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Assessment of Rainfall Trends, Variability, and Distribution under Climate Change in Southern Plateau State, Nigeria

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ABSTRACT
The effect of climate change on rainfall trends, variability, and distribution, which in turn affects agricultural activities and food security, is alarming. This study attempts to assess the rainfall trends, variability, and distribution in Southern Plateau State, Nigeria. The study utilized 42 years of monthly and annual rainfall data (1981-2022) derived through the NASA POWER archive. Seasonal patterns were analyzed using monthly rainfall, whereas annual totals were utilized to analyze long-term trends and spatial variability of rainfall in the area. Inferential statistics, including the Mann-Kendall (MK) trend test and Sen's slope estimator, were used in conjunction with descriptive statistics. The findings show that the rainfall regime is unimodal with a start in April-May, a peak in July-August, and cessation in September-October, with a short growing season of 5-7 months. The trend analysis reveals that the rainfall has steadily decreased in all LGAs, with the Sen's slope values varying between -7.6 mm/year and -11.9 mm/year. The MK test reveals statistically significant decreasing trends ($p < 0.05$) in all locations, which depict an upsurge in dryness and variability. Spatial analysis reveals that the distribution of rainfall is uneven, with the highest amounts in Langtang South and Qua'an Pan and the lowest values in Wase. These findings indicate growing climate instability, which is very problematic for rain-fed agriculture in the study area.

Keywords: Climate change; Rainfall variability; Seasonal rainfall pattern; Spatial variability; Temporal trend analysis

INTRODUCTION
Rainfall is an essential part of the hydrology cycle and a determining factor of the agricultural yield, especially in places like the Southern Plateau, where agriculture is mainly rain-fed. In these settings, the time, intensity, and distribution of rainfall have a direct impact on crop growth cycles, availability of soil moisture, and the overall agricultural yield. Rainfall refers to the water in the form of droplets that have condensed out of water vapor in the atmosphere and have become sufficiently heavy to fall under the influence of gravity (Udo-Inyang &and Edem, 2012). Rainfall variability can be understood as the degree to which rainfall amounts vary or fluctuate across an area or through time, which could be monthly or yearly (Udo-Inyang & Edem, 2012). It refers to the variations and changes in the amount, intensity, frequency, and spatial distribution of rainfall over a certain period of time and area. This variability has significant effects on agricultural productivity, water supply, and flood risk, which directly impact food security, economic stability, and human health (Kinda &Badolo, 2019; Tahroudi, 2025). Animals' breeding cycles align with rainfall patterns, and crop cultivation, yield, and harvests are influenced by rainfall and scheduled according to their respective optimal seasons to promote better productivity (Zitta & Madaki, 2020). Similarly, the soil's moisture content is periodically affected by rainfall. Therefore, an in-depth insight into the trends and patterns of rainfall that is essential in the most vulnerable areas to develop adaptive measures that would curtail the effects of these weather variables on livelihoods and ecosystems (Balogun *et al*., 2016; Tahroudi, 2025).
Climate change has resulted in tremendous changes in global precipitation patterns through changes in the intensity, frequency, and spatial distribution of precipitation events (Tahroudi, 2025). Recent studies have revealed a notable change in the dynamics of precipitation in the world, in particular, since 2002, when the total precipitation increased by around 1.8% (Adler *et al*., 2018). This development is in line with the climate change forecasts that show that global warming will increase the occurrence and intensity of extreme precipitation events (IPCC, 2021). The agricultural sector is more susceptible to the changing rainfall. The shift of rainfall regimes, coupled with the increase in temperature, will change the dynamics of pests, posing an even greater threat to crop productivity (Skendžić *et al*., 2021). Farm practices like rain-fed agriculture, including those in West Africa, are under a significant threat because of rising temperatures and irregular rainfall, which can lead to lower harvest quantities and food insecurity (Sultan & Gaetani, 2016). Moreover, changes in precipitation due to climate have been found to have a detrimental impact on certain crops, such as *Arabica coffee*, the suitability of which under changing climatic conditions may lead to a decrease in yield and quality (Ovalle-Rivera *et al*., 2015).

The topic of rainfall variability and climatic change and its impact on agriculture has been widely investigated globally, which offers a solid base of research on localized studies like this one in Southern Plateau State, Nigeria. Trenberth *et al*. (2014) analyzed the relationship between global warming and drought dynamics, revealing that rising temperatures intensify the hydrological cycle, leading to increased frequency and severity of droughts in some regions and excessive rainfall in others. The results of their study highlight the issue of uneven rainfall variability in the world. In the same manner, Ovalle-Rivera *et al.* (2015) estimated the changes in climatic suitability of *Coffea arabica* with changing rainfall and temperatures. The findings showed that climate variability has a significant impact on crop suitability and productivity of major producing areas. In a different international evaluation, Kazemzadeh *et al*. (2021) used linear and nonlinear methods to examine the trends of satellite-based precipitation between 1998 and 2017. Their findings indicated that there was a considerable spatial heterogeneity in the rainfall trends, as some areas were witnessing an increase in precipitation, whereas others were experiencing a reduction. These global studies collectively demonstrate that climate change influences rainfall variability, making it a complex and spatially uneven phenomenon.

In Africa, rainfall variability in regions such as the Sahel and Guinea Coast is correlated with contrasting rainfall anomalies in neighboring areas, indicative of intricate dipole patterns influenced by fluctuations in sea surface temperature, particularly related to the Atlantic. Similarly, studies about the seasonality of East African rainfall present a mix between unimodal and bimodal regimes due to varied climatic influences. Regions close to the equator have semi-annual peaks in rainfall, whereas those that are much farther south show an annual cycle due to the effect of the tropical and subtropical forces (Broman et al. 2019). The Atlantic Multidecadal Oscillation (AMO) is one of the most important reasons for long-term rainfall variability in West Africa (Awode *et al*., 2025). It has been extensively documented that it changes the intensity of the monsoon, moisture movement, and livelihoods (Crétat *et al.* 2024). For example, Sultan & Gaetani (2016) studied climate change scenarios and their implications for agriculture in West Africa. Their findings indicate that increasing rainfall variability, coupled with rising temperatures, poses significant risks to crop productivity, particularly in rain-fed systems. Similarly, Gadedjisso-Tossou *et al*. (2021) investigated rainfall and temperature trends using the Mann–Kendall test in Northern Togo and assessed their implications for rain-fed cereal yields. The study found significant variability in rainfall patterns, which directly affected crop productivity.

