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Flood Frequency Analysis of Ikpoba River Catchment at Benin City Using Log Pearson Type III Distribution

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Abstract

In this study, a flood frequency analysis (FFA) of Ikpoba River Catchment at Benin City, Edo State Nigeria was undertaken using the Log-Pearson Type III probability distribution, one of the numerous probability distribution functions used to model hydrologic phenomena that are characterized by significant variability not deterministically explained by physical principles. The study was motivated by the need for safe and economic hydrologic design and assessments in the catchment area. The log-Pearson type III probability distribution was used to model the annual peak discharge for the river for the period 1989 to 2000 based on stream flow measurements carried out by Benin Owena River Basin Development Authority. The probability distribution function was applied to return periods (T) of T = 2 yrs, 5yrs, 10yrs, 25yrs, 50yrs, 100yrs and 200 yrs commonly used in for engineering design of hydraulic structures. The estimated discharges obtained are 46.34m^3/s, 55.84m^3/s, 61m^3/s, 66.89m^3/s, 70.73m^3/s, 74.18m^3/s and 77.38m^3/s respectively. these values are useful for hydraulic design of structures in the catchment area and for storm water management The model which relates the expected discharge(y) to return period is given by y= 6.546ln(x) + 44.4

Keywords: flood frequency analysis, return period, log pearson distribution frequency factor

INTRODUCTION

Flood has been identified world wide as highly destructive and hydrological and meteorological data such as flow rate and rainfall are used in engineering design of hydraulic structures to mitigate flooding (Ibrahim and Isiguzo, 2009). As dams which are not designed to withstand major storms may be destroyed by them, to protect lives and properties downstream, it is needful for hydraulic structures to be constructed to safely handle an approximate percentage of the probable maximum flood (Engineering Group, 2004). As much of the hydraulic data like flow rate (discharge) and rainfall are statistical in nature, statistical methods are most frequently needed to be used often with the goal of fitting a statistical distribution to the data (Prasuhn, 1992). Design flood is the discharge adopted for the design of a hydraulic structure (Asawa, 2005) and it is obviously very costly to design any hydraulic structure so as to make it safe against the maximum flood possible in the catchment. Whereas, structures like culverts, storm drainage systems can be designed for relatively small (more frequent floods), failures of structures such as spillways which cause huge loss of life and property are designed for relatively more severe floods which have relatively longer return periods. Therefore, to select a design flood, which is not likely to occur during the life of a hydraulic structure, the design return period (T) should be much greater than the estimated life of the structure hence the return period of very important structures like spillways for high dams is taken very long to reduce the risk of failure.

Frequency based flood find their application in the estimation of design flood for almost all types of hydraulic structures and for the design of flood control structures, T- year design flood (T = 100 years, 50 years, 20 years, 10 years, or any desired year) is often required or calculated from the best fit distribution, hence probability distribution plays a vital role in designing and proper management of water resources. Flood frequency analysis (FFA) is used to predict design floods for sites along a river, the technique involves using observed annual peak flow discharge data to calculate statistical information such as mean value, standard deviation, skewness and recurrence interval. These statistical data are used to construct frequency distributions which are graphs and tables that tell the likelihood of various discharges as a function of recurrence interval or exceedence probability.

Flood frequency analyses commonly focus on the estimation of return periods associated with annual maximum flood peaks of various magnitudes. Based on an assumed distribution, it is possible to make a probability statement of future flows of various magnitudes. The estimated value of the random variable is also estimated for a given probability. Flood frequency analysis can take on many forms depending on the equation used in carrying out statistical analysis. Flood frequency analysis is a viable method of flood flow estimation in most situations and provides reliable prediction in regions of relatively uniform climatic condition from year to year and it is now an established method of determining critical design discharge for small to moderately sized hydraulic structures (Haktan, 1992). Therefore, flood frequency analysis of a river is vital. A random variable is a quantity that depends on chance the values or range of values can be predicted only with probability not with certainty. Examples of hydrologic random variables are mean monthly or annual stream discharge, precipitation etc. and a frequency relationship represents the likelihood of occurrence of values of a random variable. A distribution function provides a probabilistic model of phenomenon represented by a particular random variable.

