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Development of Rainfall Intensity-Duration-Frequency (IDF) Model of Gassol Town in Central Zone, Taraba State, Nigeria

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Abstract

Rainfall intensity has been one of the contributory factors to most frequent yearly flooding. Precipitation data collected by Nigerian Meteorological Agency (NIMET) and other relevant agencies often require refinement and statistical analysis to be effectively utilized. In this study, the precipitation data series gotten from NIMET, Yola office was used to develop the IDF model of the study area under consideration, which is not available. The IDF model will help to predict rainfall events, assist in the designing of urban drainage systems and basin outlets, serve as demonstrative learning aid for engineering students and other related fields. An annual maximum daily rainfall data during the last 43 years (1979 to 2022) obtained from NIMET, Yola office; from which, respective rainfall depths of short durations (10-min, 15-min, 30-min, 2-hr, 6-hr, 12-hr, and 24-hr) using the Indian Meteorological Department one third reduction formulation were determined. Gumbel's Distribution Method was then adopted to determine a daily rainfall depth corresponding to a given return period and subsequently rainfall intensity for the various duration and return period were determined. Results of the rainfall intensity were then entered into Minitab stat 19 model to determine the coefficients C, K, α and β in the IDF model. The results indicated that the model has a reliability of 99.98% with an error of 0.5925%. After validation it was found out that the model could assist to predict rainfall intensity for the various duration and frequency in the design of drainage system of Gassol town with errors varying from 0.075% to 1.11%; indicating that there is a good agreement between the observed and the predicted data.

1.0. Introduction

Rainfall intensity-duration-frequency (IDF) model is a mathematical relationship that exist between the three quantities (IDF) which could be used to predict rainfall intensity for a particular shorter duration of a known return period. IDF model provides a good basis for design of storm water and flood management infrastructures by estimating uncertainties damage risk of these structures [1]. Rainfall intensity has been one of the contributory factors to most frequent yearly flooding. Precipitation data collected by Nigerian Meteorological Agency (NIMET) and other relevant agencies often require refinement and statistical analysis to be effectively utilized. In this study, the precipitation data series gotten from NIMET, Yola office was used to develop the IDF model of the study area under consideration, which is not available. The IDF model may help to predict rainfall events, assist in the designing of urban drainage systems and basin outlets, serve as demonstrative learning aid for engineering students and other related fields. Much researches have been carried out to represent IDF in a mathematical form amongst which included studies conducted by [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12].

2.0. Materials and Methods

2.1. Description of the study Area

Taraba State Central Senatorial District consisted of five LGAs: Bali, Gashaka, Gassol, Kurmi and Sardauna. The district extends from Latitude 6º 30' 00" N to 8º 48' 46" N of the Equator, and Longitude 10º 01' 00" E to 11º 50' 18" E of the Meridian (Fig. 1). The Republic of Cameroon bounds the district in the South, Adamawa State in the North East, and Karim-Lamido, Ardo-Kola, and Yorro LGA to the North, Wukari and Donga LGA, to the West and Ibi LGA to North-West. The total land area of the district calculated in this study is 32,110.82 km². Like most parts of Northern Nigeria, Taraba State Central District has a wet and dry climate. The wet season lasts, on the average, from April to October [13].

