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RAINFALL-RUNOFF RELATIONSHIPS AND FLOW FORECASTING, OGUN RIVER, NIGERIA

D.O. Olukanni[1]
M.O. Alatise[2]

[1]Department of Civil Engineering, Covenant University, 0ta, Ogun State, Nigeria
[2]Department of Agric. Engineering, Federal University of Technology, Akure, Ondo State, Nigeria

An excess or a lack of rainfall are the major causes of most hydrological hazards, and the need for a systematic approach to river flow forecasting based on rainfall is imperative, especially in Nigeria. A study was carried out on three major gauging stations of the Ogun river basin to determine the rainfall-discharge relationship and model equations for use in the basin and similar basins. Stream flow and rainfall data for at least seven consecutive years for each station were collected and analyzed. The rainfall-runoff data were subjected to linear, exponential and higher order analysis. Stream flow data were also fitted to normal, log-normal and log-Pearson Type III distributions. The selection of the appropriate probability distribution model for each gauging station was based on graphical comparisons between observed and predicted flows and goodness-of-fit tests using chi-square and probability correlation coefficients. Results show that model equations with logarithmic and exponential relationships between rainfall and discharge gave better and more realistic prediction estimates and can be used for the basin. It was determined that the peak discharges occurred when the rainfall values were at their maximum, and a distinct relationship between the discharge and rainfall exists at each of the gauging stations.

INTRODUCTION

Throughout history, the prosperity of nations has always been known to correlate very closely with the management of water resources while the well-being of future generations depends largely on its wise management. It is also known that precipitation, one of the important components of the hydrologic cycle, is the primary source of fresh water supply and its records are the basis of most studies dealing with water supply in all its forms, floods and droughts. The process of linking rainfall and river flow is a deterministic one, in that it is governed by definite physical laws which are known.

The solution to this problem involves the application of these laws to the measured rainfall and the boundary conditions, that is, the physical description of the catchment and the initial distribution within it. Applying exact laws to appropriate boundary conditions with limited ranges of variables encountered would achieve very little since a basin is not a random assembly of different parts, but a geomorphological system whose parts are related to each other by a long common history.

It has also been observed that of all the hydrometeorological data, rainfall data are most readily available and have been collected for longest periods.

In Nigeria, it is of considerable concern that of the several relevant government agencies established for hydrological and meteorological data collection, none of them have any up-to-date data for the last ten years. The reasons are clear and include (i) poor, nonfunctional and obsolete equipment and instruments, (ii) poor funding, (iii) lack of dedicated and committed personnel, (iv) lack of focus and direction, (v) lack of education, and (vii) poverty, all conditions that are common throughout Africa.

Although a vast amount of literature exists on the selection of an appropriate probability distribution for annual maximum flood flows, few studies have examined which probability distribution are most suitable to fit sequences of annual minimum stream flows (Vogel and Kroll, 1989).

Therefore, the question of a better fit among these countless models is always a fresh one, and many studies with this theme have been conducted (Topaloglu, 2002).

The statistical inferences of rainfall are essentially independent of location within a region and are similar in many parts of the world. Analysis of short-term rainfall data suggest that there is a reasonably stable relationship governing the characteristics of the rainfall (Reining, 1989). This relationship appears to be independent of the long-term average rainfall at a particular location. The concept of design rainfall has often been used to characterize a runoff event, and generation which is defined as the total amount of rain which will provide sufficient runoff to generate discharge to satisfy water requirements.

Although meteorological satellites and early flood warning systems exist, the dates of occurrence and magnitudes of extreme events cannot be predicted accurately. Frequency analysis is an established method for determining critical design discharge for small to moderate sized hydraulic structures (Haktanir, 1992).

This paper addresses the rainfall-discharge relationships and flow forecasting at three major gauging stations in the Ogun river basin.

The objectives of the study are to:

(i) Determine the rainfall-discharge relationship for the study area, and

(ii) Ascertain suitable models for use in the Ogun and similar basins

RESEARCH METHODOLOGY

Data Collection

The study was carried out on three major rivers in the Ogun river basin located within latitude 6^o 33' and 8^o 58'N and longitude 2^o 40' and 4^o 10'E.

Hydrological and hydrometeorological data consisting of stream flow/discharge, water level/ stage, and rainfall for the Ogun river basin at Ajura, Ijaka-Oke, and Yewa-Mata gauging stations spanning (7,18,11), (18,23,20), and (14,18,21) years respectively were obtained from the Ogun River Basin and Rural Development Authority, Abeokuta, Ogun State, Nigeria (1980).

The hydro-met data collected for the three sub-basins as shown in Table 1 were then analyzed.

Data Analysis and Evaluation of Probability Distribution Models

The annual discharges, their corresponding gauge heights and rainfalls for each year were evaluated. The selected annual discharges were ranked in descending order of magnitude to form an annual maximum series (AMS) based on the recommendation of the U.S Water Resources Council Bulletin (1981).

Three statistical methods were fitted to the ranked annual discharges at Ajura, Ijaka-Oke and Yewa-Mata gauging stations namely; normal (N), log-normal (LN) and log-Pearson type III (LP) distributions. A skew coefficient of zero was assumed for both the N and LN distributions. The parameters of the distributions were estimated by method of moments (Van-Thanh et al., 1989)

For the LP distribution, the skew coefficient of the log transforms of the annual discharges, the mean and the standard deviation were determined.

The frequency factor k^1 was determined using the LP distribution table. The calculated skew coefficient was used in determining the frequency factors, and the LP distribution model was fitted on each observed annual discharges to get the expected discharges (Wilson, 1990; Viessman and Lewis, 1996).

