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Research Article

Variability and Trends of Rainfall and Associated Extreme Indices in the Lake Kivu Climatological Zone, Rwanda.

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Abstract

Assessing the spatio-temporal variability and trends of climate variables and associated extreme events is fundamental for effective climate change mitigation and adaptation strategies. This study investigated the variability and trends in rainfall and nine extreme rainfall indices within the Lake Kivu climatological zone of Rwanda, utilizing data from the Rwanda Meteorology Agency for the period 1983-2021. Variability was quantified using the Coefficient of Variation, while trends and their magnitudes were determined by the Modified Mann-Kendall test and the Theil-Sen estimator, respectively. Results reveal a complex north-south gradient in both seasonal and annual rainfall distribution, largely influenced by topography. Seasonal rainfall ranged from 82 mm to 802 mm, while annual rainfall fluctuated between 1200 mm and 2200 mm. Regarding variability, the January-February (JF) season exhibited low variation (20-40%) in the southwestern edge but high variation (100-120%) in north-central areas. For March-May (MAM), higher variation (80-120%) was noted in a large eastern spot between the north and central regions, while low variability (20-40%) persisted in the southwestern edge. During June-August (JJA), most areas experienced low to moderate variability (20-80%), with a small central-north area showing higher variability (100-120%). The September-December (SOND) season was characterized by widespread moderately high variability (80-100%), with the north-central area again displaying the highest variation (100-120%). Extreme rainfall indices also demonstrated high variability, ranging from 9.43% to 182%. Overall, both total rainfall and its associated extreme indices displayed complex increasing trends, attributed to topographical variations. These findings provide critical evidence to guide further research, inform policy, and support decision-making in developing effective climate change mitigation and adaptation strategies within the Lake Kivu climatological zone.

Keywords : Extreme indices, Lake Kivu climate zone, Rainfall Variability, Trends, spatio-temporal analysis.

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INTRODUCTION

Globally, the climate has changed and continues to change [1,70-73].Climate change is a global issue resulting from different human activities, leading to changes in hydro climatic variables such as rainfall, riverine flow, and extreme hydro- climatic events [2,74-76].Climate change is linked with greenhouse gases, which have been responsible for an increase of 1.1 °C on Earth's surface from the pre-industrial era. Recently, due to this phenomenon, IPCC is predicting the extreme hydro-meteorological occurrences across numerous zones comprising North America, Europe, and Asia, characterized by water-related disasters [3].

In the last decades, it had been observed an increase in intensity, frequency and extent of natural disasters and environmental degradations in different places worldwide associated with climate change and variability [4], a typical example is found in the sixth report of International Panel on Climate Change (IPCC) which stated that a global worming of 1.09 o C has been observed from the Industrial Revolution period up to the present leading to climate change and variability[5].

This phenomenon is mainly attributed to anthropogenic activities, and it will continue with the projection to reach an average of 1.5 o C by 2040 without taking into consideration the rate of greenhouse gas emissions rise or fall in the incoming decade[6]. Climate change and variability are associated with climate extremes, and climate change will modify the frequency, intensity, and character of extreme events in the future[7]. According to the Expert Team on Climate Change Detection and Indices (ETCCDI), there are 27 climate extreme indices, including 16 indices in temperature and 11 indices in precipitation (rainfall). These indices can be divided into four categories i.e:1. Absolute indices: hottest day per year (TXx) and coldest night per year (TNn),...; 2. Annual daily (RX1day) per year or five days maximum (RX5day) per year,...;3. Threshold indices:10th percentile(10p) and 90th percentile (90p),..., 4. Duration indices a) based on threshold, there are length of warm spell (WSDI) and length of wet spell (CSDI),...;5. Based on percentile, there are the length of dry spell (CDD) and length of wet spell (CWD) [8]. A study conducted in Bangladesh revealed an increasing trend in heavy precipitation and a decreasing trend in consecutive dry days [9]. From the study conducted in Brazil about precipitations, there was a significant increase in consecutive dry days and consecutive wet days, thus intensifying the seasonality with rainfall events exceeding the threshold of 95% and 99% in the distribution [10]. The IPCC special report emphasizes that a 0.5°C rise in global temperature causes statistically significant increases in extremes worldwide, including more frequent heatwaves, intensified heavy rainfall, worsening droughts in some regions, and changes in tropical cyclone activity[11]. Rainfall and temperature extremes in Africa show complex regional patterns with significant variability [12]. Mid-21st-century projections indicate a 40–100% increase in extreme wet days in parts of West Africa, the Sahel, and East Africa, with increased rainfall intensity in Kenya and Tanzania but declines in the Congo basin [13]. Temperature extremes are expected to become hotter and more frequent across sub-Saharan and tropical Africa, extending heatwaves into previously less affected areas [14-16]. Rainfall changes are seasonally and regionally variable, critically impacting rain-fed agriculture. For example, Nigeria's Kaduna River basin shows a warming trend in temperature extremes and moderate variability with a slight decrease in rainfall extremes [17-20]. Overall, these changes exacerbate vulnerabilities in agriculture-dependent livelihoods, requiring urgent just transition pathways for sustainable and climate-resilient agricultural systems in Africa [21]. The greatest part of the East African Region displayed a significant decrease in rainfall due to the variation in the trend of rain. This is a great threat in this region because most of its population depends on the Agriculture sector, i.e., more than 80%. This situation has been indicated by the tendency toward annual precipitation decrease associated with an increase in climatic extremes and low frequency [22]. In Ethiopia the analysis of 40 years of total rainfall revealed that the coefficient of variation ranges between 20 and 90% [23], another study about rainfall extreme indices has indicated that the mean annual maximum one-day (RX1day) was ranged from 46.51 mm at Haik to 69.02 at Dassie while mean annual five days (RX5day) rainfall amount fluctuated from 99.43 mmm at Haik to 138.48 at Dassie. In general, it has been found that no clear and significant trend in mean annual one-day (RX1day) rainfall, whereas for mean annual maximum five-day rainfall, except Amba Mariam and Mekaneselam other stations displayed an increasing trend [24]. In Kenya from 1981 to 2021, it had been observed a substantial variability of rainfall patterns was observed at both national and local levels in long and short rainy seasons. The seasonal and intra-seasonal variability became significant after 2013, equivalent to diminished coherence between El Niño Southern Oscillation and rainfall [25]. In Uganda, traditionally it has been revealed a bimodal annual rainfall pattern i.e., March-May and September, November, representing heavier to lighter rainfall events respectively. The recent investigation has shown the upward trend from 2010 onwards in rainfall patterns annually and seasonally[26]. Burundi, like other Eastern African countries, has experienced rainfall events that caused severe consequences on climate-sensitive sectors due to different climatic drivers, namely El Niño South Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden Julian Oscillation (MJO) [27].

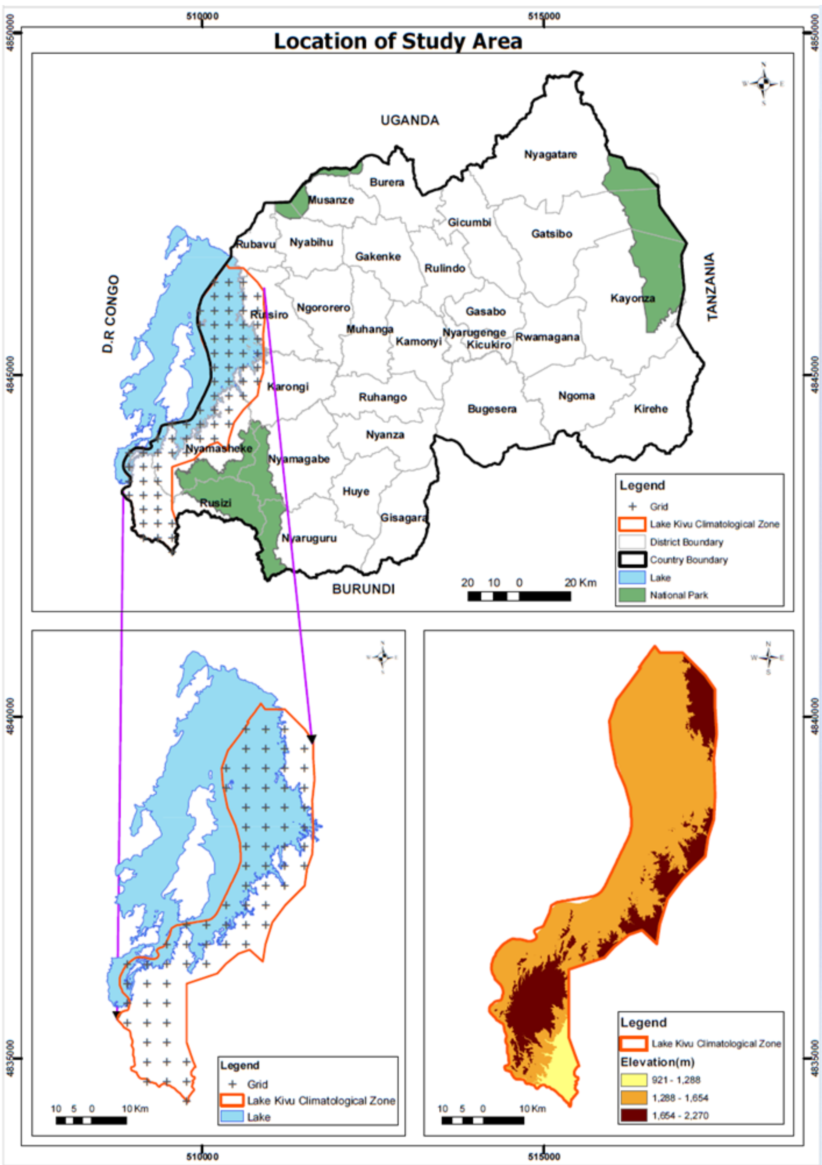
At national level, Rwanda due to its hilly topography stretching from east to west [28] coupled with the global climatic factors such as El Nino-Southern Oscillation (ENSO), La Nina, Indian Dipole Oscillation (IDO), and Madden Julian Oscillation (MAJO) had experienced and continue to experience floods, landslides and drought episodes [29]. The rainfall varies considerably in such a way that the projections revealed that the increase in annual rainfall may attain 20% by 2050 since 1970 [30]. Rainfall is among the fundamental concepts to understand climate change or climate variability [24]; the variability of rainfall affects agricultural practices in different ways [22]. The recent study conducted in Rwanda, which examined 12 rainfall extreme indices, observed an increasing trend in all studied extreme rainfall indices [31]. The specific objectives of this study were (1) to determine the variability and trends in rainfall, (2) to assess the rainfall extreme indices (3) to determine the variability and trends of rainfall extreme indices in the Lake Kivu Climatological zone. To understand the variability and trend of climate variables is important to inform policy and decision making on climate change mitigation and adaptation measures [32]. The availability and quality of rainfall data further complicate analysis, while high temporal resolution data offer detailed insights, they often lack sufficient spatial and long-term coverage, whereas long-term datasets may not capture short-term extremes effectively.

