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

Assessment of Hydroclimatic Trends and Water Availability Dynamics in Mubi North, Adamawa State, Nigeria

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ABSTRACT

Water availability in semi-arid regions is highly sensitive to fluctuations in climate and land-surface processes; however, the limited knowledge of long-term hydroclimatic behavior in northeastern Nigeria limits effective resource management. This work investigated four decades of hydroclimatic variability (1985-2024) in Mubi North, Adamawa State, exploring the interlinkages between temperature, precipitation, runoff, soil moisture, vapour pressure, and water deficit. Data were gathered from the Climate Engine website through the TerraClimate and GRIDMET datasets (~4-km resolution). Monthly records were summarized into annual means. Analyses used the Mann-Kendall trend test, Sen's slope estimator, and Pearson correlation to assess the trends and interdependencies. Among the more pronounced changes, minimum temperature increased by +0.41 °C per decade, runoff by +1.9 mm/year, soil moisture by +3.4 mm/year, and vapor pressure by +0.12 kPa per decade, with a reduction in water deficit by -2.6 mm/year, thus signalling an improvement in water availability despite ongoing warming. In addition, maximum temperature and precipitation increased insignificantly, at +0.09 °C per decade and +2.8 mm/year, respectively. Highly statistically significant positive correlations between precipitation, runoff, and soil moisture ($r = 0.756$-0.932, $p < 0.001$) confirm rainfall as the dominant driver of hydrology, while land-surface conditions affect storage and flow responses. Overall, this study has shown that Mubi North has undergone significant hydroclimatic transformation driven by warming, increased soil moisture, enhanced runoff, and reduced water stress. To ensure the continuation of such positive changes, this study prioritizes integrated land-water management that promotes soil moisture conservation through, for instance, agroforestry and mulching, erosion control, and climate-resilient agricultural planning supported by regular hydroclimatic monitoring and land-use studies to enhance adaptive water policies in semi-arid northeastern Nigeria.

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1 Introduction

Water availability is a cornerstone of human livelihoods, agricultural productivity, and the functioning of ecosystems, particularly in semi-arid regions where rainfall is highly variable and evapotranspiration rates are elevated. In these environments, examining long-term trends in hydrological variables such as runoff and soil moisture is essential for sustainable water resource management amid climate variability (FAO, 2021; Trenberth et al., 2014). These indicators reflect both natural processes and human interventions, influencing crop performance, groundwater recharge, and the viability of surface water systems (Li et al., 2022; Oloruntade et al., 2018).

Across Africa, these challenges are especially pronounced. Large portions of the continent are classified as arid or semi-arid, and freshwater resources are unevenly distributed. In sub-Saharan regions, surface and groundwater availability are increasingly constrained by irregular rainfall, elevated evaporation, and rising human water demand. Variability in precipitation reduces natural recharge, exacerbates seasonal water scarcity, and, when coupled with rising temperatures, accelerates water losses through evaporation. Moreover, unsustainable land use practices, including deforestation, repeated soil cultivation, and overextraction of resources, further degrade soils and impair catchment functions. This combination of climatic and anthropogenic pressures highlights that water scarcity arises from both environmental and human factors, underscoring the need for integrated management strategies that incorporate climate insights alongside adaptive land-use planning (Dembélé et al., 2020; MacDonald et al., 2021; Masih et al., 2020). Empirical studies from the Sahel and savannah zones consistently show that soil moisture and runoff patterns are closely linked to rainfall frequency, vegetation cover, and land management, rather than occurring randomly (Nketia et al., 2022; Okello et al., 2024).

In northern Nigeria, especially within the semi-arid belt, the climate has exhibited considerable variability over recent decades, with both shifts in precipitation and land use changes shaping local hydrology (Adebayo & Tukur, 1999; Tukur et al., 2020). Mubi North, Adamawa State, is particularly susceptible. Prolonged dry seasons,

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and mounting pressure on farmland and water sources has reduced soil moisture, limited infiltration, and curtailed surface runoff. These cumulative stresses contribute to noticeable water shortages and ongoing land degradation (Odiji et al., 2023; Ntekim et al., 2021).

The majority of residents depend on rain-fed agriculture, so variations in soil moisture or runoff have immediate implications for crop yields, household incomes, and water allocation practices (Akinbile et al., 2020). Long-term monitoring of these parameters is therefore vital to understand how water availability responds to climate fluctuations and land cover changes (IPCC, 2021; FAO, 2023).

