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Full Length Research Paper

Flood frequency analysis of Gurara River catchment at Jere, Kaduna State, Nigeria

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A flood frequency analysis (FFA) of Gurara River Catchment at Jere, Kaduna State, Nigeria, was carried out. Four probability distributions were used in the study namely, Extreme value type1, Normal, Exponential and Pearson type 3 distributions due to their desirable properties. The analysis was based on seventeen (17) years daily discharge data converted from gauge height readings. Partial duration series with a threshold of 273.95 m^3/s, being the lowest annual maximum discharge of the 17 years annual peak flow was adapted for the FFA. A reduced variate principle was applied to fit a distribution to the generated data. Of the four probability distributions employed, Pearson type 3 distribution exhibited the best fit for the data.

Key words: Flood frequency analysis, recurrence interval, reduced variate, probability distribution.

INTRODUCTION

Flood has been known and declared all over the world as highly destructive. Hydrological and meteorological data such as flow rate and rainfall are used in the engineering design of hydraulic structures to mitigate flooding. Uncontrolled floodwaters are one of the most powerful and destructive forces in nature. Dams that are not designed to withstand major storms may be destroyed by them, thus increasing flood damage downstream. This damage is too often catastrophic. In order to protect lives and properties downstream, there is the need for hydraulic structures to be constructed to safely handle an appropriate percentage of the Probable Maximum Flood (Engineering Group, 2004).

Although meteorological satellites and early flood warning systems exist, the dates of occurrence and magnitudes of extreme events cannot yet be predicted. Frequency analysis is an established method for determining critical design discharge for small to moderate sized hydraulic structures (HaktanÝr, 1992). Therefore, flood frequency analysis of a river is vital, especially when past experience has shown that the said river had at one time or the other, flooded. In 1998 and 1999, Gurara River flooded above the capacity of its channel taking over farm lands and houses in Kutamgba, a village same time when heavy rains pressured the Kainji, Jebba and Shiroro dams located in the same middle belt region of Nigeria with Gurara River, to open their sluice gates once more, thereby causing flooding which took over agricultural lands and Urban areas downstream of the dams (Nigerian Tribune, 1999).

This flooding was attributed to the occurrence of high rainfalls over a period of days in the catchment (Jimoh and Ayodeji, 2003). Flooding is virtually displacing desertification in Northern Nigeria as some states in the North who hitherto were desert threatened, now suffer serious flood calamities (Nigerian Tribune, 1999). It was also reported that the occurrence of flood in both Kano and Adamawa States led to the submergence of a whole town and washing away of both crops and livestock (Terra Daily, 2004).

Floods not only damage properties and endanger the lives of humans and animals, but have other negative effects on the environment and aquatic life. These include soil erosion, sediment deposition downstream and destruction of spawning grounds for fish and other wildlife habitat. The analysis of flood frequency of river Gurara catchment has therefore become very necessary in order to curtail hazards of this nature.

Flood frequency analyses are used to predict floods for sites along a river. The technique involves using observed annual peak flow discharge data to compute statistical information such as mean values, standard deviation, skewness and recurrence intervals. These statistical

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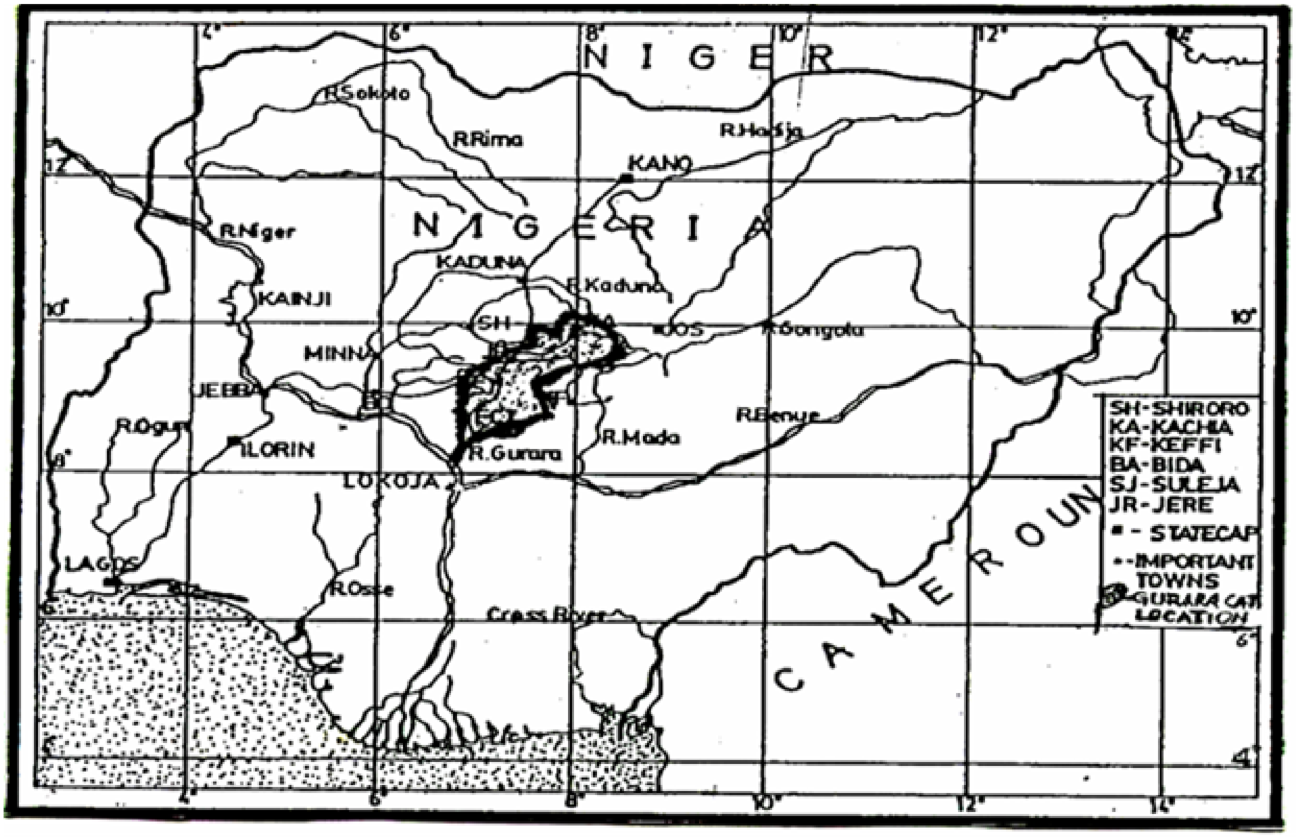

Figure 1. Location map of Gurara River Basin (Source: Jimoh and Sule, 1992).

statistical data are then used to construct frequency distributions, which are graphs and tables that tell the likelyhood of various discharges as a function of recurrence interval or exceedence probability.

