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Research Article

Rainfall-Intensity-Duration-Frequency Models for selected Cities in Southern Nigeria

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Abstract

Rainfall-Intensity-Duration-Frequency (IDF) models for five selected cities in Southern Nigeria were developed using standard statistical bivariant analyses. The Gumbel Extreme Type 1 distribution was applied to estimate 5-, 10-,15-,20-,25-,35- and 40-year return period maximum values for durations of 0.083 to 24hrs. Two-parameter models (Types-1 and 2), three-parameter model (Type-3) and four-parameter (general) models (Type-5) were developed for each station; thus, giving rise to four IDF models per station. The coefficients of variation (r^2) for the two-parameter models range between 0.6 and 1.0; three-parameter models range between 0.915 and 1.0 while those of the four-parameter models range between 0.645 and 1.0, respectively. Based on the high magnitude of r^2, the IDF models developed are useful and programmable tools for hydrologic design of structures for control of storm runoff and flooding.

Keywords: Rainfall, Intensity, Duration, Frequency models, design, runoff structures.

INTRODUCTION

The Rainfall-Intensity-Duration-Frequency (IDF) models are hydrologic tools for planning, design and operation of water resources projects against floods. An IDF model provides the basic probabilistic rainfall information for runoff estimation, and establishes a statistical basis for design, using the return period as the measure of frequency of failure. Bilham (1962) performed the best study of short-period (5 minutes to 2 hours) continuous rainfall in the United Kingdom, which was published in 1936 and reissued by the Meteorological office in 1962 (Shaw, 1994). The equations developed by Bilham (1962) overestimated the probabilities of high intensity rainfall. Holland (1967) updated the equations developed by Bilham (1962) and extended the durations to 25 hours. Bell (1969) derived rainfall intensity equations for parts of United States of America. Following Bell (1969), National Weather Services (NWS, 1982) published IDF Atlas assets of isohyetal maps of United States. Froehlich (1975) summarized the standard IDF equations following the work of Chow (1962). More recent IDF studies in Nigeria are those of Port Harcourt (Nwaogazie and Duru, 2002) and Uyo city (Nwaogazie and Uba, 2001).These IDF models were developed based on data length of 10 years. Consequently, they are inadequate for determination of a representative frequency patterns (Shaw and Lynn, 1972; Hall and O'Connell, 1972).

Countries without isohyetal maps, collate recorded rainfall data in order to develop IDF models. This is the case with Nigeria. The earliest IDF models in Nigeria are those of Lagos and Kano (Federal Ministry of Works and Housing, FMW and H, 2006). The IDF models and curves are limited to Kano and Lagos areas and therefore deficient in a real coverage. Oyebande (1982) derived IDF relationships and estimates for regions with adequate data, in graphical forms and therefore are inefficient in computer programming as intended in modern applications. Awokola (2004) derived IDF models for selected locations in Southern Nigeria for return periods of 2, 5 and 10 years. The length of data employed by Awokola (2004) was rather short. Okonkwo and Mbajiorgu (2010) carried out IDF analyses for South Eastern Nigeria but the stations do not cover those in this study, besides the results were mainly in graphical form. Oguarekpe (2014) developed and compared three IDF models, using exponential, logarithmic and power models. These models are not the standard forms of IDF models (Chow, 1962).

The present study is based on a satisfactory data length (17-35yrs) and the models developed are suitable for computer modeling of rainfall-runoff processes.

MATERIALS AND METHODS

Data Collection

The recorded daily rainfall data (amount and duration) for the five selected cities in Southern Nigeria are Onitsha (6.08^{o}N, 6.47^{o}E (17 years)); Port Harcourt (4.46^{o}N, 7.01^{o}E (23 yrs)); Calabar (4.59^{o}N, 8.20^{o}E (21 yrs)); Warri (5.13^{o}N, 5.45^{o}E (26 yrs)) and Benin City (5.20^{o}N, 5.37^{o}E (34 yrs)) were extracted from FORM MET 141 (Tabulation of Autographic Rain Guage Records). The records were obtained from the Nigerian Meteorological Department (NIMET), Oshodi Lagos, Nigeria. Figure 1 shows map of the study area.

