

Spatio-Temporal Changes in Rainfall Patterns and Their Implications for Water Resources in Eleyele Dam Basin

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Abstract: This study investigates the spatio-temporal variability and long-term rainfall trends in the Eleyele Dam Basin, southwestern Nigeria, using daily ERA5/ERA5-Land datasets covering 1981–2023. Preprocessing ensured homogeneity, persistence control, and serial correlation adjustment. Trend analysis was performed using the non-parametric Mann–Kendall test and Sen’s slope estimator, with trend-free prewhitening applied to mitigate autocorrelation effects. Spatial rainfall distribution was generated through Inverse Distance Weighting (IDW), optimized via leave-one-out cross-validation. Results indicate a persistent north–south gradient, with annual totals ranging from ~1,266 mm in the north to ~1,539 mm in the south. The basin exhibits a distinct bi-peak regime, with maxima in June and September, and 86% of rainfall concentrated between April and October. Statistically significant negative trends were identified in March, April, May, and December (Sen’s slope -0.48 to -1.62 mm yr⁻¹), pointing to a delayed onset and weakened early wet-season contribution. Annual rainfall shows a significant decline (-5.26 mm yr⁻¹), and dry-season totals also decreased (-2.91 mm yr⁻¹). Coefficients of variation highlight increased interannual variability, especially in dry months, underscoring unreliability of inflows. Spatial maxima occur in the southern sub-catchment, where high rainfall intensity coincides with greater erosion and sediment delivery risks. These shifts imply reduced inflows, prolonged dry-season deficits, and heightened supply shortfalls. The findings underscore the need for adaptive reservoir rule-curve updates, catchment erosion mitigation, and climate-resilient water resource planning to safeguard Eleyele’s multipurpose role in Ibadan.

Keywords: Rainfall variability; Spatio-temporal analysis; Mann–Kendall test; Sen’s slope estimator; Inverse Distance Weighting (IDW); Climate variability; Hydrological trends; Reservoir inflows; Water resource management; Eleyele Dam Basin

Highlights

- ★ Rainfall trends (1981–2023) show significant early wet-season decline.
- ★ Annual rainfall decreased by -5.26 mm/yr; dry-season totals by -2.91 mm/yr.
- ★ 86% of annual rainfall concentrated in April–October bi-peak regime.
- ★ Spatial maxima in the south raise erosion and sediment delivery risks.
- ★ Findings support adaptive reservoir rule-curves and climate-resilient planning.

I. Introduction

Rainfall serves as the primary climatic determinant influencing surface water availability, groundwater recharge, reservoir inflows, and sediment transport within tropical basins (Scanlon et al., 2006; De Araújo et al., 2014; Armijos et al., 2020). In rapidly urbanizing catchments such as the Eleyele Dam Basin, the timing and magnitude of rainfall critically affect reservoir management, flood risks, sediment deposition, and the dependability of water supply. Prior research has demonstrated that Eleyele Reservoir experiences capacity reductions attributable to severe sedimentation (Oyelakin et al., 2023) and watershed stress resulting from urban expansion (Adejumo, 2023). Additionally, alterations in the onset and cessation of rainfall across Ibadan further underscore potential threats to reservoir refilling and water security (Fuwape & Ogunjo, 2018).

At the regional level, West Africa has experienced increasing rainfall variability, characterized by shifts in seasonal distribution, heightened inter-annual fluctuations, and the intensification of short-duration extremes that exacerbate flooding and erosion (Ibebuchi & Abu, 2023; Awode et al., 2025). These patterns are driven by large-scale mechanisms such as the Intertropical Convergence Zone (ITCZ) and Atlantic Ocean forcing, in addition to local land-use changes that influence runoff response (Funk et al., 2015). Nevertheless, there exists a paucity of basin-specific studies employing robust trend detection techniques and spatial mapping to analyze Eleyele rainfall records.

This study endeavors to fill that gap by systematically analyzing daily ERA5/ERA5-Land rainfall data from 1981 to 2023, employing the Mann–Kendall test and Sen’s slope method for trend quantification, and utilizing Inverse Distance Weighting (IDW) for spatial interpolation. The objectives are: (i) to quantify rainfall trends at monthly, seasonal, and annual intervals; (ii) to

delineate spatial variability across the basin; and (iii) to interpret the hydrological implications related to inflow timing, sediment transportation, and water-supply reliability.

II. Methodology

The methodology was devised with three primary objectives: firstly, to quantify long-term rainfall trends across monthly, seasonal, and annual scales employing the Mann–Kendall (MK) test and Sen’s slope estimator; secondly, to delineate spatial variability in rainfall through the application of the Inverse Distance Weighted (IDW) interpolation method; and thirdly, to analyze the hydrological implications of observed rainfall variations regarding reservoir inflow timing, sediment delivery risks, and water supply reliability.

Study Area

Eleyele Reservoir in Ido LGA, Oyo State, on the Ona River, is a multipurpose dam supporting water supply, irrigation, fisheries, and flood control. Its catchment spans 320–324 km², with a 1.6 km² surface area. The humid tropical climate has 1,250 mm annual rainfall and 26.6°C average temperature, with bimodal rainfall—wet from April to October, dry from November to March, and a mid-season dry in July and August.