This study investigates long-term changes in water availability in Mubi North by analyzing 40 years (1985–2024) of runoff and soil moisture data. Data were sourced from the Climate Engine platform, which combines satellite-derived measurements with reanalysis datasets suitable for regions lacking extensive ground-based records. Trend analysis employed the Mann–Kendall test alongside Sen's slope estimator, both robust non-parametric methods widely used to detect monotonic trends and quantify their magnitude, particularly when data are non-normally distributed or exhibit serial correlation. The 40-year period aligns with the World Meteorological Organization's recommendation of using at least 30 years of data for reliable climate trend assessment (WMO, 2017). The anticipated results will provide insights into hydroclimatic dynamics in semi-arid northeastern Nigeria and inform strategies for sustainable water management, drought mitigation, and climate adaptation.

2 Materials and methods

2.1 Study area

Mubi North Local Government Area (LGA) is situated in the northeastern part of Adamawa State, Nigeria, lying between latitudes 10°11′ and 10°32′ N and longitudes 13°12′ and 13°35′ E. The area shares an international border with the Republic of Cameroon to the east and spans approximately 1,250 km² (Adebayo et al., 2023). According to the 2006 National Population Census, the LGA had a population of 151,515, comprising 78,059 males and 73,456 females (NPC, 2006). More recent estimates suggest the population reached around 233,600 by 2022, reflecting steady growth trends observed across northeastern Nigeria (City Population, 2024). This demographic expansion has significant implications for land use, water demand, and agricultural pressure, making Mubi North an important site for investigating environmental and hydroclimatic dynamics.

The LGA lies within the Sudano–Sahelian ecological zone, characterized by a tropical wet-and-dry climate. The rainy season generally occurs between May and October, while the dry season extends from November to April. Annual rainfall averages between 900 and 1,000 mm, and mean temperatures range from 18 °C to 38 °C (Akinmayowa Shobo, 2025; Nigerian Meteorological Agency [NIMET], 2024).

Topographically, Mubi North features gently undulating terrain with elevations ranging from approximately 600 m to 900 m above sea level. The landscape gradually slopes toward the Yedzaram River Basin, a key drainage system that supports both agricultural irrigation and domestic water supply. The geomorphology of the area promotes the collection of surface runoff into the river basin, reinforcing its role in local water resource management. Similar patterns of elevation and drainage are observed across northeastern Nigeria, where river basins such as the Yedzaram constitute vital components of regional hydrological networks and rural livelihoods (Adebayo & Tukur, 2022; Nwankwoala & Udom, 2021).

Soils in the area are predominantly ferruginous tropical and sandy loams. They are moderately fertile but prone to erosion and desiccation, particularly during extended dry periods (Adebayo & Tukur, 1999). Vegetation consists mainly of savannah grasses interspersed with shrubs and scattered drought-tolerant trees such as *Acacia senegal*, *Parkia biglobosa*, and *Vitellaria paradoxa* (Tukur et al., 2020).

Agriculture dominates the local economy, engaging over 70% of the population. Major crops include sorghum, millet, maize, groundnut, and cowpea, often complemented by livestock rearing (Adebayo et al., 2023). However, agricultural productivity and water resource sustainability are increasingly challenged by land degradation, soil moisture depletion, and erratic rainfall patterns. These environmental pressures make Mubi North an appropriate case study for examining long-term changes in water availability, particularly through the analysis of runoff and soil moisture trends.