The fit is usually determined by means of criteria depending on the differences between the observed and the expected (theoretical) distributions (Kottegoda, 1980).

To ascertain the best probability model for each of the stations, two goodness-of-fit tests were used to evaluate the suitability of different probability distributions.

Table 1. Summary of data collected at gauging stations in the Ogun River basin.

Data	Ajura	Ijaka-Oke	Yewa-Mata
Rainfall (mm)	1983-1994	1984-2003	1983-2003
Gauge height (m)	1981-2000	1980-2002	1983-2001
River Discharge(m^3/s)	1981-1987	1980-1997	1982-1995

The most popular chi-square and the probability plot correlation coefficient goodness-of-fit tests were chosen for they are the ones currently in use by several agencies and they fit in perfectly for the number of observations that are available at the gauging stations (Onoz and Bayazit, 1995). This gives the two test statistics an advantage over others. The chi square statistic is explained further because of its detailed features.

Chi-squared test (χ^2test)

In this classical goodness-of-fit test, frequencies of the observed events in a number of class intervals were compared with their expected value for a given distribution function with parameters estimated from the sample.

The test statistic is based on the sum of the squares of the difference between the observed and the expected frequencies (Onoz and Bayazit, 1995).

The smaller the value of the chi-squared statistic, the better the expected fit of the model to the sample at hand and the larger the value of the chi-square, the greater the discrepancy between the observed and expected frequencies.

The set of possible events E_1, E_2, $E3$,..., E_k in years that occurred with the frequency discharges O_1, O_2, O_3,...,O_k, are called the observed frequencies and according to probability rules, are expected to occur with frequencies e_1, e_2, $e_{3,...,}$ $e_{k,}$ known as the expected or calculated frequency.

The equation applied is given as

$$\chi^2 = \frac{(o_1 - e_1)^2}{e_1} + \frac{(o_2 - e_2)^2}{e_2} + ...+ \frac{(o_k - e_k)^2}{e_k} = \sum_{j=1}^{k} \frac{(NO_j - NE_j)^2}{NE_J} \tag{1}$$

where NO_j and NE_j are the number of elements in the *i*th subinterval of the observed and expected frequencies, which are sliced into *K* subdivisions.

The statistic computed by Equation (1) approximately obeys a chi-squared distribution with a degree of freedom (*DOF*) defined as

$$DOF = k\text{-}1\text{-}mp \tag{2}$$

where *k* is the number of parameters present in the model. Classically, the confidence interval is computed with this DOF, and the adopted model is said to be acceptable if the chi-squared value calculated with Equation (1) is within this interval (Haktanir, 1991).

In this study χ^2/χ^2_{005} values were determined for the probability functions. A value of the ratio χ^2/χ^2_{005} smaller than one shows that the hypothesized distribution is accepted at that site at the 5% level of significance. The χ^2 test is highly sensitive to the location of the data near the class limits and small errors in the parameters of the distribution or observed data value may have significant effects on the test results. The model that gives a value very close value to 1 is the best distribution model for that gauging station.

Probability plot correlation coefficient (PPCC) test

This test uses the correlation coefficient (r^2) between the ordered observations and the inverse value of the hypothesized cumulative function. It evaluates the linearity of the probability plot so that if the sample is actually drawn from the hypothesized distribution, $r_{0.05}/r$ is expected to be close to 1. Values of the ratio smaller than one correspond to the acceptance of that distribution at the 5% level significance.

In applying the PPCC test, the Filliben plotting formula was used for N. This test is known to be more powerful than the chi-square test, (Onoz and Bayazit, 1995). It would be emphasized that in every case, the computed value r, measures the goodness of fit between the equation actually assumed and the data. It does not necessary indicate a direct dependence of the variable since the observed value and the expected value are directly related.

The quantity r, called the coefficient of correlation is given by

$$r = \pm\sqrt{\frac{\text{explained variation}}{\text{total variation}}} = \pm\sqrt{\frac{\sum\left(Y_{est} - \overline{Y}\right)^2}{\sum\left(Y - \overline{Y}\right)^2}} \qquad (3)$$

and varies between -1 and +1. The + and – signs are used for positive linear correlation and negative linear correlation, respectively.

If there is zero explained variation, this ratio is 0 and if there is zero unexplained variation, the ratio is 1. In other cases the ratio lies between 0 and 1. Since the ratio is always non negative, it is denoted by r^2, known as the coefficient of determination.

Values of the ratio $r_{0.05}/r$ smaller than 1 correspond to the acceptance of that distribution at the 5% level of significance.

Grade of correlation

Excellent	0.75-1.00
Good	0.50-0.75
Weak	less than 0.50.

The PPCC can be useful in deciding which distributional family is most appropriate and the best fit will be indicated. It has been widely used in hydrology as an aid to assess the goodness of fit of alternative distributions.

RESULTS AND DISCUSSION

Rainfall-Discharge for the Ogun River Basin

Table 2 shows the mean annual rainfall and mean annual discharge for the periods of record with their coefficients of variation for the three major sub-basins.

The lower the coefficient of variation, the more reliable is the mean annual rainfall and mean annual discharge obtained. This implies that the Ijaka-Oke sub-basin gives the most reliable mean annual rainfall, followed by the Ajura sub-basin, while the Yewa-Mata sub-basin has the least reliable data. With regards to discharge, Ajura gives the most reliable mean annual discharge followed by Yewa-Mata and Ijaka-Oke.

