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Modeling Rainfall Intensity Duration Frequency (R-IDF) Relationship for Seven Divisions of Bangladesh

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Abstract:

The target of this study was to model Rainfall IDF relationship for seven divisions of Bangladesh using LPT III and Gumbel method to estimate the rainfall intensity for any duration and any return period with least effort. By developing these relationships urban drainage works, e.g. storm sewers, culverts and other hydraulic structures can be designed. Yearly maximum rainfall data for last 41 years (1974-2014) from Bangladesh Meteorological Department (BMD) was used in this study. Empirical reduction formula of Indian Meteorological Department (IMD) was used to estimate the short duration rainfall intensity from yearly maximum rainfall data. Log Pearson Type III and Gumbel's Extreme-Value Distribution method was used to develop IDF curves and equations. The results obtained using Gumbel method are somewhat higher than the outcomes obtained using the LPT III distribution method. Rainfall intensities obtained from these two methods showed good agreement with results from previous studies on some parts of the study area. The parameters of the IDF equations and coefficient of correlation for different return

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periods (2, 5, 10, 25, 50 and 100 years) are calculated by using least square method. The results obtained presented that in all the cases the correlation coefficient is very high representing the goodness of fit of the formulae to estimate IDF curves in the region of interest. It was found that intensity of rainfalls decreases with increase in rainfall duration. Further, a rainfall of any given duration will have a larger intensity if its return period is large.

Key words: Climate Change, Rainfall Intensity, Rainfall Duration, Rainfall Frequency, Return Period, Gumbel's Extreme Value Distribution Method, Log Pearson Type III, Bangladesh Meteorological Department (BMD)

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 [11]. IDF curves are used to aid the engineers while designing urban drainage works. The establishment of such relationships was done as early as 1932 [11 & 12]. 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 [13]. In Bangladesh water logging and flood is a common problem during Monsoon period because of inadequate drainage system. In order to solve this problem new drainage design is needed where rainfall data of different duration is needed. But due to instrumental limitation these data were not available. This study was conducted to develop IDF curves and equations for various duration of rainfall in seven divisions (Dhaka, Chittagong, Barisal, Khulna, Rajshahi, Rangpur, and Sylhet) of Bangladesh. In the present study, annual maximum rainfall series is considered for Rainfall Frequency Analysis (RFA). Rainfall in a region can be characterized if the intensity, duration and frequency of the diverse storms occurring at that place are known [1, 3]. The frequency-data for rainfalls of various durations, so obtained, can be represented by IDF curves, which give a plot of rainfall intensity versus rainfall duration and recurrence interval.

IDF curve was developed for North-East region of Bangladesh and also found that the rainfall data in this region follow Gumbel's Extreme Value Distribution [4]. Short duration rainfall IDF curve was developed for Sylhet with return period of 2, 5,10,20,50, and 100 years [5]. IDF curves accuracy was improved by using long and short duration separation technique [6]. L-moments and generalized least squares regression methods was applied for estimation of design rainfall depths and development of IDF relationships [7]. Pearson Type-III Distribution was applied for modelling of short duration rainfall and development of IDF relationships for Sylhet City in Bangladesh [8].

In probability theory, extreme value distributions namely Gumbel, Frechet and Weibull are generally considered for frequency analysis of meteorological variables. On the other hand, Atomic Energy Regulatory Board (AERB) guidelines described that the Order Statistics Approach (OSA) is the most appropriate method for determination of parameters of Gumbel and Frechet distributions [9]. In this present study Gumbel's Extreme Value Distribution method is used to develop IDF curves and equations. In this context, an attempt has been made to estimate the rainfall for different return periods for different durations of 'n' such as 10-min, 20-min, 30-min, 60-min, 120-min, 180-min, 360-min, 720-min, 1440-min adopting Gumbel distributions for development of IDF relationships for seven divisions of Bangladesh. Model performance indicators (MPIs) such as correlation coefficient (R) is used to analyze the performance of the developed IDF relationships by Gumbel distributions for estimation of rainfall intensity for the stations under study.