Flood frequency distribution can take on many forms depending on the equations used to carry out the statistical analyses. The results of flood flow frequency analysis, generated from this study can be used for many engineering purposes, such as design of dams, bridges and flood control structures; to determine the economics of flood control projects; and to delineate flood plains and assess the effect of encroachments on the flood plain.

Objectives of study

This study is aimed at analysing the flood frequency of Gurara River. The specific objectives of the study are:

1. To convert available gauge height readings to discharge.
2. To fit a probability distribution to the discharge data.
3. To predict probable flooding of Gurara River catchment using FFA.

The study area

The Gurara River basin (catchment) is situated in Northern Nigeria, between latitudes 8°15' and 10°05'; N and longitudes 6°30' and 8°30' E, and has a catchment area of 16650 km^2 at Izom, with Jere occupying about 4016 km^2 of the area. Jere is where the Federal Ministry of Agriculture and Water Resources (FMA&WR) is constructing a dam for the purpose of interbasin water transfer to supplement the lower Usama and Shiroro reservoirs for municipal water supply and hydroelectric power generation, respectively (FMAWR, 1986). The basin is oriented NE-SW with its headwaters originating from the west of the Jos Plateau (Figure 1). The basin lies in the intermediate zone between the semi-arid north and the sub-humid climate in the South. Its climate is characterised by dry Northern-winters and wet Northern-summers. The vegetation type is basically savannah (Southern guinea savannah zone) grassland interspersed with tropical forest remnants. The watercourses are forested with large trees. The terrain is undulating and dissected, conforming to the dominant structure of the underlying rocks-undifferentiated basement complex. The soil type is generally gravely red laterites and in the river valleys, it is alluvial (Jimoh and Sule, 1992). The mean annual rainfall at the location is 1400 mm, while the mean monthly maximum and minimum temperatures in the catchment are 37.3°C and 19.7°C, respectively (Jimoh and Ayodeji, 2003).

Four hydrological stations namely Gurara at Gantan, Gurara at Izom, Gurara at Jere and Gurara at Kurmin

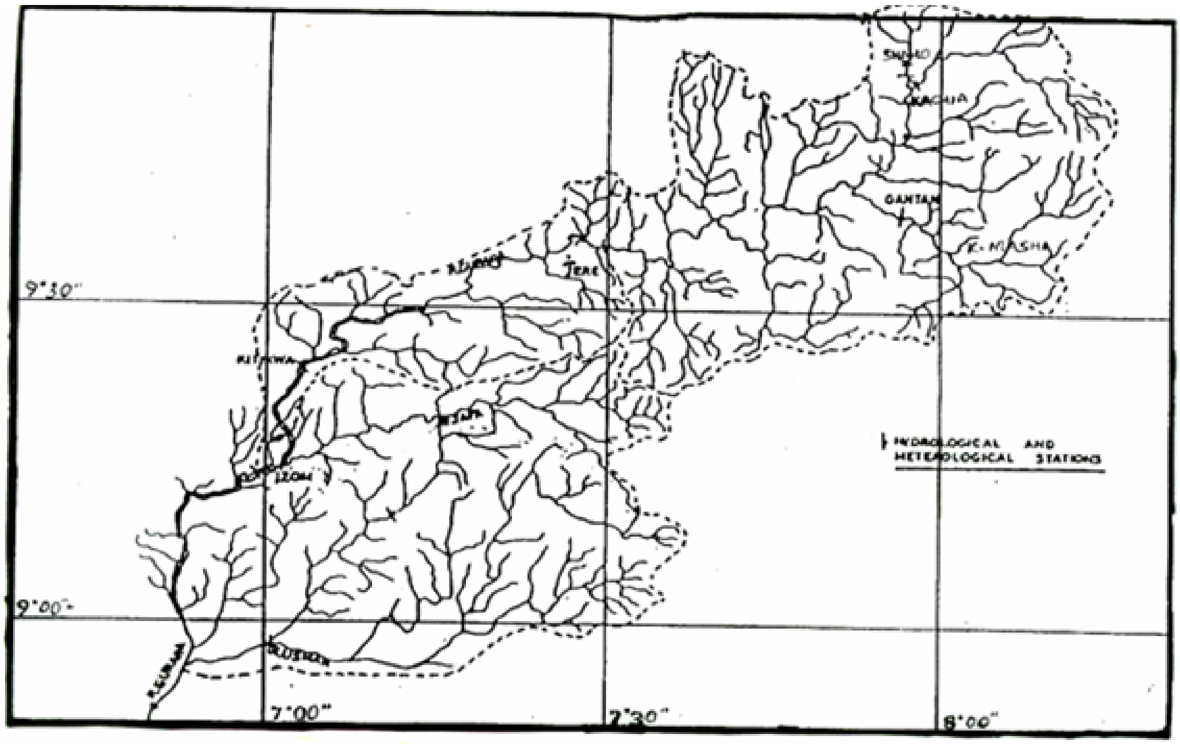

Figure 2. Hydrological map of Gurara River Basin Catchment (Source: Jimoh and Sule, 1992)

Musa, were established on the Gurara River and its major tributaries between 1961 and 1981, for monitoring the stream flow (Figure 2).

METHODOLOGY

The study entailed discharge estimation due to insufficient measured discharge records, using least square methods of linear regression. The converted gauge height data were analysed using frequency analysis technique to fit in a distribution and subsequently, the flood frequency analysis of the catchment was determined both statistically and graphically.

