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Research Article

RAINFALL INTENSITY-DURATION-FREQUENCY RELATIONSHIPS DERIVED FROM HOURLY RAINFALL DATA USING ORDER STATISTIC APPROACH OF PROBABILITY DISTRIBUTIONS

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ABSTRACT
Rainfall intensity for a particular frequency and duration is one of the most important parameter for the hydrologic design of storm sewers, culverts and many other hydraulic structures. This can be obtained from Intensity-Duration-Frequency (IDF) relationship, which is determined by frequency analysis of rainfall data. This paper illustrates the use of Gumbel and Frechet distributions for modelling of annual n-hourly maximum rainfall for different duration of 'n' such as 1-hour (hr), 2-hr, 3-hr, 6-hr, 12-hr, 18-hr, 24-hr, 48-hr and 72-hr for Bhavnagar and Jabalpur regions. The parameters of the distributions are determined by order statistics approach and used for estimation of extreme rainfall to develop the IDF relationship. Model performance indicators viz., correlation coefficient and root mean square error are used to analyze the performance of the IDF relationships given by Gumbel and Frechet distributions. The paper presents the IDF relationships obtained from Gumbel distribution are better suited for estimation of rainfall intensity at Bhavnagar and Jabalpur regions.

Keywords: *Correlation Coefficient, Frechet, Gumbel, Intensity-Duration-Frequency, Order Statistics Approach, Rainfall, Root Mean Square Error*

INTRODUCTION
The rainfall Intensity-Duration-Frequency (IDF) relationship is one of the most important tools in water resources engineering to assess the vulnerability of water resources structures as well as planning, design and operation. The IDF relationship can be developed through Rainfall Frequency Analysis (RFA) that is used to estimate rainfall depth at a point for a specified exceedance probability and duration (Burlando and Rosso, 1996). RFA is based either on annual maximum series at a site (at-site analysis) or from several sites (regional analysis). Rainfall in a region can be characterised if the intensity, duration and frequency of the diverse storms occurring at that place are known (Koutsoyiannis *et al.*, 1998; Bougadis and Adamowski, 2006). The frequency data for storms of various durations, so obtained, can be represented by IDF curves, which give a plot of rainfall intensity and duration.

Nhat *et al.*, (2006) applied Gumbel distribution for estimation of rainfall for different return periods for development of IDF curves for Vietnam region and Yodo catchments of Japan. Raiford *et al.*, (2007) have developed IDF curves and isopluvial maps for the region encompassing South Carolina, North Carolina and Georgia using newly developed RFA methods. Kim *et al.*, (2008) improved the accuracy of IDF curves by using long and short duration separation technique. They derived IDF curves by using Cumulative Distribution Function (CDF) of the interesting site and multi-objective genetic algorithm. Ben-Zvi (2009) proposed a procedure for basing IDF curves on partial duration series which are substantially larger than those commonly used for this purpose. He concluded that the proposed procedure superior to the current ones where the use of large samples would reduce the sensitivity of predicted intensities to sampling variations. Bara *et al.*, (2009) applied simple scaling theory to the IDF characteristics of short duration rainfall. They have concluded that the IDF relationships developed from daily rainfall showed acceptable results in comparison with the IDF curves obtained from at-site short duration rainfall data.

Okonkwo and Mbajiorgu (2010) have developed IDF curves using graphical and statistical methods for southeastern Nigeria and the results were compared. They have found that the IDF curves developed from the graphical and statistical methods were very close for the lower return periods of 2-year (yr) to 10-yr and differ for higher return periods of 50-yr to 100-yr, but the difference was not significant at 5% level.

Khaled *et al.*, (2011) applied L-moments and generalized least squares regression methods for estimation of design rainfall depths and development of IDF relationships. Eman (2011) adopted six probability distributions for modelling of hourly rainfall data for development of IDF curves for Sinai Peninsula in the northeast part of Egypt. Rashid *et al.*, (2012) applied Pearson Type-III distribution for modelling of short duration rainfall and development of IDF relationships for Sylhet City in Bangladesh. Dourte *et al.*, (2013) developed rainfall IDF relationships for various regions of Andhra Pradesh for prediction of runoff and estimation of groundwater recharge.