Data Collection and Methodology

For this study 24 hr daily rainfall data from year 1974 to 2014 were collected from Bangladesh Meteorological Department (BMD). From the daily data maximum yearly rainfall data was used in the analysis.

Estimation of Short Duration Rainfall

Indian Meteorological Department (IMD) use an empirical reduction formula (EQ. 1) for estimation of various duration like 1-hr, 2-hr, 3-hr, 5-hr, 8-hr rainfall values from annual maximum values. Indian Meteorological Department (IMD) empirical reduction formula was used to estimate the short duration rainfall from daily rainfall data in Sylhet city and found that this formula give the best estimation of short duration rainfall [5]. In this study this empirical formula (EQ. 1) was used to estimate short duration rainfall in all the seven divisions of Bangladesh.

$$P_t = P_{24} \sqrt[3]{\frac{t}{24}} \qquad (1)$$

Where, P_t is the required rainfall depth in mm at t-hr duration, P_{24} is the daily rainfall in mm and t is the duration of rainfall for which the rainfall depth is required in hr.

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:

$$P_T = P_{ave} + KS \quad (2)$$

Where K is Gumbel frequency factor given by:

$$K=-\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left[\ln\left[\frac{T}{T-1}\right]\right]\right] \quad (3)$$

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

In utilizing Gumbel's distribution, the arithmetic average in Eq. (2) is used:

$$P_{ave}=\frac{1}{n}\sum_{i=1}^{n} Pi \quad (4)$$

Where Pi 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. (5) computed using the following relation:

$$S=\left[\frac{1}{n-1}\sum_{i=1}^{n}(Pi - Pave)^2\right]^{1/2} \quad (5)$$

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_T (in mm/h) for return period T is obtained from:

$$I_T=\frac{Pt}{Td} \quad (6)$$

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 [10].

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. 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:

$$P^* = \log(\mathrm{Pi}) \tag{7}$$

$$P_T^* = Pave^* + K_T S^* \tag{8}$$

$$Pave^* = \frac{1}{n}\sum_{i=1}^{n} P^* \tag{9}$$

$$S^* = \left[\frac{1}{n-1}\sum_{i=1}^{n}(P^* - Pave^*)^2\right]^{1/2} \tag{10}$$

Where P_T^*, Pave*, S* are as defined previously in previous but based on the logarithmically transformed Pi values; i.e. P* of Eq. (7). K_T is the Pearson frequency factor which depends on return period (T) and skewness coefficient (Cs). The skewness coefficient, Cs, is required to compute the frequency factor for this distribution. The skewness coefficient is computed by Eq. (11) [12&13]

$$C_S = \frac{n\sum_{i=1}^{n}(Pi^* - Pave^*)^3}{(n-1)(\mathrm{n}-2)(\mathrm{S}^*)^3} \tag{11}$$

K_T values can be obtained from tables in many hydrology references; for example reference [12]. 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.

IDF empirical equation

IDF empirical equations are the equation that estimates the maximum rainfall intensity for different duration and return period. Different procedures and formulas have been proposed in various literatures [5, 7, 8, 9]. IDF is a mathematical relationship between the rainfall intensity *i*, the duration t*d*, and the return period T [10, 11]. Equations (12) is the form of IDF empirical equation which is used in this study.

$$i = x^* (t_d)^{-y} \qquad (12)$$

Where, i is the rainfall intensity in mm/hr, td is the rainfall duration in min. x and y are the fitting parameter. These empirical equations are widely used in various hydrological applications. These equations indicate that for a given return period the rainfall intensity decreases with the increase in rainfall duration. Least-square method was applied to find the parameter x and y for the rainfall IDF empirical formula. Correlation coefficient (R) was estimated to find the best fit IDF empirical equation. For a specific return period the equation that gives R value nearer to 1 have the best fit.

