Journal homepage www.jzs.univsul.edu.iq
Journal of Zankoy Sulaimani
Part-A- (Pure and Applied Sciences)

Developing of Rainfall Intensity-Duration-Frequency Model for Sulaimani City

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Article info

Original: 31 October 2016
Revised: 2 May 2017
Accepted: 16 May 2016
Published online: 20 September 2017

Key Words:
IDF relationships,
Rainfall intensity,
Rainfall duration,
Rainfall frequency,
Sulaimani city

Abstract

The intensity-duration-frequency (IDF) relationships are crucial for water resources planning, management and design of hydraulic structures. Sulaimani City is one of the largest cities in Iraq, needs special stormwater management due to rapid development in land use. In this study IDF curves were generated from daily rainfall data for different rainfall durations (10, 20, 30, 60, 120, 360, 720, 1440 minutes) with returning frequencies of (2, 5, 10, 25, 50, 100 years), to predict rainfall intensity in different durations and return frequencies for Sulaimani City. Furthermore, an average empirical formula was developed, to be used as a general equation to predict the rainfall intensity at any duration and returning period straightforwardly. Results of the study showed a good match between the rainfall intensities using the general empirical formula compared to the IDF curves with excellent coefficient of determination (R^2=1) between results from the empirical formula and the IDF curves. Also performance of the empirical equation was confirmed through a chi-square test between rainfall intensity values for both the IDF curves and the empirical equation.

1. Introduction

The intensity-duration-frequency (IDF) relationship is one of the prerequisite statistics in water recourses engineering planning, development, management and to assess the vulnerability of hydraulic structures. IDF curves describe the amount of rainfall in a watershed area for a given period of time [1] and [2].
IDF relationships have been established since 1932 in developed countries, but these relationships do not exist accurately for many developing countries up to now. The accessibility of accurate and long-term rainfall data in the former places and lack of that information in the latter countries is the major factor for the IDF curves construction [1].

The magnitude of an extreme rainfall event has an inverse relation to its occurrence frequency, therefore the severe rainfall events have less frequency compared to moderate rainfall events. The frequency analysis of rainfall data is to relate the magnitude of extreme events to their frequency of occurrence using the probability distribution. The IDF relationship is a mathematical relationship between the rainfall intensity, the duration, and the return period using extreme rainfall data [3, 4].

Hershfield (1961) [5] presented for the first time a statistical method to estimate the rainfall intensity and rainfall analysis and development of IDF relationships using extreme rainfall data. Hadadin (2005) [6] established a relationship between rainfall data with intensity and duration for a basin in Jordan; he claimed that the result obtained from Gumbel method is similar with the other methods. Nhat et al. (2006) [7] established IDF frequency curves for precipitation in the monsoon area of Vietnam; they derived a generalized IDF formula using rainfall depth. AlHassoun (2011) [8] developed an empirical formula to estimate the rainfall intensity for Riyadh region in Saudi Arabia; he stated a good match was achievement between Gumbel method with other analytical methods. Elsebai (2012) [9] derived rainfall depth–duration–frequency relationships for two regions in Saudi Arabia through the analysis of rainfall data; he found that the results obtained using Gumbel distribution method better than the results obtained using other distributions such as LPT III distribution. Jaleel and Farawn (2013) [10] established rainfall IDF relationships for Basrah city, Iraq using Gumbel method, their results showed that maximum intensities occur at short durations with high variation.

Numerous researches conducted to derive and establish empirical rainfall estimation equations and IDF curves for different regions worldwide, especially in developing countries [1], [2], [11], [12], [13], [14], [15], [16], [17], [18], [19] and [20].

The objective of this study was to establish IDF relationships for Sulaimani City using measured daily rainfall depth data from Sulaimani Weather Station. In addition, an empirical formula derived for the rainfall intensity assessment more simply with different returning period and rainfall duration compared to IDF curves.

