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ORIGINAL ARTICLE

Developing rainfall intensity–duration–frequency relationship for two regions in Saudi Arabia

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Abstract Intensity–duration–frequency (IDF) relationship of rainfall amounts is one of the most commonly used tools in water resources engineering for planning, design and operation of water resources projects. The objective of this research is to derive IDF relationship of rainfall at Najran and Hafr Albatin regions in the kingdom of Saudi Arabia (KSA). These relationships are useful in the design of urban drainage works, e.g. storm sewers, culverts and other hydraulic structures. Two common frequency analysis techniques were used to develop the IDF relationship from rainfall data of these regions. These techniques are: Gumbel and the Log Pearson Type III distribution (LPT III).

An equation for estimating rainfall intensity for each region was derived using both techniques. The results obtained using Gumbel distribution are slightly higher than the results obtained using the LPT III distribution. Rainfall intensities obtained from these two methods showed good agreement with results from previous studies on some parts of the study area. The chi-square goodness-of-fit test was used to determine the best fit probability distribution. The parameters of the IDF equations and coefficient of correlation for different return periods (2, 5, 10, 25, 50 and 100) are calculated by using non-linear multiple regression method. The results obtained showed that in all the cases the correlation coefficient is very high indicating the goodness of fit of the formulae to estimate IDF curves in the region of interest.

1. Introduction

Rainfall intensity–duration–frequency IDF curves are graphical representations of the amount of water that falls within a given period of time in catchment areas (Dupont and Allen, 2000). IDF curves are used to aid the engineers while designing urban drainage works. The establishment of such relationships was done as early as 1932 (see Chow (1988) and Dupont and Allen (2006)). Since then, many sets of relationships have been constructed for several parts of the globe. However, such relationships have not been accurately constructed in many developing countries (Koutsoyiannis et al., 1998).

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Nomenclature

C	the skewness coefficient;	P_i	the individual extreme value of rainfall
I	rainfall intensity;	P_T	the desired rainfall peak value for a specific frequency;
IDF	Intensity–duration–frequency relationship;	S	standard deviation of P data;
K	Gumbel frequency factor	S^*	standard deviation of P^* data;
K_t	Log Pearson frequency factor	T	return period;
n	number of events or years of record;	T_d	rainfall duration;
P^*	the logarithm of the extreme value of rainfall;		
P_{ave}	average of maximum precipitation corresponding to a specific duration		

(Koutsoyiannis et al., 1998; Koutsoyiannis, 2003) cited that the IDF relationship is a mathematical relationship between the rainfall intensity *i*, the duration *d*, and the return period *T* (or, equivalently, the annual frequency of exceedance *f* typically referred to as 'frequency' only). Indeed the IDF-curves allow for the estimation of the return period of an observed rainfall event or conversely of the rainfall amount corresponding to a given return period for different aggregation times.

In Kentucky, for example IDF curves are used in conjunction with runoff estimation formulae; e.g. the Rational Method, to predict the peak runoff amounts from a particular watershed. The information from the curves is then used in hydraulic design to size culverts and pipes (Dupont and Allen, 2000). Further studies by Ilona and Francés (2002) performed rainfall analysis and regionalisation of IDF curves for different regions.

In recent studies, various authors attempted to relate IDF-relationship to the synoptic meteorological conditions in the area of the hydrometric stations (see Dupont and Allen (2006); Mohymont1 et al. (2004)). Al-Shaikh (1985) derived rainfall depth–duration–frequency relationships (DDF) for Saudi Arabia through the analysis of available rainfall intensity data. He added that Saudi Arabia could be divided into six rainfall zones. 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. Al-Shaikh, (1985) recommended that rainfall estimates from individual stations and regional analysis may be modified in future when new rainfall data become available.

Al-Dokhayel (1986) performed a study to estimate the rainfall depth duration frequency relationships for Qasim region in KSA at various return periods, using two continuous probability distributions, the extreme value type I distribution (Gumbel) and the LPT III distribution. Al-Dokhayel (1986) found that among the two distributions used in the study, the LPT III distribution method gave some larger rainfall estimates with small standard errors. Al-Khalaf (1997) conducted a study for predicting short-duration, high-intensity rainfall in Saudi Arabia. He found in the results that the short duration/high intensity rainfall was far from the universal relationship suggested by other researchers and concluded that a relation for each region has to be obtained to act as a useful tool in estimating rainfall intensities for different durations and return periods ranging between 2 and 100 years. Further studies by Al-Sobayel (1983) and Al-Salem (1985) performed Rainfall Frequency Distribution and analysis for Riyadh, Shaqra and Al-Zilfi areas in KSA.

With the recent technology of remote sensing and satellite data, Awadallah et al. (2011) conducted a study for developing IDF curves in scarce data region using regional analysis and satellite data. Awadallah et al. (2011) presented a methodology to overcome the lack of ground stations rainfall by the joint use of available ground data with TRMM satellite data to develop IDF curves and he used a method to develop ratios between 24-hr rainfall depth and shorter duration depths.

AlHassoun (2011) developed an empirical formula to estimate the rainfall intensity in Riyadh region. He found that there is not much difference in the results of rainfall analysis of IDF curves in Riyadh area between Gumbel and LPT III methods. He attributed this to the fact that Riyadh region has semi-arid climate and flat topography where variations of precipitation are not big.

