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ORIGINAL RESEARCH ARTICLE

Rainfall and Temperature Trends in Kaduna North and Their Implications for Water Resources

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ABSTRACT

Rainfall and temperature variability can impact the availability of water resources for agricultural and domestic use. This study examined the trends in rainfall and temperature, as well as their implications for water resource management. The Nigerian Meteorological Agency (NiMet) provided the meteorological data used in this study. The precipitation concentration index (PCI), rainfall anomaly index (RAI), and coefficient of variation (CV) were used to assess rainfall variability. The Mann-Kendall (MK), Modified Mann-Kendall (MMK), and innovative trend analysis (ITA) methods were employed to identify trends in temperature and rainfall. The results showed that rainfall and temperature had very low variability in Kaduna North, with CVs of 0.08 and 0.012, respectively. According to the RAI, 2013 was identified as the driest year, with RAI values of -6.075, while 2010 was the wettest, with RAI values of 7.913. The PCI indicated that annual rainfall in Kaduna North LGA is characterized by high and moderate concentration levels, with values of 71.0% and 29%, respectively. Using conventional methods, the rainfall experienced a nonsignificant decreasing trend (MK: -1.05, MMK: -1.53, $p > 0.05$), while the mean temperature increased significantly (MK: 1.97, MMK: 2.45, $p < 0.05$). However, the innovative trend analysis revealed a significant decrease in rainfall (S_{ITA}: -2.540, $p < 0.05$) and a significant increase in the mean temperature (SITA: 0.007, $p < 0.05$). Findings highlight risks of water scarcity and the need for adaptive management. Therefore, the study recommends implementing adequate water conservation measures to address the declining water resources, especially rainfall, and increasing awareness about the challenges posed by this decline.

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INTRODUCTION

Climate change is a growing global issue that significantly affects various aspects of the environment. Climate change poses a significant threat to the sustainability of water supplies worldwide, altering their temporal and spatial distributions (Luo et al., 2017). According to the World Meteorological Organization (WMO), 2023 was the hottest year on record, and the average global temperature is expected to rise by 2 °C over the next 20 years (WMO, 2024). Recent projections suggest that global temperatures could increase by 1.1°C to 6.4°C by 2100 (Bedair et al., 2023). The International Panel on Climate Change (IPCC) in its Sixth Assessment Report (AR6) has demonstrated that climate change is evident, and sub-Saharan Africa is one of the most susceptible regions (IPCC, 2023). The warming of the African continent is anticipated to exceed the world's annual mean temperature this century, with drier regions getting warmer than the wetter regions (WMO, 2024).

As one of the most important components of climate, rainfall determines a region's environmental conditions (Khavse et al., 2015). The implications of climate change on patterns of rainfall and temperature represent a substantial threat to the availability, distribution, and overall quality of water sources since rainfall is a major determining variable influencing how much water is available to meet varying needs, including those for hydroelectric power generation, domestic water supply, agriculture, and industry (Rankoana, 2020). Climate change may alter rainfall patterns, impacting water supplies, and increase the frequency of severe droughts and floods (Pizzorni et al., 2024). In Nigeria, rainfall has undergone and continues to undergo changes due to both natural and human factors, which influence its distribution on different timescales (Abaje et al., 2015). Rainfall variations have a significant impact on soil conservation, agriculture, water resources, and severe weather events, such as floods and droughts, which can have a disastrous effect on food security and often accompany other tragedies and hardships (Ifabiyi & Ashaolu, 2015).

Climate change presents significant challenges and new opportunities for the exploitation of water resources. Climate change is anticipated to alter the quality and

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availability of water, with far-reaching consequences for food security, sanitation, and overall health (United Nations Global Compact (UNGC), 2009). Water resource changes are essential to every facet of the economy. Human-induced global warming will have significant consequences for the quality of water in the ecosystem, as well as the availability of water in terms of time and volume (Cherkauer et al., 2021). Scientists and decision-makers agree that there is evidence of human-caused climate change, and that even with further decreases in the emission of greenhouse gases (GHGs), there will be significant, inevitable effects (IPCC, 2022). However, since the impacts of climate change are permanent, we must adapt to the new environment as it arises. These actions are referred to as adaptation strategies by the IPCC (2022), which emphasize that communities must address both the opportunities and threats associated with the changing climate. Since few mitigating measures have been taken thus far, adaptation techniques have become increasingly crucial in addressing the limited changes and their effects on local communities (Marquardt et al., 2023).

A nation or territory is considered water-strained when the population consumes over 20 per cent of its natural freshwater supply (Vorster, 2014), whereas extractions of water exceeding 40% imply such a country has significant water stress (Zhang et al., 2024). Many countries in Sub-Saharan Africa (SSA) are experiencing water stress. Studies have shown that the exploitation of groundwater for household and agricultural use has led to aquifer depletion and declining water tables (Isukuru et al., 2024). The International Dialogue on Water and Climate issued a warning in 2004 that Sub-Saharan Africa may see a significant rise in water-related stress. There is an increasing interest in conducting climate change research using bottom-up methodologies, which involve studying local areas where the risks and consequences are primarily experienced (Bardosh, 2015).

Since the mid-20th century, the maximum temperature in Kaduna, central and northern Nigeria, has been rising noticeably (Bello et al., 2025). In the South, the duration of the wet season ranges from nine to twelve months, while in the central part (including Kaduna), the rainy season lasts for 6 to 8 months. In the country's far northeastern region, the rainy season typically lasts around 2 to 3 months (Abubakar et al., 2025b; Odekunle et al., 2008). As Kaduna North relies heavily on water resources for domestic, agricultural, and industrial uses, it becomes crucial to comprehend and address these changes.

There is an increasing demand for a comprehensive assessment that can measure the implications and trends of the changing climate on various aspects of water resources, such as temperature and rainfall. Thus, this study employed traditional and innovative trend analysis to examine the temporal patterns of rainfall and temperature in Kaduna North LGA. This study applies ITA alongside conventional MK tests to better capture complex trends in Kaduna North, an understudied locality. The ITA can be more sensitive to nonlinear trends, while Mann-Kendall primarily detects monotonic trends. This allows ITA to capture complex patterns in the data more effectively. Additionally, the ITA is often considered more reliable when the time series exhibits seasonality and autocorrelation, which can impact the reliability of the Mann-Kendall tests. Therefore, this research aims to assess rainfall trends and mean temperature, and their implications on the management of water resources in Kaduna North LGA.

MATERIALS AND METHODS

2.1 Study Area

Kaduna North LGA is located between the latitudes 10° 04' and 10° 30' North of the Equator, and between longitudes 7° 20' and 7° 30' East of the Greenwich Meridian (Figure 1). To the north, it is bordered by Igabi LGA, and in the West by both Igabi and Kaduna South LGAs of the state. To the south and southeast, it is bordered by Kaduna South LGA (Umar et al., 2025). The climate of Kaduna North is characterized by monsoon and harmattan (Köppen *Aw)* (Muhammad & Abubakar, 2025). The harmattan lasts from October to April of the next year, whereas the monsoon lasts from April to mid-October, reaching its zenith in August (Abubakar et al., 2024). Kaduna experiences a mean annual rainfall of 1323 mm/year (Abubakar et al., 2025a).