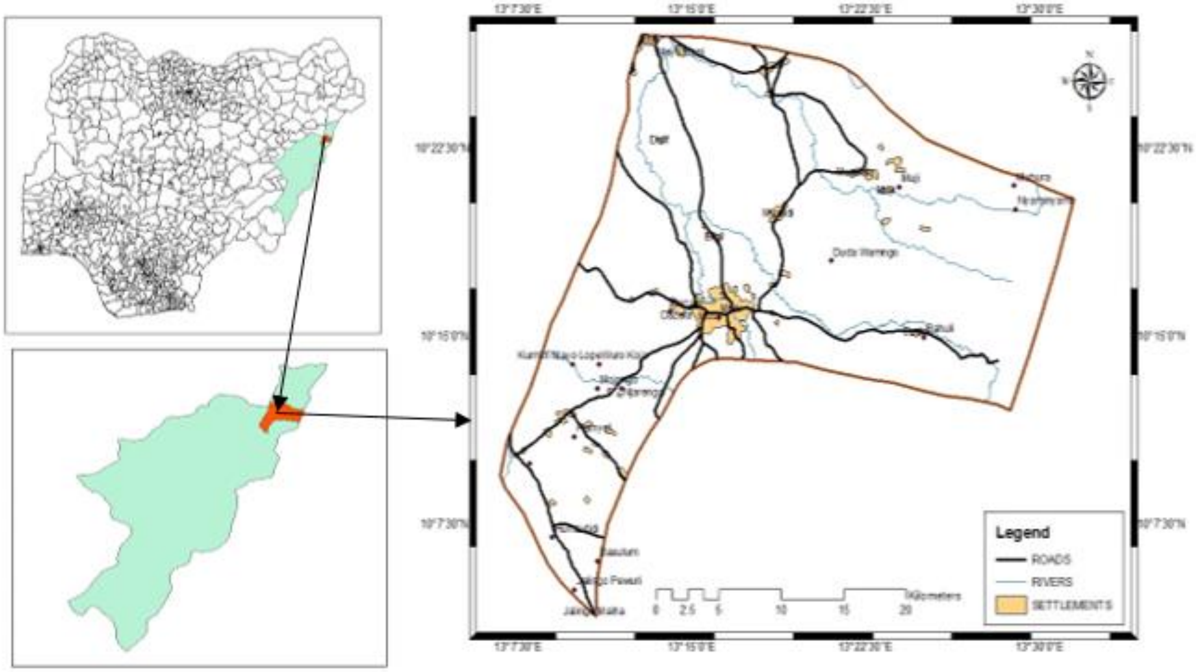

Figure 1: Study area

2.2 Data Sources

This study employed a 40-year dataset (1985–2024) of climatic and hydrological variables to examine long-term environmental changes influencing water availability in Mubi North, Adamawa State. The climate variables analyzed included minimum and maximum monthly temperatures (°C), monthly precipitation (mm), runoff (mm), soil moisture (mm), vapour pressure (kPa), and water deficit (mm). These data were sourced from the Climate Engine platform (ClimateEngine.org), a cloud-based analytical system that integrates information from NASA, NOAA, and other global repositories (Huntington et al., 2017).

Hydrological parameters, specifically runoff, soil moisture, and water deficit, were extracted from Climate Engine using the TerraClimate and GRIDMET datasets, which provide high-resolution (~4 km) monthly gridded climate observations. These datasets have demonstrated reliable performance in West African and Nigerian settings, showing strong agreement with ground-based measurements obtained from NIMET and other regional meteorological stations (Tanimu et al., 2024; Abiodun et al., 2021; Akinyemi & Orimoloye, 2023). The combination of fine spatial resolution and temporal consistency makes these datasets particularly suitable for assessing hydroclimatic trends in semi-arid regions such as Mubi, where continuous ground-based observations are often limited or spatially sparse (Abatzoglou et al., 2018). Additionally, their widespread use in regional hydroclimatic studies is supported by their high spatiotemporal reliability and bias correction using in-situ measurements (Huntington et al., 2017; Abatzoglou et al., 2018).

2.3 Data Processing

The study area was delineated directly within the Climate Engine platform using its built-in boundary tracing and polygon selection tools, ensuring that all extracted data correspond precisely to the Mubi North LGA. Monthly values for seven climatic and hydrological variables—minimum and maximum temperature (°C/month), precipitation (mm/month), runoff (mm/month), soil moisture (mm/month), vapour pressure (kPa/month), and water deficit (mm/month)—were retrieved for the period 1985–2024. These monthly observations were then aggregated into annual averages to facilitate the analysis of interannual trends and long-term hydroclimatic variability. While this approach emphasizes year-to-year changes, it smooths out seasonal variations, which could be examined in future studies to gain a more detailed understanding of intra-annual dynamics.

The selected variables were chosen for their direct relevance to water availability and their sensitivity to climate change impacts. Extracted data were exported in CSV format, checked for missing values, and statistically summarized using Microsoft Excel 2021 and SPSS version 23. Time-series plots were generated to visualize temporal variations and support trend analysis.

To assess the temporal evolution of the climatic and hydrological parameters, the Mann–Kendall (MK) test and Sen’s slope estimator were applied to detect trends and quantify their magnitude. Before conducting the analysis, the time series were evaluated for autocorrelation using the Durbin-Watson statistic, since positive autocorrelation can artificially increase the significance of trends. When significant autocorrelation was identified, the pre-whitening technique was employed to remove serial dependence, thereby ensuring the robustness of the MK test results. This methodology is widely recognized for evaluating long-term hydroclimatic trends in regions where in-situ data are limited (Hamed & Rao, 1998; Yue et al., 2002).