Data Sources and Preprocessing

Daily rainfall data from 1981 to 2023, obtained from ERA5/ERA5-Land reanalysis, was used as the basin-mean series. Quality control removed implausible values, interpolated short gaps (up to three days), and adjusted longer gaps with monthly anomaly ratios. Homogeneity was tested using the Pettitt test. Lag-1 autocorrelation (ϕ_1) was estimated to address persistence; if significant, the Trend-Free Prewhitening Mann–Kendall (TFPW-MK) method was applied, involving detrending, prewhitening, and trend reapplication. Data were aggregated into monthly, seasonal, and annual totals for trend analysis.

Trend Detection and Magnitude

Monotonic trends were examined utilizing the Mann–Kendall (MK) statistic S and the standardized Z score. Furthermore, the magnitudes of these trends were estimated employing Sen’s slope β ($\alpha = 0.05$).

MK statistic:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (1)$$

Where x_j and x_k are the annual data values in years j and k , $j > k$, respectively, n is the number of observations. The $\text{sgn}(x_j - x_k)$ is determined:

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (2)$$

and S is normally distributed with mean = 0

The variance $\text{VAR}(S)$ and Z was computed:

$$\text{Var}(s) = \frac{n(n-1)(2n+5)}{18} \quad (3)$$

Computation for the Z score:

$$Z = \begin{cases} \frac{1-S}{\sqrt{V}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S-1}{\sqrt{V}} & \text{if } S < 0 \end{cases} \quad (4)$$

For a given level of significance α , this test rejects the null hypothesis of no trend in the time series if $|Z| > z_{1-\alpha}$. More specifically, $Z > z_{1-\alpha}$ indicates existence of an increasing trend and $Z < -z_{1-\alpha}$ implies a decreasing trend. The magnitude of trend will be analyzed by the Sen’s estimator (Anandakumar et al., 2008). Here, the slope (T_i) of all data pairs will be computed:

$$T_i = \frac{x_j - x_k}{j - k} \quad (5)$$

where x_j and x_k are considered as data values at times j and k ($j > k$). The median of these N values of T_i is represented as Sen’s estimator of slope:

$$Q_i = \begin{cases} T_{\frac{N+1}{2}} & N \text{ is odd} \\ \frac{1}{2} \left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}} \right) & N \text{ is even} \end{cases} \quad (6)$$

Sen's estimator is computed as $Q_{med} = T_{\frac{N+1}{2}}$ if N appears odd, and is considered as $Q_{med} = \frac{1}{2} \left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}} \right)$ if N appears even. At the end, Q_{med} is computed by a two-sided test at 100 (1- α) % confidence interval and then a true slope can be obtained by the non-parametric test. A positive value of Q_i indicates an increasing trend, and a negative value of Q_i gives a decreasing trend in the time series.

Spatial Interpolation of Rainfall

Spatial rainfall variability was mapped using Inverse Distance Weighting (IDW) in ArcGIS 10.8, with parameters set to power $p = 2$, adaptive search radius, and minimum neighbors = 8. The IDW predictor:

$$\hat{R}(s_0) = \frac{\sum_{i=1}^n d_{i0}^{-p} R(s_i)}{\sum_{i=1}^n d_{i0}^{-p}} \quad (7)$$

where $R(s_0)$ is rainfall at location s_0 , $R(s_i)$ is observed rainfall at station i , and d_{i0} is the distance between i and s_0 . Model accuracy was validated with leave-one-out cross-validation (LOOCV), minimizing Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (R_i - \hat{R}_i)^2} \quad (8)$$

Hydrological Implications Diagnostics

To analyze rainfall variability's impact on basin hydrology, three indicators were developed. First, the timing of inflow was examined by identifying shifts in the onset and cessation months of rainfall relative to the reservoir cycle. Second, sediment delivery risk was inferred from peak rainfall months and spatial distribution, noting that intense southern rainfall accelerates erosion and sediment inflow. Third, water supply reliability was assessed by correlating rainfall anomalies with reservoir recharge deficits during dry years when rainfall was below average by more than one standard deviation. These tools link rainfall trends to hydrological outcomes, aiding management.

Methodological Framework

The methodological workflow encompasses multiple stages, from data acquisition to hydrological interpretation. Figure 2.1 delineates the structured sequence: (i) data collection and preprocessing, including quality control and homogeneity testing; (ii) implementation of the TFPW-MK framework to reduce autocorrelation effects; (iii) Mann-Kendall and Sen's slope analyses across monthly, seasonal, and annual scales (Eqs. 1–6); (iv) spatial interpolation utilizing IDW with leave-one-out cross-validation (LOOCV) for parameter optimization (Eqs. 7–8); (v) derivation of hydrological diagnostics concerning inflow timing, sediment delivery risk, and water-supply reliability; and (vi) uncertainty quantification through Mann-Kendall confidence intervals and cross-validation error metrics.