Before the analysis, the hydrological data were selected to fairly satisfy the assumptions of independence and identical distribution. This is often achieved in some cases by selecting the annual maximum of the variable being analysed, which may be the largest instantaneous peak flow occurring at any time during the year (Chow et al., 1988).

Data collection

The gauge and discharge data were collected by Kaduna State and Niger State Water boards. Staff scale was used for gauge height readings and current meter for discharge readings. These measuring instruments are not automated but are manually placed and read within a specified time period. Niger State Water board reads and records gauge and discharge at Izom station out of the four considered. The remaining three stations (Gantan, Jere and Kurmin Musa) are recorded by Kaduna State Water board. These readings are collected on a daily basis; the summary of the gauge and discharge readings are shown in Table 1.

After data collection at the four stations, it was observed that none of the stations had more than a decade discharge record, and the only station that has reasonable years of gauge height reading that could be used to estimate discharge through rating curve analysis is Jere station (Table 1).

Data length and estimation

Jere station has seven years daily discharge/gauge height records and seventeen years daily gauge height record that have no corresponding discharge readings. The non-availability of required discharge data can be attributed to many factors, among which are: lack of funds to carry out the task as at when due, human and natural factors like laxity, death, sickness, heavy storm and lack of proper documentation and information storage facilities.

Rating curve

A straight-line graphical equation of a rating curve was derived from the seven years discharge and gauge height records. This was to convert the available seventeen years gauge heights to discharge. The method employed was the least square method of linear regression.

The following relation was used (Raghunath, 1986):

$$Q = m\,(h-a)^c \qquad (1)$$

Which can be written in logarithmic form as:

$$\log Q = m\log\,(h-a) + \log c \qquad (2)$$

Where Q = discharge (m^3/s) and h = gauge height (m).

The "a" was considered to be 0.048, being the reading of gauge height when discharge reading is zero (0). The 0.048 in the gauge

Table 1. Basic features of the four stations for gauge heights and discharge measurement on the River Gurara.

S/N	Location	Long.	Lat.	Area (km)^2	Daily discharge readings (years)	Daily gauge height readings (years)
1	Gantan	$7^0$57'E	9^0 39'N	718	8	12
2	Izom	$7^0$00'E	$9^0$15'N	6200	5	14
3	Jere	$7^0$30'E	$9^0$32'N	4016	7	17
4	Kurmin Musa	$8^0$05'E	$9^0$35'N	5016	4	12

readings was eliminated from the seven years gauge height before the analysis. Therefore, the equation later used for the analysis is (Stroud, 1995).

$$Q = mh^c \tag{3}$$

And

$$\log Q = m\log h + \log c \tag{4}$$

Frequency analysis

The discharge analysed were assumed to be independent and identically distributed, and the hydrological system (Gurara River) producing them considered to be stochastic, space and time independent (Sule and Jimoh, 1992).

Recurrence interval

The recurrence interval is said to be the average interval in years between occurrence of a flood of specific magnitude and an equal or larger flood. The *m*th largest flood in a data series has been equalled or exceeded *m* times in the period of record *N* years and an estimate of its recurrence interval, *Rp*, as given by Weibull formula is:

$$Rp = \frac{n+1}{m} \quad \text{or} \quad P = \frac{m}{n+1} \tag{5}$$

Where P is the probability of the event.
m is the rank and n is the number of data points (years of data).
Since the only possibilities are that the event will or will not occur in any year, the probability that it will not occur in a given year is 1 – *P*. From the principles of probability, the probability *J* that at least one event that equals or exceeds the *Rp* year event will occur in any series of *N* years is:

$$J = 1 - (1 - P)^N \tag{6}$$

Hence, $J = 1 - (1 - \frac{1}{Rp})^N$ is the probability that the event will occur during a span of *N* years (Linsley and Frazini, 1992).

Distribution fit

To determine a best-fit distribution, it is common to fit the observed distribution to a theoretical distribution by comparing the frequent-cies observed in the data to the expected frequencies of the theoretical distribution. Furthermore, distributions are selected as fit after attaining a goodness of fit for a particular analysis. Reduced variate analysis was employed for the fit. The reduced variate of various distributions was plotted alongside the reduced variate of the return period against the observed discharge. Therefore, the distribution that best fits the reduced variate curve of the return period against discharge was selected as the best fit for the data, from the four probability distributions.

SUMMARY OF PROBABILITY DISTRIBUTION MODELS USED FOR THE FLOOD FREQUENCY ANALYSIS

Extreme value type 1 distribution.

The Extreme Value Type 1 Probability Density Function (PDF) is given by (NIST/SEMATECH, 2006) as

$$f(x) = \frac{1}{\alpha}\exp\left[-\frac{x-u}{\alpha} - \exp\left(-\frac{x-u}{\alpha}\right)\right] - \infty < x < \infty \tag{7}$$

Where α and μ are parameters of the distribution, while $\bar{x} = mean$ and $\delta = s\tan dard\ deviation$.

$$\alpha = \frac{\sqrt{6}\delta}{\pi} \tag{8}$$

$$u = \bar{x} - 0.5772\alpha \tag{9}$$

Reduced variate = y

$$y = \frac{x-u}{\alpha} \tag{10}$$

Normal distribution

The general formula for the Probability Density Function (PDF) of the normal distribution is given by (NIST/SEMATECH, 2006) as:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] - \infty \le x \le \infty \tag{11}$$

Where μ is location parameter and σ is the scale parameter.
Reduced Variate = y

$$y = \frac{(x-\bar{x})}{\sigma} \tag{12}$$

Where $\bar{x} = mean$, $\delta = s\tan dard\ deviation$.

Exponential distribution

The Probability Density Function (PDF) of the exponential distribution is (NIST/SEMATECH, 2006).

$$f(x) = \lambda.e^{-\lambda x} \Rightarrow f(x) = \frac{1}{\beta}e^{-(x-\mu)/\beta}, x \geq \mu; \beta > 0 \quad (13)$$

Where $\bar{x}$ = sample mean, μ and β are location and scale parameters, respectively.
Reduced Variate = y

$$y = \frac{(x - x_0)}{\beta} \quad (14)$$

$$\bar{x} = x_0 + \beta \quad (15)$$

$$\beta = \delta$$

$$\bar{x} = x_0 + \delta \quad (16)$$

Where $\bar{x} = mean$, $\delta = s\tan dard\ deviation$.