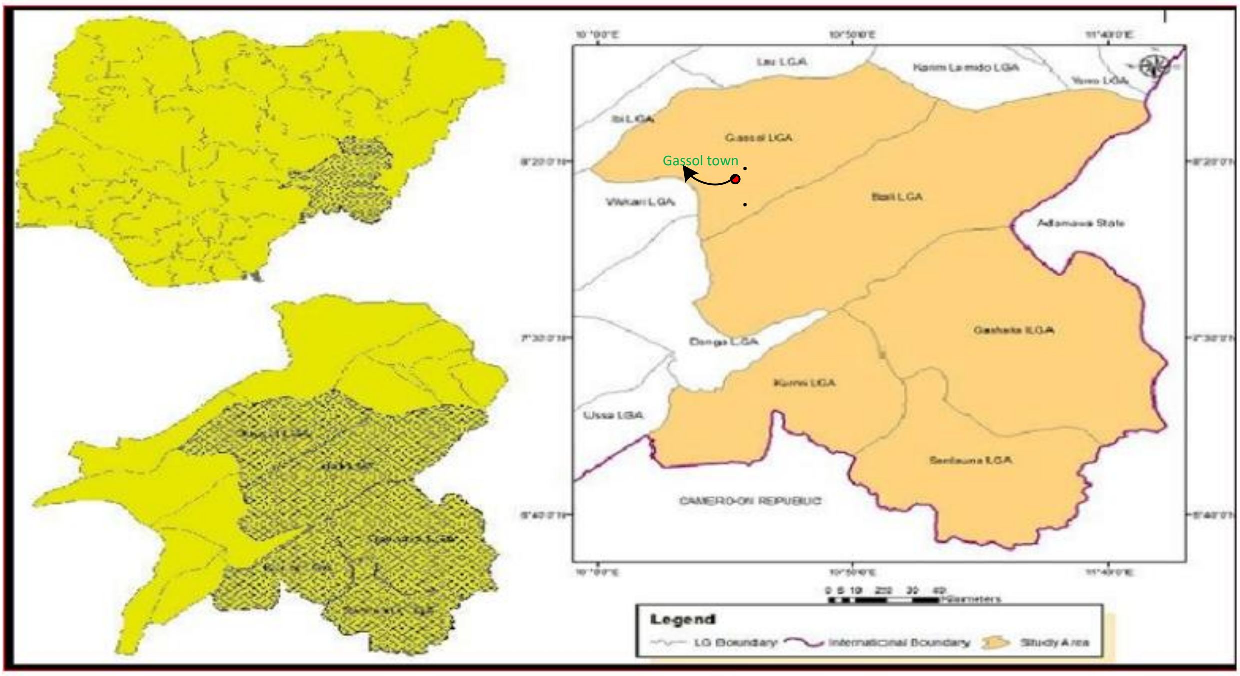

Figure 1: Map of the study area (Modified from [14])

2.2. Collection of available Rainfall Data

Annual maximum precipitation records gotten from NIMET, Yola office was the basis of the data used in this study; this is undoubtedly the data base for most climatic parameters in Taraba state and its environs. Respective rainfall depths of short durations (10-min, 15-min, 30-min, 2-hr, 6-hr, 12-hr, and 24-hr) were determined using the Indian Meteorological Department (IMD) one third reduction formula, as given in Equation (1).

$$P_t = P_{24}(t_d/24)^{0.33} \qquad (1)$$

where, P_t = rainfall in mm for t-hrs duration, P_{24} = daily rainfall data in mm, t_d = shorter duration in hours

2.3. Determination of Intensity-Duration-Frequency

In this study, Gumbel's Distribution Method (GDM) was adopted to determine frequency rainfall depth for various duration and return period, T_r because of its convenient and the parameters do not require reading on a chart; GDM specifically, takes care of extreme values of $T_r(yrs)$.

The frequency rainfall depth, P_t for each duration t_d at each given return period T_r using the Gumbel's Distribution is given in Equation (2).

$$P_t = \sigma + K_T\bar{P} \quad (2)$$

where, K_T is the frequency factor to be determined by the formula given in Equation (3).

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

The frequency factor is used to obtain P_t corresponding to return periods of 5, 10, 25, 50, 100 and 1000 years for durations of 0.17, 0.25, 0.5, 2, 6, 12 and 24 hours. Then, the intensity of rainfall I_T is obtained for the return period T_r given in Equation (4).

$$I_T = \frac{P_t}{t_d} \quad (4)$$

2.4. Development of Intensity Duration Frequency (IDF) Model

Rainfall intensity I_T and duration of rainfall t_d are inversely related.
Mathematically.

$$I_T = \frac{C}{(t_d)^{\alpha}} \quad (5)$$

A general expression for IDF can be obtained by assuming that the constant C in Equation (5) is related to return period as.

$$C = K(T_r)^{\beta} \quad (6)$$

Where K is a coefficient, T_r is return period and β is an exponent. Therefore, the IDF model is of the form.

$$I_T = \frac{K(T_r)^{\beta}}{(t_d)^{\alpha}} \quad (7)$$

Taking the logarithm of the terms in Equation (5) yields.

$$\log\,(I_{T)} = logC - \alpha\log\,(t_d) \quad (8)$$

Also, logarithm of the terms in Equation (6) yields.

$$logC = logK + \beta log(T_r) \quad (9)$$

where, I_T(mm/hr), $t_d(hr)$, C, K, α and β are determine by using the Minitab Stat 19 model.

