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SPECIAL ISSUE: CELEBRATING 20 YEARS OF GEOGRAPHY IN KADUNA STATE UNIVERSITY - ADVANCES AND FRONTIERS IN GEOGRAPHY

Analysis of Rainfall Variability, Trends, and Anomalies in Gashaka-Gumti National Park, Nigeria (2002-2022)

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ABSTRACT
Rainfall variability greatly influences vegetation distribution, growth, and density. This study analysed rainfall variability, trends, and anomalies in Gashaka-Gumti National Park, Nigeria, for a period of 21 years (2002-2022). Annual average gridded rainfall data from the Climate Research Unit (CRU_TS 4.07) were used, while the coefficient of variation (CV), modified Mann–Kendall (MMK) trend test, and rainfall anomaly index (RAI) were used for the analysis. The results revealed that rainfall had low variability, with a CV of 10.9%. The MMK trend had a ZMK score of 0.507, a Kendall's tau coefficient of 0.048, and a p-value of 0.613, along with a Sen's slope estimate of 1.003, suggesting no statistically significant trend. The rainfall anomalies revealed fluctuating periods of wet and dry conditions. The wettest periods occurred in 2002 and 2003 (+3.89 and +3.33), and the dry periods occurred in 2008 and 2009 (-4.19 and 3.27). The most severe dry period was recorded in 2011, with an RAI of -10.66. Additionally, 2012 and 2016 experienced notably wet RAIs (+4.09 and +7.24), whereas 2015 showed a dry RAI of -4.23. The study concludes that climate stability in the park is good for the environment because it makes it easier to protect biodiversity and make ecosystems more resilient. The study therefore recommends adopting an adaptive management framework, such as water reservoir management, based on rainfall anomaly patterns rather than long-term averages to increase the ecological resilience of Gashaka-Gumti National Park.

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1 Introduction

Rainfall is the most influential climate variable affecting hydrological and climatic changes that impact the environment, as most hydrological processes depend on rainfall and its spatial and temporal distributions, with fluctuations significantly affecting ecosystems and water resource management (Abubakar et al., 2024). Rainfall variability, exacerbated by global warming, has long been a vital aspect of environmental, social, and economic change in many parts of the world. It is crucial for proactive planning and building resilience against climate-related risks, especially in sectors such as agriculture, water resources, and urban infrastructure (Awode et al., 2025; Granados et al., 2017). The variations in rainfall pose major concerns that could greatly impact society and the environment, particularly in terms of water availability for domestic, industrial, and agricultural use. Likewise, the pattern of rainfall behaviour and the increased inter-annual rainfall variability have long been associated with climate change and variability (Umar et al., 2019).

Rainfall, along with its variability and spatial distribution, plays a crucial role in shaping hydrological processes, which are important for maintaining ecosystem health and effective water resource management. Understanding these fluctuations is essential for assessing ecosystem dynamics and optimizing sustainable management strategies for water resources (Mathew et al., 2021). The report of the Intergovernmental Panel on Climate Change asserted that while the rainfall amounts of some African countries are likely to decrease, their rainfall variability tends to increase (Animashaun et al., 2020). Some regions in sub-Saharan Africa have experienced a shift towards more extreme rainfall patterns in recent decades (Edokpa et al., 2025). Different studies have noted that rainfall variability in the tropics, including Nigeria, is an important factor because of complex interactions between global and regional climate drivers, such as the El Niño–Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO) (Awode et al., 2025).

