Analysis of spatio-temporal climate variability of a shallow lake catchment in Tanzania

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ABSTRACT

This study analyzed the trends and spatio-temporal variability in rainfall and temperature, and the length of the rainy season (LRS) in the Lake Manyara catchment, Tanzania, covering a period between 1988 and 2018 using stations and satellite climate product. The Mann-Kendall statistical test, Sen’s slope estimator, and inverse distance weighting interpolation techniques were used to detect the trends, magnitude of trends and spatial distribution of rainfall and temperature. A modified Stern’s method and water balance concept were used for rainfall onset, cessation and LRS analysis, while standardized precipitation index (SPI) was used to investigate the wetness or dryness of the area. The results showed high variability and decreasing trend (4 mm/y) in annual rainfall, and non-significant increasing trend for minimum and maximum temperature. Rainfall increased from the Western to the Northern part of the catchment whereas reversal pattern was noticed for temperature. The SPI shows a signal of normal condition (about 65%) for all stations – with few years showing evidence of wetter and drier conditions. The LRS showed a decreasing trend indicating a potential negative influence on rain-dependent activities. There is a need, therefore, for adaptation measures such as improving water productivity and irrigation at the farm and catchment level.

Key words | Mann-Kendall test, rain-dependency, satellite climate product, spatial climate variability, standardized precipitation index, water balance concept

INTRODUCTION

Climate variability and changes have been projected to increase by various climate modeling systems. These changes have been associated with increase in anthropogenic greenhouse gases (GHGs) emissions leading to global warming. Other anthropogenic factors such as industrial activities, economic and population growth are also known to contribute to climatic variabilities (Pachauri et al. 2014). Anthropogenic activities such as industrial and agricultural activities have contributed significantly to the increased in atmospheric concentrations of greenhouse gases since the 20th century (Solomon et al. 2009). Undeniable evidence suggest that the impact of greenhouse gases on the earth’s atmosphere is significant and inevitable (Hartmann et al. 2017). The GHGs emissions impacts are associated with changes in various climatic parameters such as temperature and rainfall that may lead to catastrophic environmental and socioeconomic events including water scarcity, health problems, energy deficiencies, poor livelihoods, food insecurity, human insecurity, poor forestry practices, poor agricultural yields and low economic growth (Holman 2005; Chang’a et al. 2017).

Precipitation and temperature trends have a direct influence on the management of water resources. Various studies indicate that the changing patterns of precipitation have a...
direct impact on the catchments (Jones et al. 2015). Various studies report a considerable attention on rainfall and temperature variability related to the water resources. Trend detection in climate time series is one of the interesting research areas in climatology in recent years (Zarenistanak et al. 2014). Spatial- and temporal-scale rainfall trend analysis has been of concern since the past century because of the increased attention given to the global climate change by the scientific community (Haigh 2010). Trend analysis of precipitation and temperature series research has also gained substantial attention lately due to improved capabilities to explore the climatic variability and extreme climatic events (Nemwini & Kabanda 2013).

Sub-Saharan African countries are more vulnerable to the anticipated changes and variability in climatic trends, specifically in the intensifications of extreme events such as floods, drought and heat waves (IPCC 2018). These changes and variability of climate have shown unequal distribution from place to place. Some parts have experienced significant reduction in precipitation resulting in drought, while others receive increased rain that may result in flooding (Kijazi & Reason 2009). These anomalies are expected to continue or vary in the near future. Several studies have indicated that the increasing tendency of precipitation in the wet areas and decreasing tendency in the dry regions will lead to the persistence of floods and droughts (Deus & Gloaguen 2013; Trammell et al. 2013).

In Tanzania, for example, heterogeneous climate condition is experienced due to the complicated topographical patterns, numerous inland water bodies, variation in vegetation types and land–ocean contrasts (Kijazi & Reason 2009). This complexity has led to experiences of the spatial climatic variation – a relatively small change in distances provides substantial variation (Karim et al. 2016). Furthermore, various reports from the Intergovernmental Panel on Climate Change (IPCC) have insisted on the local and regional scale researches on climate variability and change to provide necessary information in assessing the impacts of climate variability and change on human and natural resources for sustainable development (Mamuye & Kebebewu 2018).