2.5 Model Validation

For each return period, values of rainfall intensity determined from observed data were plotted against those gotten from the IDF equation in order to check for their consistency. If the linear graph gives an angle of 45^0, it shows that the equation is 100% reliable otherwise means it has an error and its extent can be determined by Equation (10) given as.

$$\%error = \left|\frac{theoretical - actual}{theoretical}\right| \times 100 \quad (10)$$

For instance, if the slope angle of the straight line is given as 44. 92^0.
then the $\%error = \left|\frac{44.92-45}{44.92}\right| \times 100 = 0.18\%$

3.0. Results and Discussion
3.1. Rainfall Data generation
Available annual maximum rainfall depths in mm of Gassol town, for 24 hours during the last 43 years (1979 to 2022) obtained from NIMET, Yola office was used in this research (Figure 2). It was from the data of maximum daily rainfall depth $\boldsymbol{P_{24}}$ where Equation (1) was used to determine respective rainfall depths of the short durations (10-min, 15-min, 30-min, 2-hr, 6-hr, 12-hr, and 24-hr) for each year, as shown in Table 2, which was subsequently use in order to determine IDF data.

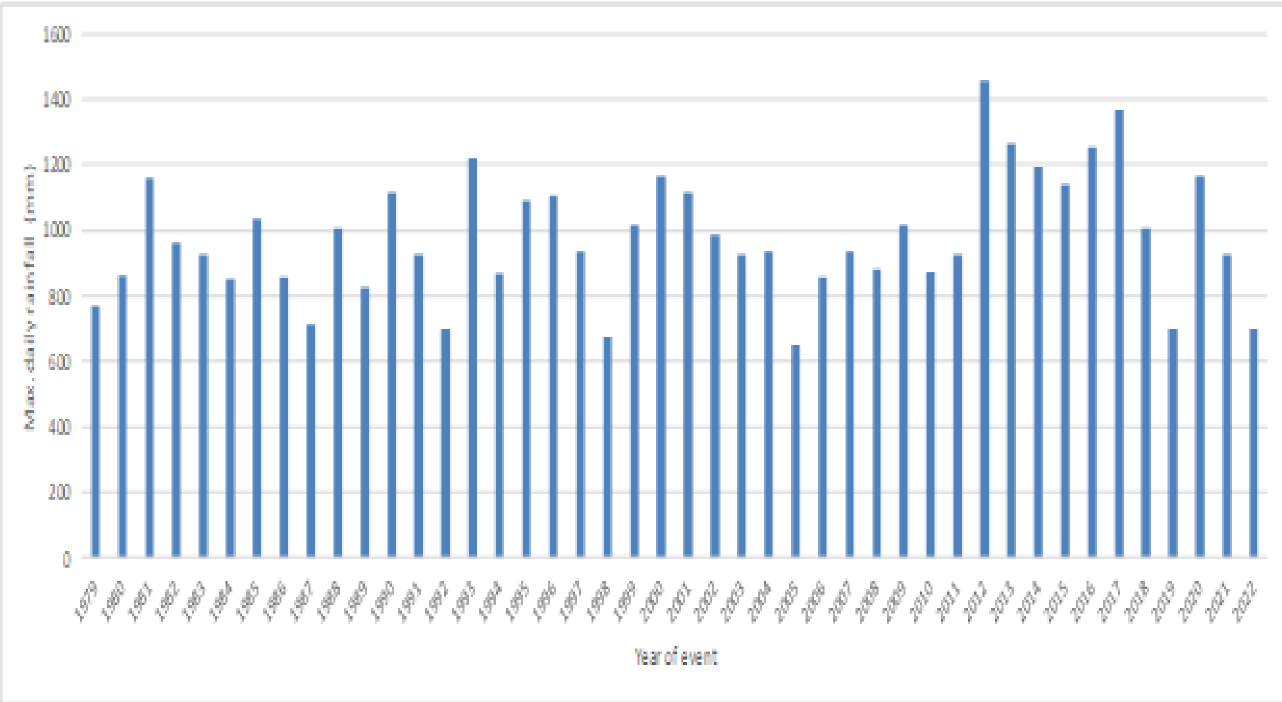

Figure 2: Annual maximum daily rainfall

3.2. Intensity-Duration-Frequency data
Equation (3) was used for the return periods of 5, 10, 25, 50, 100 and 1000 years to calculate frequency factors' values as 0.7195, 1.3046, 2.0439, 2.5923, 3.1367 and 4.9355, respectively. The values of the mean and standard deviation of rainfall depth for shorter duration of the annual series were also computed, as shown in Table 2, which were then used to obtained the frequency rainfall depth, P_t corresponding to return periods of 5, 10, 25, 50, 100 and 1000 years for durations of 0.17, 0.25, 0.5, 2, 6, 12 and 24 hours, using Equation (2).
Then, the intensity of rainfall I_T is obtained for the return period T_r, using Equation (4).
Data for Rainfall Intensity in mm/hr at various rainfall durations and return periods are shown in Figure 3. The results showed that I_T decreases with an increase in duration and increases with an increase in T_r. Return period, T-1000, has the highest value of I_T 0f 91.3774mm/hr and T-5 has the lowest value of 53.3623mm/hr. The results have agreed with the IDF relation in Equation (7).

