Regional flood frequency of Gongola basin (Nigeria) based on L-moment Technique

O. D. Jimoh,
Department of Civil Engineering,
Federal University of Technology, Minna, Nigeria.

Abstract

Gongola basin, which has a catchment area of 23,880 square kilometres at Dadinkowa, has only three gauges established in the 1980s. A dam constructed in the 1990s on one of the ungaged rivers failed due to inadequate spillway capacity, which was based on short length of hydrological data. Regional flood frequency of the basin has been developed using L-moment technique to estimate peak flood for the ungaged sub-basin (Cham sub-basin). Daily streamflow data from the three gauged stations (Dadinkowa, Balanga and Tallum) were utilized for the study. L-moment heterogeneity test showed that the three sites constitute a homogenous region. The annual maximum series was fitted to five distributions, namely: extreme value type 1 (EV1), general normal (GNO), Pearson type III (P3), generalized Logistic (GL) and generalized Pareto distributions (GPA). The GPA was adjudged as the best-fit distribution. The mean annual peak floods for various return periods were estimated for the ungauged sub-basin (River Cham basin). The estimated l00 - year flood is 54.88m^3/s, which is higher than the value used to construct a dam across River Cham in 1990.

Keywords: ungauged catchment, L-moment, flood frequency, return period, Pareto distribution

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1. Introduction

Information on flood magnitudes and frequencies is needed for design of hydraulic structures such as weirs, barrages, dams, spillways, bridges and urban drainage systems. In most cases, there are no observed data at the design site and little time can be spent on the estimate, precluding use of other data in the region (Kumar *et al*, 2003). There are two basic approaches for determination of design peak flood, namely, deterministic and probabilistic approach. The deterministic approach includes the rational method, unit hydrograph and soil conservation services. The probabilistic approach is based on the frequency analysis of past flood records and requires lesser data as compared to the deterministic approach (Jaiswal *et al*, 2003). Many studies have been carried out on the application of deterministic model to catchments in Nigeria (Jimoh and Sule, 1992, Campling *et al*, 2002). A little effort has been devoted to the development of the regional estimation techniques in the country. The advantages of regional flood frequency analysis as against the traditional at-site analysis are: (i) the reliability of the estimated design events increases due to the inclusion of additional spatial information, and (ii) the design events can be estimated at ungauged sites. The regional flood estimation method includes the index-flood method and L- moments technique (Hosking and Wallis, 1997). In flood frequency modeling, the sample data, usually annual maximum series, is used to fit frequency distributions, which in turn are used to extrapolate from record events to design events.

The Gongola basin lies within Latitude 9° 30′ and 11°N and Longitude 12° and 13° E (Fig. 1). The main river within the basin, River Gongola, has gauging stations at Dadinkowa, Tallum and Balanga. Another river within the catchment, River Cham, has been identified as a potential source of water for agricultural purposes. Unfortunately, there is no gauging station on the river. The peak flood of River Cham was estimated (Water and Dam Services Company, 1983) by conventional method to be 20 m^3/s for a 100-year return period; and the river was impounded in 1990. The estimate was based on about 10 years of data in the adjacent basin. In September 1998, the dam embankment breached at multiple locations, and it was suggested (Water and Dam Services Company, 2003) that the failure could be due to inadequate spillway capacity probably as a result of underestimation of the design flood of the ungauged catchment.

The aim of this study is to use L-moment technique to develop a regional flood frequency model for the Gongola Basin, and estimate the peak flood for the ungauged river. The methodology has been applied successfully in modeling peak floods in a number of basins in Australia (Vogel *et al*, 1993a), USA (Vogel *et al*, 1993b), New Zealand (Pearson, 1991, 1993 and Madsen *et a*l, 1997)**,** South Africa (Kjeldsen *et al*, 2001**) a**nd India (Jaiswal *et al*, 2003).

