Rainfall intensity-duration-frequency analysis for Southeastern Nigeria

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Abstract: Inadequate hydrologic data and the need for proper planning of water resources development have forced engineers to analyze available data more critically. This is particularly so in developing countries. The Intensity-Duration-Frequency (IDF) relationship is one of the most commonly used basis for water resources planning and development. This study analyzed rainfall data and characteristics for locations in seven states of Southeastern Nigeria. IDF curves were developed for these locations using two methods (Graphical and Statistical) and the results were compared. The locations are Onitsha in Anambra State, Enugu in Enugu State, Abakiliki in Ebonyi State, Umuahia in Abia State, Owerri in Imo State, Port Harcourt in Rivers State and Uyo in Akwa Ibom State. Break-point, short duration, rainfall data are not generally available in the historical records at the locations. Generalized accumulated rainfall patterns developed by USDA Soil Conservation Service were matched with rainfall data for the locations of study, and the advanced pattern had the best fit with the observed characteristics and was used to break down recorded daily totals into shorter duration rainfall data. The method of annual maxima series was used to select data sets for the rainfall analysis. In the statistical method, the Type I extreme-value distribution (Gumbel) was applied to the annual maximum series for each of the seven stations to estimate the relevant parameters of the IDF model. The non-parametric Kolmogorov-Smirnov test and the χ^2 test were used to confirm the appropriateness of the fitted distributions for the locations. IDF data developed from the graphical and statistical methods applied were very close for the lower return periods of two to ten years, but differed for higher return periods of 50 to 100 years. However, the difference is not significant at 5% level. The data developed by either of the methods will facilitate planning and design for water resources development in Southeastern Nigeria.

Keywords: rainfall, intensity, water resources, hydrologic data

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1 Introduction

Extreme environmental events, such as floods, droughts, rainstorms, and high winds, have severe consequences for human society. Planning for weather-related emergencies, design of engineering structures, reservoir management, pollution control, and insurance risk calculations, all rely on knowledge of the frequency of these extreme events (Hosking and Wallis, 1997). The assessment of extreme precipitation is an important problem in hydrologic risk analysis and design. This is why the evaluation of rainfall extremes, as embodied in the intensity-duration frequency (IDF) relationship, has been a major focus of both theoretical and applied hydrology (Andreas and Veneziano, 2006). Dupont et al. (2000) defined rainfall IDF relationships as graphical representations of the amount of water that falls within a given period of time. These graphs are used to determine when an area will be flooded, and when a certain rainfall rate or a specific volume of flow will reoccur in the future.

According to Brian et. al. (2006), rainfall frequency analyses are used extensively in the design of systems to handle storm runoff, including roads, culverts and

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drainage systems. Smith (1993) states that the "the precipitation frequency analysis problem is to compute the amount of precipitation *y* falling over a given area in a duration of *x* min with a given probability of occurrence in any given year." For engineering design applications, it is necessary to specify the temporal distribution of rainfall for a given frequency, or return interval. According to Stedinger et al. (1993), IDF or Depth-Duration-Frequency (DDF) curves "allow calculation of the average design rainfall intensity [or depth] for a given exceedance probability over a range of durations" and is the result of the rainfall frequency analysis. IDF estimates are important statistical summaries of precipitation records used for hydrologic engineering design (Gerold and Watkins, 2005).

In Southeastern Nigeria, IDF curves are not readily available. Also the number of years of data used to develop a few IDF curves for the region found in the literature, Oyebande (1983) and Metibaiye (1990) was rather short. The methods employed were also simplistic and lacking rigorous analyses. This work attempts to address these short-comings and develop IDF data for different locations in SE of Nigeria.

2 Southeastern Nigeria

A map of Nigeria showing the southeastern geographical region is shown in Figure 1. Some characteristics of observed daily rainfall in the area are shown in Figure 2 and 3, based on data from the Nigeria Meteorological Office, Lagos. Annual rainfall total varies widely from year to year and across the area. The distribution of the mean annual rainfall in the area is shown in Figure 2. The highest mean annual rainfall of 2,380 mm occurred at Owerri while the lowest of 1,860 mm occurred at Enugu. According to Ayoade (1975), the month at which the peak of the monthly rainfall occurs varies from one part of the country to another. The areas covered by this study have highest daily rainfall in the months of July through September (Figure 3).

In the area, humidity and temperature are high year-round (Nigeria, 2008). There are two seasons in the Nigeria, the wet season (March through November) and dry season (December through February). The dry season starts with Harmattan - a dry chilly spell with a dusty atmosphere brought about by the NE winds blowing from the Arabian Peninsula across the Desert. During the rainy season, a marked interruption in the rains occurs during August, resulting in a short dry season often referred to as the "August break", though for years now this has not been consistent in August due to climate change. Temperatures are slightly lower in the humid tropical region of the south east when compared with northern Nigeria. Similarly, humidity is lowered in December and January during the Harmattan or dry season when cool dry winds blow off the desert.