Results and Discussions

From the raw data, the maximum rainfall (P) and the statistical variables (average and standard deviation) for each duration (10, 20, 30, 60, 120, 180, 360, 720, 1440 min) were calculated. Various duration of rainfalls like 10, 20, 30, 60, 120, 180, 360, 720 and 1440 min were estimated from annual maximum 24 hours rainfall data using Indian Meteorological empirical reduction formula. These estimated various duration data were used in Gumbel's Extreme Probability Method and

Log Pearson Type III to determine rainfall (P_T) values and intensities (I_T) for seven divisions of Bangladesh. After finding out the rainfall (P_T) values and intensities (I_T) in figure 1 to 7 Rainfall IDF curves are shown using Gumbel method and in figure 8 to 14 R-IDF curves are shown using Log Pearson Type III method for seven divisions of Bangladesh. Then finally for each division for each return period an equation has been developed. It was found that the correlation coefficient for each equation is above 0.97 which indicates a strong relationship in IDF equations. 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.

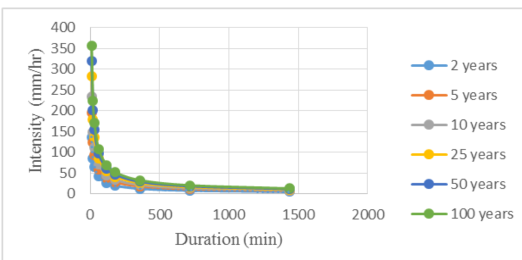

Figure 1: Rainfall IDF curve for Dhaka Division

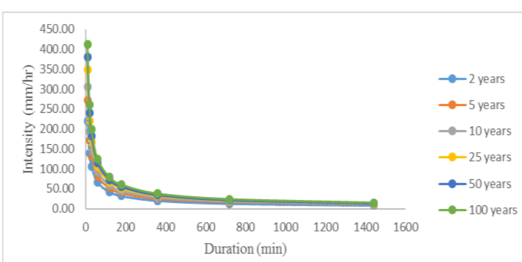

Figure 2: Rainfall IDF curve for Sylhet Division

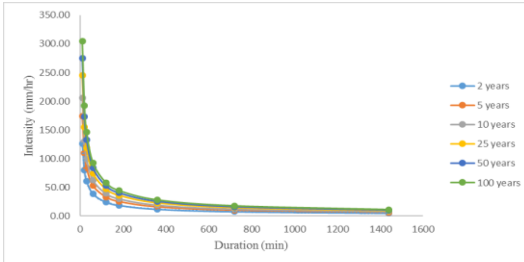

Figure 3: Rainfall IDF curve for Rajshahi Division

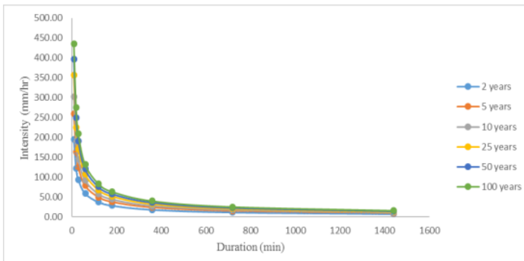

Figure 4: Rainfall IDF curve for Rangpur Division

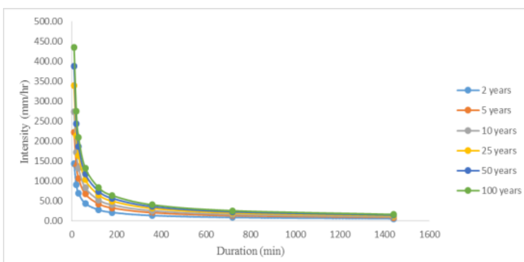

Figure 5: Rainfall IDF curve for Khulna Division

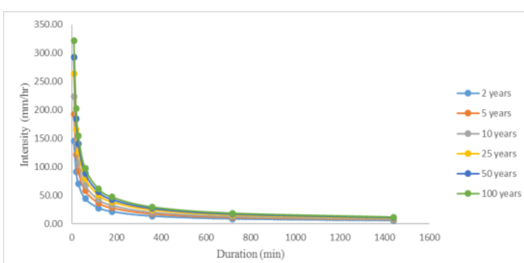

Figure 6: Rainfall IDF curve for Barisal Division

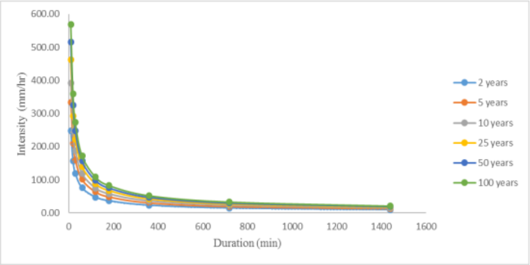

Figure 7: Rainfall IDF curve for Chittagong Division

Table 1: Rainfall IDF empirical equation using Gumbel method and their correlation coefficient, R for Dhaka Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 634.47X^{-0.667}$	0.982
5	$Y = 907.84X^{-0.667}$	0.987
10	$Y = 1089.3X^{-0.667}$	0.987
25	$Y = 1318X^{-0.667}$	0.984
50	$Y = 1487.7X^{-0.667}$	0.987