The MK test is a non-parametric approach that identifies monotonic trends in hydro-meteorological time series without requiring assumptions about data normality (Mann, 1945; Kendall, 1975). Sen's slope estimator was subsequently used to determine the magnitude and direction of detected trends (Sen, 1968). Both analyses were conducted at a 95% confidence level (α = 0.05) using XLSTAT and the R programming environment (trend package), ensuring statistical reliability and comparability with similar regional studies.

2.4 Correlation Analysis

The relationships among key hydrological variables, runoff, soil moisture, and precipitation, were evaluated using the Pearson correlation coefficient (r) in SPSS version 23. This analysis was conducted to determine how variations in rainfall influence soil water retention and surface runoff within the study area (Ferchichi et al., 2024). The correlation analysis specifically focused on precipitation, soil moisture, and runoff, thereby isolating the primary hydrological pathway that governs water availability. Variables such as temperature and vapour pressure were excluded because their effects on water dynamics are largely indirect, operating through evapotranspiration, while water deficit was omitted to prevent mathematical redundancy with precipitation. This methodological approach is consistent with established hydrological principles and provides a statistically robust framework for interpreting water resource dynamics in semi-arid environments (Han et al., 2019; Shi et al., 2024).

3 Results and Discussion

3.1 Time Series Variability from 1985 to 2024

The analysis of hydroclimatic data for Mubi North from 1985 to 2024 indicates a gradual shift toward higher atmospheric moisture and improved soil water conditions, despite persistently elevated maximum temperatures and variable rainfall (Figure 2). Maximum temperatures generally range between approximately 33 °C and 34.5 °C, with only a modest increase observed in the most recent decade, while minimum temperatures remain near 19.5–20 °C, suggesting limited overnight or baseline warming. In contrast, moisture-related indicators show more pronounced changes. For example, global total precipitable water (TPW) has increased at rates of roughly 0.66 % to 0.88 % per decade, reflecting the influence of warming on atmospheric moisture content through the Clausius–Clapeyron relationship (Wan et al., 2022). Similarly, soil moisture measurements in certain locations indicate upward trends, associated with increased rainfall and enhanced retention capacity (Burrows, 2024), while water deficits have declined, highlighting the inverse relationship between soil saturation and deficit. Together, these patterns suggest a transition toward a wetter, more moisture-rich environment, even though interannual variability in rainfall and runoff remains substantial.

Several processes appear to drive these trends. The rise in atmospheric moisture is primarily a result of warmer air holding greater amounts of water vapour, as evidenced by observed increases in TPW (Wan et al., 2022; Ren et al., 2023). Higher vapour pressure and increased moisture availability enhance soil infiltration and saturation, reducing water deficits and improving soil water storage. Importantly, positive trends in soil moisture are more closely linked to precipitation increases than to temperature alone. For instance, studies in the U.S. for 2011–2020 showed that changes in precipitation accounted for most of the observed soil moisture rise, rather than warming-induced drying (Burrows, 2024). Thus, although rainfall remains highly variable and does not follow a simple upward trend, shifts in rainfall intensity and timing, combined with improved moisture retention and elevated atmospheric humidity, appear to be modifying the regional water balance.

Overall, the hydroclimatic analysis for Mubi North over the 1985–2024 period reveals notable changes in temperature, precipitation, soil moisture, runoff, vapour pressure, and water deficit, reflecting alterations in regional water availability. Table 1 presents the results of the Mann–Kendall trend analysis alongside Sen's slope estimates for these variables, summarizing the magnitude and direction of observed changes.

Table 1: Mann–Kendall trend analysis of climatic and hydrological variables (1985–2024)

Variable	Kendall's Tau	Z-Statistic	p value	Trend	Significance	Sen's Slope (Change rate)
Max Temp (°C)	0.102	1.38	0.168	Increasing	Not significant	+0.09 °C/decade
Min Temp (°C)	0.712	9.64	<0.001	Increasing	Significant	+0.41 °C/decade
Precipitation (mm)	0.085	1.15	0.250	Increasing	Not significant	+2.8 mm/year
Runoff (mm)	0.412	5.58	<0.001	Increasing	Significant	+1.9 mm/year
Soil Moisture (mm)	0.822	11.13	<0.001	Increasing	Significant	+3.4 mm/year
Vapour Pressure (kPa)	0.812	11.00	<0.001	Increasing	Significant	+0.12 kPa/decade
Water Deficit (mm)	−0.698	−9.46	<0.001	Decreasing	Significant	−2.6 mm/year

