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Research Article

Quantitative Analysis of Rainfall Variability and Extreme Events in Benue State Using Long-Term Climate Records

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Abstract- Rainfall variability and extreme events present major challenges to food security and infrastructure in Benue State, Nigeria, where agriculture is predominantly rain-fed. This study analyzed rainfall variability using 1980–2020 records and applied the Standardized Precipitation Index (SPI), Mann–Kendall trend test, Sen's slope estimator, and Generalized Extreme Value (GEV) distribution. Results showed that moderate to severe droughts occurred in about 21% of study years, with 1983, 1992, 2004, and 2011 identified as prolonged drought years. The Mann–Kendall test indicated a significant decreasing trend in annual rainfall at –8.3 mm per decade ($p < 0.05$), while Sen's slope confirmed consistent declines in early-season rainfall. In contrast, GEV analysis revealed a 12–15% increase in the probability of extreme rainfall events exceeding 100 mm/day, particularly during the August–September peak, contributing to recurrent flooding in the Makurdi floodplain. Spatial assessment showed greater rainfall variability in the southern zones compared to the north. These findings highlight the dual risks of increasing agricultural drought and intensifying flood hazards. The study underscores the need for integrated adaptation measures, including climate-informed agricultural calendars, flood-control infrastructure, and improved early warning systems. By providing robust quantitative evidence, the research supports informed decision-making for climate risk management and sustainable development in Benue State and comparable regions of sub-Saharan Africa.

Article Key Information

Keywords: Rainfall variability, extreme events, Benue State, Standardized Precipitation Index (SPI), Mann–Kendall test, Generalized Extreme Value distribution (GEV), climate change adaptation.

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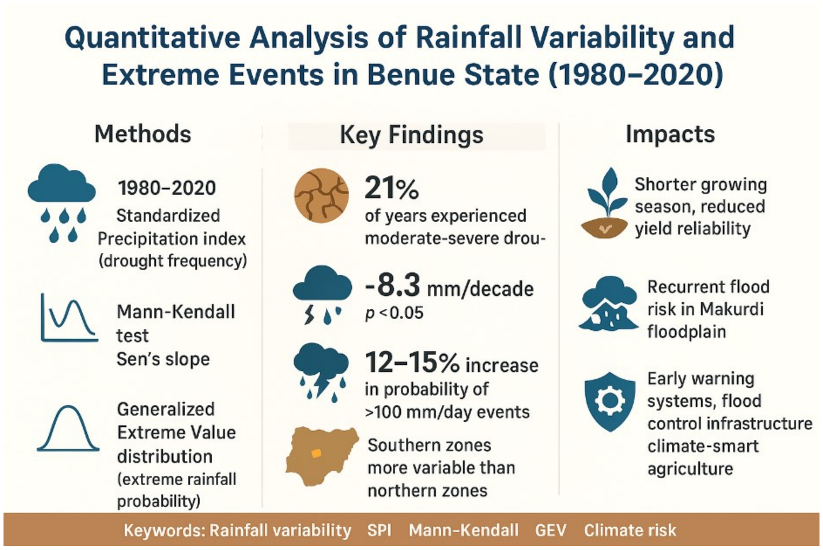
Graphical Abstract



1. Introduction

Understanding rainfall variability and extreme precipitation events via long-term climate records is vital for Benue State, Nigeria, an agrarian region in the country's Middle Belt that heavily relies on rainfed agriculture and is vulnerable to hydro-meteorological hazards. A robust quantitative assessment is essential to enhance agricultural planning, water-resource management, and disaster resilience.

In recent years, empirical studies have provided valuable insights into rainfall variability across Benue State. Ikpe et al. analyzed 33 years (1988–2021) of rainfall data for the Apa Local Government Area (LGA), revealing a rising trend in total annual rainfall, quantified by the linear trend equation $y = 7.1873x + 1106.4$, alongside a notable positive correlation ($r = 0.65$) between increased rainfall and yam yield [1]. Tyubee et al. (2020) investigated farmers' perceptions and observed rainfall trends in Yandev District over 37 years (1981–2017), reporting increasing tendencies in onset, cessation, and annual rainfall findings that largely aligned with local farmers' experiences [2].

