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Research Article

Multi-Scale Rainfall Variability and Hydroclimatic Extremes in Northwestern Nigeria

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ABSTRACT

Understanding rainfall variability is essential for climate adaptation, agricultural planning, and water resource management in the Sudano-Sahelian region of West Africa. This study examined rainfall variability and hydroclimatic behaviour across northwestern Nigeria using NASA-POWER rainfall data (1983–2024). Rainfall trends, persistence, oscillatory behaviour, and hydroclimatic anomalies were analysed using Mann-Kendall trend testing, Sen's slope estimation, autocorrelation analysis, wavelet analysis, and the Standardised Precipitation Index (SPI). The results revealed substantial spatial and temporal variability in rainfall across the region. Statistically significant increasing rainfall trends were observed in Katsina, Kebbi, and Sokoto States, while Zamfara exhibited a significant decreasing trend ($p < 0.05$). However, no significant long-term trend was detected for northwestern Nigeria as a whole, indicating that strong interannual fluctuations dominate regional rainfall variability. Autocorrelation analysis revealed strong seasonal persistence but weak annual rainfall memory, while wavelet analysis identified significant oscillatory behaviour across multiple temporal scales. The SPI analysis further showed alternating wet and dry phases, highlighting the recurrent occurrence of hydroclimatic extremes and rainfall anomalies. Although wetter conditions appeared more frequently in recent decades, the weak SPI trend suggests that caution is required when inferring long-term climatic transitions. The study concludes that rainfall variability in northwestern Nigeria is characterised by spatial heterogeneity, weak long-term persistence, evolving oscillatory behaviour, and recurring hydroclimatic extremes. These findings provide valuable insights for climate adaptation planning, drought preparedness, and sustainable water resource management within the climate-sensitive Sudano-Sahelian region of West Africa.

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1.0 INTRODUCTION

Rainfall variability and hydroclimatic extremes have become increasingly important subjects in contemporary climate research due to their profound implications for water resources, agricultural productivity, ecosystem stability, and socioeconomic sustainability across vulnerable regions of the world (Awode et al., 2025; Tahroudi, 2025; Tefera et al., 2025; Wang et al., 2025). Recent decades have witnessed increasing occurrences of droughts, floods, erratic rainfall patterns, and shifting seasonal regimes associated with changing atmospheric circulation processes and intensified climate variability (Tefera et al., 2025; Wang et al., 2025). These hydroclimatic disturbances are particularly critical within semi-arid and tropical regions where livelihoods and food systems remain highly dependent on rainfall-sensitive sectors such as rain-fed agriculture. Consequently, understanding the temporal variability, persistence, and oscillatory behaviour of rainfall systems is essential for climate adaptation planning, drought preparedness, flood risk reduction, and sustainable environmental management.

The West African Sahel represents one of the most climatically sensitive regions globally because of its strong exposure to rainfall instability and hydroclimatic extremes. Rainfall variability across the Sahel is characterised by substantial interannual and decadal fluctuations associated with the complex interaction between the West African Monsoon system, atmospheric circulation processes, and large-scale ocean-atmosphere interactions (Biasutti, 2019; Dia-Diop et al., 2020; Nicholson, 2013). The region has historically experienced severe drought episodes, prolonged dry periods, and episodic extreme wet conditions that have significantly affected food security, water availability, ecosystem sustainability, and socioeconomic stability. Increasing evidence further suggests intensification in hydroclimatic extremes across parts of West Africa, including increasing occurrences of flood events, rainfall anomalies, and irregular seasonal rainfall distributions (Biasutti, 2019; Tefera et al., 2025; Wang et al., 2025).

Northwestern Nigeria occupies a climatically sensitive section of the Sudano-Sahelian ecological zone and remains highly vulnerable to rainfall irregularities because of its strong dependence on rain-fed agriculture and seasonal water availability. Previous studies conducted within the region have reported substantial rainfall variability, changing rainfall regimes, drought occurrence, and increasing hydroclimatic instability. For instance, Ekpoh & Nsa (2011) identified significant interannual rainfall fluctuations and recurrent drought episodes across northwestern Nigeria, while Abaje et al. (2014) reported increasing rainfall amounts and associated flood risks in Kano State since the mid-1990s. Similarly, Mohammed et al. (2015) observed considerable variability in rainfall onset, duration, and intensity over Kano during a century-long rainfall assessment. More recently, Edokpa et al. (2023) identified moderate rainfall variability and strong seasonal rainfall dependence in Kano and Katsina States, further highlighting the climatic vulnerability of the region. Several other studies across Nigeria and sub-Saharan Africa have similarly documented substantial hydroclimatic variability and increasing climate extremes. Olalere et al. (2021) utilised the Standardised Precipitation Index (SPI) to identify alternating wet and dry rainfall anomalies across northwestern Nigeria, while Butu & Emeribe (2019) reported increasing moisture deficits and gradual aridity expansion within the Sudan Savannah region of Nigeria. Adeyeri et al. (2019) further projected increasing extreme rainfall events and warming trends across northern Nigeria using regional climate model simulations. Beyond Nigeria, studies by Gebrechorkos et al. (2019) and Muthoni et al. (2018) emphasised the importance of high-resolution climatic analyses for understanding localised rainfall variability and climate impacts across African drylands.

Despite the growing body of research on rainfall variability across Nigeria and the wider West African Sahel, most previous studies have focused on isolated aspects of rainfall behaviour, including trend detection, drought assessment, rainfall seasonality, or climatic extremes. While these studies have provided valuable insights into regional hydroclimatic conditions, limited attention has been given to the integrated assessment of rainfall variability, climatic persistence, oscillatory behaviour, and hydroclimatic anomalies within a unified analytical framework. Furthermore, northwestern Nigeria occupies a climatically sensitive section of the Sudano-Sahelian region where livelihoods, water resources, and agricultural systems remain highly dependent on rainfall. Despite the socio-economic importance of the region, comprehensive hydroclimatic investigations that simultaneously evaluate rainfall trends, climatological characteristics, temporal persistence, oscillatory variability, and rainfall anomalies over long observational periods remain scarce. This knowledge gap limits the development of evidence-based climate adaptation and water resource management strategies. This study addresses these limitations by integrating linear trend analysis, Mann-Kendall significance testing, Sen's slope estimation, rainfall climatology, autocorrelation function (ACF) analysis, continuous wavelet transform (CWT), and Standardised Precipitation Index (SPI) assessment to examine rainfall behaviour across northwestern Nigeria during the period 1983–2024.

2.0 METHODOLOGY

2.1 Study Area

The study was conducted in northwestern Nigeria, comprising the states of Kano, Jigawa, Katsina, Kaduna, Kebbi, Sokoto, and Zamfara (Figure 1). The region lies approximately between latitudes 9°00′N and 14°00′N and longitudes 3°00′E and 12°00′E, covering a substantial portion of the Sudano-Sahelian belt of Nigeria. Northwestern Nigeria occupies a climatically sensitive transition zone between the Sahel Savannah, Sudan Savannah, and northern Guinea Savannah ecological regions (Adedibu et al., 2022).

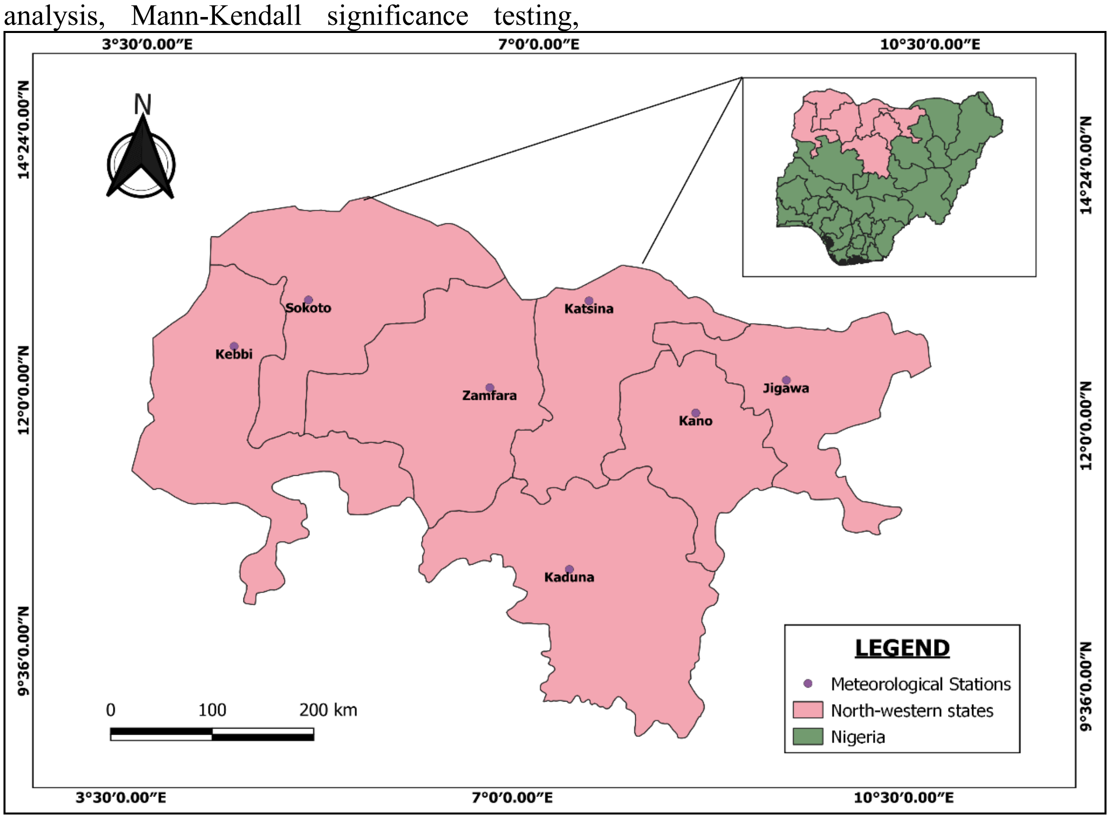

Figure 1: The Study Area (North-western Nigeria)
Source: Adopted from (Tanko et al., 2026)

