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Rainfall Intensity-Duration-Frequency Analysis Using Order Statistics Approach of Gumbel and Frechet Distributions

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ABSTRACT

Rainfall intensities of various frequencies and durations are the important parameter for the hydrologic design of storm sewers, culverts and many other hydraulic structures. This can be achieved by rainfall Intensity-Duration-Frequency (IDF) relationship, which is determined through Extreme Value Analysis (EVA) of hourly rainfall data. This paper details a study on EVA of 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. Order statistics approach is applied for determination of parameters of Gumbel and Frechet distributions, which are used for estimation of rainfall for different return periods. The estimated n-hourly maximum rainfall for different duration of 'n' is used to develop the IDF curves. The adequacy of Gumbel and Frechet distributions used for development of IDF relationships is evaluated by model performance indicators viz., correlation coefficient and root mean squared error. The paper presents the IDF relationship given by Gumbel distribution could be used for estimation of rainfall intensity for Bhavnagar and Jabalpur.

Keywords: *Correlation coefficient, Frechet, Gumbel, Intensity-Duration-Frequency, Mean squared error, Order statistics approach, Rainfall*

INTRODUCTION

The rainfall Intensity-Duration-Frequency (IDF) analysis 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 (IDFR) can be developed through Extreme Value Analysis (EVA) of hourly rainfall data that is used to estimate rainfall depth at a point for a specified exceedance probability and duration [1]. EVA 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 [2-3]. The frequency-data for storms of various durations, so obtained, can be represented by IDF Curve (IDFC), which gives a plot of rainfall intensity (mm/hour) and duration (hour).

Nhat et al. [4-5] applied Gumbel distribution for estimation of rainfall for different return periods for development of IDFR for Vietnam region and Yodo catchments of Japan. Prodanovic and Simonovic [6] developed rainfall IDFC for London city under different climatic conditions. Raiford et al. [7] have developed IDF relationships (IDFR) and isopluvial maps for the region encompassing South Carolina, North Carolina and Georgia using newly developed EVA methods. Kim et al. [8] improved the accuracy of IDFC by using long and short duration separation technique. They derived IDFC by using Cumulative Distribution Function (CDF) of the interesting site and multi-objective genetic algorithm. Ben-Zvi [9] proposed a procedure for basing IDFR 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. [10] applied simple scaling theory to the IDF characteristics of short duration rainfall. They have concluded that the IDFC, which were deduced from daily rainfall, showed acceptable results in comparison with the IDFC obtained from at-site short duration rainfall data. Okonkwo and Mbajiorgu [11] have developed IDFR using graphical and statistical methods for southeastern Nigeria and the results were compared. They have found that IDFR

developed from graphical and statistical methods are very close to each other 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. [12] applied L-moments and generalized least squares regression methods for estimation of design rainfall depths and development of IDFR. Eman [13] applied six probability distributions for modelling of hourly rainfall data for generation of IDFC for Sinai Peninsula in the northeast part of Egypt. Rashid et al. [14] applied Pearson Type-III distribution for modelling of short duration rainfall and development of IDFR for Sylhet City in Bangladesh. Dourte et al. [15] developed rainfall IDFR 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 the present study, Weibull distribution is not considered for EVA because of non-convergence of the recorded data while determining the distributional parameters. In addition to the above, AERB (Atomic Energy Regulatory Board) guidelines described that Order Statistics Approach (OSA) could be applied for determination of parameters of Gumbel and Frechet distributions though number of methods is available for parameter estimation. In this paper, a study on rainfall IDF analysis adopting Gumbel and Frechet distributions (using OSA) for Bhavnagar and Jabalpur regions is carried out. The estimated 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) are used for development of IDFR. Model Performance Indicators (MPIs) viz., Correlation Coefficient (CC) and Root Mean Squared Error (RMSE) are used for selection of suitable IDFR for estimation of rainfall intensity for the regions under study.

METHODOLOGY

The methodology adopted in development of IDFR and computations of MPIs are briefly described in the following sections.

Probability Distributions

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

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

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

Where, α_G and β_G are location and scale parameters of Gumbel distribution [16]. The parameters of the distribution are computed by OSA and further used to estimate the rainfall (R_G) for different return periods (T) using the relation $R_G=\alpha_G+Y_T\beta_G$ 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 rainfall (R_F) using $R_F=\text{Exp}(R_G)$, $\beta_F=\text{Exp}(\alpha_G)$ and $\lambda_F=1/\beta_G$. The procedures adopted in determination of parameters of Gumbel distribution by OSA [17] are as follows:

$$\alpha_G = r^{*}\alpha_M^{*} + r^{'}\alpha_M^{'} \text{ and } \beta_G = r^{*}\beta_M^{*} + r^{'}\beta_M^{'} \quad \ldots (3)$$

