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Flood Frequency Analysis Based on Gumbel's Distribution Method: A Study of Makurdi Catchment of the Benue River, Benue State, Nigeria

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Abstract

Flood frequency analysis and prediction are crucial in hydrology, estimating flood probability for water resource infrastructure design and management. This presents result of frequency analysis and prediction of future peak flow of the Benue River using the Gumbel's distribution method which is one of the probability distribution methods used to model stream flows. The method was used to model the annual maximum discharge of the river from Makurdi hydrological station for a period of 36 years (1988 to 2023). Regression analysis was used to test the suitability of the method, and to predict the future peak discharge for every return period. The R^2value obtained (0.978) shows that, Gumbel distribution is suitable for predicting the expected discharge in the study area. The result also revealed that, 2, 20 and 100 years flood with the exceedence probability of 0.5, 0.05, and 0.01, have expected peak flood values of approximately 11528.5, 15354.7 and 17750 meter cube per second respectively. The frequency curve at 95% confidence interval also shows anincreasing trend at progressive recurrence interval, highlighting the potential variability of flood magnitude in the study area. Findings from this study provides useful information for flood risk management in Makurdi and it environ.

KEYWORDS: Flood Frequency Analysis, Gumbel's Distribution Method, Benue River, Makurdi

1. Introduction

Floods have been recognized as one of the most significant natural disasters, posing challenges to the sustainable development of economies and societies globally (Wu & Xue, 2018). In Nigeria and Makurdi area, there has been destruction of properties, displacement of people, and pollution of drinkable water sources (Isma'il & Kersha, 2018). Effective planning and mitigation strategies require reliable data and information, which can be challenging to obtain in many developing regions due to financial, technical, and organizational constraints (Ekeu-wei *et al*., 2020). To address this issue, researchers have explored various approaches, including catchment flood frequency analysis, which utilizes precipitation and or discharge data from the available hydrological station or geospatial sources.

Many studies utilizing advanced techniques like GIS and statistical methods have been utilized to predict flood discharges and extents. Research on the Asa River for instance implemented the Gumbel Extreme Value Distribution method to estimate future flood discharges, aiding in flood risk management (Adebayo & Ogunlela, 2024). Satellite technology has also been employed to monitor flood inundation in the confluence region of Rivers Niger and Benue, highlighting major flooding incidents over a decade (Odiji *et al,* 2024). Flood hazard assessments in Makurdi has also been conducted using integrated GIS analyses with flood frequency predictions, the result revealed an increase in flood inundation extent with progressive recurrence intervals, emphasizing the need for effective flood management strategies (Oyatayo *et al,* 2021). This study however explores the application of Gumbel's distribution method in analyzing flood frequency in Makurdi using peak river discharge data.

2. Study Area & Data Collection

Makurdi is strategically located in the North-Central region of Nigeria, doubling as the headquarters of Makurdi Local Government Area (LGA) and the capital city of Benue State. It covers an area of approximately 937.4 square kilometers, with a population of over 472,000 residents as at 2024, as projected from the 2006 National Populations Commission (Peter*et al*., 2020, and NPC, 2006). It is bounded by Tarka L.G.A to the East, Guma to the North, Gwer – West to the West and Gwer to the South. Makurdi LGA is made up of eleven council wards (Figure 1).