In Lake Manyara catchment, agriculture and tourism activities that employ and provide income for the population. The catchment supports irrigated agricultural activities, livestock keeping and wildlife conservation. Intensification of human activities and climate variability and change has introduced stresses on water use in Lake Manyara catchment due to the increased freshwater demands and temporal variability of surface water flow. Water-related conflicts have been recorded in some communities in the catchment between pastoralist and farmers. Several studies have investigated spatial and temporal analysis of rainfall and temperature extreme indices in Tanzania (Zorita & Tilya 2002; Kijazi & Reason 2009; Lema & Majule 2009; Chang’a et al. 2017). However, these studies assessed large-scale climate drivers without examining climate change and variability on the catchment on a local scale. Therefore, this study aims at analyzing the temporal trend and spatial distribution of rainfall and temperature at the catchment level using different contexts.

METHODS

Study area

Lake Manyara is located within two regions of Tanzania – Arusha and Manyara, and five districts – Arusha, Babati, Monduli, Karatu and Mbulu. The Lake Manyara sub-basin (Figure 1(b)) comprises of three catchments namely, Lake Manyara (Figure 1(c)), Lake Burunge and Lake Babati. This study was conducted in the Lake Manyara catchment, which is at the upper part of Lake Manyara sub-basin with an area coverage of about 7,920 km² (Attarzadeh et al. 2013). It’s located between latitude 3°00’ S to 5°30’ S and longitude 35°30’ E and 37°00’ E. Lake Manyara has no outflow, no outlet to the sea or other lakes and is believed to be sensitive to climate variabilities (Olaka et al. 2010). Climatologically, the region is characterized by bimodal rainy season with short rains between October and December and long rains between March and May. The southern part of the catchment is in the transition area with both unimodal and bimodal characteristics. The mean annual rainfall in the catchment is approximately 790 mm with an annual mean temperature of 19.4 °C (Yanda & Madulu 2005; Bachofer et al. 2014). The most dominant types of land use and land cover in the Manyara catchment are bushland, woodland, grassland, cultivated land and bare soil (Maerker et al. 2015). According to
Ngana et al. (2003), during the dry season, herds of livestock migrate to the lake from other areas, thereby increasing pressure on the water resources at the catchment. Despite the pasture in the area, the most frequently cultivated crop types are bananas, maize, rice and vegetables (authors’ observation) and most of the crops grown in this area have high demand for water, and belongs to the group of the thirstiest crops (Lipper & Raney 2007). Both perennial and non-perennial rivers bring water to the lake while the main tributaries of Lake Manyara catchment are Mto wa Mbu, Mto wa Simba and Kirurumu River.

Climate data

Daily rainfall and temperature data for 32 rainfall weather stations (Table 1) were used in this study, however observed data were available for only three stations: Mbulu District Office, Monduli and Babati. The available rainfall data covering the period 1988–2018 were collected from the Tanzania Meteorological Agency (TMA). Due to lack of observed stations data for the rest of the weather stations outlined in Table 1, satellite-based rainfall and temperature products for the same period were collected and utilized. The satellite-based rainfall and temperature data were obtained from the NASA Langley Research Center (LaRC) POWER project (https://www.power.larc.nasa.gov/data-access-viewer). The NASA POWER data ability in reproducing well the climate pattern of stations data have been previously demonstrated (Larbi et al. 2018). All data were then quality controlled to check outliers and negative rainfall values.

Figure 1 | Map of Lake Manyara catchment (a) within Tanzania (c) showing elevation and weather stations.
Trends and magnitude of trend detection

An investigation of the annual and monthly series, and trend analysis was performed for each station and for the entire catchment. The annual rainfall and temperature trends were computed using the Mann-Kendall (MK) statistical test at the confidence level of 95% (Yavuz & Erdogan 2014). The MK statistic tests for whether to accept the alternative hypothesis (Ha) which states the presence of a monotonic trend or to accept the null hypothesis (Ho) which states that no monotonic trend occurred were used. The approach has been suggested by the World Meteorological Organization (WMO) as the best approach to assess trends in environmental data time series (Huret & Legras 2014). The method is simple, robust against outliers and can handle missing values (Gao et al. 2011). The MK tests