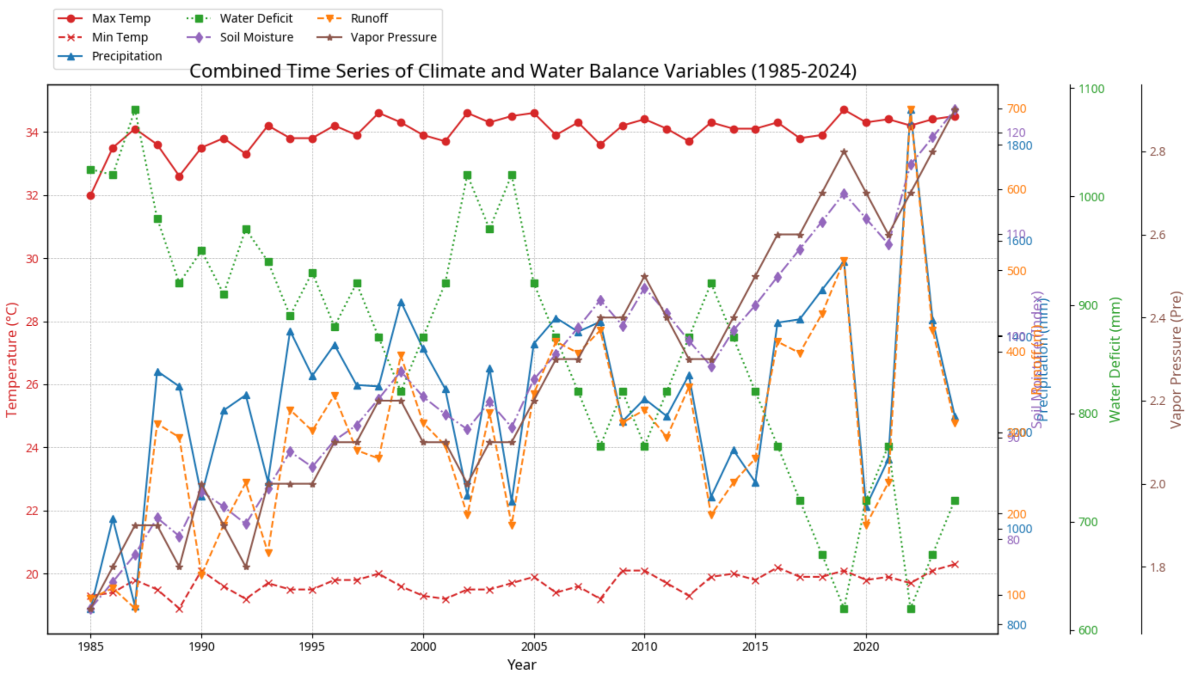

Figure 2: Time Series

The results presented in Table 1 and Figure 2 indicate notable hydroclimatic changes in Mubi North over the 1985–2024 period. Minimum temperatures have risen significantly at a rate of approximately +0.41 °C per decade, reflecting pronounced night-time warming. This pattern is consistent with regional studies in northern Nigeria, which suggest that minimum temperatures are increasing more rapidly than maximum temperatures due to climate change and urbanization effects (Nasara et al., 2025; Garba & Udokpoh, 2023). Elevated night-time temperatures can influence evapotranspiration, soil-water retention, and crop water requirements, all of which are critical for agricultural productivity in semi-arid regions. In contrast, maximum temperatures increased only slightly (+0.09 °C per decade) and were not statistically significant, likely moderated by factors such as vegetation cover, cloudiness, and local wind patterns (Nasara et al., 2025).

Precipitation showed a modest positive trend (+2.8 mm/year), but this increase was not statistically significant, reflecting the high interannual variability observed in annual rainfall totals across Nigeria (Alli et al., 2019). Despite relatively stable rainfall, both runoff and soil moisture exhibited significant increases, at +1.9 mm/year and +3.4 mm/year, respectively. Rising runoff may be driven by a combination of climatic and land-use changes, including deforestation, soil compaction, and enhanced soil saturation resulting from warmer minimum temperatures (Alfa et al., 2018; Lawal et al., 2024). The increase in soil moisture suggests improved short-term water availability; however, this may be confined to surface soil layers, potentially causing uneven moisture distribution within the root zone or localized waterlogging (Kehinde & Umar, 2021).

