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Observed Meteorological Trends and Climate Variability in the Lake Babati Catchment, Tanzania

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Abstract

Lake Babati is a shallow, semi-closed freshwater lake in Babati District, Manyara Region, north-eastern Tanzania, whose water storage is highly sensitive to climate variability. This study provides what is, to the authors' knowledge, the first systematic station-based analysis of observed meteorological trends and rainfall variability for the Lake Babati catchment, using records from Babati meteorological station over the period 2006-2025. The Mann-Kendall (MK) trend test, Sen's Slope Estimator, and the Standardized Precipitation Index (SPI) at 3-month and 12-month accumulation scales were applied to a complete dataset with no missing values. Mean annual rainfall was approximately 887 mm but showed extreme year-to-year variability, ranging from 600 mm to 1373 mm with a coefficient of variation of 22%. No statistically significant trend was detected in annual or seasonal precipitation, with all results interpreted as observed tendencies over the 2006-2025 period given the short record length. The monthly rainfall pattern reveals a single, nearly continuous wet season from October through May with no meaningful dry break in January and February, a pattern more accurately described as a modified unimodal regime than the conventional bimodal classification applied regionally. Annual maximum temperature (Tmax) and minimum temperature (Tmin) both showed weak, equally non-significant tendencies ($p = 0.721$ for both), with no meaningful change in the diurnal temperature range. SPI-12 analysis identified three multi-year drought periods (2006-2008, 2013-2016, and 2018-2019) and two wet spells (2020-2021 and 2024-2025). These findings establish a useful observational climate baseline for the catchment and provide the foundation for future hydrological modelling and water resources planning in Babati District.

Keywords

Climate Variability, Mann-Kendall Trend Test, Standardized Precipitation Index, Unimodal Rainfall, Lake Babati, Tanzania

1. Introduction

Freshwater lakes are among the most hydrologically sensitive systems on Earth. They collect the combined effect of all the water fluxes in a catchment, including precipitation, evapotranspiration, and surface runoff, and they respond quickly to changes in climate conditions (Dahal et al., 2025; Woolway et al., 2020). In shallow lake systems with limited or no outflow, which are common across the East African Rift Valley, this sensitivity is even greater because a small change in the water balance can produce a large change in lake level, surface area, and stored volume (Mbanguka et al., 2016; VanDeWeghe et al., 2022). East African lake systems also experience strong year-to-year changes in rainfall driven by two major climate systems: the El Niño-Southern Oscillation (ENSO), which originates in the Pacific Ocean, and the Indian Ocean Dipole (IOD). Both systems have a strong influence on the amount of rainfall received during the short rains season from October to December and the long rains season from March to May across the region (Palmer et al., 2023; Siderius et al., 2021). Since the 1980s, researchers have also documented a shift in East African rainfall seasonality, with the long rains weakening and the short rains intensifying in parts of the region, further complicating the hydroclimatic environment for lake water resources (Palmer et al., 2023).

Lake Babati is a shallow, semi-closed freshwater lake located at approximately 1345 m above mean sea level in Babati District, Manyara Region, north-central Tanzania. The lake supports wildlife of regional importance, including hippopotamus populations and artisanal fisheries, and contributes to tourism. It also provides a critical water supply for approximately 100,000 residents, making it a water body of significant socioeconomic importance (Katonge & Gayo, 2025; Mbanguka et al., 2016; Okwir et al., 2022). Historical records show dramatic and sometimes catastrophic changes in lake level, including major floods that inundated Babati town in 1964, 1979, and 1990, and periods of near-complete drying in the 2000s that threatened both water supply and aquatic ecosystems (Mbanguka et al., 2016; Peter et al., 2020; Sandström, 1995). These changes have been linked to a combination of natural climate variability and human-caused changes in the catchment, including deforestation, the expansion of farmland, and increasing water use (Katonge & Gayo, 2025).

The scientific literature contains useful information about the Lake Babati catchment and nearby areas. Mbanguka et al. (2016) assessed how sensitive the lake water balance is to hypothetical climate changes, and Okwir et al. (2022) examined surface water and groundwater interactions over several years. Nyembo et al. (2021) analyzed spatio-temporal climate variability in a nearby shallow lake catchment. However, to the authors' knowledge, no previous study has applied formal non-parametric trend detection methods or drought index analysis to an observed long-term meteorological station record specifically for the Lake Babati catchment. In addition, the rainfall seasonality at the local catchment scale has not previously been examined in detail against the regional bimodal classification commonly adopted from the broader northern Tanzania literature. This gap means there is currently no observational baseline for catchment climate variability that could be used to calibrate hydrological models or to design evidence-based water resources management strategies for Babati District.

This study addresses this gap through two specific objectives: first, to characterize observed trends and year-to-year variability in rainfall and temperature at Babati meteorological station over the period 2006-2025 using the Mann-Kendall trend test, Sen's Slope Estimator, and monthly climatological analysis; and second, to identify, characterize, and classify drought and wet episodes in the station record using the Standardized Precipitation Index at 3-month and 12-month accumulation scales. In doing so, this study produces, to the author's knowledge the first systematic station-based climate analysis for the Lake Babati catchment, which is a necessary starting point for calibrating hydrological models, designing water resources management strategies, and assessing the future impact of climate change on this important water body.

2. Study Area

2.1. Location

Lake Babati is situated in Babati District, Manyara Region, north-central Tanzania, within the East African Rift System (**Figure 1**). The lake surface lies at an elevation of approximately 1345 m above mean sea level and covers a surface area of approximately 7 - 8 km^2 under normal water level conditions, within a semi-closed catchment of approximately 355 km^2. It is a shallow water body with a historical mean depth of approximately 5 - 6 m when full (Mbanguka et al., 2016). Babati meteorological station used in this study is located at a separate elevation of approximately 999 m a.s.l. within the same district; these two elevation values refer to different features, the lake surface and the meteorological station site, and are not contradictory. Hydrologically, Lake Babati is semi-closed, meaning it does not have a permanent natural outflow. A man-made spillway at the north-eastern lake margin, built in 1964 to protect Babati town from flooding, is the only surface outflow pathway and is activated only during extreme high-water events (Sandström, 1995).