The highest air temperature is recorded in April every year (28°C), while the lowest is recorded in December (22.9°C) and remains constant until January (23.1°C). During the wet and dry seasons, the typical atmospheric relative humidity is, respectively, 70–90% and 25–30%. The highest water loss through evaporation takes place in the dry season (Musa & Abubakar, 2024). Kaduna State is situated in the Guinea Savanna Ecological Zone, where tree densities and other vegetation decrease as one moves towards its northern region. The zone is important, both as a major provider of cereals and tubers, due to its significantly greater rainfall compared to the more northern Sudan and Sahel Savannas (Atedhor, 2016).

2.2 Data Sources

Daily mean temperature and rainfall time series were provided by the Kaduna Synoptic Station of the Nigerian Meteorological Agency (NIMET). The data is for three decades (1990 to 2023). This data was tabulated and tested for homogeneity.

2.3 Data Analysis

2.3.1 Homogeneity test

The study examined the homogeneity of yearly rainfall and mean temperatures in Kaduna North using the Standard Normal Homogeneity Test (SNHT) and Pettitt's (PT) homogeneity tests. Prior research has shown that different homogeneity tests may exhibit varying levels of sensitivity to specific breakpoints, which is a crucial aspect in determining whether homogeneity exists or not. Additionally, the SNHT can be used to detect sudden changes that take place at the beginning or end of time-series data. However, by detecting changes that occur within the time series, the PT test can enhance the study's overall accuracy (Abubakar et al., 2025b).

The SNHT, developed by Alexandersson (1986), is a statistical analysis method used to identify irregularities in time-series datasets. The SNHT employs a probability ratio test to determine whether a series of rainfall observations exhibits abrupt changes, such as leaps or breaks, as opposed to steady and consistent variations. This method is based on the assumption that the time series is normally distributed in general and that any deviations appear suddenly at a specific point in time.

The PT is a nonparametric test used to identify changepoints in time series, without requiring underlying assumptions about the distribution of the data (Pettitt, 1979). Thus, the premise is based on the notion that observations are autonomous and evenly distributed over time (Yozgatligil & Yazici, 2016).

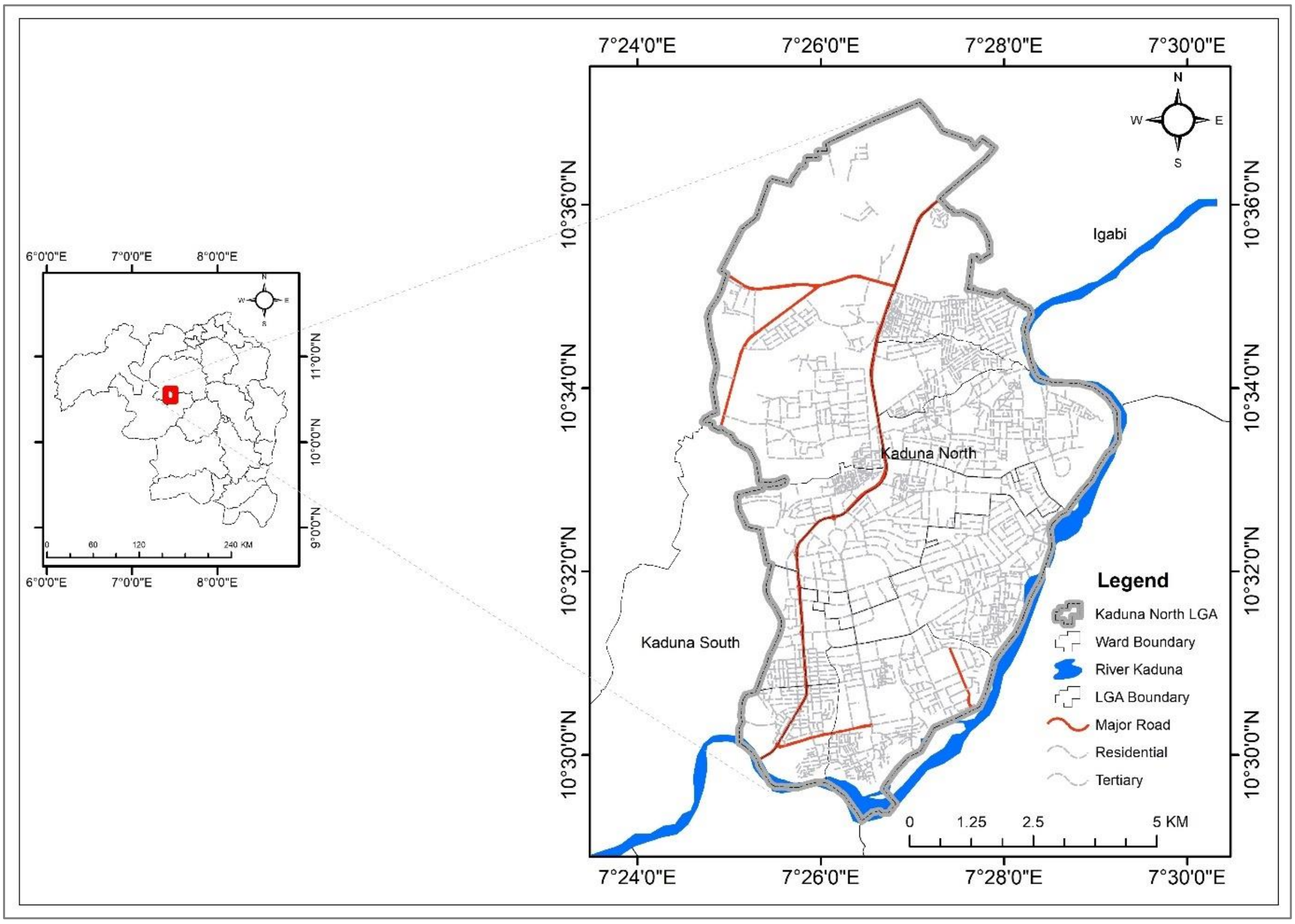

Figure 1: Map of Kaduna North Local Government Area
Source: Adapted from GRID3 - Nigeria, 2024

2.3.2 Coefficient of Variation (CV)

The coefficient of variation (CV) was utilized to determine the temporal and spatial variability of rainfall in Kaduna State. The 'hydroTSM' package on R Studio was used to determine the CV, as shown in Eq. (1).

$$CV = \frac{\sigma}{\bar{X}} * 100 \qquad (1)$$

where σ represents the standard deviation, while $\bar{x}$ is the rainfall's mean. The CV scores were categorized as low (less than 20%), medium (between 20% and 30%), high (more than 30%), and very high (more than 40%) (Abubakar et al., 2025a; Asfaw et al., 2018).

2.3.3 Rainfall Anomaly Index (RAI)

Positive and negative severities of rainfall anomalies are categorized using the Rainfall Anomaly Index (RAI), developed by van Rooy (1965). Mohamed et al. (2022) noted that RAI responds to shifts in rainfall that have been excessively wet or excessively dry, as shown in Table 1. Since only rainfall data is needed, the RAI is a remarkably straightforward procedure.