MATERIALS AND METHODS

Study area

The area of study of this research is the Lake Kivu climatological zone. This climate zone is localized along Kivu Lake. It is characterized by wind-circulation interacting with high evaporation rates prevailing in Lake Kivu [33]. slightly decreasing temperatures (+0.5K), and a decrease in rainfall around 50mm [34].

Figure 1. Location of study area: Administrative Boundary, Elevation (m) of Lake Kivu climatological zone.



Data

The daily rainfall dataset used in the present study was obtained from the Rwanda Meteorology Agency (Meteo Rwanda) covering the period from 1983 to 2021. They can be accessed online at https://www.meteorwanda.gov.rw, accessed on February 26, 2024. This dataset is part of the Enhancing National Climate Services (ENACTS) initiative, which combines quality-controlled station observations with satellite to generate spatially and temporally complete climate data. The rainfall data is gridded at a high spatial resolution of 0.0375 degrees (approximately 4 km) and covers all grid points in the Lake Kivu climatological zone. The dataset was reconstructed by organizing and quality-controlling station data and merging it with satellite-derived data to fill gaps and ensure completeness, resulting in decadal (10-day) time series for rainfall across Rwanda based on the methodology defined by Dinku et al. [59] and Siebert et al. [60] This dataset has been previously used in Rwanda for climate studies[61,62].

Methods

Rainfall variability was assessed using the coefficient of variation, calculated from the standard deviation (σ) Of rainfall values, which quantifies the dispersion from the mean and provides valuable insights into temporal rainfall fluctuations [35-36].

$$\sigma\text{:}\sqrt{\frac{\Sigma\left(x-\bar{x}\right)^{2}}{n}}$$

$$\text{CV:}\frac{\sigma}{\bar{x}}\times 100$$

with x indicating the value of rainfall observations, $\bar{x}$ = representing the mean value of rainfall observations and n equation representingting the number of points in observation and CV, indicating the coefficient of variation.

For trend analysis, the non-parametric Mann-Kendall test has been recommended by the World Meteorological Organization (WMO) to be used as a trend in hydrology and climate time series due to its compatibility with non-normalized data, as well as missing data values. Suppose (x_1,y_1), (x_1,y_1), (x_n,y_n) It is a set of joint observations of two random variables, respectively, of x and y, and all the values from the couple. (x_i,y_i) They are unique values. The Mann-Kendall test statistic is computed through the sum of positive and negative signs of the slopes[33,62-63]. The statistic S, called the Kendall score, is expressed as follows:

$$S=\Sigma_{k=1}^{n-1}\Sigma_{j=k+1}^{n}sign\left(x_j-x_k\right) \qquad (1)$$

Where n is the length of the sample,x_k and x_j are from *k=1, 2, n-1 and j=1, 2, n,* and the *sign* $(x_j\text{-}x_k)$ It is an indicator function that takes on the value 1, -1, or 0 as stated below.

$$\text{sign}\left(x_j-x_k\right)=\begin{cases}+1\text{ if}\left(x_j-x_k\right)>0\\0\text{ if}\left(x_j-x_k\right)=0\\-1\text{ if}\left(x_j-x_k\right)<0\end{cases} \qquad (2)$$

If *n* ≥10, the statistic S is approximately normally distributed with the mean S =0, and the variance S can be expressed as follows:

$$\text{var}\left(S\right)=\frac{n\left(n-1\right)\left(2n+5\right)-\Sigma_{j=1}^{p}t_j\left(t_j-1\right)\left(2t_j+5\right)}{18} \qquad (3)$$

With *p* being the number of ties in the series, and t_j Is the number of data points in the j^{th} Roup. Concerning the trend test, the variable Y can be time. The presence of a statistically significant trend is determined by using the Z value. This statistic is used to test the null hypothesis, such that no trend exists. The standardized test statistic Z is given through

$$\text{Z}=\begin{cases}\dfrac{s-1}{\sqrt{var\left(S\right)'}}\text{ if }S>0\\0\qquad\qquad\text{ if }S=0\\\dfrac{s+1}{\sqrt{var\left(S\right)'}}\text{ if }S<0\end{cases} \qquad (4)$$

The trend is concluded as increasing (positive) or decreasing (negative) in value of Z. To determine for either positive (increasing)or negative (decreasing) monotonic trends with a confidence level. α, null hypothesis (H_0) is rejected once |Z| > $Z_{(1-\frac{\alpha}{2})}$, with $Z_{(1-\frac{\alpha}{2})}$ being a value of p= $\frac{\alpha}{2}$ *based* on the standard normal cumulative tables and represents the standard normal deviates, and p is the significance level for the test. The existence of positive and negative correlations in the time series may increase the probability of trend detection, whereas there is no trend, vice versa. The presence of positive autocorrelation in the series may lead Mann Mann-Kendall test to conclude the existence of a trend in the series, whereas it is not always true. Contrary, the presence of negative autocorrelation in the series may lead to the opposite side. The coefficient of autocorrelation ρ_kA Discrete time series for lag-k is obtained based on the formula made by Datta and Das [33,64-68] as follows:

$$\rho_k=\frac{\Sigma_{i=1}^{n-k}\left(x_i-\bar{x}\right)\left(x_{i+k}-\bar{x}_{i+k}\right)}{\left[\Sigma_{i=1}^{n-k}\left(x_i-\bar{x}\right)^{2}\times\Sigma_{i=1}^{n-k}\left(x_{i+k}-\bar{x}_{i+k}\right)^{2}\right]^{\frac{1}{2}}} \qquad (5)$$

The Modified Mann-Kendall test has been proposed by Ahamed et al [37] to take into account the influence of autocorrelation in the data, often ignored; this led to the correlation being brought to the variance of S, replaced by:

$$\text{var*}\left(\text{S}\right)=var\left(S\right)\frac{n}{n_k^{*}} \qquad (6)$$

with $\frac{n}{n_k^*}$ stands for a correction due to autocorrelation in the data, which is given as follows [22] :

$$\frac{n}{n_k^{*}}=1+\frac{2}{n\left(n-1\right)\left(n-2\right)}\Sigma_{i=1}^{n-1}\left(n-i\right)\left(n-i-1\right)\left(n-i-2\right)\rho_k \qquad (7)$$

with *n* being the real number of observations, n_k^* stands for the effective number of observations by considering autocorrelation in the data, while ρ_k resents the auto correlation function for the ranks of observations. The non-non-significant values of ρ_k can effect negatively on the variance of S, so only significant values of ρ_k are opted to estimate n/ρ_k [33,38-40]

Theil-Sen slope estimator

With linear trends in time series, the slope or magnitude of that trend can be detected through a simple non-parametric procedure developed by Theil and subsequently modified by Se. The latter has an advantage over the slope of regression in that gross data series errors and outliers do not affect it much. The slope is determined by the mean of all pairwise slopes for any pair of points in the dataset. The equation below has been used to estimate the slope individually. [32,41-42].

$$Q_{ij} = Median\,\frac{(x_j - x_i)}{j-i}, j > i \; for \; i = 1, 2....N$$

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

Positive value of Q designates an upward or increasing trend, while its negative value indicates a downward or decreasing trend in the time series. During this study, trends and slopes were computed at each grid point of rainfall and related extreme indices using the modified Mann-Kendall test and the Sen Slope estimator approach and the significance has reported at α=0.05

RESULTS

Figure 2 presents the rainfall distribution Lake Kivu climatological zone (1983–2021). In general, rainfall distribution displayed a complex north-south rainfall gradient across all seasons in the Lake Kivu climatological zone, driven by topography/elevation. The short dry season (JF) experienced moderate rainfall (226–658 mm) with peak observed in the central-western parts (514–658 mm) while the northern edges are drying (82–226 mm), contrasting the southern edge, which is becoming wetter (514–658 mm). The complexity sharpened in the main rainy season (MAM), with northern edges receiving (226–514 mm) and north-central parts receives (658–802 mm), the central and southern parts continued to become drier (82–514 mm) while the southern edges are becoming wetter ((658–802 mm). Remarkably, even the long dry season (JJA) sustained a complexity of rainfall distribution, the northern edge receives (370–514 mm), the north-western parts (658–802 mm), while the southern, central, and eastern parts remain arid (82–370 mm). The short rainy season (SOND) maintains the pattern, though less pronounced, with northern regions at 514 –802 mm versus 226–370 mm in the south. Annually, the northern edges of Lake Kivu climatological zone received (1400- 1,800mm) while northern western parts are receiving 2000 mm -2200mm nearly double in the southern edges (1,200–1,400 mm, aligning with Rwanda's elevation-driven climatic variability and prior studies emphasizing minimal dry-season rainfall and spatial contrasts tied to landscape features.