The climate of the region is characterised by distinct wet and dry seasons controlled primarily by the seasonal migration of the Inter-Tropical Discontinuity (ITD) and the associated West

African Monsoon system. Rainfall is highly seasonal and occurs mainly between May and October, while the dry season extends from November to April under the influence of the dry continental tropical air mass originating from the Sahara Desert (Hashidu & Badaru, 2021; Olalere et al., 2021). Mean annual rainfall generally decreases northward across the region, reflecting the gradual transition from relatively wetter Guinea Savannah conditions in southern Kaduna and Kebbi States to the drier Sahelian environments of Sokoto, Katsina, Jigawa, and northern Kano States (Butu & Emeribe, 2019). Due to the strong dependence of agricultural systems on seasonal rainfall, the region remains highly vulnerable to rainfall variability, drought occurrence, and hydroclimatic extremes.

2.2 Rainfall Data, Validation and Quality Control

Monthly rainfall data for the seven states of northwestern Nigeria, namely Kano, Jigawa, Katsina, Kaduna, Kebbi, Sokoto, and Zamfara, were obtained from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA-POWER) database (https://power.larc.nasa.gov/data-access-viewer/) for the period 1983-2024. NASA-POWER rainfall data were adopted because of their temporal consistency, spatial coverage, accessibility, and demonstrated reliability in hydroclimatic studies across data-sparse regions of Africa. Previous studies including Darman et al. (2024), Rodrigues & Braga (2021), and Tayyeh & Mohammed (2023) have validated the suitability of NASA-POWER datasets for climatic analyses. The selected stations corresponded to the geographical coordinates of representative Nigerian Meteorological Agency (NiMet) synoptic stations distributed across the study area.The 42-year study period was selected to ensure adequate representation of long-term rainfall variability, trends, and climatic fluctuations across the Sudano-Sahelian region of northwestern Nigeria.

To assess the reliability of the NASA-POWER rainfall product, the annual rainfall totals derived from NASA-POWER were compared with available corresponding ground-based observations obtained from some Nigerian Meteorological Agency (NiMeT) synoptic stations within the study area. The NiMeT data obtained was only for five stations (Kano, Kaduna, Katsina, Sokoto and Yelwa) for the period of 1985 – 2015, and as such, the validation was conducted for that common period using Pearson's correlation coefficient (r), coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean bias error (MBE). These metrics provided quantitative measures of agreement, accuracy, and potential systematic bias between the satellite-derived and observed rainfall datasets.

Before analysis, the rainfall datasets were subjected to quality control procedures including screening for missing observations, consistency checks, temporal continuity assessment, and visual inspection for potential outliers and anomalous values. Regional rainfall averages for northwestern Nigeria were subsequently computed by averaging the annual rainfall totals from the seven selected stations.

2.3 Trend Detection and Rainfall Variability Analysis

Temporal trends in annual rainfall were evaluated using a combination of linear regression, the non-parametric Mann-Kendall (MK) trend test, and Sen's slope estimator. Linear regression was used to quantify the direction and magnitude of rainfall changes through time and is expressed as:

$$Y_t = \alpha + \beta_t + \epsilon_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Where: Y_t represents the rainfall amount at year or month t; α is the intercept; β_t is the slope coefficient indicating the rate of rainfall change over time; ϵ_t represents the random error term.

To determine whether observed rainfall trends were statistically significant, the Mann-Kendall test was applied. The test evaluates the null hypothesis that no monotonic trend exists within the rainfall series. Trends were considered statistically significant at $p < 0.05$. The Mann-Kendall statistic (S) is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad \ldots\ldots\ldots\ldots\ (2)$$

Where: S represents the MK statistic; n is the total number of data points (years of rainfall data); x_i and x_j are sequential rainfall data values in time periods i and j.

The magnitude of detected trends was estimated using Sen's slope estimator, which calculates the median rate of change between all possible data pairs within the time series. The Sen's slope estimator (Q) is defined as:

$$Q = median\left(\frac{x_j - x_i}{j-i}\right) \ \forall\ 1 \le i < j \le n \text{........... (3)}$$

Where: x_i and x_j represent the annual rainfall totals in years j and i $(j > i)$, respectively, and n is the total number of years in the study period.

Positive Sen's slope values indicate increasing annual rainfall trends, while negative values indicate decreasing trends, expressed in millimetres per year (mm yr^{-1}).

Rainfall variability was further quantified using descriptive statistics, including the mean, standard deviation (SD), and coefficient of variation (CV). Seasonal rainfall characteristics were examined through mean monthly rainfall climatology derived from long-term monthly averages.

2.4 Autocorrelation Function (ACF) Analysis

The autocorrelation function (ACF) was employed to investigate rainfall persistence, seasonality, and temporal dependence within the monthly and annual rainfall series. The ACF measures the correlation between rainfall observations separated by specified time lags and is expressed as:

$$\rho k = \frac{\sum_{t=1}^{N-k}(x_t - \bar{X})(x_{t+k} - \bar{X})}{\sum_{t=1}^{N}(x_t - \bar{X})^2} \text{ .... (4)}$$

Where: ρk represents the autocorrelation coefficient at lag k; x_t represents the value of the time series at time t; x_{t+k} represents the value of the time series k time steps ahead of t; $\bar{X}$ is the mean of the entire time series; N is the total number of observations in the time series; k denotes the lag interval.

The statistical significance of autocorrelation coefficients was evaluated using the 95% confidence interval, enabling identification of significant persistence and periodic behaviour within the rainfall series.

2.5 Wavelet Analysis

Wavelet analysis was employed to investigate the temporal evolution of rainfall variability across multiple timescales. Unlike conventional spectral techniques, wavelet analysis simultaneously examines both frequency and temporal characteristics of a time series, making it particularly suitable for non-stationary climatic data. The continuous wavelet transform is expressed as:

$$W_n(s) = \sum_{t=0}^{N-1} X_t\, \psi^*\left(\frac{t-n}{s}\right) \text{.............. (5)}$$

Where: $W_n(s)$ represents the wavelet transform; X_t denotes the rainfall time series; ψ^*represents the complex conjugate of the mother wavelet; s is the temporal scale; and n represents the translation parameter.

The Continuous Wavelet Transform (CWT) based on the Morlet mother wavelet was applied to the regional rainfall series to identify dominant periodicities and transient oscillatory signals. Statistical significance of wavelet power was evaluated against a red-noise background spectrum at the 95% confidence level. The cone of influence (COI) was used to identify regions potentially affected by edge effects and, therefore, requiring cautious interpretation.

2.6 Standardised Precipitation Index (SPI)

The Standardised Precipitation Index (SPI) developed by (McKee *et al.,* 1993) was used to evaluate interannual rainfall anomalies and to classify wet and dry conditions across northwestern Nigeria. Although SPI can be evaluated at multiple temporal scales for operational drought monitoring, the present study focused on broad-scale rainfall variability and long-term hydroclimatic behaviour rather than short-term drought assessment. Consequently, annual SPI was considered appropriate for examining regional-scale rainfall fluctuations over the study period. The SPI standardises rainfall departures from the long-term mean and is expressed as:

$$SPI = \frac{X - \bar{X}}{\sigma} \text{.............................. (6)}$$

Where: X represents the annual rainfall amount; $\bar{X}$ represents the long-term mean rainfall; and σ represents the standard deviation.

Positive SPI values indicate wetter-than-normal conditions, while negative values indicate drier-than-normal conditions. The SPI analysis facilitated the identification of dry and wet anomalies and long-term hydroclimatic variability across the study area. Given the objective of examining long-term rainfall variability, annual SPI was considered appropriate for evaluating broad hydroclimatic fluctuations at the regional scale.