Periods with recorded low rainfall levels exhibit a negative deviation from the mean seasonal rainfall, indicating drought years. The 'precintcon' was used to determine the RAI on R Studio. The formula is given in Eq. (2).

$$\text{RAI} = (R - \mu)/\sigma \qquad (2)$$

Where:

RAI = Rainfall Anomaly Index

R = Rainfall

μ = Long-term average rainfall

σ = Standard Deviation

Table 1: RAI Classification

Level	Value
Extremely wet	> 3.00
Very wet	2.0 to 2.99
Moderately wet	1.00 to 1.99
Slightly wet	0.50 to 0.99
Near normal	-0.49 to 0.49
Slightly dry	-0.99 to -0.50
Moderately dry	-1.99 to -1.00
Very dry	-2.99 to - 2.00
Extremely dry	< - 3.00

Source: (Raziei, 2021)

2.3.4 Precipitation Concentration Index (PCI)

The PCI was used to examine rainfall seasonality. The PCI revealed the distribution of monthly rainfall, which is a good indicator of extreme rainfall (Gocic & Trajkovic, 2013). This was determined using Eq. (3) (De Luis et al., 2000):

$$PCI = \frac{\sum_{i=1}^{12} p_i^2}{\left(\sum_{i=1}^{12} p_i\right)^2} * 100 \qquad (3)$$

Where Pi is the total monthly rainfall in the ith month.

PCI values below 10 indicate a monthly rainfall distribution that is uniform; values between 11 and 16 indicate a monthly rainfall concentration that is moderate; values between 16 and 20 indicate a monthly rainfall distribution that is irregular; and values of 20 and higher indicate a monthly rainfall concentration that is very high (Oliver, 1980). The '*precintcon*' package on R software was used to determine the PCI.

2.3.5 Mann-Kendall Trend Test

Mann-Kendall is a non-parametric testing approach widely used to detect trend patterns in series data sets, regardless of whether there is an element of seasonality in the series (Duhan & Pandey, 2013). It can also be used to analyze data with non-normal distributions, including hydrological and meteorological data sets. The World Meteorological Organization recommends it. This paper employed the Mann-Kendall method to evaluate the trends of time series data from the study area, including rainfall and mean temperature. The Man-Kendall test was calculated using the '*Kendall*' R package and determined using Eq. (4).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \qquad (4)$$

Where n is all the observations, xi and xj are the ith and *jth* *(j > i)* observations in the data, while *sgn(xj − xi)* is the sign function obtained as Eq. (5):

$$sgn(x_j - x_i) = \begin{cases} +1, if(x_j - x_i) > 0 \\ 0, if(x_j - x_i) > 0 \\ -1, if(x_i - x_j) > 0 \end{cases} \qquad (5)$$

For the series with sample size *n > 10*, the test statistic S is considered to be asymptotically normally distributed, with the mean *E(S)* and variance *Var(S)* given as Eq. (6):

E(S) = 0, and

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \qquad (6)$$

The distribution of statistics *S* tends to normalcy when *n > 10* and there is a chance of a tie in the value of x (Kendall, 1948); therefore, the variance is computed as Eq. (7):

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k - 1)(2t_k + 5)}{18} \qquad (7)$$

where *tk* is the number of ties of extent *k* and *m* is the number of connected groups. Eq. (8) represents the conventional normal test statistic *Z*, which is used to identify a significant trend:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, ifS > 0 \\ 0, ifS = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, ifS < 0 \end{cases} \qquad (8)$$

In a two-tailed test, the null hypothesis of 'no trend' is accepted at the α significance level if $-Z1-\alpha/2 < Z \le Z1-\alpha/2$, where $Z1-\alpha/2$ represents the z-score of the standard normal distribution corresponding to a cumulative probability of $1 - \alpha/2$. Thus, at the α significance level, a monotonic trend is present, and the null hypothesis must be rejected. As a result, an upward and downward trend are indicated by the positive and negative values of Z, respectively.

2.3.6 Modified Mann–Kendall (MMK) test

The MMK enhances the reliability of detecting trends in the time series by calibrating the Var(S) through an effective sample size adjustment (Hamed & Ramachandra Rao, 1998). The modified VAR(S) statistic is determined using Eq. (9), and was calculated using the 'Kendall' R package.

$$VAR(S) = \left(\frac{n(n-1)(2n+5)}{18}\right) \cdot \left(\frac{n}{n_e^*}\right) \qquad (9)$$

Using this, the factor of the correction $\left(\frac{n}{n_e^*}\right)$ is modified to the autocorrelated time series as Eq. (10):

$$\left(\frac{n}{n_e^*}\right) = 1 + \left(\frac{2}{n^3 - 3n^2 + 2n}\right) \sum_{f=1}^{n-1} (n-f)(n-f-2)\rho_e(f) \qquad (10)$$

$\rho_e(f)$ suggests the acf between the ranks of the observations and is determined using Eq. (11):

$$\rho(f) = 2sin\left(\frac{\pi}{6}\rho_e(f)\right) \qquad (11)$$

2.3.7 Sen's slope estimator test (SSE)

For determining the slope of a trend in climatological time series, the SSE is a non-parametric method that has gained popularity. The slope (Ti) for all data pairings is determined using the Sen (1968) method. Eq. (12);

$$f(t) = Qt + B \quad (12)$$

Qt represents slope, and *B* is the constant. To derive the slope estimation (*Q*) at the beginning, the slope of the complete time series were determined as stated in Eq. (13):

$$Q_i = \frac{X_j - X_k}{j - k} \quad (13)$$

The values that are present at times i and *k (j > k)* are denoted by *Xj* and *Xk*, respectively. $N = n(n-1)/2$, where n is the number of cycles, if each time frame contains only one datum. $N < (n(n-1))/2$ if there are a lot of observations in one or more time periods. The Sen's slope estimator is provided as follows after the N values of Qi are arranged in ascending order. This is given as Eq. (14):

$$Q_{med} = \begin{cases} Q * \left[\frac{(N+1)}{2}\right], if N is odd \\ \frac{Q * \left[\frac{N}{2}\right] + Q * \left[\frac{(N+2)}{2}\right]}{2}, if N is even \end{cases} \quad (14)$$

Lastly, Q_{med} was computed to determine the trends and magnitude of the slope using the non-parametric approach. In time series, a positive *Qi* indicates an increasing trend, whereas a negative *Qi* indicates a decreasing trend. However, a zero indicates the absence of trend in the time series. The magnitude of the slope in original units per year, or percent per year, is the unit of subsequent *Qi* (Haruna et al., 2025).