In probability theory, extreme value distributions include Gumbel, Frechet and Weibull are generally applied for frequency analysis of meteorological parameters. In addition to above, AERB (Atomic Energy Regulatory Board) guidelines described that Order Statistics Approach (OSA) could be used for determination of parameters of Gumbel and Frechet distributions though number of methods is available for parameter estimation. In the present study, Weibull distribution is not considered for RFA because of non-existence of OSA for determination of parameters of Weibull distribution. In this paper, an attempt has been made to estimate the extreme rainfall for different return periods for different durations of ‘n’ such as 1-hour (hr), 2-hr, 3-hr, 6-hr, 12-hr, 18-hr, 24-hr, 48-hr and 72-hr adopting Gumbel and Frechet distributions (using OSA) for development of IDF relationships for Bhavnagar and Jabalpur regions. Model Performance Indicators (MPIs) viz., Correlation Coefficient (CC) and Root Mean Square (RMSE) are used for the selection of a suitable distribution for development of IDF relationships for estimation of rainfall intensity for the regions under study. The methodology adopted in developing IDF relationships using probability distributions and computations of MPIs are briefly described in the following sections.

MATERIALS AND METHODS

Methodology

Probability Distributions

The CDFs [F(R)] of Gumbel and Frechet distributions are given by:

$$F(R) = e^{-e^{-\left(\frac{R_G-\alpha_G}{\beta_G}\right)}},\ \alpha_G,\beta_G > 0 \qquad \ldots (1)$$

$$F(R) = e^{-\left(\frac{R_F}{\beta_F}\right)^{(-\lambda_F)}},\ \lambda_F,\beta_F > 0 \qquad \ldots (2)$$

Where, αG and βG are location and scale parameters of Gumbel distribution (Gumbel, 1960). The parameters of the distribution are computed by OSA and further used to estimate extreme rainfall (R_G) for different return periods (T) are computed from $R_G=\alpha_G+Y_T\beta_G$ with $Y_T=-\ln(-\ln(1-(1/T)))$. Based on extreme value theory, Frechet distribution can be transformed to Gumbel distribution through logarithmic transformation using natural logarithm of the actual variable. Under this transformation, the scale (β_F) and shape (λ_F) parameters of Frechet distribution are determined by OSA for estimation of extreme rainfall (R_F) using $R_F=\mathrm{Exp}(R_G)$, $\beta_F=\mathrm{Exp}(\alpha_G)$ and $\lambda_F=1/\beta_G$.

OSA is based on the assumption that the set of extreme values constitutes a statistically independent series of observations. The OSA parameters of Gumbel distribution are given by:

$$\alpha_G = r^*\alpha^*_M + r'\alpha'_M \text{ and } \beta_G = r^*\beta^*_M + r'\beta'_M \qquad \ldots (3)$$

Where, r^* and r' are proportionality factors, which can be obtained from the selected values of k, n and n' using the relations as follows:

$$r^* = kn/N \text{ and } r' = n'/N \qquad \ldots (4)$$

Here, N is the sample size containing the basic data that are divided into k sub groups of n elements each leaving n' remainders. α^*_M and β^*_M are the distribution parameters of the groups, and α'_M and β'_M are the parameters of the remainders, if any. These can be computed from the following equations:

$$\alpha^*_M = (1/k)\sum_{i=1}^{n}\alpha_{ni}S_i;\ \alpha'_M = \sum_{=i=1}^{n'}\alpha_{n'i}R_i;\quad \beta^*_M = (1/k)\sum_{i=1}^{n}\beta_{ni}S_i \text{ and } \beta'_M = \sum_{=i=1}^{n'}\beta_{n'i}R_i \qquad \ldots (5)$$

Where, $S_i = \sum_{i=1}^{k} R_{ij}$, j=1,2,3,..,n. Table 1 gives the weights of α_{ni} and β_{ni} used in determination of OSA parameters of Gumbel and Frechet distributions (AERB, 2008).