Rainfall Variability Across the Sub-basins During Periods of Record

Figure 1 shows rainfall against water years for the three sub-basins. Rainfall varied from year to year in each of the sub-basins, but the variation was greatest in the Yewa-Mata sub-basin. It has high rainfall between 1986 and 1989; 1996 and 1999 and low rainfall in 1983, 1986 and 1994. A significant variation was also observed for the Ajura sub-basin, with high rainfall between 1990 and 1996 and in 1999.

Table 2. Rainfall-discharge for the sub-basins.

	Ajura 1983-1994	Ijaka-Oke 1984-2003	Yewa-Mata 1983-2003
Mean annual rainfall(mm)	1425.11	1003.83	1424.78
Coefficient of variation	0.182	0.129	0.331
	1981-1987	1980-1997	1982-1995
Mean annual discharge(m3/s)	53.360	3.154	9.680
Coefficient of variation	0.278	1.313	0.896

Rainfall is generally uniform and highest at Ajura while Ijaka-Oke receives the lowest rainfall. A cursory look at the pattern reveals that significantly ($P<0.05$) low rainfalls were recorded in 1983, 1993 and 2003 in all the stations suggesting that frequency of drought may be on the order of 10 years in the sub-basins.

Qualitative Comparison Between Measured and Computed Discharges

Figures 2, 3, and 4 show the N, LN and LP distributions of the observed and computed discharges with respect to the water years for the three major sub-basins. For the Ajura sub-basin, the N and LP distributions of the observed and the computed discharges gave close correlations.

On the other hand, the LN and LP distributions for the observed and computed discharges for Ijaka-Oke sub-basins in Figure 3 gave very close correlations, but the correlation on the N Distribution for the same sub-basin as shown in the Figure 3 is wide.

For the Yewa-Mata sub-basin, the observed and the computed discharge as shown in Figure 4 for the N, LN and LP distributions gave close correlations, but the LP distribution is preferred.

In Figure 2, all the models behave in a similar way over-predicting for most years, and under-predicting in 1985 and 1987 while in Figure 3, all the models also over-predict for most of the years and predict well for the dry years.

However, in Figure 4, the N model slightly over-predicts for most years while the other models predict well for most years.

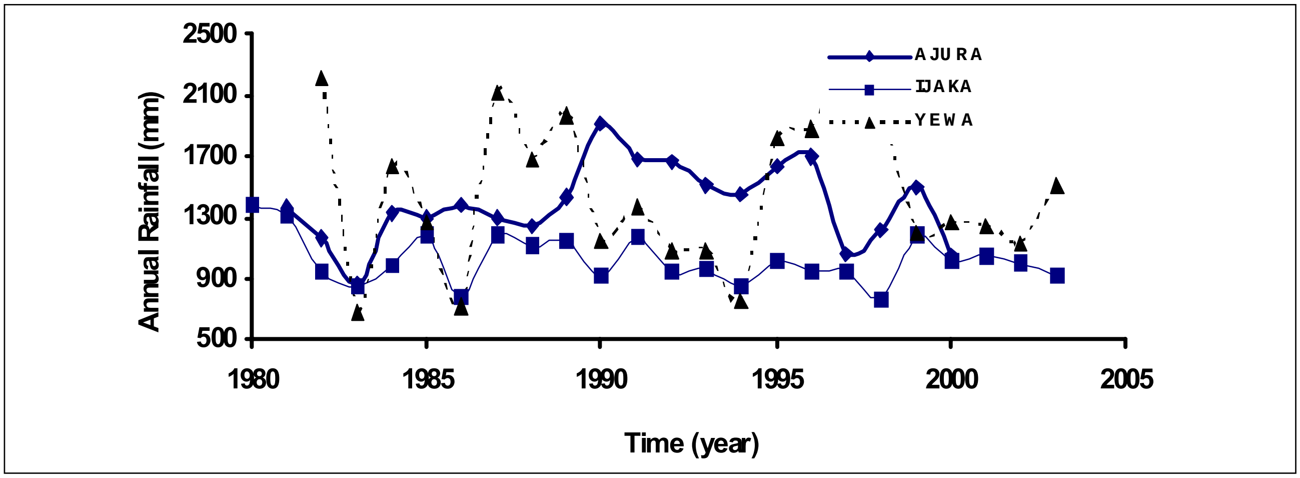

Figure 1. Variation in annual rainfall for Ajura, Ijaka-0ke and Yewa-Mata gauging stations.