2. Methodology

2.1. Study area and data collection

The City of Sulaimani is one of largest cities of Kurdistan Regional Government, which is located at north east of Iraq of geographic coordinate Latitude and Longitude of 35°33′40″N and 45°26′14″E respectively. The weather of the city is dry and warm in summer with average temperature of 31.5°C, while the city is cold and wet during winter season with average temperature of 7.6°C [22]. Precipitation starts with light rainfall in October, strengthens during November, and regularly continues to May. The average annual precipitation varies between 328mm for dry years and 848mm for wet years [22].

In this study, historical annual highest daily (24 hours) rainfall data from Sulaimani Weather Station was used (Table 1). The 23 years (1993 to 2015) of annual highest daily amount of rainfall data (mm/h) used to generate IDF curves and intensity formula derivation (Table 1). Sulaimani Weather Station has geographic coordinates of Latitude = 35°33′20″ N and Longitude =45°27′11″E with elevation of 879.6m above sea level.

2.2. Precipitation duration reduction formula

From the available 23 years' data, the annual extreme values of precipitation were extracted from each year data. The daily (24hours) data points were reduced to shorter time durations (namely 10, 20, 30, 60, 120, 360, 720, 1440 minutes) using a formula recommended by the Indian Meteorological Department to reduce the rainfall duration to smaller time scale less than 24 hours [10], [22] and [23], as shown in equation (1).

$$P_t = P_{24}\left[\frac{t}{24}\right]^{(1/3)} \tag{1}$$

Where P_t is the required precipitation depth for duration less than 24 hrs in mm, P_{24} is the daily precipitation depth in mm, and t is the required duration time in hours.

Table-1: Maximum daily precipitation for duration of 1993-2015.

No.	Year	24hrs precipitation (mm)	No.	Year	24hrs precipitation (mm)
1	1993	56	13	2005	71
2	1994	56	14	2006	130.4
3	1995	43.5	15	2007	53.9
4	1996	51.1	16	2008	42.4
5	1997	82	17	2009	66.7
6	1998	43	18	2010	72.5
7	1999	40.5	19	2011	50.9
8	2000	44.5	20	2012	56.2
9	2001	46.3	21	2013	88.1
10	2002	73.6	22	2014	61.2
11	2003	78.5	23	2015	64.4
12	2004	45.3			

2.3. Frequency distribution and development of IDF curves

In order to establish the IDF relationships, essential information extracted from the existing rainfall data using statistical tools. To derive the information, probability distribution functions are applied to hydrological data such as normal, lognormal, exponential, Gamma, Pearson, Log-Pearson and extreme values distributions [3]. While the data used in the IDF relationship studies are extreme values of precipitation, for this reason the extreme values distribution which is known as Gumbel distribution found to be effective to model the rainfall intensity [6], [8], [9], [10] and [13].

Therefore, in this study, a Gumbel distribution function (which described below) applied to the extreme values of rainfall to explain the change of the parameters of the frequency distribution with time.

From the fitted frequency distribution (Gumbel) the rainfall intensity for any duration and returning period can be described according to equation (2) [8[, [9] and [10].

$$P = P_{av} + KS \tag{2}$$

Where *P* is the frequency of precipitation in (mm) for a specific duration t minutes with any returning period of T years, P_{av} is the average of the maximum precipitation data points (*n*) as in equation (3).

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

K is the Gumbel frequency factor, as in equation (4).

$$K = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left[ln\left[\frac{T}{T-1}\right]\right]\right] \tag{4}$$

S is the standard deviation of precipitation data *P* as in equation (5).

$$S = \left[\frac{1}{n-1}\sum_{i=1}^{n}[P_i - P_{av}]^2\right]^{1/2} \tag{5}$$

Then the intensity of rainfall *I* in (mm/h) for any duration *t* can be calculated using equation (6) for any return period of *T* years.

$$I = \frac{P}{t} \tag{6}$$

Where *I* is the intensity of rainfall (mm/h), *P* is the depth of precipitation (mm) and *t* is the rainfall duration (hours).