Figure 2. Rainfall mean in the Lake Kivu Climatological Zone between 1983-2021.

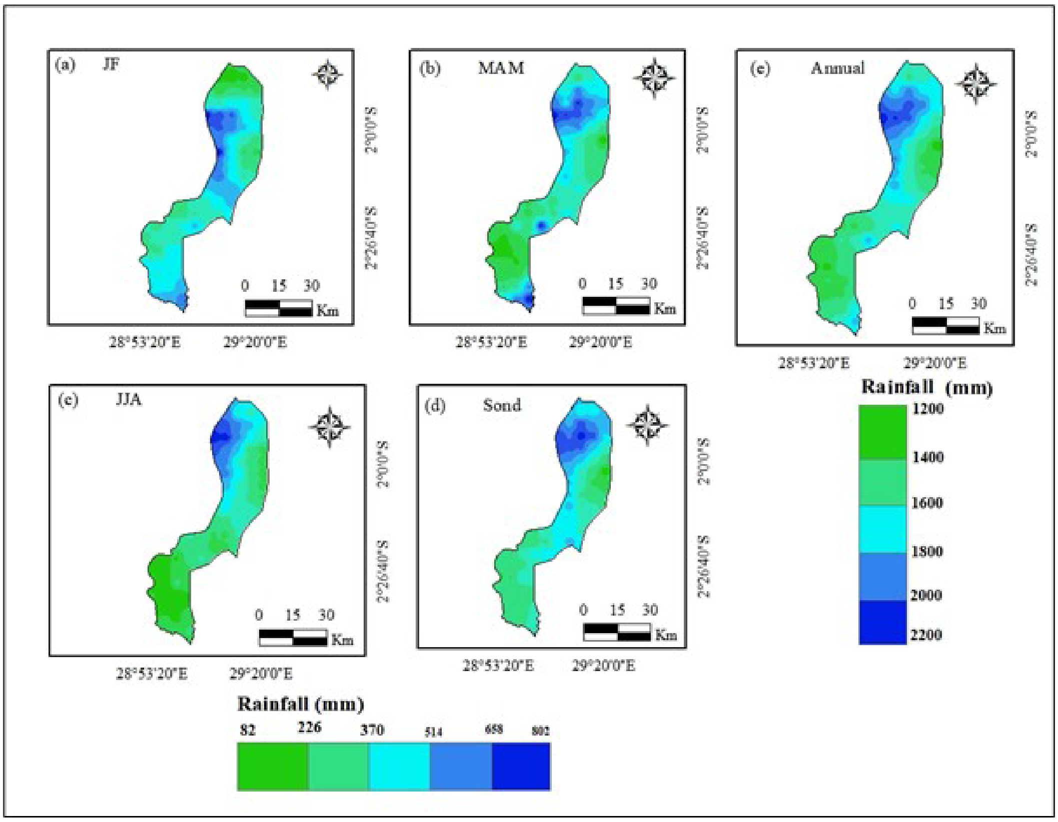


Figure 3 presents the spatial, seasonal, and annual rainfall variability in the Lake Kivu climate zone for 1983-2021. Rainfall during JF season showed complex variation, the top of northern region displayed moderate rainfall variability (20-80%), though the central parts of this northern showed extreme variability (80-120%); the central part and the majority of southern part showed high variability (60-100%) some areas at beginning of southern part having low variability 20-40%. During the MAM season, most of the region showed moderate variability (20-80%), except for a small part of the central east region, which showed extreme variability from 80-120%. This likely corresponds to one of Rwanda's rainy seasons. The JJA season showed generally low to moderate variability (20-80%) across most of the region, with some small spots of higher variability (100-120%) in the central-northern area. This suggests relatively consistent precipitation patterns during this season across most of the zone, which likely aligns with Rwanda's dry season. SOND season displayed high variability, predominantly ranging 60-100% across much of the region, with a small part at the beginning of the southern part which showed the low variability (20-40%). This indicates that SOND rainfall is less predictable throughout the zone. The annual variability showed a pattern of 14-24% across the region. The north zone showed a variability of 16-20 %; the central and southern portions showed a complex variation in rainfall, which is between 14-24%. In general, the annual rainfall variability (14-24%) in the Kivu climatological zone aligns with the results of the study by Sebaziga et al (2022), which found low variability of rainfall in the western part of Rwanda.

Figure 3. Rainfall variability in the Lake Kivu Climatological Zone between 1983-2021.

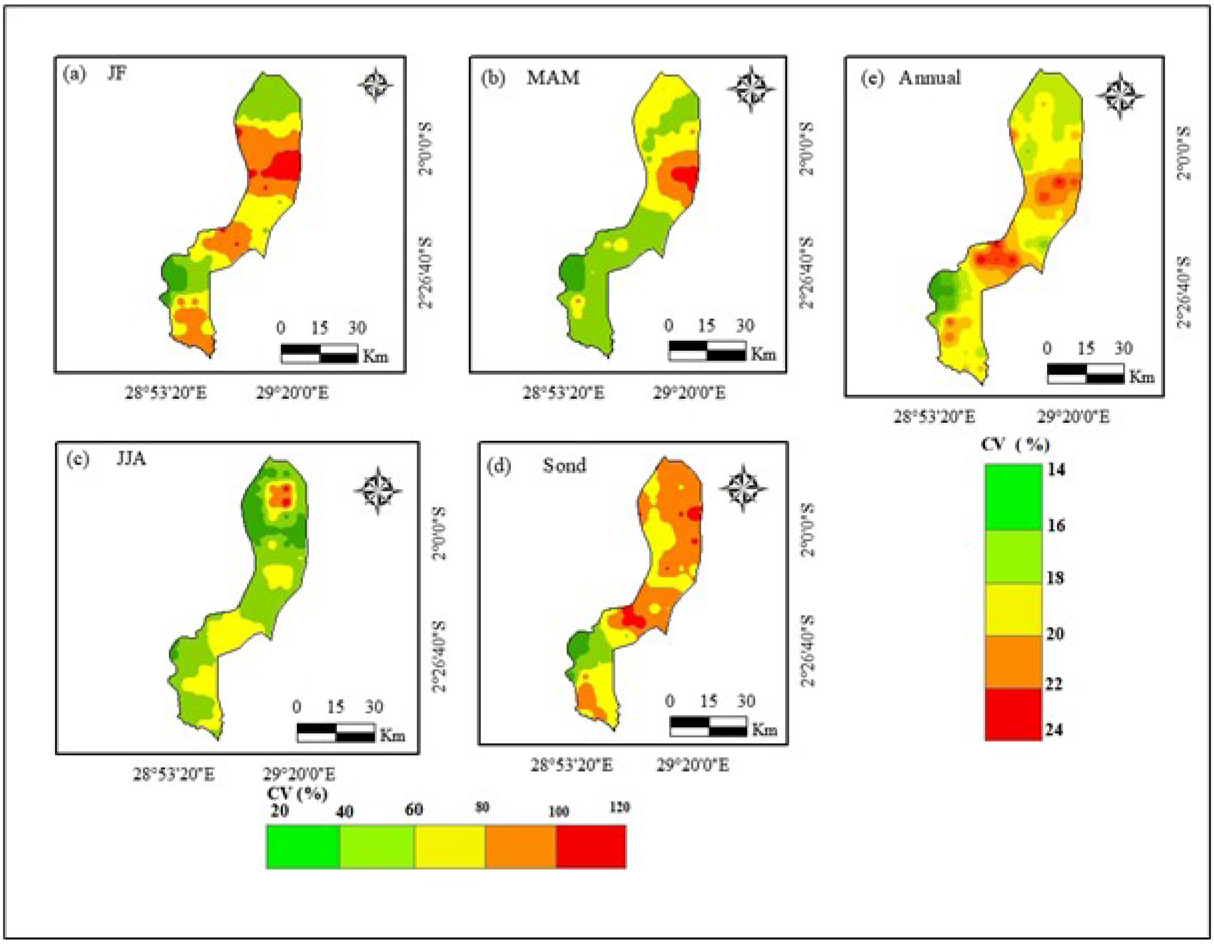


Figure 4 presents the rainfall trends in the Lake Kivu Climatological Zone in the period of 1983-2021