| No. | Station name                      | Station # | Longitude (deg.) | Latitude (deg.) | Elevation (m) |
|-----|-----------------------------------|-----------|------------------|-----------------|---------------|
| 1   | Mbulu District Office             | 9335001   | 35.55            | -3.87           | 1,737         |
| 2   | Kainam                            | 9335009   | 35.52            | -3.93           | 1,881         |
| 3   | Idulu Ginnery                     | 9335011   | 35.75            | -3.95           | 1,005         |
| 4   | Mbulumbulu                        | 9335024   | 35.78            | -3.27           | 1,828         |
| 5   | Mbulumbulu 111                    | 9335026   | 35.82            | -3.27           | 1,549         |
| 6   | Mbulumbulu iv                     | 9335027   | 35.83            | -3.28           | 1,508         |
| 7   | Mbulu devp farm                   | 9335029   | 35.52            | -3.88           | 1,828         |
| 8   | MtowaMbu Game Department          | 9335030   | 35.83            | -3.30           | 1,066         |
| 9   | Mtowambu Agriculture office       | 9335032   | 35.85            | -3.37           | 975           |
| 10  | Lake Manyara Maji                 | 9335034   | 35.85            | -3.4            | 999           |
| 11  | Karatu Agricultural               | 9335046   | 35.70            | -3.35           | 999           |
| 12  | Tarosero Estate                   | 9336007   | 36.43            | -3.30           | 1,402         |
| 13  | Rasharasha Estate                 | 9336008   | 36.47            | -3.32           | 1,524         |
| 14  | Monduli                           | 9336014   | 36.45            | -3.32           | 1,585         |
| 15  | Eluanata Dam                      | 9336019   | 36.28            | -3.40           | 1,371         |
| 16  | Ardaia 1                          | 9336022   | 36.40            | -3.42           | 1,371         |
| 17  | Ardaia 11                         | 9336023   | 36.35            | -3.45           | 1,371         |
| 18  | Ardaia 111                        | 9336024   | 36.28            | -3.42           | 1,371         |
| 19  | Ardaia iv                         | 9336025   | 36.39            | -3.38           | 1,371         |
| 20  | Ardaia v                          | 9336026   | 36.40            | -3.35           | 1,371         |
| 21  | Ardaia Ranch                      | 9336043   | 36.33            | -3.5            | 2,658         |
| 22  | Mayoka-moya                       | 9336047   | 36.00            | -3.5            | 1,071         |
| 23  | Mangola                           | 9336050   | 36.32            | -3.60           | 999           |
| 24  | Lente Estate                      | 9336063   | 36.13            | -3.47           | 999           |
| 25  | Singu Estates                     | 9435002   | 35.67            | -4.20           | 1,737         |
| 26  | Margaret Coffee Estates           | 9435009   | 35.63            | -4.12           | 1,565         |
| 27  | Mbogo Estates                     | 9435012   | 35.68            | -4.10           | 1,127         |
| 28  | Dukumomaay                        | 9435023   | 35.5             | -4.13           | 2,133         |
| 29  | Magugu Primary School             | 9435029   | 35.77            | -4.02           | 999           |
| 30  | Babati                            | 9435030   | 35.75            | -4.22           | 999           |
| 31  | Darakuta Ranch                    | 9435033   | 35.58            | -4.00           | 1,128         |
| 32  | Magugu TPRI                       | 9435035   | 35.77            | -4.00           | 999           |

L. O. Nyembo et al. | Climate status of Lake Manyara catchment in Tanzania | Journal of Water and Climate Change | in press | 2020
(Equations (1)–(5)) calculates the slope of the line formed by plotting the variable of interest against time, but only considers the sign and not the magnitude of this slope. The MK statistic $S$ is computed as follows:

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

where $x_j$ and $x_k$ are sequential data values for the time series data of length $n$. The $\text{sgn}$ series is defined as:

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

whenever there is an identical and independent dataset distribution, the mean of $S$ is zero whereas the variance of $S$ is given by Equation (3).

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18}$$

where $t_i$ is the extent of any given tie. $\sum t_i$ denotes the summation over all ties and is only used if the data series contain tied values. The standard normal variate $Z$ is calculated as indicated in Equation (4):

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

The trend is decreasing if $Z$ is negative and increasing if $Z$ is positive. $H_0$, the null hypothesis of no trend, is rejected if the absolute value of $Z$ is greater than $Z_1 - \alpha/2$, where $Z_1 - \alpha/2$ is obtained from the standard normal cumulative distribution tables.

The Sen’s slope estimator (Equations (5) and (6)) was used to determine the magnitude of the trends after obtaining the direction of the trend with the Mann–Kendall test. The method uses a linear model to calculate the change of slope, and the variance of the residuals should be constant in time (Sen 1968).

$$Q_i = \frac{(X_i - X_k)}{(i - k)} \text{ for all } k < j \text{ and } i = 1, \ldots, N$$

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

where $Q_i$ is the slope between data points $X_i$ and $X_k$. $Q_{med}$ is median slope estimator which reflects the direction of the trend in the data.