Pearson type 3 distribution

The Probability Density Function (PDF) for the distribution is given as (Abramowitz and Stegun, 1972):

$$f(x) = \frac{\lambda^{\beta}(x - x_0)^{\beta-1}e^{-\lambda(x-x_0)}}{\Gamma(\beta)} \qquad x \geq x_0 \quad (17)$$

Where $\bar{x} = mean$, Γ = gamma function.
Reduced Variate = y

$$y = \frac{(x - x_0)}{\beta} \quad (18)$$

$$\bar{x} = x_0 + \beta\gamma \quad (19)$$

$$\beta = \frac{\sqrt{v}}{\sqrt{\gamma}} \quad (20)$$

$$\gamma = \left(\frac{2}{g}\right)^2 \quad (21)$$

Where $\bar{x} = mean$, $\beta = s\tan dard\ deviation$,
$v = \mathrm{var}iance\ \ g = skewness$

RESULTS

Rating curve

The seven (7) years daily gauge heights and their corresponding discharge were used to obtain a fitting straight-line equation from the least square technique of linear regression.
A logarithm equation was obtained as

log Q = 1.23log h + 1.45 (22)

Where Q = discharge (m^3/s) and h = gauge height (m).

The seventeen (17) years discharge values were there-after estimated using equation (22). The equation uses gauge height readings as its parameter for the estima-tion. The discharges were estimated in logarithm; these were later converted to a linear form. It is important to note that the equation produces discharge only when the gauge height is greater or equal to 0.0049 m. This shows that, a gauge height of less than 0.0049 m will produce no flow.

The seventeen years estimated discharge values and their corresponding gauge height were used to plot the rating curve (Figure 3).

Flow duration curve

The seventeen years flow duration curve in Figure 4 is to be used in deciding what proportion of flow should be used for a particular purpose, as the area under the curve represents the expected water volume if a reservoir is to be constructed across the river at that point.

The volume under the curve has shown that, the proposed water transfer scheme by FMAWR from river Gurara at Jere to lower Usama dam for water supply purpose to the Federal Capital Territory Abuja is very adequate, provided an accurate storage-reservoir yield and capacity study is carried out.

Frequency curve

Frequency curves are very important elements of hydrology, used by water resources engineers to describe both simple and critical behaviour of events during hydro-logical analysis. Therefore, the hydrologist should be able to deduce from the curve trend, either negative or positive behaviour of an event, which will depend on the expected result. The seventeen years discharge fre-quency curve in Figure 5, has shown same behavioural trend which can be interpreted as:

1) The seventeen years estimated discharge from the available gauge height, can be said to be fairly reliable, because the 1986, 1998 and 2000 year flood can clearly be deduced from the curve.
2) The low rainfall experienced in 1981, 1985, 1987 and 1989 can equally be deduced from the curve.

Figure 6 shows six years hydrograph (1981, 1985, 1986, 1987, 1998 and 2000) with low flows in 1981, 1985 and 1987 and high flows in 1986, 1998 and 2000. The maximum discharge experienced in low flow years falls

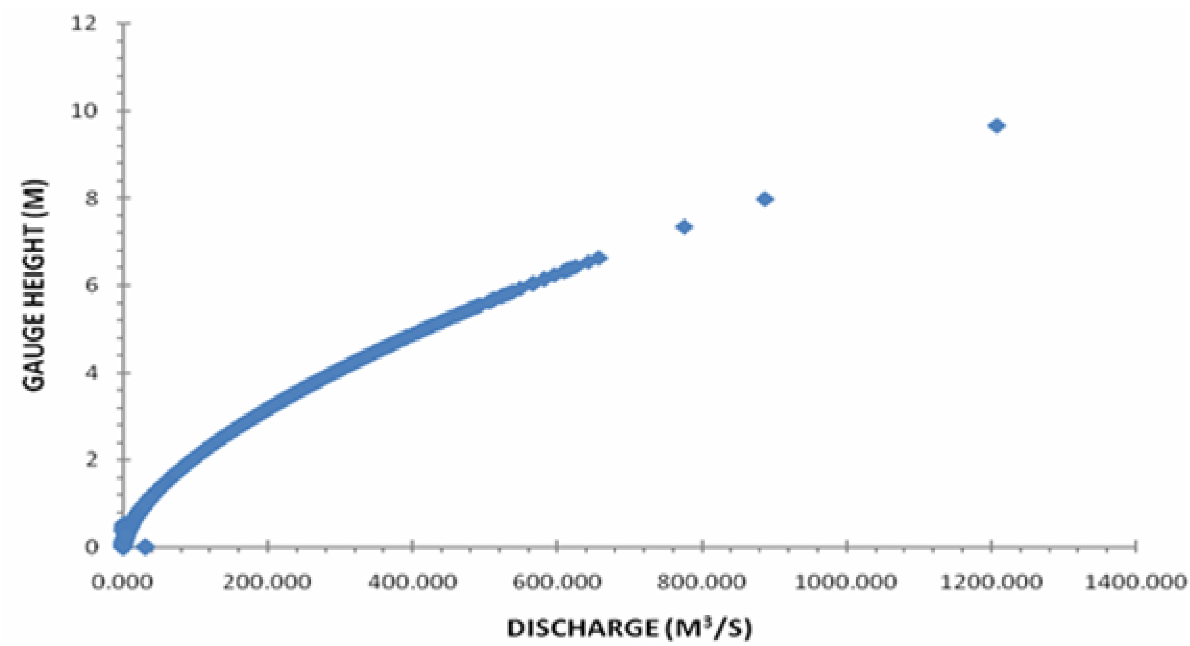

Figure 3. Seventeen years rating curve of Gurara River at Jere.

