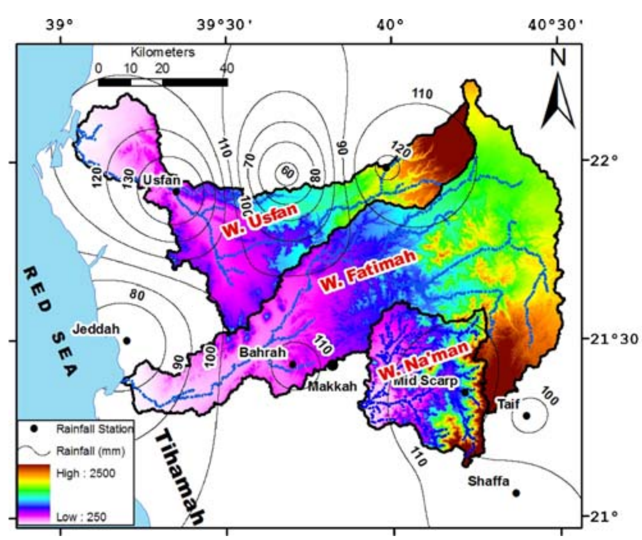

Fig. 4 Annual maximum observed of 24-h rainfall

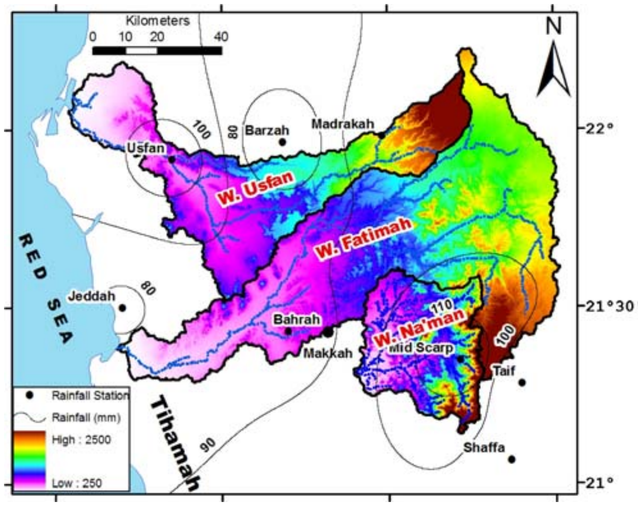

Fig. 5 Probable maximum 24-h rainfall for 50-year return period

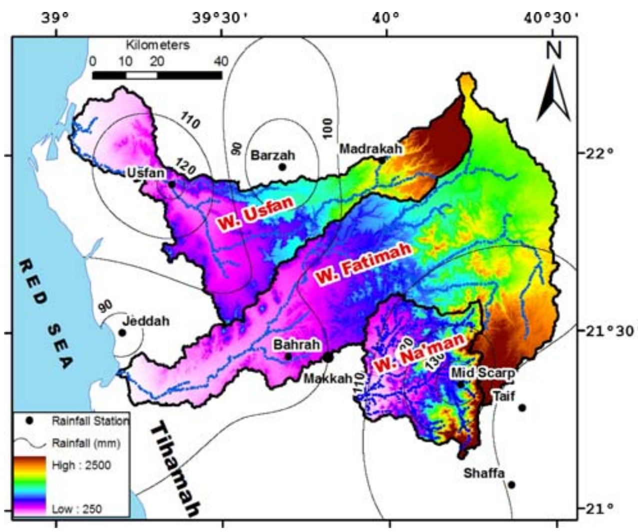

Fig. 6 Probable maximum rainfall of 24 h for 100-year return period

Calculating the PMF begins with obtaining an estimate of the PMP as shown in Figs. 4, 5, and 6, along with the runoff coefficient, C_R, for the basins of ungauged wadis from their catchment areas using Eq. 9 as shown in Table 2. Additionally, the observed flood volume was estimated from the maximum observed 24-h rainfall as shown in column 5 of Table 3. The PMF was calculated for 50- and 100-year return periods using Gumbel's pdf as shown in columns 7 and 9, respectively. Figure 7 shows a comparison of PMF estimations between observed 50- and 100-year return periods. In the Fatimah basin, the observed PMF was between the 50- and 100-year estimates. In contrast, the Usfan and Na'man basins displayed less than the observed results due to rainfall variability and the availability of short-term records.

Conclusion

In Makkah area of western Saudi Arabia, flash floods often take place as a consequence of excessive highly intense rainfall. Urban areas and major wadis are subject to destructive floods. Three major wadis, namely Na'man, Fatimah, and Usfan, with eight rainfall stations were selected to quantify rainfall frequency curves and flood probabilities. Gumble's pdf was elucidated to be the best fit for predicting annual maximum 24-h rainfall over 5-, 10-, 50-, and 100-year return periods. Flood analysis was investigated indirectly since records were unavailable for floods in the study area. However, PMP and PMF maps were also presented for different return periods. These results can be used for the design of future water projects and flood hazard management. Furthermore, it is recommended to install a new network of daily rainfall stations. Runoff measurement stations in the major streams of basins are also needed, as well as flood warning systems in populated areas.

Table 3 Runoff coefficients, PMP, and PMF of wadis in Makkah area

Basin	Area (km^2)	Runoff coefficients	Maximum observed rainfall (mm)	Runoff volume (10^{6}m^3)	PMP 50-year (mm)	Runoff volume (10^{6}m^3)	PMP 100-year (mm)	Runoff volume 10^{6}m^3)
Na'man	1,543	0.0717	120	13.3	105	11.6	116	12.8
Fatimah	5,085	0.0467	105	24.9	100	23.8	110	26.1
Usfan	2,830	0.0576	110	17.9	90	14.7	100	16.3

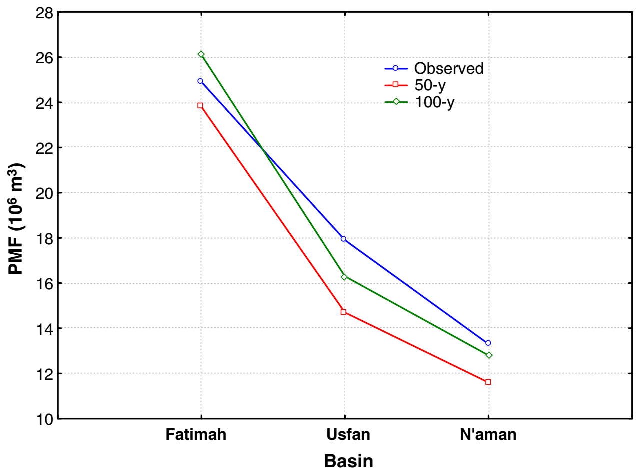

Fig. 7 Comparison between observed and 50- and 100-year PMF

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