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:

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

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. Likewise, $\alpha_M^{'}$ and $\beta_M^{'}$ are the parameters of the remainders, if any. These can be computed from the following equations:

$$\alpha_M^{*} = (1/k)\sum_{i=1}^{n}\alpha_{ni}S_i,\ \alpha_M^{'} = (1/k)\sum_{i=1}^{n'}\alpha_{n'i}R_i$$

$$\beta_M^{*} = (1/k)\sum_{i=1}^{n}\beta_{ni}S_i,\ \beta_M^{'} = (1/k)\sum_{i=1}^{n'}\beta_{n'i}R_i$$

$$\text{Here, } S_i = \sum_{i=1}^{k}R_{ij},\ j=1,2,3,..,n \quad \ldots (5)$$

Where The weights of α_{ni} and β_{ni} used in determining the parameters of Gumbel distribution by OSA are presented in Table 1.

Procedure for Development of IDFR

IDFR is a mathematical relationship between the rainfall intensity, duration, and return period [18]. 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.

The general form of empirical formula used in development of IDFR is expressed by:

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

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 of empirical formula. By applying logarithm on both sides of Eq. (6), we get $\ln(I)=\ln(A)-B\ln(T_d) \Rightarrow Y=a-BX$. Parameters A and B are computed from Eqs. (7 and 8) and are expressed by:

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

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

Model Performance Analysis

The performance of IDFR given by Gumbel and Frechet distributions are evaluated by CC and RMSE. Theoretical descriptions of CC and RMSE [19] are as follows:

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

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

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 recorded rainfall intensity and $\overline{I^*}$ is the average estimated rainfall intensity.

Application

An attempt has been made to develop IDFR for different return periods from 2-yr to 1000-yr for Bhavnagar and Jabalpur regions. Hourly rainfall data [20] recorded at Bhavnagar for the period 1980 to 2005 and Jabalpur for the period 1969 to 1991 are used to compute the series of 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 was used to estimate the rainfall for different return periods using Gumbel and Frechet distributions. The estimated rainfall values are considered as a base values for development of IDFR using Eq. (6).

Results and Discussions

By applying the procedures described above, a computer program was developed and used. The program computes the parameters of distributions, rainfall estimates and model parameters of IDFR and values of MPIs.

Table1. *Weights of* α_{ni} *and* β_{ni} *used in determining the parameters of the distributions by OSA*

α_{ni} or β_{ni}	i					
	1	2	3	4	5	6
α_{2i}	0.916373	0.083627				
α_{3i}	0.656320	0.255714	0.087966			
α_{4i}	0.510998	0.263943	0.153680	0.071380		
α_{5i}	0.418934	0.246282	0.167609	0.108824	0.058350	
α_{6i}	0.355450	0.225488	0.165620	0.121054	0.083522	0.048867
β_{2i}	-0.721348	0.721348				
β_{3i}	-0.630541	0.255816	0.374725			
β_{4i}	-0.558619	0.085903	0.223919	0.248797		
β_{5i}	-0.503127	0.006534	0.130455	0.181656	0.184483	
β_{6i}	-0.459273	-0.035992	0.073199	0.126724	0.149534	0.145807

Estimation of Rainfall using PDFs

The estimated rainfall for different return periods for different duration of 'n' obtained from Gumbel and Frechet distributions for Bhavnagar and Jabalpur are presented in Tables 2 to 5. These estimates were further used to develop the IDFC. From Tables 2 to 5, it may be noted that the estimated rainfall for return periods from 5-yr to 1000-yr by Frechet distribution are higher than the corresponding values of Gumbel.

Table2. *Rainfall estimates for different durations of 'n' given by Gumbel distribution for Bhavnagar*

Return Period (yr)	Estimated 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
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

Table3. *Rainfall estimates for different durations of 'n' given by Frechet distribution for Bhavnagar*

Return Period (yr)	Estimated 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
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

Table4. *Rainfall estimates for different durations of 'n' given by Gumbel distribution for Jabalpur*

Return Period (yr)	Estimated 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
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

Table5. *Rainfall estimates for different durations of 'n' given by Frechet distribution for Jabalpur*

Return Period (Yr)	Estimated 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
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

IDFR using Empirical Formula

The estimated rainfall values were used to compute the rainfall intensity for different durations using the relation of $I=P/T_d$, where P is the rainfall depth (i.e., estimated rainfall) and T_d the duration. These rainfall intensities are used to develop IDFC. The parameters (A and B) of the IDF empirical formula were determined from Eqs. (7 and 8) and presented in Tables 6 and 7. The values of CC and RMSE given by the fitted model were computed from

Eqs. (9 and 10) and also presented in Tables 6 and 7. The plots of IDF curves for different return periods given by Gumbel distribution for Bhavnagar and Jabalpur regions are presented in Figures 1 and 2.