2. Data collection

Data from different climatological stations in and around Najran city were obtained from the Ministry of Water and Electricity, however, only one of these stations had a good record (1967–2001) and time intervals (10, 20, 30, 60, 120, 180 min, etc...) with few missing data and the other stations have very few records of the data which are not presentable at all to be considered in the study. Also, data from seven rainfall stations representing the Central and Eastern region were available for different durations, but only Hafr AlBatin station among them had a good record (1967–2001) with the same time intervals, as previously mentioned. These zones are shown in Fig. 1. The available rainfall data were analysed to determine the peak rainfall for each year.

3. Development of IDF curves

For accurate hydrologic analyses, reliable rainfall intensity estimates are necessary. The IDF relationship comprises the estimates of rainfall intensities of different durations and recurrence intervals. There are commonly used theoretical distribution functions that were applied in different regions all over the world; (e.g. Generalized Extreme Value Distribution (GEV), Gumbel, Pearson type III distributions) (see Dupont and Allen (2000); Nhat et al. (2006); Hadadin (2005); Acar and Senocak (2008); Oyebande (1982); Raiford et al. (2007) and (AlHassoun, 2011). Two common frequency analysis techniques were used to develop the relationship between rainfall intensity, storm duration, and return periods from rainfall data for the regions under study. These

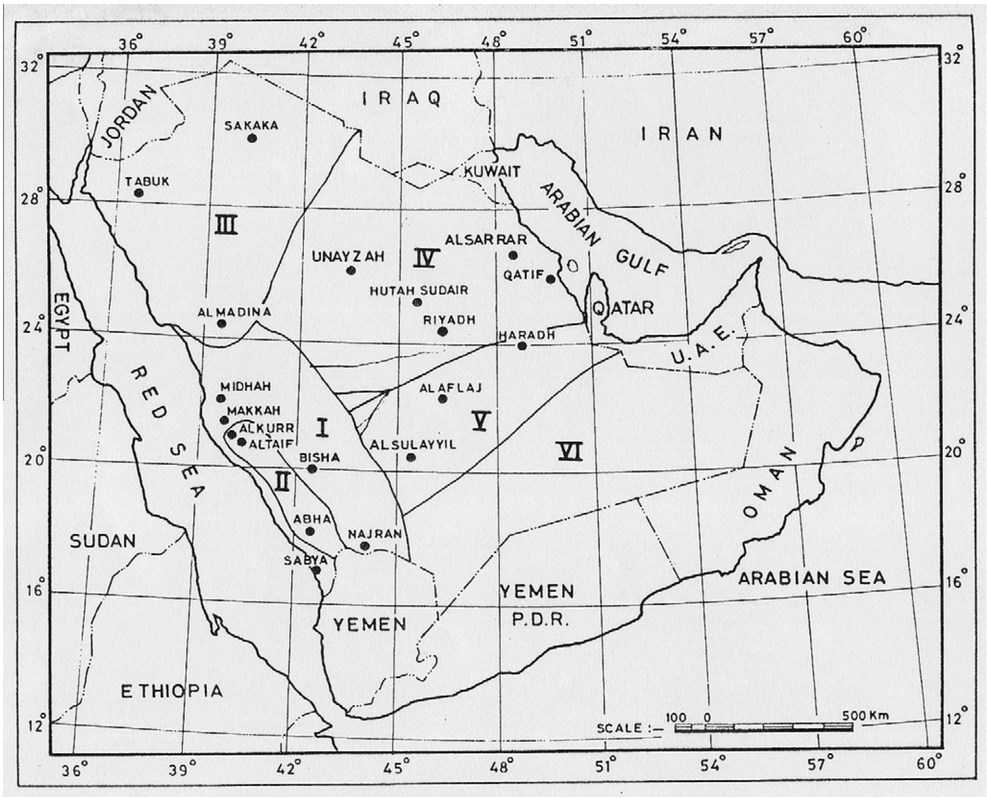

Figure 1 Rainfall zones in Saudi Arabia.

techniques are: Gumbel distribution and LPT III distribution. Either may be used as a formula or as a graphical approach.

3.1. Gumbel theory of distribution

Gumbel distribution methodology was selected to perform the flood probability analysis. The Gumbel theory of distribution is the most widely used distribution for IDF analysis owing to its suitability for modelling maxima. It is relatively simple and uses only extreme events (maximum values or peak rainfalls). The Gumbel method calculates the 2, 5, 10, 25, 50 and 100-year return intervals for each duration period and requires several calculations. Frequency precipitation P_T (in mm) for each duration with a specified return period T (in year) is given by the following equation.

$$P_T = P_{\text{ave}} + KS \tag{1}$$

where K is Gumbel frequency factor given by:

$$K = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left[\ln\left[\frac{T}{T-1}\right]\right]\right] \tag{2}$$

where P_{ave} is the average of the maximum precipitation corresponding to a specific duration.

In utilising Gumbel's distribution, the arithmetic average in Eq. (1) is used:

$$P_{\text{ave}} = \frac{1}{n}\sum_{i=1}^{n} P_i \tag{3}$$

where P_i is the individual extreme value of rainfall and n is the number of events or years of record. The standard deviation is calculated by Eq. (4) computed using the following relation:

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

where S is the standard deviation of P data. The frequency factor (K), which is a function of the return period and sample size, when multiplied by the standard deviation gives the departure of a desired return period rainfall from the average. Then the rainfall intensity, I (in mm/h) for return period T is obtained from:

$$I_t = \frac{P_t}{T_d} \tag{5}$$

where T_d is duration in hours.