Table 1: Weights α_{ni} and β_{ni} for Determination of OSA Parameters

α_{ni} (or) β_{ni}	i: 1	2	3	4	5	6
α_{2i}	0.91637	0.08363				
α_{3i}	0.65632	0.25571	0.08797			
α_{4i}	0.51099	0.26394	0.15368	0.07138		
α_{5i}	0.41893	0.24628	0.16761	0.10882	0.05835	
α_{6i}	0.35545	0.22549	0.16562	0.12105	0.08352	0.04887
β_{2i}	-0.72135	0.72135				
β_{3i}	-0.63054	0.25582	0.37473			
β_{4i}	-0.55862	0.08590	0.22392	0.24879		
β_{5i}	-0.50313	0.00653	0.13046	0.18166	0.18448	
β_{6i}	-0.45927	-0.03599	0.07319	0.12672	0.14953	0.14581

Procedure for Development of IDF Relationship

IDF is a mathematical relationship between the rainfall intensity, duration, and return period. Intensity is defined as the time rate of rainfall, which is the depth per unit time (mm/ hr, or mm/ day as the case may be). It can either be the instantaneous intensity or the average intensity over the duration of rainfall. Theoretically, the intensity of storm in a region varies with duration in such a way that high intensity generally corresponds to short duration, and low intensity to longer duration (Chowdhury *et al.*, 2007). The general form of empirical equation used in development of IDF relationship is expressed by:

$$I = A*(T_d)^{-B} \quad \dots (6)$$

Where, I is the rainfall intensity (mm/ hr), T_d is the rainfall duration (hr) corresponding to return period (T), and the terms A and B are constants. Method of least squares is applied to compute the constant terms for the rainfall IDF empirical formula. By applying logarithm on both sides of Equation (6), we get log(I) = log(A)-Blog(T_d) $\Rightarrow$ Y=a-BX. The parameters A and B are computed from Equations (7 and 8) and are expressed by:

$$B = \frac{\sum_{i=1}^{N} Y_i \sum_{i=1}^{N} X_i - N \sum_{i=1}^{N} X_i Y_i}{N \sum_{i=1}^{N} X_i^2 - \left(\sum_{i=1}^{N} X_i\right)^2} \quad \dots (7)$$

$$A = \mathrm{Exp}\left(\overline{Y} + B\overline{X}\right) \quad \dots (8)$$

Performance Analysis

The performance of IDF relationships given by Gumbel and Frechet distributions are evaluated by CC and RMSE. Theoretical descriptions of CC and RMSE and CC are expressed by:

$$CC = \frac{\sum_{i=1}^{N} \left(I_i - \bar{I}\right)\left(I_i^* - \overline{I^*}\right)}{\sqrt{\left(\sum_{i=1}^{N} \left(I_i - \bar{I}\right)^2\right)\left(\sum_{i=1}^{N} \left(I_i^* - \overline{I^*}\right)^2\right)}} \quad \dots (9)$$

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} \left(I_i - I_i^*\right)^2\right)^{0.5} \quad \dots (10)$$

Where, I_i is the recorded rainfall intensity of i[th] event, I_i^* is the estimated rainfall intensity of i[th] event, $\bar{I}$ is the average value of recorded rainfall intensity and $\overline{I^*}$ is the average value of estimated rainfall intensity (Acar *et al.*, 2008).

Application

An attempt has been made to develop IDF curves for different return periods from 2-year (yr) to 1000-yr for Bhavnagar and Jabalpur regions. Hourly rainfall data recorded at Bhavnagar for the period 1980 to 2005 and Jabalpur for the period 1969 to 1991 are used to compute the series of annual n-hourly maximum rainfall for different durations of 'n' such as 1-hr, 2-hr, 3-hr, 6-hr, 12-hr, 18-hr, 24-hr, 48-hr and 72-hr.

The series were further used to compute the Extreme Rainfall (ER) estimates for different return periods using OSA parameters of Gumbel and Frechet distributions. The estimated ERs are considered as a base values for development of IDF relationships using Equation (6). Table 2 gives the average hourly maximum rainfall for different durations of 'n' for the regions under study.

Table 2: Average Hourly Maximum Rainfall of Different Durations of 'n' for Bhavnagar and Jabalpur

Region	Average Hourly Maximum Rainfall (mm) for Different Durations of 'n'								
	1-hr	2-hr	3-hr	6-hr	12-hr	18-hr	24-hr	48-hr	72-hr
Bhavnagar	44.0	65.4	79.1	101.9	126.4	141.0	151.2	184.0	199.8
Jabalpur	48.7	67.4	78.9	100.9	124.8	143.1	155.0	195.1	228.5

RESULTS AND DISCUSSION

Estimation of Extreme Rainfall

By applying the procedures, as described above, a computer program was developed and used to fit the recorded rainfall data at Bhavnagar and Jabalpur regions.

