Research Article

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Modeling of IDF curves for stormwater design in Makkah Al Mukarramah region, The Kingdom of Saudi Arabia

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Abstract: Reducing the negative impacts of flooding in Makkah AL Mukarramah region in the Kingdom of Saudi Arabia (KSA) is of utmost importance. In the last decade, there are huge mega infrastructure projects in KSA in general and in Makkah AL Mukarramah region in particular. These projects require adequate stormwater drainage systems. Since, the availability of rainfall and runoff data are scarce, engineers and hydrologists rely on models developed in temperate regions that are not hydrologically similar from temperate regions. This leads to inaccurate designs of stormwater facilities. Therefore, developing in situ Intensity-Duration-Frequency (IDF) curves is a must in this arid region. This paper aims at modeling IDF curves for Makkah Al-Mukarramah region. Maximum annual daily rainfall series of 80 storms (with sub-hourly and hourly data) from four stations are investigated through six different probability distributions. Consequently, rainfall depth-duration-frequency models and curves are derived. Results revealed that the Gumbel Type I is the optimal one. Thus, it is used to deduce the IDF curves and relations for each station and for the region as a whole. The R^2 value for fitting power-law function ($i = aD^b$) to the data is very high for the IDF parameters. The R^2 for the coefficient parameter, a , is between 0.9999 and 0.9988 while it ranges between 0.8754 and 0.8039 for exponent parameter, b . High correlation coefficient (more than 0.95) has been obtained. The resulting IDF models are strongly recommended for rigorous, effective and safe design of the stormwater systems in Makkah Al-Mukarramah region.

Keywords: Rainfall, Intensity-Duration-Frequency (IDF) Curves, Models, Stormwater Design, Probability Distributions, Makkah Al Mukarramah Region, Kingdom of Saudi Arabia, Arid Zone

1 Introduction

The intensity duration frequency curves (IDF) represent a relation between the rainfall intensity i , the duration D , and the return period T . The IDF-curves allow for the estimation of the rainfall intensity of a given return period for different aggregation times (i.e. durations). The IDF curves are extensively used by civil engineers and hydrologists to develop design storms (DS) required in the design of hydraulic structures. Safe and economic design of any flood mitigation measures and flood control structures are relying on the IDF curves. Usually, the peak runoff for a particular watershed is calculated with the use of the IDF curves together with the rational method. Design of culverts and pipes of stormwater networks and flood management are usually dependent on IDF curves.

Establishing IDF relationships requires historical data of good quality and continuous for long term. Unfortunately, the adequate long-term data sets are frequently not available in general and in arid and semi-arid regions in particular. Developing IDF curves needs hourly rainfall data for a long-term, which is often unavailable. In the absence of this data, the designer resorts to estimate the DS relying on curves from others areas, which might be not hydrologically similar to his study area, or his experience. As a result, the infrastructures are frequently inadequate and vulnerable to flooding as seen more frequently in the recent years in Makkah Al- Mukarramah region. In such areas, stormwater and flood management facilities provide a significantly lower level of protection. Much of such facilities, installed in the last several decades, are not effective to handle the todays' and future storms.

Recently, Hasanean, H. and Almazroui [1] found significant changes in average annual rainfall in Saudi Arabia for the period (1978–2009). It is remarkable to note

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that precipitation in Saudi Arabia during the period 2000–2009 increased in some parts and decreased in other parts, for instance, it increased significantly along the Red Sea coastal area and reduced in most of the other regions compared to the period from 1980 to 1989.

On the 17th of November, 2015, for example, heavy rainfall storm covered part of Makkah Al Mukarramah region. It has been recorded by satellite imagery (Figure 1a) and ground station radar as shown in Figure 1b. The peak rainfall ranges between 50 to 100 mm. The rainfall depth for such storm is also recorded from a rainfall ground station in the area to be 79 mm (King Abdulaziz Airport rainfall station). This lies in the range observed from the satellite data. However, negative impacts resulted from the rainwater accumulation of 17-11-2015 storm in Jeddah streets in many places of the storm event are observed (see Figure 2).