2.4. Derivation of IDF empirical formula

A power function can describe generalized IDF relationship between rainfall intensity (I), rainfall duration (t) and return period (T). The following procedure used to derive a formula for intensity of rainfall I from the IDF relationships [3], [8] and [9]:

- The general form of intensity equation can be defined in the form of power-law relation as in equation (7):

$$I = \frac{CT^m}{t^a} \tag{7}$$

Where *I* is the intensity of rainfall (mm/h), *t* is the duration of rainfall (minutes), *T* is the returning period (years) and constants (*C, m* and *a*) are empirical parameters depend on precipitation data, shape, size and location of the study area which can obtained from logarithmic transformation of the equation.

- After applying logarithmic transformation of equation (7), the following equation (8) can be obtained:

$$\log I = \log(CT^m) - a \log t \tag{8}$$

Assuming ($CT^m=k$), equation (8) can be rewritten as in equation (9).

$$\log I = \log(k) - a \log t \tag{9}$$

- For each return period, plot the values of *log I* (log of precipitation intensity values) against *log t* (log of duration time). From the linear relationship, find the slope of the straight line which represent the constant *a* (the average values of constant *a* for all retuning periods) in equation (8), while the term (logk) in equation (9) represents the intercept from the plot for each returning period.
- To find the values of *C* and *m*, we need to plot the log of that intercept (*log* CT^m) values against the log of returning period *(logT)* in a new graph as in equation (11).

Assumed that:

$k= CT^m$ (10)

Taking log of both sides of equation (10) results in the following equation (11):

$log\ k= log\ C + m\ log\ T$ (11)

- Plotting *log k* and *log T* in equation (11), a linear equation of the plot can be obtained, then we can find *m* that represents the slope of the linear relationship. The value of the anti-log of the intercept from the plotted curve represents the *C* coefficient for equation (7).

3. Results and discussion

3.1. Reducing the daily precipitation data to smaller durations

The calculation was started with reducing the value of daily (24 hours) annual highest daily rainfall data (mm/h) into smaller time scale of (10, 20, 30, 60, 120, 360, 720, 1440 minutes) using equation (1). The standard deviation (*S*) and the corresponding average value of precipitation (P_{av}) corresponding to each rainfall duration are calculated as in (Table- 2).

Table 2. Standard deviation (*S*) and average precipitation values (P_{av}) for different durations

duration(min)	*S*	P_{av} (mm/h)
10	3.90	11.76
20	4.91	14.82
30	5.62	16.96
60	7.08	21.37
120	8.92	26.93
360	12.87	38.84
720	16.21	48.93
1440	20.43	61.65

3.2. Developing IDF curves

Gumbel distribution frequency method was applied to the reduced duration rainfall data to find each of the *K* and *P* in equation (2) for each duration of rainfall (10, 20, 30, 60, 120, 360, 720, 1440 minutes) with returning period of (2, 5, 10, 25, 50, 100 years) separately. Then the corresponding rainfall intensities *I* calculated using equation (6). Tables 3 and 4 show results of the frequency and rainfall intensity calculations for returning periods of 2, 5, 10 and 25, 50, 100 years respectively.

Then the IDF curves are plotted between the rainfall intensity and rainfall duration for each retuning period of 2, 5, 10, 25, 50 and 100 years as shown in *(Figure-1)* on a log-log scale, while *(Figure- 2)* shows IDF curves for 2, 5, 10, 25, 50 and 100 years' frequencies on ordinary scales.

Table-3: Computed frequency precipitation values and intensities for different durations and return periods of 2, 5 and 10 years.

	Frequency of 2 years k= - 0.1642		Frequency of 5 years k= 0.7194		Frequency of 10 years k= 1.3046	
duration (min)	P (mm)	Intensity (mm/h)	P (mm)	Intensity (mm/h)	P (mm)	Intensity (mm/h)
10	11.12	66.73	14.57	87.40	16.85	101.08
20	14.01	42.04	18.35	55.06	21.22	63.67
30	16.04	32.08	21.01	42.02	24.30	48.59
60	20.21	20.21	26.47	26.47	30.61	30.61
120	25.46	12.73	33.35	16.67	38.57	19.28
360	36.72	6.12	48.10	8.02	55.62	9.27
720	46.27	3.86	60.60	5.05	70.08	5.84
1440	58.30	2.43	76.35	3.18	88.30	3.68

Table-4: Computed frequency precipitation values and intensities for different durations and return periods of 25, 50 and 100 years.