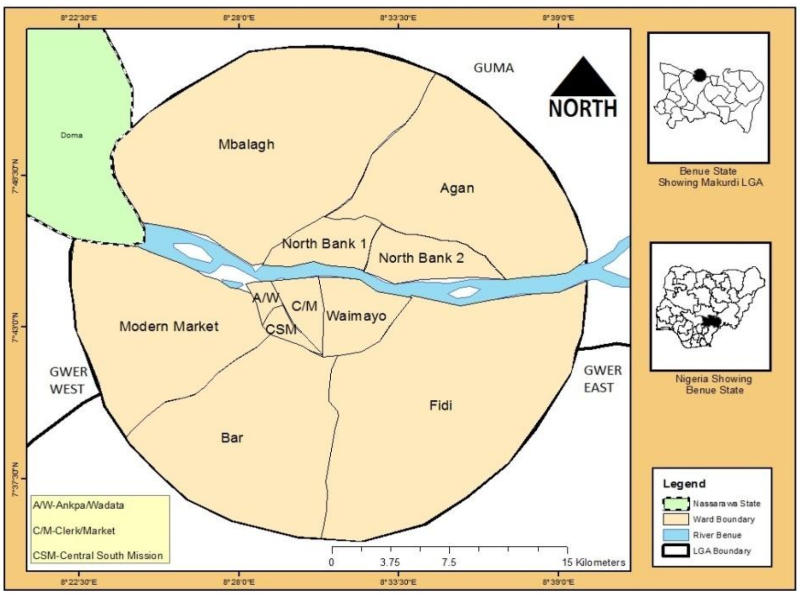

Figure 1: Map of Makurdi showing the Benue River

3. Methodology

The flood frequency analysis of the Benue River at the Makurdi hydro-station was computed using Gumbel's distribution on a 36 years of peak flood data (1988-2023). The process began by ranking the annual peak flood data in descending order. The probability of non-exceedence was then calculated using the formula

$$F = 1\frac{M-0.44}{N_t+0.12} \qquad (4)$$

Incorporating a bias correction factor (-0.44) and a term (0.12) to account for the discrete nature of the data, where (M) is the return period in years and (N_t) is the number of years in the record. This probability was transformed into the reduced variate (Y) using (Y = -Ln(-Ln(F))). The magnitude of extreme flood events was estimated by a linear regression equation involving the reduced variate, (X = AY + B), with the slope (A) and intercept (B) coefficients calculated using the covariance and variance of the dataset. To validate the Gumbel distribution fit, the observed flood data was plotted against the reduced variate and the straightness of the plotted line confirmed the suitability of Gumbel distribution for the data. The inverse cumulative distribution function for estimating the magnitude of flood peaks was from Bhagat (2017) and used, which is given by

$$X^T = A\left(-Ln\left(-Ln\left(1-\frac{1}{T_r}\right)\right)\right) + B \qquad (5)$$

Where: X_T = the quartile (the value of the variable X at a given return period), A and B = the slope and intercept coefficients respectively, estimated from the data. T_r = the return period (the reciprocal of the probability of exceedance) and Ln = the natural logarithm. And the results were presented in tables, and graphs.

4. Results and Discussion

The analysis shows a highest flood risk year in 2012, with a maximum flood flow of 17,418.75 m^3/s. The second-highest flood flow was 14,900 m^3/s in 2018, while the least flow within the 36years temporal period was 7,563.90 m^3/s and was recorded in 1992 (Table 1).

Table 1: Gumbel Goodness of Fit Computation using Least Square Method

Year	Peak Discharge (m^3/s)	Peak Discharge in Descending order (m^3/s)	Rank (m)	Probability of non Exceedence $F = 1\frac{M-0.44}{Nt+0.12}$	Y of Gumbel/ Reduced Variate Y=-Ln.(-Ln.(F))	Gumbel Value Using least square Method X=AY+B
1988	11,398.00	17418.75	1	0.984496124	4.158862738	17101.47388
1989	12,384.00	14900	2	0.956810631	3.12016723	15575.07414
1990	11,684.00	13875	3	0.929125138	2.610308703	14825.81902
1991	11,574.00	13734.8	4	0.901439646	2.265653658	14319.33625
1992	7,563.90	13698.036	5	0.873754153	2.002804756	13933.07051
1993	10,491.95	13697.37	6	0.84606866	1.788835164	13618.63463
1994	13,420.00	13420	7	0.818383167	1.607317001	13351.88728
1995	10,680.00	13236.9	8	0.790697674	1.448852589	13119.01823
1996	9,444.00	13188	9	0.763012182	1.307552379	12911.37258
1997	9,603.60	13051.68	10	0.735326689	1.179474019	12723.1569
1998	11,398.00	12780	11	0.707641196	1.061842367	12550.29304
1999	13,188.00	12463	12	0.679955703	0.952623793	12389.79248
2000	12,102.00	12384	13	0.65227021	0.850277432	12239.39089
2001	9,978.00	12214.75	14	0.624584718	0.753601675	12097.32245
2002	10,509.00	12146	15	0.596899225	0.661634982	11962.17415
2003	11,040.00	12102	16	0.569213732	0.573589209	11832.78777
2004	11,751.50	11751.5	17	0.541528239	0.488803135	11708.19164
2005	12,463.00	11737.167	18	0.513842746	0.406708879	11587.55123
2006	12,780.00	11687.208	19	0.486157254	0.326806702	11470.13216
2007	12,146.00	11684	20	0.458471761	0.248645249	11355.27114
2008	11,737.17	11574	21	0.430786268	0.171805196	11242.35197
2009	12,214.75	11398	22	0.403100775	0.095884791	11130.78425