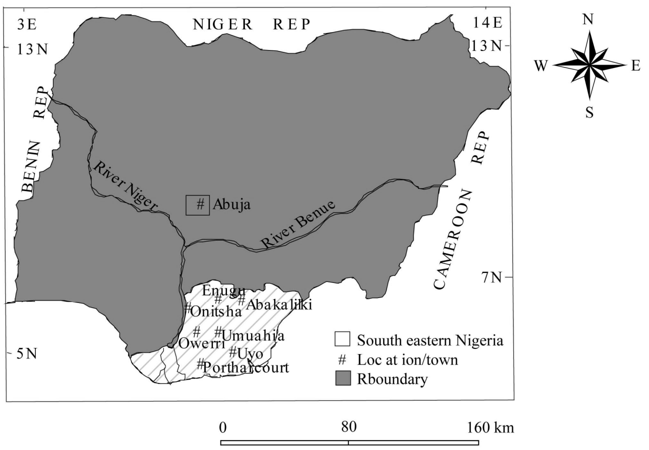


Figure 1 Map of Nigeria showing the Southeastern Region

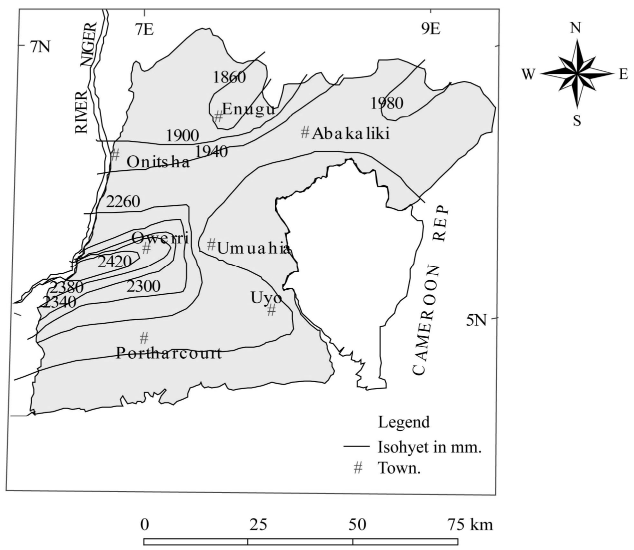


Figure 2 Mean annual rainfall in Southeastern Nigeria

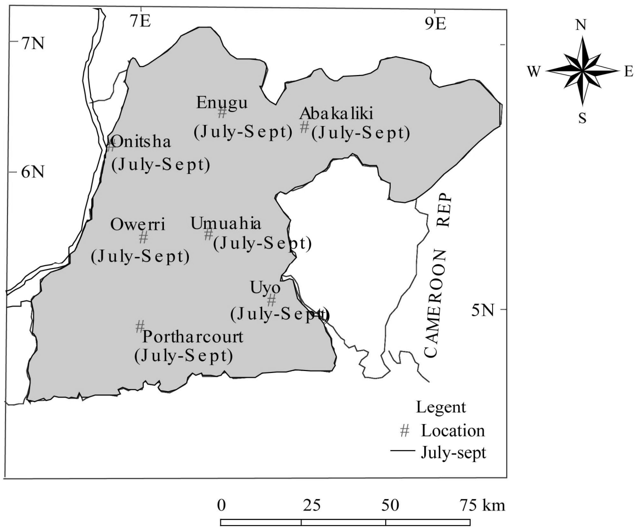


Figure 3 Months in which the highest recorded rainfall occur in Southeastern Nigeria

3 Concept and theory

The principal characteristics of a storm are its intensity, duration, total amount and frequency or recurrence interval. Rainfall intensity is expressed as the rate of rainfall in inches or millimeters per hour. The intensity is an important characteristic of rainfall because, other things being equal, more soil erosion is caused by one rainstorm of high intensity than by several storms of low intensity. Similarly, rainfall duration is the period of time that rain falls at a particular rate or intensity. For every storm the rainfall intensity may vary from high to very low; hence, the duration is how long time rainfall intensity lasts at a particular rate. Generally, the high-intensity portion of a storm has a shorter duration than the low-intensity portion.

Frequency is how often a storm of specified intensity and duration may be expected to occur. It can be reported in two ways (Brikowski, 2007 and Rick, 2007):

- *p*: probability that an event of specified depth and duration will be exceeded in a year

-*T*: average length of time between events of a given depth and duration.

Hence,

$$p = \frac{1}{T} \tag{1}$$

Where: *p* is exceedence probability and *T* is return period (years).

