Sahel Journal of Geography, Environment & Development Vol. 5 No.2 December, 2024

ISSN: Online: 2756-536X www.sjged.com.ng ISSN: Print: 2756-5378

# Spatio-Temporal Analysis of Rainfall Patterns in Guinea and Sudano-Sahelian Agro-Ecological Zones of Nigeria

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## ABSTRACT

*Climate change, driven by anthropogenic activities, has altered hydro-climatic systems globally, with critical implications for regional rainfall patterns. This study evaluates long-term (1982–2021) spatio-temporal rainfall trends in Nigeria's Guinea and Sudano-Sahelian agro-ecological zones using satellite-derived reanalysis datasets. Applying the Mann-Kendall test, Theil-Sen's slope estimator, linear regression, and inverse distance weighting interpolation, we quantified trends, magnitudes, and spatial distributions of rainfall trend. Results reveal a non-significant decreasing trend (−1.9 mm/year; $p > 0.05$) in the Guinea Savannah, alongside low interannual variability (3%), signalling a gradual aridification that may threaten rain-fed agriculture and freshwater availability in this densely populated zone. In contrast, the Sudano-Sahelian region shows non-significant increases of 0.78 mm/year (Sudan Savannah) and 1.2 mm/year (Sahel Savannah), with 0.9% and 3.1% variability, respectively, suggesting a potential shift toward marginally wetter conditions. These contrasting trends underscore the potential implications for agricultural productivity, water resource availability, and ecosystem resilience in these regions. Specifically, the decreasing trend in the Guinea Savannah may exacerbate water scarcity and soil degradation, necessitating adaptive strategies such as improved irrigation systems and drought-resistant crop varieties. Conversely, the increasing trend in the Sudano-Sahelian zones could lead to heightened flood risks and land-use challenges, requiring enhanced flood management practices and sustainable land planning. Proactive measures, including sustainable land management, water conservation strategies, and policy interventions aimed at reducing greenhouse gas emissions, are essential to mitigate the adverse impacts of these climatic shifts.*

**Keywords:** Climate Change, Spatio-temporal trends, Rainfall, Agro-ecological Zones, Nigeria.

## 1. INTRODUCTION

The analysis of spatio-temporal rainfall patterns is critical for understanding climatic and environmental dynamics in agro-ecological zones, particularly in regions vulnerable to climate variability. In Nigeria, the Guinea and Sudano-Sahelian agro-ecological zones represent contrasting climatic regimes, where rainfall serves as a key driver of agricultural productivity, water resource sustainability, and food security (Atedhor, 2014; Ibrahim *et al.*, 2021). The humid Guinea zone faces increasingly erratic rainfall, while the semi-arid Sudano-Sahelian zone experiences pronounced rainfall deficits and prolonged droughts (Sanni *et al.*, 2012; Ahmad, 2024). Quantifying these spatial and temporal patterns is essential to address vulnerabilities and formulate targeted adaptation strategies for these regions.

Rainfall variability in these zones is modulated by global climatic phenomena, including the El Niño-Southern Oscillation (ENSO) and the seasonal migration of the Intertropical Convergence Zone (ITCZ) (Mashi *et al.*, 2020; Njouenwet *et al.*, 2021). These drivers induce marked heterogeneity in rainfall distribution, disrupting hydrological cycles, soil moisture regimes, and rain-fed agriculture. Although prior studies have identified broad trends in rainfall variability, significant gaps remain in characterizing fine-scale spatio-temporal dynamics, particularly the timing of onset/cessation, intra-seasonal dry spells, and rainfall intensity are critical factors for crop planning and water management (Ibrahim *et al.*, 2018; Tambuwal *et al.*, 2019).

A key limitation of existing research is its reliance on localized station data or coarse-resolution datasets, which inadequately capture spatial gradients and temporal shifts at scales relevant to agricultural decision-making (Usman *et al.*, 2020). To address this, high-resolution satellite-based climate products coupled with advanced geospatial methods (e.g., trend analysis, spatial interpolation) are urgently needed to unravel rainfall heterogeneity in these zones.

This study conducts a comprehensive spatio-temporal assessment of rainfall patterns across Nigeria's Guinea and Sudano-Sahelian agro-ecological zones using ERA-5 reanalysis data (0.25° resolution) and geostatistical techniques. The objectives are to: (1) quantify the trends in rainfall at intra-seasonal and inter-annual scales; (2) map the spatial distribution of the identified trend so as provide actionable insights for sustainable agricultural practices, enhance water resource management, and inform adaptive policy frameworks for mitigating the impacts of climate variability in these regions.

## 2. MATERIALS AND METHODS

### *2.1 Study Area*

The study was conducted in the Savannah zones of Nigeria, which are further classified into three agro-ecological zones: the Guinea, Sudan, and Sahel Savannahs. The study area extends from longitude 2°42' E to 14°5' E and latitude 6°2' N to 13°56' N (Figure 1). It is bordered by the Republic of Benin to the west, the Republic of Cameroon to the east, the Sahelian countries of Chad and Niger to the north, and the tropical high forests, freshwater swamp forests, mangrove forests, and coastal vegetation zones of the Atlantic Ocean to the south.