The potential that extreme rainfall events hold for disrupting human activities is of special concern, given their potency and usually manifested as short-term, high-intensity rainfall. Such events have extensive consequences on urban flooding, soil erosion, and agricultural losses (Ayanlade *et al*., 2018). An example is the rainfall patterns and the duration of the growing season in Nigeria, where Odekunle (2004) established that variability in the onset and termination of rainfall is a major determinant of agricultural productivity. The experiment showed that the changes in the timing and the duration of rainfall have a direct impact on crop cycles and yields. Building on this, Matawalli (2021) conducted a spatio-temporal analysis of rainfall trends in the Sudano-Sahelian region of Nigeria and linked these trends to agricultural production. The research revealed that there was a great disparity and a decrease in rainfall in certain regions, with direct effects on diminished crop production. Similarly, Ati *et al*. (2022) examined meteorological drought and temperature conditions in the Sudano-Sahelian area under the rising global warming. Their results suggest that increasing drought frequency and warming temperatures are severe challenges to the sustainability of agriculture.

Specifically, Plateau State studies (Binbol *et al.*, 2016; Zitta & Madaki, 2020; Binbol *et al*., 2020; Danbauchi, 2023; Fredricks & Goyol, 2025) indicate that rainfall is highly variable both within and across years, with shifts in the onset, cessation, and duration of rainy seasons. These shifts have significant repercussions on rain-fed agriculture in the Jos Plateau, but the available literature has mostly focused on the Jos Plateau without directly examining the scenario in the Southern Plateau State. While regional trends and variability have been identified, the Southern Plateau remains under-researched, despite its significant contribution to food production in the state and Nigeria as a whole. Existing gaps include a lack of evaluation of seasonal rainfall patterns, a lack of long-term evaluation, and insufficient analysis of growing season characteristics and direct agricultural implications. Thus, this study addresses these critical gaps by providing a localized, empirically grounded assessment of seasonal and long-term rainfall variability in the Southern Plateau. The objectives of the study include: i). examine the seasonal (monthly) rainfall variability to identify patterns of rainfall onset, peak, and cessation across six LGA of Southern Plateau and their implications for farming activities; ii). Analyze the temporal trends and magnitude of change in annual rainfall across the LGAs between 1981 and 2022; and iii). Analyze the spatial variability of rainfall distribution across the LGAs during the study period.

MATERIALS AND METHODS

Description of the Study Area

The study area is located in the central part of Nigeria, particularly Plateau State. It is geographically located between latitudes 8º21’57"N and 9°36' 18"N and longitudes 8º 50’ 56”E and 10° 40' 41"E It comprises of six LGAs, which include Langtang North and South, Mikang, Qua’an Pan, Shendam, and Wase, respectively (Figure 1).

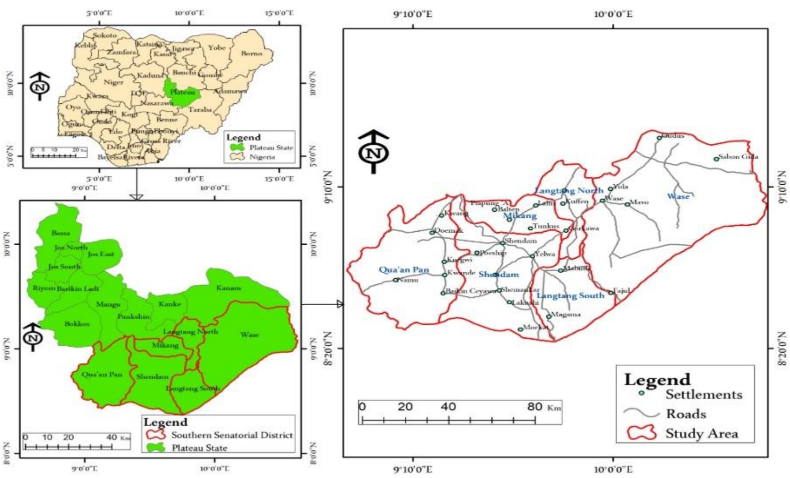

Figure 1: Location of the Study Area

The climate of the area is a tropical continental wet and dry climate, which is classified as an Aw climate by the Koppen classification. The average annual precipitation in the study area differs, with the average annual precipitation totaling 1200 mm (Binbol *et al*., 2016). The rainy season lasts from April to October, with the highest precipitation in August, and the dry season begins in November and ceases at the beginning of April (Binbol *et al*., 2021).

The seasonal changes in rainfall are caused by the movement of two air masses: the warm and humid tropical maritime air mass (mT), which is formed in the Atlantic Ocean, and the relatively cold and dry tropical continental air mass (cT), which is formed in the Sahara Desert and is called harmattan. The air masses meet at a boundary called the Inter-Tropical Discontinuity (ITD). The rainy season in the region is at its height during August when ITD flows north across the state (around latitude 21 to 22 °N), and its dry season is at its peak in January or February when ITD flows to the southernmost part of the country (approximately at 6 °N) (Abaje *et al.,* 2016; Binbol *et al*., 2016). The warmest monthly temperature of the region is in March-April, and the coolest is in the month of December to February. The highest temperature of the day is more than 30°C, and the lowest temperature of the day is less than 20°C during the night.

The rainy season has a high relative humidity (approximately 80 percent) peaking in August, and the dry season has a relative humidity of about 10 percent. The location lies in the zone of Guinea vegetation with trees dispersed across it.