Methodological Framework for Rainfall Variability and Hydrological Diagnostics

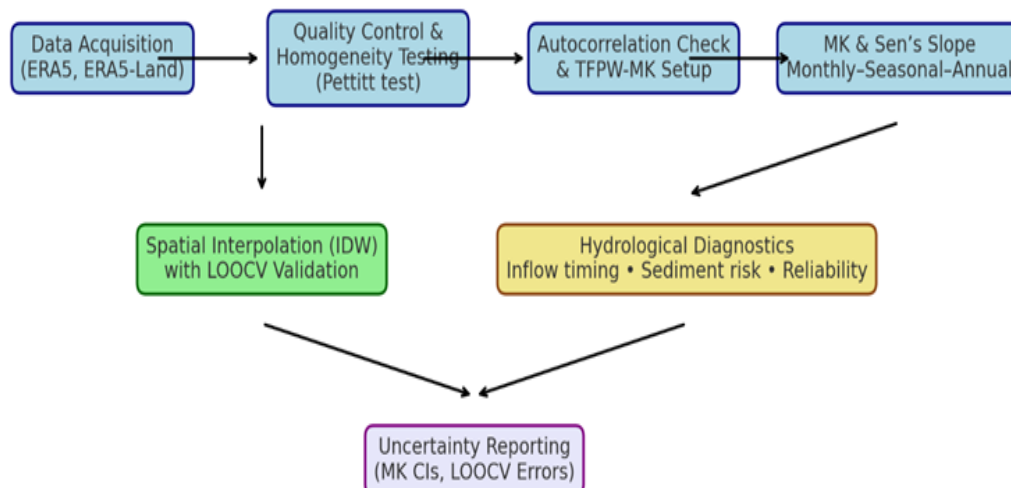


Figure 1. Methodological Framework for Rainfall Variability and Hydrological Diagnostics

III. Results and Discussion

The study's results include rainfall climatology, trends, deviations, distribution, variability, and operational implications for the Eleyele Dam Basin. It combines statistical data, Mann–Kendall and Sen's slope analyses, spatial maps, and comparisons from similar tropical basins, ensuring findings are statistically rigorous and hydrologically significant. This influences reservoir inflows, sediment transport, and long-term water resource stability.

Rainfall Amount of the Study Area

The rainfall climatology of the Eleyele Dam Basin demonstrates a pronounced seasonal pattern influenced by the Intertropical Convergence Zone (ITCZ). The basin's long-term annual mean rainfall is quantified at 1,515.04 mm, with an uneven distribution between the wet and dry seasons—approximately 86% (1,302.56 mm) occurring from April to October, and about 14% (approximately 86 mm) from November to March. Monthly data indicate a bi-peak pattern, with maxima in June (210.94 mm) and September (208.18 mm), separated by the so-called "August break" (213.75 mm). More than half of the annual precipitation occurs between June and September, which is crucial for reservoir inflows. The months of December and January record the lowest totals, reflecting the influence of continental air masses. The coefficient of variation (CV) values suggest reliable rainfall during the wet season (June CV=0.18, September CV=0.21) and significant variability during the dry season (January CV=0.85, February CV=0.73). These findings correspond with previous research conducted in southwestern Nigeria regarding bi-peak rainfall patterns and high dry season variability (Chineke et al., 2010; Ibebuchi & Abu, 2023).

Table 1. Monthly, seasonal, and annual rainfall patterns in the Eleyele Dam Basin (1981–2023).

Month/Season	Rainfall (mm)	Standard deviation	Coefficient of Variation	% Contribution
JAN	20.02	16.97	0.85	1.32
FEB	35.87	26.08	0.73	2.37
MAR	86.36	37.46	0.43	5.7
APRIL	120.54	28.95	0.24	7.96
MAY	181.73	41.82	0.23	12
JUNE	210.94	37.64	0.18	13.92
JULY	208.42	51.32	0.25	13.76
AUGUST	213.75	65.93	0.31	14.11
SEPTEMBER	208.18	43.92	0.21	13.74
OCTOBER	159	45.77	0.29	10.49
NOVEMBER	50.42	19.24	0.38	3.33
DECEMBER	19.81	15.3	0.77	1.31
Dry season (Nov–Mar)	212.48	27.62	0.13	14.02
Wet season (Apr–Oct)	1302.56	35.16	0.03	85.98
Annual	1515.04	80.11	0.05	100

Temporal Trends in Rainfall Amounts (1981–2023)

Dry Season Trends

Dry season totals show a significant 43-year decline. Linear regression (Figure 2) shows a slope of -2.89 mm/year ($R^2=0.37$), and Mann–Kendall test gives $Z = -3.73$ ($p < 0.001$) with Sen's slope of -2.91 mm/year (Table 2). Rainfall exceeded 300 mm in early 1980s (e.g., 1983, 1985, 1988), but levels were rarely surpassed after 2000, with lows in 2015 and 2021 (~ 100 mm). These results align with noted dry season contraction in northeastern and central Nigeria, with Mann–Kendall and Sen's tests confirming reduced rainfall from November to March (Ishaku, 2024; Odekunle, 2010). Such declines heighten Eleyele's vulnerability to dry-season deficits and recharge reduction, consistent with basin-scale observations in other semi-humid tropical catchments (Enyew et al., 2024).