Evans et al. (1993) assigned return periods in relation to human risk. Hence, dams on major rivers are designed to handle storms with a 100 year return period, while culverts on bridges are designed for the 20-year flood, reflecting the risk associated with failure.

Mathematically, the IDF relationship is expressed as follows (Mohymont et al., 2004):

$$i = f(T, d) \tag{2}$$

Where: *i* is rainfall intensity; *T* is the Return period, and *d* duration.

But generally, the relationship is in the following form:

$$i = \frac{a(T)}{b(d)} \tag{3}$$

Where: *a* and *b* are parameters.

In equation (3), the dependency of *i* on *d* and *T* can be modeled by two separate equations *a*(*T*) and *b*(*d*), thus

$$i = \frac{a(T, p1)}{b(d, p2)} \tag{4}$$

Where: *p*1 and *p*2 are two vectors of parameters. The estimation of IDF-curves is achieved by the estimation of these parameters and, according to Koutsoyiannis et al., (1998):

$$b(d) = (d + \theta)^{\eta} \tag{5}$$

Where: θ and η are parameters, and

$$a(T) = \lambda T^{k} \tag{6}$$

or

$$a(T) = c + \lambda \ln T \tag{7}$$

Where: *k* is a dimensionless parameter and λ and *c* denote parameters having the same dimensions as the random variable *y*.

According to Mohymont et al. (2004), *a*(*T*) can be determined theoretically from the probability distribution function of the maximum rainfall intensity *I*(*d*). Therefore, if y_T is the (1-1/*T*) quantile of the distribution function F_Y, then

$$y_T \equiv a(T) = F_Y^{-1}(1 - 1/T) \tag{8}$$

The IDF-relationship forms a group of parallel decreasing curves. The intensity decreases with duration and increases with return period.

4 Materials and methods

4.1 Data requirement and acquisition for the study

The data required in this study are rainfall depths for short durations, for example, 15 min, 30 min, 1 h, etc. Unfortunately, only daily rainfall data are available for all the stations in the area of study. The length of the available records varies from 22 to 30 years. To estimate rainfall data of shorter durations than daily, a model was used.

4.2 Model selection for breakdown of daily rainfall data

Figure 4 shows percentage breakdown of rainfall that can be expected for proportionate durations of a storm for different types of rainfall (USDA SCS, 1955). In the figure, curve *A* is for advanced type of storm in which the greatest intensity occurs in the early part of the storm; Curve *B* is for intermediate storm type with highest intensity occurring in the middle of the storm; and Curve *C* is for the retarded storm type with high intensity occurring late in the storm duration. The curves were applied to breakdown daily rainfall data as collected by the Nigeria Meteorological Agency, to shorter durations of 0.25 hr, 0.5 hr, 1 hr, 2 hrs, 4 hrs, and 6 hrs. The data generated for each model curves were compared with Oyebande's (1983) data for Enugu. Curve A proved the best fit for the region and was applied to breakdown the daily rainfall data to shorter durations in this work. To confirm this approach, a rainfall pattern study was conducted at Nsukka and the advance storm type was found dominant.

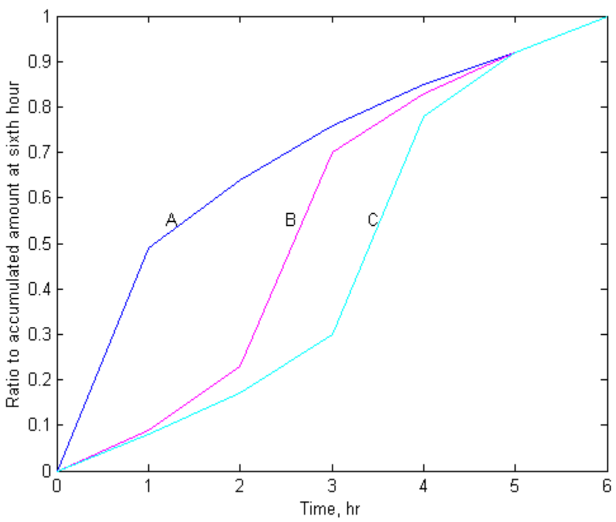


Figure 4 Generalized accumulated rainfall curves for A (advanced), B (intermediate), and C (retarded) types of storms. (USDA SCS, 1955)

4.3 Procedure of data analysis

4.3.1 Graphical method

The data series were obtained as annual maximum series and the following operations applied:

1) Maximum intensities computed from

$$I = \frac{R}{t} \tag{9}$$

Where: *I* is the intensity in mm/hr; *R* is the amount of rainfall in mm; and *t* is the duration of rainfall in hours.