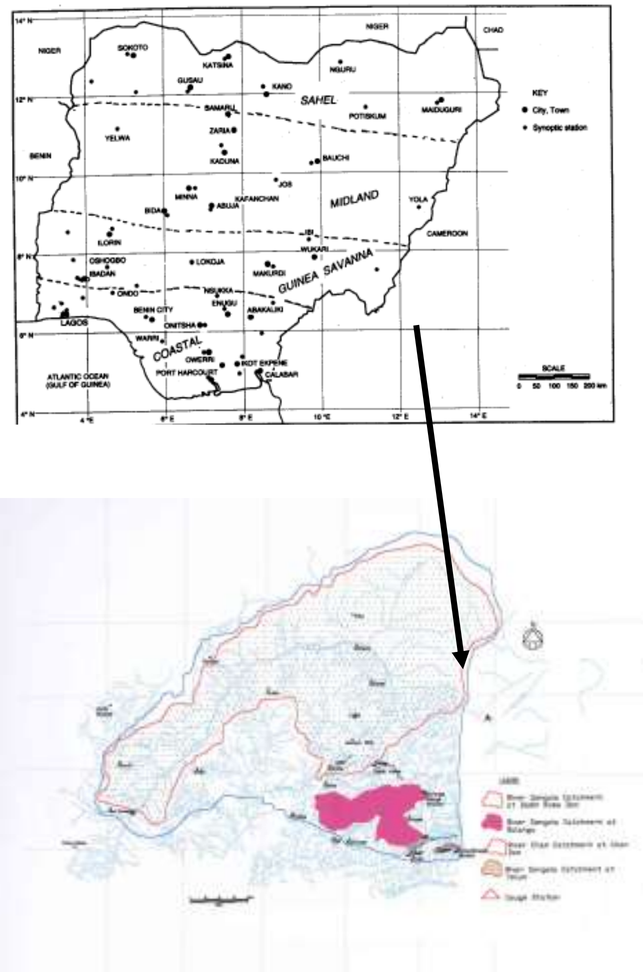


Fig. 1: Map of Nigeria showing the study area

2. The Study Area and Method of Investigation

2.1 The Study Area and Data Collation

The basin lies within the Sahel and Guinea Savannah climatic zone of Nigeria. The climate is influenced by the movement of the Inter Tropical Convergence Zone (ITCZ), resulting in two distinct seasons (wet and dry seasons). The wet season occurs between April and October, while the dry season is between November and March. Both the mean annual rainfall and wet season duration decrease in a northeasterly direction across the basin. The seasonal nature of rainfall is reflected in the flow of the rivers. River Gongola, which drains to River Benue, has three gauging stations, namely, Dadinkowa, Tallum and Balanga. Each station has 20 years of daily stage record, and stage-discharge record sufficient for developing discharge rating curve for the streamflow record. Cham River, which lies within the basin, is ungauged. Another river within the basin, River Kaltunga has only two years of daily discharge record. This station was not used in the study.

Method of investigation involved the collation of hydrological as well as catchment characteristics and establishment of rating curve for each station. The hydrological and rainfall records of the basin were collated from (1) Federal Ministry of Water Resources, Abuja, (2) Upper Benue River Basin Development Authority Yola, and (3) Federal Ministry of Aviation, Metrological office Oshodi, Lagos. The hydrological characteristic of the basin is presented in Fig. 1. The summary of hydrological data collated for the study is presented in Table 1.

L-moment technique was used for the homogeneity test, estimation of the parameters and determination of best-fit distribution. A logarithmic relationship between mean annual peak flood and catchment characteristic was then developed. The regional flood model for the gauged basins was used to estimate the peak flood for the ungauged river.

Table 1: Summary of hydrological data collated

	River	Stage record	Flow record
Cham	Cham	no record	no record
Tallum	Gongola	1982-2002	1982-1983
Dadinkowa	Gongola	1982-2002	1981-1986
Balanga	Gongola	1982-2002	1981-1984

A rating curve of the form of equation (1) was developed for each station to convert the daily stage reading to daily discharge.

$$Q = k(h - a)^{x} \quad (1)$$

where *h* is the stage reading and *a* is the height in meters between zero on the stage and the elevation of the zero flow. The constants *k* and *x* are determined from the rating curve. The rating equations for Dadinkowa, Tallum and Balanga are respectively:

$$Q_{DAD} = 33.096\ (h - 1)^{2..219} \quad (2)$$

$$Q_{TAL} = 9.1939\ (h - 0.4)^{1..8437} \quad (3)$$

$$Q_{BAL} = 8.096\ (h - 0.2)^{2..22} \quad (4)$$

2.2 L-moments ratios

The mean, standard deviation, variance, coefficient of variation, coefficient of skewness, coefficient of kurtosis and the lag one correlation coefficient of the daily discharge, and the log-transformed discharge were calculated. The L-moments of the series were determined using the theory of probability weighted moments (PWMs), which are as expressed as:

$$\beta_r = E\{X[F_X(x)]^r\} \qquad (5)$$

where β_r is the rth order PWM and $F_x(x)$ is the cumulative distribution function of *X*. The unbiased sample estimator (b_i) of the β_r were estimated using the following equations (Hosking and Wallis, 1997):