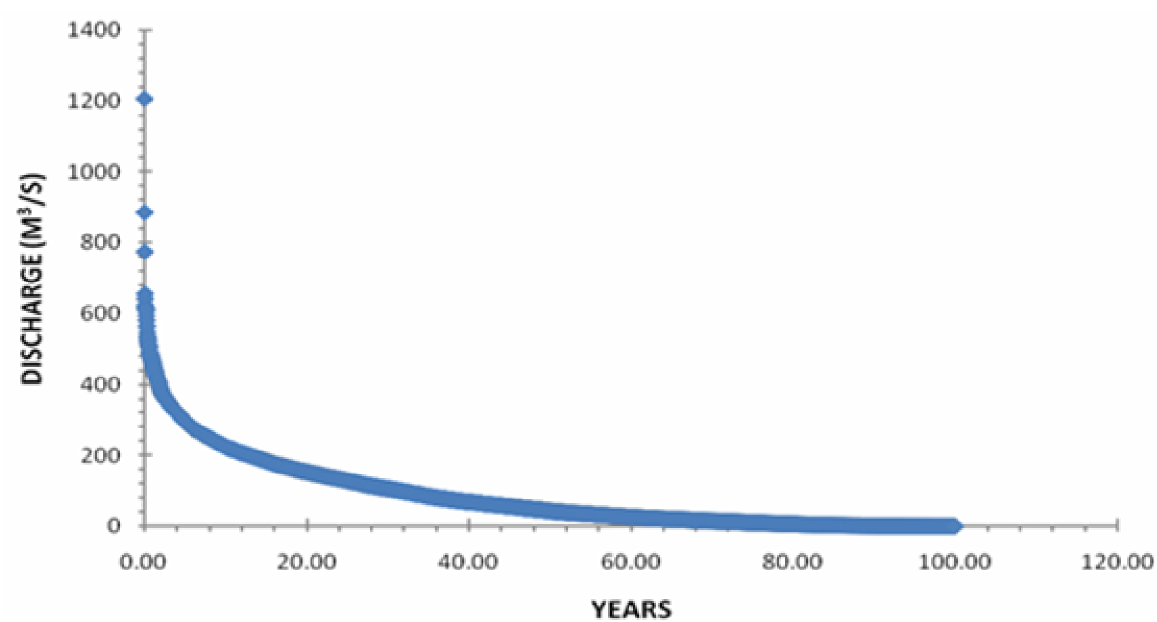

Figure 4. Seventeen years flow duration curve of River Gurara at Jere

between 350 and 400 m^3/s, while the maximum discharge of high flow years falls between 600 and 1300 m^3/s in the seventeen years record.

The high flow experienced in the recorded seventeen years, that threatened some villages downstream with flood, as shown in Figure 6, occurred in the 200 and 300 days of the high flow years, which falls within the months of July, August and September.

Fitting distribution

The following distributions reduced variates were used for the fitting trial: Normal, Extreme value type 1, Exponential and Pearson type 3. Three graphs were drawn, one each for Normal and Extreme value type 1 distributions, while the third graph is for Exponential and Pearson type 3 distributions since they operate with the same return

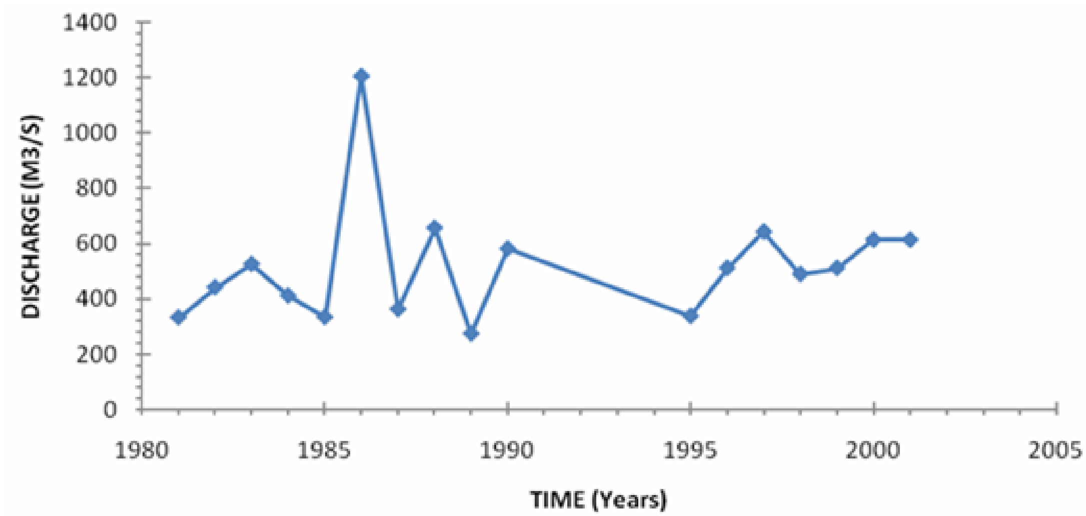

Figure 5. Seventeen years variation of annual discharge at Jere.

period variate.

Figure 7 shows discharge against Normal distribution reduced variate and return period reduced variate of a normal distribution. From the graph, it is shown that normal distribution does not fit the data.

Figure 8 shows discharge against Extreme value type 1 distribution reduced variate and return period reduced variate of an Extreme value type 1 distribution. From this figure it is equally clear that Extreme value type 1 distribution does not fit the data.

Figure 9 shows discharge against Exponential and Pearson type 3 distributions reduced variate and return period reduced variate of the two distributions. From this figure it is clearly shown that only Pearson type 3 distribution fairly fits the data out of the three distributions tested.

Flood frequency analyses

From the above graphs, it has been deduced that Pearson type 3 distributions is the best fit for the data, therefore, to analyse the flood frequency of Gurara River at Jere station, Pearson type 3 distribution was to be applied.

Flood estimation

For twenty years return period

With,

Rp = 20

$$\bar{x} = 399.59$$
$$\delta = 119.46$$
$$g = 2.548$$

$$\gamma = \left({}^{2}\!/_{g} \right)^2 = 0.62$$

$$\beta = {}^{\delta}\!/_{\sqrt{\gamma}} = 152.22$$

$$x_o = \bar{x} - \beta\gamma = 305.84$$

$$G(y) = 1 - \frac{1}{T} = f(y)$$
$$x_T = x_0 + \beta.y$$

$$G(y) = 0.95 = f(y)$$

and,

The corresponding value of 2.996 for the reduced variate (y) on Pearson type 3 was used for the analysis, (NERC, 1975).