The program computes the parameters of the distributions, ER estimates for different return periods from 2-yr to 1000-yr for different durations and model parameters of IDF curves together with RMSE and CC values.

The ER estimates for different return periods adopting Gumbel and Frechet distributions (using OSA) for Bhavnagar and Jabalpur are presented in Tables 3 to 6.

Table 3: ER Estimates for Different Return Periods for Different Durations of 'n' given by Gumbel Distribution for Bhavnagar

Return Period (yr)	Estimated ER (mm) for Different Durations of 'n'								
	1-hr	2-hr	3-hr	6-hr	12-hr	18-hr	24-hr	48-hr	72-hr
2	41.0	59.2	71.2	90.4	109.3	120.5	129.0	155.6	169.4
5	56.1	87.6	109.8	145.2	183.8	208.5	222.7	271.0	294.7
10	66.0	106.4	135.3	181.5	233.1	266.8	284.7	347.4	377.7
20	75.6	124.4	159.8	216.4	280.4	322.7	344.1	420.7	457.3
50	88.0	147.8	191.6	261.5	341.7	395.1	421.1	515.6	560.3
100	97.2	165.3	215.3	295.2	387.6	449.3	478.8	586.6	637.5
200	106.5	182.7	239.0	328.9	433.3	503.4	536.3	657.5	714.4
500	118.7	205.7	270.3	373.3	493.6	574.6	612.1	750.9	815.9
1000	127.9	223.1	293.9	406.9	539.2	628.5	669.4	821.6	892.6

Table 4: ER Estimates for Different Return Periods for Different Durations of 'n' Given by Frechet Distribution for Bhavnagar

Return	Estimated ER (mm) for Different Durations of 'n'								
Period (yr)	**1-hr**	**2-hr**	**3-hr**	**6-hr**	**12-hr**	**18-hr**	**24-hr**	**48-hr**	**72-hr**
2	38.7	53.3	62.3	75.5	86.7	92.4	99.6	119.0	131.2
5	56.4	84.9	107.7	140.6	171.5	191.9	199.7	243.1	271.3
10	72.4	115.6	154.6	212.1	269.6	311.5	316.6	390.1	439.0
20	92.0	155.4	218.8	314.8	416.0	495.8	492.6	614.1	696.4
50	125.4	227.9	343.0	524.8	729.3	904.7	872.9	1104.7	1265.6
100	158.1	303.7	480.3	769.6	1110.8	1419.7	1340.1	1715.4	1980.1
200	199.3	404.2	671.9	1127.0	1689.1	2224.4	2054.3	2659.5	3093.0
500	270.4	589.4	1046.1	1864.4	2936.5	4022.5	3609.2	4742.7	5570.9
1000	340.6	783.8	1461.8	2727.3	4460.1	6294.1	5525.8	7343.3	8690.8

Table 5: ER Estimates for Different Return Periods for Different Durations of 'n' given by Gumbel Distribution for Jabalpur

Return	Estimated ER (mm) for Different Durations of 'n'								
Period (yr)	**1-hr**	**2-hr**	**3-hr**	**6-hr**	**12-hr**	**18-hr**	**24-hr**	**48-hr**	**72-hr**
2	54.2	76.0	88.9	120.1	150.1	168.4	179.0	218.2	260.7
5	71.8	100.6	117.6	163.9	203.0	229.8	247.1	303.0	353.7
10	83.5	116.8	136.5	192.8	238.0	270.5	292.3	359.1	415.3
20	94.6	132.4	154.7	220.6	271.6	309.5	335.5	413.0	474.4
50	109.1	152.6	178.2	256.6	315.1	360.0	391.6	482.7	550.9
100	120.0	167.7	195.9	283.6	347.6	397.9	433.6	534.9	608.2
200	130.8	182.8	213.4	310.4	380.1	435.6	475.4	587.0	665.3
500	145.1	202.7	236.6	345.9	422.9	485.4	530.6	655.7	740.7
1000	155.8	217.7	254.1	372.7	455.3	523.0	572.3	707.6	797.6