Data, Source, and Usage

This study utilized secondary rainfall data obtained for the Southern Plateau, covering a period of 42 years (1981–2022). The data included the monthly rainfall (January to December) and annual rainfall totals in the six LGAs. The data were obtained from the NASA POWER (Prediction of Worldwide Energy Resources) project, which offers credible and standardized meteorological data (Al-Adwan *et al*. 2022; Jiqin *et al*., 2023). The data used in the POWER project is provided by the following NASA sources: World Climate Research Program (WCRP), Global Energy and Water Cycle Experiment (GEWEX), Surface Radiation Budget Project (NASA GEWEX SRB), and the Clouds and the Earth Radiant Energy System and Assimilation Office at the Goddard Space Flight Center. NASA POWER data have been widely used by other researchers in their studies and are recommended for their use in meteorological daily data to apply them in agro-meteorology (Al-Adwan *et al*. 2022; Jiqin *et al*., 2023). The rainfall data obtained was computed and compared with the figures of rainfall from meteorological stations used by Binbol et al. (2020), Zitta and Madaki et al (2020), Danbauchi (2023), and Fredricks & Goyol (2025) in the Jos Plateau, to validate its reliability. It was discovered that there is no much difference in the figures. The difference that exists could be due to differences in location (the Jos Plateau vs. Plateau Lowland).

The rainfall data served various analytical objectives of the study. The monthly data was used to analyze seasonal variations, especially the time when the rainfall begins, peaks, and ends, which is vital in the agricultural planning process. The long-term trends and variability were analyzed using annual rainfall totals, which allowed for the identification of how the rainfall patterns changed over time. In addition, the data enabled a comparison between LGAs at the spatial level, enabling the study to determine the variations in the rainfall distribution and how they can impact agricultural practices in the area.

Data Analysis

The analysis of rainfall variability was structured to align with the stated objectives and involved a combination of descriptive and inferential statistical techniques. The analysis of monthly data of rainfall was conducted to determine the typical pattern of rainfall distribution over the year and to study the variability of rainfall seasonally. The average monthly rainfall in each LGA was calculated, and graphical analysis methods, including line graphs, were applied to analyze the seasonal cycle. This method enabled the identification of the commencement of the rainy season, the peak rainfall, and the cessation in the study area. The equation to compute the average rainfall is as shown in equation (1):

$$\overline{X} = \frac{\sum X}{N} \qquad (1)$$

Where: x = Monthly rainfall values

X= Mean

N = Number of months

Σ = Summation

Mann-Kendall Test

The study utilized the Mann-Kendall (MK) trend test, a non-parametric statistical tool to determine long-term rainfall trends, which is commonly applied in identifying trends of hydro-climatic time series. The MK test was employed to establish whether the rainfall had a statistically significant increasing or decreasing trend over the period of study. Several scientists have followed this method to comprehend the tendencies in the temperature and rainfall processes (Agarwal *et al*., 2021; Yaouba & Dieudonne, 2022; Jiqin *et al*., 2023).

The MK trend test is founded on two hypotheses: the null (H_0) and the alternative (H_1) hypotheses (Gadedjisso-Tossou *et al*., 2021). The H_0 explains the presence of no trend, whereas H_1 explains a strong increasing or decreasing trend of precipitation data. Essentially, based on a 5% significance level, when p-value ≥ 0.05, the H_0 is accepted, indicating the absence of a trend in the data, and when p-value ≤ 0.05, then the H_0 is rejected, indicating the presence of a trend in the data (Baig *et al*., 2021). It is mathematically expressed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}(X_j - X_i) \quad (2)$$

Where n is the numbers of data points, X_j and X_i are annual values in years j and i, $j > 1$ and Sign $(X_j - X_i)$ calculated using the equation:

$$\operatorname{Sign}(X_j - X_i) = \begin{cases} -1 \text{ for } (X_j - X_i) < 0 \\ 0 \text{ for } (X_j - X_i) = 0 \\ +1 \text{ for } (X_j - X_i) > 0 \end{cases} \quad (3)$$

Sen's Slope Estimator Test

Complementing this, the Sen's slope estimator in XLSTAT software was applied to quantify the magnitude of the detected trend. The test was initially designed by Sen to verify the linear relationships (statistically) (Agarwal *et al*., 2021). It is used to calculate the magnitude of trends in the long-term temporal data (Agarwal *et al*., 2021). Sen's slope is considered better for detecting the linear relationship, as it is not affected by outliers in the data (Ray *et al.*, 2021). This study utilizes Sen's slope to determine the magnitude of the trend in temperature and rainfall data. The following equation is used to estimate each slope (Qi):

$$Q_i = \frac{Y_j - Y_i}{j - 1} \quad (4)$$

Where $i = 1$ to $n - 1$, $j = 2$ ton, Y_j and Y_i are data values at time j and i ($j > i$), respectively. If in the time series, there are n values of Y_j, estimates of the slope will be $N = n$ ($n - 2$)/2. The slope of the Sen Estimator is the mean slope of such slopes' N values. The Sen's slope is:

$$Q_{ij} = \begin{cases} \frac{Y_j - Y_i}{j - 1} & \text{if } n \text{ is odd} \\ \frac{1}{2}\left(Q\frac{N}{2} + Q\left[\frac{N+2}{2}\right]\right) & \text{if } n \text{ is even} \end{cases} \quad (5)$$

The spatial variability of rainfall was measured by comparing the rainfall characteristics of the six LGAs. The estimation of the distribution of rainfall in the study area was done using an interpolation technique, specifically the IDW in the Spatial Analyst tools of ArcMap 10.8. This analysis was useful in determining spatial rainfall variability and the LGAs that had relatively more or less rainfall. Tables, comparative graphs, and maps were used to clearly depict the results, highlighting the spatial differences and their implications for agricultural activities in the study area.

RESULTS AND DISCUSSION

Seasonal (Monthly) Rainfall Variability and Patterns of Rainfall Onset, Peak, and Cessation across the Six LGAs and their Implications for Farming Activities

The distribution of seasonal rainfall (Figure 2) across LGAs shows a distinct unimodal pattern characteristic of the Guinea savanna. The long dry season lasts from November to March, and the majority of rain occurs between April and October. Rainfall starts around the months of April and May, albeit with some variability in timing and intensity due to localized climatic controls. The maximum intensity of rainfall occurs in July and August, with much higher values in Langtang South (236.6 mm) and Qua'an Pan (225.3 mm), and much lower values in Shendam (190.4 mm), but thereafter, it decreases dramatically to the point of ceasing in September and October. The other LGAs, Langtang North, Mikang, and Wase, portray significant peak rainfall with a range of about 214 mm to 224 mm. This means that even though the peak rainfall is recorded during a similar period in all LGAs, the intensity differs spatially, with Langtang South and Qua' an Pan receiving the higher rainfall intensities. This short rainy season of 5-7 months shows that there is a limited agricultural period that is very vulnerable to fluctuations in the start, peak, and end.