Now,

$$X_T = 305.84 + (152.22 * 2.99) \quad X_T = 761.88 m^3 / s$$

For twenty-five years return period

With,

$$G(y) = 0.96$$
$$y = 3.40$$
$$X_T = x_0 + \beta.y$$
$$X_T = 814.88 m^3 / s$$

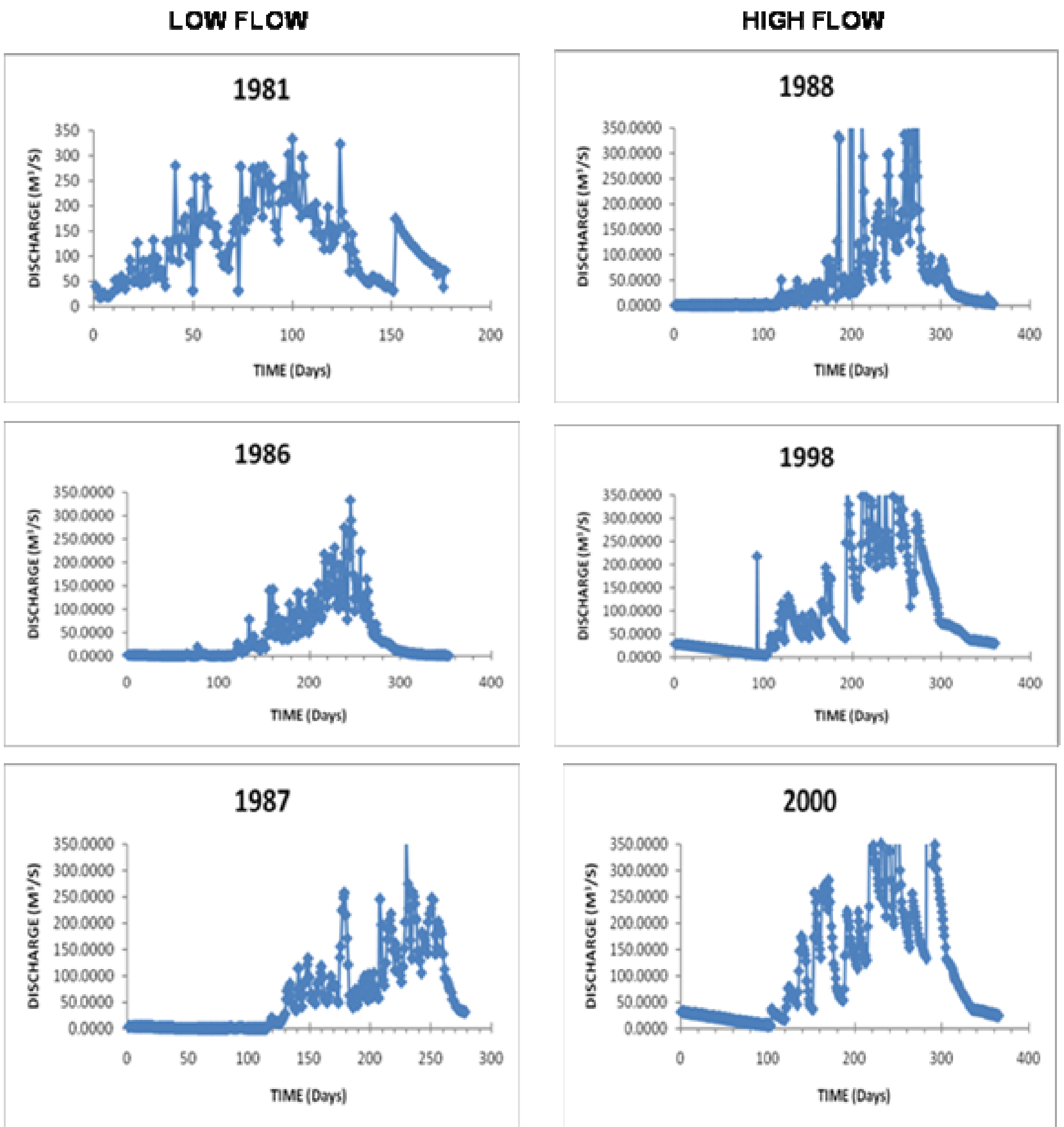

Figure 6. River Gurara discharge at Jere.

