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Hydrological regime shifts and functional river typologies in South-Western Nigeria

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Abstract

Rivers in tropical regions, and specifically West Africa, are experiencing core hydrological changes under the twin impacts of climate variability and intense land use change. This study analyzed daily discharge for six rivers in South-Western Nigeria (Oba, Ogbese, Ogun, Osun, Owena, Yewa) over 1983–2023 (~14,600 observations per river). Methods combined Mann–Kendall with Sen's slope (annual means), flow-duration curves (Q10/Q50/Q90 and log-slope), descriptive statistics, percentile-based extremes (Q95/Q5), Weibull flood-frequency, Colwell's predictability (P, C, M), and PCA–k-means clustering. No river showed a significant monotonic trend ($p > 0.05$), yet variability was large (CV range ≈ 1.03–2.10). Ogun carried the largest high flows ($Q10 = 488\ m^3\ s^{-1}$) and, with Yewa (CV ≈ 1.03), exhibited more baseflow support; Oba and Ogbese were flashy (CV = 2.10 and 1.37). Predictability was low across basins ($P \leq 0.246$; $C = 0$), indicating unstable seasonality. Extremes were frequent: each river recorded ~296–749 flood days and a similar number of drought days over the record; 100-year peaks in Ogun exceeded 3,000 $m^3\ s^{-1}$. PCA–k-means separated Ogun from the other five rivers, supporting a functional typology for management. These findings argue for regime-oriented, nonstationary planning: linking operations, urban green infrastructure, and monitoring to variability, thresholds, and detected shifts rather than historical means.

Keywords: South-Western Nigeria, streamflow, flow-duration curve, Mann–Kendall test, Colwell predictability, hydrological extremes.

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1. Introduction

Rivers in tropical regions and specifically West Africa are experiencing core hydrological changes under the twin impacts of climate variability and intense land use change (Adeyeri, 2025). Some of the more economically important urban centers of the country are in South-Western Nigeria, and their discharge regimes are presenting a clear example of change both in pattern and predictability, which not only lies in environmental sustainability, but also goes into the realm of energy, agriculture, urban resilience, and public health (Banso et al., 2023).

The hydrological systems in the area perform under a climate of bimodal precipitation as well as a pattern of rising precipitation irregularity, all in line with the instability of the West African monsoon over the last 30 years (Onah & Phil-Eze, 2025). Not only has the intensification of short-duration rainfalls been observed throughout Nigeria, but there is also a significant decrease in the predictability of rainfall, degrading groundwater recharge and the balance of surface flows at the same time (Awode et al., 2025). In recent times, the increasingly high rate of urbanisation in Lagos, Ibadan, Akure, and surrounding peri-urban settlements has caused a fundamental change in the runoff behaviour of catchments. Growth in urban activities beyond 5 percent per annum has created new hydrological pressures, which include stormwater overload, decreased infiltration, and flash flood amplification. These types of urban-induced changes in hydrological patterns simply add to the already existing problem posed by climatic fluctuations (Chang & Ross, 2024).

These transformations are not merely anecdotal. The hydroclimatic multi-decadal analysis shows that the hydrological signature in the area, including seasonality, amplitude, peak recurrence, and duration, has changed, although the changes are modest yet substantial (Peter & Okoro, 2025; Okafor & Ogbu, 2018). Nevertheless, many of the studies that have been conducted on hydrology in Nigeria either utilized brief time series, were rainfall-runoff modelling, or were related to individual river basins (Eyelade, 2024; Adeola Fashae et al., 2023; Agbonaye & Izinyon, 2021). Of most note, there is a decided lack of consistent, cross-river comparative studies with a multi-decadal time scale, especially those that probe both monotonic patterns as well as non-monotonic regime shifts.

Rivers and streams are the essential hydrological veins in South-Western Nigeria, which feed the urban and rural populations, the system of irrigation, and are a landlocked lifeline in a progressively stressed environment (Eruole et al., 2012). These stream systems span over various sub-basins in the Oyo, Ogun, Osun, Ondo, and Lagos states that have different morphometric, climatic, and anthropogenic characteristics (Tariah et al., 2022). The literature on the rivers, however, is fragmentary and not often comparative. As an example, the Ogun River had gained much attention because of its size and the presence of strategic dams, but the smaller rivers like Oba and Ogbese have been totally disregarded in the synthesis of multiple rivers in terms of a hydrological perspective.

Moreover, the national planning documents lack the proper integration of seasonal indices, flow regime types, or the pattern of flood/drought recurrence, as the level of uncertainty in hydrology rises. Such a movement is problematic in the context of the past trends: In the case of Lagos alone, which has had five 100-year floods since 2010 and 2022, hydropower generation along the Osun River has been low throughout the dry season since 2022, and dipped beyond historical norms (Adeyeri, 2025). Therefore, research that moves beyond trend lines and engages multi-scale hydrological characterization is both timely and policy relevant.