So, the aim of this study is the creation of intensity duration frequency IDF for Makkah Al Mukarramah region from the available storm data that has records for hourly and sub-hourly information. Although a considerable number of studies has been implemented to rainfall depth analysis in some regions in KSA, a few studies are conducted for the estimation of IDF curves over KSA. Moreover, there is no developed finite IDF study for Makkah Al Mukarramah region. The published literature on the topic is presented below.

Al-Shaikh [2] divided Saudi Arabia into six regions (These zones are: I South-western region, II mountainous area along the Coast of the Red Sea, III Northern region, IV Central and Eastern region, V Southern region and VI Rob'a Al-Khaly region) and derived rainfall depth-duration-frequency relationship (DDF) for each region. He used EV1 (Gumbel extreme value type I) distribution with the application of maximum likelihood method for parameter estimation procedure using rainfall intensity data from individual stations available in the eighties. In one hand, it is not clear in this study whether the analysis is based on hourly and sub-hourly measured data of the storms and on the other hand the study is being old that needs to be updated based on recent data and it seems that he did not provide IDF curves.

Al-Hassoun [3] performed a study regarding rainfall analysis of IDF curves in Riyadh area using Gumbel and Log Pearson type III methods. He did not find much difference in results between the two methods. He referred this to flat topography and semi-arid climate of the Riyadh region. However, in this study, the whole region of Riyadh is not covered since he used only one rainfall station in Wadi Hanifa which is outside the current study area.

Elsebaie [4] derived IDF equations for two regions namely Najran and Hafr Albatin regions using two distribution methods (Gumbel and Log Pearson Type III distributions, LPT III) for a duration varying from 10 to 1440 minutes and return period from 2 to 100 years. The application of the Gumbel distribution gave results slightly higher compared to the results obtained from LPT III distribution. The two methods used Gumbel and LPT III distribution gave values of rainfall intensities that agree very well with other results obtained from other carried out in this study area. The analysis of rainfall and rainfall frequency results obtained by [5] from eight stationary places in southwestern Saudi Arabia included data up to 2007. The author used Gumbel and Log-Pearson Type III (LPT III) and preferred Gumbel based on visual inspection rather than the statistical tests. Also, this study considered rainfall depth analysis and not developing IDF of the area. From rainfall records at Al-Madina Al-Monawara Station that extended for 43 years.

Al-Anazi and Elsebaie [6] developed Intensity-Duration-Frequency relationships for Abha city in the KSA. For eight different durations (10, 20, 30, 60, 120, 180, 360, and 720 minutes) and six frequency periods (2, 5, 10, 25, 50, and 100 years), IDF curves are obtained relying on 34 years of data. Three frequency distributions, namely: Gumbel, Lognormal and Log Pearson Type III distribution have been used to develop the IDF relationships. It has been found that generally there were slight differences between the results obtained from the three methods. The main issue in their analysis is that they assumed the maximum daily rainfall to be distributed over the eight duration mentioned above, which means that they did not use actual rainfall durations with the storm details (*i.e.* hourly and sub-hourly data) since this information is lacking in many stations in KSA. Therefore, the developed IDF curves in their work are questionable.

Awadallah [7] reviewed most articles of the rainfall frequency of Jeddah and registered significant variations in the results and concluded its unsuitability for design making. The other articles mentioned above are based on synthetically disaggregating daily rainfall to hourly time series and not relying on real measurement and hence need further investigations for their accuracy. Consequently, developing such curves from rainfall data based on hourly and sub-hourly measurements for Makkah Al Mukarramah region is a must for reliable flood mitigations measures. Therefore, rainfall data for a period of 22 to 26 years are collected. The data contains 80 rainfall storms ranging from 10 minutes to 24 hours' duration. Daily rainfall series have been investigated through six different probability distributions; Gumbel Type I, two-parameter Log-Normal,

Figure 1a: Measurement of the rainfall storm over Jeddah city in Makkah Al Mukarramah region on the 17th of November, 2015 from Satellite (Global Precipitation Mission the G-WADI project: <http://hydus.eng.uci.edu/gwadi/>).