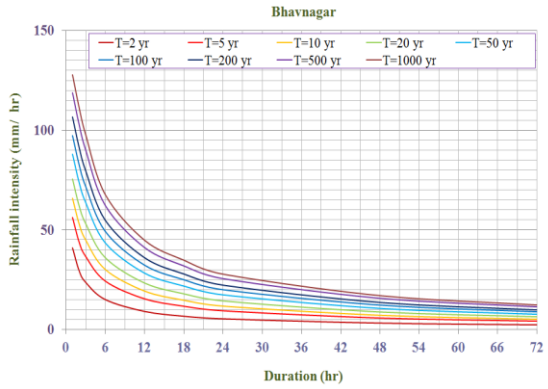

Figure1. *IDF curves for different return periods given by Gumbel distribution for Bhavnagar*

From Tables 6 and 7, it is 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.

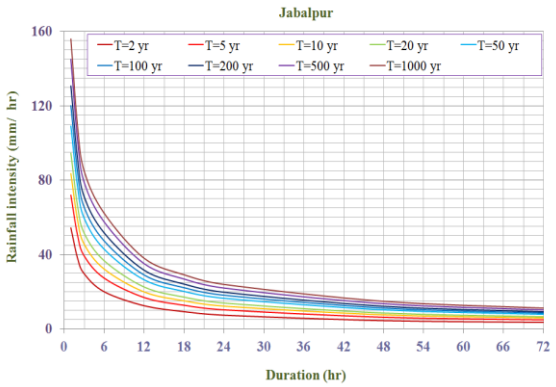

Figure2. *IDF curves for different return periods given by Gumbel distribution for Jabalpur*

Therefore, the study suggested that the fitted IDFRs for different return periods given by Gumbel may be used for estimation of rainfall intensity for Bhavnagar and Jabalpur regions.

Table6. *Parameters of IDFR 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 IDFR							
	Gumbel				Frechet			
	Model Parameters		MPIs		Model Parameters		MPIs	
	A	B	RMSE	CC	A	B	RMSE	CC
2	46.970	0.683	2.1	0.993	43.431	0.734	1.7	0.994
5	67.086	0.627	3.9	0.986	67.017	0.652	3.8	0.987
10	80.365	0.608	5.1	0.982	89.311	0.598	6.2	0.978
20	93.165	0.595	6.5	0.986	117.660	0.546	9.7	0.965
50	109.750	0.584	7.8	0.976	168.070	0.479	16.8	0.938
100	122.110	0.577	8.9	0.974	219.530	0.429	25.3	0.905
200	134.490	0.572	10.1	0.973	286.530	0.379	37.8	0.857
500	150.810	0.567	11.6	0.971	407.110	0.312	64.6	0.762
1000	163.120	0.564	12.7	0.969	530.920	0.262	97.3	0.661

Table7. *Parameters of IDFR 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 IDFR							
	Gumbel				Frechet			
	Model Parameters		MPIs		Model Parameters		MPIs	
	A	B	RMSE	CC	A	B	RMSE	CC
2	59.119	0.647	1.7	0.997	54.410	0.656	1.4	0.998
5	78.199	0.637	2.3	0.997	77.193	0.643	1.9	0.998
10	90.788	0.633	2.6	0.997	97.289	0.634	2.5	0.998
20	102.840	0.630	3.0	0.997	121.490	0.626	3.1	0.998
50	118.500	0.626	3.5	0.997	161.930	0.615	4.2	0.997
100	130.260	0.625	3.8	0.997	200.880	0.607	5.4	0.997
200	141.930	0.623	4.2	0.997	248.980	0.599	6.9	0.997
500	157.370	0.622	4.6	0.997	330.410	0.588	9.7	0.996
1000	168.980	0.621	4.8	0.997	409.240	0.580	12.6	0.995

CONCLUSIONS

The paper presented a computer aided procedure for EVA of hourly rainfall data for development of IDFRs for Bhavnagar and Jabalpur. From the

results of the data analysis, the following conclusions were drawn from the study:

i) The estimated rainfall 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 OSA was used for development of IDFR for different return periods.

ii) The CC values obtained from fitted IDFR adopting Gumbel distribution are very close the perfect correlation value of 1 for Jabalpur. For Bhavnagar, the CC values based on fitted IDFR given by Gumbel are varied from 0.969 to 0.993.

iii) The RMSE values indicated the IDFR developed through empirical formula using the estimated rainfall values of Gumbel distribution provide better results when compared to Frechet.

The study suggested that the IDFR given by Gumbel distribution may be useful for decision makers to compute rainfall intensity for planning and designing of any water resources projects in Bhavnagar and Jabalpur.

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