The frequency of the rainfall is usually defined by reference to the annual maximum series, which consists of the largest values observed in each year. An alternative data format for rainfall frequency studies is that based on the peak-over-threshold concept, which consists of all precipitation amounts above certain thresholds selected for different durations. Due to its simpler structure, the annual-maximum-series method is more popular in practice (see Borga, Vezzani and Fontana, 2005).

From the raw data, the maximum precipitation (P) and the statistical variables (average and standard deviation) for each duration (10, 20, 30, 60, 120, 180, 360, 720, 1440 min) were computed. Tables 1 and 2 show the computed frequency precipitation (P_T) values and intensities (I_T) for different

Table 1 Computed frequency precipitation values and intensities for different durations and return periods using Gumbel Method for Najran region (Zone I).

Computed precipitation (P_T) and intensity (I_T) Gumbel method

Tr (year)	10 min			20 min			30 min		
	P_{ave} = 6.87		S = 3.08	P_{ave} = 7.96		S = 4.73	P_{ave} = 9.89		S = 6.46
	K	P_T	I_T	K	P_T	I_T	K	P_T	I_T
2	−0.164	6.362	38.175	−0.164	7.179	21.537	−0.164	8.828	17.656
5	0.719	9.081	54.489	0.719	11.356	34.068	0.719	14.536	29.072
10	1.305	10.882	65.290	1.305	14.122	42.365	1.305	18.315	36.630
25	2.044	13.156	78.938	2.044	17.616	52.847	2.044	23.090	46.180
50	2.592	14.844	89.063	2.592	20.208	60.624	2.592	26.632	53.265
100	3.137	16.519	99.113	3.137	22.781	68.343	3.137	30.149	60.297
	60 min			120 min			180 min		
	P_{ave} = 11.88		S = 7.56	P_{ave} = 12.89		S = 8.36	P_{ave} = 13.16		S = 8.77
2	−0.164	10.635	10.635	−0.164	11.515	5.757	−0.164	11.723	3.908
5	0.719	17.320	17.320	0.719	18.904	9.452	0.719	19.475	6.492
10	1.305	21.746	21.746	1.305	23.797	11.898	1.305	24.608	8.203
25	2.044	27.338	27.338	2.044	29.978	14.989	2.044	31.093	10.364
50	2.592	31.486	31.486	2.592	34.564	17.282	2.592	35.905	11.968
100	3.137	35.604	35.604	3.137	39.116	19.558	3.137	40.680	13.560
	360 min			720 min			1440 min		
	P_{ave} = 17.38		S = 10.51	P_{ave} = 16.97		S = 8.99	P_{ave} = 17.04		S = 7.86
2	−0.164	15.658	2.610	−0.164	15.494	1.291	−0.164	15.744	0.656
5	0.719	24.945	4.158	0.719	23.435	1.953	0.719	22.692	0.946
10	1.305	31.094	5.182	1.305	28.692	2.391	1.305	27.293	1.137
25	2.044	38.863	6.477	2.044	35.335	2.945	2.044	33.106	1.379
50	2.592	44.627	7.438	2.592	40.263	3.355	2.592	37.418	1.559
100	3.137	50.348	8.391	3.137	45.154	3.763	3.137	41.698	1.737

durations and six return periods following the methodology previously described.

3.2. Log Pearson type III

The LPT III probability model is used to calculate the rainfall intensity at different rainfall durations and return periods to form the historical IDF curves for each station. It is commonly used in Vietnam. LPT III distribution involves logarithms of the measured values. The mean and the standard deviation are determined using the logarithmically transformed data. In the same manner as with Gumbel method, the frequency precipitation is obtained using LPT III method. The simplified expression for this latter distribution is given as follows:

$$P^* = \log(P_i) \quad (6)$$

$$P^*_T = P^*_{\text{ave}} + K_T S^* \quad (7)$$

$$P^*_{\text{ave}} = \frac{1}{n}\sum_{i=1}^{n} P^* \quad (8)$$

$$S^* = \left[\frac{1}{n-1}\sum_{i=1}^{n}(P^* - P^*_{\text{ave}})^2\right]^{1/2} \quad (9)$$

where P^*_T, P^*_{ave} and S^* are as defined previously in Section 3.1 but based on the logarithmically transformed P_i values; i.e. P^* of Eq. (6). K_T is the Pearson frequency factor which depends on return period (T) and skewness coefficient (C_s).

The skewness coefficient, C_s, is required to compute the frequency factor for this distribution. The skewness coefficient is computed by Eq. (10) (see Chow (1988) and Burke and Burke (2008).

$$C_s = \frac{n\sum_i^{ni}(P^*_i - P^*_{\text{ave}})^3}{(n-1)(n-2)(S^*)^3} \quad (10)$$

K_T values can be obtained from tables in many hydrology references; for example (reference Chow (1988)). By knowing the skewness coefficient and the recurrence interval, the frequency factor, K_T for the LPT III distribution can be extracted. The antilog of the solution in Eq. (7) will provide the estimated extreme value for the given return period.

Tables 3 and 4 show the computed frequency precipitation P^*_T values and intensities (I_T) for six different durations and six return periods using LPT III methodology.

4. Derivation of IDF equation

The IDF formulae are the empirical equations representing a relationship between maximum rainfall intensity as a dependant variable and other parameters of interest; for example the rainfall duration and frequency as independent variables. There are several commonly used functions relating those variables previously mentioned found in the literature of hydrology applications (see Chow (1988); Burke and Burke (2008) and Nhat et al. (2006)).