2010	10,863.58	11398	23	0.375415282	0.020485966	11019.98302
2011	9,512.40	11376	24	0.34772979	-0.054800227	10909.3473
2012	17,418.75	11040	25	0.320044297	-0.13041041	10798.23546
2013	11,687.21	10863.58	26	0.292358804	-0.206829966	10685.93423
2014	13,236.90	10680	27	0.264673311	-0.284621645	10571.6166
2015	13,734.80	10509	28	0.236987818	-0.364467083	10454.28091
2016	13,051.68	10491.95	29	0.209302326	-0.447231002	10332.65641
2017	13,875.00	9978	30	0.181616833	-0.534067111	10205.04768
2018	14,900.00	9877.2	31	0.15393134	-0.626605919	10069.05863
2019	9,877.20	9603.6	32	0.126245847	-0.72731868	9921.057673
2020	11,376.00	9512.4	33	0.098560354	-0.840310441	9755.012289
2021	9,046.88	9444	34	0.070874862	-0.973366275	9559.48204
2022	13698.04	9046.88	35	0.043189369	-1.14491075	9307.391374
2023	13697.37	7563.9	36	0.015503876	-1.427116009	8892.680776
Average:	11820.19	11820.19				

The 36-year mean instantaneous flood flow of 11,820.19 m^3/s indicates moderate long-term increase in flood risk (Table 1).This is in agreement with the findings of Clement (2012) and Oyatayo *et al*., (2021), who also reported that; historical peak flood in Makurdi shows an increasing trend levels. According to them, rising discharge levels contribute to the high extreme flood inundation reported in the study area.

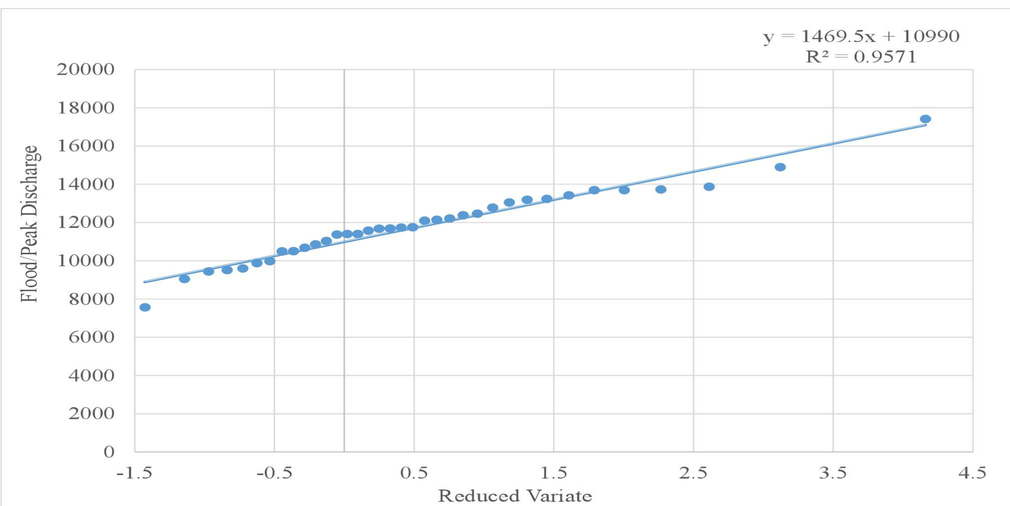

Figure 2: Plot Gumbel Goodness of Fit for Benue River at Makurdi

A plot of reduced variate against flood peak/discharge shows a resulting linear relationship(Y = 1469.5X + 10990), indicating a strong correlation, with high coefficient of variability R^2 = 0.9571 (Figure 2).This suggests that, the Gumbel distribution accurately models Makurdi's flood peak data. This strong correlation implies that the catchment's flood risk is predictable as it follows a consistent pattern, with higher flood peaks corresponding to more extreme events. This is also true for Eke*et al.* (2020), Adebayo & Ogunlela (2024) who reported that Gumbel's distribution is suitable for predicting the expected flow especially when discrete data is involved. Table 3 show the expected floods in the river reach for return periods of 2yrs, 5yrs, 10yrs, 20yrs, 50yrs, 100yrs, 200yrs and 400yrs.