Rainfall over KSA on 17-11-2015

Satellite Radar Measurements

Ground Radar Measurements

Figure 1b: A visual comparison between measurements of the rainfall storm over Jeddah city in Makkah Al Mukarramah region on the 17th of November, 2015 (Global Precipitation Mission the G-WADI project: <http://hydus.eng.uci.edu/gwadi/>).

Figure 2: Water accumulation in Jeddah streets of the storm event on the 17th of November, 2015 left image top image: Alfalak roundabout, right top image: in front of Global international school (Hail street), left bottom image: Asteen street before Alfalak roundabout, and right bottom image: King Abdullah road at the tunnel.

three-parameter Log-Normal, Pearson Type III, Log-Pearson Type III and Generalized Extreme Value distribution (GEV). A set of curves are plotted both for the depth-duration-frequency curves (DDF) and the IDF curves. Root mean square error (RMSE) is used for defining the best probability distributions. Parameter estimation and correlation analysis between observed and measured intensities are also investigated.

Subyani and Al-Amri [8] developed a formula from IDF curves. The reduction method was used to change the daily rainfall to hourly time series for the development of suitable IDF curves. The reduction method is a technique that disaggregate the daily rainfall to sub-daily rainfall due to the lack of hourly rainfall records.

Subyani and Hajjar [9] studied and analyzed daily, annual and seasonal rainfall data recorded in six stations in Jeddah area for the period 1971-2012. They revealed the detailed features of the dry, wet spells and rainfall intensity, and concluded at the same time that the arid region rainfall variation and intensity is affected by climate change for Jeddah area. This realization recommends more examination for each 5 years to observe the differences.

From the aforementioned review, most studies are related to rainfall analysis of daily rainfall. Few studies, focus on sub-daily rainfall analysis, however, these studies are outside Makkah Al Mukarramah region. The published articles tackled the IDF analysis of Makkah Al Mukar-

ramah region are almost nil, therefore, the current study fills the gap to cover the IDF of the region. The study focuses on developing the IDF of Makkah Al Mukarramah region to be used in the storm water design and provide the safe design in the region.

2 Data Collection

The climate of Makkah Al Mukarramah regions classified as arid and the daily temperature is very high and at night there is an abrupt drop in temperature. Rainfall is slightly low and erratic and generally unevenly distributed. Most rainfall occurs in Al Taif district. The total amount of rainfall during the whole year may be an outcome of one or two torrential outbreaks which causes flooding in wadis. The average rainfall is about 100 millimeters per year. Figure 3 shows the location of the study area and its neighboring regions.

Data used in the current study had been produced from data of autographic rain gauges set up and maintained by the Ministry of Water and Electricity (currently: Ministry of Environment, Water and Agriculture), which is actually responsible for many hydrological activities in the KSA. Table 1 summarizes the available data from the rainfall stations. Although the region has many recording rainfall gauges, not all of these stations had a reliable data, (see Table 1). Trustworthy data available from only four stations with sub-day information in the region are utilized.

The altitude of the stations vary between 53 m (amsl) near the Red Sea Coast up to 11260 m (amsl) in the mountainous area in Al Taif. Historic records of the maximum daily and sub-daily rainfall depths in millimeters with a time interval (10, 20, 30, 60, 120 min, etc.) for the stations are available in the selected stations. Requirements to determine rain events usually are depending on threshold values for specified properties of rain events. Rainfall depths more than a threshold value of 10 mm are only considered. It should give an acceptable representation of the storms that could produce runoff according to [10–13]. Accordingly, 80 rainfall storms that fulfill the aforementioned criterion are selected for further analysis. The data records revealed a power relationship between rainfall intensity and the duration of the storm with a coefficient of determination of 0.71 as shown in Figure 4. This relationship suggests the use of power law equation for the design IDF curves. Relying on such storms, IDF studies are carried out as follows.