To derive an equation for calculating the rainfall intensity (I) for the regions of interest, there are some required steps for establishing an equation to suit the calculation of rainfall intensity for a certain recurrence interval and specific rainfall period which depends mainly on the results obtained from the IDF curves. Two approaches were tried to estimate the equation parameters;

Table 2 Computed frequency precipitation values and intensities for different durations and return periods using Gumbel Method for Hafr AlBatin (Zone IV).

Computed precipitation (P_T) and intensity (I_T) Gumbel method

Tr (year)	10 min			20 min			30 min		
	$P_{ave} = 8.45$		$S = 4.79$	$P_{ave} = 10.69$		$S = 6.10$	$P_{ave} = 12.15$		$S = 7.01$
	K	P_T	I_T	K	P_T	I_T	K	P_T	I_T
2	−0.164	7.667	46.002	−0.164	9.689	29.068	−0.164	10.999	21.998
5	0.719	11.902	71.414	0.719	15.078	45.233	0.719	17.191	34.382
10	1.305	14.706	88.239	1.305	18.645	55.936	1.305	21.290	42.581
25	2.044	18.249	109.497	2.044	23.153	69.459	2.044	26.470	52.940
50	2.592	20.878	125.268	2.592	26.497	79.491	2.592	30.313	60.626
100	3.137	23.487	140.922	3.137	29.816	89.449	3.137	34.127	68.254
	60 min			120 min			180 min		
	$P_{ave} = 14.76$		$S = 8.34$	$P_{ave} = 17.32$		$S = 9.87$	$P_{ave} = 19.46$		$S = 9.72$
2	−0.164	13.391	13.391	−0.164	15.699	7.849	−0.164	17.866	5.955
5	0.719	20.757	20.757	0.719	24.425	12.213	0.719	26.453	8.818
10	1.305	25.635	25.635	1.305	30.203	15.101	1.305	32.138	10.713
25	2.044	31.797	31.797	2.044	37.502	18.751	2.044	39.321	13.107
50	2.592	36.368	36.368	2.592	42.918	21.459	2.592	44.650	14.883
100	3.137	40.906	40.906	3.137	48.293	24.147	3.137	49.940	16.647
	360 min			720 min			1440 min		
	$P_{ave} = 20.87$		$S = 10.24$	$P_{ave} = 22.87$		$S = 10.97$	$P_{ave} = 31.27$		$S = 15.32$
2	−0.164	19.190	3.198	−0.164	21.072	1.756	−0.164	28.754	1.198
5	0.719	28.235	4.706	0.719	30.764	2.564	0.719	42.297	1.762
10	1.305	34.224	5.704	1.305	37.182	3.099	1.305	51.263	2.136
25	2.044	41.791	6.965	2.044	45.291	3.774	2.044	62.593	2.608
50	2.592	47.405	7.901	2.592	51.306	4.276	2.592	70.997	2.958
100	3.137	52.977	8.829	3.137	57.277	4.773	3.137	79.340	3.306

A. By applying the logarithmic conversion, where it is possible to convert the equation into a linear equation, and thus to calculate all the parameters related to the equation. The following steps are followed to derive an

1. Convert the original equation in the form of power-law relation (see Chow (1988); Koutsoyiannis et al. (1998), and AlHassoun (2011)) as follows:

$$I = \frac{CT_r^m}{T_d^e} \tag{11}$$

By applying the logarithmic function to get

$$\log I = \log K - e \log T_d \tag{12}$$

where

$$K = CT_r^m \tag{13}$$

and e represents the slope of the straight line

2. Calculate the natural logarithm for (K) value found from Gumbel method or from LPT III method as well as the natural logarithmic for rainfall period T_d.
3. Plot the values of ($\log I$) on the y-axis and the value of ($\log T_d$) on the x axis for all the recurrence intervals for the two methods.
4. From the graphs (or mathematically) we find the value of (e) for all recurrence intervals where, then we find out the average e value, e_{ave}, by using the following equation:

$$e_{ave} = \frac{\sum e}{n} \tag{14}$$

where n represents recurrence intervals (years) value noted as Tr.

5. From the graph, we find ($\log K$) values for each recurrence interval where ($\log K$) represents the Y-intercept values as per Gumbel method or LPT III method. Then we convert Eq. (13) into a linear equation by applying the natural logarithm to become:

$$\log K = \log c + m \log \text{Tr} \tag{15}$$

6. Plot the values of ($\log K$) on the y-axis and the values of ($\log \text{Tr}$) on the x-axis to find out the values of parameters c and m as per Gumbel method or LPT III where (m) represents the slope of the straight line and (c) represents the (anti log) for the y intercept.

B. Estimation of the equation parameters by using non linear regression analysis: Using the SOLVER function of the ubiquitous spreadsheet programme Microsoft Excel, which employs an iterative least squares fitting routine to produce the optimal goodness of fit between data and function. The R^2 value calculated is designed to give the user an estimate of goodness of fit of the function to the data.

5. Goodness of fit test

The aim of the test is to decide how good is a fit between the observed frequency of occurrence in a sample and the expected

Table 3 Computed frequency precipitation values and intensities for different durations and return periods using LPT III Method for Najran region (Zone I).

