2021

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IWA Publishing

https://doi.org/10.2166/wcc.2020.197

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 a 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 a 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

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INTRODUCTION

Climate variability and changes have been projected to increase by various climate modeling systems. These changes have been associated with an 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 increase in atmospheric concentrations of greenhouse gases since the 20th century (Solomon *et al.* 2009). Undeniable evidence suggests 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

doi: 10.2166/wcc.2020.197

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 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 (Nenwiini & 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. 2015).

In Tanzania, for example, heterogeneous climate conditions are 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 local and regional scale research on climate variability and change to provide necessary information to assess 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 are the main economic 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 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 km^2 (Attarzadeh et al. 2015). 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 a 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

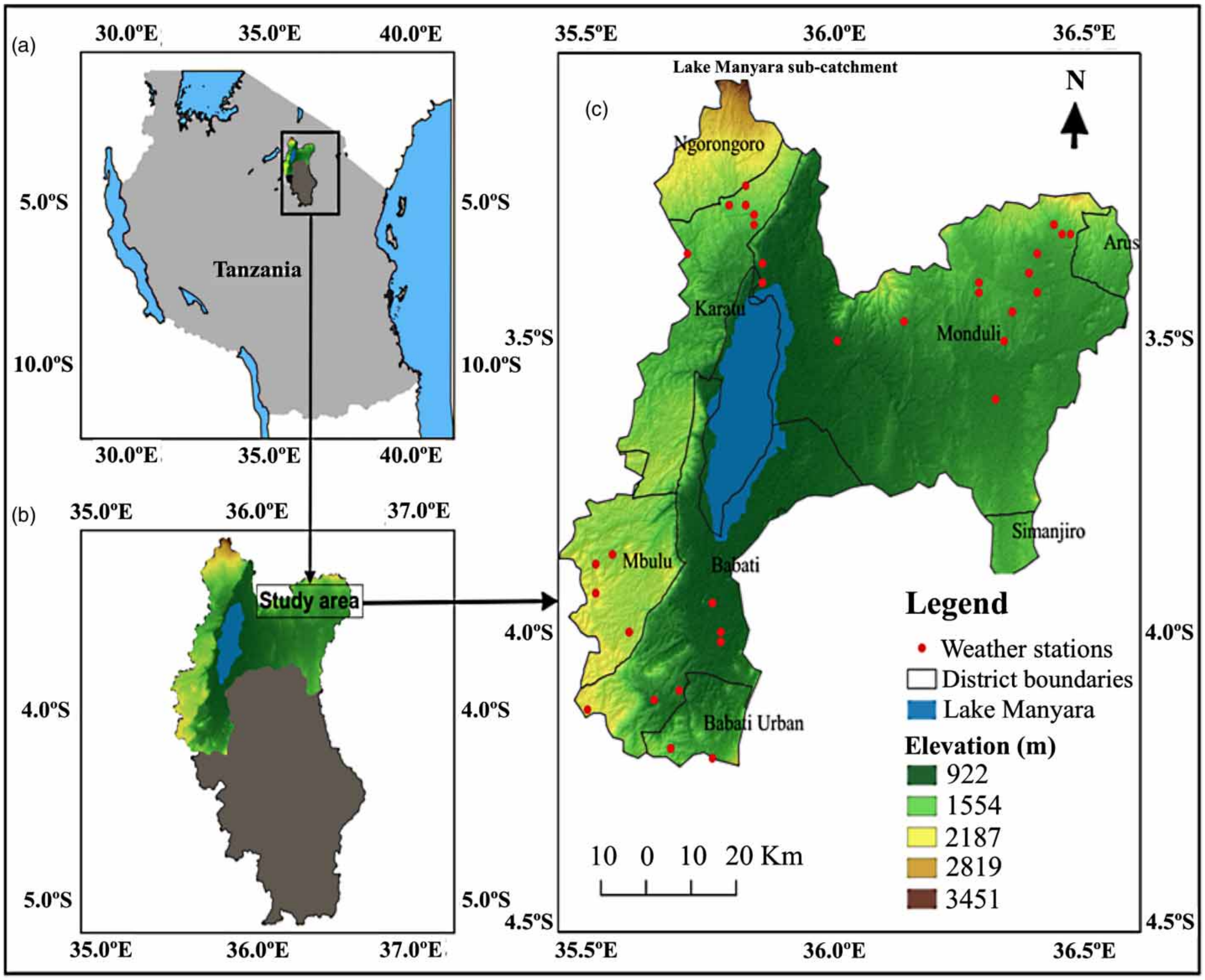

Figure 1 | Map of Lake Manyara catchment showing: (a) its location within Tanzania, (b) the study area, and (c) study area elevation and weather station locations.

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 belong 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 ability to successfully reproduce the climate pattern of stations data has been previously demonstrated (Larbi et al. 2018). All data were then quality controlled to check outliers and negative rainfall values.