The catchment can be divided into two main physiographic zones based on geology and topography. The southern zone is dominated by ancient Precambrian basement rocks, characterized by steep slopes with thin and stony soils that drain surface runoff rapidly toward the lake from the Nou Forest highlands. The northern zone consists of younger volcanic rocks and ash soils of moderate depth, formed from historic volcanic activity in the East African Rift. Close to the lake, the lower catchment and lake margins are covered by black cotton clay soils, locally known as mbuga, and sandy alluvial deposits brought by seasonal streams. These soil types absorb water readily and allow significant lateral water movement below the surface toward the lake. Over the past century, the land cover of the catchment has changed considerably, shifting from predominantly natural woodland and forest to a mixture of smallholder rainfed farms, overgrazed rangelands, and growing peri-urban settlements around Babati town (Hongoa, 2014; Katonge & Gayo, 2025). This progressive loss of natural vegetation is expected to have affected catchment hydrology, including surface runoff generation and sediment delivery to the lake, although quantifying these effects is beyond the scope of this study.

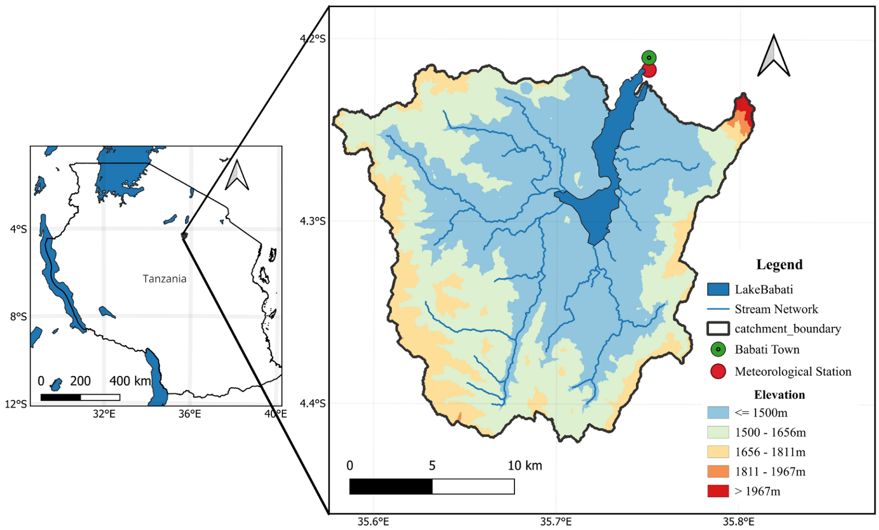

Figure 1. Location of Lake Babati and its catchment in Babati District, Manyara Region, Tanzania, showing the stream network, elevation gradient, meteorological station location, and Babati town.

2.2. Climate

The climate of the Lake Babati catchment is semi-arid and tropical, controlled primarily by the seasonal movement of the Inter-Tropical Convergence Zone (ITCZ), which is a belt of rising air and rainfall that shifts northward and southward across the equator throughout the year. At longer timescales, rainfall is further influenced by ENSO and the Indian Ocean Dipole (IOD), both of which can significantly increase or reduce seasonal rainfall from one year to another (Palmer et al., 2023; Siderius et al., 2021).

The catchment lies within the broader northern Tanzania region, which is generally described as having a bimodal rainfall pattern, meaning two separate rainy seasons: a short rains season from October to December and a long rains season from March to May, with a main dry season from June to September (Mbanguka et al., 2016; Nyembo et al., 2021). Although the region is generally classified within the bimodal rainfall belt of northern Tanzania, the local rainfall distribution may be influenced by the orographic character of the surrounding highlands, including the Nou Forest to the south and the Mbulu Plateau to the west. Mean annual rainfall at Babati averaged approximately 887 mm over the study period 2006-2025. This is considerably less than the potential evapotranspiration estimated at approximately 1300 mm per year (Mbanguka et al., 2016), creating a persistent water deficit that makes the lake water balance highly sensitive to year-to-year variability in rainfall amount and timing. Mean annual air temperature ranges from approximately 19˚C to 21˚C, with the warmest daytime temperatures occurring in October and November and the coolest in July. The lake receives catchment inflows from direct rainfall onto the lake surface and through seasonal stream flows from the surrounding catchment. Water leaves the lake mainly through evaporation from the open water surface. In most years there is no outflow and the lake functions as a closed basin, with the spillway at the north-eastern margin only becoming active during exceptionally high-water level events.

2.3. Socioeconomic Activities

Babati town serves as the administrative headquarters of Babati District with a population of approximately 100,000 people. The lake catchment supports multiple water-dependent livelihoods including smallholder irrigated agriculture, livestock watering, brick making using lake clay, and small-scale fishing. Water abstraction for domestic use and small-scale irrigation from both the lake and its tributary streams is increasing in line with population growth, placing additional pressure on catchment water resources (Hongoa, 2014; Katonge & Gayo, 2025).

3. Material and Methods

3.1. Data Sources and Data Quality

Daily and monthly records of precipitation, maximum temperature (Tmax), and minimum temperature (Tmin) were obtained from the Tanzania Meteorological Authority (TMA) for Babati meteorological station (station ID 9435030; **Figure 1**) covering the period 2006-2025. This is the primary and longest-operating meteorological station within the Lake Babati catchment. The station is located at approximately 999 m a.s.l, whereas the catchment spans approximately 355 km^2 with substantial elevation contrasts, from the lake margin to the Nou Forest highlands in the south and the Mbulu Plateau in the west (**Figure 1**); as a single-point record, the station cannot fully resolve this spatial heterogeneity, and catchment-scale conclusions drawn from it carry corresponding uncertainty, quantified below using gridded comparison products. The data were put through a systematic quality control process comprising four steps: first, checking that all values fall within the expected climatic range for a semi-arid highland station in northern Tanzania; second, checking that daily and monthly totals are internally consistent with each other; third, testing for homogeneity using the Standard Normal Homogeneity Test (SNHT) to detect any artificial shifts in the record caused by station changes; and fourth, identifying and counting any missing records.

The quality control assessment confirmed that the rainfall dataset is complete, with all 240 monthly records present across the 20-year study period and no missing values. No infilling or gap-filling was therefore required or applied. A total of 22 monthly rainfall records have a value of exactly zero, all occurring during the dry season months of July, August, and September, representing genuine observed values rather than missing data. August is the driest calendar month, recording zero rainfall in 12 out of 20 years (60% of the record). The Tmax and Tmin records are similarly complete, with all 240 monthly values present for every year from 2006 to 2025. All values fall within physically plausible ranges, and the SNHT test detected no statistically significant breakpoints in either the rainfall or temperature records, confirming that the station record is homogeneous over the study period. The 20-year record analyzed for this station is shorter than the 30-year baseline conventionally recommended for climatological normal (WMO, 2011), and it introduces uncertainty for both SPI-based drought severity classification, since the fitted Gamma distribution parameters are estimated from a comparatively short sample, and for Mann-Kendall trend detection, which has correspondingly reduced statistical power.