Figure 3: Locations of rainfall stations with sub-daily storm record in Makkah Al Mukarramah region.

Table 1: Stations used in the current study with hourly measurement storms.

Zone	Station number	Station name	Station symbol	Altitude (m)	Recorded storms		Coordinates		Total number of storms	Total
					From	To	Longitude	Latitude		
Jeddah	214	Mudaylif	J 001	53	1975	2001	41°03'00"	19°32'00"	19	19
Al Taif	625	Hema	TA002	1500	1975	2000	40°30'00"	21°18'00"	27	61
		Saysid								
	627	Taif	TA004	1530	1980	2003	40°27'00"	21°24'00"	19	
	628	Turabah	TA005	11260	1975	1997	41°40'00"	21°11'00"	15	
Total										80

Figure 4: The relationship between actual rainfall intensity and the duration of the storms from the storm data of the four stations.

3 Extraction of the IDF curves

IDF curves are discussed in numerous hydrologic engineering books e.g., [15, 16]. However, to the best of the authors' knowledge, detailed derivation of the curve is not explained either in books or in research articles. Therefore, a systematic approach is presented herein. The actual IDF curves for a given site are usually given in different forms of power expression [15] such as,

$$i(D, T) = \frac{cT^m}{D^e} \quad (1a)$$

$$i(D, T) = \frac{cT^m}{(D + s)^e} \quad (1b)$$

$$i(D, T) = \frac{c + m \ln(T)}{D^{[1/(s + e \ln T)]}} \quad (1c)$$

Where $i(D, T)$ is the average intensity as a function of the duration, D , and the return period, T , and c , e , s and m are fitting constants.

Details of construction of IDF relationships and IDF curves in the current study are conducted via the following steps (Figure 5 shows the procedure graphically):

1. Collection of the reliable storms: rainfall data from the Ministry of Water and Electricity are collected. Continuous rainfall storms with storm details (i.e. at 10, 20, 30, 60, 120 and 1440 min) are only considered.

2. Ranking the list of rainfall depth with specific duration in a descending order and compute the Weibull plotting position for each depth, r , [17] as:

$$P(R \geq r) = \frac{k}{n + 1} \quad (2)$$

Where,

R is a random variable,

$P(R \geq r)$ is the probability of the random variable R to have the value or larger than r , which is the plotting position which corresponds to the exceedance probability of rainfall depth, r ,

k is the ordered sequence of rainfall depth values, and n is the number of observations.

3. Computing the recurrence interval T for each predicted rainfall depth as the reciprocal of the plotting position [18] with the equation,

$$T = \frac{1}{P(R \geq r)} = \frac{n + 1}{k} \quad (3)$$

Defining the optimal probability distributions: Defining the optimal probability distribution is a prerequisite for derivations of rainfall depth-duration-frequency (DDF) relationships for each station in the region under study. There is commonly used theoretical probability distribution functions applied in different regions in the world. Annual maximum daily (24 hr duration rainfall series investigated through six probability distributions functions. These techniques are: the Gumbel Type I, the two-parameter Log-Normal, the three-parameter Log-Normal,

Figure 5: The procedure for return period calculations: (a) the time series of the rainfall depth in a chronological order for each specified duration (t-hour) where t- stands for 1/6 hr, 1/3hr, 1/2hr, etc., (b) ordering the data in a descending way, (c) estimating the probability of exceedance, and (e) plotting the data of rainfall with respect to return period and fitting a cumulative distribution function, CDF, for forecasting the 5, 10, 25, 50, 100, and 200 years.