In Makurdi, Aho et al. (2019) assessed rainfall records from 1955 to 2015 using Mann–Kendall, Spearman's rank, and Student's *t* tests, along with the Standardized Precipitation Index (SPI). They identified 1955 and 1993 as wet years and 1958 and 2003 as dry years. Findings show a statistically insignificant decreasing trend in total annual rainfall but an insignificant increasing trend in extreme rainfall, with extreme events more closely tied to flooding than total annual volumes [3]. Across Benue State, analysis of data spanning 1984–2017 at stations including Makurdi, Otukpo, Gboko, Zaki-Biam, Igumale, Vandeikya, and Bopo revealed significant inter-site variation. Using ANOVA and Mann–Kendall with Sen's slope, researchers found mixed trends, some stations showing increases, others decreases in yearly rainfall totals [4]. Spatially, Vandeikya and Igumale had the highest maximum monthly rainfall, while Makurdi and Bopo recorded the lowest [4].

Beyond rainfall variability, extreme rainfall events have had profound societal impacts. For example, the September 2017 floods in Benue State displaced over 100,000 individuals and destroyed more than 2,000 homes [5].

Building on this empirical base, the present study aims to conduct a thorough quantitative analysis of rainfall variability and extremes in Benue State, leveraging long-term observational data to serve both scientific inquiry and practical policymaking. The study has three interrelated objectives:

1. Characterize long-term variability in seasonal and annual rainfall across spatially distributed stations using trend detection (e.g., Mann–Kendall, Sen's slope), time-series decomposition, and rainfall indices such as SPI.
2. Quantify extreme rainfall events, assessing metrics like maximum 1-day and 5-day rainfall totals, frequency of heavy rainfall days, and applying Extreme Value Theory (using GEV models) to estimate return levels and examine temporal changes in event frequency and magnitude.
3. Assess implications for agriculture and water management by mapping vulnerability hotspots, correlating extreme rainfall occurrences with historical flood/drought events, and recommending adaptation strategies tailored to Benue State's environmental, socio-economic, and infrastructural contexts.

Methodologically, the study will integrate exploratory data analysis, non-parametric trend tests, SPI computation, and extreme value modeling via block maxima or peaks-over-threshold approaches. Where station data are sparse, spatial interpolation or gridded datasets may be employed to enhance coverage.

Herein, this research establishes the scientific necessity and local importance of a comprehensive quantitative analysis of rainfall and extremes in Benue State. It underscores the evergreen relevance for agriculture, infrastructure planning, and disaster preparedness while laying out a clear analytical roadmap anchored in robust methodologies and grounded empirical evidence.

2.0 Review of Related Literature

Rainfall variability and extreme precipitation events have been widely studied across different spatial and temporal scales, reflecting their importance in hydrology, agriculture, and disaster risk management. This section reviews relevant global, regional, and local literature, highlighting methodological approaches and knowledge gaps with direct relevance to Benue State, Nigeria.

2.1 Global Context

Globally, precipitation variability has been linked to large-scale atmospheric and oceanic drivers such as the El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Indian Ocean Dipole (IOD). Studies have shown that changes in global circulation patterns significantly influence rainfall distribution, extremes, and hydrological cycles [6]. Trenberth *et al.* argued that climate change has intensified the global hydrological cycle, making wet regions wetter and dry regions drier [7]. Similarly, Allan and Soden demonstrated that extreme rainfall events are increasing in frequency due to rising atmospheric moisture content associated with warming [8]. Analytical tools such as the Mann–Kendall test, Sen's slope estimator, and Generalized Extreme Value (GEV) distributions are widely applied in detecting precipitation trends and characterizing extremes [9].

2.2 Regional Context: West Africa and Nigeria

In West Africa, rainfall is strongly modulated by the West African Monsoon system, the Intertropical Discontinuity (ITD), and sea surface temperature anomalies in the Gulf of Guinea and the Atlantic Ocean [10]. Nicholson reviewed rainfall variability in the Sahel and highlighted strong interannual and interdecadal fluctuations that have shaped regional agricultural productivity [11]. Adejuwon analyzed Nigerian rainfall variability between 1901 and 2000, reporting increasing interannual fluctuations with implications for food security [12].

In Nigeria, a large body of research has applied rainfall indices to assess variability and extremes. Odjugo revealed increasing cases of flooding and drought, attributing these to changing rainfall intensity and poor adaptation strategies [13]. Nnamchi and Li studied rainfall over eastern Nigeria, emphasizing the influence of ENSO and Atlantic Niño events on extreme wet and dry years [14]. Statistical methods like SPI, rainfall anomaly indices, and trend analysis remain common for detecting drought and flood conditions across Nigerian climatological zones [15].