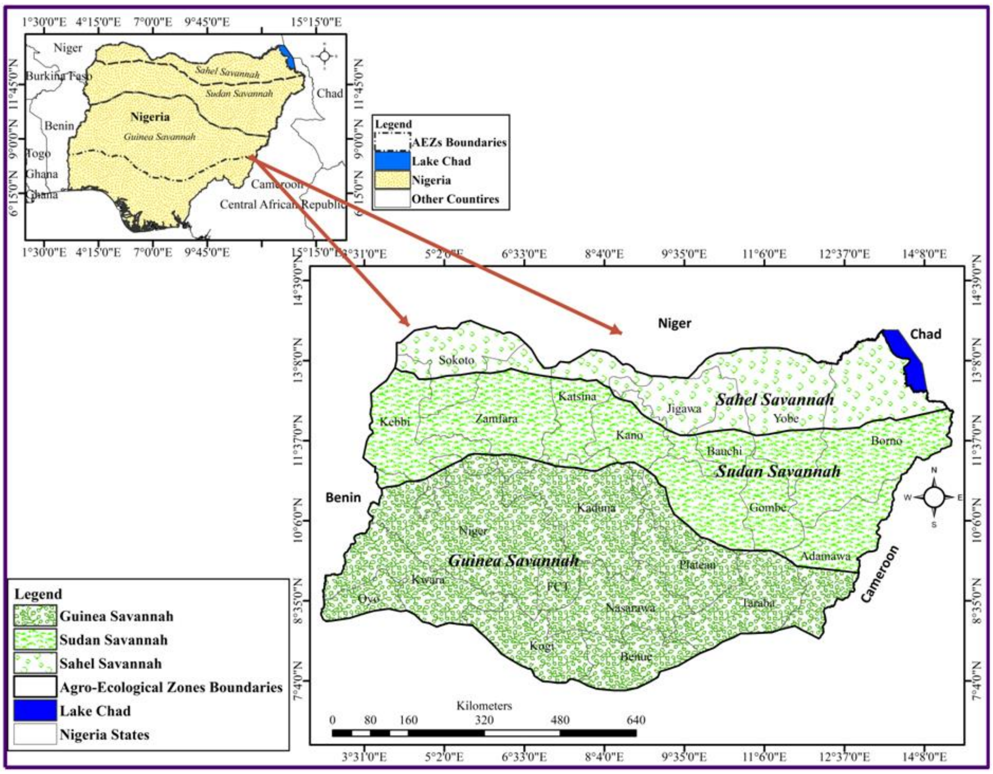


**Figure 1: The Study Area; (Guinea and Sudano-Sahelian Agro-Ecological Zones of Nigeria)**
***Source: Adapted from Aremu et al. (2017); 2022.***

The climate of the region is influenced by two predominant air masses: the Tropical Continental (cT) air mass and the Tropical Maritime (mT) air mass (Abdulkadir *et al.*, 2015). The cT air mass, originating from the Sahara Desert, is characterized by dry and dusty conditions, while the mT air mass, originating from the Atlantic Ocean, is dense and moist. The region experiences a mean annual rainfall of 1120 mm, with higher precipitation levels of up to 1500 mm observed in the plateau areas. Mean annual temperatures range from 24°C to 30°C.

### *2.2 Data Used*

In this study, 40 years (1982–2021) of daily rainfall data from 914 grid-based stations were obtained from the ERA-5 climate reanalysis dataset (available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5, accessed on June 30, 2022). The data were retrieved using a 0.25° × 0.25° grid resolution (approximately 27 km × 27 km) and a 1-hour temporal resolution. The ERA-5 precipitation dataset has been extensively validated for tropical and semi-arid regions, making it highly suitable for studies in the Nigerian Savannah. For instance, Lavers *et al.* (2022) and Jiang *et al.* (2021) demonstrated ERA5's accuracy in capturing tropical precipitation patterns and extreme events, while Wanzala *et al.* (2022) confirmed its reliability for regions with distinct wet and dry seasons. Furthermore, Tarek *et al.* (2020) highlighted ERA5's effectiveness in hydrological modelling and extreme event analysis, further supporting its applicability to the climatic conditions of the Savannah. The dataset was used to analyse rainfall trends across the study area. All data were downloaded at the surface level. The fair spatial distribution of the observation points justifies their use for interpolating non-observed points.