JF season displayed a statistically significant (∝ =0.05) positive trend of 9-14mm in the north edge, in the north-central part, and the central region; other remaining parts showed no on-significant trend. During the MAM, the northern region showed a statistically significant (∝ =005) increasing trend of -2 to 4 mm at the northern edge, the central part experienced a statistically significant (∝ =0.05) positive trend of 4-19mm at a small spot. In contrast, the southern region showed a statistically significant (∝= 0.05) strong positive trend of 14-24 mm at the eastern edge, indicating significant rainfall increases during this season in this portion. The period of the JJA season showed a statistically significant (∝= 0.05) positive trend of 4-14mm at the north edge. The central and south regions showed a statistically significant (∝ =0.05) positive trend of 9-19mm in some spots, while the remaining showed non-significant trends. The season of SOND non-significant trend except few spots in the northern and southern which showed statistically significant statistically significant. $\propto$ =0.05) positive trend of -2 to 4mm. The annual trends showed predominantly positive rainfall trends across the entire region, with statistically significant (α= 0.05) increasing trend of 9 to 13mm at the north north-western edge and another north-western spot of statistically significant ($\propto$= 0.05) increasing trend of 5 to 9mm in other parts of the north and central region showed a statistically significant ($\propto$ =0.05) positive trend of 5-13 mm/year) while the southern part displayed a statistically significant ($\propto$= 0.05)positive trend of 13-21 mm at the western edge. Generally, rainfall showed an increasing trend in all parts of the Lake Kivu climatological zone.

Figure 4. Rainfall trends in the Lake Kivu Climatological Zone between 1983-2021

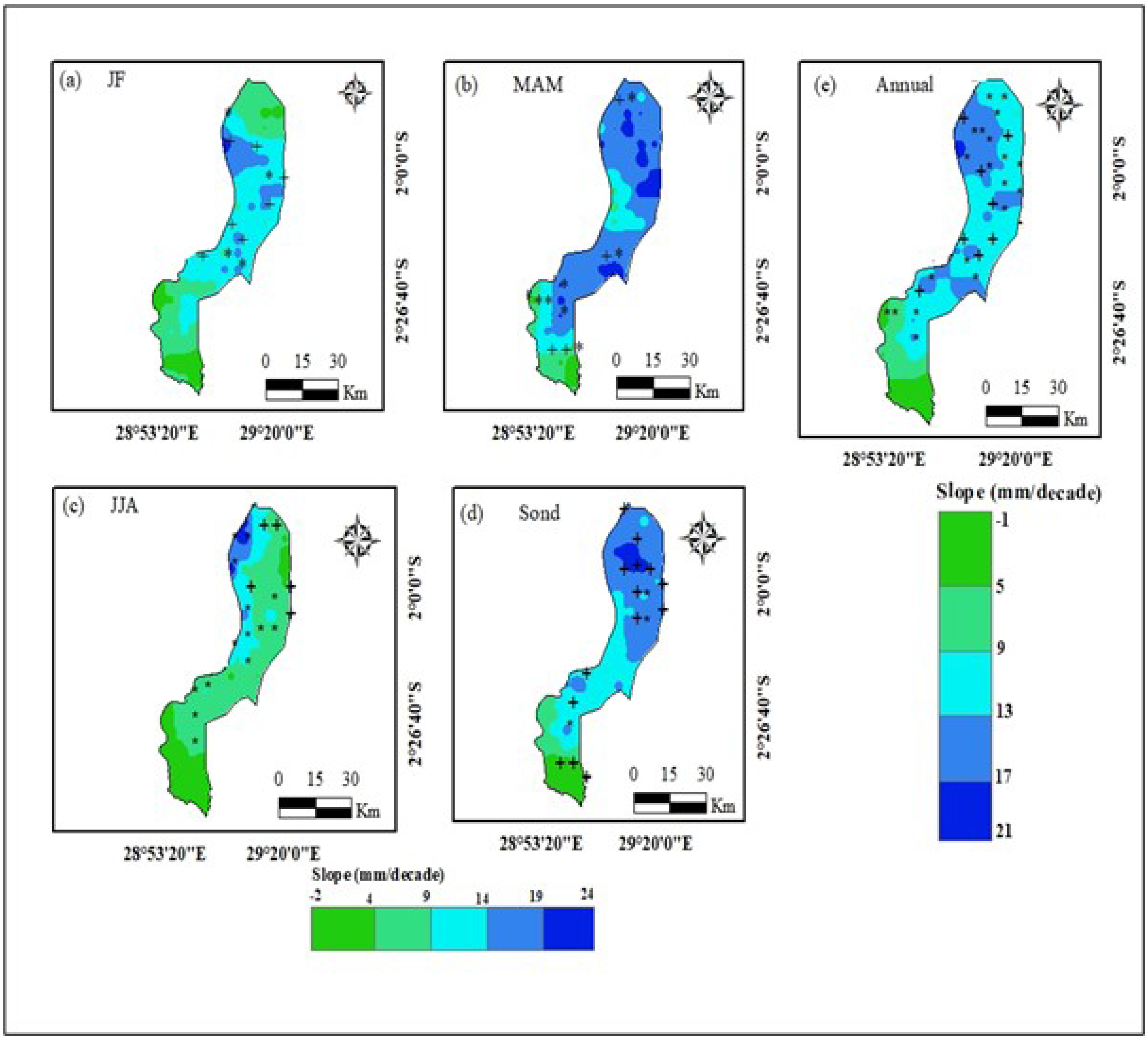


Figure 5 presents the distribution of rainfall extreme indices in the Lake Kivu climate zone (1983–2021). Almost all studied rainfall extreme indices (9) revealed a pronounced north–south gradient, with the northern region exhibiting higher intensity, frequency, and magnitude of extreme rainfall events compared to the south. SDII mean in the northern region experienced a moderate intensity in rainfall (458.8 -1362.4mm) at the northern edge and in the middle part, a higher intensity in rainfall in the central part in northern region (1814.2 -2266 mm) while the southern region experienced lower intensity precipitation (458-910.6 mm). This indicates that when it rains in the northern areas, the rainfall is much more intense in the northern region. The R5-day mean, in the northern region, experienced a moderate to extremely high 5-day rainfall (910.6 -2266 mm) while the central part and all the southern region showed low to moderate values (7-1362.4 mm). Also, for R1day mean, the northern region experienced high single-day precipitation events (910.6 -2266 mm) in the top part, whereas the central and southern parts experienced low to moderate values (7-1362.4 mm). About PRCPTOT, the northern region received significantly higher total precipitation (458.8-2266 mm) compared to the central and southern regions (7-1362.4 mm). Concerning the CWD mean, the southern tip showed 20 -35 days of consecutive rainfall, the central part experienced 15- 20 days, while the northern

regions generally showed 10- 15 days. For the R10mm mean, the northern region experienced 15-35 days, the central region showed 20-25 days, and the southern region showed 10-15 days. The pattern of R20mm mean in northern areas experienced 20-35 days transitioning to 15-25 days in the central and 10- 15 days in southern regions. For R95pTOT, the northern region received higher rainfall from east to western part (910.6-2266 mm), the central part experienced the moderate quantity (458.8-1362.4mm) whereas the southern displayed a low quantity (7-458.8 mm) with an exception found at the southern edge (910.6-1814.2 mm). The R99pTOT mean showed the similar pattern with R95pTOT with small nuance, the northern tip experienced the moderate values (910.6-1362.4mm), the central part in northern region received significantly higher rainfall from east to western part (1362.4-2266 mm), the central and southern parts experienced low to moderate values (7-1362.4 mm) with some portion of high value at the southern edge (910.6-1814.2mm).

Figure 5. The mean values of rainfall extreme indices in Lake Kivu climatology between 1983 and 2021