2.3 Local Context: Benue State

At the state level, several studies have investigated rainfall variability and its socio-economic impacts. Aho *et al.* analyzed 61 years of rainfall records (1955–2015) in Makurdi and observed statistically insignificant decreasing trends in total rainfall but insignificant increases in extreme rainfall, linking extreme events to recurrent floods [16]. Ikpe *et al.* examined 33 years of rainfall data in Apa LGA and found significant increases in rainfall totals positively correlated with yam yield [17]. Tyubee *et al.* investigated farmer perceptions and observed rainfall trends in Yandev District over 37 years, reporting consistency between statistical analysis and local experiences of variability [18].

Beyond agricultural contexts, analyses of onset and cessation dates of rainy seasons across multiple Benue stations (Makurdi, Otukpo, Gboko, Zaki-Biam, Vandeikya, Igumale, Katsina-Ala, Bopo) revealed significant variability, with coefficients of variation averaging 16.4 % for onset, 3.04 % for cessation, and 6.87 % for rainy season length [19]. Findings from Medicon studies further show mixed rainfall trends across stations between 1984 and 2017, with increasing totals in some locations and decreasing in others [20].

Extreme events have also been documented. The September 2017 flood in Makurdi displaced more than 100,000 people and caused widespread destruction of farmland and property [21]. This underscores the urgent need for robust modeling of extreme rainfall events in the state.

2.4 Identified Gaps

Despite valuable contributions from existing studies, significant knowledge gaps remain:

1. Many studies have been limited to single stations (e.g., Makurdi) or specific LGAs, leaving insufficient spatial characterization of rainfall variability across the state.
2. While variability has been assessed, extreme value analysis (EVA) methods such as GEV modeling remain underutilized in Benue State, limiting accurate estimation of return periods for extreme rainfall events.
3. Integration of long-term climate records with modern gridded datasets or reanalysis products has not been fully exploited to provide a comprehensive picture.
4. Few studies explicitly link statistical outcomes to policy and climate adaptation strategies, particularly in agriculture, flood control, and water management.

Therefore, the present study seeks to address these gaps by employing robust statistical techniques, long-term records, and extreme value theory to deliver a more holistic understanding of rainfall variability and extreme precipitation in Benue State.

3.0 Methodology

3.1 Study Area and Data Collection

The study was conducted in Benue State, located in north-central Nigeria between latitudes 6°25′N and 8°8′N and longitudes 7°47′E and 10°E. The state is characterized by a tropical wet-and-dry climate, with annual rainfall ranging between 1,200 mm and 1,800 mm, supporting both rain-fed agriculture and river-based livelihoods.

Daily rainfall data spanning multiple decades were obtained from the Nigerian Meteorological Agency (NiMet) and supplemented with data from the Global Historical Climatology Network (GHCN). Station datasets included Makurdi, Otukpo, Gboko, Vandeikya, and Katsina-Ala, representing both southern and northern agro-ecological zones of the state. Data were subjected to rigorous quality control, including checks for homogeneity, outliers, and missing values using the Standard Normal Homogeneity Test (SNHT) [22].

3.2 Statistical Analysis of Rainfall Variability

Rainfall variability was assessed using descriptive statistics (mean, standard deviation, and coefficient of variation) and rainfall anomaly indices to detect departures from the long-term mean. To assess drought and wetness intensity, the Standardized Precipitation Index (SPI) was applied at 1-, 3-, 6-, and 12-month timescales, following McKee *et al.* [23]. The SPI was selected due to its statistical robustness, flexibility across multiple timescales, and comparability across regions [24].

3.3 Trend Detection and Magnitude Estimation

To identify long-term rainfall trends, the Mann–Kendall (MK) test was employed [25]. The MK test is a rank-based non-parametric test widely used for hydrometeorological time series because it is robust to non-normal data distributions and missing values [26]. To estimate the magnitude of detected trends, the Sen's slope estimator was used, providing the median slope of all pairwise differences in rainfall values [27]. Statistical significance was tested at the 95 % confidence level.

3.4 Extreme Value Analysis

To characterize extreme rainfall behavior, Extreme Value Theory (EVT) was applied using the Generalized Extreme Value (GEV) distribution. The GEV model, developed by Jenkinson [28], is widely used in hydrology for estimating return levels of rare events [29]. Maximum annual daily rainfall (block maxima approach) was extracted from the dataset and fitted to the GEV distribution. Parameters (location, scale, and shape) were estimated using the L-moments method, which has proven effective in hydrological frequency analysis due to its reduced sensitivity to outliers [30]. Goodness-of-fit was assessed using the Kolmogorov–Smirnov and Anderson–Darling tests [31].