Numerous studies concerning rainfall variability have also been conducted in Nigeria. For example, Salami et al. (2025) examined the spatial distribution of rainfall in Nigeria via rainfall data from 48 weather stations and two long-term satellite-based precipitation products spanning 39 years (1981–2019). The study revealed that ecoclimatic regions have varying contributions to total annual precipitation, with higher rainfall in southern Nigeria. Similarly, Haruna et al. (2025) examined rainfall in Lere,

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Kaduna State, and reported that rainfall exhibited a nonsignificant decreasing trend ($Z_{MK} = -1.431$, $p > 0.05$). Furthermore, Abubakar et al. (2024) analysed the spatiotemporal variability of rainfall and drought characterization in Kaduna, Nigeria. The study revealed that rainfall trends vary across the state, with the southern parts having higher rainfall. Ibebuchi and Abu (2023) examined rainfall variability patterns in Nigeria during the rainy season. During the analysis period (1979–2022), the northern part of Nigeria presented a coherent rainfall anomaly that was coupled with rainfall variations over the Sahel (Pearson correlation coefficient (r) of 0.55) and sea surface temperature anomalies (SSTa) in the global oceans ($r = 0.5$).

Rainfall variability is a critical climatic factor in Nigeria that directly affects water availability for agricultural productivity and ecosystem stability (Ishaku et al., 2024). Varying rainfall patterns due to climate change significantly impact vegetation growth and distribution (Sipayung et al., 2018). This is because the variability of rainfall directly affects the mutability of vegetation (Islam et al., 2025). Gashaka-Gumti National Park is the largest national park in Nigeria, covering an area of 6,731 sq km. Gashaka-Gumti National Park serves as a vital water source for neighbouring communities. Regrettably, this crucial ecosystem faces multiple threats, such as climate variability, vegetation change, habitat degradation, and illegal poaching activities (Danladi et al., 2022).

Based on this extensive review, there is a paucity of literature concerning our understanding of rainfall variability in Gashaka-Gumti National Park. Thus, this study provides a comprehensive assessment of rainfall variability, trends, and anomalies in Gashaka-Gumti National Park by using a combination of the coefficient of variation, the modified Mann–Kendall trend test, and the rainfall anomaly index. By addressing this knowledge gap, the results will increase our understanding of the annual and long-term variations in rainfall patterns, which will help with better conservation planning and ecosystem management in this ecologically important area.

2 Materials and methods

2.1 Study area

Gashaka-Gumti National Park is located between latitudes 6° 06' 99" N and 8° 08' 61" N and longitudes 11° 13' 20" E and 12° 20' 85" E of the Greenwich Meridian, covering an area of approximately 6,731 sq km (Fig. 1). It is the largest and most diverse national park in West Africa in terms of size, rugged terrain, and seamless transition into various ecosystems. Established in 1991, the park was designated an important bird area in 2001 (Birdlife International, 2019). It spans two neighbouring states in northern Nigeria, Taraba and Adamawa, and is notable for its rare population of Nigerian-Cameroon Chimpanzees (Aina et al., 2018).