Before applying the Mann-Kendall trend test, each annual and seasonal time series was checked for serial autocorrelation using the lag-1 autocorrelation coefficient. No statistically significant autocorrelation was detected in any of the rainfall, Tmax, or Tmin series at the annual or seasonal scale, and the standard Mann-Kendall test was therefore applied to all series without variance correction. As an additional check on station representativeness, the monthly rainfall totals from Babati station were compared with CHIRPS v2.0 (0.05˚ spatial resolution; Funk et al., 2015) grid-cell values extracted for the station location, and against the spatial average of CHIRPS values across the full catchment. Agreement at the station-coincident grid cell was excellent (Pearson r = 0.9997; percent bias, PBIAS = −0.1%; Nash-Sutcliffe efficiency, NSE = 0.999), confirming that CHIRPS closely re-produces the station record at the point scale. Agreement remained strong but weakened when CHIRPS values were averaged across the full catchment (r = 0.9826; PBIAS = −15.5%; NSE = 0.929), with the catchment-wide average systematically underestimating the station record by approximately 15%, consistent with the station's position relative to the catchment's orographic gradient. A parallel comparison using ERA5-land temperature fields showed a similar but more pronounced pattern: agreement at the nearest grid cell (NSE = 0.653 for Tmax; 0.732 for Tmin) was notably stronger than at the catchment average (NSE = 0.233 for Tmax; 0.569 for Tmin), indicating that temperature is more spatially heterogeneous across the catchment's elevation gradient than rainfall. Together, these comparisons confirm that the Babati station record represents interannual rainfall variability well at point scale, but that catchment-wide magnitudes, especially for temperature, should be interpreted with the caution noted above.

3.2. Mann-Kendall Trend Test

Year-to-year trends in annual records of rainfall, Tmax, and Tmin, and in seasonal records of rainfall, were assessed using the non-parametric Mann-Kendall trend test (Mann, 1945; Kendall, 1975). This test is widely used in hydrology and climate studies because it does not assume any particular shape of data distribution and is not sensitive to extreme values or skewed data, both of which are common characteristics of rainfall records in semi-arid areas (Güçlü, 2018; WMO, 2011). The MK test was applied to annual aggregated values (n = 20 annual data points per series), consistent with the objective of detecting year-to-year tendencies in rainfall and temperature. The test statistic S is calculated as:

$$S = \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} sgn\left(x_k - x_j\right) \tag{1}$$

where n is the number of observations, x_j and x_k are values at two different points in time, and sgn is a sign function defined as:

$$sgn(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \tag{2}$$

The variance of S, adjusted for repeated values in the data, is given as:

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

The standardized test statistic Z is calculated as:

$$Z = \begin{cases} (S-1)\big/\sqrt{Var(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ (S+1)\big/\sqrt{Var(S)} & \text{if } S < 0 \end{cases} \tag{4}$$

A trend is considered statistically significant when p is less than 0.05 using a two-tailed test. The four seasons analyzed were January-February (JF), March-April-May (MAM), June-July-August-September (JJAS), and October-November-December (OND), following standard East African climatological practice (Nyembo et al., 2021).

3.3. Sen's Slope Estimator

The magnitude of each observed tendency was estimated using Sen (1968) non-parametric slope method, which is calculated as the median of all possible pairwise slopes between data points:

$$Q = median\left(\frac{x_j - x_k}{j-k}\right) \text{ for all pairs where } j > k \tag{5}$$

This gives a robust estimate of the rate of change per year that is not sensitive to extreme values. The result is expressed in mm per year for rainfall and degrees Celsius per year for temperature. Confidence intervals were computed at the 95% level following Sen (1968). All 95% confidence intervals computed for the variables in this study cross zero, confirming the absence of any statistically detectable directional tendency for all variables assessed.

3.4. Standardized Precipitation Index (SPI)

Temporal variability in rainfall and the identification and classification of drought and wet episodes were quantified using the Standardized Precipitation Index (SPI; McKee et al., 1993). SPI was calculated at two accumulation scales: SPI-3 (3-month), reflecting seasonal moisture conditions; and SPI-12 (12-month), reflecting longer-term hydrological conditions relevant to lake storage and groundwater recharge. SPI values were computed using an Excel-based implementation following the computational procedure of McKee et al. (1993). For each accumulation scale *k*, the *k*-month accumulated rainfall was computed for each calendar month. A two-parameter Gamma probability distribution was fitted separately to the non-zero accumulated values for each of the 12 calendar months, accommodating the strong seasonal non-stationarity in rainfall variance:

$$g(x) = \frac{x^{\alpha-1} e^{\frac{-x}{\beta}}}{\beta^{\alpha}\Gamma(\alpha)} \text{ for } x > 0 \tag{6}$$

where α and β are shape and scale parameters respectively estimated using maximum likelihood, and $\Gamma(\alpha)$ is the Gamma function. The initial $k - 1$ months of each accumulation scale were treated as missing and excluded from analysis, as is standard practice when insufficient prior months are available for accumulation.

The probability of zero rainfall, which occurs regularly in the dry season months at Babati station, was handled through a mixed distribution, and the resulting cumulative probabilities were converted to standard normal values using the probit transformation

$$H(x) = q + (1-q)G(x) \tag{7}$$

where q is the observed probability of zero rainfall, estimated from the frequency of zero values, and $G(x)$ is the fitted Gamma cumulative distribution function for non-zero rainfall totals. The resulting probabilities $H(x)$ were then converted to standard normal values using the probit transformation to produce the SPI.

$$\text{SPI} = \Phi^{-1}\left[H(x)\right] \tag{8}$$

where Φ^{-1} is the inverse cumulative distribution function of the standard normal distribution. The drought and wet classification thresholds follow McKee et al. (1993) as shown in **Table 1**. Drought events were defined as consecutive months with SPI below −1.0. SPI categories based on a 20-year record should be interpreted as indicative of relative severity within the available data period rather than absolute climatological classifications.

Table 1. Standardized precipitation index (SPI) classification thresholds after McKee et al. (1993).

SPI Value Range	Category	Hydrological Class
SPI ≥ 2.0	Extremely wet	Wet
1.5 ≤ SPI < 2.0	Very wet	Wet
1.0 ≤ SPI < 1.5	Moderately wet	Wet
−1.0 < SPI < 1.0	Near normal	Normal
−1.5 < SPI ≤ −1.0	Moderately dry	Drought
−2.0 < SPI ≤ −1.5	Severely dry	Drought
SPI ≤ −2.0	Extremely dry	Drought

4. Results

4.1. Monthly Climatology and Seasonal Rainfall Distribution

The mean monthly climatology at Babati station over 2006-2025 is shown in Figure 2. Mean monthly rainfall exhibits a clear seasonal cycle characterized by a single uninterrupted period of elevated rainfall extending from October through May and a well-defined period of near-zero rainfall from June through September. The highest mean monthly rainfall values are recorded in March at approximately 194 mm and April at approximately 177 mm, followed by December at approximately 128 mm, January at approximately 123 mm, and February at approximately 88 mm. The mean February value of approximately 88 mm is climatologically indistinguishable from November at approximately 87 mm, which falls unambiguously within the recognized wet season. Mean monthly rainfall does not fall below 87 mm at any point between October and April, confirming the absence of a dry interruption within this period. The driest calendar month is August, with a mean of less than 1 mm and zero rainfall in 60% of years in the record.