Standard probability distribution functions commonly used in water resources engineering have been identified in the literature e.g. (Wilson, 1990; Wurbs and James, 2009) to include Normal, log Normal, Pearson, Log Pearson Type III and Extreme value Type 1 (EVI) and each distribution can be used to predict design floods. In this study the log Pearson Type III probability distribution function have been used to model the annual peak discharge data of Ikpoba River at Benin City from 1989 to 2000 obtained from the measurements carried out by the Benin Owena River Basin Development Authority (BORBDA).The study was motivated by the need to ensure safe and economic hydrologic design and assessment in the catchment area. The main objective of the study was to perform flood frequency analysis of the river catchment using annual peak flow or maximum discharge data obtained in the river in the water years 1989 to 2000. The specific objectives of the study were:

(i) Fit the Log Pearson Type III probability distribution to the annual peak discharge data and hence

(ii) Predict design for the following return periods (T= 2yrs, 5yrs, 10yrs, 25yrs, 50yrs, 100yrs and 200 years)

The results of the flood frequency analysis (FFA) generated from the study gives information of likely values of discharge to be expected in the river at the various return periods based on the observed data which information is useful for many engineering purposes such as when designing structures in or near the river that may be affected by flood as well as in designing structures to protect against the largest expected events. This may include the design of dams, bridges and flood control structures which will reduce flood damage in the catchment or aid storm water management in the catchment.

THE STUDY AREA/CATCHMENT

The study area/catchment for which this flood frequency analysis is carried out is situated within the Western Littoral hydrological area (HA-6) of Nigeria (Akintola, 1986). The Western Littoral hydrological area (HA-6) is one of the eight hydrological areas (HAs) into which Nigeria is subdivided. The gauging station from which the data for this study was collected is located along Ikpoba River at Benin City which is some 160km due East of Lagos. Benin City is located at about 117km away from Benin River which discharges into the Gulf of Guinea. Important parameters pertaining to the hydrological gauging station are given in Table 1.1.

Table 1.1: Ikpoba River Hydrological Gauging Station Parameters

Location of Station	State of Location	Basin	Latitude	Longitude	Drainage area (km^2)
Ikpoba river at Benin City	Edo, Nigeria	Ossiomo	$6^0 21'$N	$5^0 39'$E	922

Source: (BORBDA, 2005).

The Theory of Log-Pearson Type III Probability Distribution

The log-Pearson Type III distribution is a statistical technique for fitting frequency distribution data to predict the design flood for a river at some site. Once the statistical information is calculated for the river site, a frequency distribution can be constructed. The probabilities of floods of various sizes can be extracted from the curve.

The probability density function (PDF) for the distribution is given as (Abramowitz and Stegun, 1972);

$$f(x) = \frac{X^{\beta}(x - x_0)^{\beta-1} \ell^{-x(x-x_0)}}{\Gamma(\beta)}, \; x \geq x_0 \qquad (2.1)$$

Where $\bar{x}$ = mean, Γ = gamma function

y = reduced variate

$$y = \frac{(x - x_0)}{\beta} \qquad (2.2)$$

$$\bar{x} = x_0 + \beta\gamma \qquad (2.3)$$

$$\beta = \frac{\sqrt{V}}{\sqrt{\gamma}} \qquad (2.4)$$

$$\gamma = \left(\frac{2}{g}\right)^2 \qquad (2.5)$$

where β = standard deviation

V = variance, g = skewness

Because the problem with most hydrologic data is that an equal spread does not occur above and below the mean as the lower side is limited to the range from the mean to zero (although in many cases the minimum may be well above zero) while there is theoretically no limitation on the upper range, it contributes to what is called a skewed distribution (Prasuhn, 1992). The coefficient of skew (g) being mathematically defined by:

$$g = \frac{N \sum_{i=1}^{N} \left(x_i - \bar{x}\right)^2}{(N-1)(N-2)\sigma^3} \qquad (2.6)$$

where σ = standard deviation

Pearson (1930) proposed a general formulation that fits many probability distribution including the normal, beta and gamma distribution. A form of the Pearson probability distribution called the Pearson type III has 3 parameters that include the skew coefficient (equation 2.6), as well as the mean and standard deviation. The Pearson Type III distribution is represented by equation (2.7) [Arora, 2007; Wurbs and James, 2009].

$$X = \bar{X} + K\sigma \qquad (2.7)$$

Where k = frequency factor determined from Tables. The model parameters $\bar{X}$, standard deviation and the skew coefficient (g) are computed from n observations X, with the following formular

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad (2.8)$$

$$\sigma = \left[\frac{1}{(n-1)}\sum \left(X_i - \bar{X}\right)^2\right]^{1/2} \qquad (2.9)$$

$$g = \frac{n\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^3}{(n-1)(n-2)\sigma^3} \qquad (2.10)$$