These findings are consistent with those of Zitta & Madaki (2020), who reported increasing rainfall irregularity and declining predictability on the Jos Plateau, as well as Binbol *et al.* (2020), who identified shifts in seasonal rainfall characteristics and growing season length. Likewise, Danbauchi (2023) has also highlighted that rainfall timing and distribution in Jos Metropolis have changed due to climate change, which supports the variability in this study. Farmers in the area should ensure that their farming activities are in line with the seasonal rainfall pattern. Planting is to begin as soon as rains (April-May) occur, at which point the soil is moist enough to allow seed germination and early crop growth.

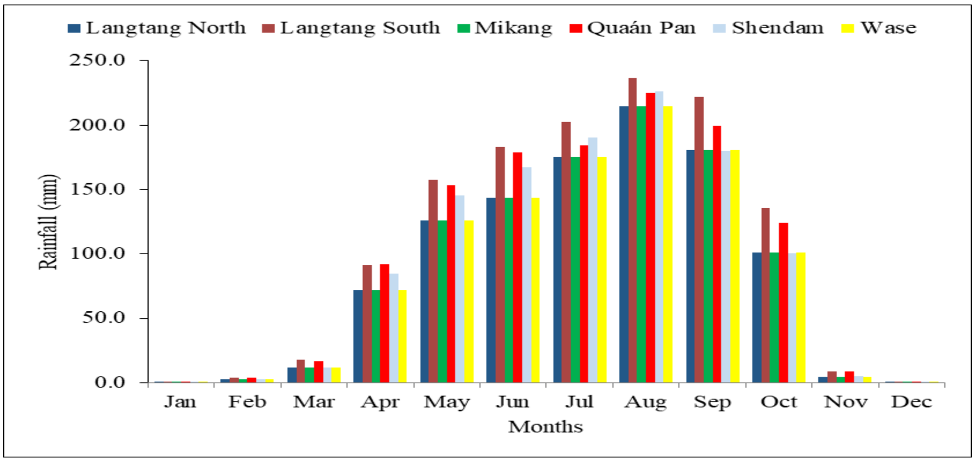

Figure 2: Seasonal (Monthly) Rainfall Variability in the Study Area

Temporal Trends and Magnitude of Change in Annual Rainfall across the Six LGAs between 1981 and 2022

The rainfall trend in Langtang North (1981–2022) shows a decrease (−12.05 mm/year) and strong interannual variability, indicating a transition to lower reliability and greater climatic uncertainty (Figure 3). This corresponds to a reduction magnitude of between 480-500 mm over 42 years, which is significant in a region that primarily relies on seasonal rainfall for agriculture and water supply. This negative trend indicates a change in the long-term rainfall regime, moving toward increased dryness. This result aligns with Magaji *et al*. (2025), who reported that the spatial and temporal variability of rainfall increased with the degree of dryness in northern Nigeria. Further, even though rainfall amount is declining, the changes across the years are not uniform, but irregular. Rainfall peaked at 1698.05 mm in 1982, dropped sharply to 569.53 mm in 1999, and later recovered to 1151.94 mm in 2022. These substantial variations suggest that rainfall is becoming more erratic rather than decreasing steadily.

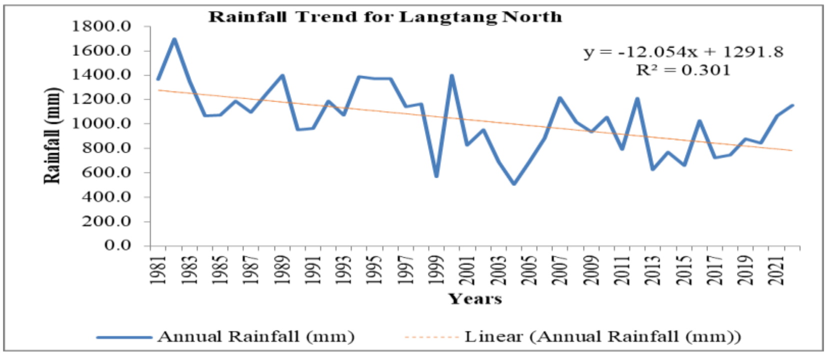

Figure 3: Rainfall Trends for Langtang North

For Langtang South, the trend (1981–2022) reveals that rainfall has decreased slowly by approximately -11.33 mm annually, and the cumulative magnitude decrease of between 470–480 mm across the 42 years (Figure 4). The pattern of rainfall variation in the area is also irregular, with extreme values ranging between wet years (e.g., 1935.4 mm in 1982 and 1898.4 mm in 2000) and dry years (e.g., 696.1 mm in 2004), not a steady decrease. This finding reflects Oluwadare & Oluwadare (2025)'s report of presence of a high temporal fluctuation and a change in the distribution of rainfall in southwestern Nigeria. Also, the observed irregular concentration of rainfall is also consistent with the results of Ezenwaji *et al*. (2020), who demonstrated that rainfall is frequently not evenly distributed over the year, thus resulting in the occurrence of excesses and deficits in Awka, Anambra State.