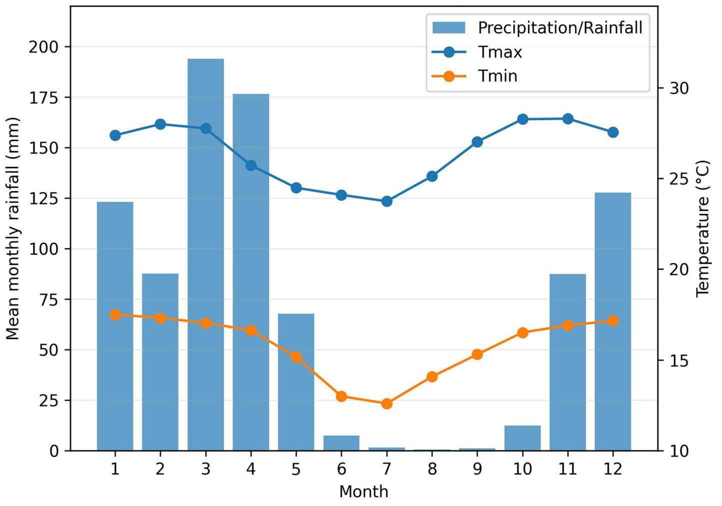

Figure 2. Mean monthly climatology at Babati meteorological station (2006-2025). Bars show mean monthly rainfall (left axis); blue circles show mean monthly Tmax and orange circles show mean monthly Tmin (right axis).

Mean monthly Tmax peaks in November at approximately 28.3˚C, closely followed by October at approximately 28.3˚C, and reaches its annual minimum in July at approximately 23.7˚C, giving an annual range of approximately 4.6˚C. Mean monthly Tmin is highest in January at approximately 17.5˚C and lowest in July at approximately 12.6˚C, giving an annual range of approximately 4.9˚C. The diurnal temperature range (DTR), the difference between mean monthly Tmax and Tmin, is widest in September and October at approximately 11.7˚C - 11.8˚C and narrowest in April at approximately 9.1˚C (**Figure 2**).

The seasonal rainfall breakdown (**Figure 3**) confirms that the MAM long rains season contributes the largest mean seasonal total at approximately 438 mm per season (range: 304 - 735 mm; CV = 24%), followed by OND at approximately 228 mm per season (range: 71 - 529 mm; CV = 55%) and the JF transitional period at approximately 211 mm per season (CV = 43%). The JJAS dry season contributes negligible rainfall in all years (mean approximately 11 mm). The markedly higher CV of OND (55%) compared to MAM (24%) confirms that the short rains are substantially more variable from one year to the next than the long rains. Combining the MAM, OND, and JF seasonal means (877 mm) against the residual JJAS contribution of approximately 11mm shows that approximately 99% of mean annual rainfall (877 of 887 mm) fall within the October-May window, providing direct quantitative support for the modified unimodal classification discussed in Section 5.1.

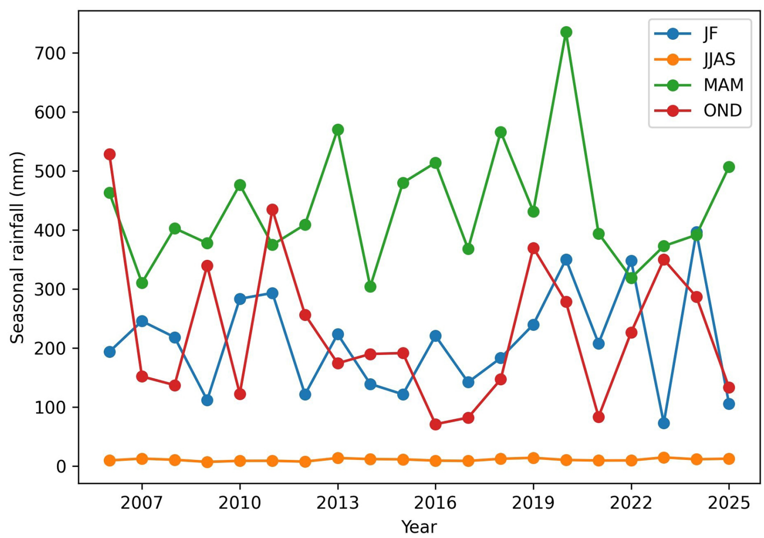

Figure 3. Seasonal rainfall totals at Babati station (2006-2025) for JF (blue), JJAS (orange), MAM (green), and OND (red). JJAS totals are consistently near-zero throughout the record.

4.2. Annual and Seasonal Rainfall

Annual rainfall at Babati station averaged approximately 887 mm over 2006-2025, with extreme year-to-year variability (**Figure 4**). Observed annual totals ranged from approximately 600 mm in 2017 to approximately 1373 mm in 2020, a more than two-fold range yielding a coefficient of variation of 22%. The MK test applied to annual aggregated values (n = 20) returned S = +6, Z = +0.162, and p = 0.871, indicating a very weak positive tendency that is not statistically significant at α = 0.05. Sen's slope was +1.76 mm per year (95% CI: −14.73 to +17.10 mm per year). At the seasonal scale, neither the MAM series (S = +14; Z = +0.422; p = 0.673; Sen's slope = +1.70 mm per year) nor the OND series (S = −10; Z = −0.292; p = 0.770; Sen's slope = −3.19 mm per year) nor the JF series (S = +10; Z = +0.292; p = 0.770; Sen's slope = +1.34 mm per year) showed statistically significant tendencies (Table 2). The JJAS series was not assessed given the near-zero rainfall throughout the record. All 95% confidence intervals for Sen's slope cross zero, consistent with the non-significant p-values. These results should be interpreted as observed tendencies over the 2006-2025 period; the 20-year record is insufficient for reliable long-term trend detection at this high-variance site (WMO, 2011).