Vapour pressure also rose significantly (+0.12 kPa per decade), indicating higher atmospheric moisture and a greater potential for evapotranspiration. When considered alongside increasing soil moisture, these trends suggest a more dynamic hydrological system with enhanced latent heat fluxes and sufficient water storage to support vegetation and agricultural needs. Correspondingly, water deficit decreased significantly (−2.6 mm/year), indicating a narrowing gap between water supply and atmospheric demand. While this trend could support crop growth, it may also reflect elevated runoff and soil saturation rather than consistently favourable moisture conditions (Berg et al., 2017).

Generally, the hydroclimatic changes at Mubi North reflect a combination of warming, heightened atmospheric moisture, and land-surface dynamics. Increased soil moisture and decreased water deficit indicate enhanced water availability, but increasing runoff could pose a threat of soil erosion, nutrient loss, and reduced infiltration capability. The inexistence of significant precipitation and maximum temperature trends highlights the contribution of nocturnal warming and terrestrial surface processes on local water resources.

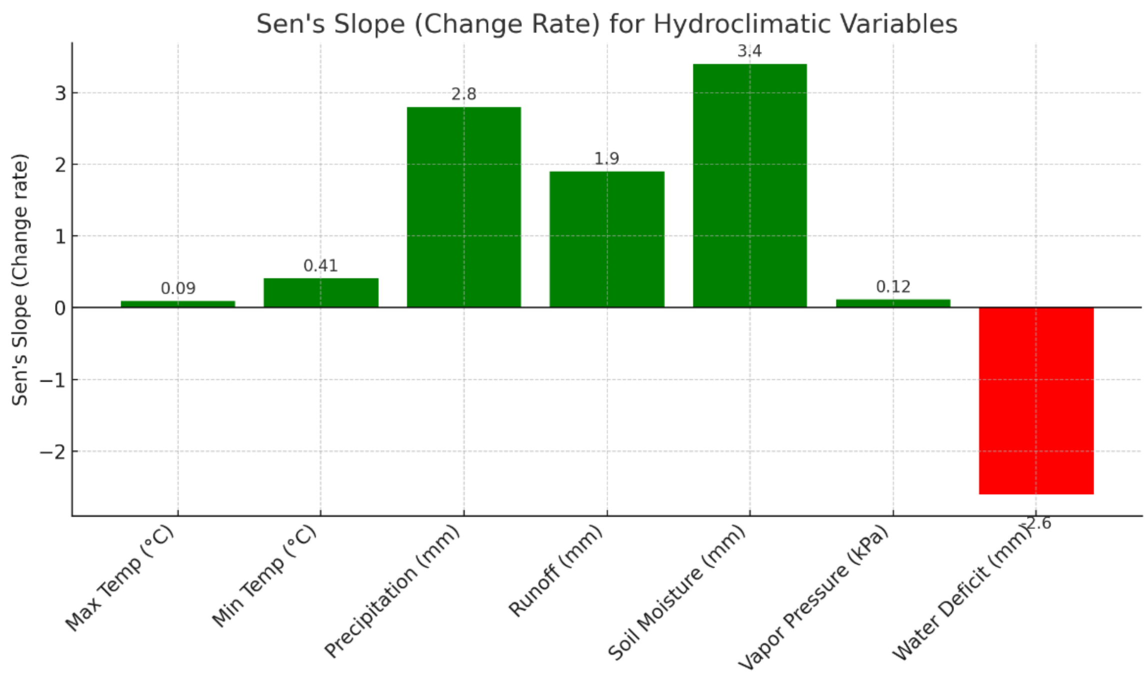

Figure 3: Changes in Sen's Slope for Decades

In analyzing hydroclimatic dynamics in Mubi North, Adamawa State, Nigeria, the relationships among runoff, precipitation, and soil moisture were investigated using Pearson correlation analysis. The results, presented in Table 2 and Figure 4, reveal strong positive correlations among these three essential hydrological variables, indicating that changes in rainfall are closely linked to variations in soil water content and surface runoff.

Table 2: Pearson correlation matrix for runoff, soil moisture, and precipitation

Variable	Runoff (mm)	Precipitation (mm)	Soil Moisture (mm)
Runoff (mm)	r = 1.000, p = —, CI = —	r = 0.821, p < 0.001, 95% CI: 0.65–0.91	r = 0.932, p < 0.001, 95% CI: 0.86–0.97
Precipitation (mm)	r = 0.821, p < 0.001, 95% CI: 0.65–0.91	r = 1.000, p = —, CI = —	r = 0.756, p < 0.001, 95% CI: 0.57–0.87
Soil Moisture (mm)	r = 0.932, p < 0.001, 95% CI: 0.86–0.97	r = 0.756, p < 0.001, 95% CI: 0.57–0.87	r = 1.000, p = —, CI = —

Note: *Significance markers (p* ***< 0.001)*** *alongside r values, p values, and 95% confidence intervals.*

The

The strongest correlation observed in the study was between runoff and soil moisture (r = 0.932, p < 0.001, 95% CI: 0.86–0.97), indicating that higher soil moisture levels in Mubi North are closely associated with increased surface runoff. This strong relationship aligns with hydrological research showing that as soils become wetter, their infiltration capacity can be reduced or soil layers approach saturation, promoting overland flow and runoff generation (Nkiaka, Bryant & Dembélé, 2024).