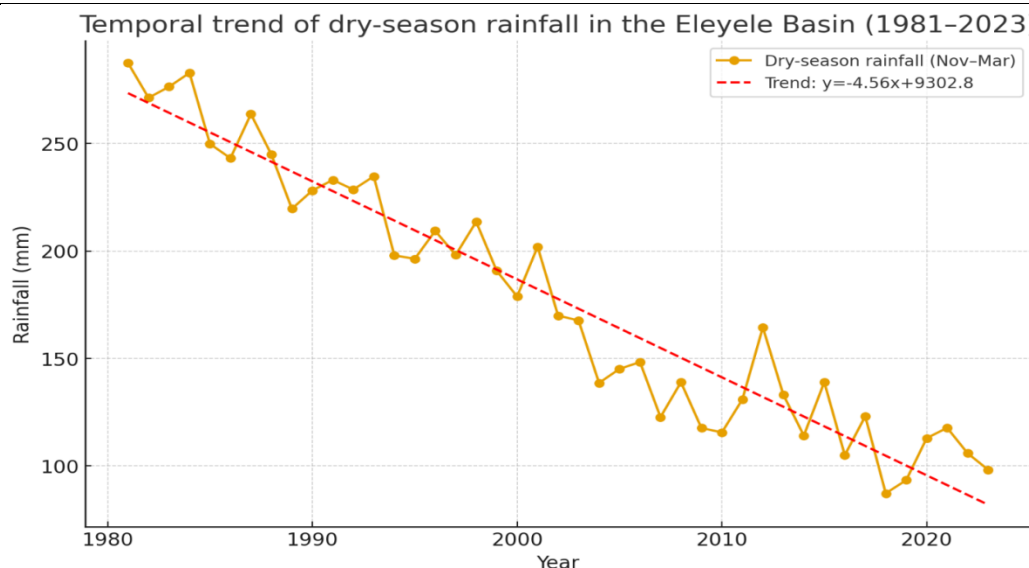


Figure 2. Temporal trend of dry-season rainfall in the Eleyele Basin (1981–2023).

Wet Season Trends

The wet season mainly influences the hydrological balance but shows a weak, non-significant decline (see Figure 3). Mann-Kendall test results indicate $Z = -1.34$ and Sen's slope = -2.82 mm/year (Table 2). The highest total precipitation, over 1,500 mm, was recorded in 1988, 1991, and 1996, while deficits below 1,100 mm occurred in 2007, 2015, and 2021. Peaks in June and September rainfall remain, but September–October totals declined during the 2010s, suggesting a shortened wet season. Similar shifts in rainy season dates and duration have been noted across West Africa, affecting agriculture and reservoir recharge (Fuwape & Ogunjo, 2018; Awode et al., 2025).

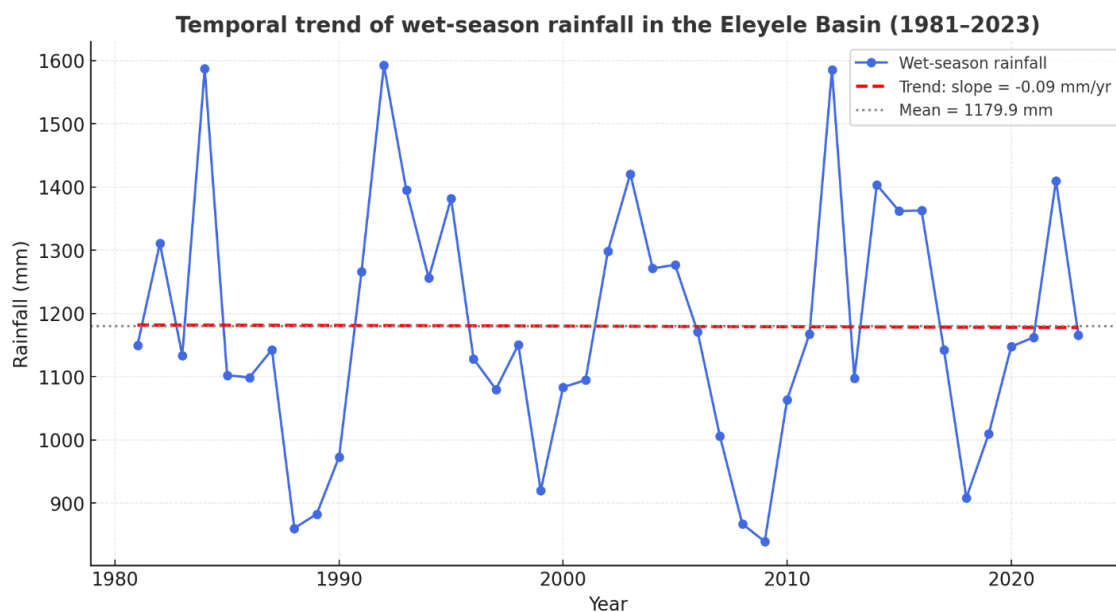


Figure 3. Temporal trend of wet-season rainfall in the Eleyele Basin (1981–2023).

Annual Trends

Rainfall exhibits a persistent decline over the long-term at the annual scale, with a slope of -4.17 mm/year ($R^2 = 0.09$). The Mann-Kendall test corroborates this trend, yielding a Z value of -2.01 ($p < 0.05$), and Sen's slope is measured at -5.26 mm/year (see Table 2). Throughout the 1980s, annual totals frequently exceeded 1,600 mm; however, they declined below 1,200 mm in the years 2001, 2007, 2015, and 2021. Instances of rainfall surpassing 1,500 mm, such as in 2010 and 2017, are infrequent. These observed patterns are consistent with regional studies of West African rainfall, which indicate decreasing or stagnant trends coupled with increased variability (Nicholson, 2018; Akinsanola et al., 2020). Specifically, for Eleyele, this declining trend signifies a reduction in renewable water resources and underscores the importance of implementing drought mitigation policies.

Table 2. Mann–Kendall test and Sen’s slope results for rainfall trends (1981–2023).

Month/Season	Test Z	Significance level (%)	Sen’s slope (mm yr ⁻¹)	Trend
January	−0.96	–	−0.205	Stable
February	−1.53	–	−0.455	Decreasing trend
March	−2.78	**	−1.483	Decreasing trend
April	−3.41	***	−1.253	Decreasing trend
May	−2.85	**	−1.618	Decreasing trend
June	0.13	–	0.083	Stable
July	−1.38	–	−1.002	Decreasing trend
August	0.96	–	0.92	Stable
September	1.09	–	0.489	Stable
October	−1.26	–	−0.499	Stable
November	−0.61	–	−0.150	Stable
December	−3.64	***	−0.483	Decreasing trend
Dry season	−3.73	***	−2.906	Decreasing trend
Wet season	−1.34	–	−2.816	Decreasing trend
Annual	−2.01	*	−5.260	Decreasing trend

Note: * significance at 0.05; ** significance at 0.01; *** significance at 0.001; (-) slopes indicate decreasing rainfall, positive slopes indicate increasing rainfall.