	Frequency of 25 years k= 2.0438		Frequency of 50 years k= 2.5923		Frequency of 100 years k= 3.1367	
duration(min)	P (mm)	Intensity (mm/h)	P (mm)	Intensity (mm/h)	P (mm)	Intensity (mm/h)
10	19.73	118.36	21.86	131.18	23.99	143.91
20	24.85	74.56	27.55	82.64	30.22	90.66
30	28.45	56.90	31.53	63.07	34.59	69.19
60	35.85	35.85	39.73	39.73	43.58	43.58
120	45.16	22.58	50.06	25.03	54.91	27.46
360	65.14	10.86	72.19	12.03	79.20	13.20
720	82.07	6.84	90.96	7.58	99.78	8.32
1440	103.40	4.31	114.60	4.78	125.72	5.24

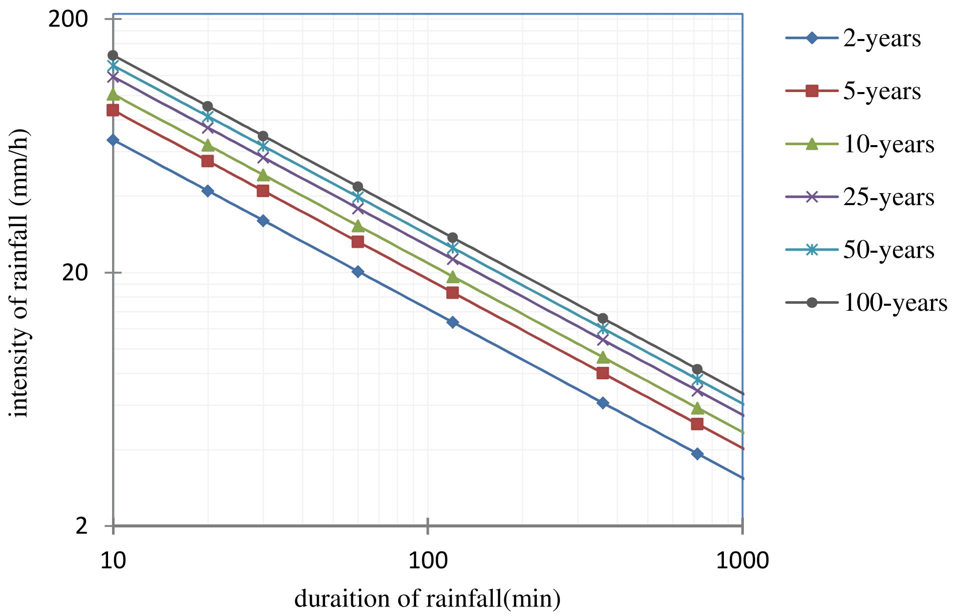

Figure- 1: IDF curves for 2, 5, 10, 25, 50 and 100 years returning periods on logarithmic scale