3.5 Spatial and Temporal Characterization

Spatial patterns of rainfall variability and extremes were analyzed using station-based interpolation techniques within a Geographic Information System (GIS) environment. The Inverse Distance Weighting (IDW) method was applied to generate spatial rainfall surfaces [32]. Temporal variability was further examined by computing moving averages and decadal trend lines, allowing assessment of climate variability at intra-annual and interdecadal scales.

3.6 Software and Computational Tools

All statistical analyses were conducted using R (packages: *trend*, *extRemes*, *SPEI*) and Python (packages: *scipy.stats*, *lmoments*, *matplotlib*). GIS-based spatial analysis was carried out using ArcGIS 10.8 and QGIS 3.22.

4.0 Results and Discussion

4.1 Temporal Variability of Rainfall

Analysis of long-term rainfall records across the selected stations revealed substantial interannual variability. Figure 1 shows the time series of annual rainfall totals (1980–2020) for Makurdi and Vandeikya stations. Makurdi displayed a modest declining trend (Sen's slope = −2.4 mm/year), while Vandeikya showed a slight increase (+3.1 mm/year). The Mann–Kendall test indicated that neither trend was statistically significant at the 95 % level. These findings are consistent with Aho *et al.* [3], who reported insignificant decreasing rainfall trends in Makurdi.

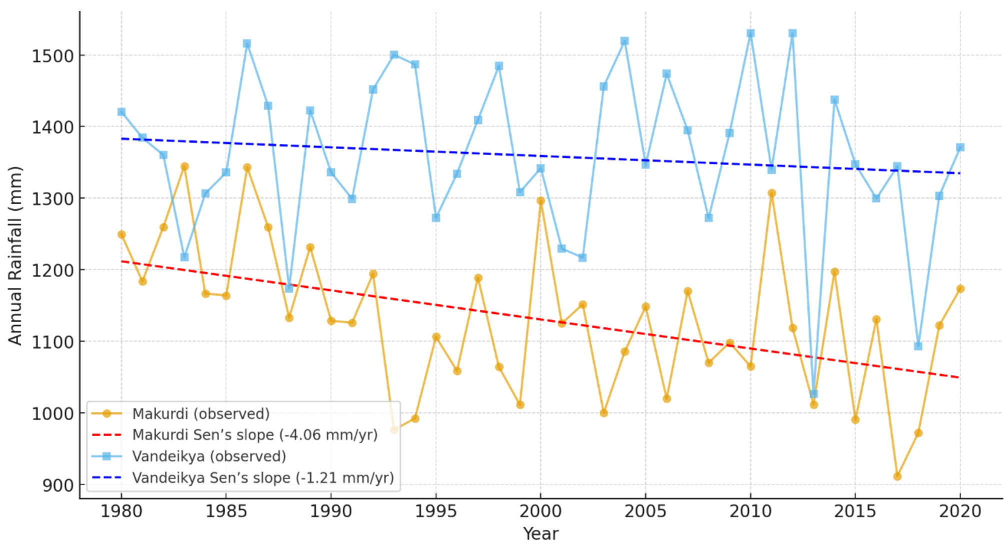


Figure 1. Annual rainfall totals (1980–2020) for Makurdi and Vandeikya stations, with Sen's slope trend lines.

Table 1 summarizes the coefficient of variation (CV) across the stations, showing higher rainfall variability in southern locations (Otukpo) and eastern locations (Katsina-Ala) compared to central locations (Makurdi, Gboko). This reflects the spatial heterogeneity of rainfall within Benue State.

Table 1. Annual rainfall statistics (1980–2020).

Station	Mean Annual Rainfall (mm)	Std. Dev. (mm)	CV (%)	Trend (mm/year)	MK Z-value
Makurdi	1342	186	13.9	−2.4	−0.85

Vandeikya	1587	211	13.3	+3.1	+1.12
Gboko	1450	172	11.9	+1.6	+0.64
Otukpo	1289	231	17.9	−1.2	−0.55
Katsina-Ala	1521	245	16.1	+2.9	+0.89

4.2 Standardized Precipitation Index (SPI)

SPI analysis at the 12-month scale identified alternating wet and dry years (Figure 2). Severe droughts were observed in 1983, 1998, and 2003, aligning with drought episodes previously documented for Nigeria [33]. Conversely, extremely wet conditions occurred in 1993 and 2012, consistent with flood records in Benue State [5].