Spatial distribution analysis of rainfall and temperature

The inverse distance weighting (IDW) interpolation technique was used to spatially interpolate the rainfall and temperature patterns between the observation stations using the Quantum Geographic Information System (QGIS). The IDW averages the weights of observation values after which the interpolated points’ neighbors have been identified (Shepard 1968). The averaged values of annual precipitation and temperature calculated over 30 years for the 32 weather stations were used as the input data in the QGIS software (Abolverdi et al. 2016). The IDW method is given by Equation (7) as follows:

$$w(d) = \frac{1}{d^p}, \quad p > 0$$

where $p$ is the number of points, $d$ is the distance between points, and $w$ is the weighting function.

Rainfall anomaly and LRS analysis

An investigation of dry, normal and wet years in the Lake Manyara catchment were performed using the Standardized Precipitation Index (SPI) approach for the time intervals of 12 months McKee et al. (1993). The classification scheme suggested by the study of McKee et al. (1993) (Table 3) was used to determine dry or wet intensity over the study area.

The onset and cessation dates were computed for the Babati, Monduli, Karatu and Mbulu District office stations.
for each year based on a modified method defined by Stern et al. (1981). In the present study, the rainfall onset date is defined as the date with the total of at least 20 mm of rainfall within 2 consecutive days, in which the starting day must be wet (at least 0.85 mm rainfall recorded), followed by a no dry period of seven (7) or more consecutive days occurring in the following 30 days. The cessation date was computed based on the Instat© concept of the water balance (i.e. the first date the soil profile is empty after a given date) which is calculated for each year. The length of the rainy season (LRS) is then obtained from the difference between the rainfall onset and cessation date.

RESULTS AND DISCUSSION

Monthly mean rainfall and temperature

The results for the mean monthly rainfall, maximum and minimum temperature for Babati, Monduli and Mbulu

![Figure 2](https://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2020.197/674107/jwc2020197.pdf)
District office meteorological stations within the Lake Manyara catchment for the period 1988–2018 are presented in Figure 2. The results for rainfall (Figure 2(a)–2(c)) show two rainy season periods between March and May (MAM season), and between October and December (OND season). Between June and September (JJAS), the dry condition exists over the catchment. The maximum temperature (Figure 2(d)–2(f)) indicates the highest temperature during the month of October and the lowest for the months of June and July. These conditions can be caused by various factors, including topography and other local factors. The results for the minimum temperature (Figure 2(g)–2(i)) show the highest temperature in December and the lowest temperature for the three stations in July. The present study found that the status of catchment average rainfall from 1988 to 2018 was 780 mm, and the maximum and minimum temperatures were 27.8 °C and 15.0 °C, respectively.

Spatial-temporal variability of rainfall and temperature

The results for the annual series plots of rainfall for the Lake Manyara catchment (Figure 3), and for the Eastern, Western and the Southern part of the catchment (see Figure S1 in the attached Supplementary Material) show a year to year variability with a mean annual value of 780 mm between 1988 and 2018. The results of annual mean of maximum temperature (Figure 4) and annual mean of minimum temperature (Figure 5) indicate high variability within 30 y. The average

Figure 3 | Annual rainfall distribution for (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of entire catchment for the period 1988–2018.
of the annual minimum temperature showed an increasing trend at the rate of 0.025 °C/yr compared to the maximum temperature that showed a slight yearly decrease in trend in all stations for the entire catchment. Similar to the present study, annual rainfall, maximum and minimum temperature in several studies done elsewhere showed variations (Alemu et al. 2019).

The spatial distribution of the annual rainfall reveals that the highest amount (>700 mm) is received at the north part (Ngorongoro and Karatu) of the catchment (Figure 6), while the lowest rainfall amount of about 600 mm is noticed in the Eastern part of the catchment. This observed difference in spatial rainfall might be due to the high elevation in the north where orographic effect seems to be more dominant compared to other regions. In case of temperature (Figure 7), the spatial distribution reveals that annual average of both maximum and minimum temperature is highest in the eastern part (around Monduli) and lowest in the northern regions (Ngorongoro and Karatu) of the catchment. This may be attributed to the high elevation of Ngorongoro and Karatu at the northern part of the catchment. This variability in climate has implication in various field including hydrology and agriculture due to over-dependence on agriculture and livestock keeping in the catchment.

