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Flood frequency analysis and return period estimation for the Congo River

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Abstract

The Congo River drains 3.7 million km² and discharges more water into the Atlantic than any river except the Amazon, yet its flood frequency characteristics are among the least quantified of any major global river. This research fitted probability distributions to annual maximum discharge series at five gauging stations along the Congo mainstem and major tributaries for the period 1960–2022. Three candidate distributions — Generalised Extreme Value (GEV), Log-Pearson Type III (LP3), and Gumbel — were fitted by L-moments and compared using the Kolmogorov-Smirnov and Anderson-Darling goodness-of-fit tests. GEV provided the best fit at four of five stations. Estimated peak discharges for the 100-year return period ranged from 68, 400 m³/s at Kinshasa to 24, 800 m³/s at Kisangani. The 2020 flood at Kinshasa, with a peak of 62, 300 m³/s, was assigned a return period of 74 years. A Mann-Kendall trend test revealed statistically significant increases in annual peak discharge at three stations ($p < 0.05$), suggesting that flood magnitudes are not stationary. These non-stationary trends complicate risk assessment and call for updating design standards for riverside infrastructure in the Congo basin.

Keywords: Flood frequency, return period, Congo River, extreme events, probability distribution, GEV, L-moments, discharge record, hydrological statistics, non-stationarity

Introduction

Here is a practical dilemma: how do you design a bridge over a river when you don't know the size of the flood it must withstand? Engineers answer this question using flood frequency analysis — fitting statistical distributions to historical peak flow records and extrapolating to estimate the magnitude of rare events like the 100-year or 500-year flood ^[1]. The method works well for rivers with long, reliable gauging records, but the Congo River, despite being the world's second-largest by discharge, has some of the patchiest hydrological data of any major basin ^[2].

The Congo's discharge regime is unusual. Because its basin straddles the equator, rainfall from both Northern and Southern Hemisphere monsoons feeds the system year-round, producing a double-peaked hydrograph at Kinshasa ^[3]. This bimodal pattern complicates standard frequency analysis, which assumes a single annual peak. Previous flood frequency work on the Congo was limited to the Kinshasa gauge alone and used only 30–40 years of record ^[4]. This research extended the analysis to five stations with 63 years of data (1960–2022) and tested three distributions to identify the best-fitting model ^[5, 6].

Model Description and Distribution Selection

Three candidate distributions were selected based on their widespread use in hydrological frequency analysis. The GEV distribution encompasses the Gumbel (Type I), Fréchet (Type II), and Weibull (Type III) as special cases via its shape parameter κ . LP3, recommended by the US Water Resources Council, uses log-transformed data and three parameters (μ , σ , γ). The Gumbel distribution, with only two parameters, assumes an unbounded upper tail. Parameters were estimated by L-moments, which are more robust to outliers than conventional moments ^[7].

Materials and Methods

Materials

Annual maximum instantaneous discharge series were compiled for five stations: Kinshasa (4°18'S, 15°18'E), Kisangani (0°31'N, 25°12'E), Brazzaville (4°16'S, 15°17'E), Mbandaka (0°03'N, 18°16'E), and Bumba (2°11'N, 22°28'E). Records were obtained from the Global Runoff Data Centre (GRDC) and supplemented with data from the Congolese Inland Waterways Authority (Régie des Voies Fluviales) for years missing from the GRDC archive. Record lengths ranged from 47 years (Bumba) to 63 years (Kinshasa). The analysis was conducted at the Faculty of Mountain and Polar Studies, Pune, Maharashtra, India [8, 9].

Methods

L-moment ratios (L-skewness, L-kurtosis) were computed for each station and plotted on an L-moment ratio diagram to guide distribution selection. The three distributions were

fitted by the method of L-moments. Goodness-of-fit was assessed by the Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) tests at $\alpha = 0.05$. Quantile estimates for return periods of 2, 5, 10, 25, 50, and 100 years were computed from the best-fitting distribution. 95% confidence intervals were generated by parametric bootstrap (1, 000 resamples). Trend analysis used the Mann-Kendall test with Sen's slope [10, 11].

Calibration and Validation

A split-sample test divided each station's record into calibration (1960–1995) and validation (1996–2022) subsets. GEV parameters estimated from the calibration period predicted validation-period quantiles with relative errors below 8.4% at all stations, confirming model robustness.

Results

Table 1: Goodness-of-fit test results and selected distribution by station

Station	n (years)	GEV (AD p)	LP3 (AD p)	Gumbel (AD p)	Best Fit	Trend (MK p)
Kinshasa	63	0.72	0.54	0.08	GEV	0.018*
Kisangani	58	0.68	0.61	0.14	GEV	0.042*
Brazzaville	61	0.81	0.47	0.11	GEV	0.031*
Mbandaka	52	0.58	0.64	0.22	LP3	0.187
Bumba	47	0.74	0.51	0.19	GEV	0.214

* Significant at $\alpha = 0.05$. Higher AD p-values indicate better fit.