$$b_0 = \frac{1}{n}\sum_{j=1}^{n} x_j \qquad (6)$$

$$b_r = n^{-1}\sum_{j=r+1}^{n}\left[\frac{(j-1)(j-2)...(j-r)}{(n-1)(n-2)...(n-r)}\right]x_j \qquad (7)$$

where X_{jj} represents the ranked Annual Maximum Series (AMS) in ascending order. The first four L-moments are defined by:

$$\lambda_1 = b_0 \qquad (8)$$

$$\lambda_2 = 2b_1 - b_0 \qquad (9)$$

$$\lambda_3 = 6b_2 - 6b_1 + b_0 \qquad (10)$$

$$\lambda_4 = 20b_3 - 30b_2 - 12b_1 - b_0 \qquad (11)$$

The L-moment ratios are defined as:

$$\tau_r = \frac{\lambda_r}{\lambda_2} \qquad (12)$$

2.3 Homogeneity Tests

The heterogeneity measure, *H* was used as a means of comparing the inter-site variation in sample *L*-moments for the gauged sites. The inter-site variation of *L*-moment ratio is measured (Hosking and Wallis, 1997) as the standard variation (*V*) of the at-site *L-Cv's* weighted proportionally to the record length at each site. The heterogeneity measure is expressed as

$$H = \frac{V - \mu_v}{\sigma_v} \qquad (13)$$

where μ_v and σ_v represent the mean and standard deviation of the computed inter-site variations respectively. When *H* is less than 1.0 the region is considered homogeneous. The value of *H* between 1.0 and 2.0, indicates homogeneous region. If *H* is greater than 2.0, the region is considered as heterogeneous.

2.4 Flood Frequency Modelling

The observed annual maximum series (AMS) series was fitted into extreme value type 1 (EV1), Pearson type III (P3) and the General Normal (GNO), Generalized Pareto (GPA) and generalized Logistic distributions. The goodness-of-fit test was based on Z-statistics (Jaiswal *et al*, 2003 and Kumar *et al*, 2003). The Z- statistics judged how well the L-skew and L-kurtosis of the fitted distribution match the regional average of the L-skew and L-kurtosis of the observed data.

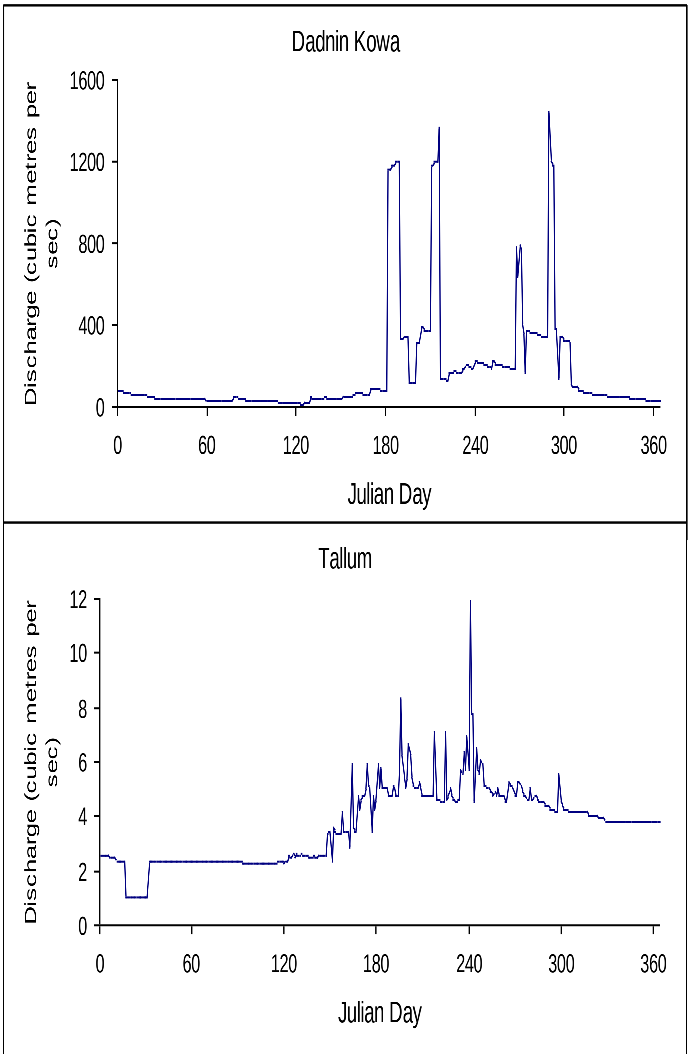
The mean annual flood of a basin (μ_i) is expressed (Kjeldsen *et al*, 2001) in terms of the catchment area and the design flood is expressed as a function of μ_I (equation 18).