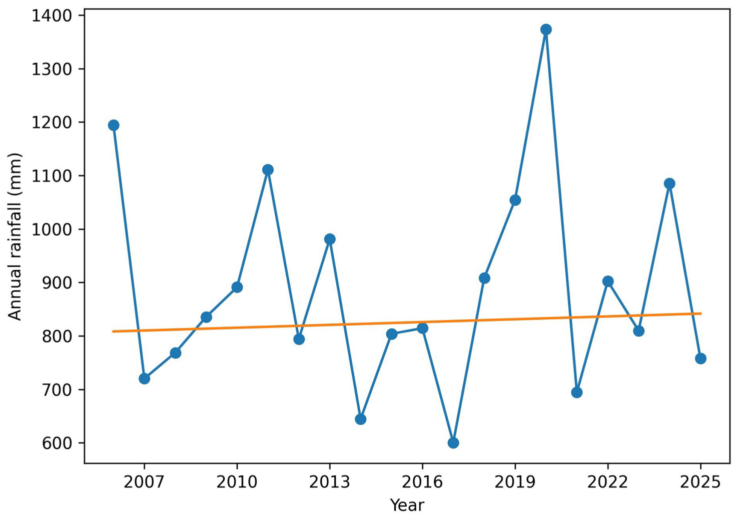

Figure 4. Annual rainfall totals at Babati station (2006-2025) with Sen's trend line (orange). The weak positive tendency (Sen's slope +1.76 mm per year; p = 0.871) is not statistically significant and is dominated by the extreme year-to-year variability (CV = 22%).

Table 2. Mann-Kendall trend test results and Sen's slope estimates for annual and seasonal rainfall and temperature at Babati station (2006-2025), computed from n = 20 annual aggregated values per series. All results represent observed tendencies over the study period only. ns = not significant at α = 0.05. All 95% CIs cross zero.

Variable	MK S	Z	p-value	Sen's Slope	Direction
Annual rainfall ($mm \cdot yr^{-1}$)	+6	+0.16	0.871	+1.8 $mm \cdot yr^{-1}$	Increase (ns)
JF rainfall ($mm \cdot yr^{-1}$)	+10	+0.29	0.770	+1.3 $mm \cdot yr^{-1}$	Increase (ns)
MAM rainfall ($mm \cdot yr^{-1}$)	+14	+0.42	0.673	+1.7 $mm \cdot yr^{-1}$	Increase (ns)
OND rainfall ($mm \cdot yr^{-1}$)	−10	−0.29	0.770	−3.2 $mm \cdot yr^{-1}$	Decrease (ns)
Annual Tmax (˚$C \cdot yr^{-1}$)	−12	−0.36	0.721	−0.008˚$C \cdot yr^{-1}$	Decrease (ns)
Annual Tmin (˚$C \cdot yr^{-1}$)	+12	+0.36	0.721	+0.006˚$C \cdot yr^{-1}$	Increase (ns)

4.3. Annual and Seasonal Temperature Trends

Annual mean Tmax ranged from approximately 25.18˚C in 2007 to approximately 27.66˚C in 2009, with a period mean of approximately 26.45˚C (**Figure 5**). The MK test returned $S = -12$, $Z = -0.357$, and $p = 0.721$, indicating a weak declining tendency that is not statistically significant. Sen's slope was −0.0076˚C per year (95% CI: −0.0757 to +0.0443˚C per year). Annual mean Tmin ranged from approximately 14.93˚C in 2018 to approximately 16.45˚C in 2009, with a period mean of approximately 15.77˚C (**Figure 6**). The MK test returned $S = +12$, $Z = +0.357$, and $p = 0.721$, indicating a weak positive tendency that is not statistically significant. Sen's slope was +0.0059˚C per year (95% CI: −0.0282 to +0.0485˚C per year). The MK statistics for Tmax and Tmin are equal in magnitude but opposite in sign ($S = -12$ and $S = +12$ respectively), yielding identical p-values of 0.721 and indicating symmetrically weak, equally non-significant tendencies over the study period. The mean annual DTR for the first five years of the record (2006-2010) and the most recent five years (2021-2025) are both approximately 10.3˚C, confirming no meaningful change in the diurnal temperature range.

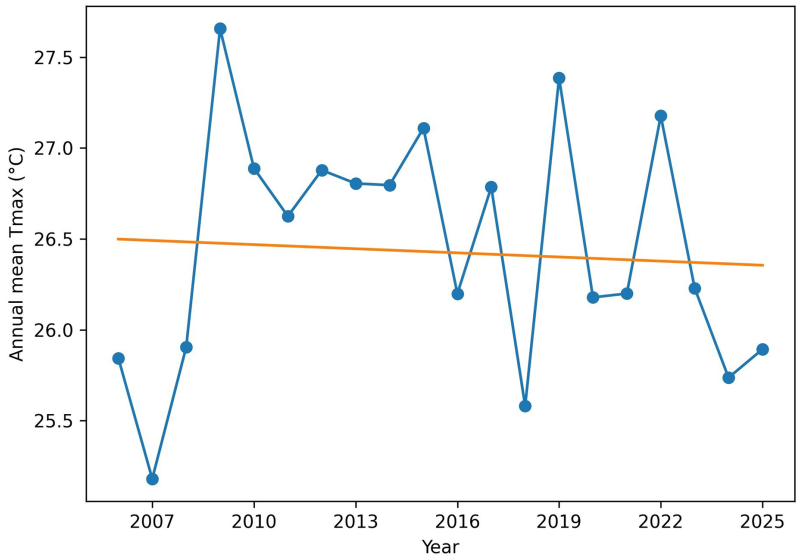

Figure 5. Annual mean Tmax at Babati station (2006-2025) with Sen's trend line (orange). The weak declining tendency (Sen's slope = −0.0076˚C per year; $p = 0.721$) is not statistically significant.

Annual mean Tmin ranged from approximately 14.93˚C in 2018 to approximately 16.45˚C in 2009, with a period mean of approximately 15.77˚C as shown in **Figure 6**. The Mann-Kendall test returned $S = +12$, $Z = +0.36$, and $p = 0.721$, showing a weak positive tendency that is not statistically significant. Sen's slope was +0.006˚C per year (**Table 2**). The MK statistics for Tmax and Tmin are equal in magnitude but opposite in sign, indicating that the two series show symmetrically opposite, equally weak, and equally non-significant tendencies over the study period. The combined direction of these two tendencies, with Tmax declining slightly and Tmin rising slightly, produces a marginal narrowing of the mean annual diurnal temperature range over the study period. The early part of the record shows a mean annual DTR of approximately 10.3˚C for 2006-2010, and the most recent years show a comparable value of approximately 10.3˚C for 2021-2025, indicating that the narrowing signal is very small and statistically indistinguishable from zero.