2.3.8 Innovative trend analysis (ITA)

Şen (2012) invented the innovative trend analysis (ITA) method. In contrast to traditional trend tests, the ITA does not require a normal distribution, and autocorrelation does not influence the outcome. According to Abubakar et al. (2025b), this method is more likely to uncover a monotonous and a sub-trend in time series in addition to distinct trend combinations through different series periods. The data is divided into two equal subseries, which are subsequently arranged in ascending order. Using a Cartesian coordinate system, the subseries are displayed on the X and Y axes, respectively (Getnet et al., 2023). A no trend is shown by the time series when the depicted data are dispersed over the ideal 45° line (1:1). When the concentration of points is below the line, the trend seems to be decreasing, however when the data are aggregated above the ideal line, the time series displays an increasing tendency (Ahmad et al., 2025). If the points fall on the 45° line, there is no trend. This allows us to categorize time series data patterns as high, medium, or low. The S_{ITA} was determined via Eq. (15).

$$S_{ITA} = \frac{2}{n}(\bar{x}_2 - \bar{x}_1) \quad (15)$$

where *n* is the number of the time series and $\bar{x}1$ and $\bar{x}2$ are the means of the 1st and 2nd subseries, respectively. By using a probability distribution function (PDF), the significance of the ITA was evaluated using Eq. (16):

$$CL_{(1-\alpha)} = 0 \pm S_{ITA^{\sigma_S}} \quad (16)$$

Where the confidence interval of the standard normal PDF has a mean of 0 and the standard deviation (σs) is at the significance level of α. CL stands for the ITA slope's confidence limit. S_{ITA} stands for the evaluated trend slope of the ITA. The null hypothesis that there is no slope is disproved if the S_{ITA} is higher than the significance level. The '*trendchange*' package in R Studio was used to do the ITA calculations for this investigation at a 95% confidence level.

RESULTS

3.1 Homogeneity test

This study evaluated the rainfall and mean temperature homogeneity in Kaduna North. The result is displayed in Figure 2 and Table 2.

Table 2: Pettitt's and SNHT homogeneity tests

	Pettitt			SNHT		
	K	T	p-value	T0	t	p-value
Mean Temperature	156	2002	0.01	10.16	2002	0.01
Rainfall	82	2010	0.74	2.58	2010	0.69

The homogeneity of all the time series was assessed using SNHT and PT at a 5% significance level. Both the PT and SNHT revealed that the mean temperature is not homogeneous ($p<0.05$). The PT revealed a K of 156, while the SNHT had a T0 of 10.16. Both detected 2002 as the changepoint in the time series. This is shown in Figure 2.

For the annual rainfall timeseries, both PT and SNHT did not detect a significant changepoint, hence the rainfall data is homogenous ($p>0.05$), although 2010 was detected as the most probable changepoint.

3.2 Rainfall and temperature variability

Rainfall variability in Kaduna North Local Government Area was determined using the CV, RAI, and the PCI.

The mean, minimum, and maximum rainfall were examined. Furthermore, the standard deviation and coefficient of variation were determined.

Table 3 revealed that there were 31 observations, covering 31 years from 1993 to 2023. The minimum rainfall was 939.24 mm, which was recorded in 2013. The maximum rainfall was 1347.49 mm, which was recorded in 2018. Rainfall in Kaduna North LGA has a mean annual value of 1191.01, with a standard deviation of 95.87, and a coefficient of variation of 0.080, which indicates very low variability. For the annual mean temperature (Tmean), Table 3 revealed that the minimum Tmean is 24.6 °C, the maximum is 25.79 °C, mean is 25.13 °C, with a standard deviation of 0.30 °C. The CV is 0.012, which suggests very low variability in mean annual temperature.

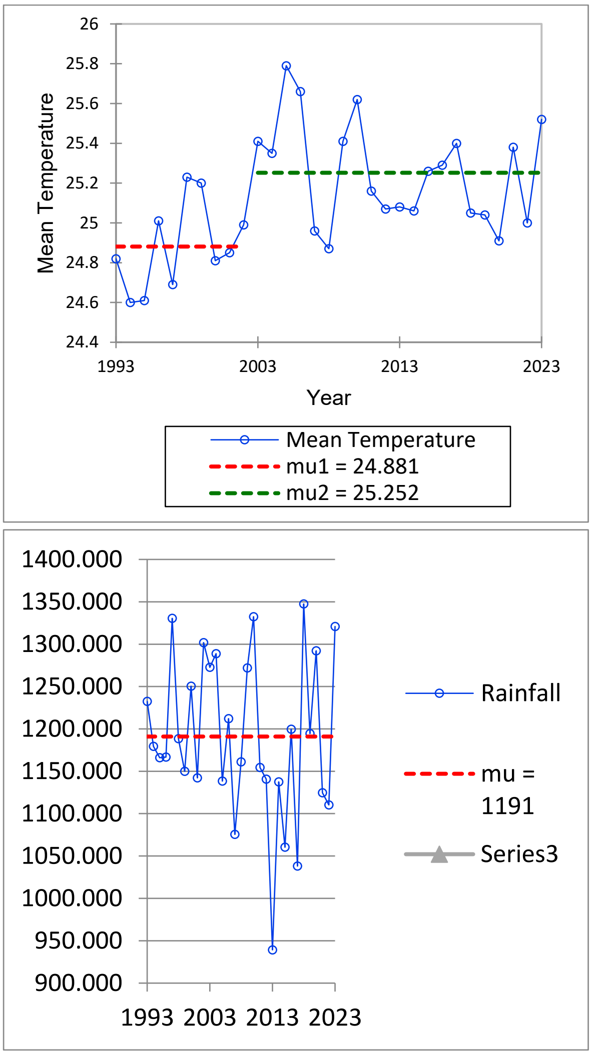

Figure 2: PT and SNHT Homogeneity tests for mean temperature and rainfall; (up) Mean temperature (down) Rainfall

Where mu is the mean, mu_1 is the mean before the changepoint, and mu_2 is the mean after the changepoint.

For the coefficient of skewness, rainfall had -0.314, which indicates a longer left tail, while mean temperature had 0.222, which shows a longer right tail. Thus, rainfall had an asymmetric distribution, while the distribution of mean temperature is symmetric. For the coefficient of kurtosis, both the rainfall and mean temperature had negative kurtosis, which indicates lighter tails and a flat peak. The monthly averages of the annual rainfall and mean temperature are shown in Figure 3.

3.3 Rainfall Anomaly Index

The average of the 10 most extreme highest and lowest anomalies was given a threshold of +3 and -3 to calculate the rainfall anomaly. From the analysis, 2013 was the driest year with a RAI value of -6.075. 2010 was the wettest year under investigation, with RAI values of 7.913. The result is shown in Figure 4.

3.4. Rainfall Concentration

The precipitation concentration distribution in Kaduna North LGA was displayed by the PCI. The result is displayed in Table 4.

According to Table 4, the findings revealed that the annual PCI in Kaduna North LGA is characterized by a high concentration (71.0%), while moderate precipitation concentration accounted for 29% of the distribution. Within the study period, neither low precipitation concentration nor very high precipitation concentration was recorded in Kaduna North LGA. This is shown in Figure 5.

3.5. Trends of Rainfall and Mean Temperature in Kaduna North LGA

The MK, MMK, and ITA were used to determine the trends of rainfall and mean temperature in Kaduna North Local Government Area. The result is shown in Table 5.

Test summary of the trends (Z_{MK}, Z_{MMK}, and S_{ITA}) is shown in Table 5. Figures 6 (a & b) and 7 (a & b) show the variations in the trends detected by the Z values of annual rainfall using the MK, MMK, and ITA tests.