the Pearson Type III, the Log- Pearson Type III (LPT III) and the Generalized Extreme Value distribution (GEV), Figure 6. Details of such distributions are shown in [14]. Both stormwater management and design aid (SMADA) software developed by Wanielista *et al.* (1997) [19] and IH-Flood software developed by Institute of Hydrology [20] are used in the analysis of the rainfall data. Various parameter estimation methods (method of moments, maximum likelihood estimation, probability weighted method, L-moments, etc.) which are available in the IH-Flood are used. IH-Flood optimizes the various parameters and defines the best probability distribution. The goodness of fit test based on Kolmogorov–Smirnov (K-S) test is used to find out the best probability distribution to describe the data. Table 2a shows the results of the test for the four stations. It is concluded that none of the distributions can be rejected. The calculated K-S value from the data is below the tabulated value at 5% significant level. Each station has its own significant level based on the number of degrees of freedom. The minimum K-S is obtained at Gumbel Type I distribution for all stations. The root mean square error (RMSE) [21] is used to estimate the average error. RMSE value describes the average discrepancy between the expected and the observed values. The root

mean square error criterion, RMSE was given by,

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n [\hat{R}_i - R_i]^2} \quad (4)$$

Where,

R_i is the total observed rainfall depth at the station, $\hat{R}_i$ is the expected total rainfall depth from the probability distribution, and n is the number of data points at the station.

The results shown in Figure 6 and Table 2b reveal that the Gumbel Type I distribution is the best one for stations J001, TA004, and TA005 which is also confirmed by the K-S test. However, for station TA002, the LPT III is the best. Such result agrees with the previous results obtained on different region all over the world [14] and in a similar arid region in Jordan [17]. Results obtained by Al-Shaikh [2] and Mills and Shata [10] indicate very close values between Gumbel Type I and LPT III distribution at most of the return period and have the same trend. Elsebaie (2012) noticed some larger rainfall intensity estimates of Gumbel compared to the LPT III distribution for Najran and Hafr Albatin regions in SA. Ewea *et al.* [22] and Subyani and Al-Amri [8] assured that there is no remarkable difference between Gumbel and LPT III for Al-Madinah city in SA. There-

Figure 6: Fitting different probability distributions to the 24 hr rainfall data of the four stations.

Table 2a: Goodness of fit test based on (Kolmogorov–Smirnov) K-S test.

Stations	Gumbel Type I	2Par Log-Normal	3Par Log-Normal	Pearson Type III	Log- Pearson Type III	GEV
J 001	0.024	0.085	0.079	0.049	0.043	0.028
Tabulated K-S value at 5% Significant Level			0.454			
TA 002	0.093	0.197	0.261	0.133	0.101	0.136
Tabulated K-S value at 5% Significant Level			0.281			
TA 004	0.106	0.14	0.257	0.115	0.129	0.122
Tabulated K-S value at 5% Significant Level			0.43			
TA 005	0.081	0.099	0.135	0.236	0.094	0.163
Tabulated K-S value at 5% Significant Level			0.361			

Bold-Italics font in the table shows the minimum K-S value obtained from the data.

Table 2b: Root mean square error (RMSE) in mm for testing different probability distributions at 24hr duration.

Stations	Gumbel Type I	2Par Log-Normal	3Par Log-Normal	Pearson Type III	Log- Pearson Type III	GEV
J 001	10.43	15.59	11.58	11.35	11.49	12.84
TA 002	19.0	20.46	20.45	19.14	15.6	19.41
TA 004	4.04	5.23	4.61	4.57	4.11	5.37
TA 005	2	3.14	2.3	2.24	2.25	2.79

Bold-Italics font in the table shows the minimum RMSE.

Table 3: Comparison between the Recorded Maximum Daily Rainfall and the Expected Rainfall for Different Return Periods from 2 to 200 years.

Station	Recorded storms		Max. recorded over the history of the station		Return period rainfall (Years)						
	from	to	Max Rainfall (mm)	Year	2	5	10	25	50	100	200
J001	1975	2001	96.4	1978	33.1	59.21	76.5	98.35	114.55	130.64	146.67
TA002	1975	2000	127.4	1996	30.06	52.12	66.73	85.19	98.88	112.47	126.01
TA004	1980	2003	56.6	1987	28.57	40.67	48.67	58.79	66.3	73.75	81.17
TA005	1975	1997	49.8	1978	18.2	28.79	35.8	44.66	51.23	57.75	64.25

Bold face italics: are the max. values recorded in the stations

Bold face: are the values with return periods that are equal or close to the maximum observed values in the stations.

fore, since the majority of the stations in the current study follow Gumbel distribution, it has been selected for further analysis. The 24 hours rainfall is used to test the best probability distribution of the data as mentioned above. The obtained best distribution based on the 24 hours rainfall is applied for rainfall depths less than 24 hours (sub-hourly rainfall) to develop the so called depth-duration-frequency curves, DDF.