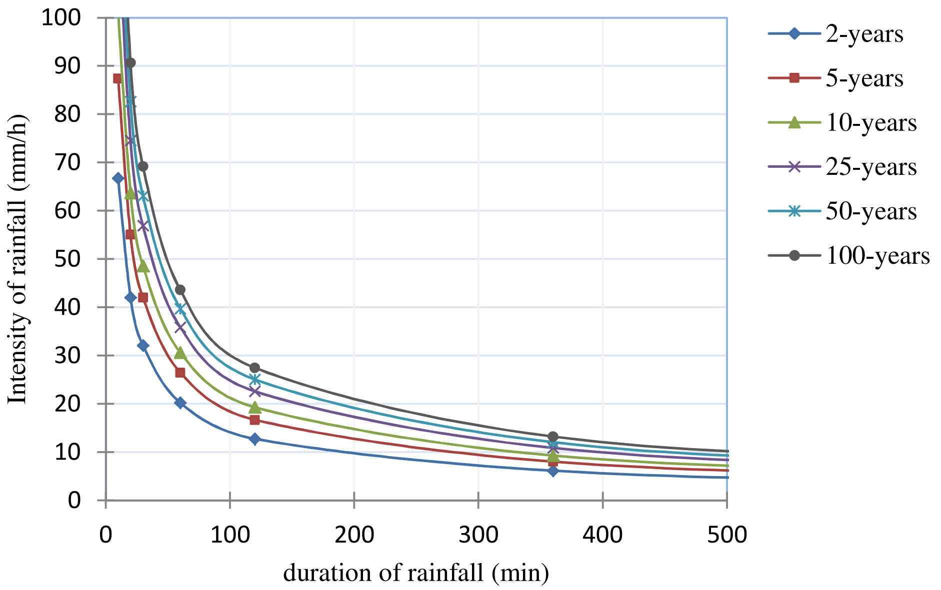

Figure-2: IDF curves for 2, 5, 10, 25, 50 and 100 years returning periods on ordinary scale

3.3. General empirical IDF formula

The rainfall intensity data for different duration with different return periods of 2, 5, 10, 25, 50 and 100 years were used to derive an empirical formula to estimate the precipitation data for Sulaimani City using Gumbel distribution frequency method. The derivation started with the application of logarithmic transformation of the data to change the equation to a linear equation as described in section 2.4. The calculation procedure of the linear equation parameters calculations resulted in the empirical equation (12).

$$I = \frac{288.4\, T^{0.191}}{t^{0.666}} \qquad (12)$$

Where *I* is the intensity of rainfall (mm/h) for duration (t) with returning period (T), *t* is the rainfall duration in (minutes) and *T* is the returning frequency in (years). This empirical formula which relates rainfall intensity (*I)* as independent variable to rainfall duration (*t)* and returning period (*T)* as dependent variables can be used as a general equation to predict rainfall intensity for any duration with every returning frequency.

The accuracy and performance of the derived empirical equation against the measured values of rainfall intensities (IDF curves) was be tested for all retuning periods and durations. Table 5 and 6 show values of coefficient of determination R^2 =1 for all returning periods of (2, 5, 10, 25, 50 and 100 years) which mean that the equation can be used successfully with perfect prediction of rainfall intensity calculations. Figures 3 shows the plot of selected frequency values (2, 25 and 100 years) from Tables 5 and 6.

Moreover, to test the goodness of the fit of the empirical equation (12), a chi-square test was performed (with 95% confidence degree) between rainfall intensity values from both the IDF curves and the empirical equation for all returning periods. As it is obvious for a good fitting function the chi-square values for a degree of freedom of 7 should be less than the critical value of 14.07, the less the value (close to zero) of chi-square the good the fit is. Table 7 shows results of chi-square test for all return periods of (2, 5, 10, 25, 50 and 100 years). From values of chi-square test in table 7, we can conclude that there is no statistical significant difference between the rainfall intensity values for all returning periods. Therefore, Figure 3 and Table 7 reveal that the empirical equation (12) can predict the rainfall intensity for Sulaimani City with a high level of accuracy for different duration and returning periods.

Table-5: Comparison of results for returning period of (2, 5 and 10 years) from IDF curves and empirical equation (12).

	2 years (R^2=1)		5 years (R^2=1)		10 years (R^2=1)	
	IDF curves	Equation(12)	IDF curves	Equation(12)	IDF curves	Equation(12)
t (min)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)
10	66.73	71.04	87.40	84.63	101.08	96.61
20	42.04	44.77	55.06	53.34	63.67	60.89
30	32.08	34.18	42.02	40.71	48.59	46.48
60	20.21	21.54	26.47	25.66	30.61	29.29
120	12.73	13.58	16.67	16.17	19.28	18.46
360	6.12	6.53	8.02	7.78	9.27	8.88
720	3.86	4.12	5.05	4.90	5.84	5.60
1440	2.43	2.59	3.18	3.09	3.68	3.53

Table-6: Comparison of results for returning period of (25, 50 and 100 years) from IDF curves and empirical equation (12).