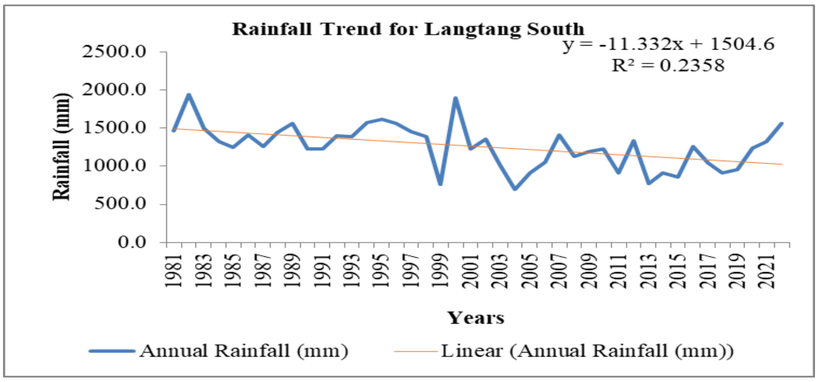

Figure 4: Rainfall Trends for Langtang South

The rainfall temporal variation in Mikang LGA exhibits a decrease of approximately -12.05 mm/yr, which translates to a total magnitude decrease of between 480-500 mm over the years (Figure 5). The rainfall regime is very unpredictable, with a high degree of variability between wet and dry years (e.g., 1698.1 mm in 1982 and 569.5 mm in 2004, respectively), showing an increasing pattern of variability. This trend is in tandem with the report of Binbol *et al*. (2020) that rainfall characteristics were greatly varying over time in the Jos Metropolis. This decreasing and unpredictable rainfall makes planting seasons less predictable, adds to exposure to drought stress, and increases unreliable crop yields, which Abaje (2023) highlighted that the rising variability of climatic conditions and the frequency of droughts are important characteristics of the altering rainfall regimes that affect crops yields in northern Nigeria.

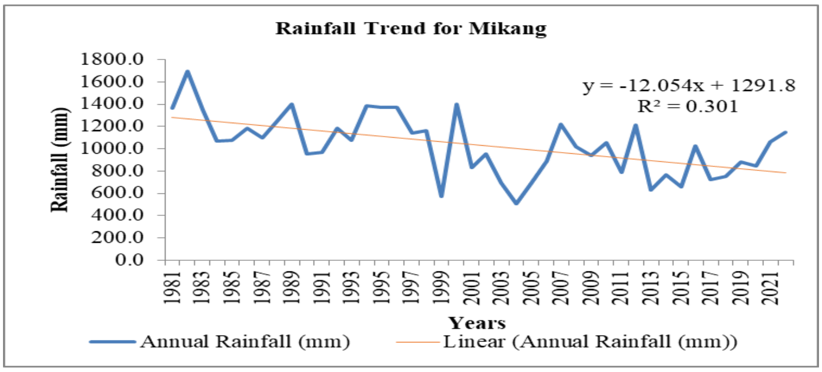

Figure 5: Rainfall Trends for Mikang

The temporal variation of rainfall in Qua'an Pan LGA also shows a decrease of approximately -13.26 mm/year, with a cumulative magnitude of 550-560 mm over the study years (Figure 6). Further, the rainfall regime is extremely irregular over the years, with wet years (e.g., 1808.8 mm in 1982 and 1830.4 mm in 2022) and dry years (e.g., 495.7 mm in 2004 and 49.4 mm in 2013). There exists strong temporal rainfall variability in the area, which reflects the report of Magaji *et al*. (2025) that there exists strong spatial and temporal rainfall variability in northern Nigeria. Thus, the findings suggest that Qua'an Pan is in a transition to a more uncertain and extreme rainfall pattern, with potential implications on water resources management.

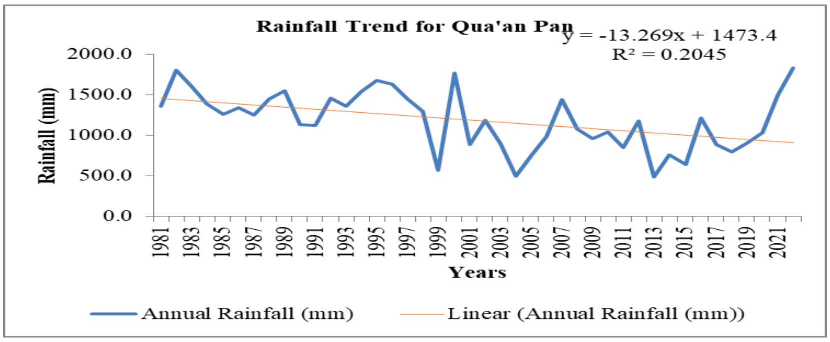

Figure 6: Rainfall Trends for Qua'an Pan

For Shendam LGA the temporal variation of rainfall also exhibit a decreased of approximately -14.0 mm/year, with a total decrease magnitude of 580–600 mm over the 42 years (Figure 7). The rainfall pattern is very erratic, and the differences between wet years (like 1729.7 mm in 1982) and dry years (like 464.1 mm in 2004) are sharp and great. This finding indicates that the rainfall in Shendam is shifting to a more unstable rainfall regime that requires adaptive measures, including better water management and climate-resistant agricultural practices.

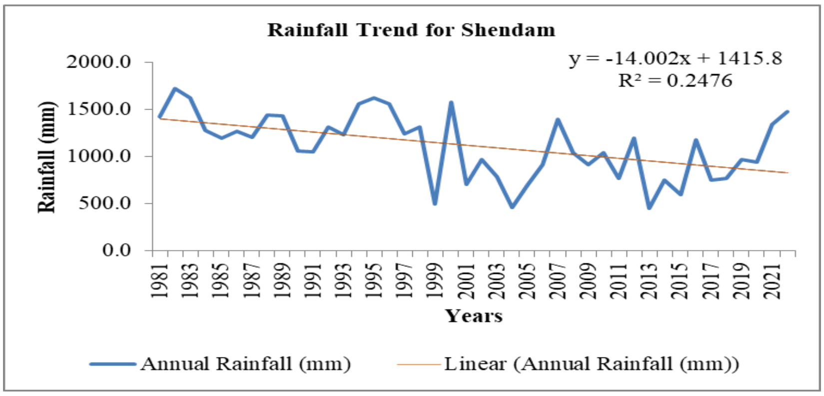

Figure 7: Rainfall Trends for Shendam

The temporal variation of rainfall in Wase LGA shows a reduction of -12.05 mm/year and a cumulative magnitude decrease of 480-500 mm over the years (Figure 8). The rainfall variation pattern in the areas was not uniform, with some wet years (e.g., 1698.1 mm in 1982) and dry years (e.g., 506.3 mm in 2004), which shows growing instability instead of consistent reduction. Animashaun *et al.* (2020) also reported variability, trend shifts, and change points in rainfall patterns across central Nigeria (in which the area of this study is found). This finding reveals that Wase is moving towards a more erratic rainfall pattern, necessitating adaptive measures in terms of enhanced water management, soil conservation measures, and climate-resilient agricultural operations.