100	$Y = 1656.4X^{-0.667}$	0.987

Table 2: Rainfall IDF empirical equation using Gumbel method and their correlation coefficient, R for Sylhet Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 1023.1X^{-0.667}$	0.984
5	$Y = 1262.4X^{-0.667}$	0.987
10	$Y = 1421.2X^{-0.667}$	0.987
25	$Y = 1621.5X^{-0.667}$	0.986
50	$Y = 1770X^{-0.667}$	0.987
100	$Y = 1917.7X^{-0.667}$	0.987

Table 3: Rainfall IDF empirical equation using Gumbel method and their correlation coefficient, R for Rajshahi Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 903.7X^{-0.667}$	0.987
5	$Y = 1203.4X^{-0.667}$	0.982
10	$Y = 1402.4X^{-0.667}$	0.987
25	$Y = 1653.2X^{-0.667}$	0.987
50	$Y = 1839.2X^{-0.667}$	0.987
100	$Y = 2024.2X^{-0.667}$	0.986

Table 4: Rainfall IDF empirical equation using Gumbel method and their correlation coefficient, R for Rangpur Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 903.7X^{-0.667}$	0.987
5	$Y = 1203.4X^{-0.667}$	0.987
10	$Y = 1402.4X^{-0.667}$	0.984
25	$Y = 1653.2X^{-0.667}$	0.987
50	$Y = 1839.2X^{-0.667}$	0.987
100	$Y = 2024.2X^{-0.667}$	0.983

Table 5: Rainfall IDF empirical equation using Gumbel method and their correlation coefficient, R for Khulna Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 665.27X^{-0.667}$	0.987
5	$Y = 1028.8X^{-0.667}$	0.987
10	$Y = 1270X^{-0.667}$	0.985
25	$Y = 1574.3X^{-0.667}$	0.987
50	$Y = 1799.9X^{-0.667}$	0.986
100	$Y = 2024.2X^{-0.667}$	0.987

Table 6: Rainfall IDF empirical equation using Gumbel method and their correlation coefficient, R for Barisal Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 674.76X^{-0.667}$	0.987
5	$Y = 893.85X^{-0.667}$	0.987
10	$Y = 1039.2X^{-0.667}$	0.987
25	$Y = 1222.6X^{-0.667}$	0.987
50	$Y = 1358.6X^{-0.667}$	0.987
100	$Y = 1493.8X^{-0.667}$	0.987

Table 7: Rainfall IDF empirical equation using Gumbel method and their correlation coefficient, R for Chittagong Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 1151.8X^{-0.667}$	0.987
5	$Y = 1551X^{-0.667}$	0.985
10	$Y = 1816X^{-0.667}$	0.987
25	$Y = 2150.1X^{-0.667}$	0.987
50	$Y = 2397.9X^{-0.667}$	0.987
100	$Y = 2644.3X^{-0.667}$	0.989

