Rainfall Intensity Analysis for Synoptic Stations in Northern Nigeria

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ABSTRACT: With the large inter-annual variability of rainfall in Northern Nigeria, a zone subject to frequent dry spells which often result in severe and widespread droughts, the need for intense study of rainfall and accurate forecast of rainfall intensity duration frequency (IDF) curves cannot be over emphasized. The Intensity Duration Frequency relationship is a mathematical relationship between the rainfall intensity and rainfall duration for given return periods. Using a subset of the network of fifteen continuous auto recording rain gauges available in Northern Nigeria, a total of seven different time durations ranging from 12 minutes to 24 hours were developed for return periods of 2, 5, 10, 25, 50 and 100 years. The maximum data series so obtained was fitted to Gumbel's Extreme Value Type 1 distribution. Linear Regression Analysis was then used to obtain the intensity-duration relationships for the various locations from which Intensity-Duration Frequency (IDF) curves were generated using Microsoft Excel for various return periods.

KEYWORDS: Extreme rainfall, intensity, duration, frequency, Northern Nigeria.

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I. INTRODUCTION

Statistical tools of analysis are normally employed to accurately capture historic rainfall events in order to plan adequately and to predict future rainfall intensity values that are used in designing hydrologic structures and for effective water resources management. Meanwhile, generally, there exists a wide variability in trends of rainfall as studied by researchers (Karl and Knight, 1998; Groisman *et al.*., 1999; Stone *et al.*., 2000; Zhang *et al.*., 2000; Osborn *et al.*., 2000; Whitfield *et al.*., 2002; Adamowski and Bougadis, 2003; Coulibaly and Shi, 2005; Ologunorisa and Tersoo, 2006; Vincent and Mekis, 2006; Markus *et al.*., 2007; Peterson *et al.*., 2008; Mailhot *et al.*., 2010; Udosen, 2012). It is extremely important to quantify and characterize whatever variability exists (Jeong, 2009). Information about this variability will help us understand the direction of future climate change (Franks, 2002).

The application of statistics and computing has made prediction of future rainfall intensities possible even though there are in most cases few available data, inhomogeneity of records (e.g. meteorological data may be the result of various incoherent climatological mechanisms) and climatological changes over long periods (Al-Mashidani *et al.*., 2009). These of course have called for the searches into what techniques to use in order to extract the maximum possible content from a set of inadequate rainfall data efficiently. Flood and rainfall being natural phenomena, are stochastic and therefore are treated as random variables which are elements of statistics of extremes particularly at the extreme cases of peak (maximum) value.

The interpolation and extrapolation of flood frequencies provide an easy answer on which practicing engineers base their designs (Al-Mashidani *et al.*., 2009) for the few available data. For the purpose of estimation, the Normal, Log Pearson type III, the Gumbel extreme value distribution, and Log Normal distribution seem to have found a wider applicability than many other distributions which suffer inaccuracy in flood forecasting using rainfall data (Al-Mashidani *et al.*., 2009; Okonofua and Ogbeifun, 2013). Chow (1953) has suggested that Gumbel extreme value distribution method of analysis be used for the prediction of rainfall intensities.

Gumbel distribution is a stochastic generating structure that produces random outcomes which has found wide applications. It is one of the probability distributions used to model hydrologic parameters (Okonofua and Ogbeifun, 2013) and has been used for predicting extreme hydrological events (Zelenhasic, 1970; Haan, 1977; Shaw, 1983).

In recent times, evolutions in the engineering designs with rainfall data saw the use of series of generalized maps for several combinations of durations and return periods due to few available data collection stations.

Generally speaking, IDF curves are important as they are the basis on which the design and function of municipal water resources management infrastructures (such as storm sewers, overland drainage facilities, street curbs and gutters, basins, culverts, dikes, bridges, etc.) are done (Oyegoke *et al.*., 2017). According to Oyegoke and Sonuga (1983), Sonuga (1972) was the first to introduce the concept of maximum entropy to hydrologic frequency anlysis. Building on the work of Sonuga (1972), Jowitt (1979) undertook rigorous analysis that deduced the EV1 distribution from the principle of maximum entropy, when the given information relating to a random variable of unrestricted sense consists solely of the first two moments. For series best described by log normal distribution, Oyegoke *et al.* (1983) proved the superiority of the concept of maximum entropy for their use for frequency analysis.

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Oyebande (1982) published the first comprehensive non-empirical IDF studies for Nigeria with return periods of 50 or more years for 14 rainfall durations ranging from 12 minutes to 24 hours using extreme rainfall series for 35 meteorological stations in Nigeria.