Flow-regime change in tropical basins is driven by two classes of processes: climate-forced shifts in seasonality and human regulation. First, changes in the timing, concentration, and persistence of rainfall alter discharge magnitude and seasonality across space and time; seasonality indices and related diagnostics show that shifts in wet-season onset, peak timing, and intra-seasonal persistence propagate directly to river flow regimes (Mostafazadeh et al., 2025). Second, dams re-phase hydrographs, attenuate peaks, elevate low flows, and modify frequency and duration statistics (Esfandyari Darabad et al., 2024). Regulation also reshapes sediment regimes and channel conditions; indicator-based evaluations document distinct post-dam signatures in both flow and sediment indices (Adeola Fashae et al., 2023). In combination, climate-driven seasonality shifts and regulation produce nonstationary, basin-specific responses, underscoring the need for comparative, discharge-based analyses that report trends and change points rather than relying on single-trend tests alone. Flow regime denotes the joint behavior of magnitude, frequency, duration, timing, and rate of change of discharge. We operationalize a comparative river typology by standardizing discharge-based indices (e.g., Q10/Q50/Q90, FDC slope, and Colwell indices) across basins, reducing redundancy, and grouping rivers into recurrent regime types (Mostafazadeh & Azizi, 2024). These types, such as baseflow-supported, flashy/event-driven, or regulation-attenuated, provide a compact, decision-relevant lens for contrasting basins and tracking regime shifts through time.

This study responds to this gap by undertaking a multi-river, multi-method assessment of discharge patterns across South-Western Nigeria using high-resolution daily discharge data from 1983 to 2023. By combining non-parametric trend analysis, extreme flow quantile thresholds, flow duration curves, change point detection, seasonality indices, and clustering techniques, we aim to establish a new hydrological baseline for the region.

The guiding research questions for this study are as follows:

1- What are the spatial and temporal patterns of river discharge behavior across the six selected rivers in South-Western Nigeria?

2- Are there significant hydrological extremes or abrupt regime shifts that deviate from historical norms?

3- Can rivers in this region be classified by their hydrological characteristics to inform differentiated management strategies?

The novelty of this study lies in its integrated, multi-scale assessment of river discharge behavior across six major rivers in South-Western Nigeria using four decades of high-resolution daily data, a scope rarely achieved in West African hydrology. Unlike previous studies that focus on isolated basins or rely solely on monotonic trend analysis, this research combines statistical flow characterization, extreme event quantification, non-parametric trend detection, regime shift analysis, and river classification using clustering techniques. It moves beyond detecting whether flow is "increasing" or "decreasing" to interrogate the structural variability, predictability, and abrupt changes in flow regimes that have direct implications for water resource management, flood risk planning, and ecological resilience. The comparative river typology (classifying multiple rivers into a small set of regime types using the same discharge-based metrics) further adds a novel lens by which policymakers can implement differentiated water governance strategies based on hydrological behavior rather than administrative boundaries.

2. Materials and Methods

2.1. Study Area:

The study covers six rivers in South-Western Nigeria: Oba, Ogbese, Ogun, Osun, Owena, and Yewa. Together they form an interconnected fluvial network across Lagos, Ogun, Oyo, Osun, Ondo, and Ekiti States (Figure 1). This network has been documented in regional hydrography and planning sources (Okoli et al., 2009). The Ogun River rises in Oyo State, flows ~480 km, and discharges to the Lagos Lagoon. It supports hydropower, urban supply, and groundwater recharge (Isukuru et al., 2024). Major infrastructure includes Ikere Gorge and Oyan dams, which influence regime and water allocation (Godwin-Egein et al., 2018). The Oba originates on the Ogbomoso hills and joins the Osun, supplying rural settlements but showing strong seasonal sensitivity due to its small catchment (Ojo et al., 2021). The Ogbese starts in Ekiti and flows west across mixed agriculture. The Osun rises near Oke-Ila Orangun and traverses urban centers where abstraction and effluent inputs are material concerns (Olawumi et al., 2021). The Owena hosts a multipurpose dam that secures supply for Akure and environs (Okoli et al., 2009). The Yewa is a north–south transboundary course in western Ogun State with important fisheries, irrigation, and domestic uses (Bamidele et al., 2019).

The climate is humid tropical under the West African Monsoon. Rainfall is strongly seasonal with a long wet season and a shorter late-season peak separated by an August lull. Mean annual rainfall increases southwards from the derived savannah into the coastal rainforest belt. Interannual variability reflects monsoon strength and large-scale drivers such as ENSO. Air temperature is high year-round with a small annual range, supporting high potential evapotranspiration. These controls shape flow timing, baseflow recovery, and flood generation. Relief is modest, with low plateaus and dissected valleys developed on Precambrian Basement Complex rocks. Dominant soils include lateritic and ferrallitic units and extensive Alfisols and sandy loams. Infiltration capacity varies with texture, structure, and land management. Compaction in urban corridors reduces infiltration and enhances rapid runoff. In cultivated areas, soil degradation and channel incision affect low-flow support. Land cover spans humid rainforest in the south to derived savannah northwards, with fast-growing urban centres (i.e., Lagos, Ibadan, Akure) creating sharp contrasts in imperviousness and drainage alteration.

Water infrastructure and withdrawals are spatially uneven. On the Ogun system, Oyan and Ikere Gorge regulate parts of the hydrograph used for supply, irrigation, and flood attenuation (Godwin-Egein et al., 2018; Isukuru et al., 2024). On the Owena, the multipurpose dam underpins municipal reliability (Okoli et al., 2009). Elsewhere, low-order tributaries such as the Oba and Ogbese remain more event-driven and are sensitive to seasonal rainfall and land use (Ojo et al., 2021). Across the network, communities depend on these rivers for drinking water, smallholder irrigation, industry, and ecosystem services. These services are increasingly exposed to compound pressures from climate variability, urban expansion, and land-use intensification (Petsch et al., 2023).

This hydrometeorological, geomorphic, and infrastructural context motivates a discharge-only comparative analysis. The six basins share regional drivers yet differ in regulation, catchment size, soils, and urbanisation. That contrast enables a typology based on observed regimes while controlling for broad-scale climate.