The Mann-Kendall test (Z_{MK}) and the Modified Mann-Kendall (Z_{MMK}) statistics for the annual rainfall in Kaduna North LGA are between -1.05 and -1.53. This indicates a decreasing trend in rainfall, although the difference is not statistically significant ($p < 0.05$). The Sen's slope of -1.66 means rainfall was decreasing by 1.66 mm per year. For the mean annual temperature, the Z_{MK} is 1.97 and the Z_{MMK} is 2.45, both of which show increasing trends that are significant at a 0.05 significance level. The Sen's slope suggested that the annual mean temperature was increasing by 0.014 °C per year. The chart of the Mann-Kendall test is illustrated in Figure 6 (a & b).

Table 3: Summary Statistics of Mean Annual Temperature and Rainfall in Kaduna North LGA

Variable	Min	Max	Mean	Std. deviation	CV	Skewness	Kurtosis
Rainfall	939.24	1347.49	1191.01	95.87	0.08	-0.314	-0.235
Mean Temp	24.6	25.79	25.13	0.30	0.012	0.222	-0.710

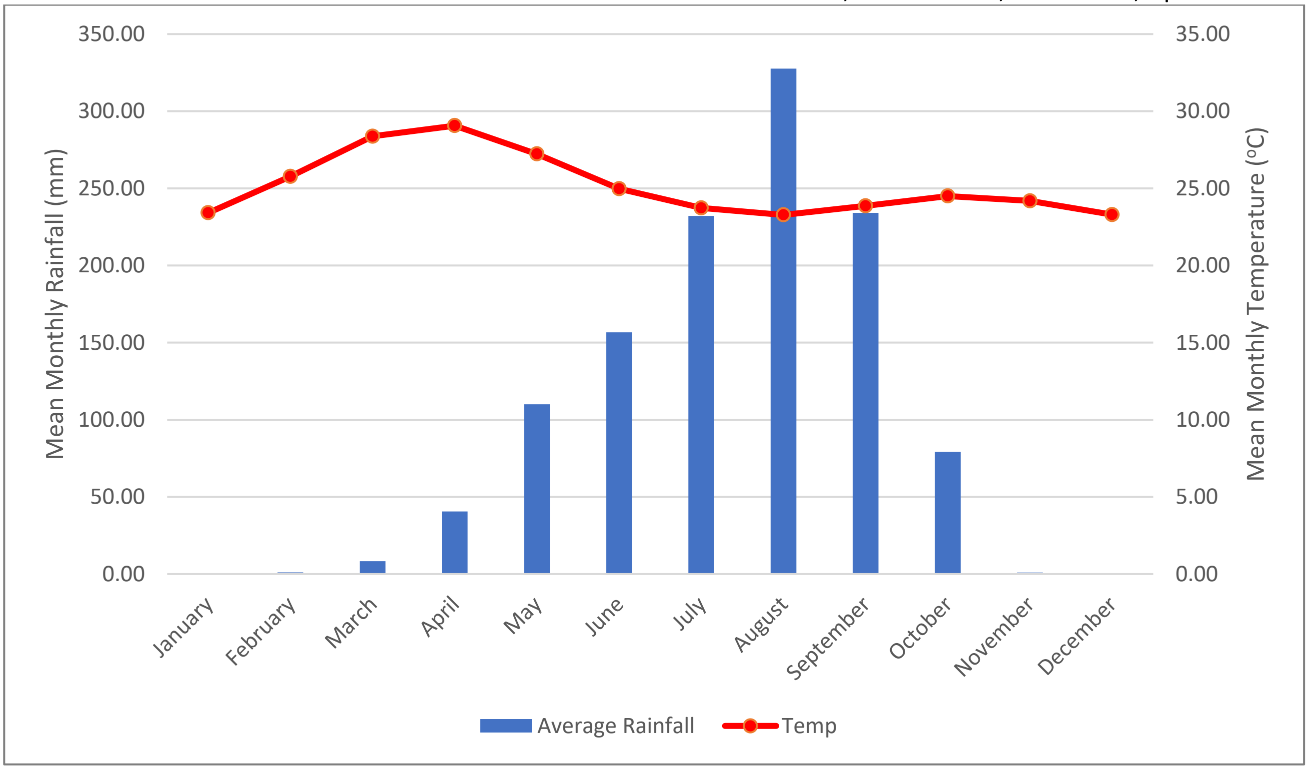

Figure 3: Mean monthly temperature and rainfall in Kaduna North LGA

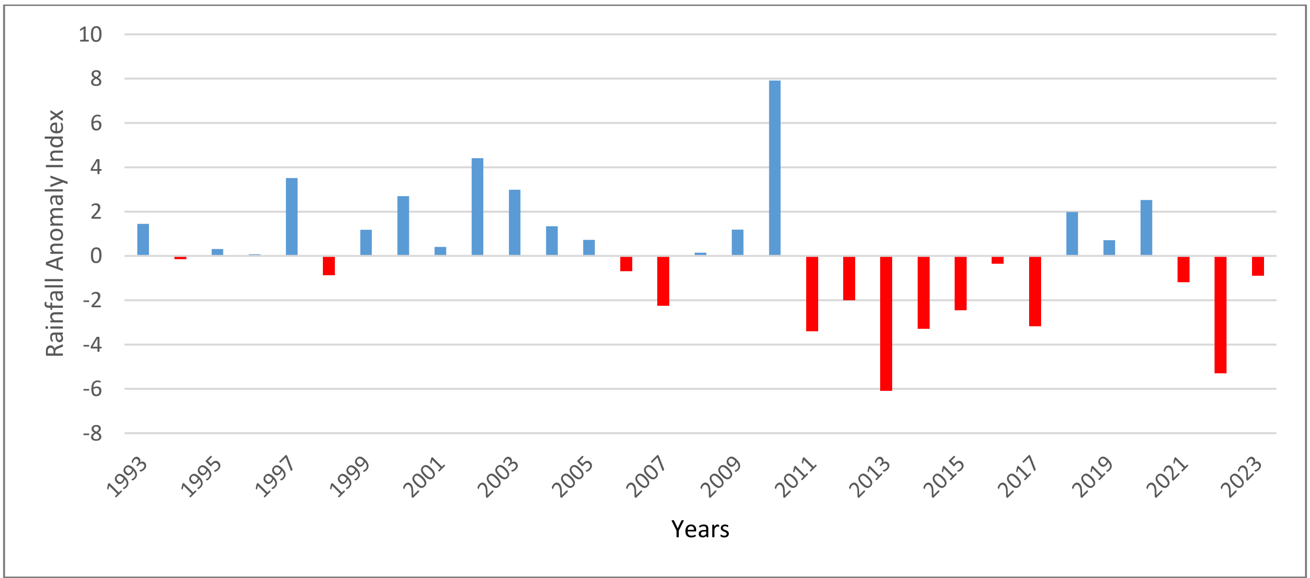

Figure 4: Rainfall Anomaly Index in Kaduna North LGA

Table 4: PCI in Kaduna North LGA

Index	Description	Frequency	Percentage
11 – 15	Moderate Precipitation	9	29
16 – 20	High Precipitation	22	71
Total			**100**

Using the ITA, a significantly decreasing trend of rainfall was detected by S_{ITA} in Kaduna North (S_{ITA} = -2.54, CL = ± 0.41). This trend is significant (p<0.05). For the annual mean temperature in Kaduna North, the ITA also identified an increasing trend (S_{ITA} = 0.0069, CL = ± 0.0013), which is statistically significant (p < 0.05). The result of the ITA analysis is shown in Figure 7 (a & b).