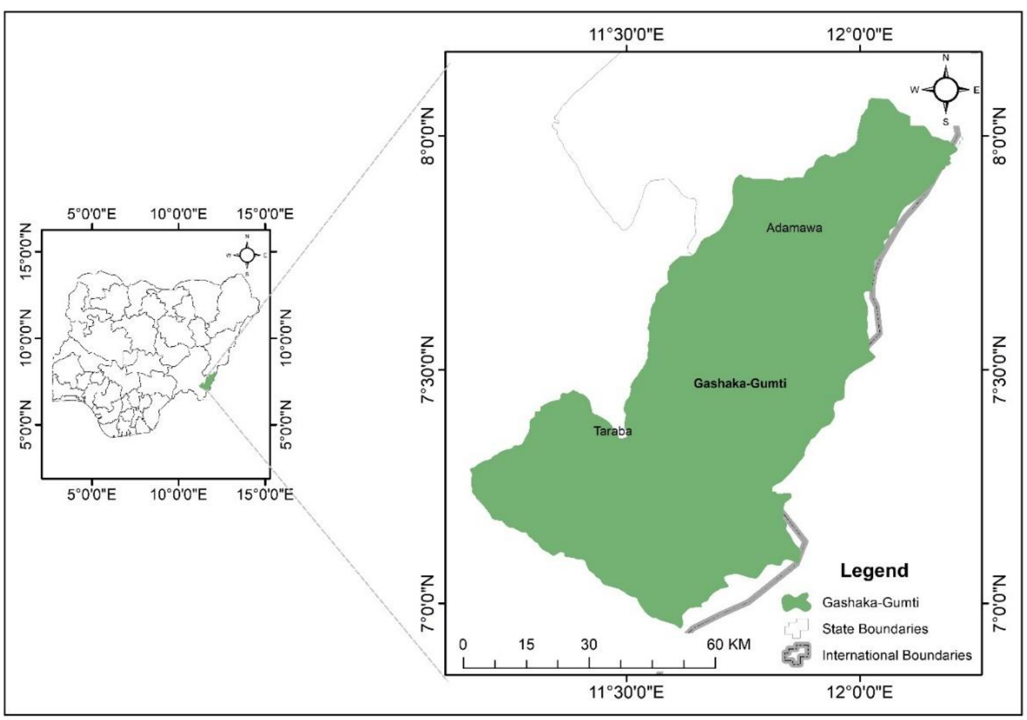

Figure 1: Nigeria showing Gashaka-Gumti National Park
Source: Modified from GRID3, 2025.

The National Park is situated in a tropical wet and dry climate zone. The annual rainfall varies from 1,000 to 1,973 mm (Akinsoji et al., 2016). The highest monthly mean rainfall occurs in August (332 mm), whereas the dry season lasts from five months in the drier lower areas to two months in the wetter highland regions. Approximately 95% of the yearly rainfall occurs between May and October (Bird-Life International, 2019). The dry period from November to April is caused by the North East trade winds (Harmattan) (Sommer & Ross, 2011). Temperatures at Gashaka-Gumti National Park vary on the basis of location within the park. The annual temperature ranges from approximately 21°C to 32°C. Daytime temperatures can exceed 40°C in March but may drop below 5°C at higher elevations in December (Nigeria National Park Services [NNPS], 2014).

Gumti, the northern part of the National Park, is generally flat, whereas Gashaka, the southern sector, is more mountainous. The environment is characterized by steep, heavily forested slopes, deep valleys, abrupt escarpments, and fast-flowing rivers. The elevation varies from 450 m above sea level in the Northern Plains to the peaks and pinnacles of Mount Gangirwal (Mountain of Death) in the southern part of the park, which is Nigeria's highest mountain at 2400 m above sea level (Mubi, 2010). Likewise, the park is known for its dense vegetation, including Montane grassland, southern Guinea savanna, and lowland rainforest (Akinsoji et al., 2016).

2.2 Data Sources

This study utilized annual rainfall data sourced from the Climate Research Unit (CRU 4.07) at the University of East Anglia (UEA). The data can be accessed at https://crudata.uea.ac.uk/cru/data/hrg/index (Accessed September 19, 2024). Version 4.07 was released in April 2023 and covers a span of 101 years, from 1901 to 2022, with a spatial resolution of 0.5° by 0.5° (Harris et al., 2020). The CRU dataset is widely recognized and has been employed in numerous studies focused on rainfall (Animashaun et al., 2020; Abubakar et al., 2024).

2.3 Data Analysis

Coefficient of variation (CV)

To calculate the temporal variability in rainfall in Gashaka-Gumti, the coefficient of variation (CV) was computed via Eq. (1):

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

where σ represents the standard deviation and $\bar{X}$ denotes the average rainfall. Typically, CV values less than 20% are classified as low, values from 20% to 30% as moderate, values from 30% to 40% as high, and values exceeding 40% as very high (Abubakar et al., 2025a; Salami, 2024). The CV was computed via the hydroTSM package in R Studio.