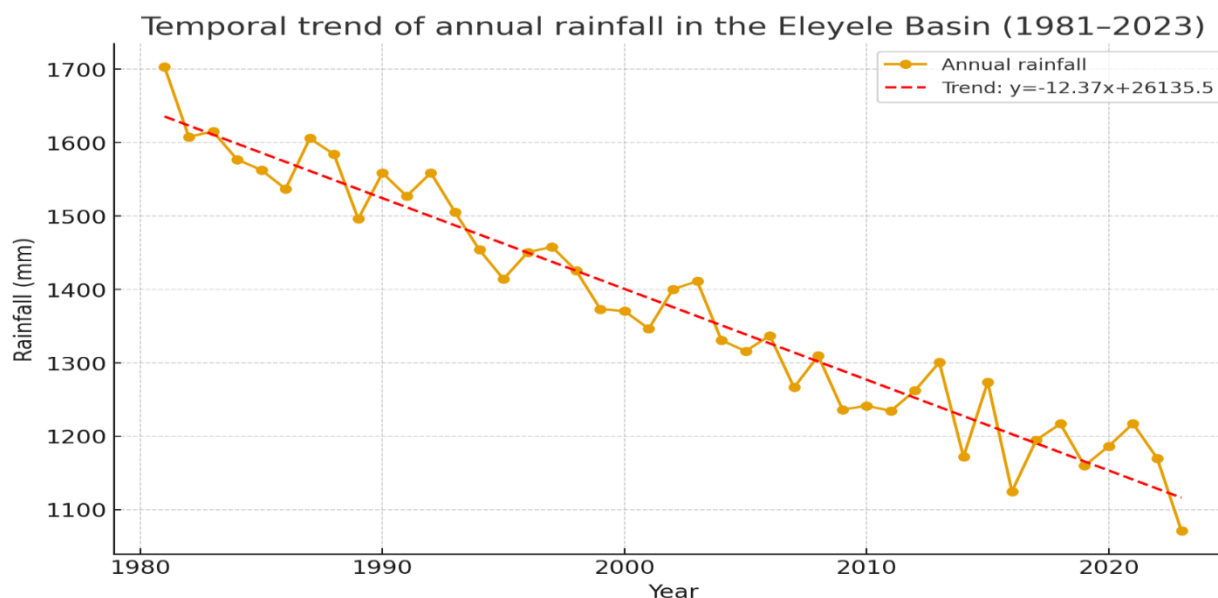


Figure 4. Temporal trend of annual rainfall in the Eleyele Basin (1981–2023).

Deviations from the Long-Term Mean

Rainfall deviations highlight frequent, severe anomalies, mainly in the 1980s dry season deficits and 1998–2000 surpluses. Wet season anomalies were more marked, with deficits in 2015, 2018, 2020 (−200 to −300 mm), and surpluses in 1998, 2013, 2021 (+200 to +400 mm). Annual deviations show negatives in 1985, 1987, 2018, and surpluses in 1998, 2002, 2019, 2021. Similar extreme anomalies relate to monsoon and Atlantic Sea Surface Temperatures (Dike et al., 2020; Akinsanola et al., 2020). These patterns increase risks for Eleyele, causing flooding and shortages.

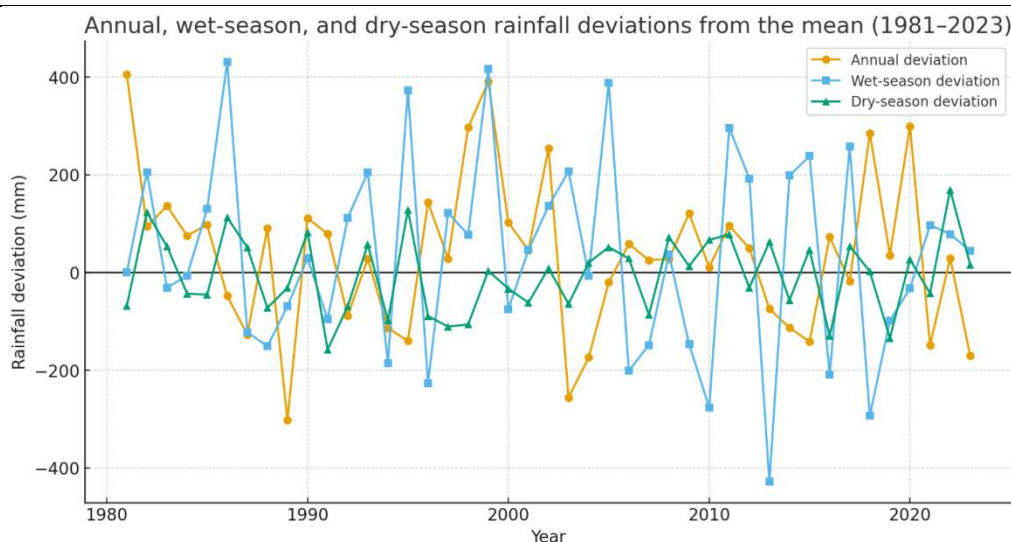


Figure 5. Annual, wet-season, and dry-season rainfall deviations from the mean (1981–2023).