### *2.3 Methods*

#### *2.3.1 Spatio-temporal Trends in Rainfall*

Monthly rainfall data series were prepared for each grid using daily data obtained from 1982 to 2021. These data were further categorized into annual (January to December) and wet season (May to October) periods for inter-annual and wet seasonal analyses. Both parametric and non-parametric Mann–Kendall (MK) statistical tests were employed for this analysis. The magnitude of the trends was estimated using Sen's slope estimator (Sen, 1968), while the statistical significance of the trends was assessed using the Mann–Kendall test (Mann, 1945). Three significance levels ($\alpha$ = 0.01, 0.05, and 0.1) were used to classify trends as extremely significant, significant, and slightly significant, respectively. This approach is particularly relevant in environmental and climatic studies, where trends often exhibit varying strengths due to regional and temporal variability (Vega-Durán *et al.*, 2021).

The Mann-Kendall (MK) test, a non-parametric method widely used to detect significant trends in hydrological and meteorological time series (Ozgur & Kocak, 2019), does not assume any specific distribution for the data and has low sensitivity to abrupt breaks caused by inhomogeneous time series. Trends were estimated for individual grid stations across the entire study area. The null hypothesis of the MK test states that there is no discernible trend in the rainfall time series data. A significant trend, whether positive or negative, is identified when the null hypothesis is rejected.

Furthermore, linear regression, a parametric method commonly used for analysing rainfall trends, was applied to each zone and the entire study area by averaging seasonal or annual rainfall values. This method models the relationship between rainfall (dependent variable) and time (independent variable), enabling the identification of significant upward or downward trends. It is particularly effective for comparing rainfall patterns across zones, providing insights into spatial and temporal variability (Bibi *et al.*, 2014; Fountalis *et al.*, 2014).

#### *2.3.2 Spatial Interpolation of Rainfall Trend*

Spatial interpolation enhances the representation of a surface by producing a continuous spatial distribution and forecasting values for unmeasured areas (Sterling, 2003). It is a mathematical approach for estimating values in regions where direct measurements are unavailable (Kyriakidis & Goodchild, 2006). Various interpolation methods, such as spline, inverse distance weighting (IDW), and Kriging, differ in complexity and effectiveness. In this study, the IDW method was employed to interpolate the derived rainfall trends and magnitudes at seasonal and annual scales using ArcGIS software for spatial analysis.

The IDW tool estimates cell values by averaging the values of sample data points in the vicinity of each processing cell. The closer a point is to the centre of the cell being estimated, the more influence, or weight, it has in the averaging process. Among the available interpolation methods, IDW provided the most representative results for this study.

## 3. RESULTS AND DISCUSSION

### *3.1 Intra-Seasonal Wet Trends and Magnitude of Rainfall Distribution*

The Mann-Kendall test (Z-statistics, p-value, and Sen's slope) results were analysed on a decadal basis for wet seasonal rainfall datasets spanning the years 1982–1991 (1980s), 1992–2001 (1990s), 2002–2011 (2000s), and 2012–2021 (2010s), as illustrated in Figure 2. The results revealed both positive and negative Z-values, indicating increasing and decreasing trends across the study area. This observed variability in rainfall patterns is consistent with findings by Ndehedehe *et al.* (2022), who highlighted the significant influence of climate change on regional precipitation patterns in West Africa. Additionally, Kim *et al.* (2021) emphasized the role of atmospheric circulation patterns in driving these changes. During the first decade (1980s), as depicted in Figure 2a, a slight to significant increase (16.0 to 65.13 mm/decade) in mean wet-seasonal rainfall was observed in the western and central parts of the study area, covering approximately 35.14% of the Sudano-Sahelian savannah zone. Similarly, an insignificant increase of 0.01 to 16.69 mm/decade was recorded across 62.04% of the agro-ecological zones (AEZs). However, the southeastern part of the study area (2.82%) experienced an insignificant decrease in wet seasonal rainfall at a rate of -4.61 to -21.39 mm/decade during the 1980s. This localized decline may be attributed to land-use changes and deforestation, as well as increased human activity impacting local hydrological cycles (Hsu *et al*., 2025; Li *et al.,* 2007).

The second decade (1990s), an insignificant decline in rainfall was observed in 66.52% of the southern and northeastern AEZs, with rates ranging from -5.52 to -35.08 mm/decade. Conversely, an insignificant increase in rainfall (0.01 to 19.13 mm/decade) was recorded in the northwestern and eastern parts of the study area (33.05%), as shown in Figure 2b. These fluctuations underscore the complexity of climate dynamics in the region, where multiple drivers, including anthropogenic activities and large-scale climatic phenomena such as El Niño-Southern Oscillation (ENSO), interact to influence rainfall trends (Jones and Ricketts, 2021).