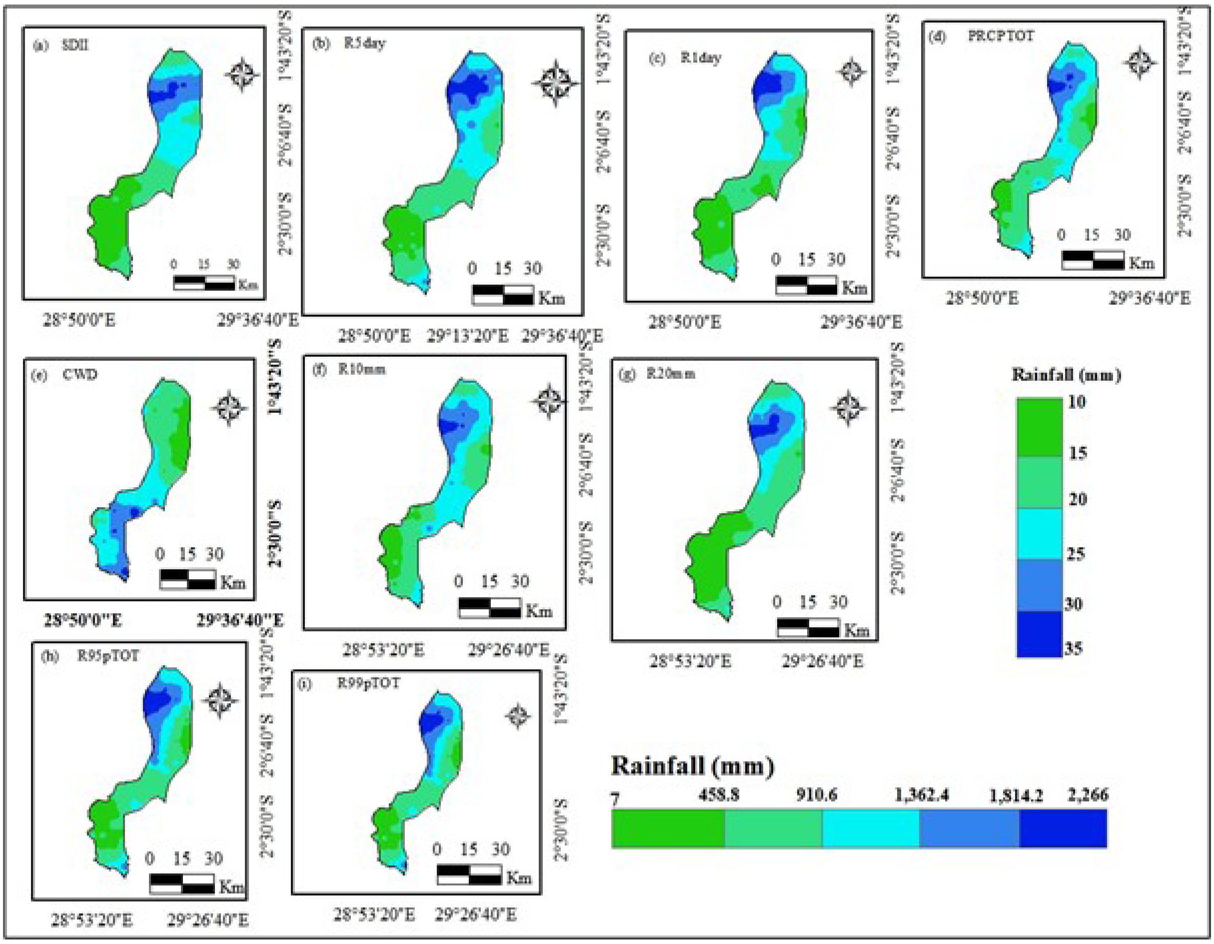


Figure 6 presents the rainfall extreme events variability in the Lake Kivu Climatological Zone from 1983 to 2021.

The Lake Kivu climate zone exhibited significant spatial variability in rainfall extreme indices. Daily rainfall intensity (SDII) demonstrated moderate to high variability in the northwestern part (28.846-105.418%), while the northeastern part showed extreme variability (105.418-182%). The central areas also experienced moderate to high variability (28.846-105.418%), whereas the southern part exhibited low to high variability (9.43-105.418%). The maximum 5-day rainfall (R5day) generally displayed stable low variability (9.43-28.846%), except for some small spots in the northern region, which exhibited very high variability (28.846-182%). Single-day rainfall extremes (R1day) revealed a pronounced north-south gradient, peaking in the north with extreme variability at the northern edge (143.704-182%). The central northern region displayed very high variability (105.418-143.704%), while the central region showed high variability (28.846-105.418%), and the southern part exhibited low to moderate variability (9.43-67.132%). Consecutive wet days (CWD) presented a complex pattern. The northeastern part showed low variability (9.43-28.846%), the northwestern and central parts experienced moderate variability (28.846-67.132%), with some areas of high variability (67.32-143.704%). The central region showed moderate variability, ranging from 9.43-67.132%, while the southern areas displayed extreme variability (67.132-182%). Annual total precipitation (PRCPTOT) fluctuated considerably. The northern portion exhibited low to high variability (28.846-105.418%), and the central part showed extreme variability (28.846-182%), whereas the southern part displayed low to high variability (9.43-143.704%). The R10mm also fluctuated significantly, with the northern region showing moderate to high variability (28.846-105.418%). This pattern was also evident in the central zones, but the edge of the central part had extreme variability (67.32-182%), while the northern part of the southern portion displayed low to moderate variability (9.43-67.132%), and the remaining areas experienced high variability (67.132-143.704%). The heavy rainfall days (R20mm) exhibited stable moderate variability primarily in the northern and central parts (9.43-67.132%), though the southern portion showed high variability (28.846-143.704%), with a small area at the western edge exhibiting extreme variability (143.704-182%). The very wet days (R95pTOT) showed low to moderate variability in the northwestern part (9.43-67.132%) and high variability in the northeastern part (67.132-143.704%), with some areas of extreme variability (143.704-182%). The central region exhibited high variability (28.846-143.704%), while the southern portion showed low variability in the eastern part and northern edge (9.43-67.132%), with high variability in the northern part of the west (67.132-143.704%). For extreme wet days (R99pTOT), there was moderate variability in the northern and central regions (28.846-105.418%), with some areas of extreme variability in the northern part (143.704-182%), while the entire southern portion exhibited low variability (9.43-28.846%). This pronounced spatial heterogeneity, particularly the unpredictability of extreme rainfall in the north, underscores the importance of targeted risk management, agricultural planning, and climate adaptation strategies in the region.[23]

Figure 6. Rainfall extreme indices variability in Lake Kivu climatology between 1983 and 2021

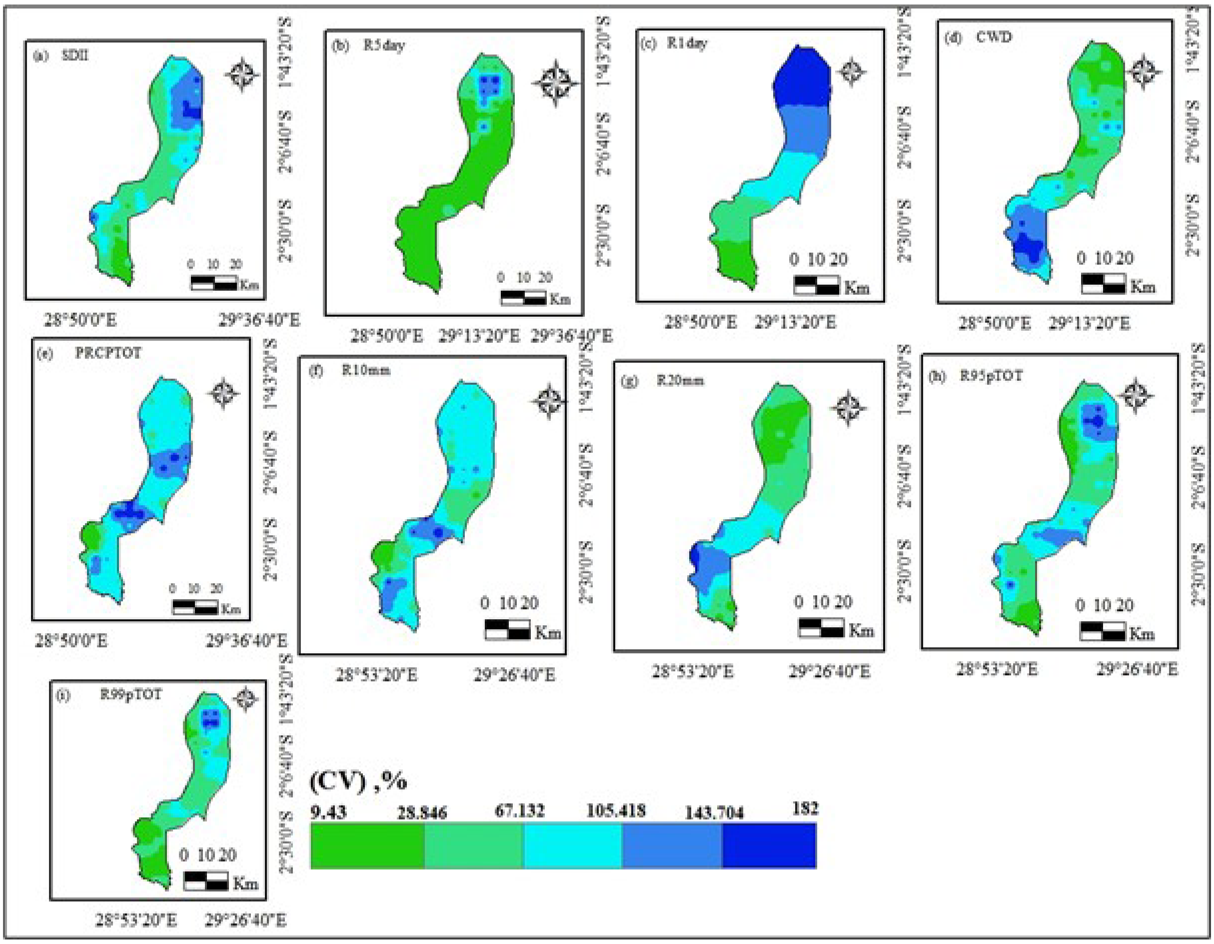
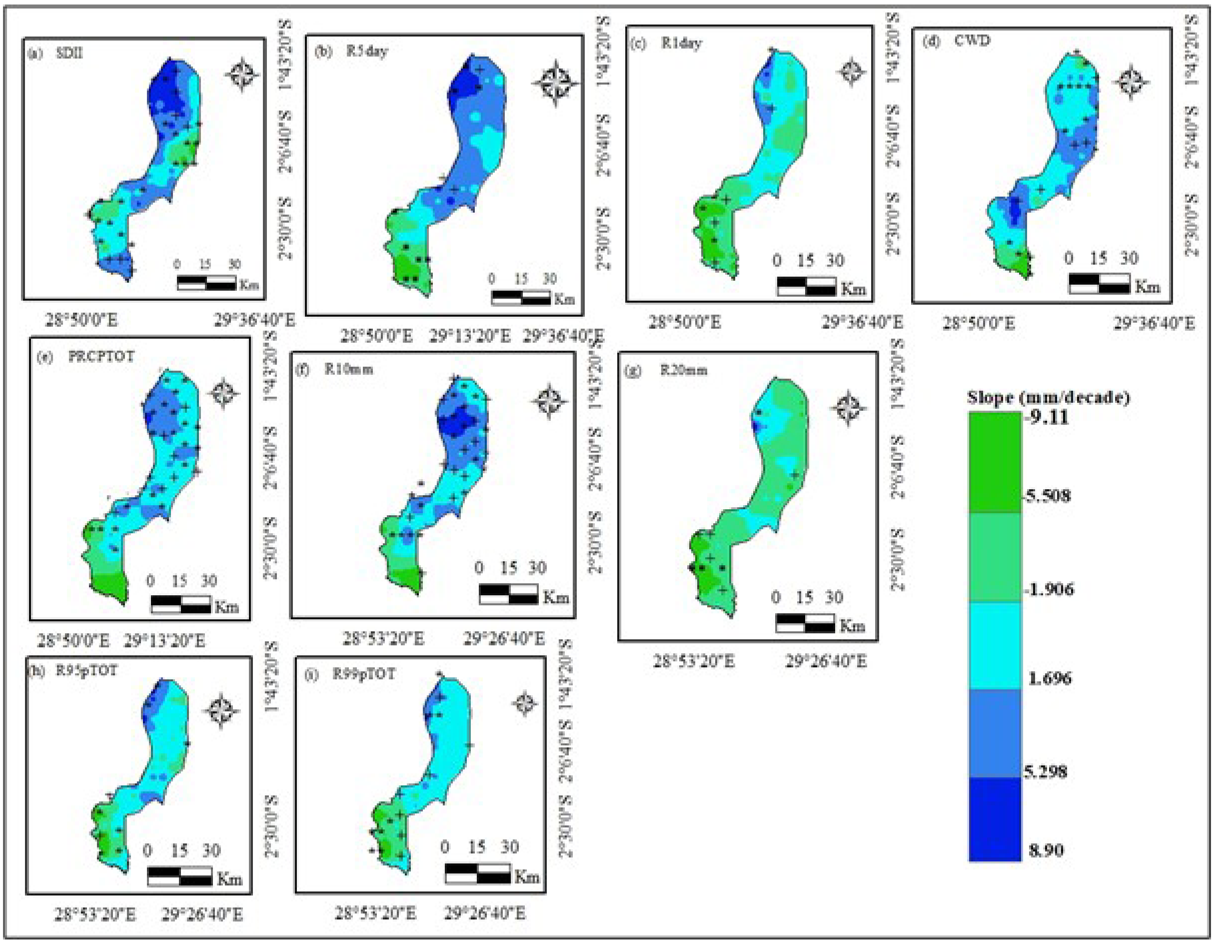