$$Q_T = \mu_i G_{RT} \qquad (18)$$

where Q_T is the design flood for T-year return period, μ_i is the mean annual flood, and G_{RT}, the regional growth curve is the $\left(1 - \frac{1}{T}\right)$ quartile in the regional frequency distribution of the normalized AMS. The regional growth curve describes the relationship between the normalized flood magnitude and the corresponding exceedence probability, and is considered constant within a homogenous region.

3. Results and Discussions

Figure 2 shows the daily hydrograph for the three stations in Gongola basin. The statistics of the annual flood series for the observed and the logarithm- transformed series are presented in Table 2. The mean flow varies from 18.4 m^3/s for a catchment area of 41 km^2 to 1076.2 m^3/s for a catchment area of 23,880 km^2. The AMS is less skewed. The correlation coefficient shows that the series is independent. Similar observation was obtained for the logarithm transformed series.



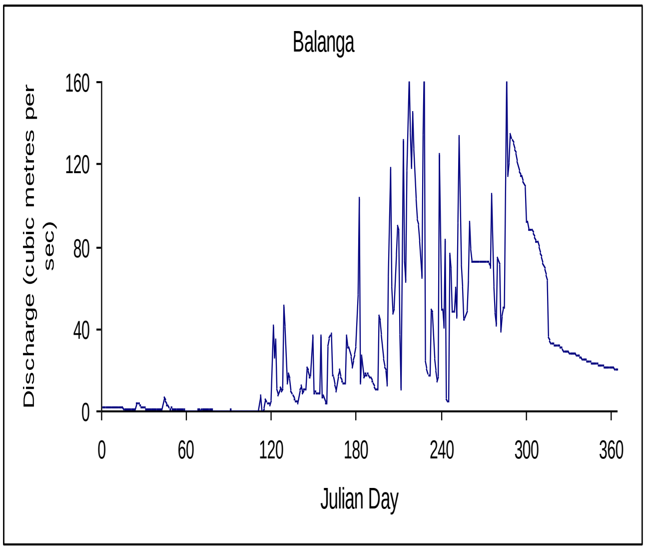


Fig.2: Daily hydrograph for 1985 in Gongola basin

Table 2: Statistics of annual flood series in Gongola Basin

Statistical variables	Dadinkowa	Tallum	Balanga
Catchment Area (km^2)	23,880	41	1377
Original series			
mean	1076.2	18.375	280
standard deviation	467.204	5.958	100.91
variance	218279.577	35.498	10182.828
C_v	0.434	0.324	0.360
C_s	0.722	-0.00447	0.648
C_k	0.161	0.123	0.172
r_1	-0.158	0.166	-0.384
Log Transformed series			
mean	2.993	1.240	2.419
standard deviation	0.193	0.153	0.161
variance	0.0372	0.0234	0.0259
C_v	0.0644	0.124	0.066
C_s	-0.174	-0.514	-0.328
C_k	0.15	0.132	0.194
r_1	-0.236	0.118	-0.441

The L-moment ratios of the observed series are presented in Table 3. Regional parameters of the four- parameter kappa distribution were computed as ξ=0.7924, α= 0.3899, k=0.1721and h=0.20. The estimated parameters were used to generate 1000 simulations of kappa distribution, and the values of heterogeneity are presented in Table 4. The value of H was found to be less than 1.0, indicating the region is homogenous. Using the observed series at the three sites, a relationship between mean annual peak flood μ_1, m^3/s and catchment area (A, km^2) was established as:

$$\mu_i = 1.9387 (A)^{0.6442} \quad (17)$$

The relationship is able to explain 98% (r^2=0.9824) of the initial variation. A graphical representation of the relationship is presented in Fig. 3. Thus, for the ungauged basin with a catchment area of 77 km^2, the mean annual peak flood is 31.8 m^3/s.