Spatial Distribution of Rainfall

IDW maps show a north–south rainfall gradient in the Eleyele Basin, with annual totals from 1,266 mm in the north to 1,539 mm in the south (see Figure 6). Wet season rainfall ranges from 1,115 mm to 1,325 mm (Figure 7), while dry season totals stay below 213 mm. Monthly maps (Figure 8) reveal peaks in the south from June to September, linked to moist maritime (mT) air, while the north remains drier. Similar patterns are noted across Nigerian basins using gridded and satellite data (Pingale et al., 2014; IWA Water Supply, 2024), supporting the reliability of these maps despite ERA5 data uncertainties.

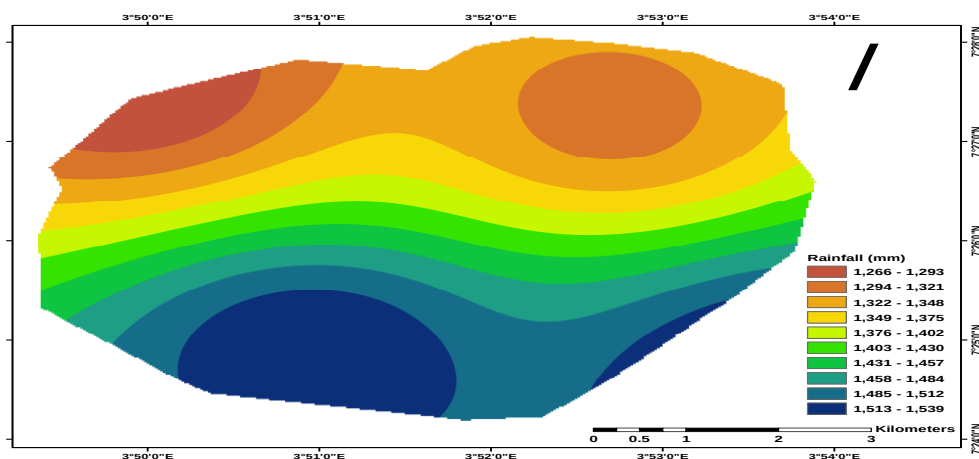


Figure 3 Spatial distribution of the mean annual rainfall over Eleyele Basin (1981–2023)

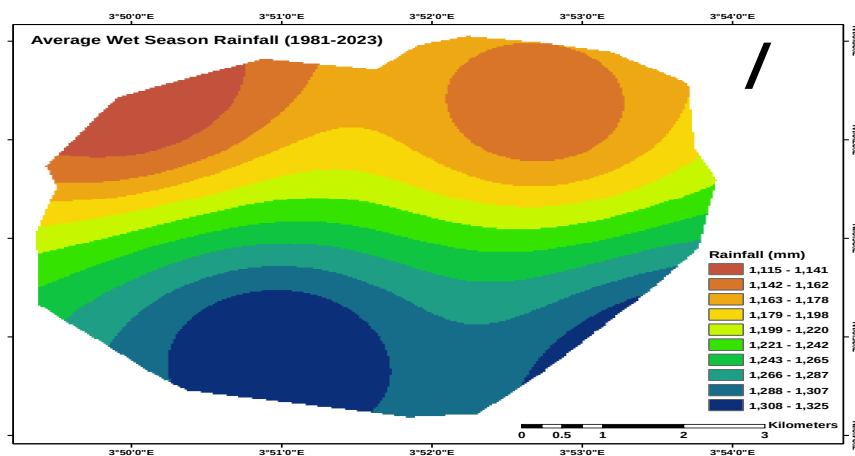


Figure 7a. Spatial distribution of seasonal rainfall in the Eleyele Basin (1981–2023).

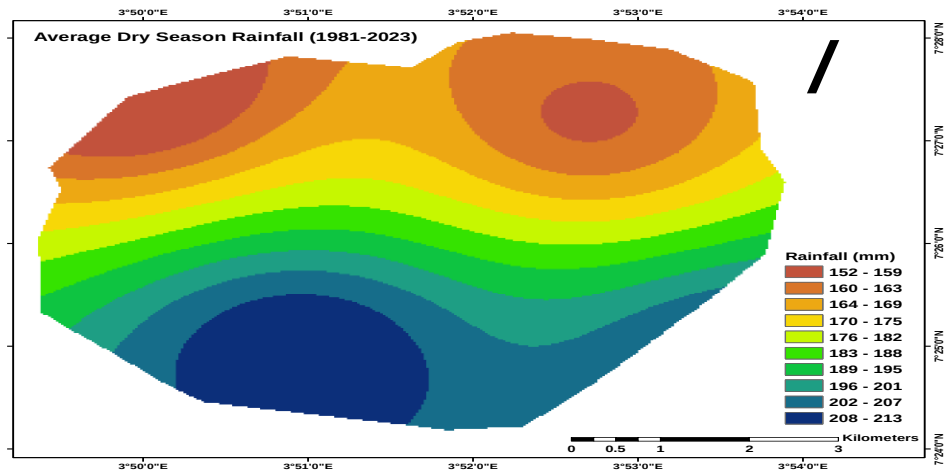


Figure 7b. Spatial distribution of seasonal rainfall in the Eleyele Basin (1981–2023).