However, the Log Pearson Type III distribution of X which has been widely adopted to reduce skewness is equivalent to applying Pearson Type III to the transformed variable log X and it is represented in the literature (e.g. Das and Saikia (2009); Jagadesh and Jayaram (2009); Wurbs and James, 2009) as:

$$\log X = \overline{\log X} + K\sigma_{\log X} \qquad (2.11)$$

where X is the flood discharge value of some specified probability, $\overline{\log X}$ is the average of the log X discharge values, K is frequency factor. $\sigma_{\log x}$ is the standard deviation of log x values. The frequency factor K is a function of skewness coefficient and return period and can be read from published tables (Table 4.3) developed by integrating the appropriate probability density function.

The flood magnitude for various return periods are found by solving the general equation. The mean, standard deviation of the data and skewness coefficient can be calculated using the following formulae

$$\overline{\log X} = \frac{\sum \log X_i}{n} \qquad (2.12)$$

$$\vartheta_{\log x} = \left[\frac{\sum\left(\log X_i - \overline{\log X}\right)^2}{(n-1)}\right]^{1/2} \qquad (2.13)$$

$$g = \frac{n\sum\left(\log X_i - \overline{\log X}\right)^3}{(n-1)(n-2)\sigma^3_{\log x}} \qquad (2.14)$$

where n is the number of entries of X the flood of some specified probability $\overline{\log X}$ i is the average of the log x discharge values,

METHODOLOGY

The daily discharge data of Ikpoba River at Benin City from 1989 to 2000 obtained from the measurements carried out by the Benin-Owena River Basin Development Authority (BORBDA) were obtained and subjected to flood frequency analysis applying the log-Pearson type III method of analysis. Before this, the hydrological data were selected to fairly satisfy the assumption of independence and identical distribution by selecting the maximum of discharge which is the largest instantaneous peak flow occurring at any time during the year (Chow et al, 1988) in order to obtain annual series data and to ensure that annual peaks are independent of one another, water year rather than calendar year was utilized for the analysis (Shaw, 1988). Estimates of the recurrence interval T were obtained using the Cunane plotting position formula as recommended in Ojha et al (2008) for Log Pearson Type III distribution and given in equation 3.1 as:

$$T = \frac{n + 0.2}{m - 0.4} \qquad (3.1)$$

where n is the number of years of record and m is the rank obtained by arranging the annual flood series in descending order of magnitude with the maximum being assigned the rank of 1.

In carrying out the flood frequency analysis using the log-Pearson Type III distribution, the following steps suggested by Jagadesh and Jayaram (2009) were adopted:

(i) The annual flood series (X_{ii}) were assembled
(ii) The logarithms of the annual flood series were calculated as $y_i = \log X_i$
(iii) The mean $\bar{y}$, the standard deviation σ_y and skew coefficient Csy of the logarithm y_i were calculated.
(iv) The logarithms of the flood discharge i.e. log Q_i for each of the several chosen probability level P_j were calculated using the following frequency formular $\log Q_j = \bar{y} + K_j S_y$ where K_j is the frequency factor, a function of the probability P_j and Skewness coefficient C_{sy} were calculated.

Table 4.3 shows the frequency factor (k) for ten selected probability levels in the range from 0.5 to 95% and skewness coefficient in the range from -3. to 3.0

(v) The flood discharge Q_j for each P_i probability level (return period T_j) is obtained by taking antilogarithms of the $\log \vartheta_j$ values.

PRESENTATION AND ANALYSIS OF RESULTS

The annual peak flow data for Ikpoba River by year for the period of record obtained from the analysis of daily discharge measurement carried out for the river from 1989 to 2000 by Benin Owena River Basin Development Authority is presented in Table 4.1 below.