Table 6: ER Estimates for Different Return Periods for Different Durations of 'n' given by Frechet Distribution for Jabalpur

Return	Estimated ER (mm) for Different Durations of 'n'								
Period (yr)	**1-hr**	**2-hr**	**3-hr**	**6-hr**	**12-hr**	**18-hr**	**24-hr**	**48-hr**	**72-hr**
2	50.5	70.1	81.8	105.4	132.3	150.2	160.4	195.6	234.8
5	71.7	100.7	116.1	154.8	190.2	221.5	243.1	298.6	342.3
10	90.4	128.0	146.3	199.8	241.7	286.5	320.2	395.1	439.3
20	113.0	161.0	182.7	255.1	304.3	366.7	417.0	517.0	558.0
50	150.7	216.8	243.6	350.0	410.0	504.8	586.9	732.0	760.7
100	187.1	270.9	302.2	443.7	512.6	641.4	758.2	949.9	959.5
200	232.0	338.3	374.7	561.9	640.3	814.1	978.6	1231.6	1209.2
500	308.1	453.4	497.4	767.4	858.7	1115.3	1370.4	1734.9	1640.7
1000	381.8	565.8	616.2	971.2	1072.0	1414.8	1767.5	2247.6	2066.4

From Tables 3 to 6, it may be noted that the estimated ERs for return periods from 5-yr to 1000-yr using Frechet distribution are consistently higher when compared to Gumbel for Bhavnagar and Jabalpur regions.

Development of IDF Relationships

The ER estimates given in Tables 3 to 6 were used to compute the rainfall intensity for different durations using the relation of $I=P/T_d$, where P is the rainfall depth (ER) and T_d the duration. These values are further used to develop IDF relationships for different return periods for Bhavnagar and Jabalpur regions. The parameters (A and B) of the IDF empirical equations were determined from Equations (7 and 8) and

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given in Tables 7 and 8. The values of CC and RMSE given by the fitted model were computed from Equations (9 and 10) and also given in Tables 7 and 8.

Table 7: Parameters of IDF Relationships together with CC and RMSE (mm/ hr) for Different Return Periods Adopting Gumbel and Frechet Distributions for Bhavnagar

Return Period (yr)	MPIs and Parameters of IDF Relationships Given by							
	Gumbel				Frechet			
	Model Parameters		MPIs		Model Parameters		MPIs	
	A	B	CC	RMSE	A	B	CC	RMSE
2	46.970	0.683	0.993	2.1	43.431	0.734	0.994	1.7
5	67.086	0.627	0.986	3.9	67.017	0.652	0.987	3.8
10	80.365	0.608	0.982	5.1	89.311	0.598	0.978	6.2
20	93.165	0.595	0.986	6.5	117.660	0.546	0.965	9.7
50	109.750	0.584	0.976	7.8	168.070	0.479	0.938	16.8
100	122.110	0.577	0.974	8.9	219.530	0.429	0.905	25.3
200	134.490	0.572	0.973	10.1	286.530	0.379	0.857	37.8
500	150.810	0.567	0.971	11.6	407.110	0.312	0.762	64.6
1000	163.120	0.564	0.969	12.7	530.920	0.262	0.661	97.3

Table 8: Parameters of IDF Relationships together with CC and RMSE (mm/ hr) for Different Return Periods Adopting Gumbel and Frechet Distributions for Jabalpur

Return Period (yr)	MPIs and Parameters of IDF Relationships Given by							
	Gumbel				Frechet			
	Model Parameters		MPIs		Model Parameters		MPIs	
	A	B	CC	RMSE	A	B	CC	RMSE
2	59.119	0.647	0.997	1.7	54.410	0.656	0.998	1.4
5	78.199	0.637	0.997	2.3	77.193	0.643	0.998	1.9
10	90.788	0.633	0.997	2.6	97.289	0.634	0.998	2.5
20	102.840	0.630	0.997	3.0	121.490	0.626	0.998	3.1
50	118.500	0.626	0.997	3.5	161.930	0.615	0.997	4.2
100	130.260	0.625	0.997	3.8	200.880	0.607	0.997	5.4
200	141.930	0.623	0.997	4.2	248.980	0.599	0.997	6.9
500	157.370	0.622	0.997	4.6	330.410	0.588	0.996	9.7
1000	168.980	0.621	0.997	4.8	409.240	0.580	0.995	12.6