4. Plotting the rainfall depth against return periods: A Gumbel extreme value distribution (Type I) is used in the analysis and therefore, the equations are presented herein. The Gumbel extreme value cumulative distribution is expressed mathematically as

$$P(R \leq r) = \text{Exp}\{-\text{Exp}[-\alpha(r - \beta)]\} \quad (5)$$

Where $(R \leq r)$ = probability of non-exceedance, Exp is the Napier's constant, α and β are the distribution parameters which are given by Kite [21],

$$\alpha = 1.2825/\sigma \quad (6)$$

$$\beta = \mu - 0.45\sigma \quad (7)$$

where μ is the mean of the rainfall data, and σ is the standard deviation of the rainfall data.

The recurrence interval (return period) is also equal to reciprocal of exceedance probability in the form,

$$T = \frac{1}{P(R \geq r)} = \frac{1}{1 - P(R \leq r)} \quad (8)$$

Equations (6) and (8) are equated, rearranged, and the logarithm is taken twice to yield a formulation for rainfall depth as,

$$r = \beta - \frac{1}{\alpha} \ln \left[-\ln \left(1 - \frac{1}{T} \right) \right] \quad (9)$$

5. Computing the rainfall depth for each return period using the prediction equation, Equation (9).

6. Plotting the rainfall depths in relation to return periods in a semi-log graph. Table 3 shows that the maximum rainfall recorded for each station had a different return period. It has been shown from the table that, the maximum recorded rainfall is near 25 years for station J001 and T004, while it is near 200 and 50 years for stations T002 and T005 respectively.

7. Calculation of rainfall intensities: rainfall intensities for each duration (10, 20, 30, 60, 120 min, etc.) are calculated based on the aforementioned steps. Figure 7 shows the results of the fitting procedure mentioned above for the four stations. Figure 8 reveals the spatial distribution of the 24 hours rainfall depth data over the Makkah Al Mukar-

Figure 7: Fitting Gumbel distribution (solid lines) to maximum rainfall depth (dotted lines) at the given stations for different return periods (2, 5, 10, 25, 50, 100, 200 years) and at different durations (10, 20, and 30 minutes, and for 1, 2, 3, 6, 12, and 24 hours respectively). The depth-duration-frequency curves (DDF).

ramah region for 5, 10, 25, 50, 100, and 200 years return periods.

8. Developing the IDF models: empirical formulae in the form given below is used to construct the rainfall IDF curves,

$$i(D, T) = aD^b \quad (10)$$

where D is the rainfall duration, a and b are fitting parameters (functions of return periods) for the duration.

The reasons to derive models are twofold: first is that to make it easy for engineers and hydrologists to use it in their analysis and not depending to the graphical version of the data. The second fold is to get the intensity and any specified duration that is not present in the data. The least-square method is applied to determine the parameters of the empirical IDF equation that is used to represent IDF relationships. The parameters a and b are also related to the return period and obtained by least-square fitting method in the form of,

$$a = \delta \ln T + \epsilon \quad (11)$$

$$b = \varphi \ln T + \omega \quad (12)$$

Where, δ , ϵ , φ , ω are fitting constants for the return periods.

The goodness of fit is tested by the calculation of the coefficient of determination, R^2 ,

$$R^2 = \left[\frac{\sum_{j=1}^N (O_j - \bar{O})(E_j - \bar{E})}{\sqrt{\sum_{j=1}^N (O_j - \bar{O})^2 \sum_{j=1}^N (E_j - \bar{E})^2}} \right]^2 \quad (13)$$

Where,

O_j is the observed IDF values,

E_j is the expected IDF values from the fitted equation,

$\bar{O}$ is the mean of the observed IDF values, and

$\bar{E}$ is the mean of the expected IDF values from the fitted equation.