Computed precipitation (P_T) and intensity (I_T) (Log Person III method)

Tr (year)	Duration(min)											
	10				20				30			
	K_T	P^*_T	P_T	I_T	K_T	P^*_T	P_T	I_T	K_T	P^*_T	P_T	I_T
2	0.089	0.811	6.473	38.837	0.075	0.838	6.886	20.659	0.050	0.913	8.185	16.371
5	0.856	0.970	9.327	55.963	0.856	1.066	11.646	34.937	0.853	1.163	14.541	29.082
10	1.210	1.043	11.040	66.240	1.224	1.174	14.917	44.750	1.245	1.284	19.249	38.499
25	1.551	1.114	12.987	77.922	1.587	1.280	19.043	57.128	1.643	1.408	25.592	51.184
50	1.754	1.155	14.305	85.832	1.806	1.344	22.065	66.196	1.890	1.485	30.540	61.079
100	1.949	1.196	15.698	94.186	2.012	1.404	25.354	76.061	2.104	1.551	35.593	71.187
	60				120				180			
2	0.048	1.000	10.006	10.006	0.027	1.029	10.686	5.343	−0.042	1.032	10.769	3.590
5	0.853	1.236	17.230	17.230	0.848	1.268	18.515	9.258	0.827	1.256	18.041	6.014
10	1.246	1.352	22.478	22.478	1.263	1.388	24.429	12.215	1.305	1.380	23.965	7.988
25	1.647	1.469	29.459	29.459	1.694	1.513	32.605	16.302	1.834	1.516	32.805	10.935
50	1.896	1.542	34.851	34.851	1.967	1.592	39.126	19.563	2.185	1.607	40.423	13.474
100	2.111	1.606	40.323	40.323	2.208	1.662	45.958	22.979	2.508	1.690	48.974	16.325
	360				720				1440			
2	0.028	1.174	14.919	2.487	0.209	1.306	20.245	1.687	0.186	1.224	16.733	0.697
5	0.849	1.392	24.664	4.111	0.839	1.435	27.249	2.271	0.846	1.373	23.607	0.984
10	1.262	1.502	31.760	5.293	1.066	1.482	30.335	2.528	1.099	1.430	26.923	1.122
25	1.691	1.616	41.311	6.885	1.244	1.518	32.991	2.749	1.307	1.477	30.014	1.251
50	1.962	1.688	48.762	8.127	1.330	1.536	34.345	2.862	1.413	1.501	31.709	1.321
100	2.200	1.752	56.440	9.407	1.390	1.548	35.332	2.944	1.490	1.519	33.021	1.376

Table 4 Computed frequency precipitation values and intensities for different durations and return periods using LPT III Method for Hafr AlBatin (Zone IV).

Computed precipitation (P_T) and intensity (I_T) (Log Person III method)

Tr (year)	Duration (min)											
	10				20				30			
	K_T	P^*_T	P_T	I_T	K_T	P^*_T	P_T	I_T	K_T	P^*_T	P_T	I_T
2	0.104	0.895	7.844	47.062	0.066	0.975	9.448	28.344	0.000	1.019	10.448	20.896
5	0.857	1.095	12.454	74.722	0.855	1.182	15.210	45.630	0.845	1.224	16.765	33.531
10	1.200	1.187	15.373	92.239	1.231	1.281	19.084	57.251	1.260	1.325	21.149	42.297
25	1.500	1.267	18.483	110.896	1.606	1.379	23.930	71.790	1.715	1.436	27.282	54.563
50	1.700	1.320	20.898	125.386	1.834	1.439	27.460	82.379	1.999	1.505	31.981	63.962
100	1.850	1.360	22.914	137.483	2.029	1.490	30.889	92.667	2.251	1.566	36.825	73.650
	60				120				180			
2	−0.030	1.103	12.683	12.683	0.066	1.192	15.548	7.774	−0.042	1.239	17.352	5.784
5	0.831	1.299	19.892	19.892	0.855	1.379	23.938	11.969	0.827	1.403	25.294	8.431
10	1.299	1.405	25.406	25.406	1.231	1.468	29.403	14.701	1.313	1.495	31.232	10.411
25	1.811	1.521	33.202	33.202	1.606	1.557	36.096	18.048	1.865	1.599	39.684	13.228
50	2.149	1.598	39.619	39.619	1.834	1.612	40.889	20.445	2.236	1.669	46.616	15.539
100	2.458	1.668	46.564	46.564	2.029	1.658	45.491	22.745	2.580	1.733	54.120	18.040
	360				720				1440			
2	−0.138	1.258	18.134	3.022	−0.064	1.311	20.476	1.706	−0.075	1.441	27.637	1.152
5	0.775	1.416	26.073	4.346	0.817	1.466	29.269	2.439	0.812	1.603	40.132	1.672
10	1.338	1.513	32.617	5.436	1.316	1.554	35.833	2.986	1.320	1.696	49.696	2.071
25	2.003	1.628	42.493	7.082	1.877	1.653	44.986	3.749	1.900	1.802	63.433	2.643
50	2.471	1.709	51.187	8.531	2.256	1.720	52.459	4.372	2.300	1.875	75.060	3.127
100	2.917	1.786	61.122	10.187	2.608	1.782	60.507	5.042	2.650	1.939	86.969	3.624

frequencies obtained from the hypothesised distributions. A goodness-of-fit test between observed and expected frequencies is based on the chi-square quantity, which is expressed as,