2) The resulting values from 1) above are ranked in descending order of magnitude such that the largest value is assigned 1. Return period is then computed using the Weibull plotting position formula:

$$T = \frac{(n+1)}{m} \tag{10}$$

Where: *T* is the return period in years; *n* is the number of items in the sample; and *m* is the rank of the individual items in the sample array.

3) Regression of the intensity values for all the durations against the Logarithm of return periods gave a linear model with Easyfit Statistical software.

4) Using the linear model, rainfall intensities for varying durations are plotted against the Logarithm of return periods on normal axes using the Matlab program. From the plots, data of intensity against return periods of 2, 5, 10, 25, 50, and 100 years are extracted from each duration.

Intensity was then plotted against duration as a function of return period on log–log paper.

4.3.2 Statistical method

There are a number of probability distribution functions that can be used to describe extreme value data such as annual maxima. These include log-normal, Type I Extreme value (Gumbel), Type III Extreme value and Pearson Type III distributions.

1) Independence of the annual maximum series

For a fixed duration, *d* and sample size, *n*, the random variable $I(d) = x_1, x_2, ..., x_n$. These data were supposed to be independent. This assumption was tested by computing the autocorrelation function for each period. Figure 5 is the graph of the autocorrelation function corresponding to the duration of one hour for Enugu. It showed that the values of the autocorrelation function are small in absolute terms and randomly distributed without a trend, as expected for dependent data series. Similar results were obtained for other durations and locations.

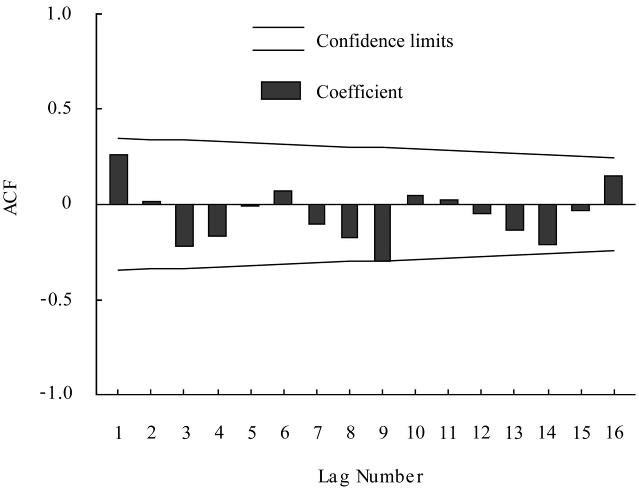


Figure 5 Graph of the autocorrelation function of the annual maximum precipitation depths for the duration of 1 hour at Enugu

2) Selecting a probability distribution function

Assuming that the distribution function underlying the series of annual maximum intensities (or amounts) is the Gumbel distribution function, then

$$F(x) = \exp\left(-\exp\left(-\frac{x - x_0}{\alpha}\right)\right) \tag{11}$$

Where: x_0 and α are location and scale parameters respectively. These parameters were estimated using the *Genstat* software and Table 1 shows the estimates for the Gumbel distribution function of annual maximum precipitation depths for different durations and locations. The assumption of Gumbel distribution was tested with the Kolmogorov-Smirnov and χ^2 tests. From the results the test statistic never exceeded the limiting 95 percent value. Therefore, the assumption is valid.

3) Establishing IDF curves

The technique for establishing IDF-curves of precipitation have three steps (Demarée, 2004). The first step consists of fitting a probability distribution function to the data for each period. Secondly, quantiles for each period and for a set of return periods are calculated using the probability function. Finally, the IDF tables are obtained by a non-linear regression on the quantiles, given a criterion function. The tables may be converted to IDF curves using a graphical package such as the *Matlab* (Okonkwo, 2008).

Suppose that the data follow a distribution *F*; the quantile x^*_T having a return period *T* is defined by the value x^* that verifies the relation,

$$F(x^*) = 1 - \frac{1}{T} \tag{12}$$

In the case of a Gumbel distribution, by inverting Equation (12) the following expression for x^*_T was found:

$$x^*_T = \alpha\left\{\frac{x_0}{\alpha} - \ln\left(-\ln\left(1 - \frac{1}{T}\right)\right)\right\} \tag{13}$$

The corresponding mean rainfall intensity $i^*_{T,d}$ is,

$$i^*_{T,d} = \frac{x^*_T}{d} \tag{14}$$

Where *d* is duration.

The set of *T*-values considered in this study are 2, 5, 10, 25, 50, and 100 years and the set of *d*-values considered are 0.25, 0.5, 1, 2, 4, and 6 hours.