3.0 RESULTS

3.1 Validation of NASA-POWER Rainfall Data

The results of the validation of the NASA-POWER rainfall product against available NiMet observations are presented in Table 1. Findings revealed varying levels of agreement across the selected stations. Correlation coefficients ranged from -0.199 in Kaduna to 0.410 in Sokoto, while RMSE values ranged from 179.21mm in Sokoto to 562.66mm in Kano. The observed discrepancies may be attributed to differences between point-based gauge observations and gridded satellite-reanalysis rainfall estimates, which represent spatially averaged atmospheric conditions. Although station-level agreement varied, the objective of the study was to evaluate broad-scale rainfall variability rather than local rainfall prediction. Additionally, NASA-POWER has been widely utilised for regional hydroclimatic assessments in data-sparse environments (Darman et al., 2024; Rodrigues & Braga, 2021; Tayyeh & Mohammed, 2023) and was therefore considered suitable for examining broad-scale rainfall variability across northwestern Nigeria because of its spatial consistency, long temporal coverage, and demonstrated applicability in regional hydroclimatic assessments.

Table 1: Validation Statistics Between NASA-POWER and NiMet Annual Rainfall Data (1985 - 2015)

Station	r	R^2	RMSE (mm)	MAE (mm)	MBE (mm)
Kaduna	-0.199	0.039	541.69	467.22	246.98
Kano	-0.126	0.016	562.66	475.26	-353.71
Katsina	0.199	0.040	215.94	156.56	-20.27
Sokoto	0.410	0.168	179.21	140.51	-104.04
Kebbi (Yelwa)	0.224	0.050	369.65	314.80	-257.96

3.2 Linear Rainfall Trends and Variability in Northwestern Nigeria

The linear regression analysis across the seven states of northwestern Nigeria from 1983 to 2024 revealed substantial spatial variability in rainfall behaviour across the region (Figure 2). Positive rainfall trends dominated most parts of the study area, although the magnitudes of increase varied considerably among the states. Kaduna State exhibited the strongest positive rainfall trend of 24.65mm/year, followed by Katsina and Sokoto States with 15.40mm/year and 13.34mm/year, respectively, indicating gradual increases in annual rainfall over the study period. Kebbi State also displayed a moderate positive trend of 8.48mm/year. Conversely, Kano (-2.55mm/year), Jigawa (-2.25mm/year), and Zamfara (-4.46mm/year) exhibited weak declines in rainfall, suggesting slight reductions in annual rainfall within these states of the study region.

Figure 2: Interannual Rainfall Trends Across Northwestern Nigerian States (1983-2024)

The rainfall trend characteristics and variability statistics for the selected states are presented in Table 2. The coefficients of determination (R^2) indicate generally weak to moderate linear relationships between rainfall and time across the study area, implying that a substantial proportion of rainfall variability is influenced by non-linear climatic processes and short-term atmospheric fluctuations rather than persistent long-term trends. Sokoto (46%) and Katsina (39%) recorded relatively stronger trend associations, whereas Kano (1.1%) and Jigawa (0.91%) exhibited very weak trend relationships, reflecting the highly erratic nature of rainfall variability within the Sahelian environment.

Table 2: Slope and Trend Summary for States of Northwestern Nigeria (1983 – 2024)

State	Mean (mm)	Slope (mm/year)	Intercept	R-squared	CV	SD
Kano	710.31	-2.55	5826.84	0.011	42.13	299.23
Katsina	662.41	15.40	-30187.77	0.39	45.91	304.08
Kaduna	1739.15	24.65	-47649.42	0.087	59.07	1027.29
Kebbi	767.30	8.48	-16228.22	0.16	33.80	259.35
Jigawa	684.16	-2.25	5190.93	0.0091	42.32	289.51
Sokoto	645.75	13.34	-26079.54	0.46	37.18	240.07
Zamfara	819.83	-4.46	9747.97	0.055	28.38	232.64

Source: Author's Analysis (2026)

Rainfall variability across the study area was further reflected by the coefficients of variation (CV), which ranged from relatively moderate values in Kebbi (33.80%) and Zamfara (28.38%) to substantially higher values in Kaduna (59.07%), Kano (42.13%), Katsina (45.91%), and Jigawa (42.32%). The elevated variability observed across much of the region highlights the instability of rainfall regimes and the vulnerability of rain-fed agricultural systems to fluctuating hydroclimatic conditions.

At the regional scale, northwestern Nigeria exhibited an overall positive rainfall trend during the 1983-2024 period (Figure 3). Although the regional trend of 7.64mm/year remained relatively weak, the rainfall series demonstrated substantial interannual fluctuations characterised by alternating wet and dry phases. Relatively wetter conditions dominated parts of the 1980s and early 1990s, while prolonged below-average rainfall conditions became more apparent between the late 1990s and 2019. However, exceptionally wet years emerged after 2020, culminating in the extreme rainfall conditions observed in 2021.

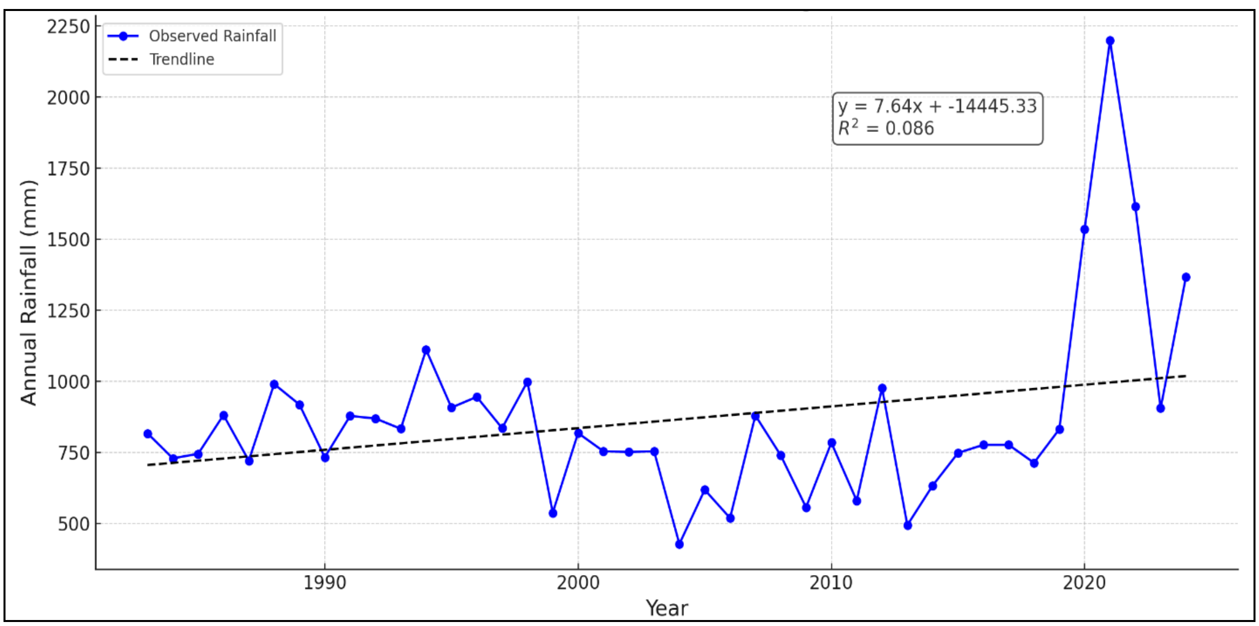

Figure 3: Regional Annual Rainfall Variability in Northwestern Nigeria (1983–2024)

The regional rainfall series further revealed the increasing occurrence of hydroclimatic extremes across northwestern Nigeria in recent years. Despite the modest positive long-term trend, the pronounced year-to-year rainfall variability suggests that regional rainfall dynamics are still strongly controlled by short-term climatic oscillations rather than stable long-term climatic shifts. The observed variability underscores the limitations of relying solely on linear regression for trend assessment and justifies the subsequent application of Mann-Kendall trend testing and Sen's slope estimation to evaluate the statistical significance and robustness of the detected rainfall tendencies.

3.3 Mann-Kendall Trend Test and Sen's Slope Estimation

The Mann-Kendall test and Sen's slope estimator were applied to evaluate the statistical significance and magnitude of annual rainfall trends across northwestern Nigeria between 1983 and 2024 (Table 3). The results revealed considerable spatial variability in rainfall behaviour across the region. Significantly increasing rainfall trends were detected in Katsina (Sen's slope = 9.38 mm yr^{-1}, $p < 0.001$), Kebbi (4.34 mm yr^{-1}, $p = 0.017$), and Sokoto (10.55 mm yr^{-1}, $p < 0.001$). Conversely, Zamfara exhibited a significant decreasing trend of -6.44 mm yr^{-1} ($p = 0.032$). Although positive rainfall tendencies were observed in Kaduna and negative tendencies in Kano and Jigawa, the Mann-Kendall test indicated that these trends were not statistically significant at the 5% significance level. Similarly, the regional rainfall series for northwestern Nigeria showed a slight positive Sen's slope of 0.65 mm yr^{-1}, however, the trend was statistically insignificant ($p = 0.770$). These findings suggest that rainfall variability across the region is dominated primarily by strong interannual fluctuations rather than a uniform long-term climatic trend.