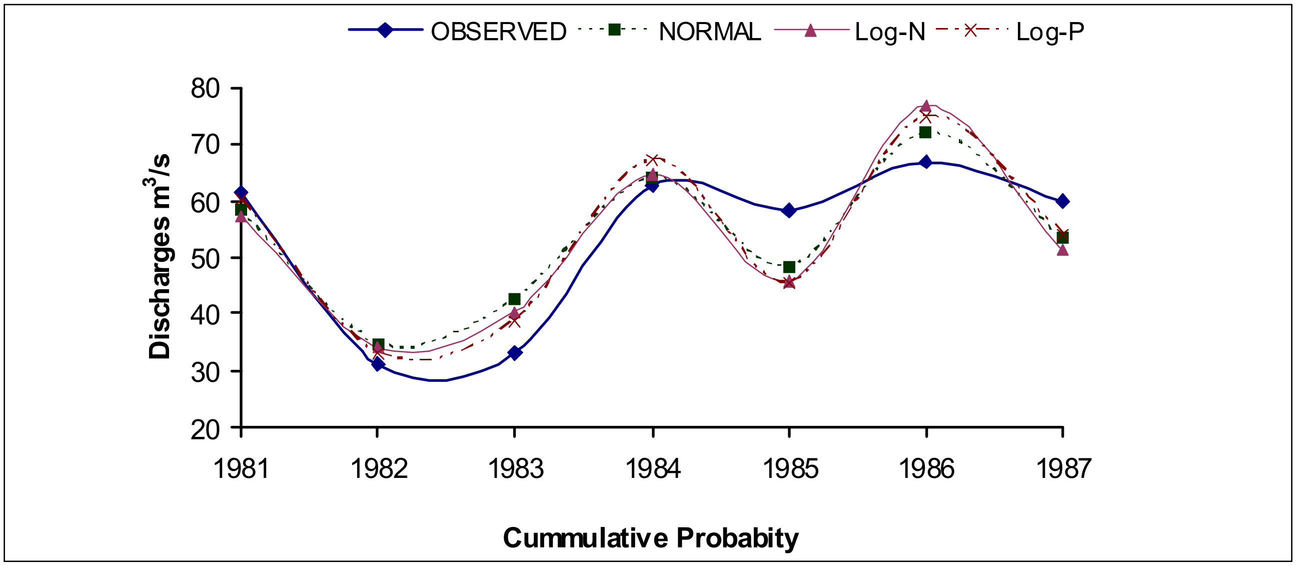

Figure 2. Comparison between observed and predicted discharges at Ajura gauging station.

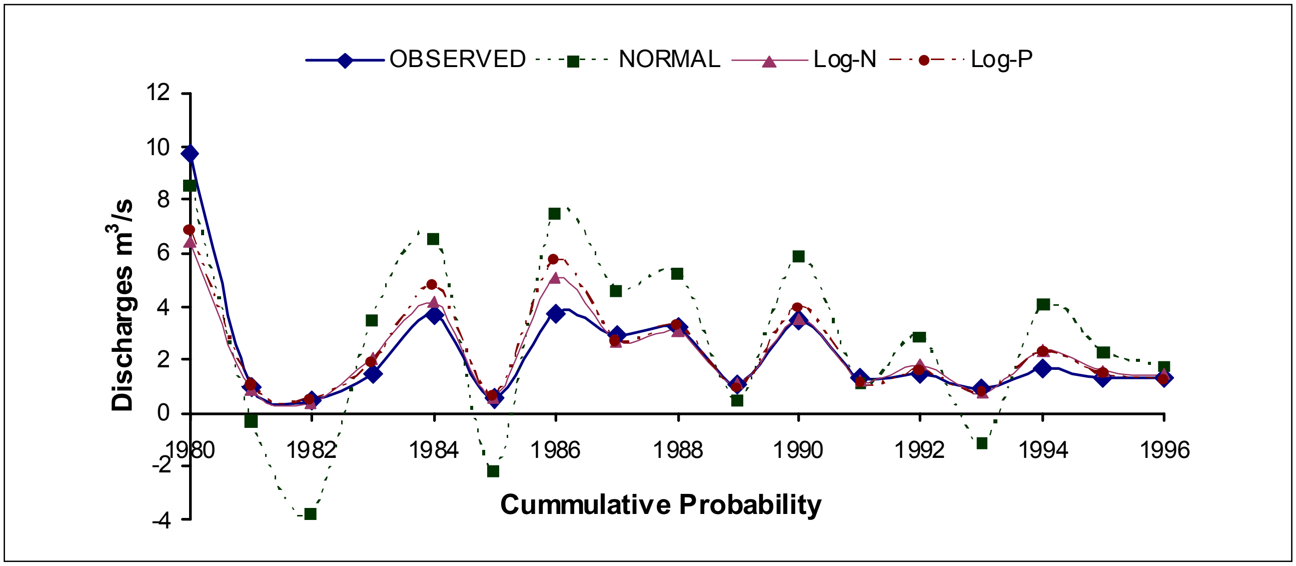

Figure 3. Comparison between observed and predicted discharges at Ijaka-Oke gauging station.