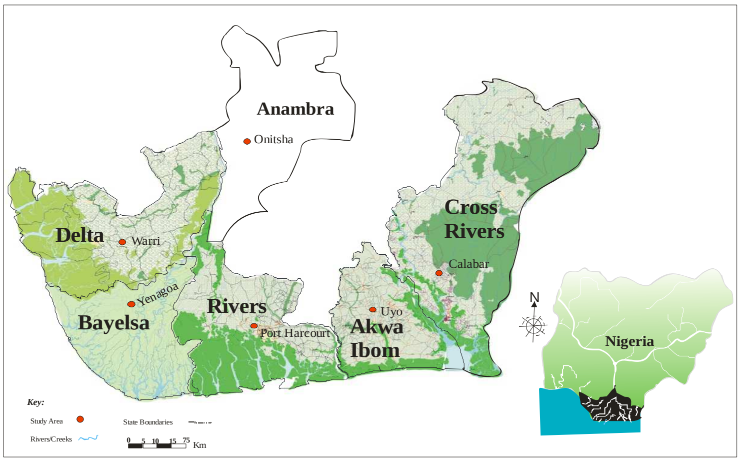

Figure 1. Map of Study Area, Southern Nigeria
Source: Chow (1962)

Rainfall Intensity Duration Equations

The four basic forms of equations used to describe the rainfall intensity-duration relation are as summarized in Table 1 and a general equation (form 5) for all the return periods. The equations are empirical and show that rainfall intensity is a decreasing function of rainfall duration for a given return period. The model parameters are catchment specific and serves as characteristic features of both the rainfall region and frequency of occurrence. Regression analyses have been used to fit equation types 1, 2, 3 and 5 to produce the results shown in Tables 2, 3, 4 and 5, respectively.

Table 1. Rainfall Intensity-Duration Equation Types

Equation. Type No.		Equation Form±	Equation Parameters
1.	I =	$\frac{a_1}{(b_1+t)}$	a_1,b_1
2.	I =	a_2/t^{b2}	a_2, b_2
3	I =	$a_3/(b_3+ t)^{c3}$	a_3, b_3, c_3
4	I =	$a_4/(b_4 + t^{c4})$	a_4, b_4, c_4
5.	I =	$\frac{cT^m}{(a+t)^n}$	c,a,m and n

±I= Rainfall intensity and t = rainfall duration.

Frequency Analysis

The primary objective of frequency analysis is to relate the magnitude of extreme events to their frequency of occurrence by using an appropriate probability distribution. The intensity-duration- frequency analysis starts by gathering time series records of different durations. Given the time series data, annual extremes were extracted from the record for each duration. The annual extreme data were then fitted to probability distribution in order to estimate rainfall quantities. The Gumbel probability distribution was used to standardized the rainfall across stations with widely varying lengths of record. The Gumbel extreme probability has the following form (Predrag et al., 2007).

$$x_t = \mu_z + k_T\sigma_z \quad \ldots\ldots(6).$$

Where x_t represents the magnitude of the T-year events, μ_z and σ_z are the mean and standard deviation of the annual maximum series and k_T is a frequency factor depending on the return period, T. The frequency, k_T is obtained using the relationship:

$$k_T = \frac{-\sqrt{6}}{\Pi}\left[0.5772 + (\ell n(\tfrac{T}{T+1}))\right] \ldots\ldots(7)$$

Good fits are usually obtained using the general IDF equation of the form:

$$I = \frac{CT_r^{\,m}}{(t+a)^{C_3}} \quad \ldots\ldots \quad (8)$$

Where I is rainfall intensity (mm/hr), t is duration (min); T_r is return period of frequency of occurrence in hours; a, c, c_3 and m are catchment specific parameters.

The best fit line that minimizes the sum of squares (S) of the deviations of the measured rainfall intensity (I_m) from those predicted (I_p) is given as:

$$S = \sum_{i=1}^{n}\left(I_m - I_p\right)^2 \quad \ldots\ldots \quad (9)$$

Where n is the number of observations and i is an index.