Runoff also demonstrated a strong positive correlation with precipitation (r = 0.821, p < 0.001, 95% CI: 0.65–0.91), emphasizing rainfall as the principal driver of surface water formation in semi-arid and tropical catchments (Zouré et al., 2023). Precipitation exhibited a moderate correlation with soil moisture (r = 0.756, p < 0.001, 95% CI:

0.57–0.87), highlighting the hydrological sequence whereby rainfall replenishes soil moisture, which in turn influences runoff processes. Previous studies in Nigeria have reported that rainfall explains a substantial portion of the variance in soil moisture content, with figures reaching approximately 69% in locations such as Umudike (Igwenyi et al., 2024).

Collectively, these findings illustrate a tightly interconnected hydrological system in Mubi North: rainfall replenishes soil water stores, higher soil moisture supports increased runoff generation, and runoff is strongly determined by rainfall input. This has important implications for land use and agriculture, as alterations in rainfall patterns, soil water storage, or catchment infiltration can cascade through the system, affecting both water availability and ecosystem stability.

The high correlation between soil moisture and runoff underscores the need to consider how water is stored or lost within the landscape. For instance, if rising soil moisture reflects primarily shallow storage with limited deep infiltration, frequent high-moisture conditions may increase runoff, accelerate drainage, and elevate erosion risk, potentially offsetting the benefits of higher soil water availability. This emphasizes that, in semi-arid regions like northern Nigeria, hydrological responses are the result of integrated interactions among rainfall, soil water storage, and surface flow dynamics, rather than single variables acting in isolation (Brocca et al., 2020; Zouré et al., 2023).

From a practical perspective, these correlations suggest that interventions aimed at enhancing soil water retention—such as mulching, improving land cover, or promoting infiltration—can not only increase soil moisture but also help moderate runoff, thereby reducing erosion and nutrient losses. Monitoring soil moisture alongside rainfall and runoff remains essential for effective water resource management under evolving climatic conditions.