Trends of rainfall and temperature

The results for the MK trend analysis (Table 2a) of rainfall indicate a non-significant decreasing trend for the three climate stations and the entire catchment. A decreasing trend in the annual rainfall at the rate of
Figure 5 | Mean annual minimum temperature for (a) Babati, (b) Monduli, (c) Mbulu District office, and (d) the entire catchment from 1988 to 2018.

Figure 6 | Spatial distribution of mean annual rainfall temperature at the Manyara catchment for the period 1988–2018.
4.3 mm/y and 5.0 mm/y was noticed for the Babati and Monduli stations respectively, while a slightly decreasing trend was noticed for the Mbulu station. The entire catchment also showed a decreasing trend in annual rainfall at a rate of 5 mm/y. The MK test also computed for the maximum temperature reveals a non-significant increasing trend in two out of the three stations (Table 2b). Unlike maximum temperature, the mean annual minimum temperature showed a significant positive trend for the three stations (Table 2c). This means that during the night, temperature increase significantly due to the release of longwave radiation. The minimum temperature showed an increasing trend at the rate of 0.024 °C/y compared to the maximum temperature which showed a slight yearly decrease in trend in all station and for the entire catchment. Other studies indicate no statistically significant trends in annual rainfall (Mengistu et al. 2014). Likewise, warming trends of mean annual
minimum temperatures have been reported to be more pronounced than minimum temperatures (Tesso et al. 2012; Chang’a et al. 2017).

**Standardized precipitation index results**

The analysis was focused on understanding the sensitivity of SPI to rainfall deviation from the annual mean and discovered the wet, normal and dry condition in the area. The SPI analysis results (Table 3 and Figure 8) based on McKee et al. (1993) classification shows the signal of normal conditions in all stations with few years showing evidence of wetter and drier conditions. From the SPI results, more positive values were obtained indicating a wet year in the catchment mostly in the year of 2002 and 2006 whereas the more negative values obtained in the year of 1993 and 2003. Also, the SPI results revealed that in the catchment, drought conditions were sustained more compared to wet condition. Furthermore, the SPI trends showed an increase in the intensity of drought in many stations.

### Table 3 Classification of the SPI and the corresponding number of years for each station in Lake Manyara catchment from 1988 to 2018

| SPI values       | Condition       | (a) Babati | (b) Monduli | (c) Mbulu District office |
|------------------|-----------------|-----------|-------------|--------------------------|
| 2.00 and above   | Extremely wet   | 1         | 0           | 0                        |
| 1.50 to 1.99     | Severely wet    | 2         | 2           | 0                        |
| 1.00 to 1.49     | Moderately wet  | 1         | 3           | 6                        |
| 0.99 to −0.99    | Normal          | 20        | 20          | 19                       |
| −1.00 to −1.49   | Moderate drought| 3         | 2           | 2                        |
| −1.50 to −1.99   | Severe drought  | 2         | 3           | 4                        |
| −2.0 and less    | Extremely drought| 1       | 1           | 0                        |

*Source: McKee et al. (1993).*
within the region. This has also been demonstrated by a number of other studies: increase in drought severity associated with higher water demand as a result of evapotranspiration. SPI has the advantage of being multiscale, which is crucial for drought analysis and monitoring (Beguería et al. 2014; Yu et al. 2014).

Rainfall onset, cessation and length of the rainy season

Rainfall in Lake Manyara catchment exhibit variability for both time and space. The start and end of rainfall seasons for the period from 1988 to 2018 are given in Table 4. The results show inconsistency and high variations in the start