The non-linear regression function and criterion function employed in the estimation of empirical quantiles are given below by Equation (15) and Equation (16), respectively:

$$i_{T,d}(\alpha, x_0, \theta, \eta) = \frac{\alpha\left(\frac{x_0}{\alpha} - \ln\left(-\ln\left(1 - \frac{1}{T}\right)\right)\right)}{(d + \theta)^{\eta}} \tag{15}$$

$$\chi^2 = \sum_{T,d}\left(1 - \frac{i_{T,d}(\alpha, x_0, \theta, \eta)}{i^*_{T,d}}\right)^2 \tag{16}$$

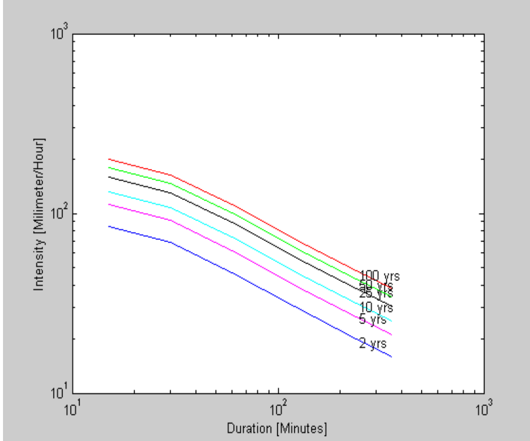
The analysis requires minimizing Equation (16). This was achieved using the MS-EXCEL spreadsheet by a trial and error procedure. The results of the analysis are $\chi^2 = 0.0029$ for $\eta = 0.99$ and $\theta = 0.008$.

5 Results

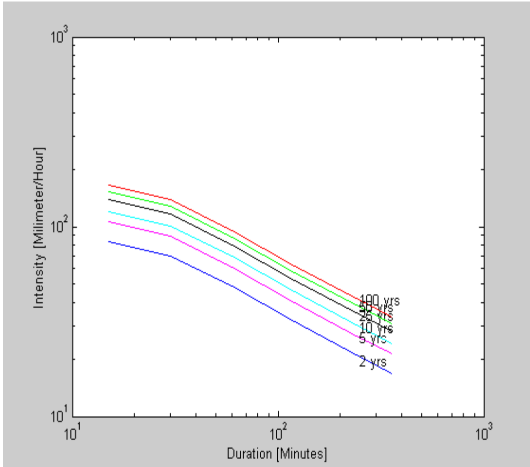
Results of the estimates $\hat{x}_0$ and $\hat{\alpha}$ for the Gumbel distribution function of the maximum precipitation depths for different durations and at the various locations were shown in Table 1. IDF curves obtained by the graphical and statistical methods for the locations were shown in Figure 6 to Figure 8.

Table 1 Parameter estimates for Gumbel distribution function for different Durations at study locations

Location	Duration/h	α/mm	x_0 /mm
Enugu	0.25	4.972	19.170
	0.5	8.136	31.370
	1	11.377	42.639
	2	14.628	54.821
	4	19.504	73.095
	6	23.219	87.018
Onitsha	0.25	5.133	19.990
	0.5	8.400	32.72
	1	11.312	44.646
	2	14.544	57.402
	4	19.392	76.536
	6	23.085	91.115
Owerri	0.25	6.271	21.390
	0.5	10.26	35.000
	1	14.174	47.460
	2	18.224	61.019
	4	24.299	81.359
	6	28.927	96.856
Port Harcourt	0.25	5.098	20.500
	0.5	8.342	33.550
	1	11.686	45.747
	2	15.024	58.818
	4	20.033	78.423
	6	23.848	93.361
Uyo	0.25	4.026	18.200
	0.5	6.588	29.780
	1	8.704	40.730
	2	11.191	52.367
	4	14.921	69.823
	6	17.763	83.123
Abakaliki	0.25	5.616	20.230
	0.5	9.190	33.110
	1	11.191	45.419
	2	14.388	58.396
	4	19.184	77.861
	6	22.838	92.692
Umuahia	0.25	5.229	19.750
	0.5	8.556	32.330
	1	11.995	43.900
	2	15.423	56.443
	4	20.563	75.258
	6	24.480	89.592



a. Graphical method



b. Statistical Method

Figure 6 Intensity-Duration-Frequency curves for Onitsha obtained

6 Analysis and discussion of the results

Some index values selected from the IDF curves developed in the study were:

1) 10-year 15-minute fall
2) 2-year 30-minute fall
3) 5-year 1-hour fall
4) 25-year 1-hour fall
5) 100-year 6-hour fall

These index values were shown in Table 2 for the seven locations studied in Southeastern Nigeria. The estimates of intensities were extracted from IDF curves and then converted to total fall for the duration. For example, the 2-year 30-minute and 25-year 1-hour falls read off Figure 6a for Onitsha were 69 mm and 88.9 mm per hour, respectively. By multiplying the respective values by 0.5 and 1, we obtained falls of 34.5 mm and 88.9 mm (see Table 2). From Table 2, we obtained some insight into the IDF regime for the region. For example, using the ratio of the 10-year 15-minute to that of the 100-year 6-hour falls, we found that Onitsha, Abakaliki and Uyo had the highest ratio of 15% to 16% while the others had a ratio of 14%. If we considered the 10-year 15-minute rainfall alone, however, we found that Owerri experienced the most intense short – duration storms. The ratio of 10-year 15-minute to the 100-year 6-hour falls indicated the comparative significance of short – duration thunderstorm type fell in contrast to long – duration monsoon rainfall.