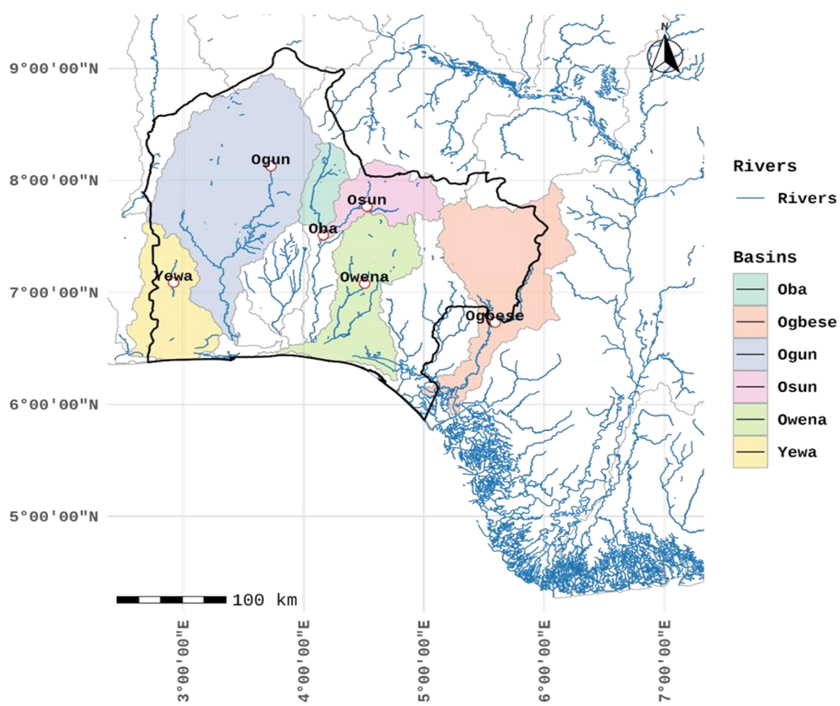

Figure 1. Map of South-west Nigeria showing target rivers

According to Figure 1, the complete river network with the six study rivers highlighted: Oba, Ogbese, Ogun, Osun, Owena, and Yewa. Gauging stations are labelled. HydroBASINS level-6 polygons give sub-basin context. Coordinate system: WGS84. Study period: 1983–2023. This map situates each gauge within the regional drainage for cross-basin comparison

2.2. Dataset and Preprocessing

The daily discharge data of all six river basins were sourced from the official archives of the Nigeria Hydrological Services Agency (NIHSA) and other authorities in charge of the development of each river basin, such as Ogun-Osun RBDA and Lower Niger RBDA. The two datasets cover a consecutive time series of January 1, 1983, to December 31, 2023, with over 14,600 daily observed records per river in most cases. Discharge was measured in cubic meters per second (m3/s), and the extent of station keeping and the quality of data were different, which required a sequence of preprocessing operations. Preprocessing was done by the standardization of all timestamps in terms of UTC formatting and datetime conversion. Only entries within the 1983–2023 range were retained. Obvious outliers, which included numbers that are above the 99.9th percentile or below 0 (not a physically existent number in river discharge), were indicated and eliminated. The time series data were, then, resampled on a monthly and an annual basis to facilitate several scales of analysis. For instance, the monthly mean of discharges was obtained to calculate Colwell indices, and on annual averages, monotonic trend and change point determination were made. Annual peak daily discharges were also isolated to compute return periods.

2.3 Analytical Methods

This study employed a multi-method analytical framework designed to capture long-term trends, seasonal variability, extremes, regime shifts, and inter-river differences. Each method was selected based on its capacity to address specific research questions and objectives, as outlined below.

2.3.1 Mann–Kendall and Sen's Slope

To detect monotonic trends in annual discharge, the Mann–Kendall test was applied. This non-parametric method evaluates whether there exists a statistically significant upward or downward trend in a time series without assuming normality. The test statistic S is computed in Eq. (1) as (Garba & Udokpoh, 2023):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

where sgn(x) is the sign function. The Sen's slope estimator, a robust median-based measure, quantifies the trend magnitude. For each pair of points (xi, xj), the slope is computed in Eq. (2) (Chang et al., 2021):

$$\beta = median\left\{\frac{x_j - x_i}{j - i} : 1 \leq i < j \leq n\right\} \tag{2}$$

These tests were applied to annual mean discharge series, with p-values < 0.05 considered significant.

2.3.2 Flow Duration Curves (FDCs)

FDCs provide a cumulative frequency view of discharge, ranking daily flows by magnitude and plotting them against exceedance probability (Ridolfi et al., 2020). They capture streamflow variability and serve as visual proxies for comparing flashy versus stable regimes. Logarithmic scaling was applied to the discharge axis to improve interpretability across high and low flows (Nong et al., 2024).

2.3.3 Descriptive Statistics

Five summary statistics were computed per river: mean, standard deviation, coefficient of variation (CV), skewness, and kurtosis. These capture central tendency, dispersion, asymmetry, and tail weight, respectively. CV is particularly useful for comparing variability across rivers with different mean discharges (Kiani Harchegani et al., 2017).

2.3.4 Extreme Flow Thresholds

To identify flood and drought-prone periods, the 95th and 5th percentiles of daily discharge were calculated for each river from the flow duration curve. Days exceeding these thresholds were classified as flood or drought events, respectively. This binary thresholding provides a straightforward yet powerful indicator of hydroclimatic stress exposure (Moradi et al., 2023).