Putting K = CT^m, Equation (8) becomes:

$$I = \frac{K}{(t+a)^{C_3}} \quad \ldots\ldots \quad (10)$$

Equation (10) was solved to provide the best values of K and C_3 for any assumed value of "a" and the best value of "a" for a given return period was found by trial and error.

RESULTS AND DISCUSSION

Results

The results of solving Equations (1), (2) and (3) for all the stations for various return periods are given in Tables 2, 3 and 4, respectively. The results for combining Equations (3) and (4) into one general IDF model (Equation (5)) for each station is presented in Table 5.

The graphical equivalents of Table 5 (calibrated version of Equation 5) are presented as Figures 2 to 6, for return periods of 5 to 20 years. The plots for return periods of 25 to 40 years are possible using IDF models in Table 5.

Table 2. Constants for 2-Parameter IDF models of Type 1±

Return Period (T)	Benin City		Calabar		Onitsha		Port Harcourt		Warri	
	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1	a_1	b_1
5	4421.1	48.504	4362.88	56.66	4073.45	57.02	3885.62	28.67	5688.95	95.97
10	5513.26	50.31	5240.34	50.74	5009.35	54.26	4676.15	22.26	6826.44	90.15
15	6131.74	51.56	5735.77	48.52	5537	53.056	5127.51	20.36	7495.35	89.27
20	6564.93	52.67	6082.82	47.52	5906.43	52.66	5442.3	19.12	7945.04	88.70
25	6898.95	52.89	6351.05	46.35	6193.01	52.32	5787.74	20.26	8327.74	88.76
30	7171.26	53.74	6586.47	46.06	6422.48	51.91	5889.95	17.93	8621.88	88.36
35	7402.49	53.50	6753.23	45.67	6620.57	52.02	6059.04	17.58	8871.68	88.71
40	7610.22	55.17	6912.66	44.91	6790.04	51.62	6205.79	17.43	8899.33	90.40
r^2	0.6 – 1.0		0.86 – 1.0		0.86 – 1.0		0.91 – 0.92		0.857 – 1.0	

± Type 1: IDF model, I = a/(t + b); r^2 = Coefficient of variation

Table 3. Constants for 2-Parameter IDF model of Type-2±

Return Period (T)	Benin City		Calabar		Port Harcourt		Warri	
	a_1	b_1	a_1	b_1	a_1	b_1	a_1	a_1
5	274.631	0.525	246.32	0.508	344.22	0.571	128.54	0.365
10	372.610	0.545	348.37	0.534	551.83	0.620	178.67	0.391
15	426.35	0.552	406.53	0.545	673.19	0.638	205.10	0.40
20	463.84	0.556	447.49	0.551	760.10	0.650	223.531	0.405
25	492.80	0.559	479.26	0..555	826.72	0.655	237.78	0.408
30	516.06	0.561	505.12	0.558	881.58	0.661	249.37	0.411
35	535.88	0.562	527.13	0.561	928.84	0.665	259.20	0.413
40	552.88	0.564	545.97	0.562	968.72	0.670	275.66	0.426
r^2	0.87 - 0.96		0.94 - 1.0		0.83 - 0.87		0.612 – 0.75	