Table 2 Rainfall Amount-Duration-Frequency estimates (mm) by graphical and statistical methods

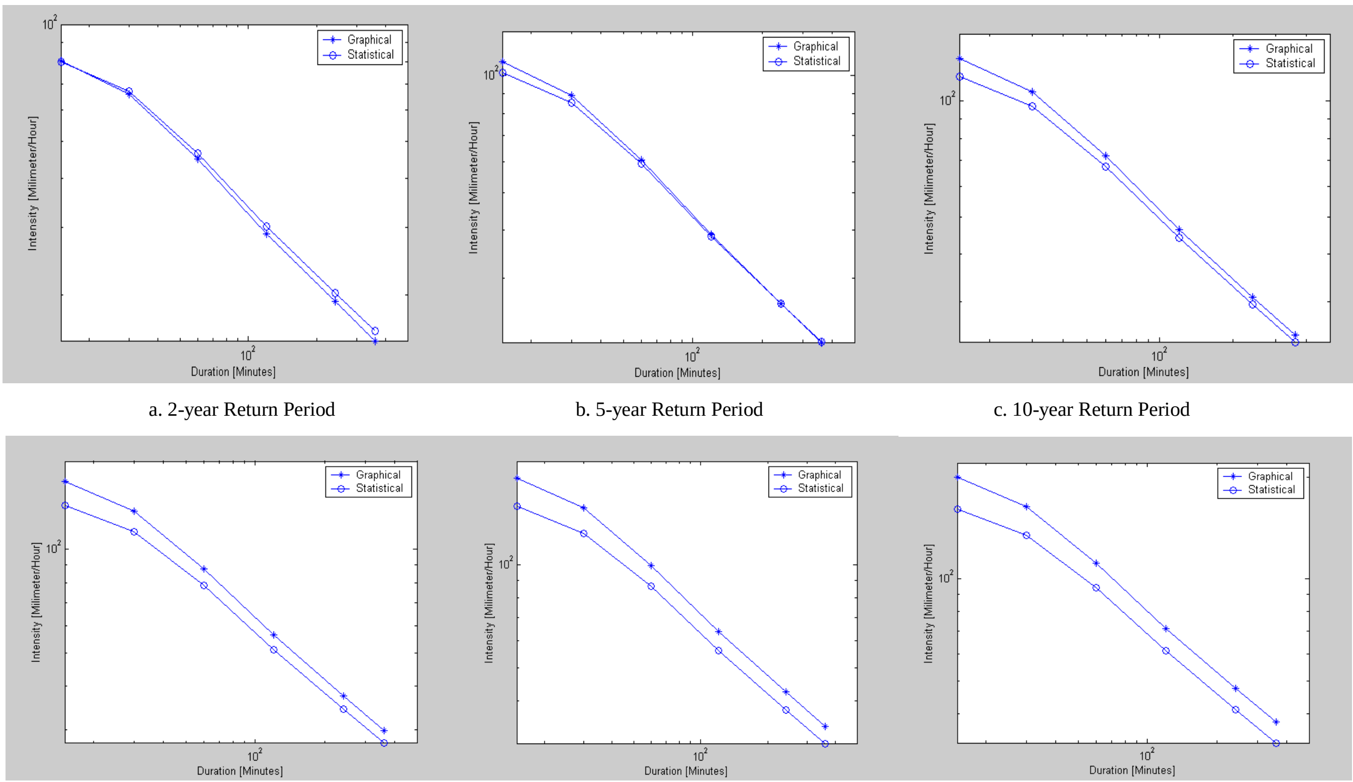
Methods	Stations	10-year 15 min	2-year 30 min	5-year 1 h	25-year 1 h	100-year 6 h
Graphical	Onitsha	33.1	34.5	62.2	88.9	228
	Enugu	32.4	33	60.5	87.7	226.8
	Owerri	37.5	37.1	69.4	102.6	267.6
	Port Harcourt	34.3	35.4	64.3	92.7	238.8
	Abakaliki	33.6	35.2	63.2	90.1	231
	Umuahia	34.2	34.1	63.4	93.1	241.8
	Uyo	28.3	31.3	54.3	74.8	188.4
Statistical	Onitsha	30.2	35	61.1	80.2	200.4
	Enugu	29.0	33.6	59.2	78.4	196.8
	Owerri	34	37.9	68.2	92.1	234
	Port Harcourt	30.6	35.8	62.8	82.5	206.4
	Abakaliki	31.4	35.7	61.7	80.6	201
	Umuahia	30.1	34.7	61.4	81.6	205.8
	Uyo	26.1	31.5	53.4	68.0	167.4