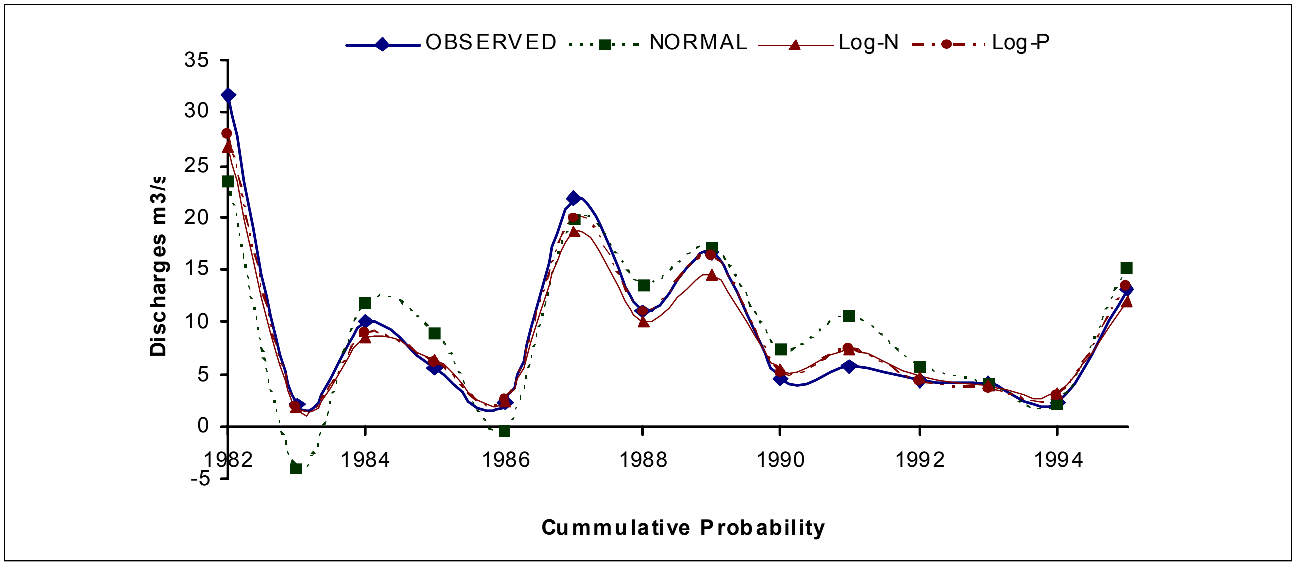

Figure 4. Comparison between observed and predicted discharges at Yewa-Mata gauging station.

It can be seen from the above that the Yewa-Mata sub-basin gave the best correlations for the three distributions, followed by the Ijaka-Oke and Ajura sub-basins.

This assertion is confirmed by the results obtained from the three sub-basins based on the result from the graphs and the goodness of fit tests performed on the models under consideration.

Evaluating Rainfall-Discharge Relationships for the Three Major Sub-basins

Figures 5, 6 and 7 show the rainfall-river stage relationships of the three sub-basins.

For the Ajura, the best relationship is logarithmic with a value of R^2 of 0.58 while for the Ijaka-Oke and Yewa-Mata, it is linear with R^2 values of 0.94 each.

The linear equations and higher coefficients of determination in Figures 6 and 7 for the Ijaka-Oke and Yewa-Mata sub-basins on the rainfall-river stage relationship show that the river stages at these stations responded directly to the rainfall and are thus less dependent on the basin characteristics. The low R^2 values for both the rainfall-discharge and rainfall-stage relationships at Ajura show that there are many basin characteristics that affect the volume of runoff that flows to the river.

Figures 8, 9 and 10 give the rainfall-discharge relationships of the Ajura, Ijaka-Oke and Yewa-Mata sub-basins.

Figure 8 shows a logarithmic relationship as the best relationship between rainfall and discharge for the Ajura sub-basin while Figures 9 and 10 gave an exponential relationship for the Ijaka Oke and Yewa-Mata, with respective R^2 values of 0.68, 0.95, and 0.96. The non-linearity of the discharge-rainfall relationship is not unexpected because the rating curve is usually nonlinear.

It can be seen that the proposed models for Ijaka-Oke and Yewa-Mata with higher coefficients of determination would give more reliable information than that proposed for the Ajura. The difference might be due to catchment characteristics, rainfall distribution patterns and other factors that affect rainfall and discharge.

Quantitative Comparisons Between Measured and Computed Discharges

The annual discharge at the Ajura station has ($\chi^2/\chi^2_{0.05}$) and ($r_{0.05}/r$) values of 8.540 and 1.217 for the N distribution, values of 11.670 and 0.912 for the LN distribution, and values of 18.300 and 0.861 for the LP distribution. From this result, the probability plot correlation coefficient test suggests the LN and LP distributions as the most suitable models for the annual discharge data. The LN and LP show that there is a close linearity between the observed and the predicted discharges.

At the Ijaka-Oke gauging station, the annual discharge has ($\chi^2/\chi^2_{0.05}$) and ($r_{0.05}/r$) values of -0.299 and 1.138 for the N distribution, values of 1.365 and 2.926 for the LN distribution, and values of 0.992 and 2.198 for the LP distribution. From this result chi-square test shows that the LP model is the most suitable for the Ijaka-Oke Station.

The annual discharge at the Yewa-Mata gauging station has ($\chi^2/\chi^2_{0.05}$) and ($r_{0.05}/r$) values of -4.236 and 1.146 for the N distribution, values of 0.670 and 1.397 for the LN distribution, and values of 0.360 and 1.195 for the LP distribution. The chi-square test suggests that the LN distribution is the most appropriate for the Yewa-Mata station followed by LP which is seen to be very weak. The probability plot correlation coefficient test did not satisfy the condition for selecting any model. Hence, it will be assumed that the LN distribution is the most suitable model for that station.