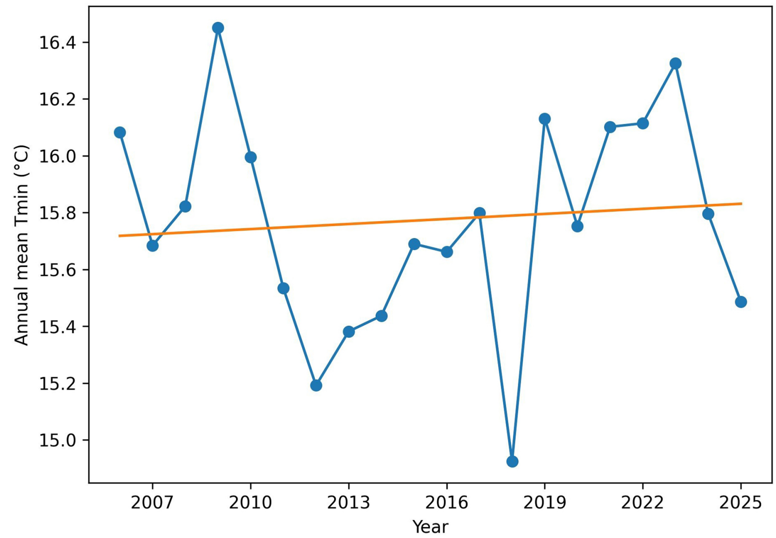

Figure 6. Annual mean Tmin at Babati station (2006-2025) with Sen's trend line (orange). The weak positive tendency (Sen's slope = +0.0059˚C per year; $p = 0.721$) is not statistically significant.

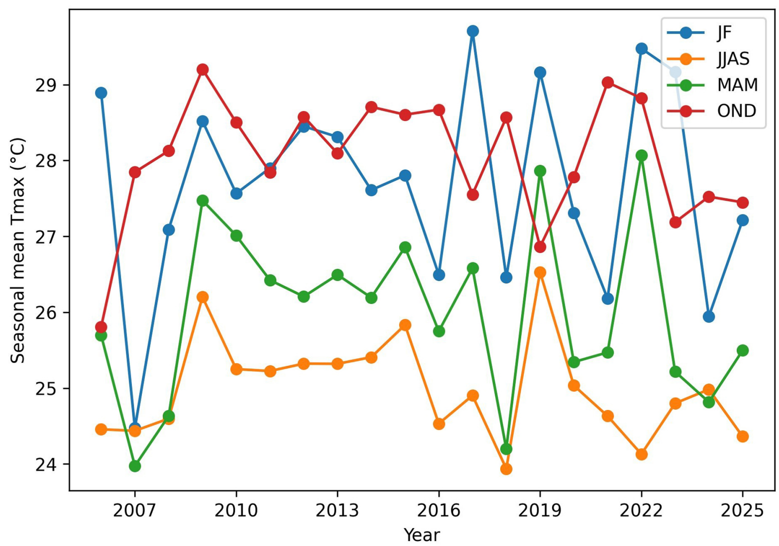

Figure 7. Seasonal mean Tmax at Babati station (2006-2025) for JF (blue), JJAS (orange), MAM (green), and OND (red).

Seasonal Tmax (**Figure 7**) shows OND is the warmest season for daytime temperatures at a mean of approximately 28.0˚C, followed by JF at approximately 27.7˚C, MAM at approximately 26.0˚C, and JJAS at approximately 25.0˚C.

Seasonal Tmin (**Figure 8**) shows JF as the warmest season for nighttime temperatures at a mean of approximately 17.4˚C, while JJAS records the lowest mean at approximately 13.8˚C. MAM and OND Tmin fall in the intermediate range of approximately 16.3˚C and 16.9˚C respectively.

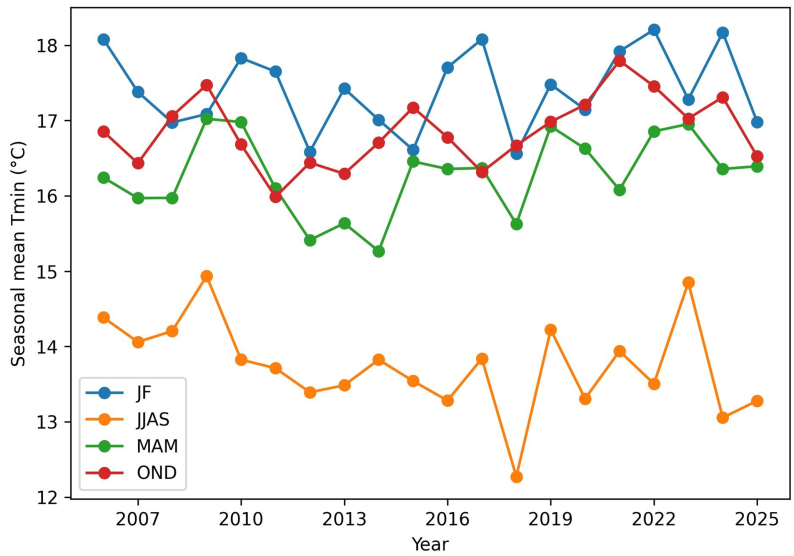

Figure 8. Seasonal mean Tmin at Babati station (2006-2025) for JF (blue), JJAS (orange), MAM (green), and OND (red). JJAS consistently records the lowest night-time temperatures in every year.

4.4. Drought and Wet Episode Characterization: SPI-3 and SPI-12

4.4.1. SPI-3: Seasonal Moisture Variability

SPI-3 at Babati station over 2006-2025 (**Figure 9**, upper panel) switches frequently between dry and wet categories, reflecting the strong year-to-year variability in both MAM and OND rainfall documented in Section 4.2. SPI-3 reached extreme drought values below −2.0 on multiple occasions during 2013-2014, coinciding with severely below-average long rains visible in **Figure 3**. An extreme wet event (SPI-3 above +2.0) is recorded during 2017-2018, corresponding to unusually high OND rainfall. The record shows no persistent directional shift, consistent with the non-significant rainfall tendencies in **Table 3**.

4.4.2. SPI-12: Multi-Year Drought and Wet Cycles

SPI-12 (**Figure 9**, lower panel) reveals three distinct multi-year drought periods and two wet spells (**Table 3**). The first drought period spans approximately 2006-2008, with SPI-12 persistently below −1.0 and reaching approximately −1.7 to −2.0. The second and most prolonged drought period extends from approximately 2013 to 2016, with SPI-12 remaining below −1.5 for several consecutive months and reaching approximately −2.0 in 2013-2014, representing the most severe period of water stress in the record. A third drought period occurred during 2018-2019 (SPI-12 ≈ −1.5), following the minimum annual rainfall of approximately 600 mm in 2017. After 2019, SPI-12 rose sharply to approximately +2.6 during 2020-2021, the highest positive value in the record, corresponding to the maximum annual rainfall of approximately 1373 mm in 2020. A second, more moderate positive anomaly is evident in 2024-2025 (SPI-12 approaching but not consistently exceeding +1.0), classified as near-normal to borderline moderately wet. SPI categories based on a 20-year record are indicative of relative severity within the available data period rather than absolute climatological classifications.