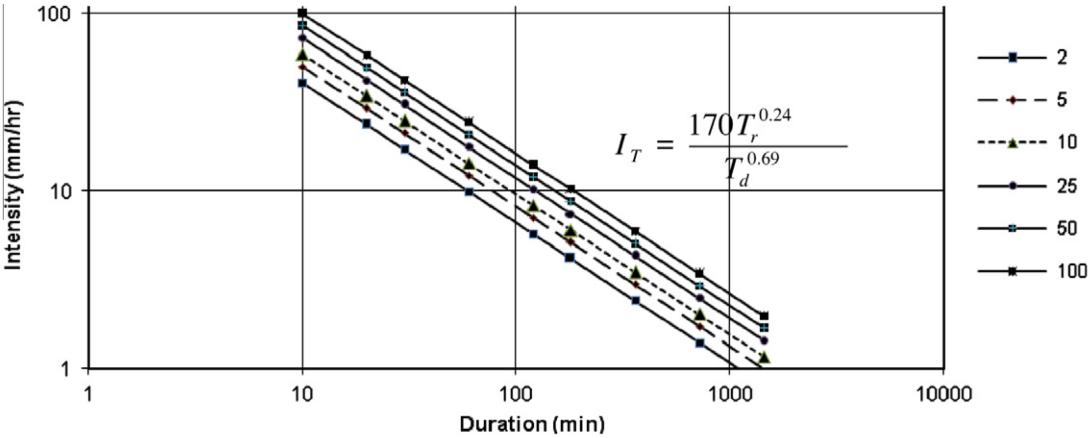

Figure 2 IDF curves by Gumbel method at Najran region (Zone I).

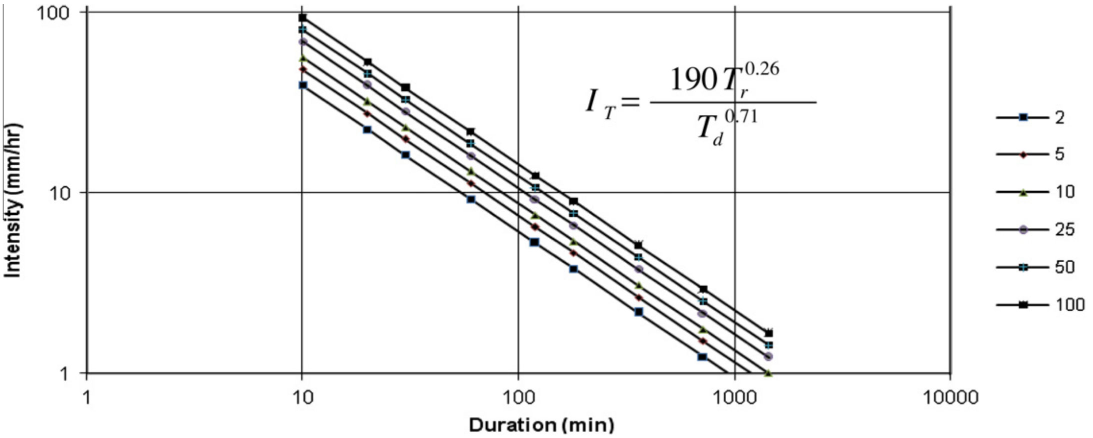

Figure 3 IDF curves by LPT III method at Najran region (Zone I).

$$\chi^2 = \sum\nolimits_{i=1}^{k} (O_i - E_i)^2 / E_i \tag{16}$$

where

χ^2 is a random variable whose sampling distribution is approximated very closely by the chi-square distribution. The symbols O_i and E_i represent the observed and expected frequencies, respectively, for the i-th class interval in the histogram. The symbol k represents the number of class intervals. If the observed frequencies are close to the corresponding expected frequencies, the χ^2 value will be small, indicating a good fit; otherwise, it is a poor fit. A good fit leads to the acceptance of null hypothesis, whereas a poor fit leads to its rejection. The critical region will, therefore, fall in the right tail of the chi-square distribution. For a level of significance equal to α, the critical value is found from readily available chi-square tables and χ^2 > constitutes the critical region (see Al-Shaikh (1985) and Oyebande (1982)).

6. Results and analysis

The purpose of this study was to develop IDF curves and derive an empirical formula to estimate the rainfall intensity at Najran and Hafr Albatin regions in KSA. The IDF curves are used as an aid when designing drainage structures for any engineering project. The curves allow the engineer to design safe and economical flood control measures.

Rainfall estimates in mm and their intensities in mm/hr for various return periods and different durations were analysed using the two techniques: (Gumbel and LPT III). The results are listed in Tables 1–4 for the two regions. According to the IDF curves, rainfall estimates are increasing with increase in the return period and the rainfall intensities decrease with rainfall duration in all return periods. Rainfall intensities rise in parallel with the rainfall return periods. The results obtained from the two methods have good consistency.

Also, the rainfall IDF relations were tabulated for the two regions. Figs. 2–4 show results of the IDF curves obtained by Gumbel and LPT III and methods for Najran region. It was shown that there were small differences between the results obtained from the two methods, where Gumbel method gives slightly higher results than the results obtained by Log Pearson III. This is shown also from parameters of the derived equation for calculating the rainfall intensity using the two methods.

Figs. 5–7 shows results of the IDF curves obtained by Gumbel and LPT III methods for Hafr AlBatin region (Zone IV). Gumbel method gives higher results than the results