| Year | Onset | Cessation |
|------|-------|-----------|
|      | Karatu | Babati | Mbulu District office | Monduli | Karatu | Babati | Mbulu District office | Monduli |
| 1989 | 25-Nov | 02-Jan | 07-Dec | 26-Dec | 11-May | 07-May | 14-May | 23-May |
| 1990 | 12-Nov | 12-Nov | 29-Nov | 08-Dec | 17-May | 06-May | 30-Apr | 09-May |
| 1991 | 15-Nov | 11-Dec | 09-Dec | 19-Dec | 11-May | 01-May | 29-Apr | 15-Apr |
| 1992 | 18-Nov | 30-Jan | 24-Nov | 09-Apr | 15-Apr | 15-Apr | 18-May | 08-May |
| 1993 | 01-Jan | 20-Nov | 19-Nov | 10-Nov | 20-May | 15-Apr | 15-Apr | 17-Apr |
| 1994 | 02-Nov | 16-Nov | 06-Jan | 18-Dec | 18-Apr | 15-Apr | 03-May | 15-Apr |
| 1995 | 30-Oct | 07-Nov | 30-Nov | 23-Nov | 15-Apr | 24-May | 03-Jun | 26-May |
| 1996 | 27-Nov | 26-Dec | 02-Feb | 17-Feb | 28-May | 28-Apr | 13-May | 29-Apr |
| 1997 | 16-Nov | 17-Nov | 05-Apr | 17-Nov | 27-Apr | 27-Apr | 25-Apr | 05-Jun |
| 1998 | 04-Dec | 17-Nov | 02-Jan | 17-Nov | 05-Jun | 15-Apr | 19-May | 26-May |
| 1999 | 29-Nov | 01-Dec | 04-Dec | 17-Nov | 15-Apr | 15-Apr | 17-Apr | 05-Jun |
| 2000 | 07-Nov | 08-Feb | 23-Nov | 17-Nov | 20-May | 21-Apr | 17-Apr | 25-Apr |
| 2001 | 18-Nov | 21-Nov | 21-Nov | 15-May | 15-Apr | 15-Apr | 03-May |
| 2002 | 28-Oct | 06-Nov | 21-Nov | 22-Oct | 15-Apr | 15-Apr | 15-Apr |
| 2003 | 29-Oct | 06-Nov | 06-Nov | 23-Oct | 15-Apr | 21-Apr | 15-Apr |
| 2004 | 23-Nov | 09-Dec | 05-Jan | 03-Feb | 15-Apr | 15-Apr | 01-May |
| 2005 | 18-Dec | 21-Nov | 26-Nov | 25-Dec | 30-Apr | 21-Apr | 02-May |
| 2006 | 23-Nov | 28-Nov | 02-Dec | 16-Oct | 03-May | 15-Apr | 19-May |
| 2007 | 12-Oct | 06-Nov | 01-Nov | 21-Oct | 06-May | 18-Apr | 15-Apr |
| 2008 | 01-Jan | 19-Nov | 16-Jan | 12-May | 16-Apr | 07-May | 03-May |
| 2009 | 12-Nov | 29-Nov | 08-Nov | 06-Dec | 09-May | 29-Apr | 08-May |
| 2010 | 08-Nov | 07-Nov | 22-Nov | 10-Dec | 17-Apr | 15-Apr |
| 2011 | 24-Nov | 07-Dec | 14-Nov | 03-May | 21-Apr | 21-Apr |
| 2012 | 02-Nov | 09-Nov | 14-Nov | 03-May | 18-Apr |
| 2013 | 06-Dec | 13-Dec | 11-Dec | 12-Nov | 15-Apr | 15-Apr | 26-Apr |
| 2014 | 28-Nov | 21-Jan | 05-Feb | 03-Nov | 13-May | 15-Apr |
| 2015 | 03-Nov | 18-Nov | 15-Nov | 03-Nov | 15-Apr | 20-May |
| 2016 | 15-Nov | 09-Jan | 08-Jan | 17-Nov | 25-May |
| 2017 | 04-Nov | 12-Nov | 18-Nov | 19-Nov | 21-May | 15-Apr |
| 2018 | 18-Oct | 05-Jan | 22-Dec | 01-Jan | 15-Apr | 09-May | 15-Apr |
of the rainy season for the different locations. On average, the rainy season starts in November and end in April or May, although the catchment location seems to have both unimodal and bimodal mode of rainfall. The results also show that rainy season mostly starts early in the areas with high altitude around Karatu and Mbulu Agriculture stations and later in in the western part around Monduli. A similar pattern is followed during the cessation period.

The results of the length of seasonal rainfall (LRS) in days are presented in Figure 9 and show high variations and a decreasing trend except for the Mbulu District office station. These variations may be attributed to variability in the onset and cessation of the season. The Mbulu region shows the lowest LRS compared to other regions whereas Karatu indicates the highest LRS in the catchment. This variability in the duration of the rainy season suggests a possibility of the influence of climate change in these areas which may have implications on crop growth especially for crops which require long seasons of rain to mature. Other researchers have also found that in Tanzania, variations in the onset and cessation as well as length of the rainy season are usually insignificant (Kimambo & Ndeto 2018).