Figure 7 illustrates trends in rainfall extreme indices across the Lake Kivu climate zone from 1983 to 2021.

SDII showed a statistically significant(∝=0.05) increasing trend of (5.298 -8.90 mm) in north western part, the central eastern parts showed a statistically significant (∝=0.05) increasing -9.11-1.906 mm while it experienced a statistically significant(∝≥=0.05) increasing trend of -5.508-1.906 mm in south western parts and the remaining parts showed nonsignificant trend. R5day displayed a statistically significant (∝=0.05) negative trend from -9.11 to -5.508 mm only in the southern part, which displayed ta non-significant trend R1day showed the non-significant trends (∝=0.05) negative t-9.11-5.508mmCWD exhibited only a statistically significant (∝=0.05) increasing -1.906 -5.508 days in the north, the central part exhibited ta non-significant trend in the southern region there were some spots which a statistically significant (∝=0.05) n negative tom -9.11 to -5.508 days.

The annual total precipitation (PRCPTOT) showed statistically significant (∝=0.05) increasing trend of -1.906-5.298 mm in the north western significant (∝=0.05) increasing trend of -1.906-5.298 mm while the southern part experienced a statistically significant (∝=0.05) negative trend of -9.11 to -1.906 mm at a given small in the western zone. R10mm displayed a statistically significant (∝=0.05) increasing trend of -1.906 -8.9 days).o Northernegions regions regions owed a statistically significant (∝=0.05) increasing trend -11.906.298 days, and a statistically significant (∝=0.05) increasing t-5.508 --.298 days. R20mm showed a statistically significant (∝=0.05) increasing trend in noteworthy western north western -5.508 -1.696 days trend, the central region showed a significant trend, and the southern region showed a statistically significant (∝=0.05) increasing trend of -9.11 to -5.508 days. Precipitation from very wet days (R95pTOT) exhibited a statistically significant (∝=0.05) increasing trend of 1.696 -5.298 mm in northern region, the central regions showed non -significant trend and the south region showed a statistically significant (∝=0.05) increasing trend of -9.11 -1.696 mm. Precipitation from extremely wet days (R99pTOT) showed a statistically significant (∝=0.05) increasing -1.906-5. 298 mm in the northern region, the central part exhibited a non-significant negative trend. The southern portion showed a statically significant(∝=0.05) decreasing trend of -9.11 to -5.508 mm in the southern area. This indicates that extreme rainfall events are increasing slightly in the north while potentially decreasing by a significant 5% in the south.

Figure 7. Rainfall extreme indices trends at Lake Kivu Climatological Zone, Rwanda.



DISCUSSION

Rainfall distribution in the Lake Kivu climatological zone exhibits a complex north-south precipitation gradient. This confirms the findings of the study conducted by Ntwali et al [43], which revealed that rainfall distribution over Rwanda significantly decreases when topography is minimized. Generally, the annual rainfall variability (14-24%) in the Kivu climatological zone aligns with the results of the study by Sebaziga et al [44], which identified low rainfall variability in the western part of Rwanda. The seasonal rainfall variability in March-April-May (MAM), averaging 50% after excluding a small area in the eastern part of our study region, corresponds with the findings of the study by Uwizeye et al [45], which reported a variation of 51.19% for the rainfall pattern during this season in Rwanda. The variability in September-October-November-December (SOND), averaging 90% in most areas, corroborates the results of Kazora et al [46], which noted the dominant variability during the SOND season. A generally increasing trend in rainfall found in the Lake Kivu climatological data corresponds with the findings of Abaje & Oladipo [35], which indicated a rising trend in rainfall in Nigeria, specifically in Kaduna, over the past two decades. Indeed, extreme rainfall indicators show a north-south gradient, with the northern portion of the Lake Kivu climatological zone experiencing more extreme rainfall in terms of intensity, duration, and frequency compared to the southern region. These findings further confirm the results of the study conducted by Ntwali et al [32], which indicated that rainfall distribution over Rwanda significantly decreases when topography is minimized. Concerning the variability of extreme rainfall indices, which ranged from [9.43-182%], CWD, R10mm, R20mm, RX1day, R95 PTOT, and PRCTOT support the findings of the study by Sebaziga et al [47], which stated that these extreme indices exhibit greater variability in Rwanda, especially RX1day, R95 PTOT, and PRCTOT in the western region of Rwanda. Additionally, the trends of the aforementioned extreme indices in the Lake Kivu climatological zone displayed a similar pattern (heterogeneity) as those indicated by Sebaziga et al [47]. The overall increasing trend of all studied extreme rainfall indices aligns with the findings of the study conducted in Rwanda by Umutoni & Limbu [31], which revealed an increasing trend for all extreme precipitation indices. These climate change behaviors have cross-sectoral impacts: agriculture faces challenges from erratic rainfall and soil erosion, necessitating crop diversification and erosion control [48-50], while infrastructure needs resilience to variable rainfall and intensified erosivity, particularly in mountainous areas [51-52]. Tourism may benefit from extended seasons but faces risks from landslides and floods [53-54], while public health confronts expanded mosquito habitats that could increase malaria transmission [55-56]. Fisheries experience disruptions due to fluctuating lake levels affecting fish stocks, threatening livelihoods [57-58]. Disaster management strategies, including early warning systems and adaptive land use planning, are crucial for mitigating flood and landslide risks exacerbated by spatial and temporal rainfall variability.