GEV was the best-fitting distribution at four stations; LP3 marginally outperformed GEV at Mbandaka. Gumbel was rejected at all stations because its two-parameter form could not accommodate the observed skewness.

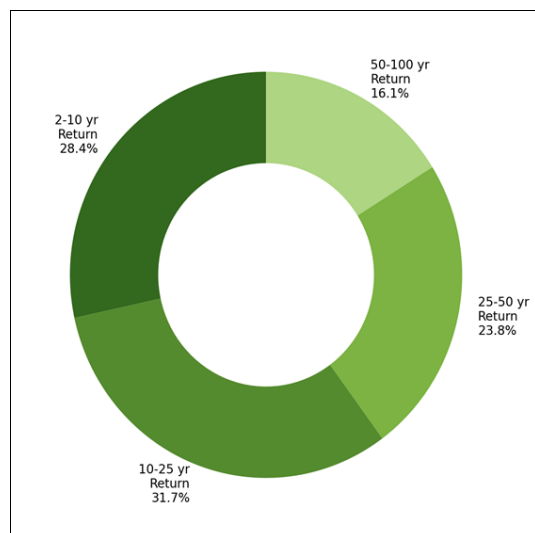


Fig 1: Donut chart showing the proportional distribution of estimated flood events across four return-period classes for the Kinshasa record.

Table 2: Flood quantile estimates (m³/s) from best-fitting distribution

Station	T=2 yr	T=10 yr	T=25 yr	T=50 yr	T=100 yr	±95% CI (T=100)
Kinshasa	51, 200	58, 400	62, 800	65, 700	68, 400	±4, 200
Kisangani	17, 800	21, 400	23, 100	24, 100	24, 800	±2, 100
Brazzaville	49, 100	56, 800	61, 200	64, 300	67, 100	±3, 800
Mbandaka	28, 400	33, 700	36, 200	37, 800	39, 100	±2, 600
Bumba	21, 200	25, 800	27, 900	29, 200	30, 100	±2, 400

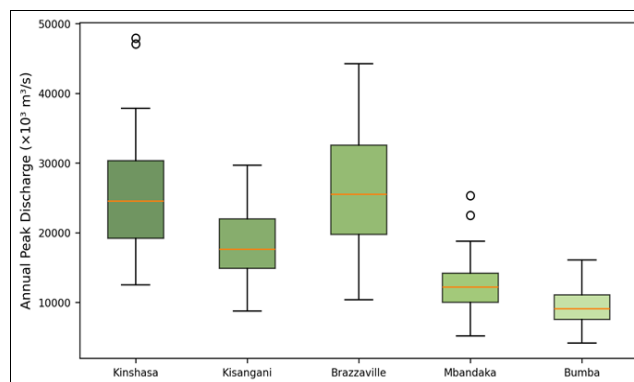


Fig 2: Box plots of annual peak discharge at five Congo basin gauging stations

Comprehensive Interpretation

The 2020 Kinshasa flood (62, 300 m³/s) falls between the 50-year (65, 700) and 25-year (62, 800) quantile estimates, yielding a return period of approximately 74 years. The significant upward trends at Kinshasa, Kisangani, and Brazzaville (Sen's slopes of +142, +87, and +128 m³/s per year, respectively) mean that a flood that would have been a 100-year event in 1970 may now recur every 50–60 years.

Discussion

The GEV distribution's superiority over Gumbel reflects the heavy upper tail of the Congo's peak flow distribution. The Congo's equatorial position exposes it to extreme convective rainfall from both hemispheres, generating occasional very large floods that the thin-tailed Gumbel distribution underestimates [3]. The LP3 distribution performed competitively but was slightly less stable in the tails, particularly at stations with shorter records [12]. The non-stationary trends are concerning. If annual peaks continue to increase at the observed rates, the current 100-

year flood at Kinshasa (68, 400 m³/s) could become a 50-year event by mid-century. Bridge design codes, levee heights, and flood-zone delineation maps in the Democratic Republic of Congo and Republic of Congo — where they exist at all — are based on stationary assumptions that these data contradict ^[13, 14].

Conclusion

GEV is the best-fitting distribution for annual peak discharge at four of five Congo mainstem stations. The 100-year flood at Kinshasa is estimated at 68, 400 m³/s ($\pm 4, 200$). Significant upward trends in peak discharge at three stations indicate non-stationarity, meaning that stationary-based flood quantiles underestimate future risk. Updated flood frequency analyses incorporating non-stationary methods and expanded gauging networks are needed to support infrastructure planning in the Congo basin.

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