Modified Mann-Kendall Trend Test

The MMK provides improved accuracy for trend detection in time series data by adjusting the variance of the test statistic using an effective sample size (Hamed & Ramachandra Rao, 1998). The modified VAR(S) statistic is calculated via Eq. (2):

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

Here, the correction factor $\left(\frac{n}{n_e^*}\right)$ is adjusted to the autocorrelated data via Eq. (3):

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

where $\rho_e(f)$ represents the autocorrelation function between the ranks of the observations and can be estimated via Eq. (4):

$$\rho(f) = 2sin\left(\frac{\pi}{6}\,\rho_e(f)\right) \quad (4)$$

The trends were categorized using the Z_{MK} statistic as classified by Salami (2024). A Significant Increasing Trend (SIT) occurs when $Z_{MK} > 1.96$, while a Non-Significant Increasing Trend (N-SIT) is recorded when Z_{MK} lies between 0 and 1.96. A No Trend (NT) condition is observed when $Z_{MK} = 0$. For decreasing patterns, a Non-Significant Decreasing Trend (N-SDT) is identified when Z_{MK} falls between –1.96 and 0, whereas a Significant Decreasing Trend (SDT) is confirmed when $Z_{MK} < -1.96$.

Sen's slope

Sen's slope is a nonparametric approach that is frequently employed to identify slope trends in hydrometeorological datasets (Bekele et al., 2017; Gocic & Trajkovic, 2013). It was developed by Sen (1968) and calculated via Eq. (5):

$$f(t) = Qt + B \quad (5)$$

In equation (11), *Qt* represents the slope, whereas B represents a constant. To calculate the slope (Q), the slopes (values) of the data were calculated via Eq. (6):

$$Q_i = \frac{X_j - X_k}{j - k} \quad (6)$$

where Xj and Xk represent the data values at intervals j and k (j > k). If each interval has a single datum, then N = n(n-1)/2, where n is the number of data points. If there are several observations in one or more periods, then N < (n(n-1))/2. Sen's slope estimator is computed via Eq. (7):

$$Q_{med} = \begin{cases} Q * \left[\frac{(N+1)}{2}\right], if\ N\ is\ odd \\ \frac{Q * \left[\frac{N}{2}\right] + Q * \left[\frac{(N+2)}{2}\right]}{2}, if\ N\ is\ even \end{cases} \quad (7)$$

Finally, Qmed is used with a nonparametric model to calculate the trend and slope magnitude. A positive Qi implies an uptrend, whereas a negative Qi suggests a downtrend. Similarly, a score of zero indicates that no trend is detected.

Rainfall anomaly index (RAI)

The rainfall anomaly index (RAI), developed by van Rooy (1965), is a rank-based index used to measure drought by assigning magnitudes to negative (deficit) and positive (surplus) precipitation anomalies (Abubakar et al., 2024). This index categorizes rainfall anomalies on a scale ranging from −3 (extremely dry) to +3 (extremely wet), with values assessed against a nine-classification scheme, as presented in Table 1. The mathematical formulation of the RAI is given in Eq. (8), as follows:

$$\mathrm{RAI} = \frac{R - \mu}{\sigma} \tag{8}$$

where RAI is the rainfall anomaly index, R is the total rainfall, μ represents the long-term average rainfall, and σ is the standard deviation.

Table 1: Rainfall anomaly index (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: Adapted and modified from (Raziei, 2021)

3 Results

3.1 Rainfall variability

Table 2 below shows the minimum, maximum, mean, standard deviation (std), and CV of rainfall in Gashaka-Gumti National Park.

Table 2: CV of annual rainfall from 2022-2022

Variable	Min	Max	Mean	Std.	CV	CV (%)
Rainfall	949.9	1647.7	1365.9	148.5	0.108	10.9%

As shown in Table 2, the reported CVs of 0.108 or 10.9% indicate a relatively low level of annual variability in rainfall, suggesting that a stable precipitation regime may benefit the diverse ecosystems of the National Park. Nevertheless, while the interannual variability remains low, the total rainfall recorded during the study period demonstrated substantial fluctuations, varying between a minimum of 949 mm and a maximum of 1647 mm. The calculated average annual rainfall during this time was 1365 mm, accompanied by a standard deviation of 148 mm.