CONCLUSION

The Lake Kivu region exhibits a complex precipitation pattern characterized by a strong north-south rainfall gradient, where northern areas receive nearly three times more rainfall than southern parts during the main rainy season (March-May). The north faces more intense rainfall events and frequent extreme precipitation days, raising flood risks, while the south sees less intense rainfall but shifting rainfall patterns. These patterns affect water resources, agriculture, flood management, and ecosystems, making northern areas more vulnerable to floods and southern areas to drought, necessitating adaptive strategies across the whole zone. Challenges in precipitation data quality and coverage complicate precise variability trend analysis and climate impact assessments. To enhance resilience, different strategies are required. Development of zone-specific agricultural strategies that account for the distinct rainfall and temperature patterns, focusing on heat-resilient crop varieties and flexible planting calendars that can withstand increasing climate variability, will facilitate agricultural adaptation to climate variability and change in the Lake Kivu Climatic zone. The responsible institutions include: the Ministry of Agriculture (MINAGRI) and the Rwanda Agriculture and Animal Resources Development Board (RAB). Develop and implement comprehensive water management plans that address the contrasting precipitation trends, particularly in areas experiencing both increased rainfall intensity and prolonged dry spells. This will help to efficiently use and manage the water resources in the Lake Kivu Climatological zone. This falls into the responsibilities of include Ministry of Environment (MoE) and the Rwanda Water Board (RWB). Enhance early warning of disasters and infrastructure resilience, especially in northern regions prone to high-intensity rainfall and potential landslide risks. This will contribute to disaster risk reduction in the Lake Kivu Climatological zone. This is a task of the Ministry in charge of Emergency Management (MINEMA) and the Rwanda Meteorological Agency (RMA).

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Authors contributions

T.M and S.N.J. designed the study, T.M collected & analysed data and designed figures; S.N.J. supervised the study; T.M, S.N.J., E.M, I.M., CM, DJM, JS, DU, GM, AT, BN, JN, WM, SK, E.U., and P.C.K.: review and editing.

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Data availability

The rainfall dataset used in the present study was obtained from the Rwanda Meteorology Agency (Meteo Rwanda). The dataset is available by request through online services at https://www.meteorwanda.gov.rw.

Conflicts of interest

The authors declare that they have no conflicts of interest.

REFERENCES

1. Mohammed, Y., Yimer, F., Tadesse, M., & Tesfaye, K. (2019). Variability and trends of rainfall extreme events in the north-north-east highlands of Ethiopia. International Journal of Hydrology, 2(5). https://doi.org/10.15406/ijh.2018.02.00131.

2. Chandra Kuniyal, J., Kanwar, N., Singh Bhoj, A., Singh Rautela, K., Joshi, P., Kumar, K., Sharjeel Sofi, M., Ullah Bhat, S., Rashid, I., Singh Lodhi, M., Anniebesant Devi, C., & Birkumar Singh, H. (2021). Climate change impacts on glacier-fed and non-glacier-fed ecosystems of the Indian Himalayan Region: people's perception and adaptive strategies.

3. IPCC. (2021). Climate Change Report IPCC 2021-a: Chimera of Science and Politics. https://ssrn.com/abstract=3913788.

4. Intergovernmental Panel on Climate Change (IPCC). (2023). Climate Change 2021 – The Physical Science Basis. In Climate Change 2021 – The Physical Science Basis. Cambridge University Press. https://doi.org/10.1017/9781009157896.

5. Thomas, V., & López, R. (2015). GloBAl InCReAse In ClImAte-RelAteD Diseases. https://ssrn.com/abstract=2709331Electroniccopyavailableat:https://ssrn.com/abstract=2709331.

6. IPCC. (2022). Framing and Context. In Global Warming of 1.5°C (pp. 49–92). Cambridge University Press. https://doi.org/10.1017/9781009157940.003.

7. Fischer, E. M., Schär, C., Ban, N., Bresch, D. N., Casanueva, A., Feigenwinter, I., ... & Wartenburger, R. (2018). Climate Extremes and Climate Indices.

8. Kim, Y. H., Min, S. K., Zhang, X., Sillmann, J., & Sandstad, M. (2020). Evaluation of the CMIP6 multi-model ensemble for climate extreme indices. Weather and Climate Extremes, 29. https://doi.org/10.1016/j.wace.2020.100269.

9. Shahid, S. (2011). Trends in extreme rainfall events of Bangladesh. Theoretical and Applied Climatology, 104(3–4), 489–499. https://doi.org/10.1007/s00704-010-0363-y.

10. Costa, R. L., de Mello Baptista, G. M., Gomes, H. B., dos Santos Silva, F. D., da Rocha Júnior, R. L., de Araújo Salvador, M., & Herdies, D. L. (2020). Analysis of climate extremes indices over northeast Brazil from 1961 to 2014. Weather and Climate Extremes, 28, 100254.

11. Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., ... &

12. Ogunjo, S., Fuwape, I., Oluyamo, S., & Rabiu, B. (2019). Spatial dynamical complexity of precipitation and temperature extremes over Africa and South America. Asia-Pacific Journal of Atmospheric Sciences, 1-14.

13. Gamal, G., Nejedlik, P., & El Kenawy, A. M. (2024). Assessing Future Precipitation Patterns, Extremes, and Variability in Major Nile Basin Cities: An Ensemble Approach with CORDEX CORE Regional Climate Models. Climate, 12(1), 9.

14. Fontaine, B., Janicot, S., & Monerie, P. A. (2013). Recent changes in air temperature, heat wave occurrences, and atmospheric circulation in Northern Africa. Journal of Geophysical Research: Atmospheres, 118(15), 8536-8552.

15. Adigun, P., Abah, E. O., & Ajileye, O. D. (2024). Intensifying human-driven heatwave characteristics and heat-related mortality over Africa. Environmental Research: Climate, 3(1), 015007.

16. Gyilbag, A., Amou, M., Tulcan, R. X. S., Zhang, L., Demelash, T., & Xu, Y. (2021). Characteristics of enhanced heatwaves over Tanzania and scenario projection in the 21st century. Atmosphere, 12(8), 1026.

17. Adu, O. E. Climatic Dynamics and Its Impact on Food Security and Livelihood in Northern Kaduna, Kaduna State, Federal Republic of Nigeria.

18. Ikpe, E. L. I. S. H. A. (2021). Effects of climate change on the yield of selected grain crops and farmers' adaptation strategies in Sokoto State, Nigeria. PhD unpublished thesis, Department of Geography and Environmental Management, Ahmadu Bello University, Zaria, Nigeria.

19. Etim, e. I. (2024). Assessing the impact of climate change in north central nigeria: a study of the herders-farmers conflict.

20. JIYA, S. B. (2022). The impact of climatic variability on yam production in shiroro local government area, niger state, nigeria (Doctoral dissertation).

21. Kabato, W., Getnet, G. T., Sinore, T., Nemeth, A., & Molnár, Z. (2025). Towards climate-smart agriculture: Strategies for sustainable agricultural production, food security, and greenhouse gas reduction. Agronomy, 15(3), 565.

22. Twahirwa, A., Oludhe, C., Omondi, P., Rwanyiziri, G., & Sebaziga Ndakize, J. (2023). Assessing Variability and Trends of Rainfall and Temperature for the District of Musanze in Rwanda. Advances in Meteorology, 2023. https://doi.org/10.1155/2023/7177776.

23. Addisu, S., Selassie, Y. G., Fissha, G., & Gedif, B. (2015). Time series trend analysis of temperature and rainfall in Lake Tana Sub-basin, Ethiopia. Environmental Systems Research, 4(1). https://doi.org/10.1186/s40068-015-0051-0.

24. Mohammed, Y., Yimer, F., Tadesse, M., & Tesfaye, K. (2019). Variability and trends of rainfall extreme events in the north north-east highlands of Ethiopia. International Journal of Hydrology, 2(5). https://doi.org/10.15406/ijh.2018.02.00131.

25. Kotikot, S. M., Smithwick, E. A. H., & Greatrex, H. (2024). Observations of enhanced rainfall variability in Kenya, East Africa. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-63786-2.

26. Ngoma, H., Wen, W., Ojara, M., & Ayugi, B. (2021). Assessing Current and Future Spatiotemporal Precipitation Variability and Trends Over Uganda, East Africa, Based on Chirps and Regional Climate Models Datasets. https://doi.org/10.20944/preprints202101.0037.v1.

27. Nkunzimana, A., Bi, S., Alriah, M. A. A., Zhi, T., & Kur, N. A. D. (2020). Diagnosis of meteorological factors associated with recent extreme rainfall events over Burundi. Atmospheric Research, 244. https://doi.org/10.1016/j.atmosres.2020.105069.

28. World Bank Group. (2021). RWANDA CLIMATE RISK COUNTRY PROFILE. www.worldbank.org.

29. Ayabagabo, P. (2018). University of nairobi college of biological and physical sciences school of physical sciences department of meteorology empirical analysis of seasonal rainfall variability and its associated effects on major food crop yields in rwanda.

30. GoR. (2011). Green Growth and Climate Resilience - Rwanda (2011). The Way Forward in International Climate Policy, October 100. http://repository.ubn.ru.nl/bitstream/handle/2066/135304/135304.pdf?sequence=1#page=8.

31. Umutoni, M., & Limbu, P. (2022). Characteristics of Extreme Precipitation and Their Effect on Bean Yield in Rwanda. Tanzania Journal of Engineering and Technology, 41(4), 24–42. https://doi.org/10.52339/tjet.v41i4.872.

32. Safari, B., & Sebaziga, J. N. (2023a). Trends and Variability in Temperature and Related Extreme Indices in Rwanda during the Past Four Decades. Atmosphere, 14(9). https://doi.org/10.3390/atmos14091449.

33. Safari, B., & Sebaziga, J. N. (2023). Trends and Variability in Temperature and Related Extreme Indices in Rwanda during the Past.

34. Henninger, S. M. (2013). Does global warming modify the local Rwandan climate? Natural Science, 05(01), 124–129. https://doi.org/10.4236/ns.2013.51a019.