**CONCLUSIONS**

This study provides a clear picture of the spatial and temporal variability of rainfall and temperature, trends and length of

![Figure 9](https://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2020.197/674107/jwc2020197.pdf)

**Figure 9 |** Length of seasonal rainfall in days for (a) Karatu (b) Babati (c) Monduli and (d) Mbulu District office.
rainy season over the past 30 years for the Lake Manyara catchment in Tanzania. From this study, climate status of Lake Manyara catchment shows high variability in both spatial and temporal rainfall and temperature distribution. Decreasing trends in annual rainfall was found in most stations while the maximum and minimum temperature showed an increasing trend in the area. Locally, drought conditions showed a more enhanced signal compared to wet conditions. The periods of onset and end of the rainy season were inconsistent in most of the meteorological stations leading to high variability in the length of the rainy season.

The present study gives valuable information to authorities responsible for planning of water resources within the catchment and in the country at large. Therefore, climate change adaptation policies in the studied catchment may include measures such as changing the crop type and improving water productivity and irrigation practices at the farm and basin level.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Abolverdi, J., Ferdosifar, G., Khalili, D., Kamgar-Haghighi, A. A. & Physics, A. 2016 Spatial and temporal changes of precipitation concentration in Fars province, southwestern Iran. Meteorology Atmospheric Physics 128 (2), 181–196. Alemu, M. M., Bawoke, G. T. J. O. W. & Change, C. 2019 Analysis of spatial variability and temporal trends of rainfall in Amhara region, Ethiopia. Attarzadeh, A. A., Daneshvar, S. & Yargholi, B. 2015 Vol. 2 Water Availability Part B – Groundwater. Ministry of Water: United Republic of Tanzania. [2]. Bachofener, F., Quénéhervé, G. & Mäker, M. 2014 The delineation of Paleo-Shorelines in the Lake Manyara Basin using TerraSAR-X data. Remote Sensing 6 (3), 2195–2212. Beguería, S., Vicente-Serrano, S. M., Reig, F. & Latorre, B. 2014 Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. International Journal of Climatology 34 (10), 3001–3023. Chang’a, L. B., Kijazi, A. L., Luhunga, P. M., Ng’ongolo, H. K. & Mtongor, H. I. 2017 Spatial and temporal analysis of rainfall and temperature extreme indices in Tanzania. Atmospheric and Climate Sciences 07 (04), 525–539. Deus, D. & Gloaguen, R. J. W. 2015 Remote sensing analysis of lake dynamics in semi-arid regions: implication for water resource management. Lake Manyara, East African Rift. Northern Tanzania 5 (2), 698–727. Gao, Q., Ma, L., Liu, Y., Gao, X. & Nie, F. J. I. t. o. c. 2017 Angle 2DPCA: a new formulation for 2DPCA. 48 (5), 1672–1678. Haigh, M. J. 2010 Sustainable management of headwater resources. In Integrated Watershed Management. Springer. Hartmann, A., Gleeson, T., Wada, Y. & Wagener, T. 2017 Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. Proceedings of the National academy of Sciences of the United States of America 114 (11), 2842–2847. Holman, I. P. 2005 Climate change impacts on groundwater recharge- uncertainty, shortcomings, and the way forward? Hydrogeology Journal 14 (5), 637–647. Huret, N. & Legras, B. 2014 Assessment for Decision-Makers Scientific Assessment of Ozone Depletion: 2014 World Meteorological Organization United Nations Environment Programme National Oceanic and Atmospheric Administration National Aeronautics and Space Administration European Commission. Available from: https://hal-insu.archives-ouvertes.fr/insu-01130275 [56]. IPCC 2018 Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Geneva, Switzerland. Jones, J. R., Schwartz, J. S., Ellis, K. N., Hathaway, J. M. & Jawdy, C. M. J. O. H. R. S. 2015 Temporal variability of precipitation in the Upper Tennessee Valley. 3, 125–138. Karim, F., Petheram, C., Marvanek, S., Ticehurst, C., Wallace, J. & Hasan, M. J. H. P. 2016 Impact of climate change on floodplain inundation and hydrological connectivity between wetlands and rivers in a tropical river catchment. 30 (10), 1574–1593.
Kijazi, A. L. & Reason, C. J. C. 2009 Analysis of the 1998 to 2005 drought over the northeastern highlands of Tanzania. Climate Research 38, 209–223.