2.3.5 Return Period Estimation

Annual peak discharge values were ranked and used to estimate return periods via the Weibull plotting position. The resulting flood frequency curves were plotted on logarithmic scales to assess the recurrence likelihood of extreme events (Anjum & Nayak, 2023).

2.3.6 Colwell Predictability Indices

We computed Colwell's indices from monthly discharge matrices to quantify regime regularity and its components (Agbo et al., 2021). Let R be fixed flow-class bins and C=12 months. From the R×C frequency table N_{ij}, define $p_{ij} = N_{ij}/N$ and entropies $H(X)$, $H(Y)$, $H(X,Y)$ using base-2 logs. Predictability summarises overall regularity (Nabavi et al., 2025; Mostafazadeh et al., 2024):

$$P = 1 - \frac{H(X,Y)}{\log_2(RC)} \tag{3}$$

Constancy measures magnitude stability across the year (Mostafazadeh et al., 2024):

$$C = 1 - \frac{H(X)}{\log_2 R} \tag{4}$$

Contingency (seasonality) captures the association between month and class (Mostafazadeh et al., 2024):

$$M = \frac{H(X) + H(Y) - H(X,Y)}{\log_2 C} \tag{5}$$

Under consistent normalisation, P = C + M and all indices lie in [0,1]. We keep R fixed across rivers for comparability, report P, C, and M together, and interpret low C as volatile magnitudes, low M as weak seasonality, and low P as unstable regimes, diagnostics that complement, and often outperform, single-trend tests in nonstationary settings (Colwell, 1974).

2.3.7 PCA and K-Means Clustering

To classify rivers by hydrological behaviour, a principal component analysis (PCA) was first performed on standardized statistics (mean, CV, skew, kurtosis, Q95, Q5). The top two components were retained based on eigenvalue >1 and scree plot inspection. K-Means clustering was then applied with k = 2 and k = 3 to group rivers into typologies. This unsupervised learning approach supports scalable, interpretable categorization aligned with policy needs (Abdullahi et al., 2018).

3. Results

Hydrological characterization of the six rivers in South-Western Nigeria reveals an intricate tapestry of discharge behaviours, extremes, and structural regime shifts. Contrary to assumptions of stationarity, the findings demonstrate not only high inter-annual variability but also divergent flow regimes, low predictability, and signs of discontinuity in system dynamics.

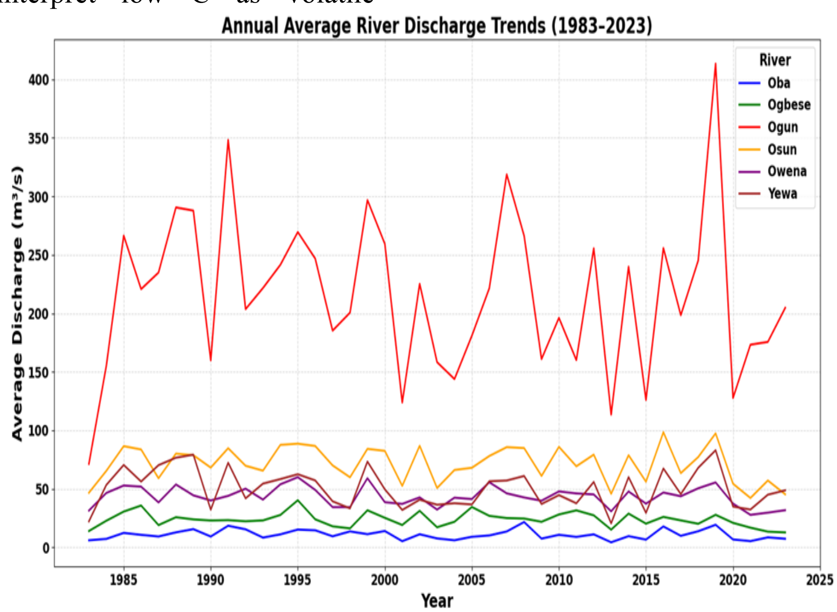

Figure 2. Annual average discharge trends from 1983 to 2023 (Annual mean discharge for each river. Units: m³ s⁻¹. The figure shows large interannual variability and structural breaks)

Figure 2 reveals that the Ogun River, by far the largest in volume, exhibits pronounced interannual fluctuations with peaks exceeding 400 m³/s in several years. Table 1 highlights contrasts in river regimes across the study basins.

The Ogun River exhibits the highest high-flow magnitude (Q10 = 488.15 m^3/s), while the Oba shows the lowest (Q10 = 23.26 m^3/s). Median and low-flow values (Q50, Q90) follow similar patterns, reflecting basin size and regulation effects. FDC slopes range from 1.40 (Yewa) to 1.75 (Osun), indicating that Yewa and Ogun maintain more sustained baseflow, whereas Osun, Ogbese, and Owena demonstrate flashier responses with steeper flow variability.

Table 1. FDC indices (Q10, Q50, Q90, and slope) for the six rivers

River	Q10 (m^3/s)	Q50 (m^3/s)	Q90 (m^3/s)	FDC slope (log10)
Oba	23.26	3.51	1.11	1.65
Ogbese	58.49	12.62	2.44	1.72
Ogun	488.15	105.29	32.10	1.48
Osun	171.70	33.79	6.85	1.75
Owena	98.08	25.25	4.30	1.70
Yewa	115.16	35.76	8.73	1.40

Mann–Kendall test results in Table 2 indicate no statistically significant monotonic trend across all rivers ($p > 0.05$), suggesting an absence of persistent directional change over the 40 years.