Table 3: Mann–Kendall Trend Test and Sen's Slope Estimates for Annual Rainfall (1983–2024)

Station	Sen's Slope (mm yr^{-1})	Kendall's Tau	Z-statistic	p-value	Trend Interpretation
Kaduna	1.531	0.027	0.238	0.8116	No significant trend
Kano	-7.031	-0.178	-1.647	0.0995	No significant trend
Katsina	9.375	0.413	3.847	0.0001	Significant increasing trend
Kebbi	4.342	0.257	2.384	0.0171	Significant increasing trend
Jigawa	-6.680	-0.167	-1.550	0.1212	No significant trend
Zamfara	-6.444	-0.231	-2.146	0.0319	Significant decreasing trend
Sokoto	10.547	0.473	4.400	<0.0001	Significant increasing trend
Northwestern Nigeria	0.647	0.033	0.293	0.7698	No significant trend

The results highlight the heterogeneous nature of rainfall changes within northwestern Nigeria and demonstrate the importance of applying robust non-parametric statistical techniques when assessing hydroclimatic trends. Reliance solely on linear regression may overstate the significance of apparent increases or decreases in rainfall where substantial year-to-year variability exists.

3.4 Monthly Rainfall Climatology in Northwestern Nigeria

The mean monthly rainfall distributions across the seven states of northwestern Nigeria from 1983 to 2024 revealed a distinct unimodal rainfall regime characteristic of the Sudano-Sahelian climatic zone (Figure 4). Rainfall onset generally commenced between April and May, intensified progressively through June, and reached peak intensity during July and August before declining rapidly from September onwards. Minimal rainfall amounts were observed between November and March, reflecting the prolonged dry season associated with the dominance of continental tropical air masses across the region. Although the general seasonal rainfall structure was broadly similar across all states, noticeable spatial differences were evident in rainfall magnitude and duration.

Kaduna and Kebbi States recorded relatively higher rainfall amounts during the peak rainy season, reflecting their stronger Guinea and Sudan Savannah influences. In contrast, Kano, Jigawa, and Katsina exhibited comparatively lower rainfall peaks and shorter effective rainy seasons, consistent with their more Sahelian climatic characteristics.

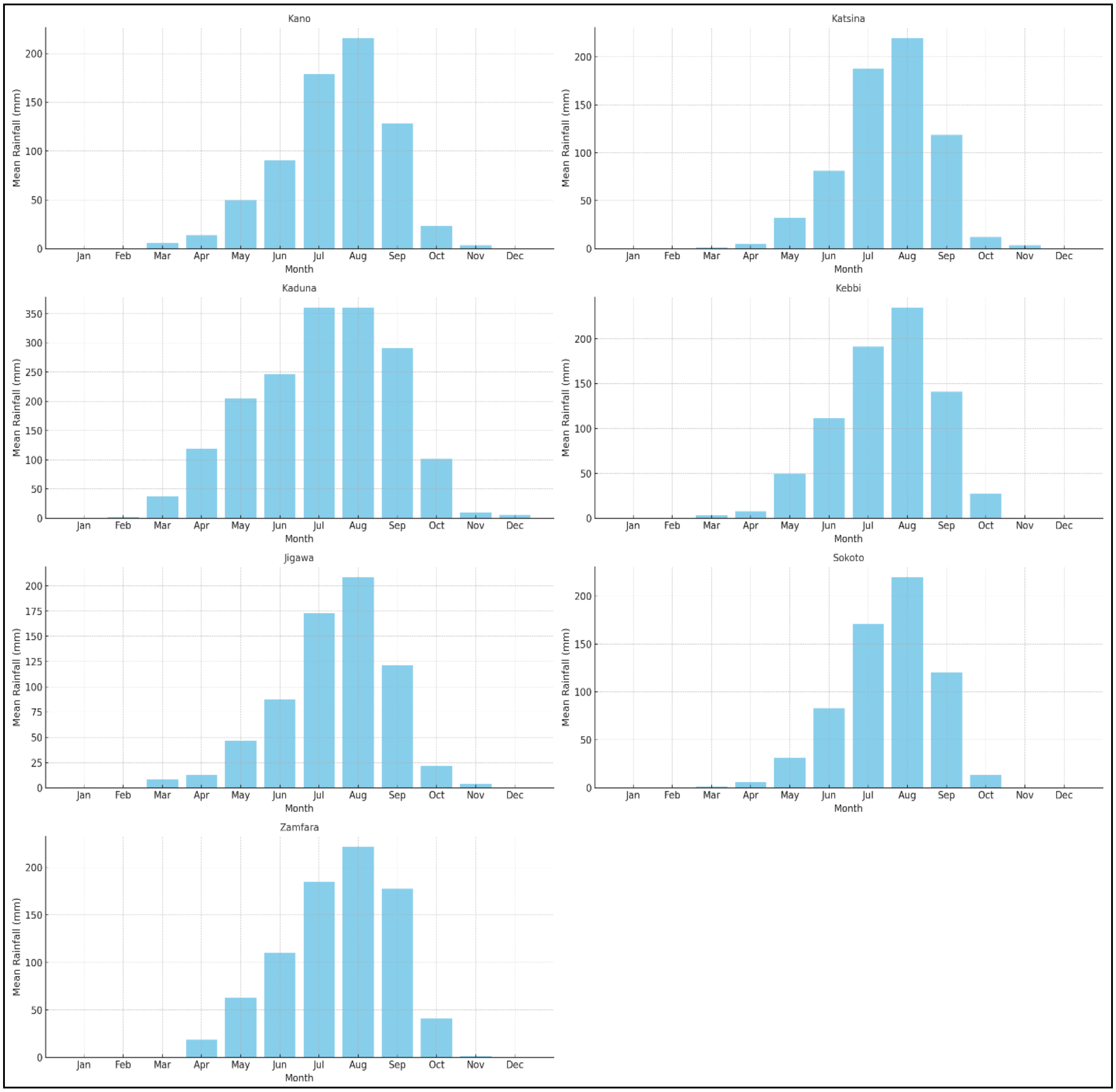

Figure 4: Mean Monthly Rainfall Climatology in States of Northwestern Nigeria (1983-2024)

The regionalised monthly rainfall climatology for northwestern Nigeria further confirmed the dominance of a single-peaked rainfall regime across the study area (Figure 5). Most annual rainfall occurred within a relatively short wet-season window extending from May to October, with July and August accounting for the highest rainfall contributions. The concentration of rainfall within this limited seasonal period highlights the strong dependence of agricultural production systems in northwestern Nigeria on the timing, intensity, and continuity of seasonal rainfall.

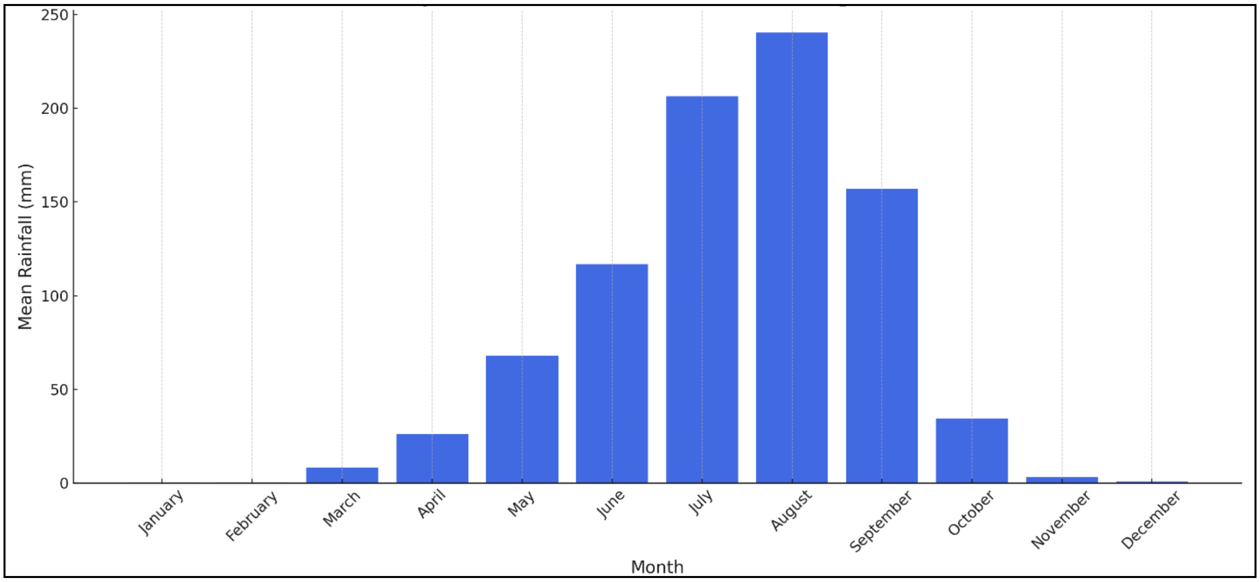

Figure 5: Regional Monthly Rainfall Climatology in Northwestern Nigeria (1983-2024)

The marked contrast between the wet and dry seasons also reflects the strong influence of the West African Monsoon system on rainfall distribution across the region. The pronounced seasonality observed in the rainfall climatology further emphasises the vulnerability of northwestern Nigeria to rainfall irregularities, delayed onset, early cessation, and seasonal drought conditions, particularly within predominantly rain-fed agricultural systems.