DISCUSSION

4.1 *Rainfall variability*

According to Abubakar et al. (2024), a CV of < 20% is regarded as low variability. Thus, in this study, both rainfall and mean temperature exhibited low variability, with CVs of 0.08 and 0.012, respectively (Table 1). The very low variability for both rainfall (0.080) and temperature (0.012) indicates that neither climate variable has changed significantly in the past 31 years. This predictability is beneficial for managing and planning water resources, particularly in areas such as agriculture, household water supply, and reservoir operations. These results align with the findings of Abubakar et al. (2024), who reported that the annual rainfall in Kaduna town exhibited low variability between 1972 and 2022. Furthermore, the findings are also similar to those of Abaje et al. (2018). High rainfall variability is associated with changes in the hydrological cycle, increased flow variability, and increased water resource stress, leading to more frequent recurring extremes (Habte et al., 2023; Mahmoud et al., 2023).

The findings of the PCI tests revealed that the precipitation concentration in Kaduna North is predominantly high (71%) and moderate (29%). This is an indication that rainfall is higher within a few months during the entire year. Thus, this concentration can lead to various environmental challenges, such as increased runoff, soil degradation, and infrastructure destruction during wet spells (Du et al., 2023). However, water shortages are expected during dry spells, which will impact the availability of water for both agricultural and domestic use, as well as the proper functioning of ecosystems (Ingrao et al., 2023).

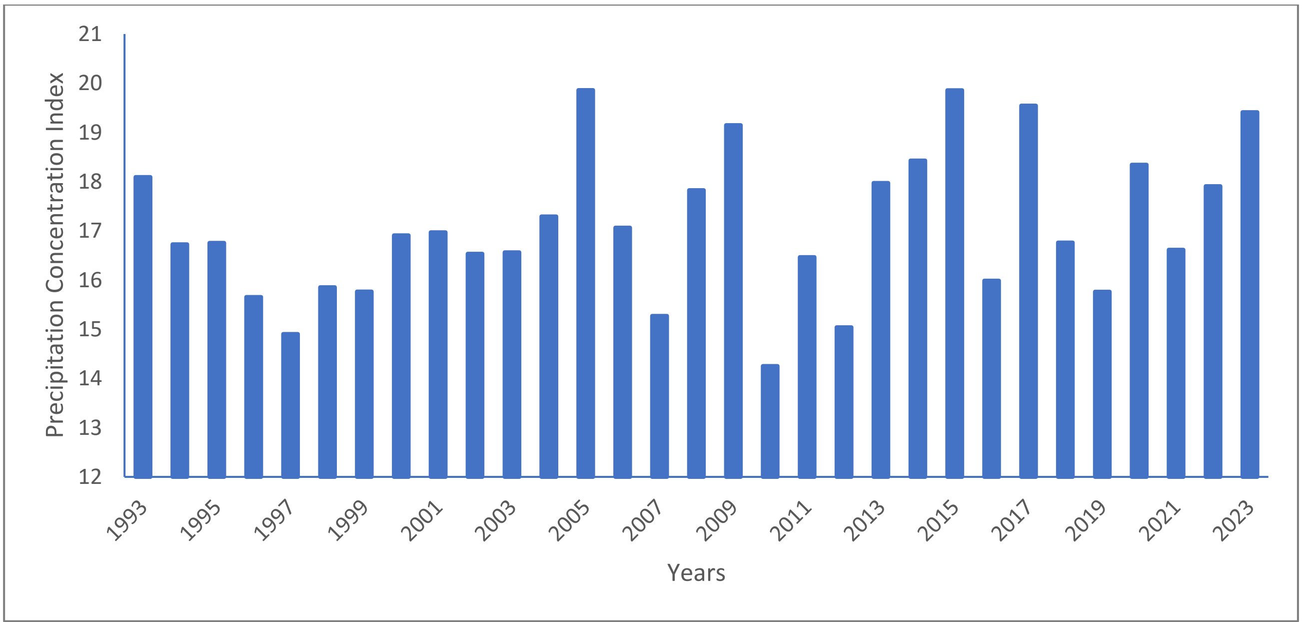

Figure 5: Precipitation Concentration Index in Kaduna North LGA

Table 5: Trend of Mean Temperature and Rainfall in Kaduna North LGA

Variable	Z_{MK}	Sens Slope	Z_{MMK}	ITA	S_{ITA}
Rainfall	-1.05	-1.660	-1.53	▼	-2.541
Mean Temperature	1.97*	0.014	2.45*	▲	0.007
* Indicates significant trend at 0.05 significance level for Z_{MK} and Z_{MMK}					
ITA ▼ significantly decreasing trend, ▲ significantly increasing trend					

4.2 *Rainfall Anomaly*

The RAI results revealed that Kaduna North experienced the driest period in 2013, while the wettest year during the period was 2010, according to the RAI results. The very low RAI in 2013 indicates a severe drought that year. This likely made it difficult to obtain sufficient water for homes, farms, and ecosystem services. Early warning systems, drought contingency plans, and prioritizing water distribution during these times should all be part of water management plans. The very high RAI in 2010 also implies heavy rain that could cause flooding. This highlights the importance of having robust stormwater management systems, including effective drainage, floodplain protection, and contingency plans for community response to floods. A study by Ibrahim and Abdullahi (2016) revealed that heavy rainfall has been associated with flooding in Kaduna Metropolis. This result confirms the findings of Abubakar et al. (2025a), Haruna et al. (2025), and Obateru et al. (2023) that several locations in Nigeria experienced meteorological drought within this period. Across the world, several studies have reported extreme water scarcity during this period. For example, in the Caribbean (Herrera et al., 2018), New Zealand (Harrington et al., 2014), India (Zhang et al., 2017), China (Yao et al., 2018) and the Americas (Rippey, 2015).

4.3 *Trend of rainfall and mean temperature in Kaduna North*

The Mann-Kendall, modified Mann-Kendall, and innovative trend analyses were employed to examine the trend of rainfall and mean temperature in Kaduna North. For the annual rainfall trends, all three tests detected a decreasing rainfall trend; however, only ITA uncovered a significant trend. The Sen's slope of -1.66 mm/year and the decreasing trend S_{ITA} found both indicate that rainfall has been declining for a long time. This suggests a steady loss in renewable water supplies, which will influence surface water bodies, groundwater recharge, and rain-fed agriculture. The significant increase in mean annual temperature (Sen's slope = 0.014 °C/year) suggests higher evaporation rates from water bodies and soils. Thus, reduced rainfall and rising temperature may adversely affect agricultural water demand, crop productivity, and food security. The results of the trend analysis agree with the findings of previous studies, which revealed that Kaduna experienced a decline in annual rainfall (Abaje et al., 2018; Abubakar et al., 2024).