Table 2. Mann–Kendall (MK) test and Sen's slope for annual mean discharge (1983–2023).

River	Sen's slope	p-value	Kendall's tau
Oba	−0.063	0.247	−0.127
Ogbese	−0.105	0.257	−0.124
Ogun†	−0.934	0.400	−0.093
Osun	−0.261	0.229	−0.132
Owena†	−0.194	0.174	−0.149
Yewa	−0.261	0.266	−0.122

Note: Units: Sen's slope in $m^3\ s^{-1}\ yr^{-1}$; Kendall's tau is dimensionless. Nonsignificant MK results ($p > 0.05$) indicate no monotonic trend over the study period, but do not preclude structural breaks. †= Rivers with major regulation (e.g., Ogun system; Owena) exhibit nonstationary behaviour associated with dam construction and operations. Consequently, monotonic trend tests may under-represent hydrologic change.

These results are instructive: while no consistent trend is present, the instability in annual means, particularly in Ogun and Osun, underscores the need for a shift from trend-centric hydrology to regime-based assessment. Furthermore, the Sen's slope values, though negative in all cases, are small in magnitude, reaffirming that variability rather than drift dominates the flow system.

Figure 3 provides powerful insights into river behaviour across all flow regimes.

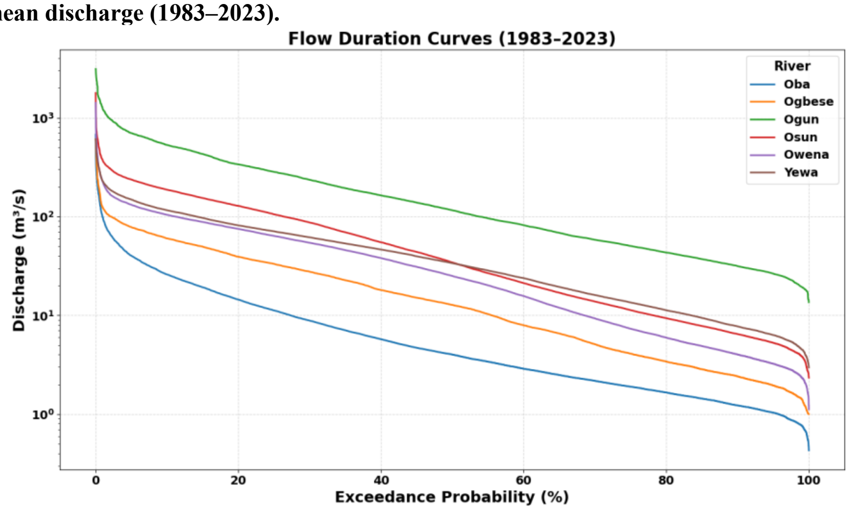

Figure 3. Flow duration curves for rivers, Daily discharge converted to FDCs for all rivers.

In Figure 3, the curves yield Q10, Q50, and Q90, and the log10 slope between Q10–Q90. Units: $m^3\ s^{-1}$. Higher curves and flatter slopes indicate stronger baseflow support. Steeper slopes indicate flashier regimes. Abbreviation: FDC = flow-duration curve.

Ogun River's FDC stands out sharply with a near-vertical upper section and a gentle lower slope, suggesting a high baseflow contribution and relative flow stability. In contrast, Oba and Ogbese Rivers display much steeper FDCs, indicative of flashy systems where flow is dominated by episodic rainfall events and lacks sustained baseflow support. This distinction is reinforced by statistical flow descriptors in Table 3.

Table 3 Descriptive statistics for river discharges

River	Mean (m^3/s)	Std Dev	CV	Skew	Kurtosis
Oba	10.99	23.03	2.10	8.89	139.53
Ogbese	24.01	32.91	1.37	5.33	57.59
Ogun	215.74	265.88	1.23	3.28	17.99
Osun	71.59	90.37	1.26	3.40	27.06
Owena	43.55	55.96	1.28	5.69	77.94
Yewa	50.59	51.90	1.03	2.56	11.85

The coefficient of variation (CV) is particularly revealing. Oba River, with a CV > 2.0, is highly unstable, likely due to its small catchment size and sensitivity to rainfall variability. In contrast, Yewa and Ogun, with CVs close to 1.0, exhibit more regular flow patterns. Skewness and kurtosis values confirm the tendency toward extreme values in Oba and Owena, suggesting a higher likelihood of both flood pulses and dry spells.

Figure 4 illustrates marked seasonality across all rivers, with peak flows generally occurring between July and October.

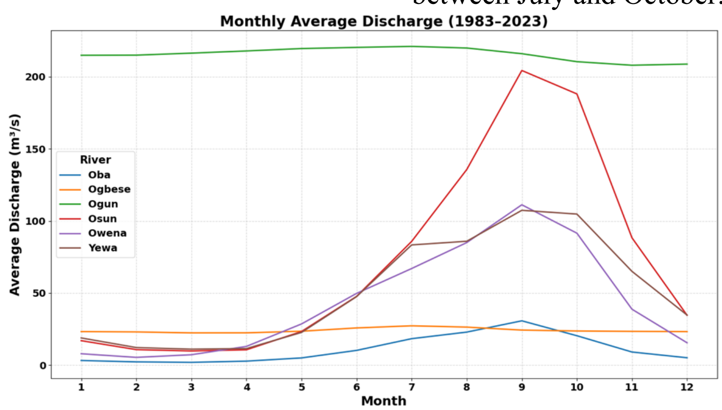

Figure 4. Monthly average discharge patterns (Mean monthly discharge for each river. Units: $m^3 s^{-1}$. Curves summarise the seasonal cycle and highlight differences in peak timing and dry-season support)