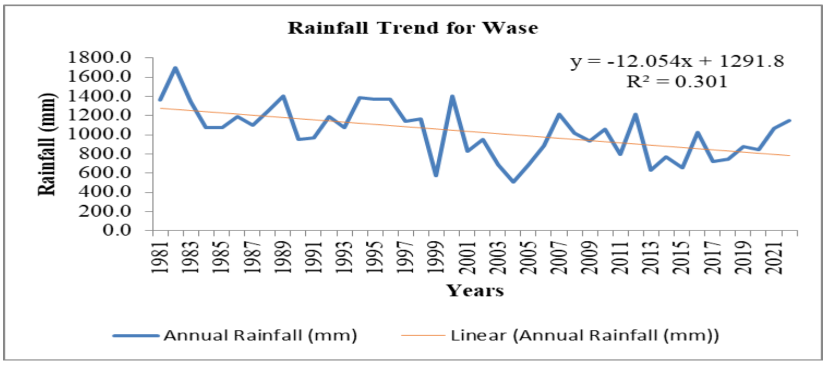

Figure 8: Rainfall Trends for Wase

Collectively, the interannual and temporal variability of the rainfall pattern across the six LGAs was high, but the overall declining tendency was slowly, which shows rising climatic instability instead of a steady decline (Figure 9). Whereas other regions like Langtang North, Langtang South, Mikang, and Wase experience moderate declines with weak reductions, Shendam shows a more substantial decline, whereas Qua'an Pan seems to be relatively stable with greater and more consistent rainfall amounts. The regular occurrence of very wet and very dry years underscores the increasing uncertainty of rainfall in the area.

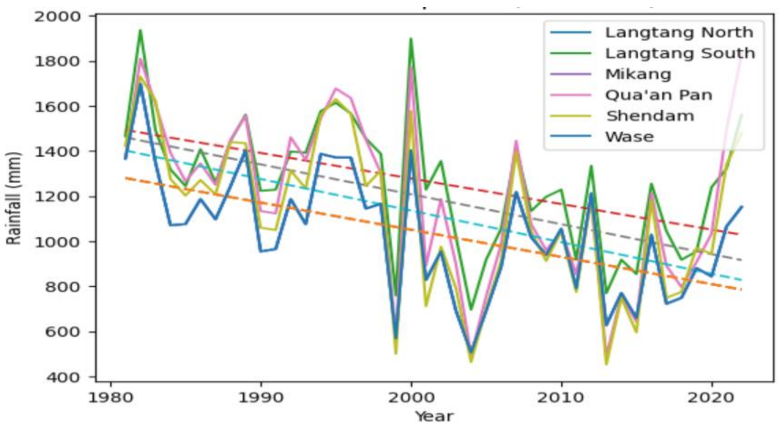

Figure 9: Comparison of Rainfall Trends for the Six LGAs

Mann – Kendall Test Results for Rainfall

Table 1 reveals that all six Local LGAs in the Plateau Southern Zone exhibited statistically significant decreasing (downward) rainfall trends over the period 1981–2022. The standardized Z-values range from −2.948 to −3.273, while all p-values were below 0.05, confirming that the observed declines are statistically significant. Among the LGAs, Langtang North, Mikang, and Wase recorded the strongest downward trend (Z = −3.273; p = 0.001), whereas Qua'an Pan showed the weakest, though still significant, declining trend (Z = −2.948; p = 0.003). These findings suggest a persistent reduction in annual rainfall across the Plateau Southern Zone, with implications for rain-fed agriculture, water resources, and drought vulnerability.

Table 1: Mann – Kendall Test Results for Rainfall in the Study Area

LGA	n (years)	Std	Z-value	p-value	Trend Direction	Decision (α = 0.05)
Langtang North	42	-303	-3.273	0.001	downward trend	Reject H_0
Langtang South	42	-284	-2.068	0.002	downward trend	Reject H_0
Mikang	42	-303	-3.273	0.001	downward trend	Reject H_0
Qua'an Pan	42	-273	-2.948	0.002	downward trend	Reject H_0
Shendam	42	-288	-3.110	0.002	downward trend	Reject H_0
Wase	42	-303	-3.273	0.001	downward trend	Reject H_0

Sen's Slope Result (Rainfall Change Rates in the LGAs)

The estimates by the Sen Slope point to a steady negative change in annual rainfall across the six LGAs, thereby confirming a continuous decreasing trend within the study area (Table 2). The extent of the decline is different across space, with the most significant decline in Langtang North, Mikang, and Wase (−11.9 mm/year) and the least decline in Qua'an Pan (−7.6 mm/year). These rates are indicatives of susceptibility to drying situations (droughts), especially in North, Mikang, and Wase. Agarwal *et al*. (2021) showed that Sen Slope analysis is efficient in capturing the direction and extent of a decreasing rainfall, which supports the validity of the findings made in the current research. The observed spatial variations indicate that topography, urbanization, vegetation cover, and land use practices are local factors that moderate the changes in rainfall in the study area.

Table 2: Sen's Slope Result (Rainfall Change Rates in the LGAs)

LGA	Sen's Slope (mm/year)	Trend Direction
Langtang North	-11.9	downward trend
Langtang South	-10.4	downward trend
Mikang	-11.9	downward trend
Qua'an Pan	-7.6	downward trend
Shendam	-9.2	downward trend
Wase	-11.9	downward trend

Spatial Variability of Rainfall Distribution across the Six LGAs during the Study Period

The result of the spatial distribution of rainfall in the study area reveals heterogeneity in the rainfall as at 1982 (Figure 10). The result indicates that the distribution of rainfall was not evenly distributed but rather follows a decreasing pattern as it moves northward to the southern/central regions. The highest rainfall was in Langtang South (1935 mm), while Wase in the northeast had comparatively lower figures (1698 mm). The intermediate conditions observed in Qua'an Pan and Mikang confirm that there is a uniform south-north gradient in rainfall distribution within the region. Topography and atmospheric processes are major factors in controlling this spatial pattern. The higher and wavy topography increases orographic rainfall, whereby the warm air in the West African monsoon is pushed up, cooled, and condensed, resulting in increased rainfall (Ati et al., 2022).