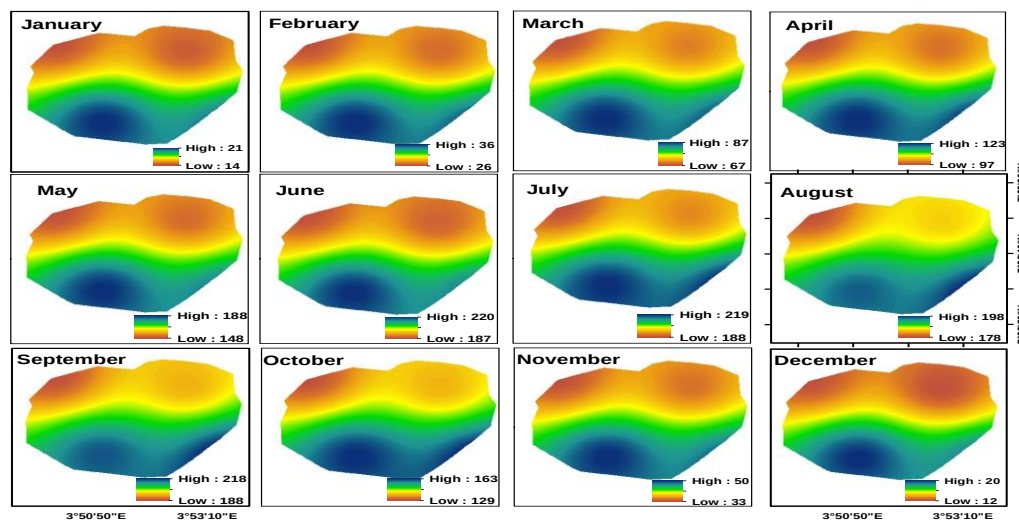


Figure 8. Spatial distribution of monthly rainfall in the Eleyele Basin (1981–2023).

Spatial and Temporal Variability (Coefficient of Variation)

The coefficient of variation (CV) indices show different stability patterns over time. Figures 9 and 10 reveal the annual rainfall CV is about 12%, mostly stable in the east. During the wet season, CV stays low at 11.76%–12.92%, confirming data accuracy. However, CV during the dry season exceeds 28%–30%, indicating unreliability from November to March. This matches other Nigerian basins where dry-season rainfall is more variable (Ishaku, 2024; Enyew et al., 2024). Reservoir reliability should mainly rely on wet-season inflows, and buffer storage must handle high CVs in dry months.

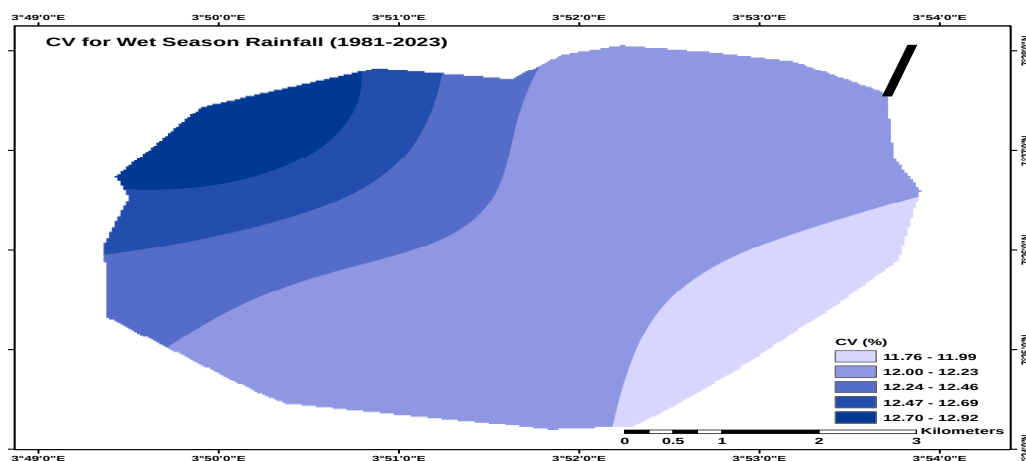


Figure 9a. Coefficient of variation of seasonal rainfall in the Eleyele Basin (1981–2023).

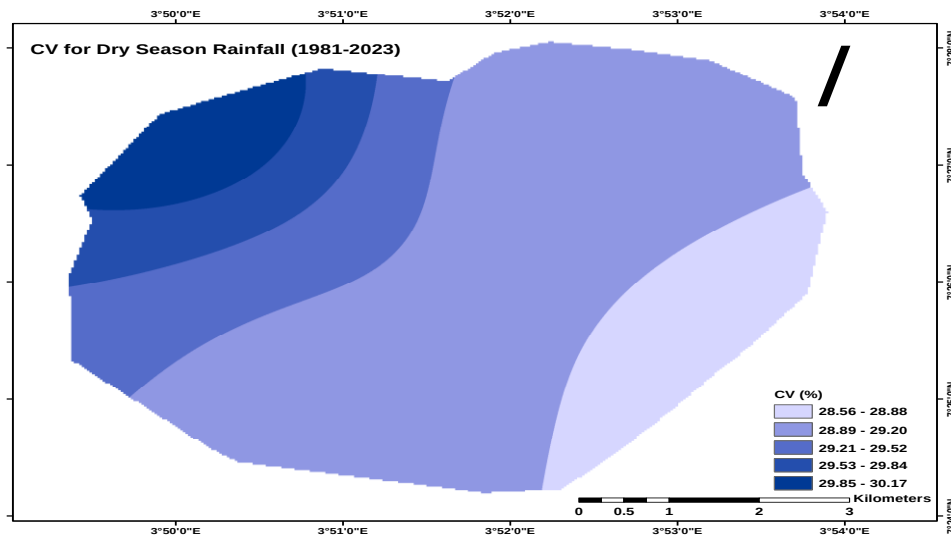


Figure 9b. Coefficient of variation of seasonal rainfall in the Eleyele Basin (1981–2023).