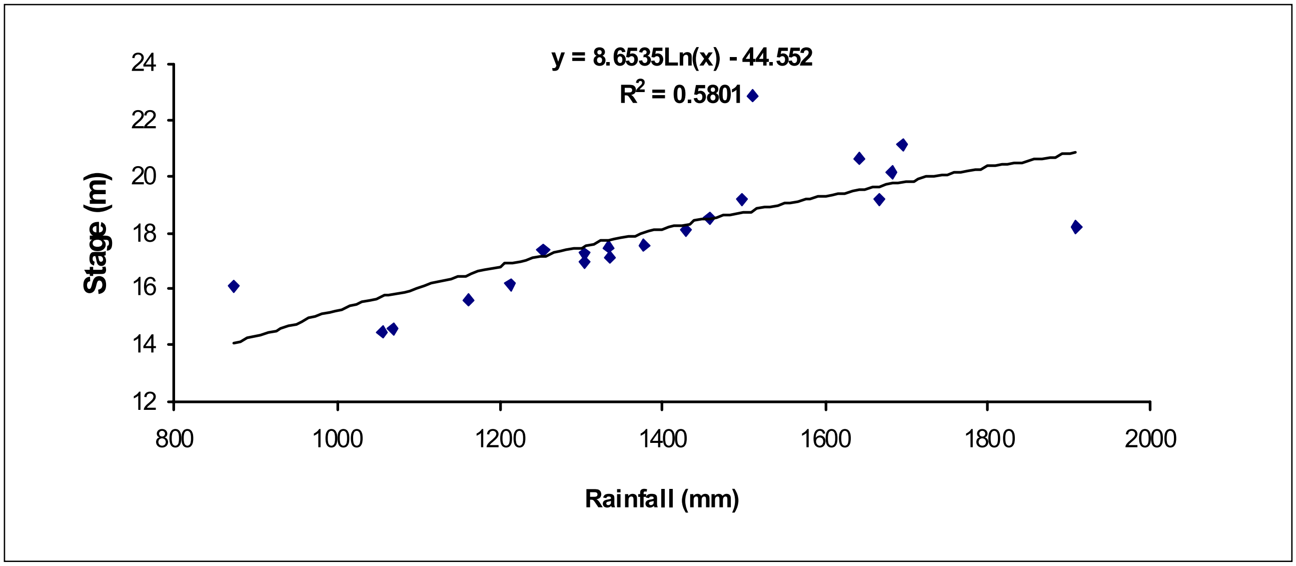

Figure 5. Graph of water level versus rainfall for Ajura station.

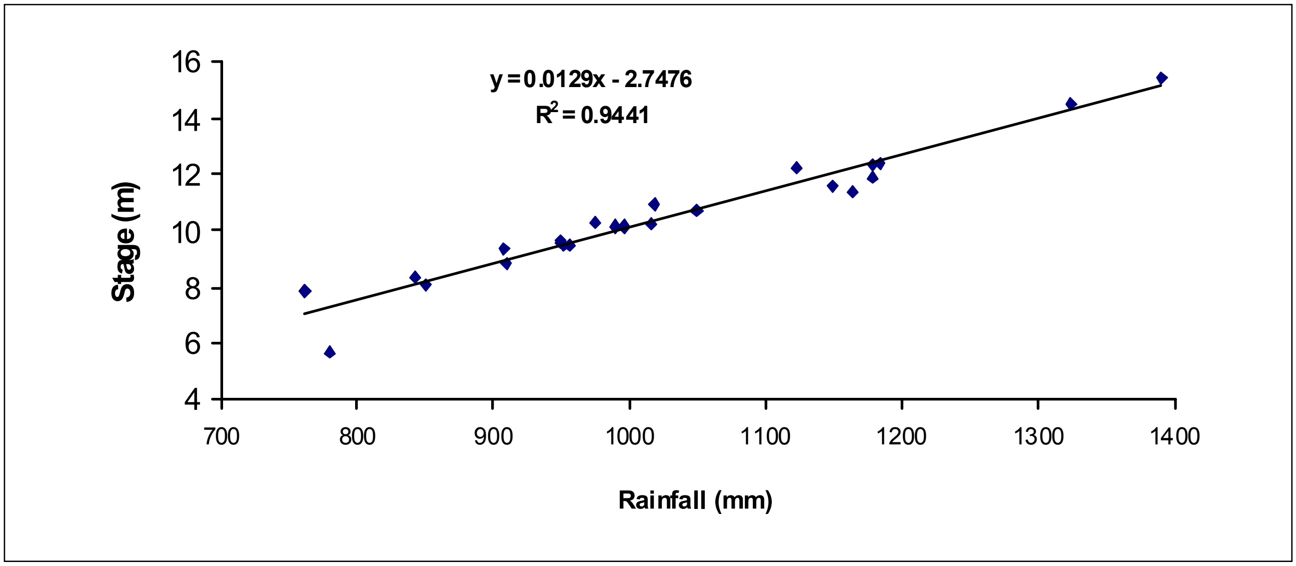

Figure 6. Graph of water level versus rainfall for Ijaka-Oke station.