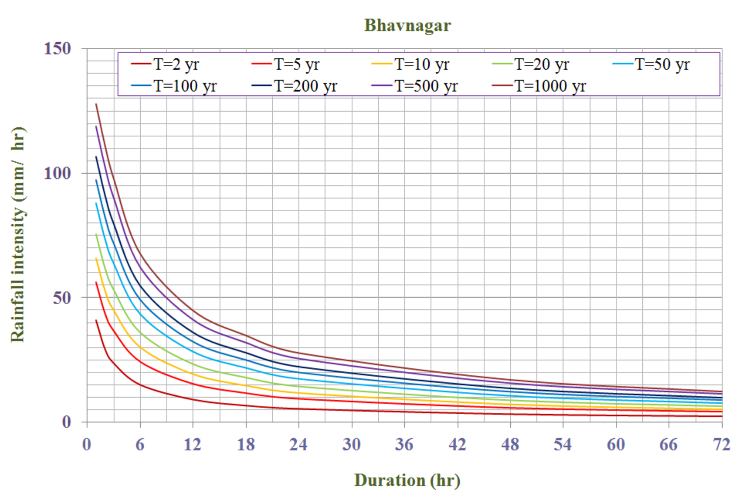

Figure 1: IDF Curves for Different Return Periods Using Gumbel Distribution for Bhavnagar

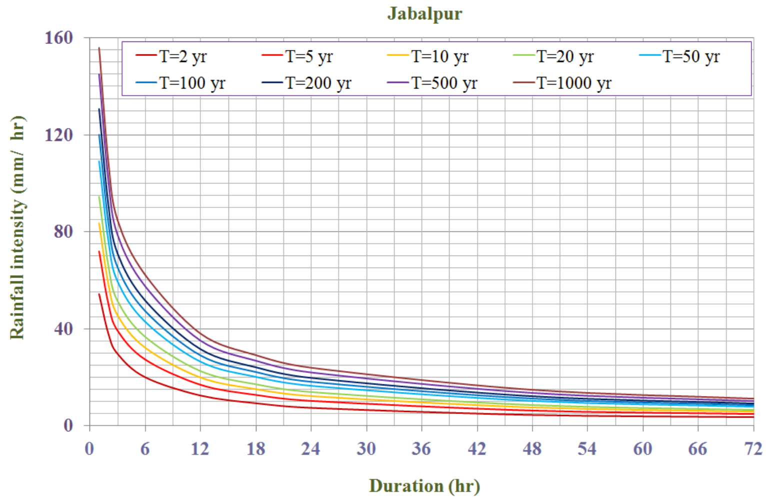

Figure 2: IDF Curves for Different Return Periods Using Gumbel Distribution for Jabalpur

From Tables 7 and 8, it may be noted that the RMSE values on the estimated rainfall intensity by Gumbel distribution are lesser when compared to Frechet for different return periods from 10-yr to 1000-yr for both the regions under study. Also, From Table 8, it may be noted that the CC values given by fitted IDF relationships adopting Gumbel and Frechet distributions are very nearer to the perfect CC value of 1 for Jabalpur. For Bhavnagar, the CC values on the fitted IDF relationships by Gumbel and Frechet distributions vary from 0.969 to 0.993 and 0.661 to 0.994 respectively. Figures 1 and 2 shows the plots of IDF curves for different return periods obtained from Gumbel distribution for Bhavnagar and Jabalpur regions. Based on RMSE values, it is suggested that the fitted IDF relationships for different return periods given by Gumbel distribution could be used for estimation of rainfall intensity for Bhavnagar and Jabalpur regions.