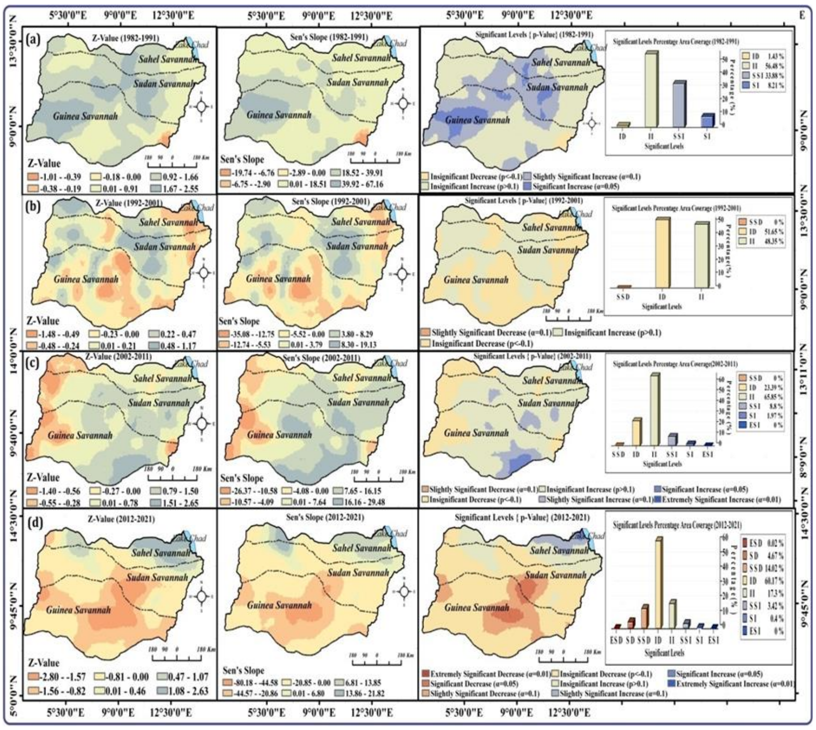

**Figure 2: Decadal Spatio-temporal Distribution of Trends Detected by Mann-Kendall Test (Z-Value, p-Value, & Sen's Slope) in Intra-seasonal Wet Rainfall: (a) 1982-1991; (b) 1992-2001; (c) 2002-2011; (d) 2012-2021.**

During the third decade (2000s), a slight to significant rise in wet seasonal rainfall (1.16 to 29.48 mm/decade) was recorded in southeastern Guinea and the central Sudan Savannah (10.77%), while 65.85% of the AEZs experienced an insignificant increase in rainfall at rates of 7.64 to 16.64 mm/decade. However, an insignificant decline in rainfall (-4.08 to -26.37 mm/decade) was observed in the western part of the AEZs (23.39%), as illustrated in Figure 2c.

harvesting techniques can mitigate the adverse effects of changing rainfall patterns (Xiao *et al.*, 2023). Furthermore, Beal *et al.* (2021) suggest that community-based approaches to water management can enhance resilience in regions experiencing increased rainfall variability.

Additionally, the Mann-Kendall test and the Theil-Sen slope estimator (β) were applied to detect wet seasonal trends in the rainfall series for the entire study period (1982–2021). The

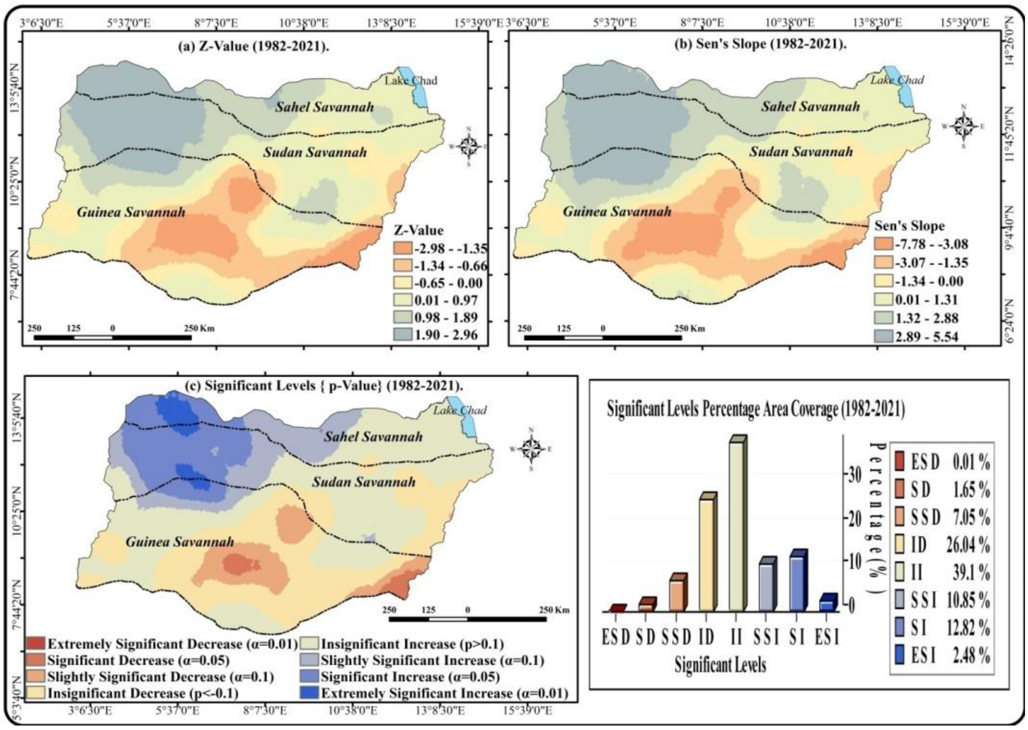


**Figure 3: Spatio-temporal Distribution of Trends Detected by Mann-Kendall Test (Z-Value, p-Value, & Sen's Slope) in Intra-seasonal Wet Rainfall (1982–2021).**