3.5 Rainfall Persistence and Climate Memory in Northwestern Nigeria

The autocorrelation function (ACF) analyses revealed contrasting temporal persistence characteristics between monthly and annual rainfall distributions across northwestern Nigeria. The monthly rainfall series exhibited a strong positive autocorrelation of ~0.75 at the 12-month interval, indicating pronounced annual seasonality and the recurrent influence of the West African Monsoon system on regional rainfall dynamics (Figure 6). Significant autocorrelation peaks of ~0.70 were also observed at the 24- and 36-month lags, although with gradually declining intensity, reflecting the persistence of seasonal rainfall cycles over time.

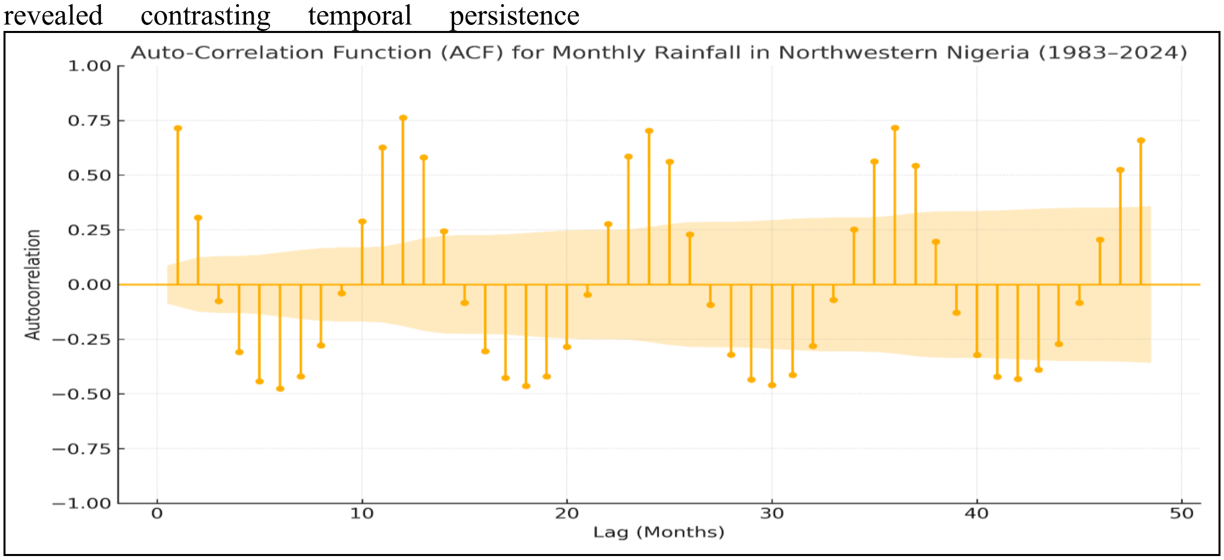

Figure 6: Monthly ACF of Rainfall in Northwestern Nigeria (1983–2024)

The gradual decay in autocorrelation strength with increasing lag suggests that rainfall predictability is considerably stronger at seasonal timescales than at multi-year timescales. This behaviour reflects the dominance of intra-annual climatic controls associated with monsoonal circulation processes and seasonal atmospheric variability across the Sudano-Sahelian region.

In contrast, the annual rainfall ACF series displayed relatively weak and statistically insignificant autocorrelation coefficients beyond the 95% confidence interval (Figure 7). The absence of strong long-term autocorrelation indicates limited interannual rainfall persistence and suggests that annual rainfall variability in northwestern Nigeria is largely stochastic in nature. This weak annual rainfall memory implies that rainfall anomalies are not strongly dependent on preceding years but are instead influenced by irregular short-term climatic fluctuations and possibly other large-scale climatic drivers. The contrasting monthly and annual autocorrelation structures therefore indicate that while rainfall occurrence in northwestern Nigeria follows a highly organised seasonal cycle, year-to-year rainfall totals remain highly variable and difficult to predict solely from historical rainfall persistence. This behaviour highlights the influence of broader atmospheric processes and short-term climatic fluctuations in shaping interannual rainfall variability across the region.

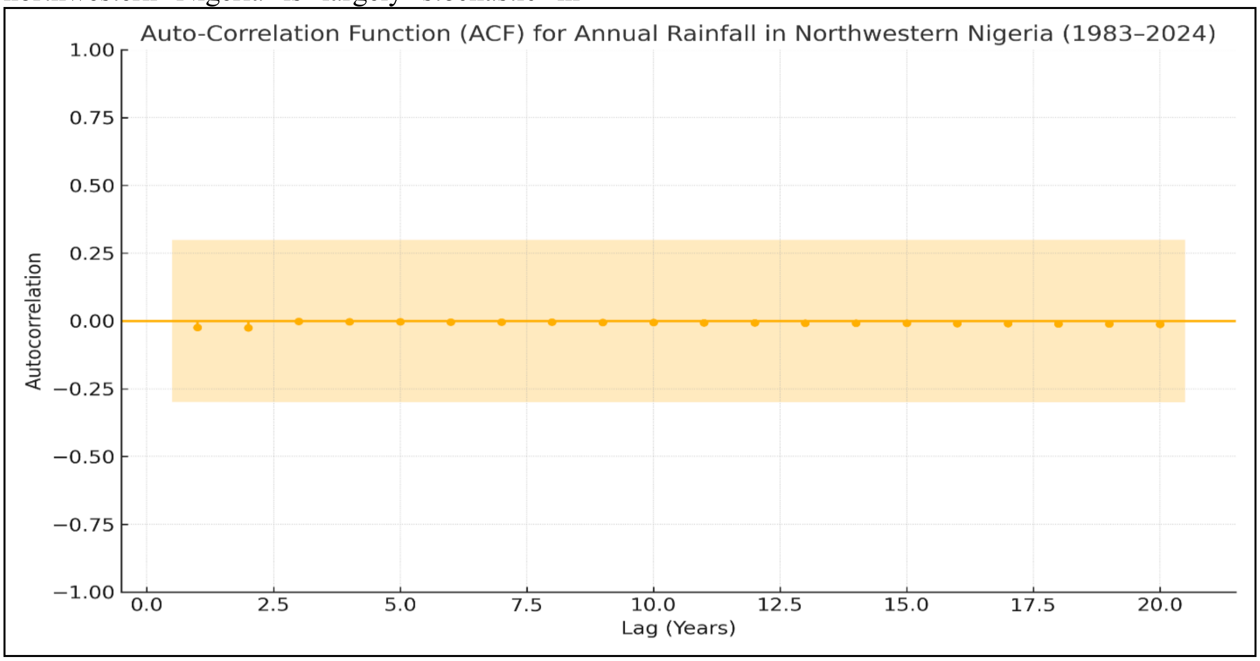

Figure 7: Annual ACF of Rainfall in Northwestern Nigeria (1983–2024)

3.6 Multi-Scale Rainfall Variability from Wavelet Analysis

The continuous wavelet spectrum of annual rainfall in northwestern Nigeria revealed significant variability across multiple temporal scales (Figure 8). The wavelet power spectrum showed a dominant annual-to-interannual signal throughout much of the study period, indicating that rainfall variability is strongly influenced by recurring climatic processes operating at short temporal scales. Several periods of enhanced wavelet power were observed between approximately 1988-1995, 2003-2010, and 2018-2024, suggesting intermittent intensification of rainfall variability during these periods. Significant oscillatory behaviour was primarily concentrated within periodicities ranging from approximately 2 to 8 years, although the strength and persistence of these signals varied through time. The significance contours indicate regions where wavelet power exceeded the 95% confidence threshold relative to the red-noise background spectrum, thereby confirming that the observed oscillations were statistically meaningful. The cone of influence identifies areas susceptible to edge effects and, therefore, limits interpretation near the beginning and end of the time series. Generally speaking, the wavelet analysis demonstrates that rainfall variability in northwestern Nigeria is characterised by non-stationary behaviour and temporal fluctuations operating across multiple timescales, highlighting the complexity of regional hydroclimatic dynamics.