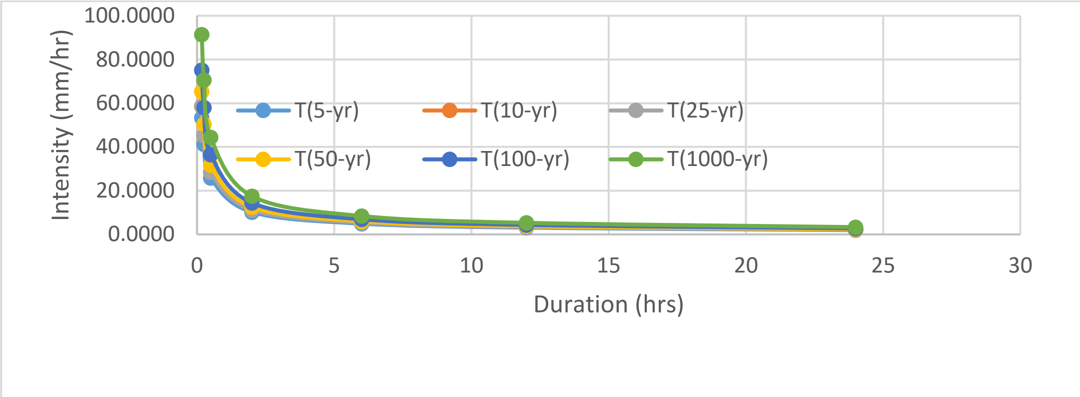

Figure 3: Intensity Duration Frequency Curves

Table 1: Shorter Duration Rainfalls Derived from Max. Daily Rainfall using IMD 1/3rd rule

YEAR	0.17hr (10min)	0.25hr (15min)	0.5hr (30min)	2hr	6hr	12hr	24hr
1979	6.254	7.103	8.929	14.108	20.273	25.484	32.033
1980	7.027	7.981	10.032	15.852	22.778	28.633	35.992
1981	9.421	10.699	13.449	21.250	30.536	38.385	48.250
1982	7.823	8.885	11.168	17.646	25.357	31.874	40.067
1983	7.560	8.586	10.793	17.054	24.506	30.804	38.721
1984	6.947	7.889	9.917	15.670	22.517	28.305	35.579
1985	8.436	9.581	12.044	19.030	27.346	34.374	43.208
1986	6.958	7.902	9.933	15.696	22.554	28.351	35.638
1987	5.809	6.598	8.294	13.104	18.831	23.671	29.754
1988	8.176	9.286	11.672	18.443	26.502	33.313	41.875
1989	6.752	7.669	9.640	15.231	21.887	27.512	34.583
1990	9.083	10.316	12.967	20.489	29.442	37.009	46.521
1991	7.558	8.584	10.791	17.050	24.500	30.797	38.713
1992	5.693	6.466	8.127	12.842	18.454	23.197	29.158
1993	9.917	11.263	14.157	22.370	32.145	40.407	50.792
1994	7.068	8.027	10.090	15.943	22.910	28.798	36.200
1995	8.888	10.095	12.689	20.050	28.812	36.217	45.525
1996	9.011	10.233	12.864	20.326	29.207	36.714	46.150
1997	7.640	8.677	10.907	17.233	24.764	31.129	39.129
1998	5.485	6.229	7.830	12.372	17.779	22.348	28.092
1999	8.285	9.409	11.828	18.689	26.855	33.757	42.433
2000	9.460	10.743	13.505	21.339	30.663	38.544	48.450
2001	9.074	10.306	12.954	20.469	29.413	36.973	46.475
2002	8.034	9.125	11.470	18.123	26.043	32.736	41.150
2003	7.552	8.577	10.781	17.035	24.479	30.771	38.679
2004	7.616	8.650	10.873	17.180	24.688	31.033	39.008
2005	5.283	6.000	7.542	11.917	17.125	21.526	27.058
2006	6.958	7.902	9.933	15.696	22.554	28.351	35.638
2007	7.640	8.677	10.907	17.233	24.764	31.129	39.129
2008	7.183	8.157	10.254	16.202	23.282	29.266	36.788
2009	8.285	9.409	11.828	18.689	26.855	33.757	42.433
2010	7.112	8.077	10.153	16.042	23.053	28.977	36.425
2011	7.558	8.584	10.791	17.050	24.500	30.797	38.713
2012	11.863	13.473	16.935	26.759	38.453	48.335	60.758
2013	10.298	11.696	14.702	23.230	33.382	41.961	52.746
2014	9.735	11.056	13.897	21.959	31.554	39.664	49.858
2015	9.270	10.528	13.234	20.911	30.049	37.771	47.479
2016	10.189	11.572	14.546	22.985	33.028	41.517	52.188
2017	11.147	12.660	15.913	25.144	36.132	45.419	57.092
2018	8.176	9.286	11.672	18.443	26.502	33.313	41.875
2019	5.693	6.466	8.127	12.842	18.454	23.197	29.158
2020	9.460	10.743	13.505	21.339	30.663	38.544	48.450
2021	7.558	8.584	10.791	17.050	24.500	30.797	38.713
2022	5.693	6.466	8.127	12.842	18.454	23.197	29.158
SDEV	**1.533**	**1.741**	**2.188**	**3.458**	**4.969**	**6.246**	**7.851**
MEAN	**7.969**	**9.050**	**11.376**	**17.976**	**25.831**	**32.469**	**40.814**