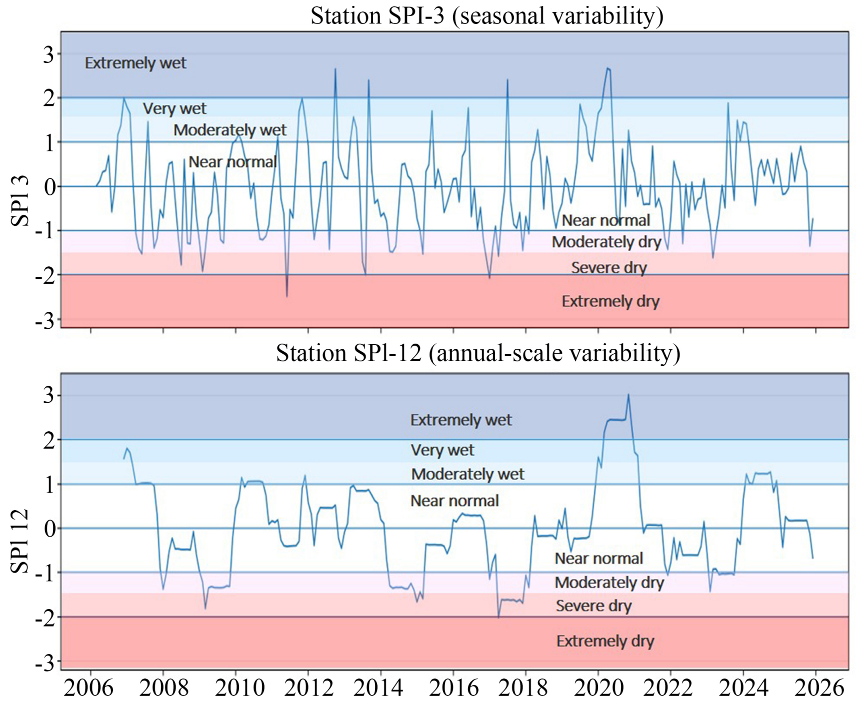

Figure 9. SPI at 3-month (upper panel) and 12-month (lower panel) accumulation scales for Babati station (2006-2025). Threshold lines at SPI = ±1.0, ±1.5, and ±2.0 follow McKee et al. (1993).

Table 3. Summary of major drought and wet periods from SPI-12 analysis at Babati station (2006-2025). The column 'Possible regional association' lists large-scale climate modes consistent with these periods in the regional literature; ENSO and IOD indices were not directly analyzed in this study.

Event	Period	Duration (months)	Peak SPI-12	Category	Possible regional association (literature-based)
Drought 1	2006-2008	~24	≈−1.7 to -2.0	Severe to Extreme	Weak MAM/OND; consistent with La Niña conditions (Palmer et al., 2023)
Drought 2	2013-2016	~36	≈−2.0	Extreme	Consistent with IOD (−) and La Niña phases reported for East Africa (Palmer et al., 2023)
Drought 3	2018-2019	~18	≈−1.5	Severe	Below-average MAM 2017-2018 (station observation)
Wet Spell 1	2020-2021	~18	≈+2.6	Extremely wet	Consistent with IOD (+) and La Niña phases reported for East Africa (Palmer et al., 2023)
Wet Spell 2	2024-2025	~10	≈+0.8 to +1.0	Near-normal to borderline mod. wet	Enhanced OND 2024 (station observation)

5. Discussion

5.1. Rainfall Seasonality: A Modified Unimodal Regime and Its Hydrological Implications

The monthly climatology in Section 4.1 reveals a rainfall distribution that does not match the conventional bimodal classification commonly applied to northern Tanzania (Mbanguka et al., 2016; Okwir et al., 2022). When examined from its hydrological starting point in October, the Babati station record shows a single, continuous wet season extending from October through May, with mean monthly rainfall remaining at or above 87 mm throughout. The January-February period, which in the bimodal pattern should represent a dry spell separating the OND and MAM seasons, records mean monthly values of approximately 123 mm and 88 mm respectively. These values are climatologically indistinguishable from November at approximately 87 mm, which is unambiguously part of the active wet season. The absence of a January-February trough in the monthly record means there is no empirical basis, within this station data, for treating OND and MAM as two hydrologically separate seasons. This conclusion is further supported by the fact that the October-May window accounts for approximately 99% of mean annual rainfall (Section 4.1), leaving only a negligible residual outside the wet season.

The physical mechanism underlying this local departure from the regional bimodal archetype is likely the orographic forcing of the surrounding highland terrain, including the Nou Forest highlands to the south and the Mbulu Plateau to the west. These highlands may sustain convective rainfall generation even as the large-scale ITCZ retreats southward following the OND passage, maintaining significant rainfall through January and February. This is consistent with mesoscale rainfall dynamics documented across the East African Rift interior (Palmer et al., 2023) and explains why Nyembo et al. (2021) identified the Babati area as a transitional climatic zone with both unimodal and bimodal characteristics. The rainfall pattern at Babati is therefore more accurately described as a modified unimodal regime, with one continuous wet season from October through May (approximately eight months) and one clear dry season from June to September (approximately four months).

This distinction carries direct implications for hydrological modelling. Model structures that impose a bimodal forcing framework with a January-February dry gap will misrepresent the continuity of soil moisture recharge and streamflow generation during this period, introducing systematic errors in simulated inflow volumes and lake storage trajectories. The OND and MAM groupings are nonetheless retained for the formal trend analysis in this study because these two atmospheric pulses retain distinct large-scale drivers and markedly different interannual variability (CV: 55% for OND vs. 24% for MAM), which are meaningful for understanding year-to-year variability even if they merge into a single hydrological wet season at the local catchment scale.

5.2. Dominance of Interannual Variability over Observed Tendencies in Rainfall

The non-significant MK results for all rainfall series (annual $p = 0.871$; MAM $p = 0.673$; OND $p = 0.770$; JF $p = 0.770$) confirm that no detectable directional tendency exists in the Babati station record over 2006-2025. Year-to-year variability is the dominant control on catchment water availability. The coefficient of variation of 22% and the more than two-fold range in annual totals (600 - 1373 mm) represent variability sufficient to shift Lake Babati between near-desiccation and overflow without any superimposed directional change. Mbanguka et al. (2016) demonstrated that annual precipitation changes of approximately ±100 mm are sufficient to drive such extreme transitions in lake storage. The 20-year record is likely too short to detect a tendency of the observed Sen's slope magnitude at adequate statistical power; formal analysis suggests approximately 35 - 40 years of data would be required for reliable detection at this site (WMO, 2011). The lack of a detectable tendency should therefore not be interpreted as evidence that long-term change is absent.