Table 4.1: Annual Peak Flow data for Ikpoba River (1989 - 2000)

Water year	**Stream flow Annual Maximum (m^3/s)**
1989	43.89
1990	28.25
1991	55.00
1992	38.30
1993	38.80
1994	50.00
1995	52.10
1996	43.89
1997	43.89
1998	43.89
1999	65.40
2000	65.10

Source: (BORBDA, 2005)

Table 4.2: Computation of Statistical Parameters

Rank (m)	Water year	Flood flow (x) (m^3/s)	y=log x	$(y-\bar{y})^2$	$(y-\bar{y})^3$	$T = \frac{n+0.2}{m-0.4}$	$P = \frac{100}{T_r}$
1	1999	65.40	1.8155	0.0227	0.0342	20.33	4.9
2	2000	65.10	1.8135	0.0221	0.00329	7.625	13.11
3	1991	55	1.7403	0.0057	0.0043	4.692	21.3
4	1995	52	1.716	0.0027	0.0014	3.38	29.59
5	1994	50	1.6989	0.0012	0.000039	2.65	37.73
6	1989	43.89	1.6423	0.0005	-0.0000113	2.178	45.9
7	1996	43.89	1.6423	0.0005	-0.0000113	2.178	45.9
8	1997	43.89	1.6423	0.0005	-0.0000113	2.178	45.9
9	1998	43.89	1.6423	0.0005	-0.0000113	2.178	45.9
10	1993	38.80	1.588	0.0058	-0.000438	1.27	78.74
11	1992	38.30	1.583	0.0067	-0.00054	1.15	86.95
12	1990	28.25	1.4510	0.0457	-0.00977	1.05	95.23
Average		47.38	1.66				

The various statistical parameters from the analysis of the peak discharge data as outlined in the methodology are presented in Table 4.2.

Standard deviation (σ) = 0.102 Skewness coefficient (g) = -0.3560

Mean ($\bar{x}$) = 47.38, Mean ($\bar{y}$) = 1.66.

The results of the application of the log-Pearson distribution to observed data are given in Table 4.4.

As can be seen in the table, the expected stream discharges for return periods of 2 yrs, 5yrs, 10 yrs, 25yrs, 50yrs, 100yrs and 200yrs are 46.34m^3/s, 55.84m^3/s, 61m^3/s, 74m^3/s and 77.4m^3/s respectively. These values are useful in the engineering design of hydraulic structures in the catchment. Log Pearson Type III distribution has been recommended for use by United State federal agencies for performing flood frequency analysis.

Table 4.3: Frequency Factors k for Pearson III Distribution

	Return Period T(y)									
	1.05	1.11	1.25	2	5	10	25	50	100	200
	Probability of exceedence P (percent)									
C_s	95	90	80	50	20	10	4	2	1	0.5
3.0	-0.665	-0.660	-0.636	-0.396	0.420	1.180	2.278	3.152	4.051	4.970
2.8	-0.711	-0.702	-0.666	-0.384	0.460	1.210	2.275	3.114	3.973	4.847
2.6	-0.762	-0.747	-0.696	-0.368	0.499	1.238	2.267	3.071	3.889	4.718
2.4	-0.819	-0.795	-0.725	-0.351	0.537	1.262	2.256	3.023	3.800	4.584
2.2	-0.882	-0.844	-0.752	-0.330	0.574	1.284	2.40	2.970	3.075	4.444
2.0	-0.949	-0.895	-0.777	-0.307	0.609	1.302	2.219	2.912	3.605	4.398
1.8	-1.020	-0.945	-0.799	-0.282	0.643	1.318	2.193	2.848	3.499	4.417
1.6	-1.093	-0.994	-0.817	-0.254	0.675	1.329	2.163	2.780	3.388	3.990
1.4	-1.168	-1.041	-0.832	-0.225	0.705	1.337	2.128	2.706	3.271	3.828
1.2	-1.243	-1.086	-0.844	-0.195	0.732	1.340	2.087	2.626	3.149	3.661
1.0	-1.317	-1.128	-0.852	-0.164	0.758	1.340	2.043	2.542	3.022	3.489
0.8	-1.388	-1.166	-0.856	-0.132	0.780	1.336	1.993	2.453	2.891	3.312
0.6	-1.458	-1.200	-0.857	-0.099	0.800	1.328	1.939	2.359	2.755	3.132
0.4	-1.524	-1.231	-0.855	-0.66	0.816	1.317	1.880	2.261	2.615	2.949
0.2	-1.586	-1.258	-0.850	-0.033	0.830	1.301	1.818	2.159	2.472	2.763
0.0	-1.645	-1.282	-0.842	0.000	0.842	1.282	1.751	2.054	2.326	2.576
-0.2	-1.700	-1.301	-0.830	0.033	0.850	1.258	1.680	1.945	2.178	2.388
-0.4	-1.750	-1.317	-0.816	0.066	0.855	1.231	1.606	1.834	2.029	2.201
-0.6	-1.797	-1.328	-0.800	0.099	0.857	1.200	1.528	1.720	1.880	2.016
-0.8	-1.839	-1.336	-0.780	0.132	0.856	1.166	1.448	1.606	1.733	1.837
-1.0	-1.877	-1.340	-0.758	0.164	0.852	1.128	1.366	1.492	1.588	1.664
-1.2	-1.910	-1.340	-0.732	0.195	0.844	1.086	1.282	1.379	1.449	1.501
-1.4	-1.938	-1.337	-0.705	0.225	0.832	1.041	1.198	1.270	1.318	1.351
-1.6	-1.962	-1.329	-0.675	0.254	0.817	0.994	1.116	1.166	1.197	1.216
-1.8	-1.981	-1.318	0.643	0.282	0.799	0.945	1.305	1.069	1.087	1.097
-2.0	-1.996	-1.302	-0.609	0.307	0.777	0.895	0.959	0.980	0.990	0.995
-2.2	-2.006	-1.284	-0.574	0.330	0.752	0.844	0.888	0.900	0.905	0.907
-2.4	-2.011	-1.262	-0.537	0.351	0.725	0.795	0.823	0.830	0.832	0.833
-2.6	-2.013	-1.238	0.499	0.368	0.696	0.747	0.764	0.768	0.769	0.769
-2.8	-2.010	-1.210	-0.460	0.384	0.666	0.702	0.712	0.714	0.714	0.714
-3.0	-2.003	1.180	-0.420	0.383	0.836	0.660	0.666	0.666	0.667	0.667