Oyegoke and Oyebande (2008) further proved the relative advantage of the use of maximum entropy concept for evaluation of the parameters of the EV1 distribution while generating IDF relationships for several synoptic meteorological stations in Nigeria. Extensive work has been done by various researchers using EVI distribution to generate IDF curves for different regions of Nigeria (Oyebande, 1982; Oyegoke and Sonuga, 1983; Oyegoke *et al...*, 1983; Awokola. 2002; Salami and Sule, 2009; Okonkwo and Mbajiorgu, 2010; Nwoke and Nwaogazie, 2013; Akpan and Okoro, 2013; Ologhadien and Nwaogazie, 2017; Ogarekpe, 2014; and Oyegoke *et al...*, 2017) but mostly on Southern Nigeria.

The Northern Nigeria has received less attention. Earlier studies that involved some Northern states were the works of Oyebande (1982), and Oyegoke and Oyebande (2008); recent studies include Sule and Ige (2016), who fitted annual series of maximum daily rainfall into the Gumbel Extreme Value Type I distribution and rainfall depths for ten northern states. Olatunde and Adejoh (2017) also studied and analyzed the intensity, duration and frequency of rainstorms in Lokoja. This study presents the analysis of auto recorded extreme rainfall data for 15 synoptic stations in Northern Nigeria for seven time durations from 12 minutes to 24 hours as shown in Table 1.

II. MATERIALS AND METHODS

A. Study Area

Nigeria covers a land of surface area 900,000 km^2, lies between longitudes 3^o and 5^o East and latitudes 4^o and 14^o North with North-South extent of about 1,050 km and its maximum East-West extent covers about 1,150km. The country is generally put in two geographical zones, Southern and Northern Nigeria (Figure 1). Both are well drained with a close network of rivers and streams that are continuously sustained by high intense annual rainfall which is generally any or combination of orographic, convective, and tropical rainfall. Northern Nigerian states like Adamawa and Jos experience orographic rainfall due to the presence of hills, convective rainfall and cyclonic rainfall also occur in some northern states.

B. Data Collection

Rainfall measurements with automatic recording rain gauges were obtained from Nigerian Meteorological Agency, NIMET, from which the series of maximum annual values for 12min, 24 min, 1hr, 3hr, 6hr, 12hr and 24hr durations were collated and analyzed for 15 synoptic Stations in Northern Nigeria. The range of data available for these stations are is presented in Table 1.

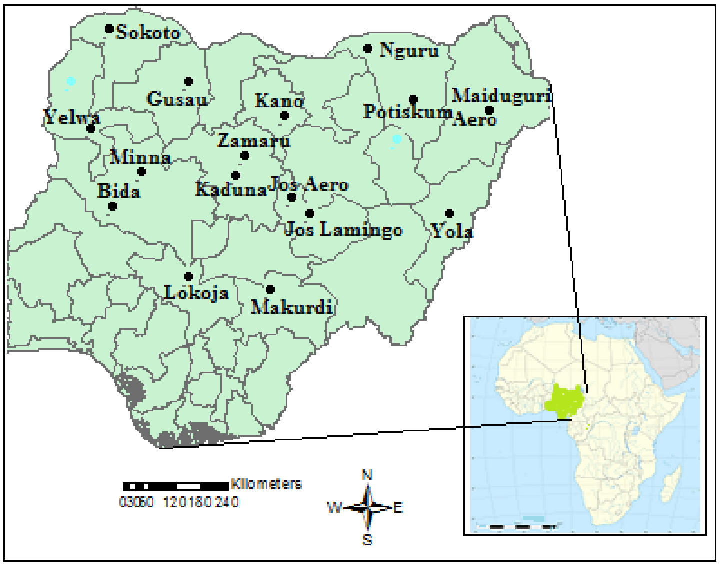

Figure 1: The rainfall stations used for the study.

Table 1: Meteorological Stations with length of period of rainfall data.

Station names	Length of Record (years)	Period
Sokoto	14	1956-1969
Yelwa	17	1960-1966, 1969-1978
Kano	19	1951-1960, 1967-1975
Samaru	14	1955-1964, 1967-1970
Gusau	11	1956-1965,
Lokoja	21	1956-1965, 1967-1968 1970-1978
Minna	16	1956-1962, 1967-1975
Jos Lamingo	11	1960-1969,
Kaduna	23	1952-1962, 1967-1978
Jos Aero	27	1952-1978
Maiduguri Aero	17	1956-1962, 1964-1968, 1970-1971, 1973-1978
Potiskum	17	1956-1966, 1968-1973
Nguru	14	1960-1973
Yola	15	1956-1966, 1969-1973
Makurdi	19	1956-1974
Sokoto	14	1956-1969

C. Gumbel Distribution

Return period is the length of years for which an event is expected to repeat itself i.e. an n-year event occurring at least once in the next n years. It is a vital tool in determining the probability of occurrence of a hydrologic event. Elementary probability theory shows that, there is a good chance that the n-year event will occur at least once before n years have elapsed.