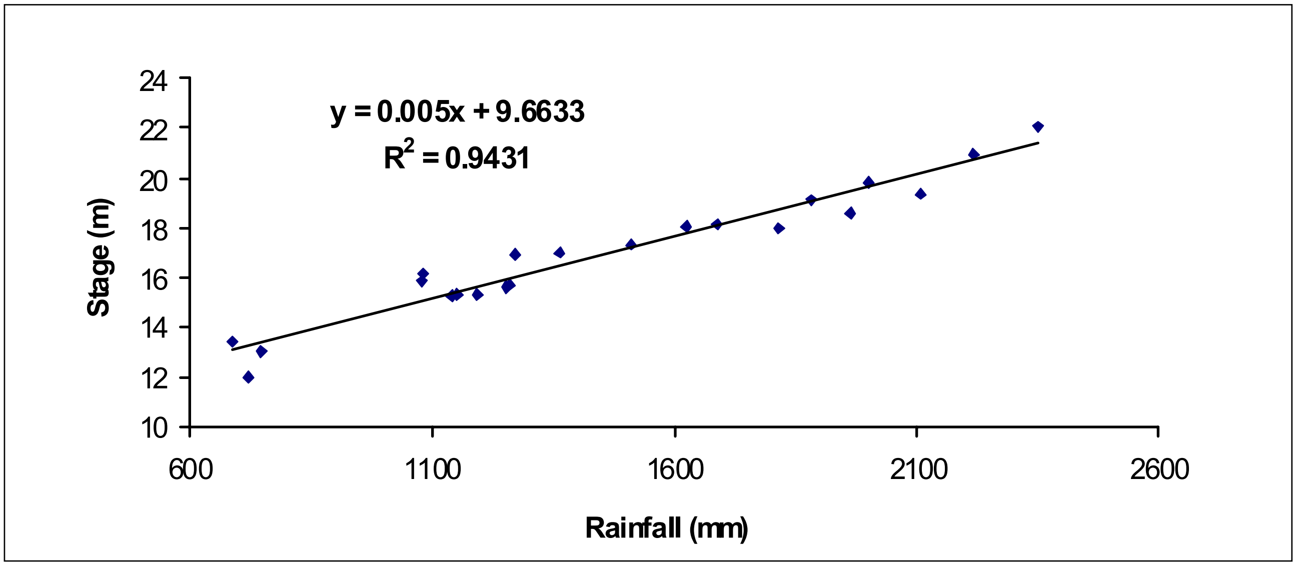

Figure 7. Graph of water level versus rainfall for Yewa-Mata station.

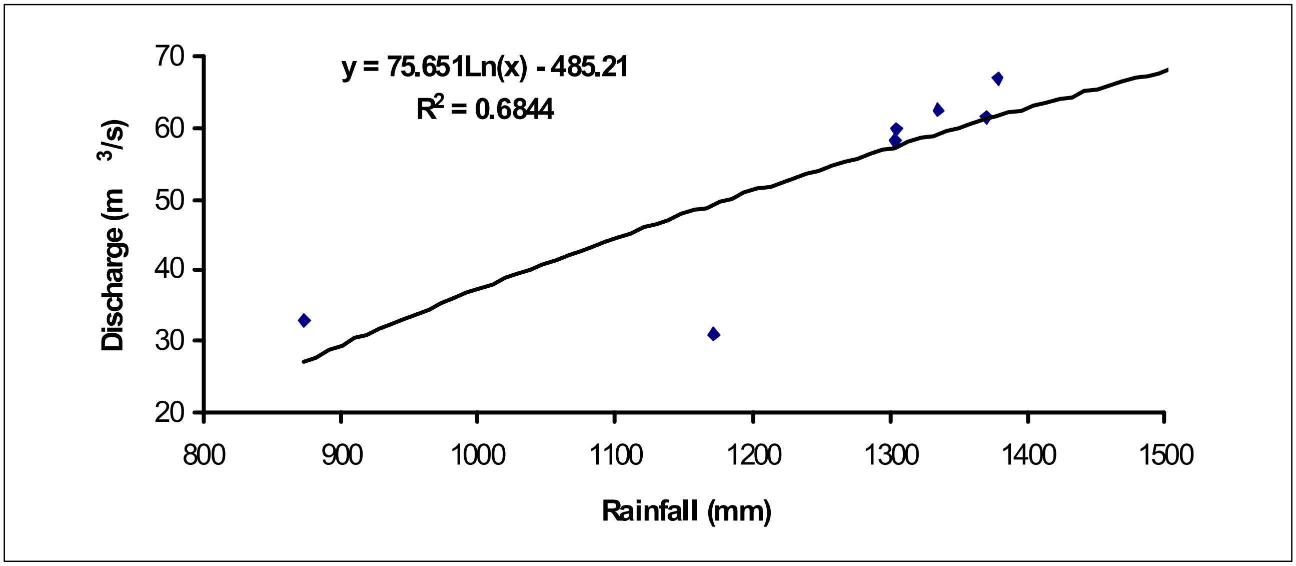

Figure 8. Rainfall-discharge relationships for Ajura station.

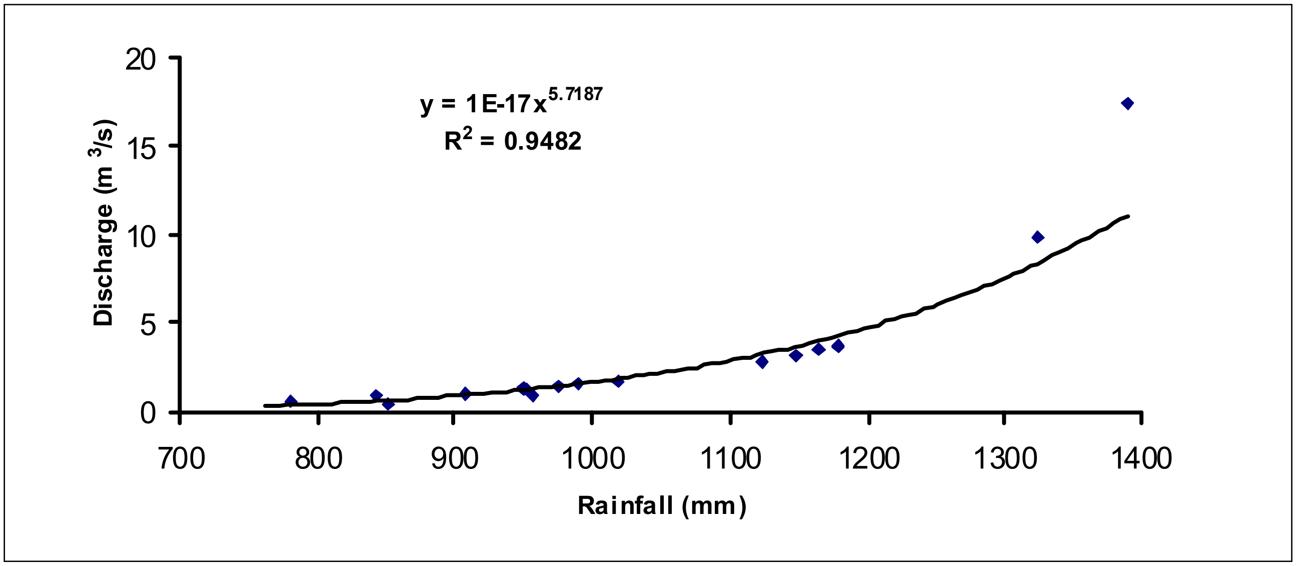

Figure 9. Rainfall-discharge relationships for Ijaka-Oke station.