For thirty-five years return period

With,

$G(y) = 0.97$

$y = 3.80$

$X_T = x_0 + \beta.y$

$X_T = 872.48 m^3 / s$

For fifty years return period

With,

$G(y) = 0.98$

$y = 4.20$

$X_T = x_0 + \beta.y$

$X_T = 939.74 m^3 / s$

For one hundred years return period

With,

$G(y) = 0.99$

$y = 4.61$

$X_T = x_0 + \beta.y$

$X_T = 1006.79 m^3 / s$

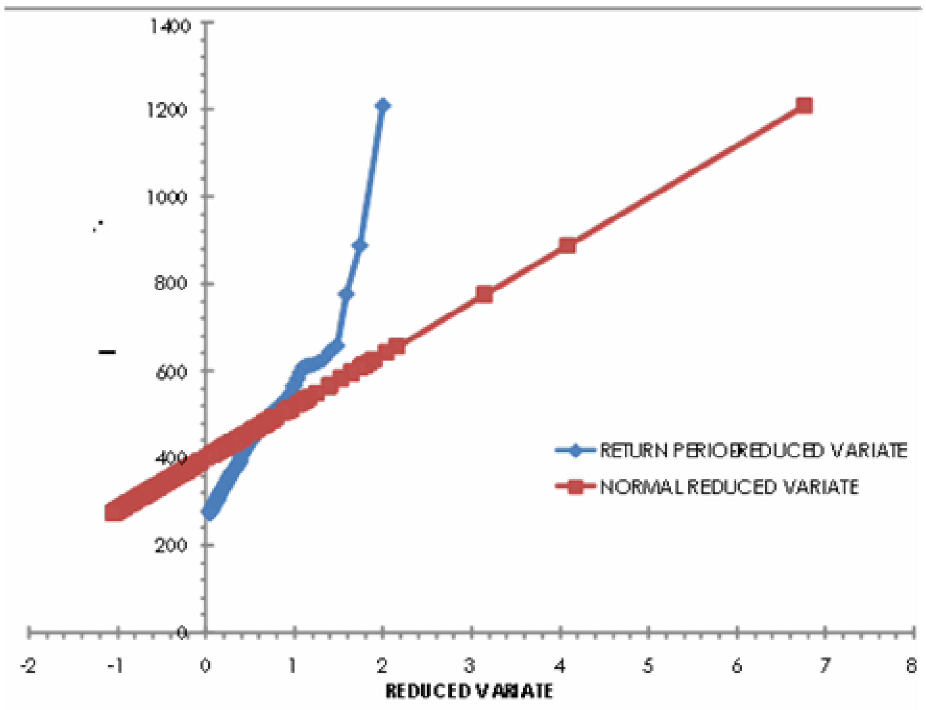

Figure 7. Normal distribution Variate Graph of River Gurara at Jere.

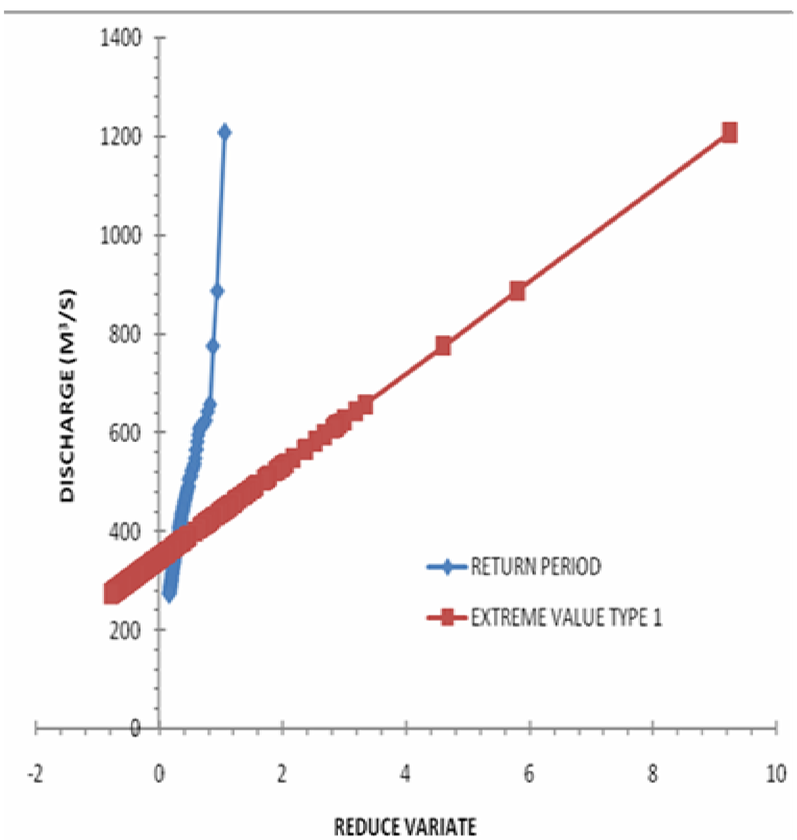

Figure 8. Extreme value type 1 distribution Variate Graph of River Gurara at Jere.