According to Gumbel (1958), the probability of occurrence of an event equal to or longer than value X_o is expressed as (Shaw, 1983):

$$P(X \geq X_0) = f(x) = exp\{-\exp[-\alpha(x - v)]\} \quad (1)$$

For a recurrence interval, T and the variate, x,

$$\frac{1}{T} = 1 - f(x) = 1 - exp\{-\exp[-\alpha(x - v)]\} \quad (2)$$

$$x = U - \frac{1}{\alpha} ln(ln \frac{T}{T-1}) \qquad (3)$$

Giving the general frequency equation as

$$x = \bar{x} + K.S_x \qquad (4)$$

where S_x is standard deviation, $\bar{x}$ is the mean for x and K is the frequency factor

$$\bar{x} = u + \frac{0.5772}{\alpha} \qquad (5)$$

$$S^2 = variance = \frac{\pi^2}{6\alpha^2} \qquad (6)$$

Substituting for $\bar{x}$, x and S in the frequency equation and solving for K.
We have;

$$K = \frac{-\sqrt{6}}{\pi}\left(0.5772 + \ln[ln \frac{T}{T-1}]\right) \qquad (7)$$

The steps given by Chow *et al...* (1988) for estimating the design flood for any return period using Gumbel's distribution were used. Annual maximum rainfall data for the various stations were assembled for a period of several *years* at durations of *12 mins, 24 mins, 1hr, 3hrs, 6hrs, 12hrs,* and *24hrs*; mean, $\bar{x}$ and standard deviation, S_x of the maximum rainfall data for the n number of years and for each of these durations are computed. Coefficients A and B were then obtained by linear ordinary least squares regression analysis and are as presented in Table 2, first row is A and second row B; can be used to compute the intensity of rainfall using a model of the form

$$i = \frac{A}{t+B}, \qquad (8)$$

taking the intensity as i.
The rainfall data for the various return periods can then be used to fit the intensity-duration frequency curves.
The above expression can then be expressed in linear form as

$$\frac{1}{i} = \frac{t}{A} + \frac{B}{A} \qquad (9)$$

Comparing with straight line equation

$$Y = a_1 X + a_0, \qquad (10)$$

The regression of $\frac{1}{i}$ versus t will give values of A and B, first by making $\frac{1}{i} =$ Y and $t = X$, thus $a_0 = \frac{B}{A}$ and $a_1 = \frac{1}{A}$, where,

$$a_0 = \frac{\sum Y \sum X^2 - \sum X \sum XY}{n \sum X^2 - (\sum X)^2} \qquad (11)$$

$$a_1 = \frac{n \sum XY - \sum X \sum Y}{n \sum X^2 - (\sum X)^2} \qquad (12)$$

III. RESULTS AND DISCUSSION

Using the procedures listed above for the rainfall intensity data from the 15 meteorological stations, IDF curves were plotted for the intensity, *I* against return period, *t* on the log-log graph as shown in Figure 2.

Table 2: Coefficients of Regression for the rainfall stations used for the study.

S/N	Station	Return Periods						
		1	2	5	10	25	50	100
1	Sokoto	1792.4	3154.1	3967.1	4505.3	5185.3		
		42	37.7	36.9	36.6	36.4		
2	Yelwa	2128.3	3317.1	4029.7	4501.7	5098.4		
		17	17.9	19	19.8	20.6		
3	Kano		3634	5445	6647	8168	9298	
			27	35	38	41	43	
4	Samaru	2128.3	1423.4	4081.2	5682.9	6746		
		17	29.3	39.2	43.2	45.2		
5	Gusau		3656.8	4453.8	4981.8	5649.2		
			24.6	30.6	33.7	36.9		
6	Lokoja	2076.1	4103.3	5314	6115.5	7128.3		
		36.7	25.8	23.8	23	22.2		
7	Minna	1230	5367	7788	9391	11417		
		51.4	48	57	61	65		
8	Jos Lamingo	2877.3	4335.4	5229.6	5823.4	6574.6		
		96	47.5	37.6	33.2	29		
9	Kaduna	2289.1	3915.6	4888.6	5533	6347.2	6951.2	7550.8
		45.9	32.3	28.9	27.4	25.9	25.1	24.4
10	Jos Aero	2044.7	3689.6	4673.9	5325.8	6149.6	6760.8	7367.6
		23.5	40.5	45.6	48.1	50.5	52	53.2
11	Maiduguri Aero	1623.1	3664.3	4889.8	5702.2	6729.6		
		-6.3	24.7	33.4	37.5	41.6		
12	Potiskum		1914.4	3544.1	4519.5	5165.5	5981.7	
			32.3	18.4	15.4	14	12.8	
13	Nguru		2649.7	3685.8	4372	5239.3	10340	11258
			18.9	22.8	24.5	26	52	53
14	Yola	1811.2	4179.5	5599.8	6540.9	8613.1		
		27.9	25.5	26	26.3	26.9		
15	Makurdi	2995.2	4754.6	5806.8	6503.6	7384	8037.1	
		30	28.2	27.7	27.5	27.3	27.2	