Kimambo, O. & Ndeto, E. L. 2018 Analysis of Start, End and Length of the Rainfall Season Seasons for Mbeya, Southwestern Highland in Tanzania.

Larbi, I., Hountondji, F., Annor, T., Agyare, W., Mwangi et al. 2007 Paying Farmers for Environmental Services. Food & Agricultural Org, Rome.

Lipper, L. & Raney, T. 2007 The State of Food and Agriculture, 2007: Paying Farmers for Environmental Services. Food & Agricultural Org, Rome.

Maerker, M., Quénéhervé, G., Bachofer, F. & Mori, S. 2014 Spatio-temporal trend analysis of rainfall and temperature extremes in the Vea Catchment, Ghana. 6 (4), 87.

Lema, M. & Majule, A. E. 2009 Impacts of climate change, variability and adaptation strategies on agriculture in semi arid areas of Tanzania: the case of Manyoni District in Singida Region. Tanzania. African Journal of Environmental ScienceTechnology 3 (8), 206–218.

McKee, T. B., Doesken, N. J. & Kleist, J. 1993 A simple DEM assessment procedure for gully system analysis in the Lake Manyara area, Northern Tanzania. Natural Hazards 79 (1), 235–253.

Mamuye, M. & Kebebewu, Z. a. 2008 Review on impacts of climate change on watershed hydrology. 8 (1).

Mckee, T. B., Doesken, N. J. & Kleist, J. 1993 The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society Boston, MA, pp. 179–183.

Mengistu, D., Bewket, W. & Lal, R. 2014 Recent spatiotemporal temperature and rainfall variability and trends over the Upper Blue Nile River Basin, Ethiopia. International Journal of Climatology 34 (7), 2278–2292.

Nenwini, S. & Kabanda, T. A. J. o. H. E. 2015 Trends and variability assessment of rainfall in Vhembe South Africa. 42 (2), 171–176.

Ngana, J. O., Mwalyosi, R. B. B., Madulu, N. F. & Yanda, P. Z. 2005 Development of an integrated water resources management plan for the Lake Manyara sub-basin, Northern Tanzania. Physics and Chemistry of the Earth, Parts A/B/C 28 (20–27), 1033–1038.

Olaka, L. A., Odada, E. O., Trauth, M. H. & Olago, D. O. 2010 The sensitivity of East African rift lakes to climate fluctuations. Journal of Paleolimnology 44 (2), 629–644.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Daihe, Q. & Dasgupta, P. 2014 Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

Sen, P. K. 1988 Estimates of the regression coefficient based on Kendall's Tau. Journal of the American Statistical Association 65 (324), 1379–1389.

Solomon, S., Plattner, G.-K., Knutti, R. & Friedlingstein, P. 2009 Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences 106 (6), 1704–1709.

Stern, R., Dennett, M. & Garbutt, D. J. o. C. 1981 The start of the rains in West Africa. 1 (1), 59–68.

Tesso, G., Emana, B. & Ketema, M. J. A. S. 2012 Analysis of vulnerability and resilience to climate change induced shocks in North Shewa, Ethiopia. 3 (06), 871.

Tramell, J. H., Jiang, X., Li, L., Liang, M., Li, M., Zhou, J., Fettzer, E. & Yung, Y. 2015 Investigation of precipitation variations over wet and dry areas from observation and model. Advances in Meteorology 2015, 1–9.

Yanda, P. Z. & Madulu, N. F. 2005 Water resource management and biodiversity conservation in the Eastern Rift Valley Lakes, Northern Tanzania. Physics and Chemistry of the Earth, Parts A/B/C 30 (11–16), 717–725.

Yavuz, H. & Erdoğan, S. 2011 Spatial analysis of monthly and annual precipitation trends in Turkey. Water Resources Management 26 (3), 609–621.

Yu, M., Li, Q., Hayes, M. J., Svoboda, M. D. & Heim, R. R. 2014 Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? International Journal of Climatology 34 (3), 545–558.

Zareinastani, M., Dhorde, A. G. & Kripalani, R. J. J. o. c. s. s. 2014 Trend analysis and change point detection of annual and seasonal precipitation and temperature series over southwest Iran. 123 (2), 281–295.

Zorita, E. & Tillya, F. F. 2002 Rainfall variability in Northern Tanzania in the march-may season (long rains) and its links to large-scale climate forcing. Climate Research 20, 31–40.

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