r^2 = coefficient of variation.
± Type 2 IDF model, $I = a_2/t^{b2}$

Table 4. Constants for 3-Parameter IDF model of Type-3±

Return Period (T)	Onitsha	Port Harcourt	Calabar	Warri	Benin city
	K, a, C_3	K , a, C_3	K, a, C_3	K, a, C_3	K, a, C_3
5	2575.12, 55, 0.9134	3035, 45, 0.935	2046, 50, 0.869	378.4, 25, 0.5544	4440.9, 52, 1.0676
10	3988.35, 55, 0.9542	5506.83, 45, 1.01	3140, 50, 0.9096	526.45, 25, 0.5806	6167.3, 52, 1.0676
15	4814.76, 55, 0.9697	7071.67, 45, 1.031	3764.45, 50, 0.9255	968.674, 25, 0.6789	7073.83, 52, 1.0676
20	5402.11, 55, 0.9787	8201.4, 45, 1.0463	4249.5, 50, 0.9348	961.9, 25, 0.6702	7745.8, 52, 1.0676
25	5858.5, 55, 0.985	9095.72, 45, 1.056	4611.13, 50, 0.9412	925.07, 25, 0.6503	8242, 52,1.0676
30	6234.42, 55, 0.9892	9833.23, 45, 1.064	4906.70, 50, 0.9459	1001.9, 25, 0.6636	8644.49, 52, 1.0676
35	6551.86, 55, 0.9927	10467.82, 45, 1.069	5159.91, 50, 0.9496	1053.38, 25, 0.6627	8985.15, 52, 1.0676
40	6826, 55, 0.9544	11016.56, 45, 1.0741	5376.35, 50, 0.9526	875.6, 25, 0.6231	9277.3, 52, 1.0676
r^2	0.941 – 0.970	0.915 – 1.0	0.819 – 0.898	0.9904 – 1.0	0.843 – 0.988

±Type-3: IDF Model, $I = k/(t + a)^{C3}$

Table 5. Summary of General IDF Models of Type-5 for 5 selected cities in Southern Nigeria

S/NO	Station (Town)	Equation Models±	r^2
1	Onitsha	$I = \frac{1322T^{0.458}}{(t+55)^{0.9723}}$	$0.823 \le r^2 \le 1.0$
2.	Port Harcourt	$I = \frac{1063.445T^{0.591}}{(t+45)^{0.9913}}$	$0.685 \le r^2 \le 1.0$
3	.Calabar	$I = \frac{1050.27T^{0.455}}{(t+50)^{0.930}}$	$0.645 \le r^2 \le 0.891$
4	Warri	$I = \frac{203.06T\,0.4648}{(t+25)^{0.6353}}$	$0.936 \le r^2 \le 1.0$
5.	Benin city	$I = \frac{2675.9\,T_r^{0.3464}}{(t+52)^{1.0676}}$	$0.671 \le r^2 \le 1.0$