3.2 Trend of Rainfall in Gashaka-Gumti National Park

The trend of precipitation within Gashaka-Gumti National Park is illustrated in Table 3 below.

Table 3: Trend of rainfall in Gashaka-Gumti National Park from 2002-2022

Z_{MK}	Kendall's tau	S	Var(S)	p-value (Two-tailed)	alpha
0.507	0.048	10	348.67	0.61	0.05

The analysis presented in Fig. 3, which uses the adapted modified Mann–Kendall trend test executed at a 95% confidence level, analyzed the annual rainfall patterns within Gashaka-Gumti National Park over a two-decade span from 2002-2022. The statistical results indicate no statistically significant trend in the rainfall data for the specified period. Specifically, the findings yielded a Z_{MK} score of 0.507 and a Kendall's tau coefficient of 0.048, which collectively suggest a negligible correlation in the annual rainfall figures. Furthermore, the calculated p-value of 0.613 notably exceeds the established significance threshold of alpha = 0.05. This outcome decisively indicates the absence of any noteworthy upwards or downwards trend in the annual rainfall patterns across Gashaka-Gumti National Park from 2002-2022.

Additionally, the analysis included Sen's slope estimate, which was calculated at 1.003, indicating the magnitude of significant change in the annual rainfall. These results underscore the stability of annual rainfall levels in Gashaka-Gumti National Park, suggesting that external factors, management practices, or climatic variability may not have exerted a measurable influence over the observed timespan from 2002-2022. Fig. 2 illustrates this result.

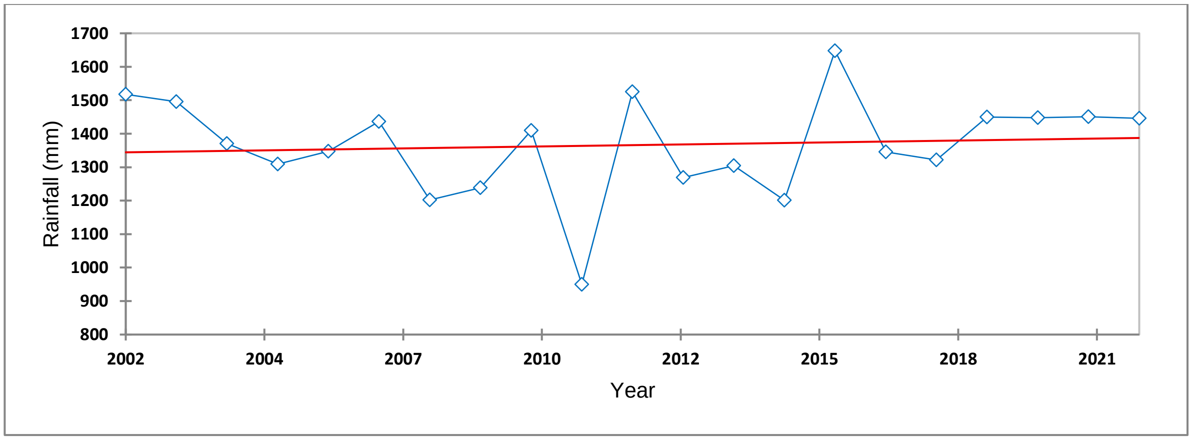

Figure 2: Mann–Kendall trend test results for Gashaka-Gumti National Park from 2002-2022

3.3 Rainfall anomaly index (RAI)

To calculate the RAI, thresholds of +3 and -3 (wet and dry) were set on the basis of the average of the most significant positive and negative anomalies, respectively.