	25 years (R^2=1)		50 years (R^2=1)		100 years (R^2=1)	
	IDF curves	Equation(12)	IDF curves	Equation(12)	IDF curves	Equation(12)
t (min)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)	Intensity (mm/h)
10	118.36	115.08	131.18	131.37	143.91	149.97
20	74.56	72.53	82.64	82.80	90.66	94.52
30	56.90	55.37	63.07	63.20	69.19	72.15
60	35.85	34.89	39.73	39.83	43.58	45.47
120	22.58	21.99	25.03	25.11	27.46	28.66
360	10.86	10.58	12.03	12.08	13.20	13.79
720	6.84	6.67	7.58	7.61	8.32	8.69
1440	4.31	4.20	4.78	4.80	5.24	5.48

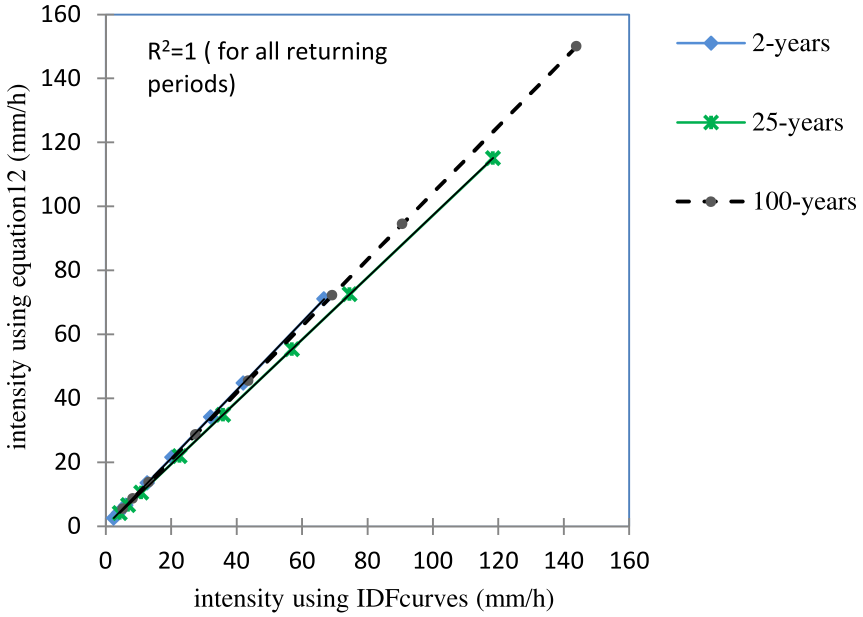

Figure-3: Rainfall intensities from empirical formula (12) against IDF curves for return periods of (2, 25 and 100 years)

Table-7: Chi square test results for all returning periods

Return period (year)	Chi-square (X2)
2	0.744
5	0.243
10	0.561
25	0.249
50	0.002
100	0.704

4. Conclusions

Management and planning of water resources and design of hydraulic structures demand extreme rainfall data for carrying out the assessment of rainfall amount. The IDF relationship is the estimation of rainfall intensities of different rainfall durations and return periods.

This study aimed at the determination of IDF curves for rainfall prediction in Sulaimani City at any time and return year period that required for different design and flood risk considerations. A set of IDF curves were developed covering a broad range of rainfall durations (namely 10, 10, 20, 30, 60, 120, 360, 720 and 1440 minutes) for different returning periods (2, 5, 10, 25, 50 and 100 years). The city stakeholders and decision makers can use this set of IDF relationships (that generated from measured daily rainfall from Sulaimani Weather Station) to predict rainfall intensity of hydraulic structures design and water resources management inside the city current municipality. In addition, a general empirical rainfall intensity equation was derived to be used as an approximate prediction more easily compared to the IDF curves.

Results of this study revealed perfect fit of the computed by the IDF curves with the predicted values of the rainfall intensities by the calibrated empirical equation with coefficient of determination of (R^2=1) from (Figure 3) and accepted values of chi-square test values (Table 7) for all frequencies of (2, 5, 10, 25, 50 and 100 years). Therefore, the derived empirical equation (12) can be used successfully to predict rainfall intensity of Sulaimani City at any duration with different return periods.

Acknowledgements

The writer expresses his sincere gratitude to the Sulaimani Weather Station for providing the data used in this research. Also special thanks to Ms. Sawsan Mohamed for delivering the data used in this research.

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