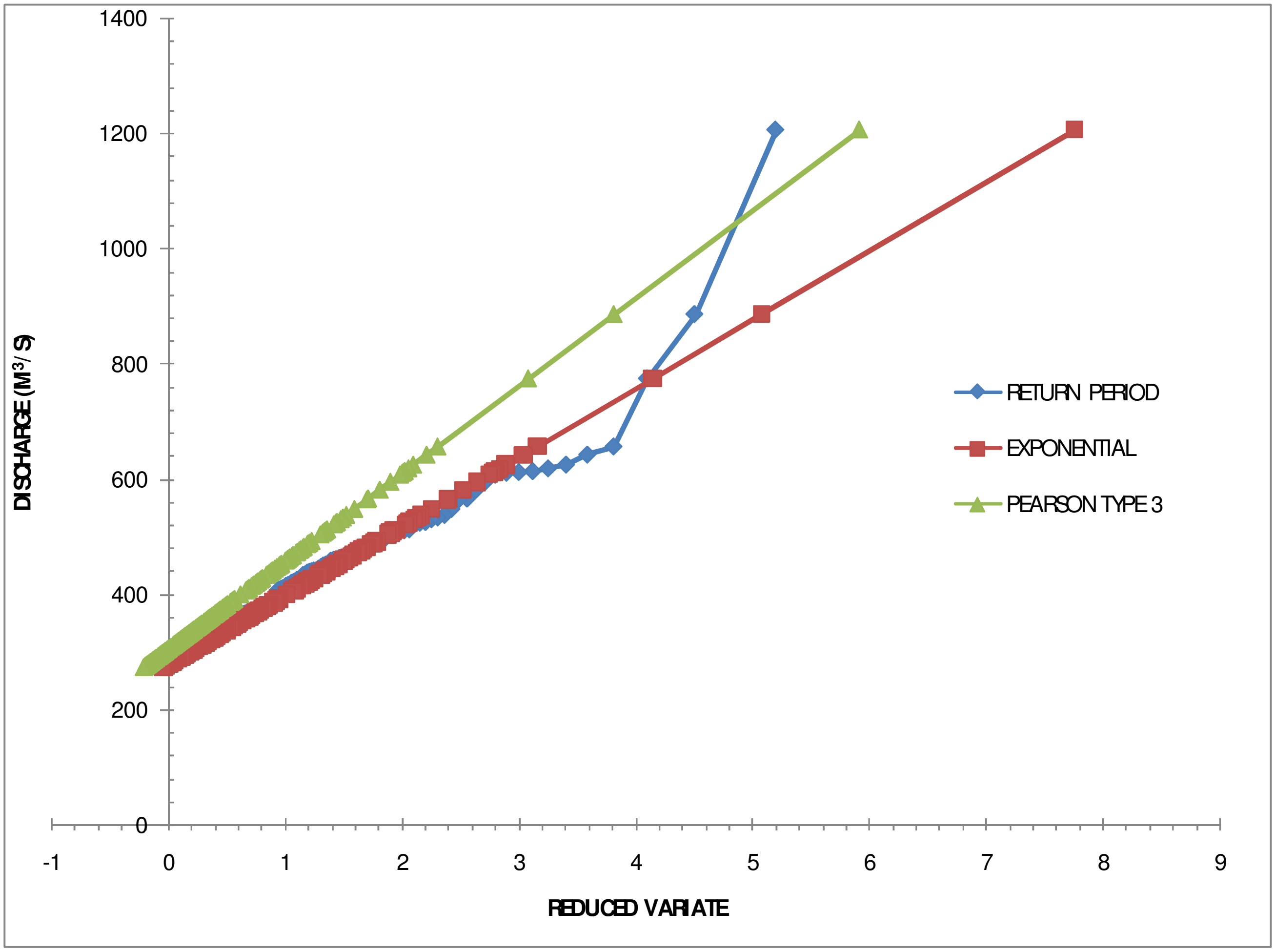

Figure 9. Exponential and Pearson type 3 Distribution Variate Graph of River Gurara at Jere.

For two hundred years return period

With,

$$G(y) = 0.995$$
$$y = 4.63$$
$$X_T = x_0 + \beta.y$$
$$X_T = 1010.59m^3 / s$$

Recurrence interval

The probability J value of flood recurrence in Gurara River catchment for return period of 20, 25, 35, 50, 100 and 200 years in any series of N at 1 to 50 years was graphically illustrated in Figure 10.

Conclusion

The partial duration series (PDS) of seventeen years discharge reading of the Gurara River at Jere station estimated from gauge height readings was fitted to Extreme value type 1, Normal, Exponential and Pearson type-3 distributions. The Pearson type 3 distributions were found to be the best model for the Gurara River at Jere. The Flood Frequency Analyses (FFA) for a return period of 35, 50, 100 and 200 years for the catchment were estimated as 872.48 m^3/s, 939.74 m^3/s, 1006.79 m^3/s and 1010.59 m^3/s, respectively. The results of the FFA generated in this study can be used in flood studies and design of hydraulic structures within the basin and similar catchments.

Recommendations

More gauge stations should be established. Also, the standard of the data recording and storage facilities should be improved upon to enable accurate data generation. The use of automatic gauge and discharge recording equipment should be encouraged to reduce errors caused by human laxity.

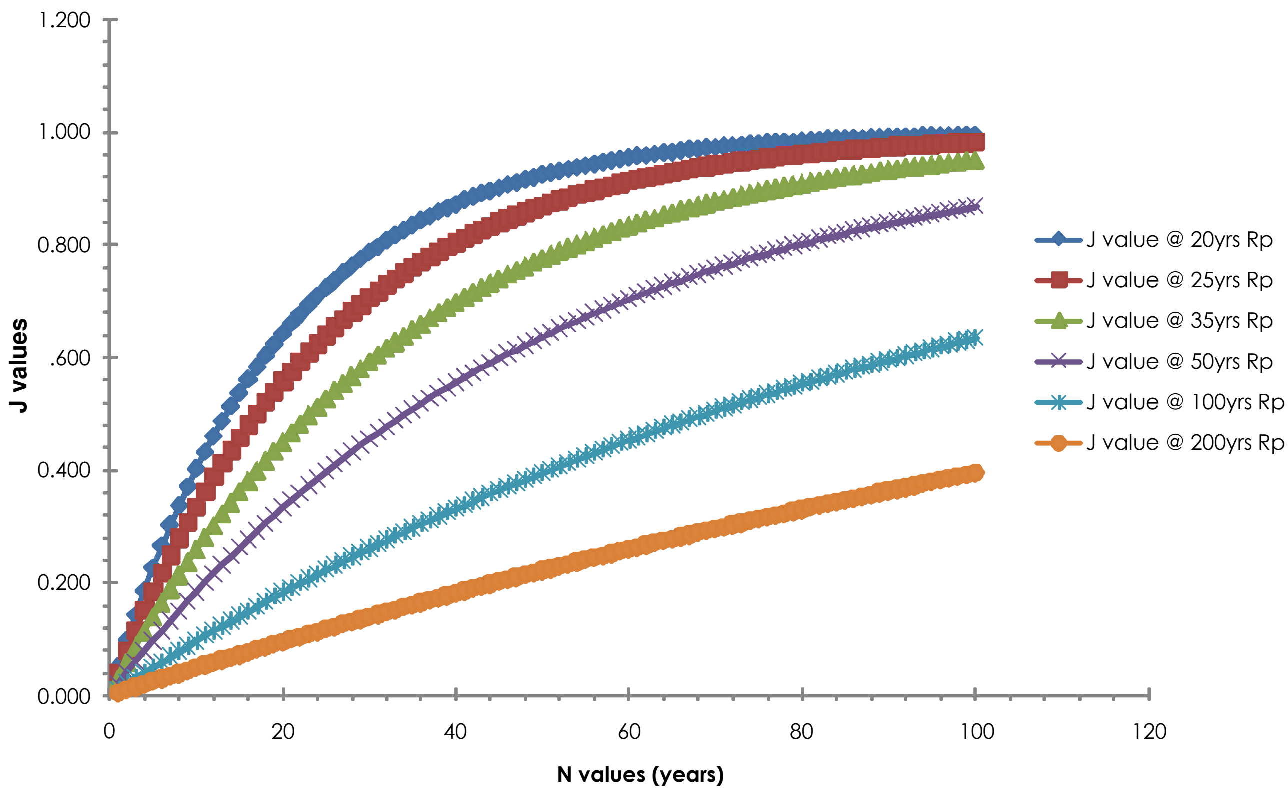

Figure 10. Probability J value of flood recurrence in Gurara River at Jere.

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