Source: (Jagadesh and Jayaram, 2009)

Table 4.4: Application of log Pearson Type III distribution to observed data

Return period T(yrs)	**Probability P (%)**	**Frequency factor K (g=-0.356)**	$y_i = \log Q$ $y_i = \bar{y} + K \times Sy$	$X_i = Q(m^3/s)$
2	50	0.059	1.666	46.34
5	20	0.854	1.747	55.84
10	10	1.237	1.786	61.09
25	4	1.622	1.8254	66.89
5	2	1.859	1.8496	70.73
100	1	2.062	1.870	74.18
200	0.5	2.242	1.888	77.38

Standard deviation (σ) = Sy = 0.102

Coefficient of skewness, g = -0.356, $\bar{y} = 1.66$

The plot of the predicted discharge against return period is presented in figure 4.1 and as can be seen the model relationship between the expected discharge and return period is given by y= 6.54ln(x) + 44.47. This can be used to extrapolate for values of expected discharge for return periods not covered in this paper.

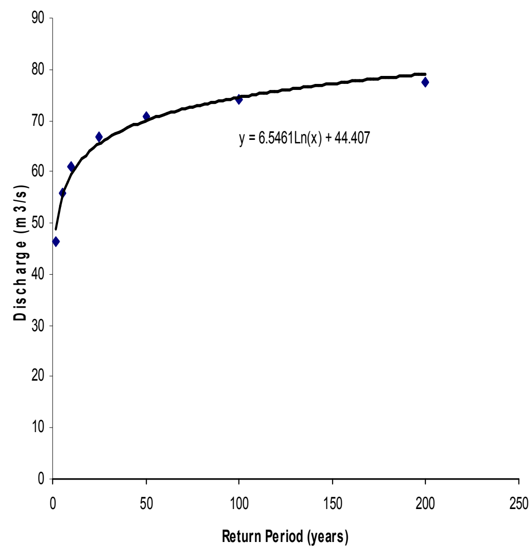

Figure 4.1: Log -Pearson Probability fit to Ikpoba river flow

CONCLUSIONS AND RECOMMENDATIONS

From the flood frequency study carried out on Ikpoba River catchment, the following conclusions are drawn.

(1) That flood frequency studies can be used as a guide in determining the capacity of a structure e.g. highway bridges, culverts, storm drains when it is permissible to take a means of estimating the probable flood damage prevented by a system of flood protection works over a period of years usually equal to the estimated economic life of the works.

(2) The hydrologic phenomena are often characterized by great variability and uncertainty precipitation, discharge and other quantities of importance in water resources engineering and hence can and, are treated as random variables with associated measure of frequency that represent likelihood, percentage of time or probability.

RECOMMENDATIONS

It is recommended that adequate allocation be given to the collection of discharge and other hydrological data in rivers and water resources engineering planning and management and for satisfactory watershed modelling. The use of automatic gauge and discharge recording equipment is recommended to reduce human errors in measurement.

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