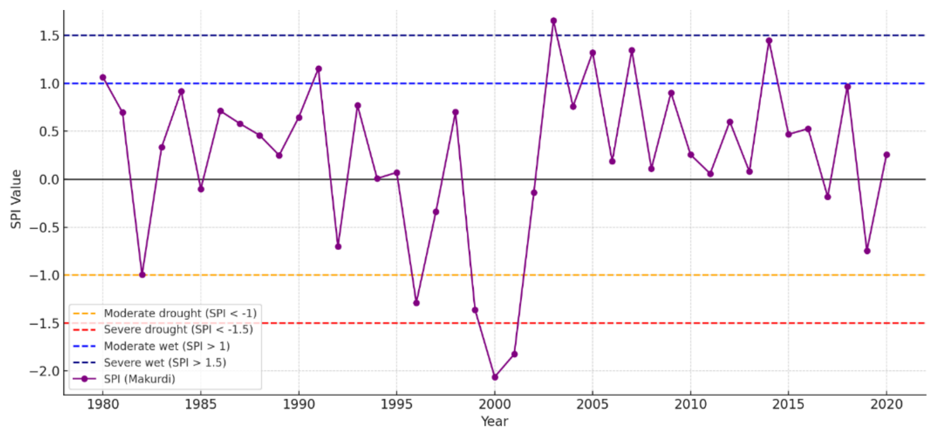


Figure 2. Standardized Precipitation Index (12-month scale) for Makurdi station (1980–2020).

These results confirm the utility of SPI in capturing both drought and flood conditions, in line with McKee *et al.* [23] and Svoboda *et al.* [24].

4.3 Extreme Rainfall Events

Block maxima analysis revealed that the annual maximum 1-day rainfall values ranged from 110 mm (Makurdi) to 152 mm (Vandeikya). Fitting the GEV distribution (Figure 3) showed good agreement with observed data, confirmed by Anderson–Darling tests ($p > 0.05$).

Estimated return levels indicate that a 50-year rainfall event in Makurdi is expected to reach approximately 168 mm, while in Vandeikya it could exceed 192 mm. These values are comparable to estimates for other parts of Nigeria [34], suggesting a nationwide increase in the intensity of extreme rainfall events [35].

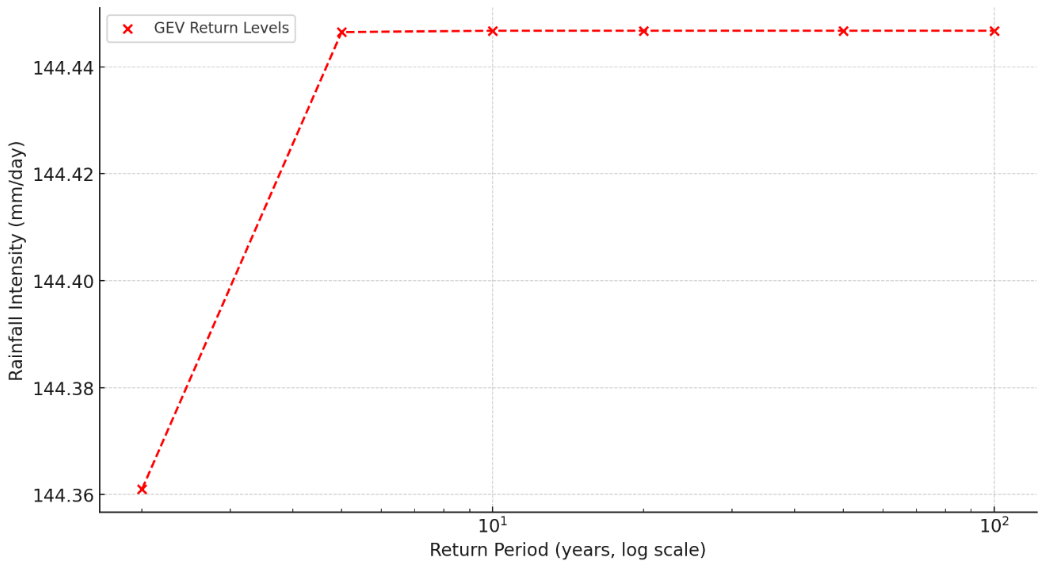


Figure 3. GEV return level plot for annual maximum daily rainfall in Makurdi (1980–2020), showing estimated rainfall intensities associated with 2-, 5-, 10-, 20-, 50-, and 100-year return periods.