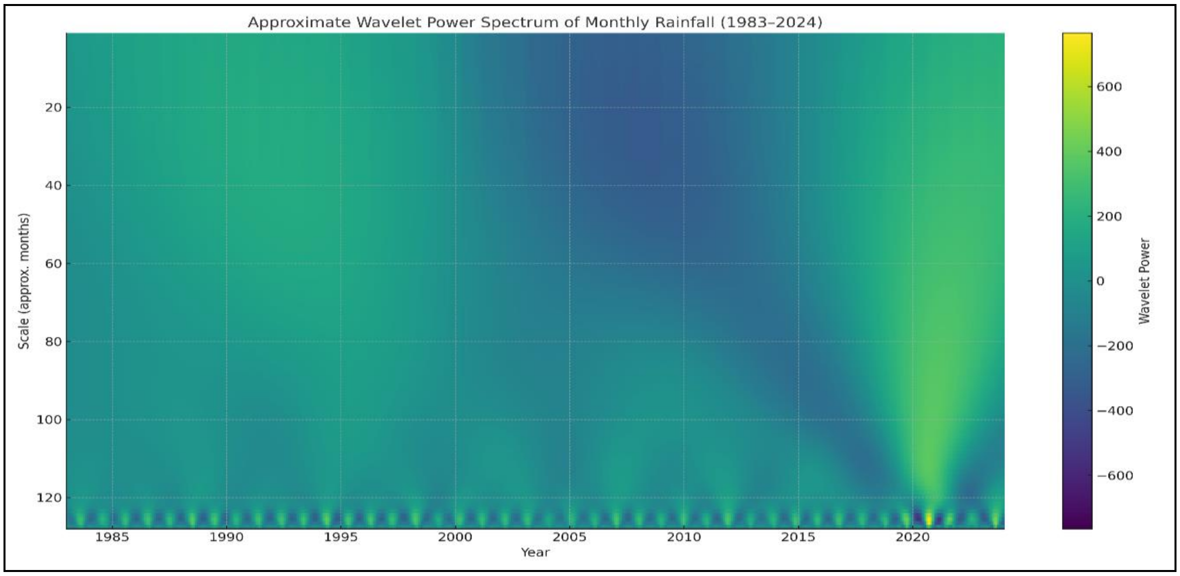

Figure 8: Wavelet Spectrum of Rainfall Variability in Northwestern Nigeria (1983 – 2024)

3.7 Rainfall Anomalies and Standardised Precipitation Index (SPI) Variability

The Standardised Precipitation Index (SPI) revealed substantial interannual variability in rainfall conditions across northwestern Nigeria during the study period (Figure 9). Alternating episodes of wet and dry conditions were observed throughout the rainfall record, indicating the highly variable nature of regional hydroclimatic conditions. Several periods of moderate to severe dry conditions were evident, particularly during the 1980s and early 1990s, while wetter conditions occurred more frequently during parts of the 2000s and recent years. However, the fitted trend line exhibited very low explanatory power ($R^2 = 0.0857$), suggesting that rainfall anomalies were dominated primarily by short-term fluctuations rather than a persistent long-term trend. Although positive SPI values became more frequent during recent decades, the observed tendency should be interpreted cautiously because the weak trend explains only a small proportion of the total variability. Overall, the SPI analysis indicates substantial hydroclimatic variability characterised by alternating wet and dry phases rather than a definitive long-term shift towards wetter climatic conditions.

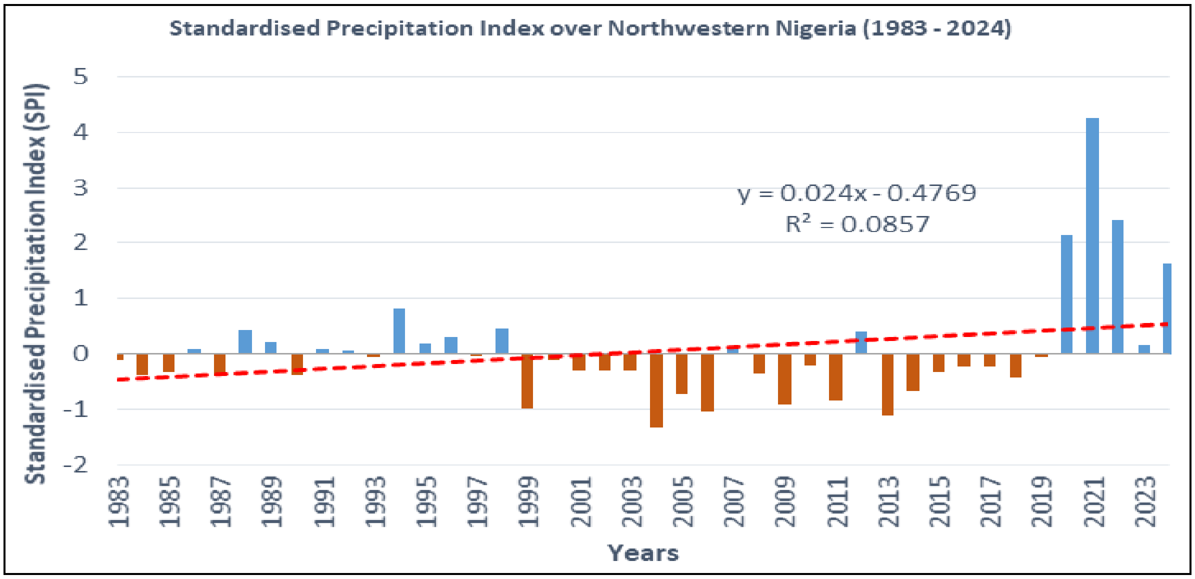

Figure 9: Standardised Precipitation Index (SPI) Variability in Northwestern Nigeria (1983–2024)

4.0 DISCUSSION

4.1 Rainfall Trends and Spatial Heterogeneity in Northwestern NIGERIA

The trend analysis revealed considerable spatial heterogeneity in rainfall behaviour across northwestern Nigeria, with significant increasing trends observed in Katsina, Kebbi, and Sokoto States, while Zamfara exhibited a significant decreasing trend. However, the regional rainfall series did not demonstrate a statistically significant long-term trend, indicating that rainfall variability across the region is dominated by localised fluctuations rather than a coherent regional-scale change. This spatial inconsistency reflects the complex climatic characteristics of the Sudano-Sahelian environment, where rainfall is influenced by multiple interacting atmospheric processes operating across different spatial and temporal scales. Similar spatial contrasts in rainfall trends have been reported across Nigeria and other parts of the West African Sahel, where neighbouring locations frequently exhibit differing rainfall tendencies despite sharing broadly similar climatic conditions (Abaje et al., 2014; Dia-Diop et al., 2020; Edokpa et al., 2023; Lüdecke et al., 2021; Tefera et al., 2025). The absence of a significant regional trend suggests that although some locations may be experiencing increasing rainfall amounts, there is insufficient evidence to conclude that northwestern Nigeria as a whole has undergone a uniform long-term rainfall increase or decrease during the study period.

The findings further highlight the importance of applying statistical significance tests when evaluating hydroclimatic trends. The non-significant trends observed in Kaduna, Kano, and Jigawa demonstrate that apparent increases or decreases identified through visual inspection or simple regression analysis may not necessarily represent meaningful climatic changes. Consequently, climate adaptation strategies should recognise the spatially heterogeneous nature of rainfall variability within the region rather than assuming uniform climatic responses.

4.2 Rainfall Persistence and Climate Memory

The autocorrelation analysis revealed strong seasonal persistence within the monthly rainfall series but weak long-term persistence in annual rainfall. This pattern indicates that rainfall occurrence in northwestern Nigeria is strongly controlled by recurring seasonal atmospheric processes, particularly the annual migration of the Inter-Tropical Discontinuity (ITD) and the associated West African Monsoon system (Olalere et al., 2021). The significant autocorrelation observed at seasonal lags reflects the regular recurrence of wet and dry seasons that characterise the regional climate.

Conversely, the weak autocorrelation exhibited by the annual rainfall series suggests limited climatic memory from one year to the next. This finding implies that rainfall conditions in a given year exert relatively little influence on rainfall behaviour in subsequent years. Such weak persistence is characteristic of semi-arid climatic systems where rainfall variability is largely governed by highly dynamic atmospheric processes rather than strong long-term internal climatic controls. The observed behaviour further explains the substantial interannual rainfall fluctuations recorded across the study area and highlights the challenges associated with long-term rainfall predictability within the Sudano-Sahelian environment.

4.3 Multi-Scale Climatic Influences

The wavelet analysis revealed statistically significant oscillatory behaviour within the rainfall series, particularly at interannual timescales. The intermittent nature of the significant power regions indicates that rainfall variability in northwestern Nigeria is not purely random but exhibits recurring temporal structures that evolve through time. The results, therefore, reinforce the need to view rainfall variability as a temporally evolving process rather than a fixed climatic characteristic. Similar oscillatory patterns have been reported across the West African Sahel, where rainfall variability is influenced by complex interactions between regional atmospheric circulation systems and broader ocean-atmosphere processes (Bello & Mamman, 2018; Chinazor, 2021; Egbuawa et al., 2017; Igbawua et al., 2024; Martin & Thorncroft, 2014; Nicholson, 2013; Tanko et al., 2026). However, because specific teleconnection indices were not explicitly analysed in the present study, the observed oscillations are considered as evidence of multi-scale climatic variability rather than direct proof of any particular climatic driver.

In addition, the SPI analysis highlights the considerable interannual variability that characterises rainfall behaviour across northwestern Nigeria. The alternation between wet and dry phases reflects the inherently unstable nature of rainfall within the Sudano-Sahelian environment, where substantial year-to-year fluctuations frequently occur. Although wetter conditions appeared more frequently during recent decades, the weak explanatory power of the SPI trend indicates that caution is required when inferring long-term climatic shifts. These findings suggest that hydroclimatic variability remains dominated by episodic fluctuations rather than a consistent transition towards wetter conditions.