Table 3: Expected Flood Magnitudes, Return Periods and Uncertainty Range

Return Period (years)	Exceedence Probability (%)	Expected Flood (m^3/s)	Margin of Error (m^3/s)	Lower Bound (m^3/s)	Upper Bound (m^3/s)
2	0.5	11528.48	1674.72	9853.76	13203.2
5	0.2	13194.09	1674.72	11519.37	14868.81
10	0.1	14296.87	1674.72	12622.15	15971.59
20	0.05	15354.69	1674.72	13679.97	17029.41
30	0.033	15963.22	1674.72	14288.5	17637.94
50	0.02	16723.92	1674.72	15049.2	18418.64
100	0.01	17749.96	1674.72	16075.24	19424.68
200	0.005	18772.26	1674.72	17197.54	20346.98
300	0.0033	19369.34	1674.72	17794.62	20944.06
400	0.0025	19792.71	1674.72	18117.99	21467.43

The result shows that a 2-year flood with a discharge of 11528.48 m^3/s has a 0.5% probability of exceedance. This indicates that a flood of this magnitude is very likely to occur frequently, posing a significant risk to the surrounding communities. Furthermore, the analysis revealed that a 100-year flood with a discharge of 17749.96 m^3/s has rare chance of occurring, with a probability of exceedance of 0.01% (Table 3). While this event is unlikely, it is not impossible in the study area.

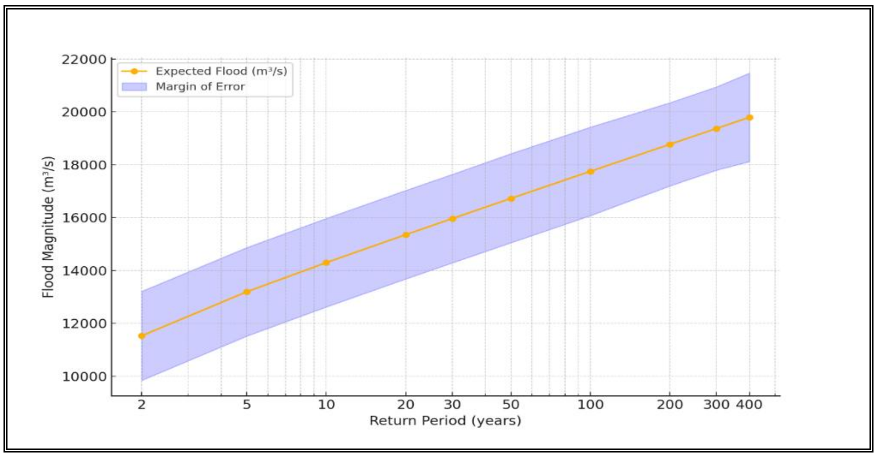

Figure 3: Flood Frequency Curve for Makurdi

The flood frequency curve shows that as the return period increases, the expected magnitude of the flood also increases. A 2-year return period for instance has an expected flood magnitude of approximately 11,528.48 m^3/s, while a 100-year return period flood is expected to reach about 17,749.96 m^3/s. The margin of error at 95% confidence interval, indicated by the shaded region, provides a visual representation of the uncertainty in these estimates.This result is in line with the findings of Oyatayo (2021). However, it contradicts the findings of Peter *et al*. (2020) whose analysis found Makurdi's 100 year flood to be way less. This is probably because their computation did not consider river discharge, they relied only on rainfall data of the catchment.

Summary and Conclusion

Thisstudy carried out a flood frequency analysis for Makurdi catchment of the Benue River, the result revealed a 36-year mean instantaneous flood flow of 11,820.19 m^3/s with a return period of 2 years indicating high risk and a long-term increase tendency.The trend line equation R^2 gives a value of 0.9571 suggesting that, the Gumbel distribution accurately models Makurdi's flood peak data. This strong correlation implies that the catchment's flood risk is predictable as it follows a consistent pattern, with higher flood peaks corresponding to more extreme events. This result highlights the predictability and potential variability in flood magnitudes,which is essential for understanding flood risk and can be used to inform the design of flood defenses and other mitigation measures which are critical for flood risk management and infrastructure planning in the Makurdi.

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