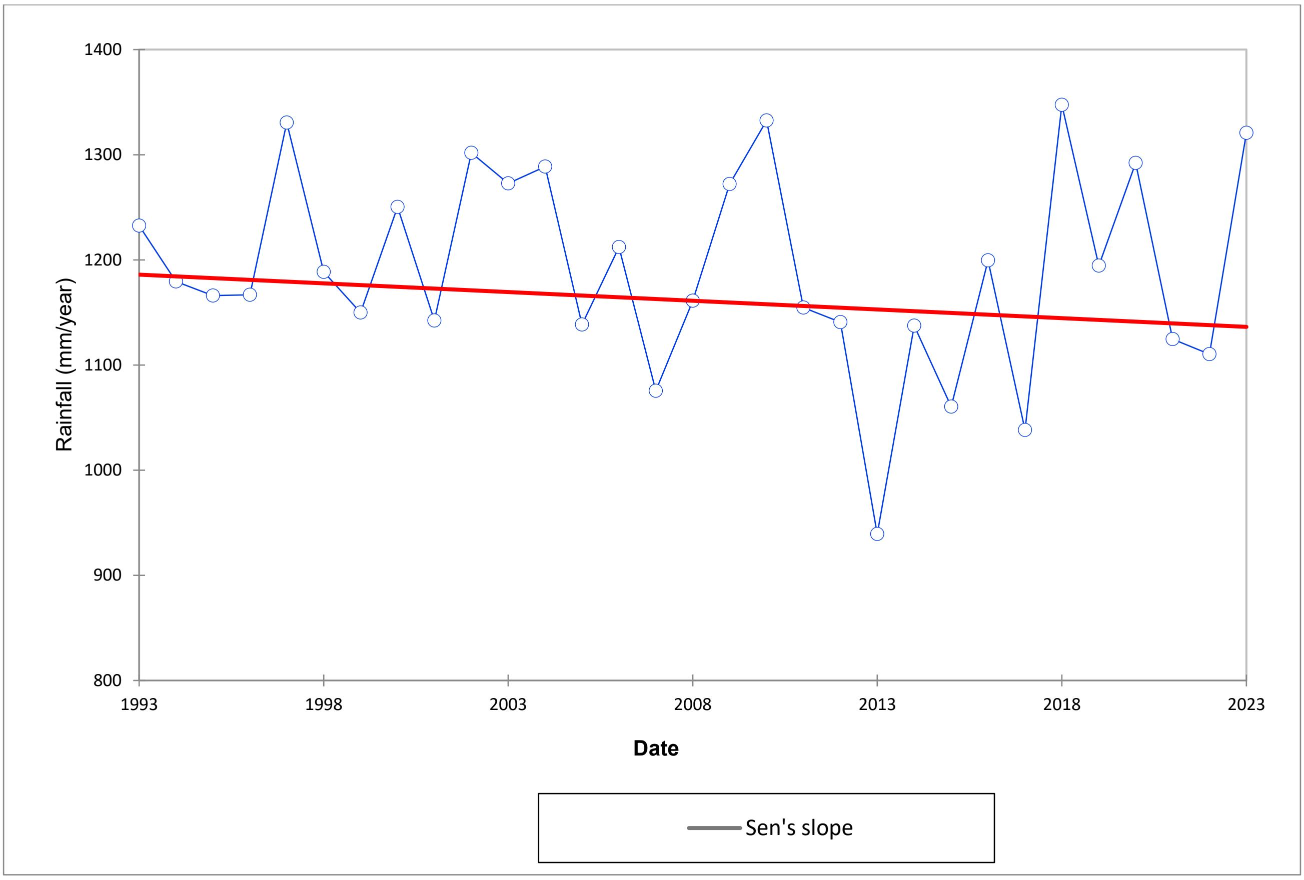

Figure 6a: Mann-Kendall trend test: Annual Rainfall

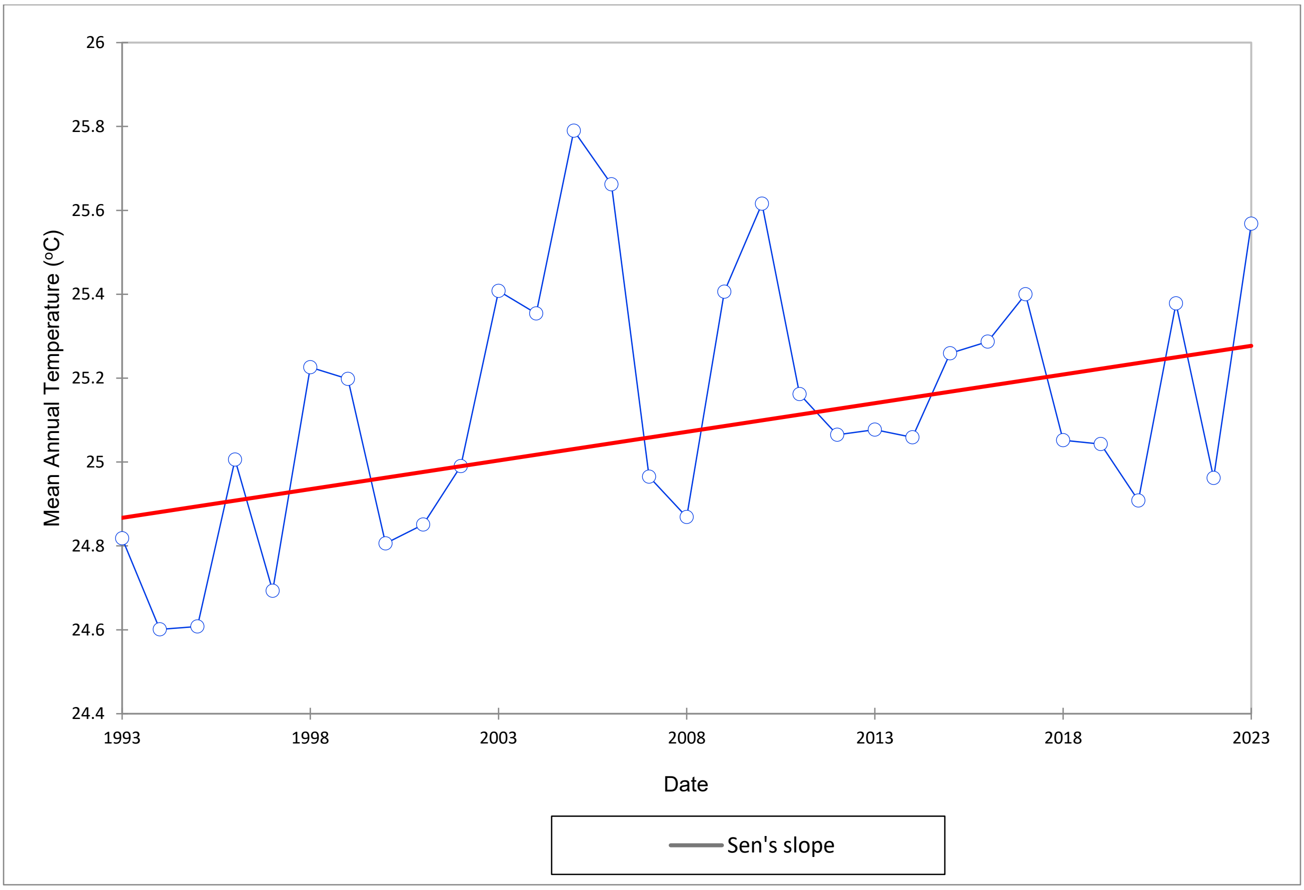

Figure 6b: Mann-Kendall trend test: Mean Annual Temperature

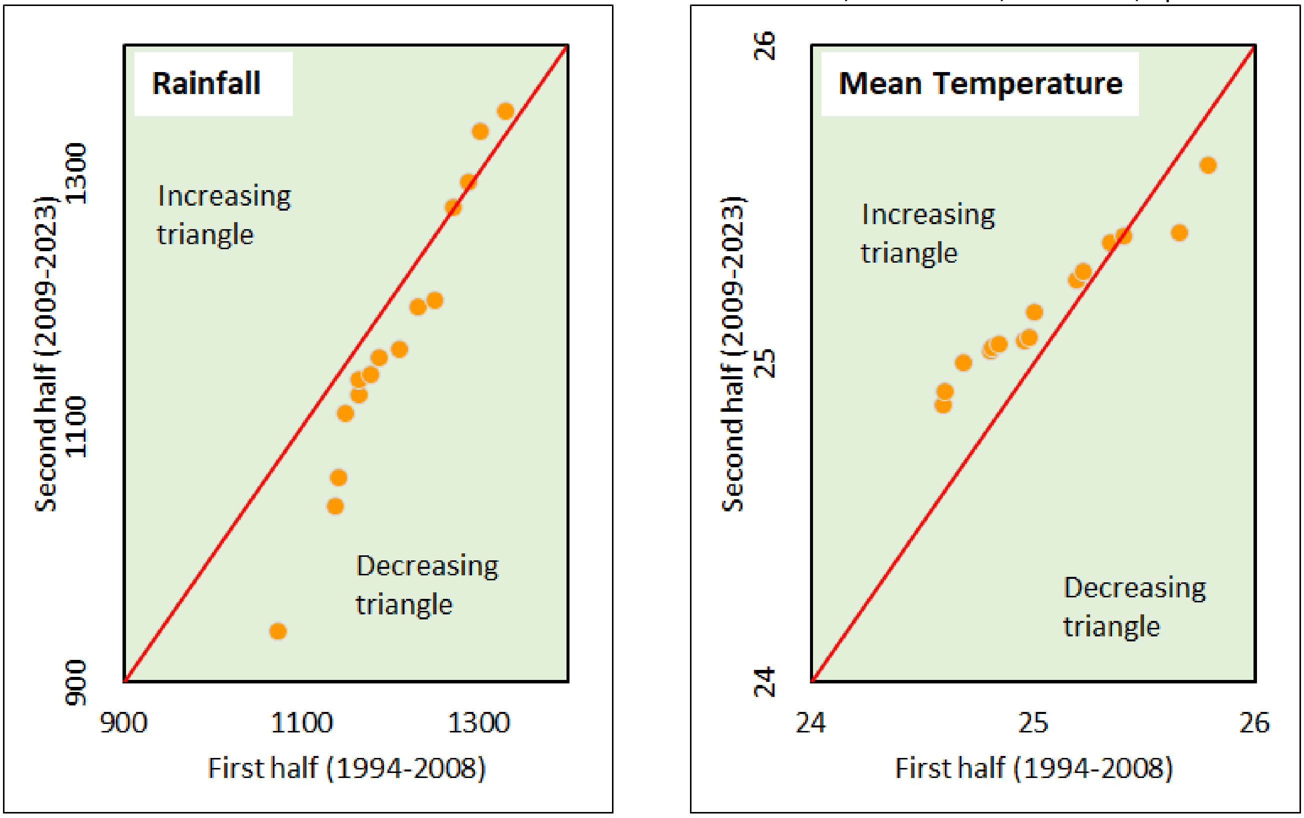

Figure 7a: Innovative trend analysis visualization (left) Annual Rainfall; (right) Mean Annual Temperature

In the wider area, Animashaun et al. (2020) revealed a declining annual rainfall in the River Kaduna Basin. A decline in yearly rainfall is likely to have an effect on water availability for crop production, as farming in the study area is predominantly rainfed. This will intensify the existing vulnerable scenario regarding food security. Additionally, decreasing annual rainfall will impact surface water availability and groundwater recharge (Wang et al., 2023).

The MK, MMK, and ITA all detected a significantly increasing trend of mean temperature in Kaduna North. Rising temperature has been shown to affect the nature of rainfall distribution and the entire hydrological cycle (Punia et al., 2022). Furthermore, increasing temperatures lead water to evaporate in higher amounts, leading to higher levels of condensation and increasingly prevalent, heavy, and severe rainfall.

The innovative trend analysis performed better than the traditional MK and MMK techniques. Several recent environmental, hydrological, and hydrometeorological studies have consistently shown that the ITA approach outperforms the MK and MMK approaches in terms of trend detection. This is partly owing to its widespread application, because it can be effectively implemented independent of the assumption of the distribution of the dataset, number, and presence of autocorrelations (Güçlü, 2018). This study reinforces prior findings, implying that the ITA is a more dependable and adaptable method for detecting trends. Furthermore, studies show that the ITA approach recognized more significant trends compared to MK and MMK procedures. This is similar to the findings of Esit (2023), Harka et al. (2021), and Nath et al. (2024), who all revealed that the ITA outperformed the traditional MK tests.