4.4 Hydroclimatic Extremes and Agricultural Implications

The occurrence of recurrent dry and wet episodes has important implications for agriculture, water resources, and climate risk management within the region. Given the heavy reliance on rain-fed agricultural systems, fluctuations in rainfall availability can substantially affect crop productivity, food security, and rural livelihoods. The prolonged below-average rainfall periods identified during parts of the late 1990s and 2000s may have contributed to recurrent agricultural stress, soil moisture deficits, shortened growing seasons, and increased drought exposure across rain-fed farming systems (Abdullahi & Marafa, 2023; Nassah et al., 2022; Prince et al., 2023; Wambua & Okeke, 2023). Similar drought tendencies have previously been associated with reduced crop productivity and heightened food insecurity across several Sahelian regions of West Africa (Abdullahi & Marafa, 2023; Dogondaji & Magawata, 2024; Henchiri et al., 2021; Umar & Kehinde, 2020). Conversely, the exceptionally wet years recorded after 2020 may increase the risk of flooding, soil erosion, nutrient leaching, and crop damage, particularly within poorly drained agricultural landscapes.

The strong concentration of rainfall within a relatively short rainy season further amplifies the sensitivity of agricultural systems to fluctuations in rainfall onset, cessation, and intra-seasonal distribution. Since agricultural production in northwestern Nigeria depends predominantly on seasonal rainfall, even slight disruptions in rainfall timing or intensity may significantly affect planting schedules, crop growth, and harvest outcomes. The increasing variability observed in the rainfall regime, therefore, poses major challenges for sustainable agricultural planning and climate resilience development within the region. The hydroclimatic instability demonstrated in this study also underscores the importance of strengthening climate adaptation strategies across northwestern Nigeria. Improved seasonal forecasting systems, climate-informed agricultural advisories, drought preparedness programmes, and sustainable water resource management approaches will be increasingly necessary to minimise the socioeconomic impacts of rainfall variability and extreme climatic events across the region's vulnerable rain-fed agricultural systems.

4.5 Comparison with Previous Studies

The findings of this study are generally consistent with previous climatological studies conducted across the West African Sahel and other tropical monsoon regions. The strong interannual rainfall variability and weak long-term rainfall persistence observed across northwestern Nigeria agree with the findings of Nicholson (2013), who reported that Sahelian rainfall behaviour is strongly influenced by dynamic ocean-atmosphere interactions and irregular climatic oscillations rather than stable long-term climatic trends. Similarly, Henchiri et al. (2021) and Igbawua et al. (2024) observed substantial rainfall fluctuations and teleconnection-driven hydroclimatic variability across different parts of West Africa. The distinct unimodal rainfall regime identified in this study also aligns with earlier findings by Abaje et al. (2014) and Edokpa et al. (2023), who reported that rainfall across the Sudano-Sahelian ecological zones is highly seasonal and strongly controlled by the northward migration of the Inter-Tropical Discontinuity and the West African Monsoon system. The concentration of rainfall between May and October further confirms the dominant monsoonal control on rainfall occurrence across northwestern Nigeria. The wavelet analysis further supports previous studies that identified dominant annual rainfall periodicities across tropical Africa, with weaker and intermittent multi-year oscillations associated with monsoonal variability (Chinazor, 2021; Ta *et al.,* 2016).

The increasing occurrence of wet extremes after 2020 observed in this study also agrees with recent reports suggesting the intensification of hydroclimatic extremes across parts of West Africa under changing climatic conditions (Almazroui et al., 2020; Igbawua et al., 2024). However, unlike many previous studies that focused primarily on rainfall trends or isolated climatic indicators, the present study integrated linear and non-parametric trend analysis, rainfall climatology, autocorrelation analysis, wavelet analysis, and SPI-based anomaly assessment within a unified hydroclimatic framework for northwestern Nigeria. This integrated analytical approach provides a more comprehensive understanding of the temporal complexity, climatic variability, and hydroclimatic risks characterising the Sudano-Sahelian environment of northwestern Nigeria.

5.0 STUDY LIMITATIONS AND UNCERTAINTY CONSIDERATIONS

The findings of this study should be interpreted within the context of several inherent sources of uncertainty:

i. The rainfall dataset was primarily derived from the NASA-POWER database, which represents gridded satellite-reanalysis estimates rather than direct point measurements. Although validation against available NiMet observations was undertaken, differences between station-based observations and gridded products may introduce uncertainty into rainfall magnitude estimates.
ii. Rainfall variability within semi-arid environments is inherently influenced by substantial spatial and temporal fluctuations, which may affect the stability of trend estimates. To minimise this limitation, both parametric and non-parametric statistical approaches were employed through the combined application of linear regression, Mann-Kendall testing, and Sen's slope estimation.
iii. The SPI analysis was based on annual rainfall totals and was intended to examine broad-scale hydroclimatic variability rather than short-term drought dynamics. Consequently, the results may not fully capture drought characteristics operating at shorter temporal scales.
iv. While wavelet analysis provided valuable insights into multi-scale rainfall variability, the interpretation of oscillatory signals remains subject to uncertainty associated with non-stationary climatic processes and edge effects near the boundaries of the time series. The cone of influence was

therefore used to guide interpretation and minimise potential distortion.

Despite these limitations, the integrated analytical framework adopted in this study provides a robust assessment of rainfall variability, climatic persistence, and hydroclimatic behaviour across northwestern Nigeria.

6.0 CONCLUSION

This study investigated rainfall variability and hydroclimatic behaviour across northwestern Nigeria using an integrated analytical framework comprising rainfall climatology, linear regression, Mann-Kendall trend testing, Sen's slope estimation, autocorrelation analysis, wavelet analysis, and the Standardised Precipitation Index (SPI). The findings revealed substantial spatial and temporal variability in rainfall behaviour across the region, characterised by significant localised rainfall trends, weak regional trend behaviour, strong seasonal persistence, multi-scale oscillatory variability, and recurrent hydroclimatic extremes. The Mann-Kendall and Sen's slope analyses demonstrated that statistically significant increasing rainfall trends occurred in Katsina, Kebbi, and Sokoto States, whereas Zamfara exhibited a significant decreasing trend. However, the regional rainfall series did not show a statistically significant long-term trend, indicating that rainfall variability across northwestern Nigeria is primarily governed by strong interannual fluctuations rather than a coherent regional climatic shift. The autocorrelation analysis further revealed strong seasonal dependence but weak annual persistence, suggesting limited long-term climatic memory within the rainfall system. Wavelet analysis identified significant oscillatory behaviour across multiple temporal scales, confirming the non-stationary nature of rainfall variability within the region. Similarly, the SPI analysis revealed alternating wet and dry phases throughout the study period, highlighting the continued occurrence of hydroclimatic extremes and rainfall anomalies. Although wetter conditions appeared more frequently during recent decades, the weak explanatory power of the SPI trend suggests that caution is required when inferring long-term climatic transitions.

Overall, the findings demonstrate that rainfall variability in northwestern Nigeria is characterised by spatial heterogeneity, weak long-term persistence, evolving oscillatory behaviour, and recurring hydroclimatic extremes. These characteristics underscore the importance of strengthening climate monitoring systems, improving drought preparedness measures, and incorporating hydroclimatic information into agricultural and water resource management strategies. The study also highlights the value of integrated hydroclimatic assessment frameworks for understanding rainfall dynamics and supporting climate adaptation planning within the climate-sensitive Sudano-Sahelian region of West Africa. Future studies should investigate the influence of specific large-scale ocean-atmosphere oscillations on rainfall variability across northwestern Nigeria using explicit teleconnection analyses.

7.0 REFERENCES

Abaje, I. B., Ndabula, C., & Adamu, G. (2014). Is the Changing Rainfall Patterns of Kano State and Its Adverse Impacts an Indication of Climate Change? *European Scientific Journal*, *10*(1), 192–206.

Abdullahi, S. A., & Marafa, A. A. A. (2023). Impact of Climate Change on Agricultural Production in Nigeria. *Jigawa Journal of Social and Management Sciences*, *1*(2), 1–13. https://doi.org/10.1201/9781003245285-9

Adedibu, P. A., Opeyemi, A. A., Lawrence, A. J., Paul, J. I., & Oguntoye, E. (2022). Savanna Biomes in Nigeria: Indicator Species and Plant Adaptation Strategies. *Department of Plant Biology, University of Ilorin, Ilorin, Nigeria*. https://doi.org/10.14293/S2199-1006.1.SOR-.PPDXHKL.v1

Adeyeri, O. E., Lawin, A. E., Laux, P., Ishola, K. A., & Ige, S. O. (2019). Analysis of climate extreme indices over the Komadugu-Yobe basin, Lake Chad region: Past and future occurrences. *Weather and Climate Extremes*, *23*(1).

https://doi.org/10.1016/j.wace.2019.100194

Almazroui, M., Saeed, F., Saeed, S., Nazrul Islam, M., Ismail, M., Klutse, N. A. B., & Siddiqui, M. H. (2020). Projected Change in Temperature and Precipitation Over Africa from CMIP6. *Earth Systems and Environment*, *4*(3), 455–475. https://doi.org/10.1007/s41748-020-00161-x

Awode, A. E., Adewumi, J. R., Obiora-Okeke, O., & Komolafe, A. A. (2025). Analysis of rainfall variability and extreme events in South-Western Nigeria: implications for water resource management and climate resilience. *Bulletin of the National Research Centre*, *49*(31). https://doi.org/10.1186/s42269-025-01324-4