Table 3: At site Characteristics of AMS in Gongola Basin

Stations	MAF (m^3/s)	L-Cv	L-skew	L-kurtosis
Dadinkowa	1076.2	0.2467	0.1732	0.1316
Tallum	18.4	0.1904	-0.0046	0.0474
Balanga	280.0	0.2052	0.1578	0.1547

Table 4: Heterogeneity measures (number of simulations is 1000)

Item	Value
Observed standard deviation of group L-CV	0.0238
Simulated mean of standard deviation of group L-CV	0.0231
Simulated standard deviation of standard deviation of group L-CV	0.0120
Standardized test value H(1)	0.06
Observed average of L-CV/L-skew distance	0.0793
Simulated mean of average of L-CV/L-skew distance	0.0728
Simulated standard deviation of average of L-CV/L-skew distance	0.0328
Standardized test value H(2)	0.20
Observed average of L-skew/L-kurt distance	0.0877
Simulated mean of average of L-skew/L-kurt distance	0.0942
Simulated standard deviation of average of L-skew/L-kurt distance	0.0355
Standardized test value H(3)	-0.18

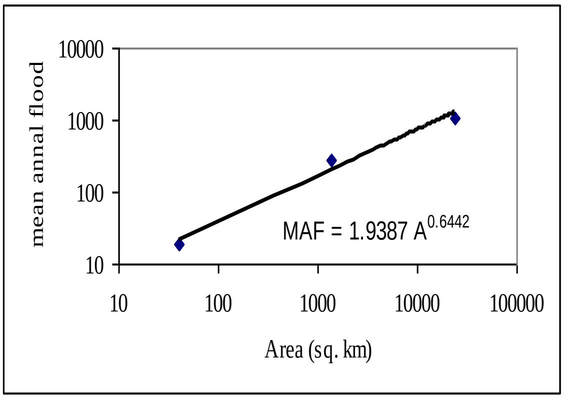


Fig. 3: Graphical representation of mean annual flood and catchment area

3.1 Selection of best-fit distribution

The *Z*-statistics of the distributions are presented in Table 5. The result shows that the five distributions are accepted at 90% level, but GPA has the least *Z*-statistic, indicating that the best distribution fitting the AMS at Gongola basin is the Pareto distribution. The regional parameters of the distribution are ξ=0.442, α=0.898, and k=0.608.

Table 5: Summary of Z-statistics for distributions considered

Distribution	Z
Extreme value 1	0.38
General normal	0.44
Pearson type III	0.32
Generalized	1.33
Generalized Pareto	0.033

The regional growth curve was obtained as:

$$G_T = -0.1744\left[-\ln\left(-\ln\left(1-\frac{1}{T}\right)\right)\right]+1.0909 \qquad (18)$$

The flood quantile Q_T (m^3/s) for a return period *T* years can be computed using the relationship

$$Q_T = \mu_i G_T \qquad (19)$$

where μ_i is the mean annual peak flood, which was obtained from equation (17) for ungauged site, while for a gauged site, μ_i was computed using the observed data. The design peak floods of the ungauged river for 2, 5, 10, 25 and 100 years return period are 30.92m^3/s, 37.34m^3/s, 41.583m^3/s, 46.95m^3/s and 54.88m^3/s respectively. The design flood value used for the design of hydraulic structure at the ungauged site in 1990 was lower than Q_2. This confirms that the dam failed within 10 years of construction due to inadequate spillway.

4. Conclusion

Hydro meteorological data for the Gongola basin were collected and analyzed. The 20 years (1983-2002) daily stage readings at Dadinkowa, Balanga and Tallum weir stations were converted to discharge readings using appropriate rating curve. The daily discharge data were used to develop regional flood frequency for the basin. The conclusions of the analysis are as follows:

(i) The L-moment based homogeneity test, heterogeneity measure, H reveals that the data of the three sites constitute a homogeneous region.

(ii) Available streamflow records was utilized to develop a relationship between mean annual peak flood and catchment characteristics. The relationship is able to explain 98% (r^2=0.9824) of the initial variation.

(iii) Five distributions namely: extreme value type 1, generalized Logistic, Pearson type III, Normal and generalized Pareto distributions have been employed. Regional parameters of the distributions have been estimated using the L-moment approach. Based on the Z-statistic criteria, the generalized Pareto distribution has been identified as the best-fit distribution for the region.

(iv) The regional growth curve for the basin was developed. The curve is applicable to the ungauged catchment. For example, the peak flood of the ungauged river was estimated to be 54.88m^3/s for a 100-year return period as against 20m^3/s estimated based on conventional method.

(v) The study reveals the dearth of stage or discharge data in Nigeria. A basin as large as 24,000 km^2 has only three gauging stations. The study could not calculate the discordancy measures, D-statistics because the minimum number of sites required is 4.

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