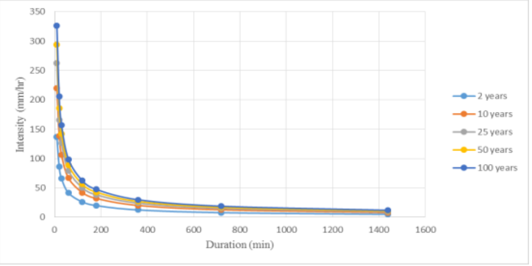

Figure 8: IDF curve for Dhaka Division

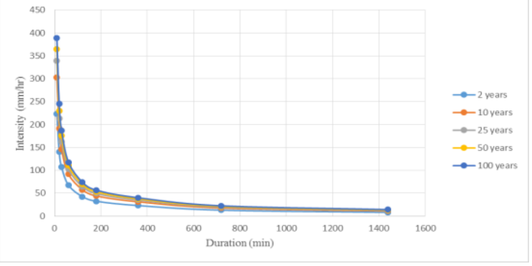

Figure 9: IDF curve for Sylhet Division

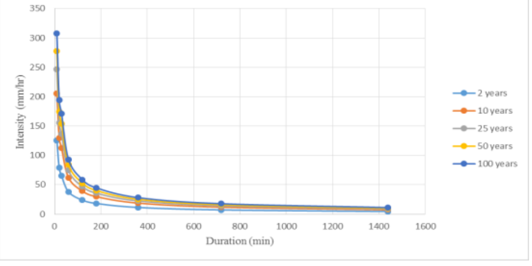

Figure 10: IDF curve for Rajshahi Division

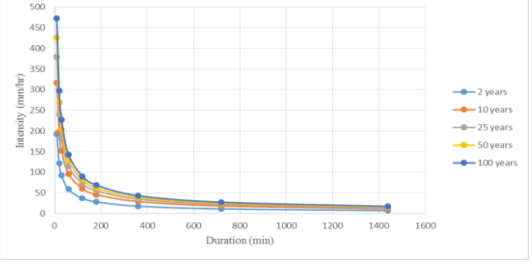

Figure 11: IDF curve for Rangpur Division

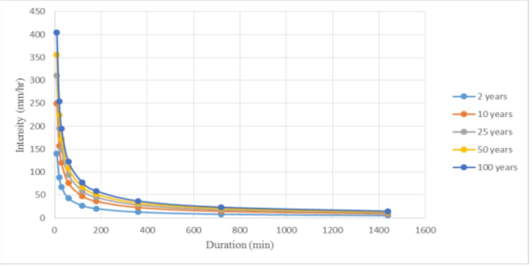

Figure 12: IDF curve for Khulna Division

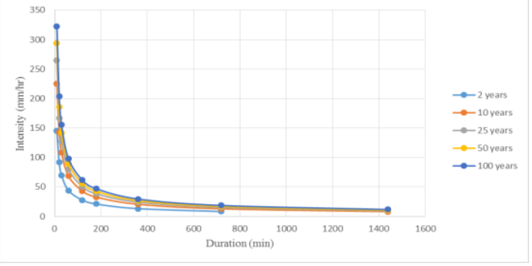

Figure13:IDF curve for Barisal Division

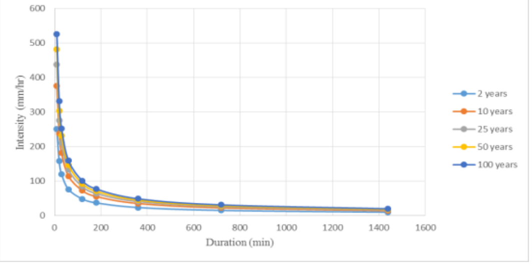

Figure 14: IDF curve for Chittagong Division

Table 8: Rainfall IDF empirical equation using LPTIII method and their correlation coefficient, R for Dhaka Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 634.76X^{-0.667}$	0.987
10	$Y = 1023.2X^{-0.667}$	0.987
25	$Y = 1219.8X^{-0.667}$	0.986
50	$Y = 1366.8X^{-0.667}$	0.987
100	$Y = 1514.1X^{-0.667}$	0.982