35. Bitrus Abaje, I., & Oladipo, E. O. (2019). Recent Changes in the Temperature and Rainfall Conditions Over Kaduna State, Nigeria. In Ghana Journal of Geography (Vol. 11, Issue 2).

36. Alemu, M. M., & Bawoke, G. T. (2020). Analysis of spatial variability and temporal trends of rainfall in Amhara Region, Ethiopia. Journal of Water and Climate Change, 11(4), 1505–1520. https://doi.org/10.2166/wcc.2019.084.

37. Kamal Ahmed, K. A., Shamsuddin Shahid, S. S., Ali, R. O., Sobri Harun, S. H., & Wang XiaoJun, W. X. (2017). Evaluation of the performance of gridded precipitation products over Balochistan province, Pakistan.

38. Taxak, A. K., Murumkar, A. R., & Arya, D. S. (2014). Long-term spatial and temporal rainfall trends and homogeneity analysis in Wainganga basin, Central India. Weather and climate extremes, 4, 50-61.

39. Mahrt, L. (2014). Stably stratified atmospheric boundary layers. Annual review of fluid mechanics, 46(1), 23-45.

40. Das, S., Datta, P., Sharma, D., & Goswami, K. (2022). Trends in temperature, precipitation, potential evapotranspiration, and water availability across the Teesta River Basin under 1.5 and 2 °C temperature rise scenarios of CMIP6. Atmosphere, 13(6), 941.

41. Theil, H. (1992). A rank-invariant method of linear and polynomial regression analysis. In Henri Theil's contributions to economics and econometrics: Econometric theory and methodology (pp. 345-381). Dordrecht: Springer Netherlands.

42. N Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. J. Am. Stat. Assoc. 1968, 63, 1379–1389.

43. Ntwali, D., Ogwang, B., & Ongoma, V. (2016). The impacts of topography on spatial and temporal rainfall distribution over Rwanda based on the WRF model. Atmospheric and Climate Sciences, 6(2), 145-157.

44. Ndakize Joseph, S., Bonfils, S., Ndiwa Joshua, N., Didier, N., Bethwel Kipkoech, M., Abdou, S., & Michel, R. (2022). Rainfall variability and trends over Rwanda. Journal of Climate Change and Sustainability, 4(1), 26–34. https://doi.org/10.20987/jccs.04.06.202.

45. Uwizewe, C., Jianping, L., Habumugisha, T., & Bello, A. A. (2024). Investigation of the historical trends and variability of rainfall patterns during the March-May Season in Rwanda. Atmosphere, 15(5), 609.

46. Jonah, K., Wen, W., Shahid, S., Ali, M. A., Bilal, M., Habtemicheal, B. A., Iyakaremye, V., Qiu, Z., Almazroui, M., Wang, Y., Joseph, S. N., & Tiwari, P. (2021). Spatiotemporal variability of rainfall trends and influencing factors in Rwanda. Journal of Atmospheric and Solar-Terrestrial Physics, 219. https://doi.org/10.1016/j.jastp.2021.105631.

47. Sebaziga, N. J., Safari, B., Ngaina, J. N., & Ntwali, D. (2025). Observed trends and variability of seasonal extreme rainfall indices and projected changes in Rwanda. Theoretical and Applied Climatology, 156(5), 245.

48. Chanza, N. (2017). Limits to climate change adaptation in Zimbabwe: Insights, experiences and lessons. In Limits to climate change adaptation (pp. 109-127). Cham: Springer International Publishing.

49. Sunday, F. X., Uwineza, Y., Ndahayo, E., Ishimwe, I. P., Rajeswaran, L., & Maryse, U. (2024). Exploring the benefits, challenges, and rationale behind growing crops of choice among farmers in Rwanda. Journal of Agriculture and Food Sciences, 22(1), 133-157.

50. Mihrete, T. B., & Mihretu, F. B. (2025). Crop Diversification for Ensuring Sustainable Agriculture, Risk Management, and Food Security. Global Challenges, 2400267.

51. Kato, T., Rambali, M., & Blanco-Gonzalez, V. (2021). Strengthening climate resilience in mountainous areas. OECD Development Co-operation Working Papers.

52. Gardner, J. S., & Dekens, J. (2007). Mountain hazards and the resilience of social–ecological systems: lessons learned in India and Canada. Natural Hazards, 41, 317-336.

53. Nyaupane, G. P., & Chhetri, N. (2009). Vulnerability to climate change of nature-based tourism in the Nepalese Himalayas. Tourism Geographies, 11(1), 95-119.

54. Africa, P. (2018). Rwanda. USAID, November 14.

55. Ligsay, A., Telle, O., & Paul, R. (2021). Challenges to mitigating the urban health burden of mosquito-borne diseases in the face of climate change. International Journal of Environmental Research and Public Health, 18(9), 5035.

56. Yadav, N., & Upadhyay, R. K. (2023). Global effect of climate change on seasonal cycles, vector population, and rising challenges of communicable diseases: a review. Journal of Atmospheric Science Research, 6(1).

57. Ogutu-Ohwayo, R., Natugonza, V., Musinguzi, L., Olokotum, M., & Naigaga, S. (2016). Implications of climate variability and change for African lake ecosystems, fisheries productivity, and livelihoods. Journal of Great Lakes Research, 42(3), 498-510.

58. Musinguzi, L., Efitre, J., Odongkara, K., Ogutu-Ohwayo, R., Muyodi, F., Natugonza, V., ... & Naigaga, S. (2016). Fishers' perceptions of climate change, impacts on their livelihoods and adaptation strategies in environmental change hotspots: a case of Lake Wamala, Uganda. Environment, Development and Sustainability, 18, 1255-1273.

59. Dinku, T., Hailemariam, K., Maidment, R., Tarnavsky, E., & Connor, S. (2014). Combined use of satellite estimates and rain gauge observations to generate high-quality historical rainfall time series over Ethiopia. International Journal of Climatology, 34(7), 2489-2504.

60. Siebert, A., Dinku, T., Vuguziga, F., Twahirwa, A., Kagabo, D. M., delCorral, J., & Robertson, A. W. (2019). Evaluation of ENACTS-Rwanda: A new multi-decade, high-resolution rainfall and temperature data set—Climatology. International Journal of Climatology, 39(6), 3104-3120.

61. Sebaziga, J. N., Safari, B., Ngaina, J. N., & Ntwali, D. (2024). Spatial variability of seasonal rainfall onset, cessation, length and rainy days in Rwanda. Theoretical and Applied Climatology, 155(8), 7591-7608.

62. Sebaziga, J. N., Twahirwa, A., Kazora, J., Rusanganwa, F., Mbati, M. M., Higiro, S., ... & Niyitegeka, J. M. V. (2023). Spatial and temporal analysis of rainfall variability and trends for improved climate risk management in Kayonza District, Eastern Rwanda. Advances in Meteorology, 2023(1), 5372701.

63. Sneyers, R. (1991). On the statistical analysis of series of observations (No. 143, pp. 192-pp).

64. Tan, C., Yang, J., & Li, M. (2015). Temporal-spatial variation of drought indicated by SPI and SPEI in Ningxia Hui Autonomous Region, China. Atmosphere, 6(10), 1399-1421.

65. Hamed, K. H., & Rao, A. R. (1998). A modified Mann-Kendall trend test for autocorrelated data. Journal of hydrology, 204(1-4), 182-196.

66. Serrano, A., Mateos, V. L., & Garcia, J. A. (1999). Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921–1995. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 24(1-2), 85-90.

67. Yue, S., Pilon, P., & Phinney, B. O. B. (2003). Canadian streamflow trend detection: impacts of serial and cross-correlation. Hydrological Sciences Journal, 48(1), 51-63.

68. Novotny, E. V., & Stefan, H. G. (2007). Stream flow in Minnesota: Indicator of climate change. Journal of Hydrology, 334(3-4), 319-333.

69. Datta, P., & Das, S. (2019). Analysis of long-term seasonal and annual temperature trends in North Bengal, India. Spatial Information Research, 27(4), 475-496.

70. Wuebbles, D., Easterling, D. R., Hayhoe, K., Knutson, T., Kopp, R., Kossin, J., ... & Wehner, M. (2016). Our globally changing climate.

71. Hoegh-Guldberg, O., Jacob, D., Taylor, M., Guillén Bolaños, T., Bindi, M., Brown, S., ... & Zhou, G. (2019). The human imperative of stabilizing global climate change at 1.5 C. Science, 365(6459), eaaw6974.

72. Lindsey, R., & Dahlman, L. (2020). Climate change: Global temperature. Climate. gov, 16, 1-5.

73. Gahlawat, I. N., & Lakra, P. (2020). Global Climate change and its effects. Integrated Journal of Social Sciences, 7(1), 14-23.

74. Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M., & Karki, P. (2022). Climate change and the hydropower sector: A global review. Wiley Interdisciplinary Reviews: Climate Change, 13(2), e757.

75. Chen, H., Liu, H., Chen, X., & Qiao, Y. (2020). Analysis on impacts of hydro-climatic changes and human activities on available water changes in Central Asia. Science of the Total Environment, 737, 139779.

76. Chu, H., Wei, J., Qiu, J., Li, Q., & Wang, G. (2019). Identification of the impact of climate change and human activities on rainfall-runoff relationship variation in the Three-River Headwaters region. Ecological Indicators, 106, 105516.