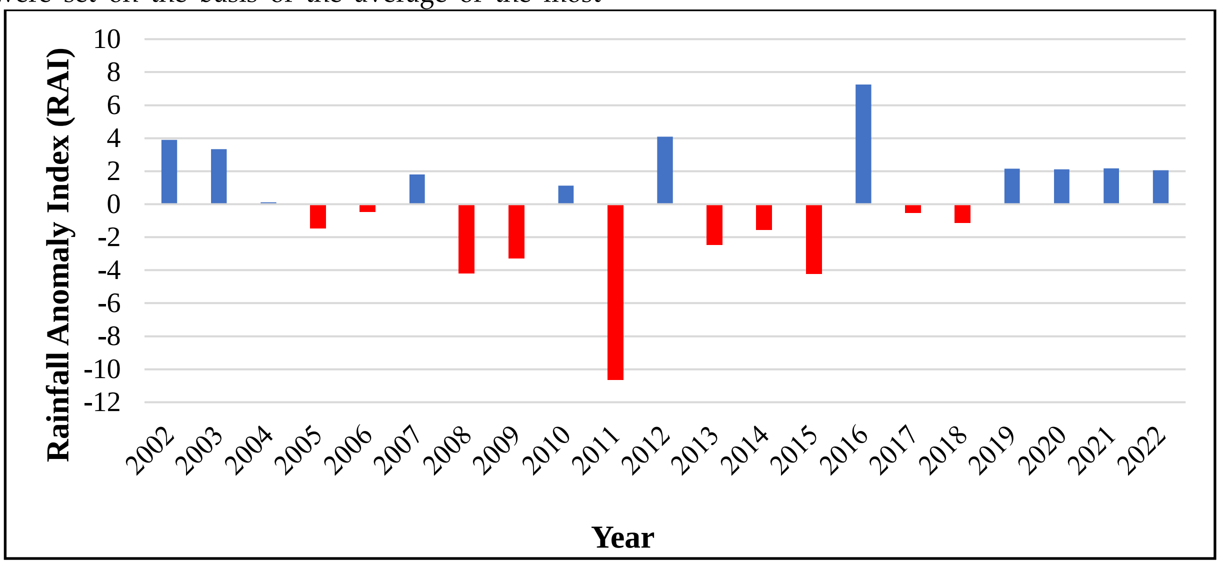

Figure 3: RAI in Gashaka-Gumti National Park from 2002-2022.

The results shown in Fig. 3 reveal a striking pattern of RAI, characterized by both wet and dry conditions over the study period. Specifically, the years 2002 and 2003 had wet RAIs of + 3.89 and + 3.33, respectively. The results revealed severely dry conditions, marked by RAIs of − 4.19 and − 3.27 in 2008 and 2009, respectively, suggesting a significant departure from normal rainfall patterns. The severe dry RAI was recorded in 2011, with an RAI of − 10.66, which is notable for its extreme magnitude and potential impact on the hydrological and ecological systems of the study area. In contrast, 2012 and 2016 were characterized by wet conditions, with RAI values of +4.09 and +7.24, respectively, indicating a return to more normal or even above-average rainfall patterns in the study area.

4 Discussion

The coefficient of variation (CV) of 10.8% for annual rainfall in Gashaka-Gumti National Park between 2002 and 2022 suggests that the amount of annual rainfall varies within a very small range (949–1,647 mm). This aligns with the findings of Abubakar et al. (2024), who reported low variability in annual rainfall in northern Nigeria. According to Murwendo et al. (2023), rainfall stability can help animals in many habitats, such as montane vegetation and savannas, maintain their ecological conditions over time. Similarly, plants and animals that require considerable moisture, such as elephants, other large mammals, and understorey trees, are less likely to be affected by excess water or flooding (Aslam et al., 2023). This low variability means that park managers can count on having enough water for tourism infrastructure, fire management, and anti-poaching patrols. This means that in most years, they do not have to take extra steps to save water.