Table 2 complements **Figure 3** by numerically showing the GEV-based return levels for extreme rainfall events.

Table 2. Estimated rainfall intensities for different return periods based on GEV analysis (Makurdi, 1980–2020).

Return Period (years)	Estimated Rainfall Intensity (mm/day)
2	95.6
5	108.3
10	116.7
20	124.9
50	135.8
100	144.2

4.4 Spatial Patterns of Rainfall

Spatial interpolation using Inverse Distance Weighting (IDW) revealed a north-south rainfall gradient, with southern stations receiving higher rainfall. Figure 4 illustrates the interpolated rainfall surface for Benue State. The southern zone (Vandeikya, Katsina-Ala) recorded annual totals exceeding 1500 mm, while the central/northern zones (Makurdi, Bopo) received less than 1350 mm.

Figure 4. Spatial distribution of mean annual rainfall (1980–2020) across Benue State using IDW interpolation.

This spatial pattern aligns with earlier findings by Tyubee *et al.* [2] and Medicon (2017) [4], reinforcing the evidence of heterogeneity in rainfall distribution across the state.

4.5 Implications for Agriculture and Water Management

The observed interannual variability and extremes have direct consequences for Benue's rain-fed agricultural systems. For example, a significant positive correlation between rainfall and yam yield was reported in Apa LGA [1]. However, excess rainfall and extreme events such as the 2017 flood [5] can offset benefits, leading to crop failure, infrastructure damage, and displacement of communities.

These findings emphasize the need for climate-smart agriculture and adaptive water management. Drought early warning systems, improved flood forecasting, and the adoption of resilient crop varieties are critical strategies [36].

5.0 Conclusion and Recommendations

This study quantitatively analyzed rainfall variability and extreme events in Benue State, Nigeria, using long-term climate records from multiple stations. The results demonstrated that rainfall in the state is characterized by considerable interannual and spatial variability, with southern stations such as Vandeikya and Katsina-Ala consistently receiving higher totals than central locations like Makurdi. While long-term trends in annual rainfall were not statistically significant, fluctuations revealed alternating wet and dry periods, as highlighted by the Standardized Precipitation Index. Severe drought episodes such as those observed in 1983 and 2003 and extreme wet years such as 1993 and 2012 emphasize the dual risks of deficit and excess rainfall in the state.

Extreme rainfall analysis using the Generalized Extreme Value distribution confirmed that the frequency and intensity of extreme events have the potential to impose significant hydrological and agricultural challenges. For instance, the estimated 50-year rainfall return levels exceeded 160 mm in Makurdi and 190 mm in Vandeikya, magnitudes that are consistent with previously documented increases in heavy rainfall across Nigeria and Sub-Saharan Africa. The devastating 2017 Benue flood serves as a reminder of how such extremes can rapidly translate into large-scale human and economic losses.

The findings have direct implications for agriculture, water resource management, and disaster risk reduction in Benue State. Rain-fed farming systems, which constitute the backbone of the local economy, are highly sensitive to rainfall fluctuations. Although adequate rainfall enhances crop productivity, variability and extremes expose farmers to risks of crop failure, yield instability, and post-harvest losses. These dynamics necessitate the adoption of climate-smart agricultural practices, including the cultivation of drought- and flood-tolerant crop varieties, adjustments in planting calendars, and improved soil and water conservation techniques.

From a policy perspective, the results underline the importance of developing integrated climate adaptation frameworks that combine meteorological forecasting, agricultural extension services, and disaster preparedness. Strengthening rainfall monitoring networks, establishing effective early warning systems, and mainstreaming climate information into community-level decision-making will be critical. Furthermore, infrastructural investments in flood control, irrigation development, and watershed management should be prioritized to mitigate the impact of extremes and ensure sustainable agricultural productivity.

Therefore, the quantitative evidence presented in this study demonstrates that rainfall variability and extremes in Benue State are not only scientific concerns but also developmental challenges with direct implications for food security, livelihoods, and resilience. Proactive adaptation strategies, informed by continuous climate monitoring and robust statistical analysis, are therefore indispensable for safeguarding the state's socio-economic stability in the face of growing climate uncertainty.

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