Finally, the fourth decade (2010s), a slight to significant rise in wet seasonal rainfall (6.81 to 21.82 mm/decade) was observed in the northeastern Sahel Savannah (3.82%), while 17.3% of the northwestern Sudano-Sahelian Savannah experienced an insignificant increase in rainfall at rates of 0.01 to 6.80 mm/decade. However, an insignificant decline in rainfall (-20.85 mm/decade) was observed in the western and eastern parts of the AEZs, while a slight to significant decline in wet seasonal rainfall (-20.86 to -44.58 mm/decade) was recorded in the central part of the Guinea Savannah (18.69%), as shown in Figure 2d.

These findings highlight the importance of adaptive strategies in agriculture and water resource management. For instance, agroforestry practices and improved water

results, depicted in Figure 3, reveal an extremely to slightly significant increase in wet season rainfall in the northwestern part of the AEZs, with a significant increase in trend (0.01 to 5.54 mm/year) covering 26.85% of the Sudano-Sahelian savannah zones. An insignificant increase of 0.01 to 1.31 mm/year in wet seasonal rainfall was also recorded in the central part of the AEZs, covering 39.10% of the area.

Conversely, an extremely to slightly significant decrease in wet seasonal rainfall was recorded in the central and eastern parts of the Guinea Savannah, representing 8.71% of the study area, with a significant decrease in trend (-1.35 to -7.78 mm/year). An insignificant decrease of -1.34 mm/year was also observed in the central Guinea and eastern parts of the Sudan

Savannah, representing 26.04% of the study area.

### *3.2 Temporal Variability of Intra-Seasonal Wet Rainfall Distribution*

The wet seasonal rainfall for each agro-ecological zone (Guinea, Sudan, and Sahel) and the entire study area was extracted, analysed over a time series, and plotted using a regression model to understand the characteristics of each zone. Figure 4 illustrates the temporal variations of wet seasonal rainfall during the study period. The results revealed a decreasing trend in wet seasonal rainfall in the Guinea Savannah at a rate of 0.72 mm/year, accounting for only 0.6% of the variability in wet seasonal rainfall decline. This trend is statistically insignificant (Figure 4a). The wettest year in this zone during the study period was 1994, with an annual mean value of 1276.67 mm, while the driest year was 2021, with an annual mean value of 758.17 mm.

productivity and water resource management, necessitating integrated approaches to address these challenges (Ebodé *et al.*, 2024).

### *3.4 Inter-Annual Trends and Magnitude of Rainfall Distribution*

Figure 5(a-d) presents the decadal spatio-temporal Mann-Kendall trends and the magnitude of mean annual rainfall distribution. During the first decade (1980s), an insignificant decline in annual rainfall was observed in the central and eastern parts of the Guinea Savannah, with a decrease in trend of -4.61 to -21.39 mm/decade, covering 2.82% of the total area. However, a slight to significant rise in annual rainfall (16.70 to 65.13 mm/decade) was recorded in the southwestern part of the Guinea Savannah and the north-central Sudano-Sahelian Savannah, representing 35.14% of the area. Additionally, 62.04% of the AEZs experienced an insignificant increase in rainfall at rates of 0.1 to 16.69 mm/decade (Figure 5a).