In addition, localized rainfall cores and isohyetal variations indicate that there are microclimatic variations within LGAs. Vegetation cover, soil moisture, and land management practices influence these variations, affecting evapotranspiration and local moisture recycling. The spatial heterogeneity of rainfall emphasizes the necessity of location-specific agricultural planning and strategies for managing water resources. Regions with a relatively high rainfall like Langtang south enjoy a sufficient amount of soil moisture and extended periods of growing, which encourages crops that require a lot of water such as maize and rice.

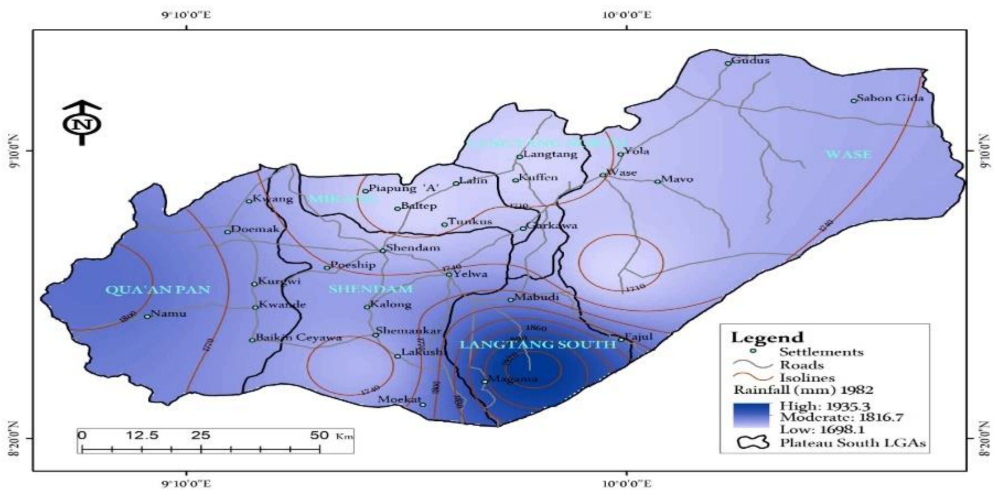

Figure 10: Spatial Variability of Rainfall Distribution across the Six LGAs (1982)

The 1992 spatial distribution of rainfall in the regions indicates a distinct west-south to northeast gradient, with the highest amount of rainfall received in Qua'an Pan and Langtang South, moderate amounts in Shendam and Mikang, and lower totals in Wase and portions of Langtang North (Figure 11). The existence of identifiable rainfall cores, particularly in the vicinity of Qua'an Pan, indicates localized intensification through orographic processes and convergence of moisture, whereas lower rainfall in the northeast implies limited uplift and a weaker impact of moisture. This trend aligns with the data of Binbol *et al.* (2020) and Zitta & Madaki (2020), who highlighted that topography and atmospheric processes have a strong influence on rainfall distribution on the Jos Plateau.

High rainfall areas like Qua'an Pan and Langtang South are conducive to crops that require a lot of water and extended growing periods. On the contrary, drier regions such as Wase are in need of drought-resistant crops and water conservation methods. Intermediate areas like Shendam and Mikang have moderate conditions yet are prone to variability.

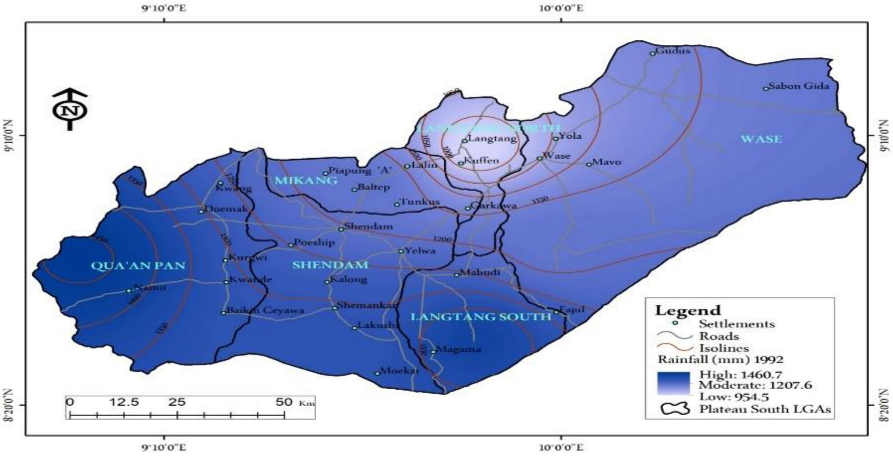

Figure 11: Spatial Variability of Rainfall Distribution across the Six LGAs (1992)

The 2002 spatial rainfall distribution indicates a moderate and more fragmented rainfall regime as compared to wet years (Figure 12). The core of the rainfalls is still Langtang South (1355 mm), with comparatively high values in Qua'an Pan, located in the west. Wase and parts of Langtang North, however, receive less rain (950-1150 mm), forming a southwest-northeast gradient with a lower level of rainfall to the northeast. The pattern of isohyets also indicates the existence of localized depressions of rainfall in the central Shendam, which means that there is an unequal distribution of moisture. Such spatial heterogeneity is consistent with the results of Binbol et al. (2020), who stressed that the rainfall of the Jos Plateau is extremely uneven and heterogeneous under the influence of topography and atmosphere. The intra-seasonal variability necessitates the use of adaptive management in moderate areas like Shendam and Mikang. Conversely, the regions with lower rainfall, such as Wase and portions of Langtang North, experience moisture stress, reduced growing periods, and dependence on drought-resistant crops and water conservation measures.