4.4 *Limitation*

Although insightful, RAI depends on past extremes and may not fully capture emerging shifts caused by climate change or future extremes beyond historical data. This can limit preparedness for non-stationary climate behaviour. Similarly, the analysis focuses only on Kaduna North LGA, without considering spatial variation across the larger region. Since water systems are often interconnected across administrative boundaries, localized findings might not reflect basin-wide dynamics, leading to suboptimal decisions for shared or transboundary water management.

CONCLUSION

This study studied the variability and trends of rainfall and mean temperature in Kaduna North using several statistical techniques. The results demonstrated little fluctuation in both rainfall and temperature, similar to earlier studies in the region. However, the precipitation concentration index (PCI) showed a significant concentration of rainfall in a few months, highlighting the hazards of floods during wet periods and water scarcity during dry spells. Rainfall Anomaly Index (RAI) results highlighted 2013 as the driest and 2010 as the wettest year, matching with national and global extreme weather occurrences during those years.

Trend analyses utilizing Mann-Kendall (MK), modified Mann-Kendall (MMK), and innovative trend analysis (ITA) found a diminishing trend in yearly rainfall and a considerably increasing trend in mean temperature. The ITA technique proved more effective in spotting important trends, proving its superiority over older methods. These climate changes pose a threat to water availability, agriculture, and overall environmental sustainability in Kaduna North. The findings underline the necessity for proactive adaptation methods to manage the rising problems of climate variability and change in the region.

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