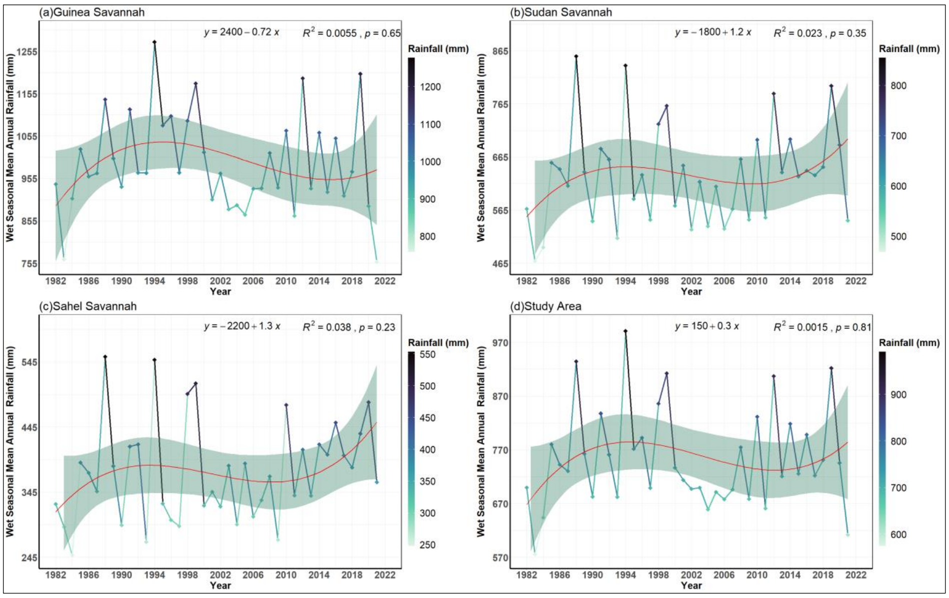


**Figure 4: Temporal Variation of Intra-seasonal Wet Rainfall Trends over the Guinea and Sudano-Sahelian AEZs (1982–2021).**

Conversely, the Sudan Savannah, Sahel Savannah, and the overall study area experienced increasing trends in wet seasonal rainfall at rates of 1.2 mm/year, 1.3 mm/year, and 0.3 mm/year, respectively. These increases account for 2.3%, 3.8%, and 0.15% of the variability in wet seasonal rainfall increase, as explained by the regression model (Figure 4b, c, & d). However, these trends are also statistically insignificant at a 5% confidence level. Such variability in rainfall trends may have profound implications for agricultural

The second decade (1990s), an insignificant decrease in annual rainfall was recorded in the Guinea Savannah, north-central, and extreme northeast of the Sudano-Sahelian Savannah, with a decrease in trend of -6.69 mm/decade, covering 66.52% of the total area. Similarly, a slight significant decrease in annual rainfall (-13.63 to -40.52 mm/decade) was observed in the central parts of the Guinea Savannah, representing 0.43% of the area. However, 33.05% of the north-western and north-central parts of the Sudano-Sahelian Savannah

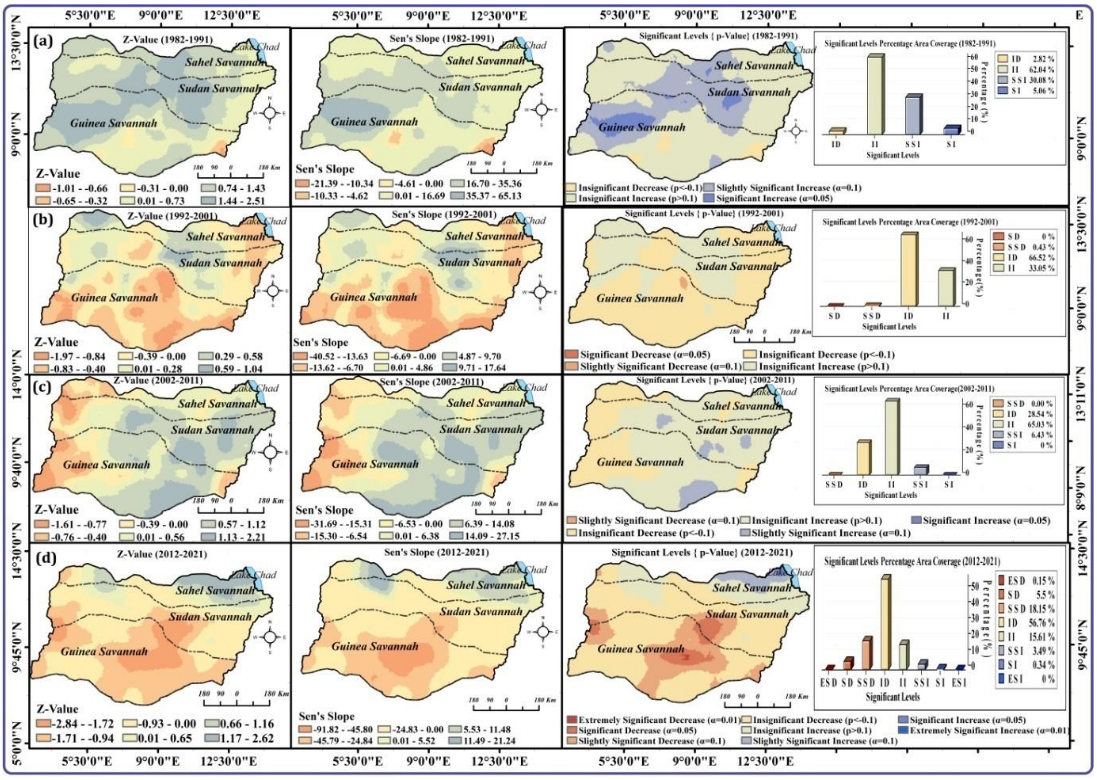


**Figure 5: Decadal Spatio-temporal Distribution of Trends Detected by Mann-Kendall Test (Z-Value, p-Value, & Sen's Slope) in Inter-annual Rainfall: (a) 1982-1991; (b) 1992-2001; (c) 2002-2011; (d) 2012-2021.**

experienced an insignificant increase in mean annual rainfall at rates of 0.01 to 17.64 mm/decade (Figure 5b).