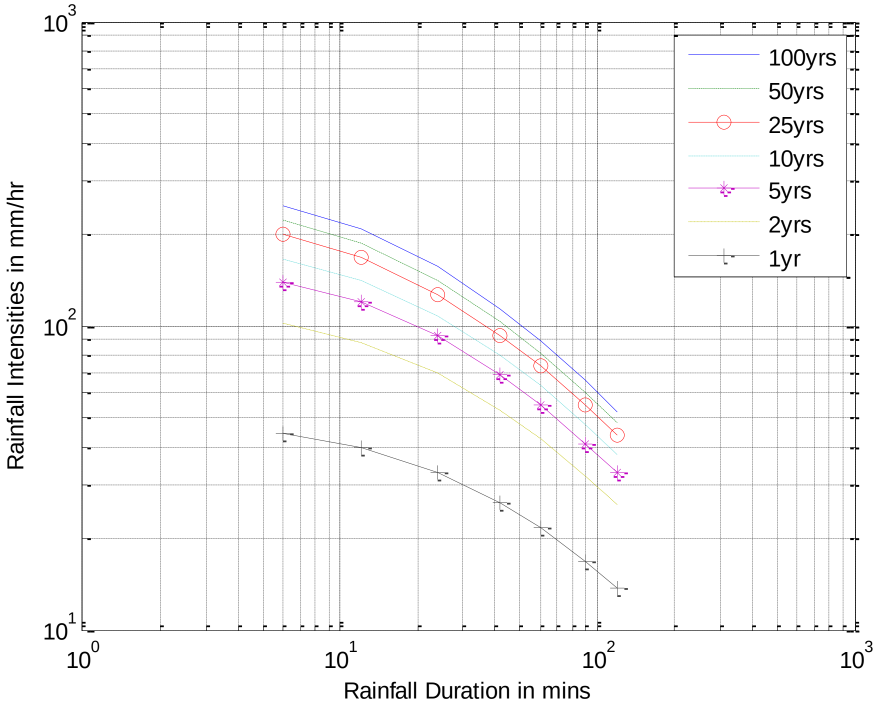

Figure 2: IDF curve for Kaduna.

Table 3: Relative intensities for different rainfall duration at 5-year return period in Potiskum.

Rainfall duration (min)	I (mm/hr)
3	192
10	190.9
15	190
30	187.5
60	182.6

Table 4: Relative intensities for different rainfall duration at 10-year return period in Potiskum.

Rainfall duration (min)	I (mm/hr)
3	367.7
10	364.6
15	362.5
30	356.2
60	344.4

Generally, while designing hydraulic structures in a given area, peak surface runoff is estimated from methods such as the rational method using the extreme rainfall data (rainfall that lasted *30 mins* or less) for the area. This will capture such disasters like flood that have capacity to hydraulically overstress structures. Rainfall Intensity-Duration-Frequency (IDF) relationships are presented as tables and/or curves which serve as guide for the description of location rainfall and in the estimation of runoffs for design of hydraulic structures.

The coefficients of regression for developing IDFs for return periods of 1 year, 2 years, 5 years, 10 years, 25 years and 50 years where possible for the various synoptic stations considered in this study are as presented in Table 2 and Figure 2 is an example for Kaduna.

As can be observed on Table 3 and Table 4, intensities of rainfall as are obtainable from the IDF curves and formulae increase with increasing length of return periods for all the stations. It is therefore important to plan design of large hydraulic structures with high length of return period of storm. Areas around coasts and rivers should expect increasing rise in flood that results from events of rainfall.

It can be seen also that for given length of return period, intensity of rainfall decreases with increasing duration of rainfall. This implies an increasing trend in expected rainfall intensity as is expected for extreme (short duration) rainfall. This program satisfactorily performs the prediction of rainfall intensity and will therefore be useful in the development of a database for the long term analysis of rainfall in northern Nigeria and in the generation of IDF curves for use in the hydrologic design of hydraulic structures and for other related purposes.

IV. CONCLUSION

This study has presented the concepts of using Gumbel's Extreme Value Type 1 distribution as a predictive tool for the expected rainfall intensity of a given place. It has been simplified for determining the value of the coefficient of variation, A and B of the given data from which rainfall intensity for a given return period is normally obtained. The values so obtained are useful in the design of hydraulic structures such as storm water drains, culverts, dams and reservoirs with a view to protecting lives and properties along the course of flow or at the downstream of a river.

The findings in this study have shown that extreme rainfall event is responsible for high intensity rainfall which could result to higher flood than longer duration rainfalls. Intensity of rainfall also increases with longer return periods of rainfall.

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