Conclusion

The paper presented a computer aided procedure for modelling of hourly rainfall data for Bhavnagar and Jabalpur regions. From the results of data analysis, the following conclusions are drawn from the study.

i) The ER estimates given by Gumbel and Frechet distributions (using OSA) for different durations of 'n' such as 1-hr, 2-hr, 3-hr, 6-hr, 12-hr, 18-hr, 24-hr, 48-hr and 72-hr formed the base values for development of IDF relationships.

ii) The CC values obtained from fitted IDF relationships for different return periods adopting Gumbel distribution are very close the perfect CC value of 1 for Jabalpur.

iii) For Bhavnagar, the CC values obtained from fitted IDF relationships using Gumbel distribution vary from 0.969 to 0.993.

iv) The RMSE values indicated the developed IDF relationships using Gumbel distribution shows better results when compared to Frechet for both the regions.

v) The study suggested the IDF relationships using Gumbel would be helpful for the stakeholders to estimate the rainfall intensity for a specific return period in a short time as also for planning and designing of water resources projects in Bhavnagar and Jabalpur regions.

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REFERENCES

Acar R, Celik S and Senocak S (2008). Rainfall intensity-duration-frequency model using an artificial neural network approach. *Journal of Scientific & Industrial Research* **67**(3) 198–202.

AERB (2008). Extreme values of meteorological parameters, Atomic Energy Regulatory Board (AERB) Safety Guide No. NF/SG/S-3.

Bara M, Gaal L, Kohnova S, Szolgay J and Hlavcova K (2009). Estimation of IDF curves of extreme rainfall by simple scaling in Slovakia. *Contributions to Geophysics and Geodesy* **39**(3) 187–206.

Ben-Zvi A (2009). Rainfall intensity–duration–frequency relationships derived from large partial duration series. *Journal of Hydrology* **367**(1-2) 104-114.

Bougadis J and Adamowski K (2006). Scaling model of a rainfall intensity-duration-frequency relationship. *Hydrological Process* **20**(17) 3747–3757.

Burlando P and Rosso R (1996). Scaling and multi-scaling models of depth-duration-frequency curves for storm precipitation. *Journal of Hydrology* **187**(1-2) 45-64.

Chowdhury R, Alam JB, Das P and Alam MA (2007). Short duration rainfall estimation of Sylhet: IMD and USWB method. *Journal of Indian Water Works Association* **9**(3-4) 285-292.

Dourte D, Shukla S, Singh P and Haman D (2013). Rainfall intensity-duration-frequency relationships for Andhra Pradesh, India: Changing rainfall patterns and implications for runoff and ground-water recharge. *Journal of Hydrologic Engineering* **18**(3) 324-330.

Eman AHE (2011). Generation of rainfall intensity duration frequency curves for ungauged sites Nile basin. *Water Science and Engineering Journal* **4**(1) 112-124.

Gumbel EJ (1960). *Statistic of Extremes*, 2nd edition, (Columbia University Press, New York, USA).

Khaled H, Ataur R, Janice G and George K (2011). Design rainfall estimation for short storm durations using L-Moments and generalised least squares regression-Application to Australian Data. *International Journal of Water Resources and Arid Environments* **1**(3) 210-218.

Kim T, Shin J, Kim K and Heo J (2008). Improving accuracy of IDF curves using long and short duration separation and multi-objective genetic algorithm. *World Environmental and Water Resources Congress* 12.

Koutsoyiannis D, Kozonis D and Manetas A (1998). A mathematical framework for studying rainfall intensity-duration-frequency relationships. *Journal of Hydrology* **206**(1-2) 118-135.

Nhat LM, Tachikawa Y, Sayama T and Takara K (2006). Derivation of rainfall intensity-duration-frequency relationships for short duration rainfall from daily rainfall data. *IHP Technical Documents in Hydrology* **6** 89-96.

Okonkwo GI and Mbajiorgu CC (2010). Rainfall intensity-duration-frequency analyses for South Eastern Nigeria. *Agricultural Engineering International*, Manuscript No. 1304, **XII**.

Raiford JP, Aziz NM, Khan AA and Powell DN (2007). Rainfall depth-duration-frequency relationships for South Carolina, North Carolina, and Georgia, *American Journal of Environmental Science* **3**(2) 78-84.

Rashid MM, Faruque SB and Alam JB (2012). Modelling of short duration rainfall intensity duration frequency equation for Sylhet City in Bangladesh. *ARPN Journal of Science and Technology* **2**(2) 92-95.