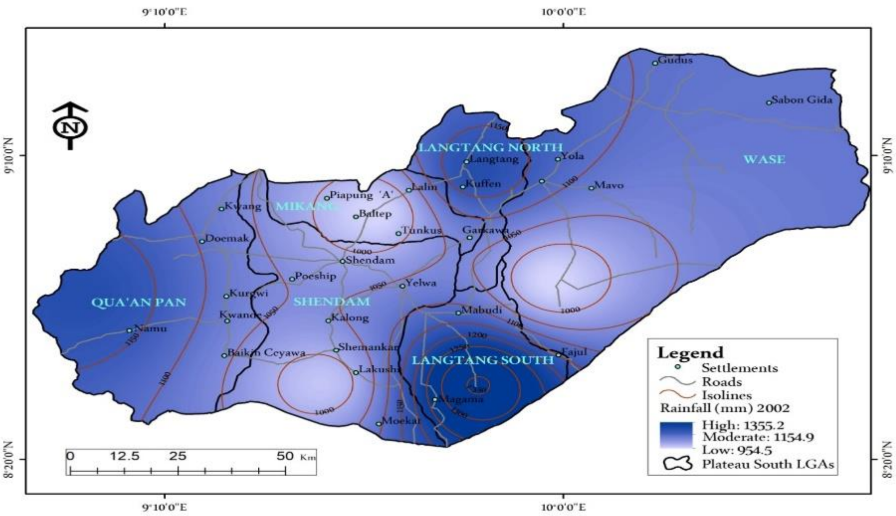

Figure 12: Spatial Variability of Rainfall Distribution across the Six LGAs (2002)

The spatial rainfall distribution of 2012 in the LGAs was relatively uniform and structured, with greater rainfall falling in the southern part, especially in Langtang South (1334 mm). Qua'an Pan, in contrast, has fewer values (1175 mm), whereas Wase and Langtang North have moderate values, which shows a south-to-north/west gradient (Figure 13). The less jagged isohyetal curve indicates more constant weather conditions than the previous years of fragmented weather, but there are still areas of reduced rainfall, which represent micro-scale variation. Compared to previous years, say 2002, where the rainfall patterns were observed to be fragmented, the 2012 map reflects a more continuous and smooth isohyetal pattern, which is indicative of relatively stable atmospheric conditions throughout the year. Nevertheless, the existence of localized low-rainfall areas, especially in portions of Quaan Pan and central Shendam, still depicts the impact of micro-scale variability, which can greatly affect local agricultural performance. Overall, 2012 could be termed a fairly wet year with fewer spatial extremes, but variability was still apparent.

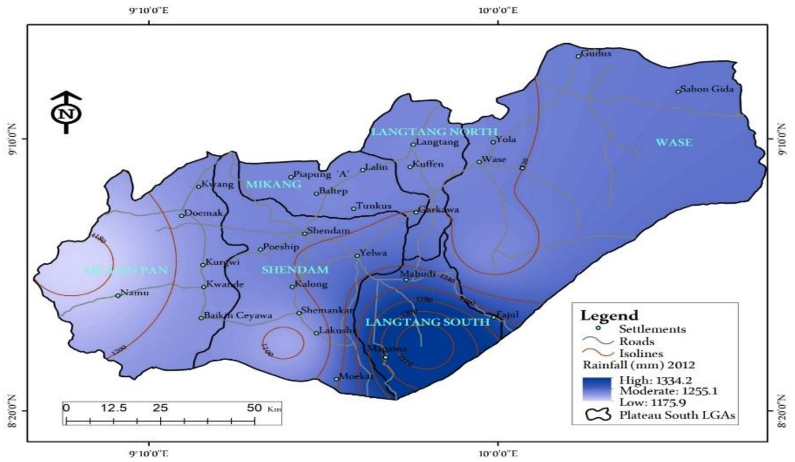

Figure 13: Spatial Variability of Rainfall Distribution across the Six LGAs (2012)

The spatial distribution of rainfall in 2022 shows that there was a high dominance in the west-south with a distinct gradient declining towards the central and northeast regions (Figure 14). The highest rainfall was in the western zone, with 1830 mm precipitating as in Qua'an Pan. The values at Langtang South were also high. Conversely, Wase and Langtang North areas experience less precipitation (1150–1300 mm), and this implies a clear wet-dry spatial difference throughout the area. Drier regions such as Wase and certain parts of the Langtang North experienced moisture stress and shorter growing seasons and need to use drought-tolerant crops and water conservation measures.

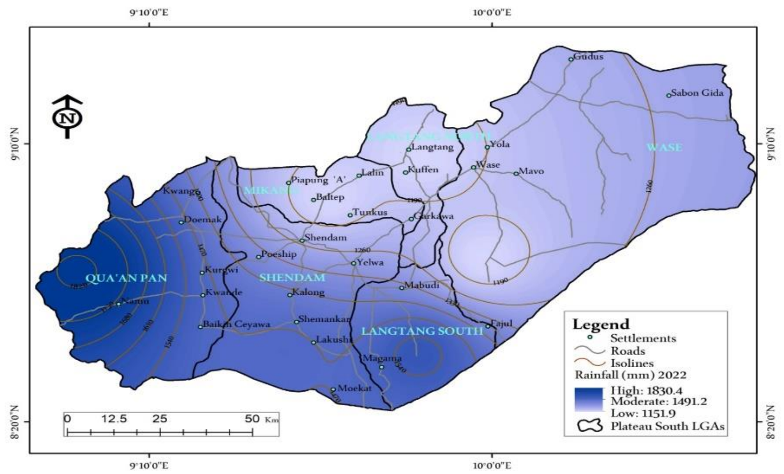

Figure 14: Spatial Variability of Rainfall Distribution across the Six LGAs (2022)

CONCLUSION

In conclusion, this paper shows that the six LGAs within the Southern Plateau are undergoing a gradual shift in terms of decreased and increasingly sporadic rainfall patterns. The changing rainfall regime presents grave threats to the sustainability of agriculture, food security, and rural livelihoods. The urgency of these changes is to reduce these effects, which is only possible by developing climate-intelligent agricultural methods, allocating funds to water management, and creating adaptive approaches based on the needs of a specific area. In the absence of these interventions, further decreases and uncertainty of rainfall can impose a serious threat to the agricultural productivity and socioeconomic stability in the area.

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