Implications for Reservoir Inflows and Sediment Management

Decreases in rainfall and shortened wet seasons impact Eleyele Reservoir operations. Reduced rainfall from March to May delays inflow, while less rain in September and October shortens recharge, causing concentrated inflows and dry season deficits unless reservoir rules are adjusted. Similar strategies are recommended elsewhere in Nigeria and West Africa. Intense rainfall increases sediment transport, especially in erosion-prone southern areas, raising sedimentation risks. Studies from Brazil and the Amazon support the need for catchment controls and sediment monitoring at Eleyele.

Synthesis of Findings

The results show a decline in annual and dry-season rainfall, a shorter wet season, and a persistent north–south rainfall gradient in the Eleyele Basin. Deviations confirm worsening extremes and high dry-season variability, indicating unreliable inflows. The conceptual framework (Figure 10) connects rainfall variability and atmospheric factors to hydrological processes, reservoir responses, and water-supply risks. Adaptive management, such as rule-curve updates and erosion controls, is crucial for resilience.

Conceptual Framework Linking Rainfall Variability, Hydrological Processes, Reservoir Responses, and Adaptive Management in the Eleyele Basin

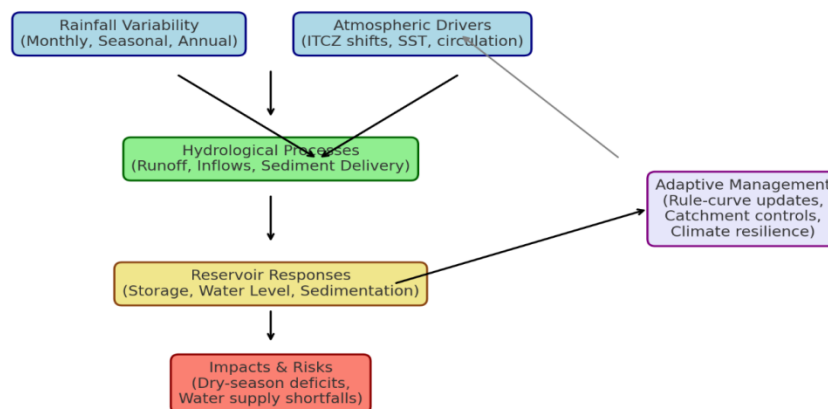


Figure 10. Conceptual Framework

IV. Conclusion and Recommendations

Conclusion

This study analyzed rainfall variability and trends in the Eleyele Dam Basin, Nigeria, using ERA5 data (1981–2023), Mann–Kendall, Sen’s slope estimators, and IDW interpolation. It confirms a bi-peak rainfall pattern (June and September) with a persistent north–south gradient, with higher totals in southern sub-catchments. Significant declines in annual rainfall (–5.26

mm/yr) and dry-season totals (-2.91 mm/yr) were found, along with weakening early wet-season contributions. Deviations from the mean show increasing extremes, and coefficients of variation indicate high unreliability in dry-season inflows. These changes suggest delayed, reduced inflows, increased dry-season deficits, and higher sedimentation risk, threatening the long-term water supply of Eleyele Reservoir.

Recommendations

- ★ Rule-curve modernization: Update reservoir operation rules to prioritize early storage capture (June–July) and account for weaker March–May and September–October rainfall.
- ★ Anomaly-based monitoring: Integrate early warning indices (SPI, ONI-linked forecasts) into release and demand-management decisions.
- ★ Catchment management: Implement erosion controls and riparian buffers in the southern sub-catchment to reduce sediment inflows.
- ★ Drought-resilience planning: Develop stepped demand-curtailement bands and buffer storage to mitigate multi-year drought sequences.
- ★ Data enhancement: Co-validate ERA5 estimates with local gauge records and publish bias-correction factors for improved operational use.
- ★ Policy integration: Mainstream climate-resilient water resource planning into Ibadan’s urban water supply strategy to safeguard Eleyele’s multipurpose role.

Policy Statement

The Eleyele Basin's declining rainfall and increasing variability require urgent policy action. Integrating adaptive reservoir management, catchment conservation, and climate-aware planning into Ibadan’s water strategy will improve reliability. Including these in Nigeria’s Water Resources Master Plan will strengthen resilience, ensuring the Eleyele Reservoir can meet urban demand despite climate challenges.

Closing Remark

This study provides robust evidence of changing rainfall patterns in the Eleyele Basin and their implications for water resource sustainability. The findings underscore the urgency of climate-resilient planning, reservoir regulation updates, and catchment management interventions to ensure long-term water security for Ibadan and its environs.

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Author Contributions

- **S.A. Adefisoye:** Conceptualization, methodology, data analysis, manuscript drafting.
- **O.S. Olaniyan:** Data curation, trend analysis, interpretation, review and editing.
- **A.A. Adegbola:** Spatial analysis, validation, visualization, and critical revision.

All authors reviewed and approved the final version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial or personal interests that could have influenced the work reported in this paper.

Data Availability

The ERA5 rainfall datasets analyzed in this study are publicly available from the European Centre for Medium-Range Weather Forecasts (ECMWF) at <https://cds.climate.copernicus.eu>. Processed datasets and supplementary materials are available from the corresponding author upon reasonable request.

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