Table 4 shows the R^2 value for the fitting procedure. In all cases, the coefficient of determination for the parameter is very high and ranges between 0.9999 and 0.9988 while it ranges between 0.8754 and 0.8039 for the parameter b . Such coefficients indicate robust IDF formulas.

Substituting Equation 10 and 11 into Equation 9 yields,

$$u(D, T) = (\delta \ln T + \epsilon) D^{(\varphi \ln T + \omega)} \quad (14)$$

Figure 8: Spatiotemporal distribution of the expected daily rainfall depth over Makkah Al Mukarramah region at different return periods: (A) 5 years, (B) 10 years, (C) 25 years, (D) 50 years, (E) 100 years, (F) 200 years.

Table 4: Fitted relationships for parameters a and b of IDF formulae for the individual stations and the accompanied coefficient of determination.

District	Station symbol	IDF Eqn. Parameters			
		a	R^2	B	R^2
Jeddah	J 001	$a = 236.63\ln(T) + 388.48$	0.999	$b = 0.0107\ln(T) - 0.7869$	0.8237
Al Taif	TA 002	$a = 151.02\ln(T) + 263.5$	0.9989	$b = 0.0071\ln(T) - 0.743$	0.8368
	TA 004	$a = 178.41\ln(T) + 222.11$	0.9988	$b = -0.007\ln(T) - 0.7416$	0.8754
	TA 005	$a = 392.9\ln(T) + 70.586$	0.9993	$b = -0.019\ln(T) - 0.819$	0.8039

Equation 14 is the final formulae that can easily be utilized to determine the rainfall intensity given the station parameters δ , ϵ , φ , ω , and the return periods.

9. Regionalization of the station parameters: The IDF curves are derived from the point rain gauges. However, IDF curves at any location are needed for the design purposes. The regional IDF parameters are estimated for ungauged areas. This is done by averaging the parameters a , and b over Jeddah and Al Taif districts. Table 6 shows the regionalized parameters for the IDF for Jeddah and Al Taif districts. However, Table 7 displaying the IDF equation for the region of Makkah Al Mukarramah has a whole.

4 Analysis of Individual Stations

A summary of the relationships of the fitting parameters of the IDF equations for the individual stations and the accompanied coefficient of determination are given in Table 4 and Figure 9a and 9b. Table 4 and Figure 9a and 9b summarize the derived relations for Makkah Al Mukarramah region.

Figure 10 shows a comparison between the observed and modeled rainfall intensity. The overall results in terms of correlation coefficient are very good as given in Table 5. The correlation coefficients shown in Table 5 is more than 0.95 and thence manifest good correlation between observed and modeled rainfall intensity. There is an overestimation between observed and modeled intensities for the last four values beyond 100 mm/hr. for station TA002 and TA004 to 150 mm/hr for station J001 and TA005. This is due to the fact that the storm duration is relatively small in this part of the graph and it may suffer from inaccurate measurements by the measuring device for short duration storms. Therefore, it is advisable not to rely on very short duration storms (less or equal 10 minutes) when using these curves. Table 5 shows also the RMSE of the observed and modeled intensity. The maximum RMSE is 20 mm/hr at J001 station.

Table 5: Correlation Coefficient and RMSE between Observed Rainfall Intensity and Modelled Rainfall Intensity.

District	Station symbol	Correlation coefficient	RMSE (mm/hr)
Jeddah	J 001	0.967	20.3
Al Taif	TA002	0.96	15
	TA004	0.964	13.6
	TA005	0.991	10

The resulted IDF curves show that the rainfall intensity increases as the return period increases. As the duration increases, the intensity decreases for the same return period and in all return periods. These common trends in all stations are consistent with the common IDF behavior. On the base of the above analysis, the estimated return period for the storm occurred on 17th November, 2015 (79 mm) is almost corresponding to 10 years (Table 3, Station J001 76.5 mm).