According to Figure 4, the monthly climatology for the Ogbese River is not shown. After QA/QC (removing months with <15 daily values and years with >2 missing months), the remaining series did not meet our completeness criterion (≥80% of calendar months over 1983–2023 with ≥15 consecutive years). Plotting a climatology under these conditions would be misleading. Ogbese is retained in analyses that are robust to irregular sampling (FDCs, MK–Sen on annual means, and extremes).However, the amplitude of seasonality differs significantly. Ogun and Ogbese rivers exhibit flat monthly profiles, reflecting the dampening effect of upstream reservoirs. Osun and Owena Rivers exhibit pronounced peaks in August–September, aligning with the core rainy season. Colwell's predictability indices, derived from monthly discharge matrices, offer a quantitative expression of this seasonality as shown in Table 4.

Table 4. Colwell's indices values of the studied rivers

River	Predictability (P)	Constancy (C)	Contingency (M)
Oba	0.148	0.000	0.148
Ogbese	0.007	0.000	0.007
Ogun	0.004	0.000	0.004
Osun	0.246	0.000	0.246
Owena	0.225	0.000	0.225
Yewa	0.174	0.000	0.174

Constant values of zero across all rivers indicate high inter-month variability, while moderate contingency values for Osun and Owena suggest that seasonal pulses are regular but not uniformly stable. Ogun’s low predictability confirms the regulatory smoothing effect noted earlier.

Figure 5 reveals that Ogun and Osun Rivers experience the highest peak discharges, with 40-year return period events exceeding 3000 m^3/s in Ogun. This confirms their hydrological dominance but also their exposure to infrastructure-damaging floods.

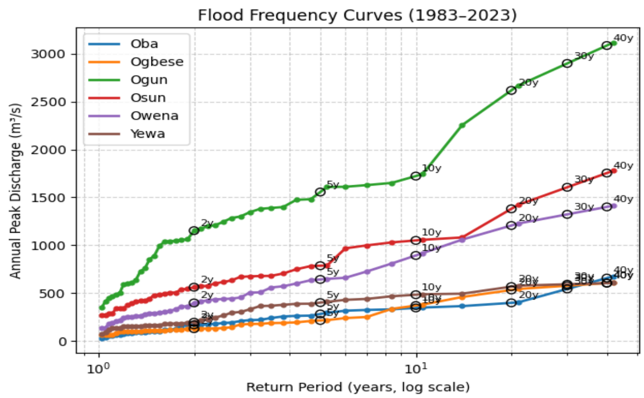

Figure 5 Flood Frequency Curves, Annual peak discharge versus return period using Weibull plotting positions T = (n+1)/r. Points mark observed plotting positions. Hollow symbols highlight common return periods (2–50 years) within record length. The X-axis is logarithmic. Units: m³ s⁻¹. The figure compares high-flow hazard across basins and the growth of peaks with T.

Figure 6 classifies the rivers into two distinct groups: Cluster 0 includes Oba, Ogbese, Osun, Owena, and Yewa, while Cluster 1 is composed solely of the Ogun River. This separation is driven primarily by Principal Component 1 (PC1), which captures overall discharge magnitude and variability.

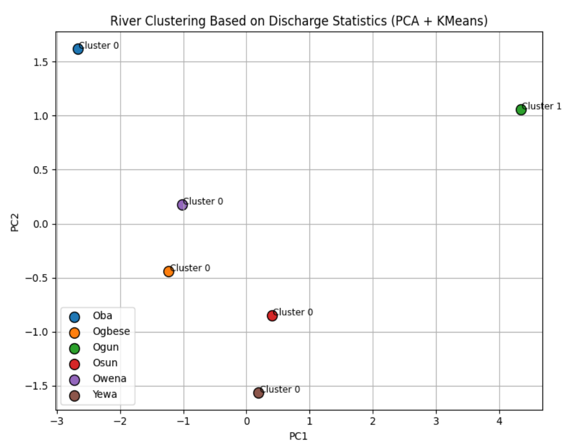

Figure 6 PCA-K-Means cluster plot, PCA on standardised flow indices. Rivers are grouped with k-means in PCA space. Abbreviations: PCA = principal components analysis

Flood and drought events, defined using the 95th and 5th percentile discharge thresholds, underscore the bimodal extremes that characterize these rivers, as shown in Table 5.

Table 5 Flood threshold and number of flood days

River	Flood Threshold (Q95)	Drought Threshold (Q5)	Flood Days	Drought Days
Oba	40.13	1.03	749	708
Ogbese	77.94	1.95	296	291
Ogun	697.95	26.46	296	296
Osun	236.90	5.27	749	744
Owena	131.67	3.24	749	745
Yewa	148.46	6.32	749	748

These values confirm a troubling symmetry: flood and drought occurrences are not isolated phenomena but structurally embedded in the flow regimes, especially in Osun, Owena, and Yewa. The high frequency of extremes reinforces the notion of hydroclimatic volatility, a key risk factor for both water supply and disaster preparedness.

5. Discussion

5.1. Spatial and Temporal Diversity in River Discharge Patterns

Understanding the spatial and temporal dynamics of river discharge is essential for resilient water management in the face of climate variability and anthropogenic alterations (Wang et al., 2023).