Table 9: Rainfall IDF empirical equation using LPTIII method and their correlation coefficient, R for Sylhet Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 1020.6X^{-0.667}$	0.985
10	$Y = 1385.9X^{-0.667}$	0.987
25	$Y = 1550X^{-0.667}$	0.986
50	$Y = 1666.2X^{-0.667}$	0.987
100	$Y = 1778X^{-0.667}$	0.989

Table 10: Rainfall IDF empirical equation using LPTIII method and their correlation coefficient, R for Rajshahi Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 602.27X^{-0.662}$	0.9994
10	$Y = 1005.6X^{-0.665}$	0.9986
25	$Y = 1209.7X^{-0.665}$	0.9984
50	$Y = 1362.5X^{-0.665}$	0.9984
100	$Y = 1514.6X^{-0.665}$	0.9983

Table 11: Rainfall IDF empirical equation using LPTIII method and their correlation coefficient, R for Rangpur Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 896.63X^{-0.667}$	0.987
10	$Y = 1402.4X^{-0.667}$	0.987
25	$Y = 1653.2X^{-0.667}$	0.986
50	$Y = 1839.2X^{-0.667}$	0.987
100	$Y = 2024.2X^{-0.667}$	0.982

Table 12: Rainfall IDF empirical equation using LPTIII method and their correlation coefficient, R for Khulna Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 653.82X^{-0.667}$	0.987
10	$Y = 1161.3X^{-0.667}$	0.987
25	$Y = 1438.7X^{-0.667}$	0.999
50	$Y = 1654X^{-0.667}$	0.987
100	$Y = 1876.9X^{-0.667}$	0.987

Table 13: Rainfall IDF empirical equation using LPTIII method and their correlation coefficient, R for Barisal Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 674.6X^{-0.666}$	0.987
10	$Y = 1047.9X^{-0.666}$	0.984
25	$Y = 1230.9X^{-0.666}$	0.987
50	$Y = 1365.4X^{-0.666}$	0.987
100	$Y = 1499.1X^{-0.666}$	0.987

Table 14: Rainfall IDF empirical equation using LPTIII method and their correlation coefficient, R for Chittagong Division

Return Period (yr)	Equation	Correlation Coefficient, R
2	$Y = 1161X^{-0.667}$	0.984
10	$Y = 1747.9X^{-0.667}$	0.987
25	$Y = 2031X^{-0.667}$	0.987
50	$Y = 2237.5X^{-0.667}$	0.988
100	$Y = 2441.6X^{-0.667}$	0.987

Table 15: IDF Parameters of Rainfall IDF empirical equations for various return periods at Dhaka Division

	IDF empirical Equation Parameter			
Return Period (yr.)	Gumbel Method		**Log Pearson Type ш**	
	x	y	x	**y**
2	634.47	0.667	634.76	0.667
10	1089.3	0.667	1023.2	0.667
25	1318	0.667	1219.8	0.667
50	1487.7	0.667	1366.8	0.667
100	1656.4	0.667	1514.1	0.667

Parameters of the selected IDF formula were adjusted by the method of least 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 except few cases where it ranges between 0.987 and 0.999. This indicates the goodness of fit of the formulae to estimate IDF curves in the division of interest. Table 15 shows the comparison of IDF parameters obtained by analyzing the IDF data using the two methods for Dhaka Division. Similarly for all other divisions this comparison table has been developed and it was found that in all cases parameters are close in both method.

Conclusions

This study reveals some insight into the way in which the rainfall is estimated in Bangladesh. Since Bangladesh has different climatic conditions from one division to another, a relation for each division has to be obtained to estimate rainfall intensities for different durations and return periods ranging between 2 and 100 years. The parameters of the design rainfall intensity for a given period of recurrence were estimated for each division in this study. Gumbel method gave some larger rainfall intensity estimates compared to LPT III distribution. The results obtained from that work are consistent with the results from previous studies done in some parts of the study area. The results obtained showed a good match between the rainfall intensity computed by the method used and the values estimated by the calibrated formula with a correlation coefficient of greater than 0.98. This indicated the goodness of fit of the formula 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. This study will be helpful in many design problems related to watershed management, such as runoff disposal and erosion control, it is necessary to know the rainfall intensities of different durations and different return periods.

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