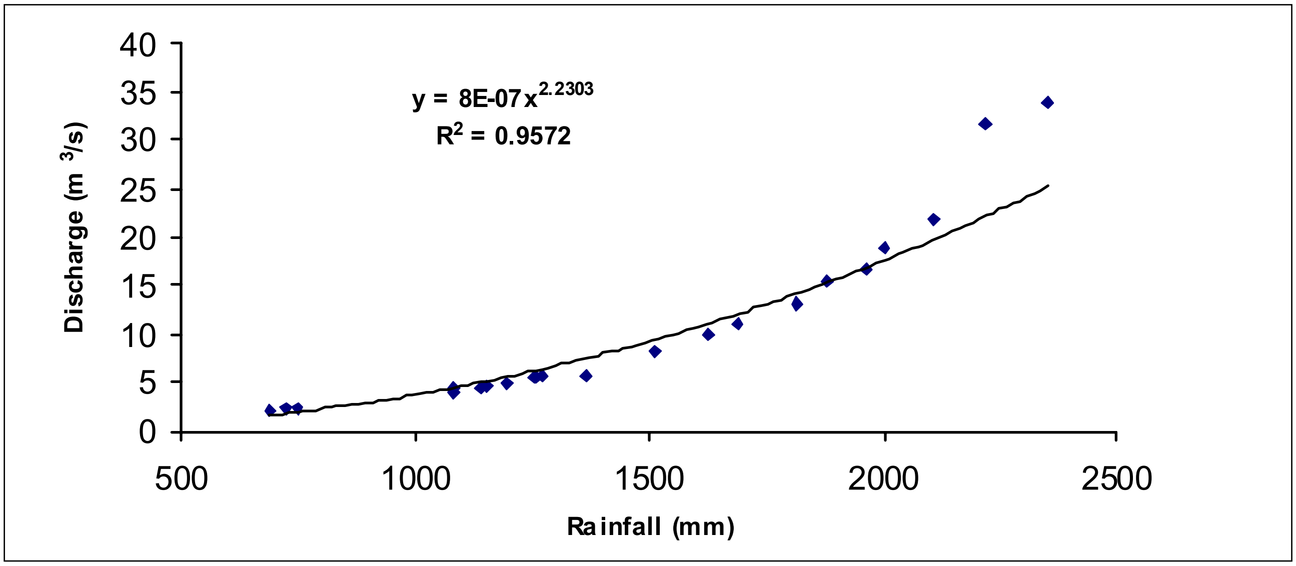

Figure 10. Rainfall-discharge relationships for Yewa-Mata station.

From the above, both from the plotted curves in Figures 2 to 10, and the test statistics, it can be stated clearly that the LN and LP distributions are the most appropriate for the Ajura gauging station. The equations are

LN $\log Q_T = 1.7095 + 0.138k$

LP $\log Q_T = 1.7095 + 0.138k^1$

Also for the Ijaka-Oke gauging station, the LN and LP are the most appropriate and the equations are

LN $\log Q_T = -0.2896 + 0.415k$

LP $\log Q_T = -0.2896 + 0.415k^1$

For the Yewa-Mata gauging station, the same LN and LP distribution is the most appropriate and the equations are

LN $\log Q_T = 0.8364 + 0.385k$

LP $\log Q_T = 0.8364 + 0.385k^1$

A similar better performance by the LN and LP was observed by Beard (1974); McMahon and Srikanthan (1981), Gunasekara and Cunnane (1991); and Vogel et al. (1993).

CONCLUSION

Rainfall, discharge, and stage data spanning several years were obtained and analyzed for three major sub-basins of the Ogun river, Nigeria.

The model equations determined for the rainfall-discharge and rainfall-stage relationships for each sub-basin were based on the graphical results and the goodness-of-fit tests. The annual flow data were fitted to the N, LN and LP distribution models.

The stage-rainfall relationship for the Ijaka-Oke and Yewa-Mata were well represented by a linear equation while that of the Ajura was best represented by a logarithmic equation. On the other hand, the runoff-rainfall relationships for the Ijaka-Oke and Yewa-Mata were well represented by exponential equations while that for Ajura was fairly well represented by a logarithmic equation. Among the three distributions applied in this study, the annual runoff was best predicted by the LN and LP distributions because they appear better at all three stations. In some cases the LN distribution performs better than the LP distribution. However the LP distribution was the most appropriate at the Ijaka-Oke station.

It is concluded that the stage-discharge at Ijaka-Oke and Yewa-Mata can be easily obtained from the developed equations. However, a detention coefficient needs to be included in estimation of stage or discharge at Ajura. The LN model is recommended for estimation of annual flow in the Ogun river basin.

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ADDRESS FOR CORRESPONDENCE
D.O. Olukanni
Department of Civil Engineering
Covenant University
P.M.B 1023 0ta, Ogun State
Nigeria

Email: oluisone@yahoo.com