6.1 Comparison of IDF curves obtained by graphical and statistical methods

The IDF curves obtained by the two methods were in agreement with the IDF theory. Figure 7a–f showed the comparison between the IDF curves obtained by the two methods for the return periods 2, 5, 10, 25, 50 and 100 years. The difference between the IDF curves was not statistically significant at 5% level of significance.

6.2 Comparison of IDF curves obtained with published IDF curves for Enugu

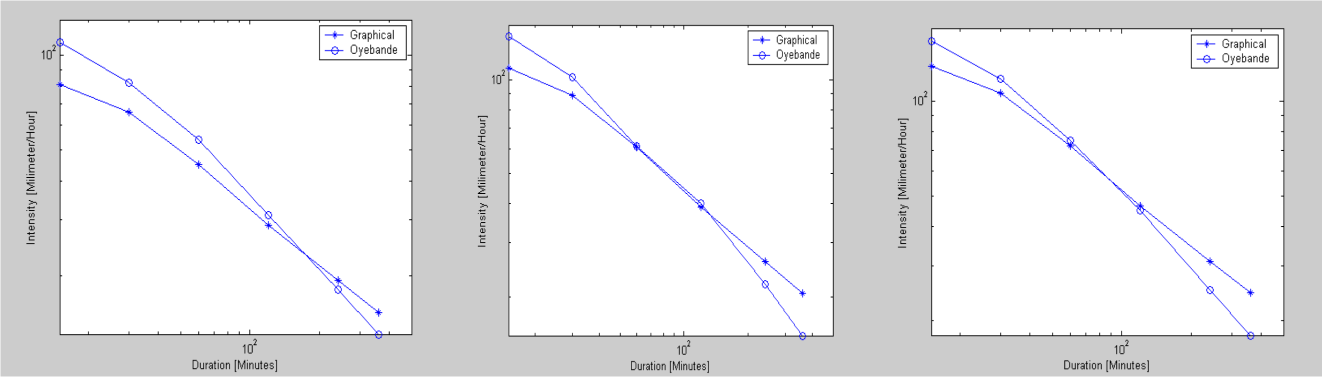
Oyebande (1983) used the graphical method to develop IDF curves for some selected locations in Nigeria. However, only Enugu was common to his work and the present study. Because of this situation the comparison would be made using the IDF curve developed by graphical method for Enugu location. Figure 8a–f below showed the difference between the IDF curves obtained by graphical method and Oyebande (1983) for Enugu, for return periods 2, 5, 10, 25, 50 and 100 years. The IDF curves obtained by graphical method were lower than those of Oyebande (1983) at shorter rainfall durations, but higher at higher rainfall durations. However, the differences were not significant at 5% level.



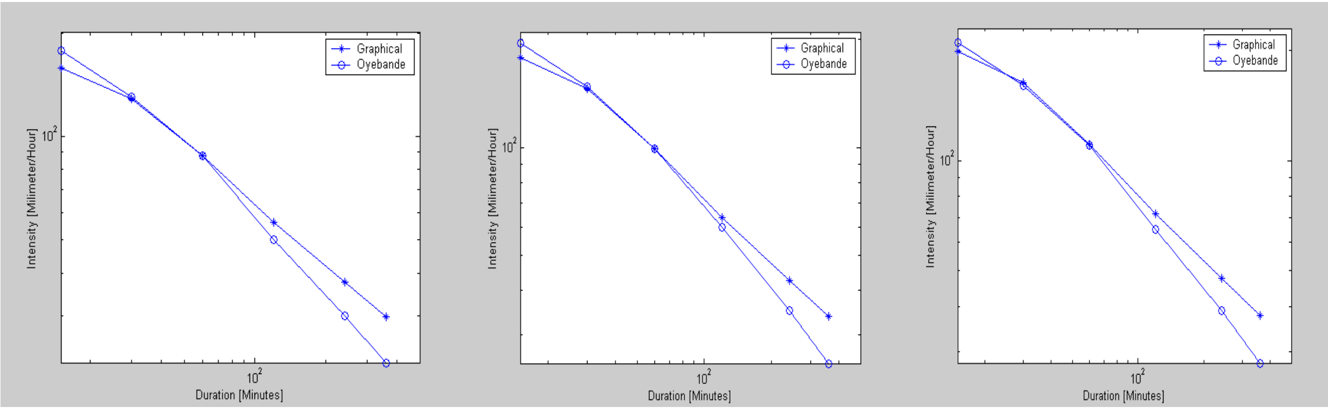
a. 2-year Return Period b. 5-year Return Period c. 10-year Return Period

d. 25-year Return Period e. 50-year Return Period f. 100-year Return Period

Figure 7 Comparison between graphical and statistical method.