3.3. IDF Model

The data for rainfall intensity in mm/hr at various rainfall durations and return periods in Figure 3 were entered into Minitab stat 19 model to determine C, K, α and β given in Equation (5) and (6), respectively, to produce the IDF relation in Equation (11). The results showed that the model has a reliability 99.98% with an error of 0.5925%.

$$I_T = \frac{14.2069\,(T_r)^{0.1006}}{(t_d)^{0.67}} \quad (11)$$

3.4. Model validation

The determined values of rainfall intensity for various rainfall duration and return period shown in Figure 3 were compared with those gotten from the IDF model of Equation (11), as presented in Figure 4 (a-f). The results showed that the errors for the respective return period varies from 0.075% to 1.11%; indicating that there is a good agreement between them.

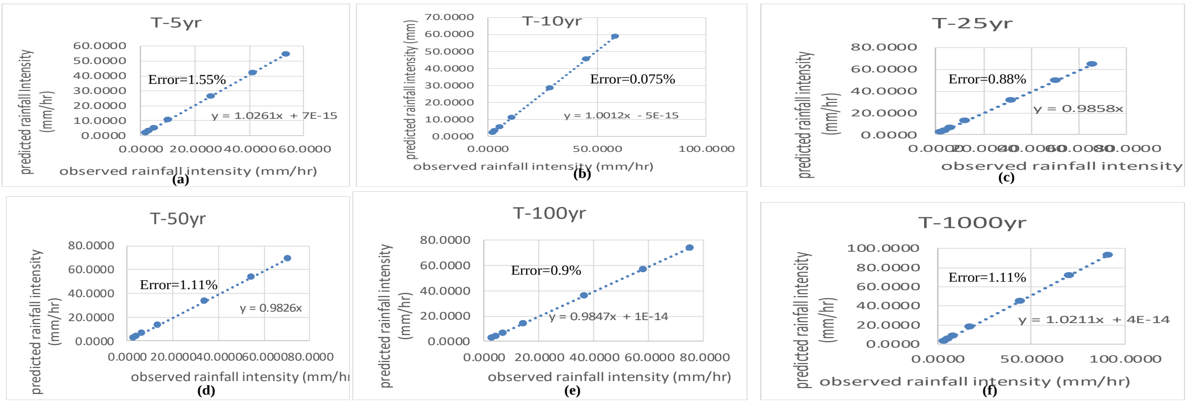

Figure 4 (a-f): Comparison between observed and predicted rainfall intensity

4.0. Conclusion

This research developed a mathematical model for the prediction of rainfall intensity for various short duration and return period. Available annual maximum rainfall depths in mm of Gassol town, for 24 hours during the last 43 years (1979 to 2022) obtained from NIMET, Yola office was used in this study out of which annual daily rainfall depth for short duration was gotten. Gumbel's Distribution Method was adopted to determine the frequency rainfall depth from which rainfall intensity was determined. Finally, results of the rainfall intensity-duration-frequency were analysed using Minitab stat 19 model to determine the coefficients C, K, α and β in the IDF model. The results indicated that the model has a reliability of 99.98% with an error of 0.5925%. After validation it was found out that the model could assist to predict rainfall intensity for the various duration and frequency in the design of drainage system of Gassol town with errors varying from 0.075% to 1.11%; indicating that there is a good agreement between the observed and the predicted data.

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