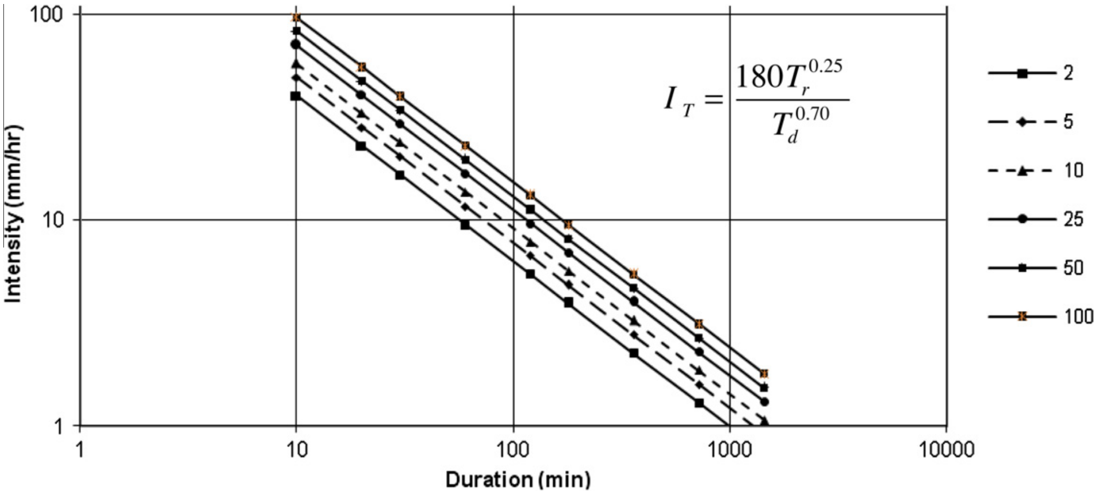

Figure 4 IDF curves by average at Najran region (Zone I).

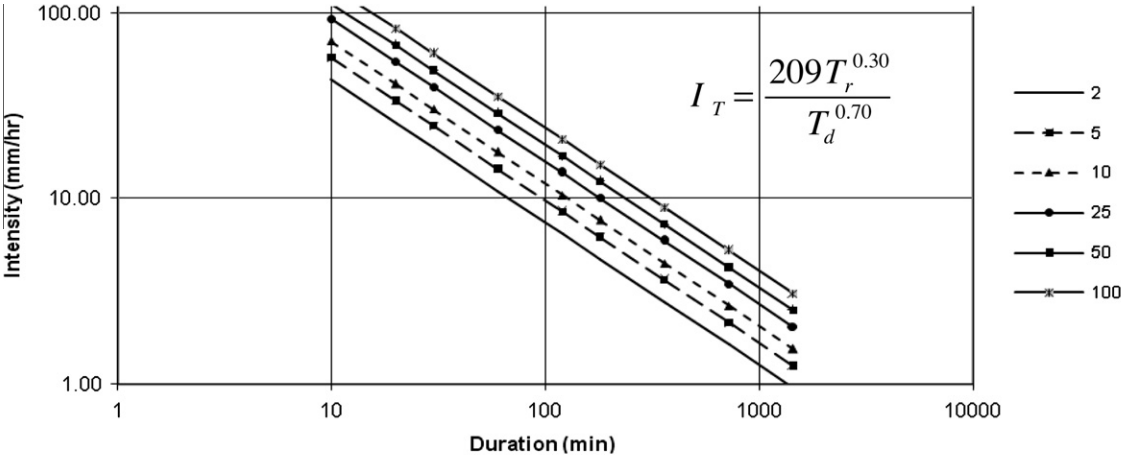

Figure 5 IDF curves by Gumbel method at Hafr AlBatin (Zone IV).

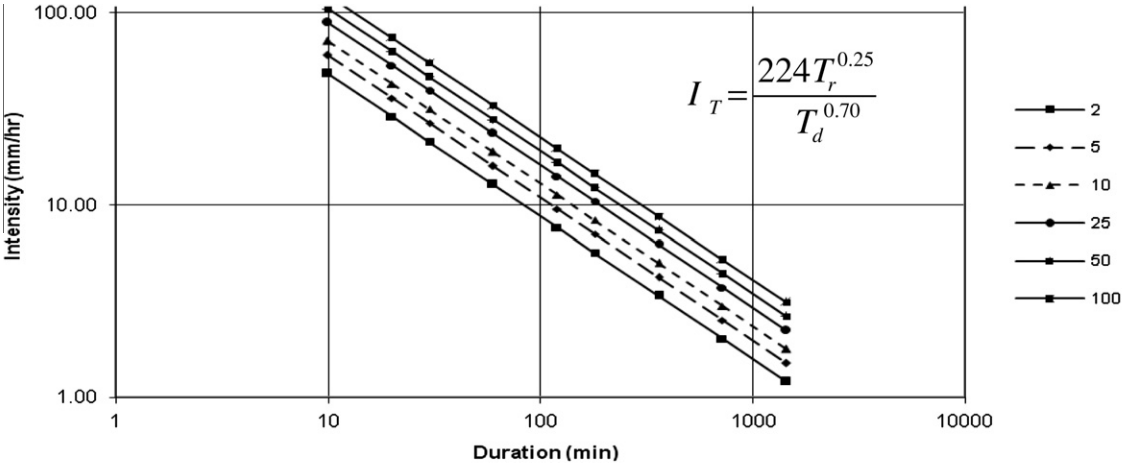

Figure 6 IDF curves by LPT III method at Hafr AlBatin (Zone IV).