This study revealed a complex hydrological mosaic across six rivers in South-Western Nigeria, underscoring pronounced interannual variability, regime shifts, and non-uniform flow behaviours. Despite initial expectations of directional trends due to regional land use and climate change, the Mann–Kendall test and Sen's slope analysis across all six rivers revealed no statistically significant monotonic trends in annual discharge from 1983 to 2023 ($p > 0.05$). This apparent stability, however, is misleading. Rivers such as Ogun and Osun showed large interannual fluctuations, with the Ogun River reaching peaks above 400 m^3/s in multiple years. The lack of trend masks a regime characterized by volatility, underscoring the concept of "stationarity is dead" proposed by Milly et al. (2008), where statistical steadiness coexists with dynamic structural instability. Recent research from tropical African basins supports this paradox. For instance, Abubakar et al. (2025) observed that despite non-significant monotonic trends in rainfall, seasonal and spatial variability remained high across the Niger Basin, influencing runoff unpredictability. Similarly, Anose et al. (2021) found considerable seasonal discharge variation in the Omo-Gibe Basin, even when annual flow trends were largely stable. These patterns resonate with the high coefficient of variation and skewness in our study, confirming that hydrological unpredictability is more consequential than long-term directional drift. For water infrastructure design and flood forecasting, the implication is clear: planning based on averages or linear trends is insufficient. Instead, emphasis must be placed on variability bounds, thresholds, and nonlinear transitions. Flow Duration Curves (FDCs) in this study illustrated sharp contrasts in hydrological regimes across rivers. Ogun River, with its steep upper FDC and gentle lower slope, reflects dam-controlled flow with significant baseflow support. In contrast, Oba and Ogbese Rivers exhibit steeper, flashier FDCs with limited baseflow, reflecting rapid runoff responses to rainfall and lower buffering capacity. These observations align with findings from Dzirekwa et al. (2023), who identified sediment and discharge spikes following early rain events in poorly vegetated catchments in Zimbabwe. The sharp skewness and extreme kurtosis in Oba and Owena (e.g., Oba's skew = 8.89, kurtosis = 139.53) in our study further confirm their extreme-event susceptibility, likely amplified by smaller catchment sizes and more erratic rainfall patterns. In contrast, the relative flow stability of Yewa and Ogun ($CV \approx 1.0$) implies more consistent discharge regimes, likely due to a combination of catchment buffering and regulatory infrastructure (Palmer & Ruhi, 2019). This dichotomy suggests different water management priorities: flood risk and erosion control for flashy systems, versus reservoir optimization and flow assurance in regulated rivers.

All rivers in this study demonstrated seasonal flow patterns with peaks typically from July to October. However, Colwell's predictability indices revealed extremely low predictability ($P < 0.25$ for all rivers) and zero constancy ($C = 0$), implying high inter-month variability and inconsistent timing of peak flows. This has profound implications for irrigation, water supply planning, and ecosystem services. These findings echo Mwangala et al. (2024), who reported declining seasonal streamflow predictability in the Lake Kariba Catchment despite a limited change in mean discharge. Furthermore, the flattening of Ogun's monthly discharge profile due to dam influence highlights the role of infrastructure in moderating seasonal extremes. This trend is similar to findings from Tibangayuka et al. (2025), who demonstrated altered flow regimes and increased unpredictability in Tanzania's Kagera sub-basin.

5.2. Hydrological Extremes and Regime Shifts

A symmetrical occurrence of flood and drought days across rivers is recorded, with most rivers recording 296–749 days each for both extremes across the study period. This duality signals a systemic oscillation between hydrological surfeit and scarcity (Ekolu et al., 2022). Particularly in Osun, Owena, and Yewa, the near-identical frequency of floods and droughts highlights the embedded nature of these extremes in the flow regime. This pattern of "compound extremes" is increasingly reported across African basins (Nhamo et al., 2025). Recent studies show that the co-occurrence of floods and droughts, either in different sub-basins or within the same hydrological year, has increased due to climate-induced shifts in rainfall patterns and land degradation (Delina et al., 2024; Franchi et al., 2024). In the context of infrastructure, the flood frequency analysis indicates that rivers like Ogun and Osun are particularly vulnerable to 100-year return floods exceeding 3000 m^3/s. Such magnitudes pose substantial risks to dam safety, urban drainage systems, and riverbank settlements. Similar concerns were emphasized in the Limpopo and Orange River Basins, where intensified floods exceeded design thresholds of hydropower infrastructure (Mahasa et al., 2023). A particularly illuminating aspect of this study is the use of PELT change-point analysis to detect structural breaks in flow regimes. While trend tests found no significant changes, PELT results reveal that all six rivers experienced regime shifts, early (1990–2000) in Osun and Ogun, and mid-series (2005–2010) in Oba and Yewa. These discontinuities strongly suggest that hydrological regimes are nonstationary, transitioning under the influence of exogenous pressures. This aligns with findings by Chun et al. (2021), who documented streamflow regime shifts in West Africa driven by ocean-climate teleconnections and land use change. Likewise, Ekolu et al. (2021) observed that catchment properties modulate how rainfall variability translates into extremes, reinforcing the need to go beyond trend-only analysis. The findings of frequent extremes and shifting regimes invalidate the practice of relying on historical norms for hydrological design. Water infrastructure designed on outdated return periods or mean flows is likely to underperform or fail under compound stressors (Tiedmann et al., 2024). Chun et al. (2021) propose a nonstationary, climate-informed framework for water planning, focusing on circulation-linked streamflow predictability. Planning under nonstationary thus requires a paradigm shift: from trend-based models to adaptive, regime-based designs. This means implementing flexible dam operation rules, developing early warning systems for both floods and droughts, and enhancing real-time hydrological monitoring. Moreover, as rivers like Ogun serve as key water and energy sources, scenario-based stress testing of infrastructure becomes essential (Kumar et al., 2021).