The modified Mann–Kendall test indicates no statistically significant trend in annual rainfall over the 20 years (Z_{MK} = 0.507, Kendall's τ = 0.048, p = 0.613 > 0.05), whereas the Sen's slope of 1.003 mm/year shows that there has been very little change. The absence of a significant long-term trend of increasing or decreasing precipitation in the park indicates relative climate stability (Ishaku et al., 2024). This result is consistent with the general expectation of rainfall stability in specific regions of northeastern Nigeria, where the orographic effect of the Mambilla Plateau results in relatively uniform precipitation (Yiyeh et al., 2024). The results also suggest that climatic variability has not significantly impacted the park's rainfall regime, potentially elucidating the continued existence of its dense forest and savannah ecosystems. Furthermore, Adeonipekun et al. (2025) reported that montane ecosystems are highly sensitive to climatic pressure and are susceptible to future warming.

The RAI results clearly show that there are irregularities in the overall stable pattern over time. The years 2002 and 2003 had positive anomalies (+3.89 and +3.33), which means that they were wet. The years 2008, 2009, and 2011 had very dry anomalies, with 2011 having the highest RAI of −10.66, which means that it was very dry. On the other hand, 2012 and 2016 had wet anomalies (+4.09 and +7.24), which means that the rainfall had returned to normal levels. These periods of alternating wet and dry weather show that even though the long-term trend may be stable, short-term changes in weather can still put stress on the ecosystem from time to time (Serra-Maluquer et al., 2021). Additionally, these changes can affect plant life, animal migration, and the start of bushfires or soil erosion.

The low coefficient of variation, lack of a significant trend in rainfall, and occasional rainfall anomalies all indicate that Gashaka-Gumti National Park is currently experiencing a generally stable but occasionally variable rainfall regime. This stability is good for the environment because it makes it easier to protect biodiversity and make ecosystems more resilient (Abubakar et al., 2025b). However, the fact that there have been very dry years, such as 2011, shows how important it is to have flexible management plans to lessen the effects of short-term droughts on the environment and water supply. Park officials could be better prepared for and respond to these kinds of problems if they keep an eye on rainfall patterns and set up early warning systems. In the long run, maintaining vegetation cover, protecting watersheds, and preventing people from damaging the park will be very important for maintaining its natural ability to protect against changes in rainfall and maintain its ecological diversity.

4.1 Limitations

A significant limitation of this study is its dependence on a relatively brief rainfall record (2002–2022), which may inadequately reflect long-term climatic variations or multidecadal variability affecting precipitation in Gashaka-Gumti National Park. The analysis concentrated exclusively on rainfall as the singular climatic variable, excluding temperature, evapotranspiration, and soil moisture data, which collectively impact hydrological and ecological conditions. These constraints indicate that subsequent research should utilize extended datasets, increased temporal resolution, and multifactorial analyses to achieve a more thorough comprehension of rainfall variability and its ecological ramifications for the park.

5 Conclusion

The analysis of rainfall variability in Gashaka-Gumti National Park from 2002-2022 revealed a generally stable precipitation regime with little interannual variability, with a coefficient of variation of 10.8%. The climatic stability during the study period was confirmed via trend analysis via the modified Mann–Kendall test, which revealed no statistically significant increase or decrease in annual rainfall. Nonetheless, the rainfall anomaly index (RAI) revealed that the years were alternately wet and dry, with exceptionally dry years occurring in 2008, 2009, and 2011 and noticeably wet years occurring in 2012 and 2016. These variations suggest that short-term anomalies may cause transient stress to park ecosystems, even though long-term rainfall patterns remain consistent.

However, the results show that while Gashaka-Gumti National Park enjoys a comparatively stable rainfall regime that supports biodiversity conservation, it is still susceptible to sporadic climatic extremes. Thus, this study recommends that park management improve early warning and climate monitoring systems to predict and lessen the effects of extreme rainfall events to guarantee ecological resilience. For a more thorough understanding of hydroclimatic dynamics, future studies should incorporate other climatic parameters, such as temperature, evapotranspiration, and soil moisture.

Furthermore, to protect vital habitats from rainfall variability, ecosystem-based adaptation techniques such as reforestation, watershed protection, and vegetative buffer maintenance should be used. Additionally, to better predict long-term biological implications and guide adaptive conservation planning, future studies should also model possible future rainfall scenarios under various climate change paths.

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