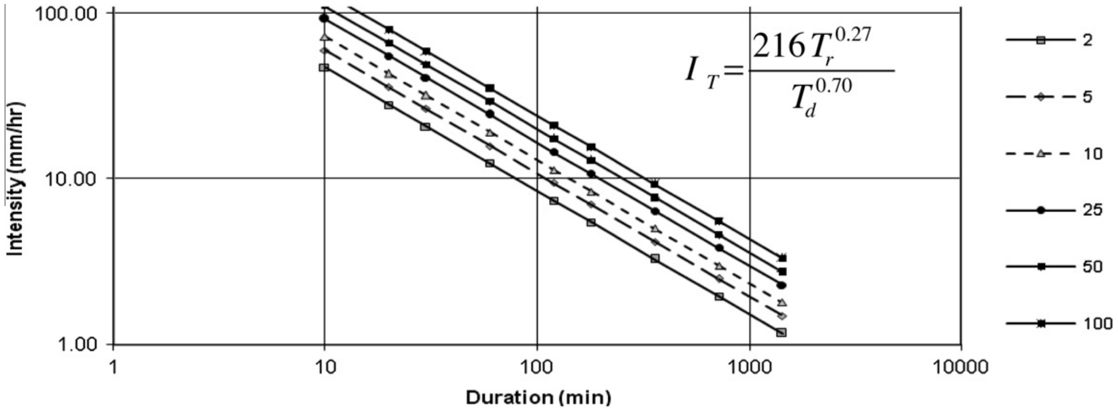

Figure 7 IDF curves by average at Hafr AlBatin (Zone IV).

Table 5 The parameters values used in deriving formulas.

Region	Parameter	Gumbel	Log Pearson III
Najran (Zone I)	c	170	190
	m	0.24	0.26
	e	0.69	0.71
Hafr AlBatin (Zone IV)	c	209	224
	m	0.30	0.25
	e	0.70	0.70

N.B: The parameters estimation of the IDF equations based on the rainfall (mm), Rainfall intensities (mm/h) for different return period (years).

obtained by LPT III when they are applied to Zone IV. Also the trend of the results is the same and they are close to each other.

Parameters of the selected IDF formula were adjusted by the method of minimum squares, where the goodness of fit is judged by the correlation coefficient. The results obtained showed that in all the cases the correlation coefficient is very high, and ranges between 0.998 and 0.994, except few cases where it ranges between 0.983 and 0.978 when using LPT III at 50 and 100 years. This indicates the goodness of fit of the formulae to estimate IDF curves in the region of interest. For each region the results are given as the mean value of the points results. Table 5 shows the parameters values obtained by analysing the IDF data using the two methods and those are used in deriving formulae for the two regions.

Also, goodness-of-fit tests were used to choose the best statistical distribution among those techniques. Results of the chi-square goodness of fit test on annual series of rainfall are shown in Table 6. As it is seen most of the data fit the distributions at the level of significance of $\alpha = 0.05$, which yields $\chi_{\text{cal}} < 3.84$. Only the data of Najran for 20 min and 1440 min do not give good fit using the Log Pearson type III distribution. Also, the data of Central and Eastern region for 120 min and 720 min do not give good fit, even at the level of significance of $\alpha = 0.01$.

7. Conclusions

This research presents some insight into the way in which the rainfall is estimated in KSA. Since the area of the Kingdom is large and has different climatic conditions from region to region, a relation for each region has to be obtained to estimate rainfall intensities for different durations and return periods ranging between 2 and 100 years.

This study has been conducted for the formulation and construction of IDF curves using data from recording stations by using two distribution methods: Gumbel and LPT III distribution. Gumbel method gave some larger rainfall intensity estimates compared to LPT III distribution. In general, the results obtained using the two approaches are very close at most of the return periods and have the same trend, this agrees with the results obtained by Al-Shaikh (1985) and AlHassoun (2011). The results obtained from that work are consistent with the results from previous studies done in some parts of the study area. It is concluded that the difference observed between the results of this study and the results done before by Al-Shaikh (1985) are accepted and in good agreement, and this

Table 6 Results of chi-square goodness of fit test on annual maximum rainfall.

Region	Distribution	Duration in minutes								
		10	20	30	60	120	180	360	720	1440
Najran	Gumbel	0.575	0.175	0.360	0.373	0.489	0.929	0.190	0.228	0.260
	Log Pearson type III	0.300	12.080	4.667	5.161	0.522	0.540	0.242	1.438	7.620*
Central and Eastern region	Gumbel	0.222	0.151	0.431	0.535	0.379	0.562	0.774	0.552	0.446
	Log Pearson type III	2.081	3.420	0.566	2.310	12.041*	1.751	6.861	8.048*	1.296

For $\alpha = 0.05$, degree of freedom = 1, the critical region is $\chi_{\text{cal}} > 3.84$.
For $\alpha = 0.01$, degree of freedom = 1, the critical region is $\chi_{\text{cal}} > 6.63$.
* χ^2 Significant at $\alpha = 0.01$.

can be attributed to the record lengths of the rainfall data used for this study and the studies before.

The parameters of the design storm intensity for a given period of recurrence were estimated for each region. The results obtained showed a good match between the rainfall intensity computed by the methods used and the values estimated by the calibrated formulae. The results showed that in all the cases data fitted the formula with a correlation coefficient greater than 0.978. This indicates the goodness of fit of the formulae to estimate IDF curves in the region of interest for durations varying from 10 to 1440 min and return periods from 2 to 100 years.

The chi-square test was used on one hand to examine the combinations or contingency of the observed and theoretical frequencies, and on the other hand, to decide about the type of distribution which the available data set follows. The results of the chi-square test of goodness of fit showed that in all the durations the null hypothesis that the extreme rainfall series have the Gumbel distribution is acceptable at the 5% level of significance, this agrees with the results obtained by Oyebande (1982). Only few cases in which the fitting was not good (20 min, 120 min and 720 min) obtained by using the LPT III distribution. Although the chi-square values are appreciably below the critical region using Gumbel distribution and few values are higher than the critical region using LPT III distribution, it is difficult to say that one distribution is superior to the other. Further studies are recommended whenever there will be more data to verify the results obtained or update the IDF curves.

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