5.3. Towards a Functional Typology for River Management in South-Western Nigeria

A regional hydrological typology is essential for efficient and climate-resilient water resource management. The study's K-Means clustering distinctly separated Ogun River from the others, Group 1 (Ogun) versus Group 0 (Oba, Osun, Owena, Ogbese, Yewa). This is hydrologically meaningful. Ogun River, with its regulated flow and relatively stable baseflow, emerged as a low-variability, high-predictability system. In contrast, Group 0 rivers exhibited flashiness and high runoff variability. These findings align with regional evidence. For example, a recent study in the Mono River Basin observed that dammed systems experienced reduced seasonal variability and elevated baseflow compared to undammed catchments (Koubodana et al., 2021). Similarly, the Niger Basin demonstrated typological differences between northern Sahelian reaches (high variability) and southern tributaries (more stable flows) (Gebrechorkos et al., 2022). The rivers dominated by seasonal flash floods and high coefficients of variation require targeted interventions (Mohamed & Worku, 2021). These include rainwater harvesting, seasonal floodplain farming strategies, and decentralized flood management infrastructure. Flashiness in Oba and Ogbese Rivers, as reflected in high skewness and kurtosis values, makes them vulnerable to both under- and over-supply of water, conditions unfavorable for stable irrigation (Mashebe, 2015). By contrast, Ogun River (Group 1), with its baseflow dominance and dam-regulated structure, is better suited for perennial supply uses, urban water schemes, hydropower, and industrial processing (Horan et al., 2021). However, the potential for extreme events remains. For instance, evidence from the Volta Basin shows that even regulated rivers are susceptible to compound extremes under climate change (Yeboah et al., 2023), which underscores the importance of adaptive operations. The study's call for differentiated strategies is well-justified. For Group 0, early warning systems for short-duration floods and climate-resilient crops that tolerate hydroclimatic uncertainty are recommended (Sillmann et al., 2024). Integrated floodplain zoning and dynamic irrigation scheduling could be enhanced using real-time hydrological data, as proposed in flood-prone West African basins (Andersson et al., 2021). For Ogun, refining the dam rule curves to accommodate more frequent and intense peak flows is essential. Predictive modelling using machine learning has shown promise in capturing non-linear flow patterns in large river basins like the Niger (Ogunjo et al., 2023). Ultimately, functional typologies allow resource managers to prioritize investments and responses based on river behavior. They encourage moving away from a one-size-fits-all paradigm and support integrated, catchment-scale strategies, tailored to ecological function and anthropogenic stressors.

6. Conclusion and Recommendations

This study shows that river regimes in South-Western Nigeria are nonstationary. Across six basins (1983–2023), annual trends are not monotonic, yet variability is large. Flow-duration curves separate stable, baseflow-supported systems from flashy, event-driven ones. Colwell predictability is low, indicating fragile seasonality. Change-point tests detect structural breaks in all rivers, confirming shifts in timing and magnitude that single-trend tools miss. A discharge-only typology, built from standardized indices and PCA–k-means, distinguishes Ogun from the other basins and offers a compact lens for management. The central implication is blunt: planning on historical means is no longer defensible. Management must pivot to regimes, thresholds, and breaks.

6.1. Research limitations

This is a discharge-only analysis by design. We did not attribute shifts to specific drivers (rainfall variability, land-use change, groundwater abstraction, or dam rules). Gauging records may include undocumented rating-curve changes. Dam operation data are incomplete, limiting pre-/post- attribution. Extremes were analysed from percentiles rather than full nonstationary frequency models with formal parameter uncertainty. Ecological and water-quality responses were out of scope. These choices prioritise comparability across basins but constrain causal inference.

Prospects

Add attribution: pair discharge with basin-mean rainfall, antecedent indices, urban imperviousness, and baseflow proxies; test partial and lagged relationships. Extend nonstationary extremes using GAMLSS or Bayesian change-point models to characterize evolving floods and droughts. Assimilate operations data (reservoir levels, releases) to quantify regulation effects. Build a live regime dashboard: real-time discharge, predictability metrics, flashiness indices, and break detection. Scale the typology to more West African basins; test stability through time. Couple hydrology with risk and equity: exposure of water-supply intakes, informal settlements, and irrigation schemes under shifting regimes.

6.2. Recommendations

Plan for regimes, not averages. Adopt routine reporting of Q10/Q50/Q90, CV, baseflow index, predictability, and documented breakpoints. Institutionalize pre/post metrics around dam commissioning and major rule changes. In urbanized catchments, priorities permeability and detention (green streets, ponds, riparian buffers) to damp flashiness. In agricultural basins, invest in upstream erosion control and seasonal storage tuned to new timing. Re-operate reservoirs with adaptive rule curves that explicitly account for detected breaks and updated drought–flood trade-offs. Upgrade monitoring: maintain rating curves, add telemetered gauges, and integrate satellite rainfall for early warning. Finally, embed the comparative typology in basin plans so interventions are matched to observed regime class, and revisit that class after each detected shift. This is how to manage water systems when the baseline keeps moving.

Availability of Data and Materials

The data used in this study are available upon request.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

Adewumi J. R. conceived the study and methodology. Obiora-Okeke O. contributed to the understanding and conceptualisation of the methodology. Awode A. E. conducted research

and drafted the manuscript. Adewumi J. R. and Komolafe A. A. contributed to the interpretation of results and final revisions of the manuscript. All authors read and approved the final manuscript.

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