± Type-5, four-parameter IDF models

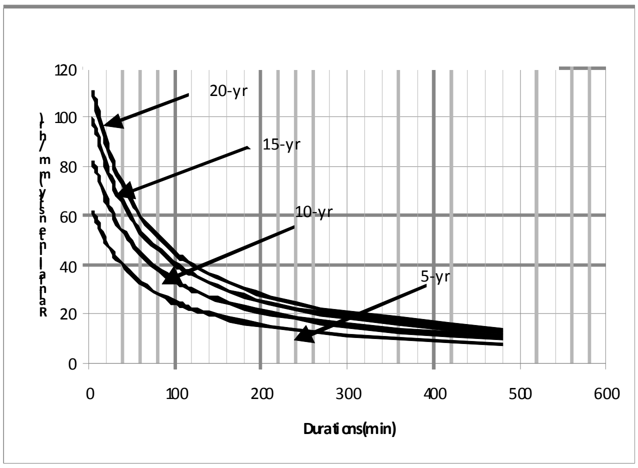

Figure 2. Rainfall IDF Curves for Onitsha City

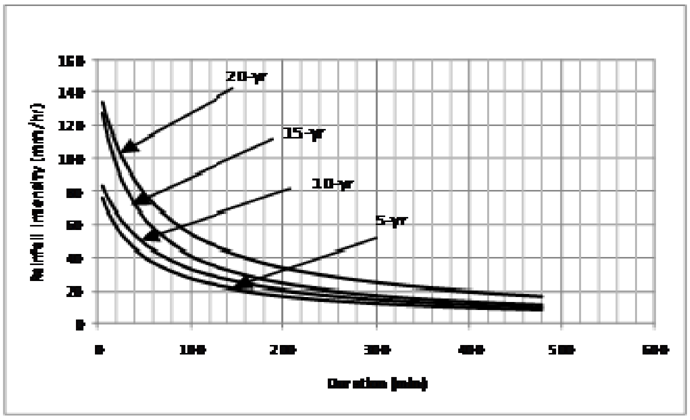

Figure 3. Rainfall IDF Curves for Port Harcourt Metropolis

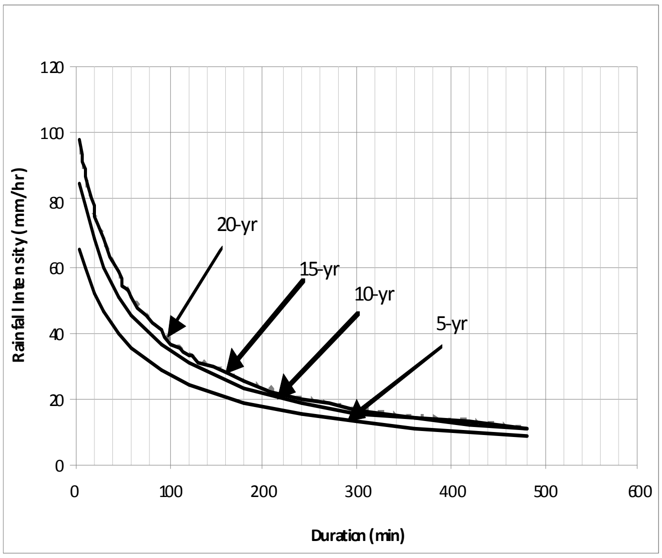

Figure 4. Rainfall IDF Curves for Calabar Metropolis

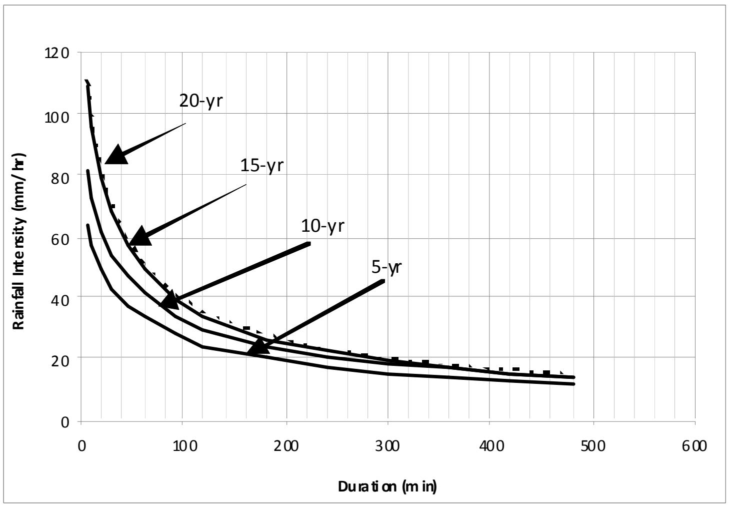

Figure 5. Rainfall IDF Curves for Warri Town

DISCUSSION

Intensity-Duration-Frequency models and their graphical equivalents reflect the rainfall pattern of an area. By specifying either rainfall duration or both duration and return period, intensity can be estimated for the specific catchment (see Table 5). From the IDF curves shown in Figures 2 – 6, it is evident that for an event with a particular return period, rainfall intensity and duration are inversely related. The relationship between frequency and intensity is linear, higher return periods yield higher intensities for a given duration.

CONCLUSION

Historic rainfall data extracted from FORM MET 414 (Tabulations of Autographic Rain Gauge Records) have been subjected to frequency analysis to develop Intensity-Duration-Frequency Models for different return periods for five stations in Southern Nigeria. The IDF models of Tables 4 and 5 and their graphical equivalents shown in Figures 2 – 6 are representative of those encountered in standard practice. The IDF models are needed by Hydrologists and Engineers involved in the planning and design of storm water management facilities and water resources projects.

The models are return period specific to reflect the economics of flood damage reduction and local practice. Based on the high magnitude of r^2, the models, thus, constitute reliable and useful tools for estimation of storm events, handy for programmable computer-aided modeling.

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