Furthermore, during the third decade (2000s), a slight significant increase in annual rainfall (14.09 to 27.15 mm/decade) was recorded in southern Guinea and patches of the Sudan Savannah, representing 6.43% of the area. Additionally, 65.03% of the AEZs, excluding the western part of the study area, experienced an insignificant increase in rainfall at rates of 0.01 to 14.08 mm/decade. However, an insignificant decrease in mean annual rainfall (-6.53 to -15.30 mm/decade) was observed in the western part of the AEZs, representing 28.54% of the area (Figure 5c).

Finally, during the fourth decade (2010s), a slight to significant increase in annual rainfall (5.53 to 21.24 mm/decade) was observed in the extreme north-eastern part of the Sahel Savannah, representing 3.83% of the area. Additionally, 15.61% of the northern parts of the Sudano-Sahelian Zone experienced an insignificant increase in rainfall at a rate of 5.52 mm/decade. However, an extremely to slightly significant decrease in mean annual rainfall (24.84 to 91.82 mm/decade) was recorded in the western and central parts of the Guinea and Sudan Savannah, covering 23.80% of the area. An insignificant decrease in mean annual rainfall (24.83 mm/decade) was also observed across the AEZs, representing 56.76% of the area (Figure 5d).

Figure 6 illustrates the overall annual rainfall trends during the study period. The results indicate an extremely to slightly significant increase in annual rainfall in the north-western part of the agro-ecological zones (AEZs), with a significant positive trend ranging from 0.01 to 5.06 mm/year, covering 23.63% of the study area. Additionally, insignificant increases were recorded in the central part of the study area. These findings align with previous studies by Abaje, Ati, and Iguisi (2012), Ifabiyi and Ojoye (2013), and Ibrahim *et al*. (2020), which reported upward trends in rainfall distribution across the Sudano-Sahelian savannah zones of Nigeria. This observed increase in rainfall in some regions could have positive implications for agricultural productivity, water resource availability, and ecosystem resilience, as noted by Adeyeri *et al*. (2019). However, erratic rainfall patterns may still pose challenges for crop planning and flood risk management (Selvaraju, 2013).

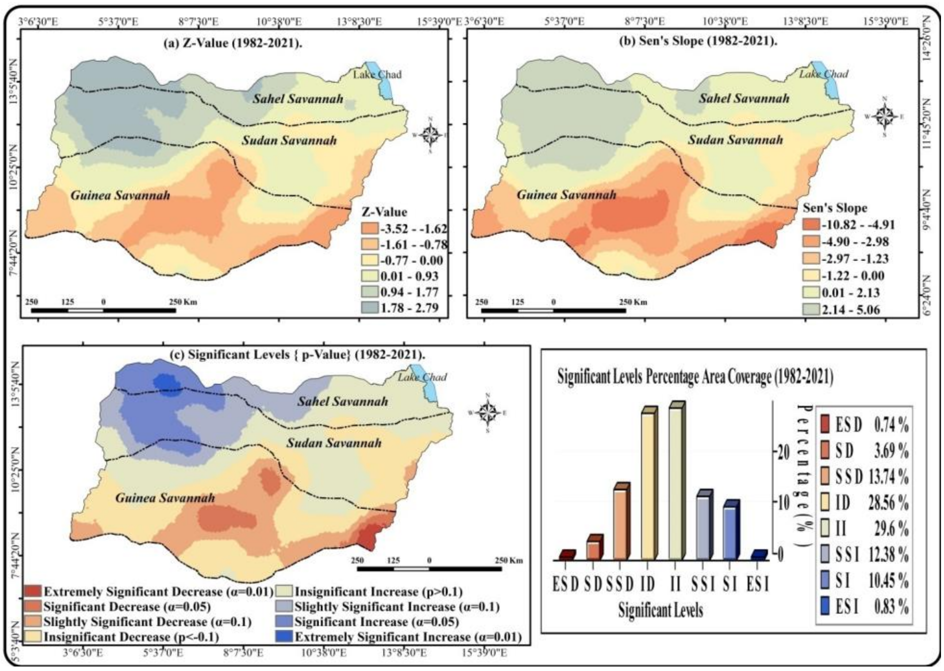


**Figure 6: Spatio-temporal Distribution of Trends Detected by Mann-Kendall Test (Z-Value, p-Value, & Sen's Slope) in Inter-annual Rainfall (1982–2021).**

Conversely, an extremely to slightly significant decrease in annual rainfall was observed in the central and south-eastern parts of the Guinea Savannah, covering 18.17% of the study area, with a notable declining trend ranging from -1.23 to -10.82 mm/year. Additionally, insignificant decreases were recorded in the Guinea and eastern parts of the Sudan Savannah, accounting for 28.56% of the study area. These results are consistent with Buba *et al*. (2017), who documented a declining rainfall trend in Guinea Savannah regions and its implications for drought occurrences and soil moisture deficits. The decreasing trend in rainfall may have significant consequences for rain-fed agriculture, groundwater recharge, and food security, as such declines in rainfall could lead to reduced crop yields, increased reliance on irrigation, and heightened competition for water resources.