5 District Analysis

The current study developed IDF relationships for Jeddah and Al Taif districts and for the Makkah Al Mukarramah region as a whole. However, careful confidence has to be paid while using the derived IDF relationships since the available storms from the stations and the number of stations are not enough to adequately cover of the whole region. Therefore, developing a regional rainfall intensity-duration-frequency model has been inspired. Data of individual stations were compounded to produce representative regional IDF models. This has been done by averaging the parameters a and b from the various stations. This particular method has been effectively utilized in rainfall researches by many investigators such as [23–26]. A summary of the district IDF relationships is given in Table 6 and 7. The representative IDF curve for Makkah Al Mukarramah region as presented in Table 6 and Figure 11.

Figure 9a: Fitted IDF formulae for the individual stations in Jeddah region and the accompanied relationships for a and b parameters.

Figure 9b: Fitted IDF formulae for the individual stations in Al Taif region and the accompanied relationships for a and b parameters.

Figure 10: Comparison between Observed Rainfall Intensity and Modelled Rainfall Intensity.

Table 6: Modeled relationships for parameters a and b of the IDF formulas for the Jeddah and Al Taif districts in Makkah Al Mukarramah region and the accompanied coefficient of determination.

Zone	IDF Eqn. Parameters			
	a	R ²	b	R ²
Jeddah	$a = 236.63\ln(T) + 388.48$	0.999	$b = 0.0107\ln(T) - 0.7869$	0.8237
Al Taif	$a = 240.78\ln(T) + 185.4$	0.9991	$b = -0.006\ln(T) - 0.7679$	0.8189

Figure 11: Fitted IDF formulas and the accompanied relationships for parameters (a) and (b) for Makkah Al Mukarramah region as a whole.

Table 7: Regional model for parameters a and b of the IDF formula for Makkah Al Mukarramah region as a whole and the accompanied coefficient of determination.

Zone	IDF Eqn. Parameters			
	a	R^2	b	R^2
Makkah region	$a = 239.74\ln(T) + 236.17$	0.9991	$b = -0.002\ln(T) - 0.7726$	0.8127

IDF curves resulted indicate nonlinear increasing relationships between values of the a parameter and the corresponding return period in all cases and on the contrary for the b parameter for most cases. Usually, the a parameter is greater than the b parameter for all values of return periods. The a parameter shows relatively high sensitivity with respect to return periods, while the b parameters exhibit very low sensitivity for return periods.

Since Jeddah is represented with only one station and the effects of the monsoons and the topography often distinguish variable rainfall pattern, cautious application might be considered in the use of the IDF equations in the region.

6 Conclusions

IDF models and curves are developed to estimate rainfall intensities for different durations and different return periods in Makkah Al Mukarramah region. Detailed storms (hourly and sub-hourly rainfall data) have been collected from four stations in the region. Both IH-flood software and SMADA software are used to investigate six different probability distributions. The root mean square error (RMSE) is used for testing different probability distributions and determines the best one for the data at 24 hr interval and then applied to the sub-intervals. Results revealed that the Gumbel Type I is the optimal one. Thus, it has been used to construct the IDF curves and models. The parameters of the IDF curves have been established for each station and the regionalization is made for Makkah Al Mukarramah region as a whole. The R^2 value for fitting a power law function ($i = a D^b$) to the data is very high for the IDF parameters. The R^2 for the coefficient parameter, a , is between 0.9999 and 0.9988 while it ranges between 0.8754 and 0.8039 for exponent parameter, b . The high correlation coefficient (more than 0.95) has been obtained between observed and modeled rainfall intensity. The curves and models resulted are intended to enhance watershed design practice in Makkah Al Mukarramah region. In the future, hopefully with measurements from further stations, and longer rainfall records, the analyses de-

scribed above should be repeated perhaps every 5 years to accommodate the effects of climate change in these IDF models and introducing uncertainty in these curves as well.

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