a. 2-year Return Period b. 5-year Return Period c. 10-year Return Period



d. 25-year Return Period e. 50-year Return Period f. 100-year Return Period

Figure 8 IDF curves obtained by the graphical method and Oyebande (1983) for Enugu location

7 Conclusions

Intensity-duration-frequency data are needed by hydrologists and engineers involved in planning and design of water resources projects. Historical rainfall records are needed to obtain design estimates for both small and large projects.

This study is an attempt to provide much needed, useful design data and guidance for water resources development in Southeastern Nigeria.

References

Andreas L., and D. Veneziano. 2006. Intensity-Duration-Frequency curves from scaling representations of rainfall. Department of Civil and Environmental Engineering, MIT, Cambridge, Mass., USA.

Ayoade J. O. 1975. A freliminary study of the magnitude, frequency and distribution of intense rainfall in Nigeria. Hydrological Sciences -Bulletin-des Sciences Hydrologiques, XXI, 3 9/J976.P.423.

Brian, H., C. Zelinka, C. Castello, and D. Curtis. 2006. Spatial analysis of storms using GIS. Unpublished paper, OneRain Inc. 9267 Greenback Lane, Orangevale, P.1

Brikowski, T. 2007. GEOS 5313 Lecture Notes, Spring 2007.

Demarée, G. R. 2004. Intensity-Duration-Frequency (IDF) curves for Yangambi, Congo, based upon long-term high-frequency Precipitation Data Set. P. 12.

Dupont B. S., D. L. Allen, and K. D. Clark. 2000. Revision of the Rainfall-Intensity-Duration curves for the commonwealth of Kentucky. Kentucky Transportation Center, College of Engineering, University of Kentucky Lexington, Kentucky. P.1

Evans T., B. Hasting, and C. Peacock. 1993 "Statistical distributions", Wiley Interscience, 169 pp.

Gerold, L. A., and D. W. Watkins. 2005. Short duration rainfall frequency analysis in Michigan using scale-invariance assumptions. Journal of Hydrologic Engineering, Volume 10, Issue 6, pp. 450－457.

Hosking, J. R. M., and J. R. Wallis. 1997. *Regional frequency analysis: an approach based on L-moments*. Cambridge University Press, Cambridge, U.K.

Koutsoyiannis, D., D. Kozonis, and A. Manetas. 1998. A mathematical framework for studying rainfall intensity-duration-frequency relationships, J. of Hydrology, Vol. 206, Pp. 118－135,.

Metibaiye J. W. E. 1990. Estabilishing Intensity-Duration-Frequency relationships for use in water projects in Nigeria. First Biennial National Hydrology Symposium, Nigeria. P. 4

Mohymont B., G. R. Demarée, and D. N. Faka. 2004. Establishment of IDF-curves for precipitation in the tropical area of central Africa – Comparison of techniques and results. Natural Harzards and System Sciences.European Geosciences Union. P.377.

Nigeria. 2008. In *Student's Encyclopedia*. Retrieved February 15, 2008, from Britannica Student Encyclopedia. http://student.britanica.com/comptons/article-229703.

Okonkwo, G. I. 2008. Rainfall Intensity-Duration-Frequency analysis for South Eastern Nigeria. Unpublished M.Eng Project Report, Department of Agric and Bioresources Engineering, University of Nigeria, Nsukka. pp 95.

Oyebande, L. 1983. Rainfall Intensity-Duration-Frequency curves and maps for Nigeria. Department of Geography, University of Lagos.

Oyebande, L. 1982. Deriving rainfall intensity-duration- frequency relationships and estimates for regions with inadequate data. Hydrological Sciences Journal. P. 353.

Rick, K. 2007. Statistics of weather and climate extremes. http://www.isse.ucar.edu/Hp_rick/

Smith, J. A. 1993. “Precipitation” in Handbook of Hydrology, edited by David R.

Maidment. New York: McGraw-Hill, Inc.

Stedinger, J. R., R. M. Vogel, and E. Foufoula-Georgiou. 1993. “Frequency analysis of extreme events” in Handbook of Hydrology, edited by David R. Maidment. New York: McGraw-Hill, Inc.

USDA SCS. 1955. Soil and water conservation engineering. Central Technology Unit. P. 20.