### *3.5 Temporal Variability of Inter-Annual Rainfall Distribution*

The temporal variations of the trends in annual rainfall from 1982 to 2021 are shown in Figure 7. The results show a non-significant decreasing trend of annual rainfall in the Guinea Savannah at a rate of 1.9 mm/year,

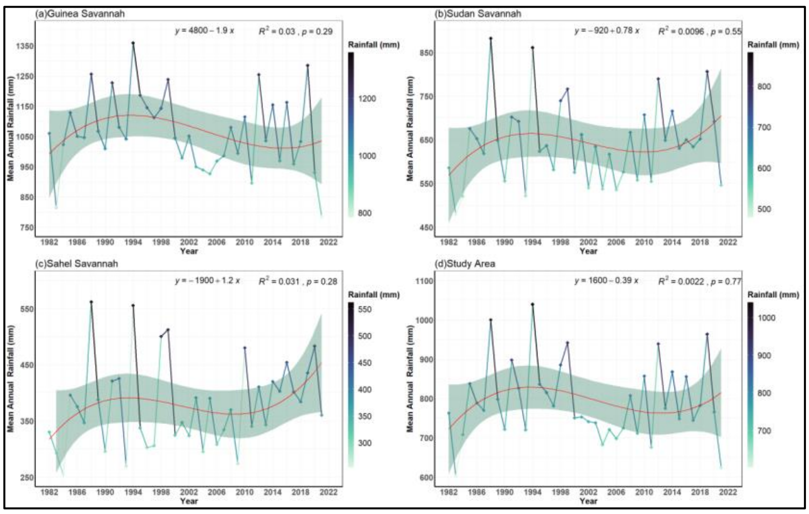


**Figure 7: Temporal Variations of Inter-annual Rainfall Trends over the Guinea and Sudano-Sahelian AEZs (1982–2021).**

accounting for only 3% of the variability (Figure 7a), and over the study area at a rate of 0.39 mm/year, accounting for only 0.2% of the variability in the decrease of mean annual rainfall (Figure 7d). However, non-significant increasing trends in mean annual rainfall were observed in the Sudan Savannah at a rate of 0.78 mm/year, accounting for 0.9% of the variability (Figure 7b), and in the Sahel Savannah at a rate of 1.2 mm/year, accounting for 3.1% of the variability in the increase in mean annual rainfall (Figure 7c). These findings emphasize the need for robust adaptation strategies to address the uncertainties posed by climate change, particularly in regions dependent on rain-fed agriculture.

## 4. CONCLUSION

This study examines intra-seasonal and inter-annual rainfall trends (1982–2021) across Nigeria agro-ecological zones (AEZs) using the Mann-Kendall test and Theil-Sen slope estimator. Spatially heterogeneous trends were identified: the Northwestern Sudano-Sahelian Savannah experienced significant wet-season increases (0.01–5.54 mm/year), while the central/southeastern Guinea Savannah saw declines (−1.35 to −7.78 mm/year). Temporally, the Sudan and Sahel Savannahs showed non-significant annual increases (0.78–1.3 mm/year), whereas the Guinea Savannah and broader region recorded decreases (−0.39 to −1.9 mm/year). These trends align with global evidence linking rainfall variability to climate change, ENSO dynamics, and anthropogenic factors like deforestation. The findings highlight the region’s vulnerability to climate-induced hydrological shifts, posing risks to rain-fed agriculture and water security. Targeted adaptive measures such as agroforestry, water harvesting, and community-based resource management are critical to enhancing resilience. This study advances understanding of localized rainfall variability in West Africa and emphasizes the need to integrate climate adaptation into policy frameworks. Future research should focus on hyper-localized monitoring systems and context-specific adaptation strategies to address compounded climatic and socio-economic challenges.

## ACKNOWLEDGEMENTS

We sincerely acknowledge the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Copernicus Climate Change Service (C3S) for providing the ERA5 reanalysis climate data used in this study free of charge. We also extend our gratitude to the Tertiary Education Trust Fund (TETFund) for their support in facilitating academic staff training and development, which has significantly contributed to advancing research and academic excellence. Finally, the authors thank the editor and reviewers for their time and constructive comments, which have greatly improved the quality of this manuscript.

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