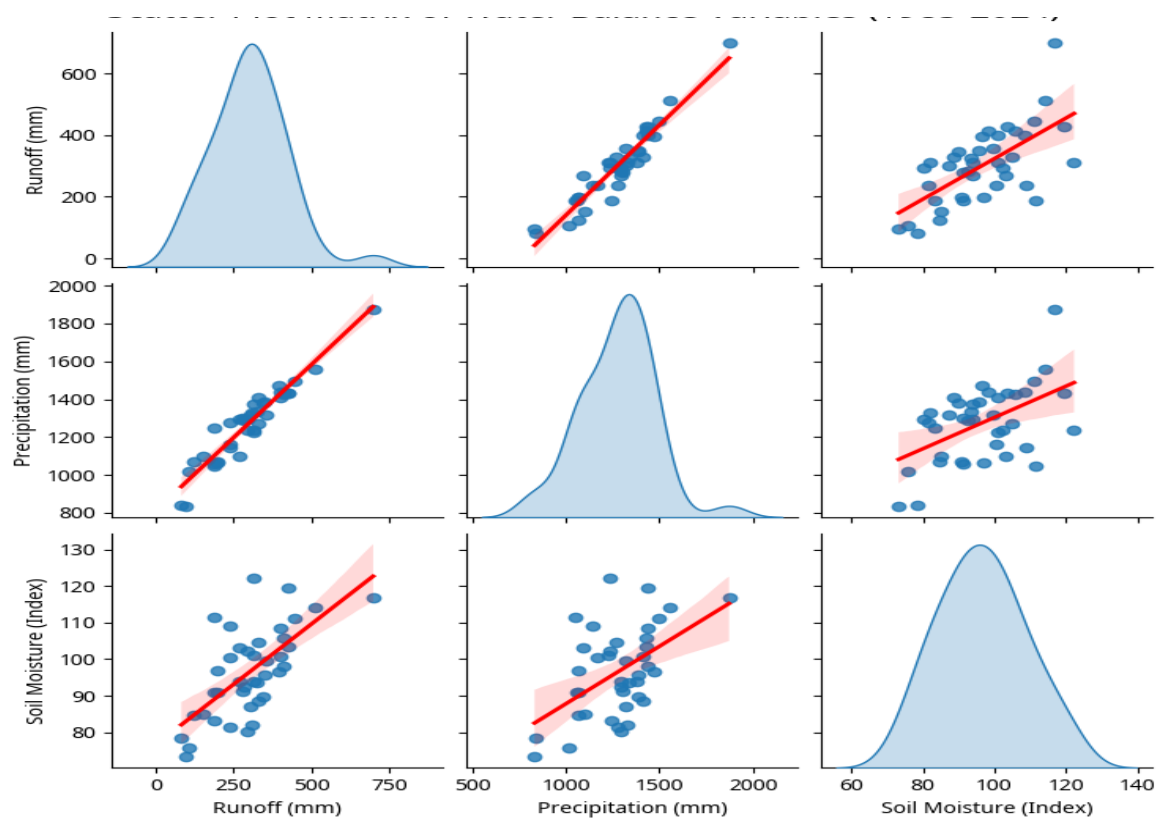

Figure 4: Scatter plot of the Pearson correlation matrix for runoff, soil moisture, and precipitation in decades

3.2 Implications for Water Availability in Mubi North, Adamawa State

The combined assessment of Mann–Kendall trends and Pearson correlation results reveals a complex but generally positive scenario for water availability in Mubi North over the study period. Notably, minimum temperatures have risen significantly, reflecting broader climate change, yet this increase coincides with significant gains in soil moisture and runoff, alongside a marked reduction in water deficit. Strong positive correlations among precipitation, soil moisture, and runoff highlight rainfall as a key driver of regional water resources.

Although the trend in total precipitation is not statistically significant, increases in soil moisture and runoff appear closely tied to both rainfall patterns and land use/land cover changes, which exert a direct influence on hydrological responses. For example, expansion of built-up areas tends to enhance surface runoff by limiting infiltration, whereas vegetated, agricultural, and bare lands promote percolation and soil water retention, shaping the observed soil moisture and runoff patterns (Neto & Souza, 2024; Han et al., 2019; Rodrigues et al., 2021).

The observed decline in water deficit is an important indicator of improved water security, particularly in a semi-arid region such as Mubi North, where groundwater availability remains a focus of ongoing studies aimed at sustainable urban and agricultural planning (Adamu et al., 2024; Shinggu et al., 2022). This enhanced water balance could support both farming activities and ecosystem functioning, which are highly sensitive to hydroclimatic variability (Shah et al., 2021; Dwivedi et al., 2024). Nevertheless, climate change impacts are often spatially heterogeneous and may increase the intensity of extreme events, making continuous monitoring essential (Terassi et al., 2024).

Future research should explore the underlying drivers of the observed increases in soil moisture and runoff, including detailed analyses of land cover changes and their interactions with climate variability. Understanding these long-term hydroclimatic trends is critical for ensuring sustainable water resources in Mubi North and other agrarian regions in Nigeria (Sasanya et al., 2024).

4 Conclusion

The findings of this study indicate that Mubi North has undergone substantial hydroclimatic changes between 1985 and 2024. These shifts are marked by significant warming, with minimum temperatures rising at +0.41 °C per decade, alongside increases in soil moisture (+3.4 mm/year), runoff (+1.9 mm/year), and vapour pressure (+0.12 kPa/decade), while water deficits have decreased (−2.6 mm/year), collectively suggesting improved water availability despite ongoing climate change. Strong correlations among precipitation, runoff, and soil moisture ($r = 0.756$–0.932) confirm rainfall as the primary driver of water resources, whereas non-significant trends in total precipitation and maximum temperature highlight the influence of land-surface dynamics on hydrological responses.

To maintain and enhance these hydrological gains, priority should be given to integrated land and water management strategies that balance runoff and soil moisture retention. Practices that conserve soil moisture, such as agroforestry, mulching, and cover cropping, can improve infiltration and reduce surface flow. Erosion control interventions—including contour bunds, check dams, and vegetative buffers—are also critical to minimize degradation caused by excessive runoff. Furthermore, climate-resilient agricultural planning is necessary to sustain land productivity under variable hydroclimatic conditions. Continuous monitoring of key hydroclimatic variables, combined with further research on land-use changes, is essential to validate long-term trends and support adaptive, evidence-based water management strategies in semi-arid regions of Nigeria.

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