The absence of a detectable tendency at Babati is consistent with the mixed picture of rainfall tendencies across interior northern Tanzania, where Nyembo et al. (2021) and Hersi et al. (2023) also report non-significant or spatially variable results at station scale. The positive but non-significant Sen's slopes for both annual and MAM rainfall provide no evidence of progressive drying over the observation period, contrasting with the documented regional weakening of MAM long rains in coastal East Africa since the 1980s (Palmer et al., 2023).

5.3. Temperature Tendencies and Their Possible Hydrological Implications

The MK results for Tmax and Tmin are symmetric: both return $S = \pm 12$, $Z = \pm 0.357$, and $p = 0.721$, indicating equally weak and equally non-significant tendencies in opposite directions. Neither variable shows any statistically detectable directional change over the study period. The mean annual DTR remained unchanged at approximately 10.3˚C between the first and last five years of the record, confirming no meaningful narrowing of the diurnal temperature range. These results are fully consistent with the short record length and the strong influence of the post-2019 wet spell on the temperature record: increased cloud cover and soil moisture during wet periods are physically expected to suppress Tmax while slightly elevating Tmin through reduced nocturnal radiative cooling (Woolway et al., 2020), producing the opposite-sign tendencies observed without any underlying long-term warming or cooling signal.

If the weak directional tendencies observed in Tmax and Tmin were to strengthen or persist over longer timescales, a sustained increase in Tmin would be expected to elevate actual evapotranspiration across the catchment and open water evaporation from the lake surface, consistent with the sensitivity relationships of Mbanguka et al. (2016). However, this remains a physical inference from the direction of the observed tendency and existing literature, not a demonstrated finding of this study. Direct measurement of actual evapotranspiration and lake surface evaporation, currently absent from the observational network, would be required to test this inference.

5.4. SPI-Identified Drought and Wet Spells: Possible Associations with Regional Climate Patterns and Lake Conditions

The associations discussed below between observed SPI-12 anomalies and large-scale climate drivers are proposed as literature-based hypothesis rather than demonstrated attributions, since ENSO and IOD indices were not directly analyzed in this study. The three multi-year drought periods identified by SPI-12 analysis correspond closely in timing to periods of lake level decline and water stress reported in the literature for Lake Babati. The most severe period from 2013 to 2016 (SPI-12 ≈ −2.0; duration approximately 36 months) coincides with lake shrinkage, reduced fishery yields, and water supply stress reported by Peter et al. (2020). During this period, large parts of East Africa experienced below-average rainfall, which Palmer et al. (2023) attribute to a combination of negative IOD conditions and La Niña forcing. This broader regional context is consistent with the SPI-12 record at Babati, though it should be noted that ENSO and IOD indices were not directly analyzed in this study, and the attribution of the Babati rainfall anomaly to these drivers is inferred from regional literature rather than directly demonstrated here.

The Drought 1 period from 2006 to 2008 occurred at a time when Lake Babati had not yet recovered from the near-complete drying of the early 2000s documented by Okwir et al. (2022), and continuation of below-average rainfall during this period likely maintained critically low lake levels. The 2020-2021 extreme wet spell (SPI-12 ≈ +2.6) followed record annual rainfall of approximately 1373 mm in 2020. This period coincides with a strongly positive IOD event and La Niña conditions reported in the regional literature (Palmer et al., 2023), consistent with a literature-based hypothesis linking the wet spell to these large-scale drivers rather than a directly demonstrated attribution within this study. Based on the nonlinear lake storage sensitivity demonstrated by Mbanguka et al. (2016), this rainfall total would be expected to have driven lake levels to near or above overflow conditions, creating potential flood risk for Babati town. Direct lake level measurements from this period are not available in this study to confirm this. The contrast between the severe 2013-2016 drought and the extreme 2020-2021 wet spell within less than a decade demonstrates that water resources planning for Babati District must simultaneously prepare for both types of extreme.

5.5. Implications for Hydrological Modelling and Water Resources Management

The primary hydroclimatic risk to water resources in Lake Babati is the extreme magnitude of year-to-year variability, amplified by the nonlinear sensitivity of the shallow lake water balance, rather than any detected directional tendency in rainfall or temperature. Three multi-year drought periods and two extreme wet spells occurring over just 20 years mean that Babati District must plan for the full range of hydroclimatic extremes within any 10-year planning window. The modified unimodal rainfall characterization established in Section 5.1 means that SWAT or other physically based models should be calibrated with a continuous October-May wet season forcing rather than a bimodal structure with a January-February gap. Scenario-based modelling using bias-corrected CMIP6 projections, anchored to the observational baseline established here, is recommended as the next research step. Future observational investments should prioritize additional weather stations within the catchment, reinstatement of streamflow gauges, installation of a lake level gauge with telemetric data transmission, and deployment of evapotranspiration sensors.

6. Conclusion

To the authors' knowledge, this is the first systematic station-based climate analysis for the Lake Babati catchment, Tanzania, covering 2006-2025. The complete and homogeneous Babati station record reveals five principal findings. First, the monthly rainfall pattern is best described as a modified unimodal regime, with one continuous wet season from October through May rather than the two-season bimodal pattern commonly assumed for the region. Second, mean annual rainfall was approximately 887 mm but showed extreme interannual variability (CV = 22%), with no statistically significant directional tendency detected. All results represent observed tendencies over the study period rather than long-term climate signals. Third, annual Tmax and Tmin both showed weak, equally non-significant tendencies (p = 0.721); no meaningful change in the diurnal temperature range was detected. Fourth, SPI-12 identified three drought periods, the most severe spanning 2013-2016, and two wet spells, the most extreme in 2020-2021, which correspond in timing to lake shrinkage and high-water conditions reported in the literature. Fifth, interannual variability, not a directional trend, is the dominant control on catchment water availability. Three limitations must be acknowledged: the analysis relies on a single station that is at approximately 999 m a.s.l., and does not fully capture the elevation contrasts across the 355 km^2 catchment, introducing uncertainty for catchment-scale magnitudes as quantified through the CHIRPS and ERA5-Land comparisons in Section 3.1; and the analysis excludes direct measurements of lake level, streamflow, and evapotranspiration; and the 20-year record length constrains both trend detection power and the reliability of SPI-based drought severity classification, as discussed in Section 3.1 and 5.2.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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