Bello, A. A., & Mamman, M. B. (2018). Monthly rainfall prediction using artificial neural network : A case study of Kano, Nigeria. *Environmental and Earth Sciences Research Journal*, *5*(2), 37–41. https://doi.org/doi.org/10.18280/eesrj.050201

Biasutti, M. (2019). Rainfall trends in the African Sahel: Characteristics, processes, and causes. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(e591). https://doi.org/10.1002/wcc.591\

Butu, A. W., & Emeribe, C. N. (2019). Spatial patterns of climatic variability and water budget over Sudan Savannah Region of Nigeria. *African Journal of Environmental Science and Technology*, *13*(21), 465–481. https://doi.org/10.5897/ajest2019.2726

Chinazor, O. F. (2021). North Atlantic Oscillation and Rainfall Variability in Southeastern Nigeria: A Statistical Analysis of 30 Year Period. *Journal of Atmospheric Science Research*, *4*(4), 42–49. https://doi.org/10.30564/jasr.v4i4.3843

Darman, L. P., Januhariadi, Yudha, M. P., & Aslan. (2024). Assessment of NASA POWER reanalysis products as data resources alternative for weather monitoring in West Sumbawa, Indonesia. *E3S Web of Conferences*, *485, 06006*, 1–14. https://doi.org/doi.org/10.1051/e3sconf/202448506006

Dia-Diop, A., Zebaze, S., Wade, M., Djiondo, R. N., Diop, B., Efon, E., & Lenouo, A. (2020). Interannual Variability of Rainfall over the West Africa Sahel. *Journal of Geoscience and Environment Protection*, *08*, 85–101. https://doi.org/10.4236/gep.2020.83007

Dogondaji, M. B., & Magawata, D. (2024). Rainfall Variability And Its Implications On Crop Production In Sokoto State. *International Journal of Innovative Environmental Studies Research*, *12*(3), 89–103. www.seahipublications.org

Edokpa, D. O., Ede, P. N., Diagi, B. E., & Ajiere, S. I. (2023). Rainfall and Temperature Variations in a Dry Tropical Environment of Nigeria. *Journal of Atmospheric Science Research*, *6*(2), 50–57. https://doi.org/10.30564/jasr.v6i2.5527

Egbuawa, O. I., Anyanwu, J. C., Amaku, G. E., & Onuoha, I. C. (2017). Assessment of the Teleconnection Between El Niño Southern Oscillation (ENSO) and West African Rainfall. *African Research Review*, *11*(4), 17–29. https://doi.org/10.4314/afrrev.v11i4.3

Ekpoh, I. J., & Nsa, E. (2011). Extreme Climatic Variability in North-western Nigeria: An Analysis of Rainfall Trends and Patterns. *Journal of Geography and Geology*, *3*(1), 51–62. https://doi.org/10.5539/jgg.v3n1p51

Gebrechorkos, S. H., Hülsmann, S., & Bernhofer, C. (2019). Long-term trends in rainfall and temperature using high-resolution climate datasets in East Africa. *Scientific Reports*, *9*(11376), 1–9. https://doi.org/10.1038/s41598-019-47933-8

Hashidu, U. S., & Badaru, S. I. (2021). Relationship between El-Niño southern oscillation and rainfall in Sudano-Sahelian Region of Northern Nigeria. *Journal of Agricultural Economics,* *Environment and Social Science (JAEESS)*, *7*(2), 211–216. http://www.jaeess.com.ng

Henchiri, M., Igbawua, T., Javed, T., Bai, Y., Zhang, S., Essifi, B., Ujoh, F., & Zhang, J. (2021). Meteorological Drought Analysis and Return Periods over North and West Africa and Linkage with El Niño – Southern. *Remote Sensing*, *13*(4730), 1–32. https://doi.org/doi.org/10.3390/rs13234730

Igbawua, T., Ujoh, F., Mkighirga, K. S., & Adagba, G. (2024). Assessment of relationship between sea surface temperature (SST) changes and precipitation types in Nigeria from 2000 to 2022. *Results in Earth Sciences*, *2*(100031), 1–15. https://doi.org/10.1016/j.rines.2024.100031

Lüdecke, H., Müller-Plath, G., Wallace, M. G., & Lüning, S. (2021). Decadal and multidecadal natural variability of African rainfall. *Journal of Hydrology: Regional Studies*, *34*(100795), 10.1016/j.ejrh.2021.100795.

Martin, E. R., & Thorncroft, C. D. (2014). The Impact of the AMO on the West African monsoon annual cycle. *Quarterly Journal of the Royal Meteorological Society*, *140*(678), 31–46. https://doi.org/10.1002/qj.2107

McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *Proceedings of the Eighth Conference on Applied Climatology*.

Mohammed, M. U., Abdulhamid, A., Badamasi, M., & Ahmed, M. (2015). Rainfall Dynamics and Climate Change in Kano, Nigeria. *Journal of Scientific Research & Reports*, *7*(5), 386–395. https://doi.org/10.9734/JSRR/2015/17098

Muthoni, F. K., Odongo, V. O., Ochieng, J., Mugalavai, E. M., Mourice, S. K., Hoesche-zeledon, I., Mwila, M., & Bekunda, M. (2018). Long-term spatial-temporal trends and variability of rainfall over Eastern and Southern Africa. *Theoretical and Applied Climatology*.

Nassah, H., Daghor, L., Chatoui, H., Tounsi, A., Khoulaid, F., Fakir, Y., Erraki, S., & Said, K. (2022). Climate Change Impact on Agricultural Production in the Sahel Region. In H. Chatoui, H. Moummou, M. Tilaoui, N. Saadaoui, & A. Brhich (Eds.), *Nutrition and Human Health* (pp. 3–11). Springer, Cham. https://doi.org/_10.1007/978-3-030-93971-7_1

Nicholson, S. E. (2013). The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability. *International Scholarly Research Notices (ISRN) Meteorology*, *2013*, 1–32. https://doi.org/10.1155/2013/453521

Olalere, G. E., Bulama, L., & Umar, A. A. (2021). Rainfall Anomalies Pattern in Northwestern Nigeria (NWN). *Journal of Geography, Environment and Earth Science International*, *25*(4), 43–52. https://doi.org/10.9734/jgeesi/2021/v25i430282

Prince, A. I., Nzechie, O., Obiorah, J., Ehi, O. E., & Idakwoji, A. A. (2023). Analysing the Critical Impact of Climate Change on Agriculture and Food Security in Nigeria. *International Journal of Agriculture and Earth Science (IJAES)*, *9*(4), 1–27. https://doi.org/10.4018/979-8-3693-3272-6.ch017

Rodrigues, G. C., & Braga, R. P. (2021). Evaluation of NASA POWER Reanalysis Products to Estimate Daily Weather Variables in a Hot Summer Mediterranean Climate. *Agronomy*, *11*(1207), 1–17. https://doi.org/doi.org/10.3390/agronomy11061207

Ta, S., Kouadio, K. Y., Ali, K. E., Toualy, E., Aman, A., & Yoroba, F. (2016). West Africa Extreme Rainfall Events and Large-Scale Ocean Surface and Atmospheric Conditions in the Tropical Atlantic. *Advances in Meteorology*. https://doi.org/10.1155/2016/1940456

Tahroudi, M. N. (2025). Comprehensive global assessment of precipitation trend and pattern variability considering their distribution dynamics. *Scientific Reports*, *15*(22458). https://doi.org/10.1038/s41598-025-06050-5

Tanko, I. A., Yahaya, T. I., Abdulkadir, A., Ezenwora, J. A., Ibrahim, I., & Kura, A. T. (2026). Predicting Rainfall Variability and Cereal Crop Yields Using Climatic Oscillation Indices and Machine Learning in Northwestern Nigeria. *Kaduna Journal of Geography (KJG)*, *8*(1), 309–320. https://doi.org/10.47514/kjg.2026.08.01.033

Tayyeh, H. K., & Mohammed, R. (2023). Analysis of NASA POWER reanalysis products to predict temperature and precipitation in Euphrates River basin. *Journal of Hydrology*, *619*(129327). https://doi.org/doi.org/10.1016/j.jhydrol.2023.129327

Tefera, M. L., Giovanna Seddaiu, Alberto Carletti, & Awada, H. (2025). Rainfall variability and drought in West Africa: challenges and implications for rainfed agriculture. *Theoretical and Applied Climatology*, *156*(41). https://doi.org/10.1007/s00704-024-05251-8

Umar, A. T., & Kehinde, M. O. (2020). Relationship of El-Nino Southern/Oscillation to Rainfall Patterns in Nigeria. *Open Journals of Environmental Research (OJER)*, *1*(1), 1–20. openjournalsnigeria.org.ng/pub/ojer20200101.pdf

Wambua, J. K., & Okeke, N. O. (2023). *The Impacts of Climate Change on Agricultural Production Systems in Nigeria* [Norwegian University of Life Sciences]. https://doi.org/10.1007/s10584-013-0803-7

Wang, N., Sun, F., Liu, W., Yang, S., Wang, H., Feng, Y., & Huang, Q. (2025). Climate drives observational changes in hydrological extremes across most global regions. *The Innovation*, *7*(4 (101171)). https://doi.org/10.1016/j.xinn.2025.101171