Table 1 | List of meteorological stations whose data (1988–2018) were used in the present study

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	Ardai 1	9336022	36.40	−3.42	1,371
17	Ardai 11	9336023	36.35	−3.45	1,371
18	Ardai 111	9336024	36.28	−3.42	1,371
19	Ardai iv	9336025	36.39	−3.38	1,371
20	Ardai v	9336026	36.40	−3.35	1,371
21	Ardai 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	9431002	35.67	−4.20	1,737
26	Margaret Coffee Estates	9435009	35.63	−4.12	1,365
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

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 & Erdoğan 2011). 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. This 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.* 2017). The MK tests

(Equations (1)–(5)) calculate 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:

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

where x_j and x_k are sequential data values for the time series data of length n. The *sgn* series is defined as:

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

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).

$$Var(\text{S}) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \quad (3)$$

where t_i is the extent of any given tie. Σt_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):

$$Z = \begin{cases} \dfrac{S+1}{\sqrt{Var(S)}} & if \rightarrow S > 0 \\ 0 & if \rightarrow S = 0 \\ \dfrac{S-1}{\sqrt{Var(S)}} & f \rightarrow S < 0 \end{cases} \quad (4)$$

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 $Z1$- $\alpha/2$, where Z1-$\alpha/2$ 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).

$$Q_i = \frac{(X_j - X_k)}{(j-k)} \; for \; all \; k < j \; and \; i = 1, ..N \quad (5)$$

$$Q_{med} = \begin{cases} Q\left[\dfrac{(n+1)}{2}\right], & \text{where } N \text{ is odd} \\ Q\left(\dfrac{N}{2}\right) + Q\left[\dfrac{N+2}{2}\right], & \text{where } N \text{ is even} \end{cases} \quad (6)$$

where Q_i is the slope between data points X_j 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 were 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:

$$w\ (d) = \frac{1}{d^p}, \quad p > 0 \quad (7)$$

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 was 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 wet or dry 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

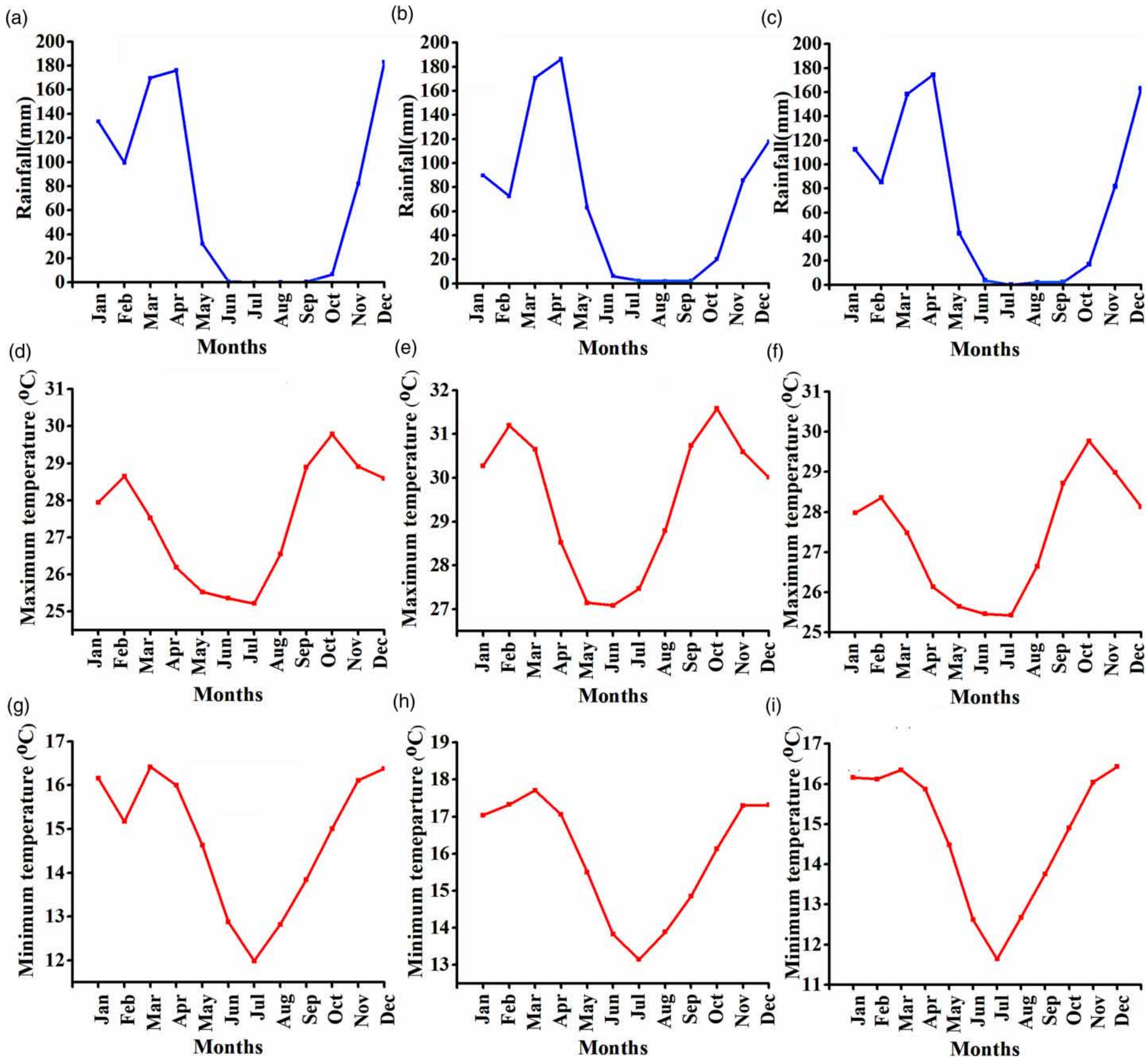

Figure 2 | Mean monthly cycle of rainfall (a–c), maximum temperature (d–f) and minimum temperature (g–i) for Babati (a, d, g), Monduli (b, e, h), and Mbulu District office (c, f, i) from 1988 to 2018.

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 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 years. The

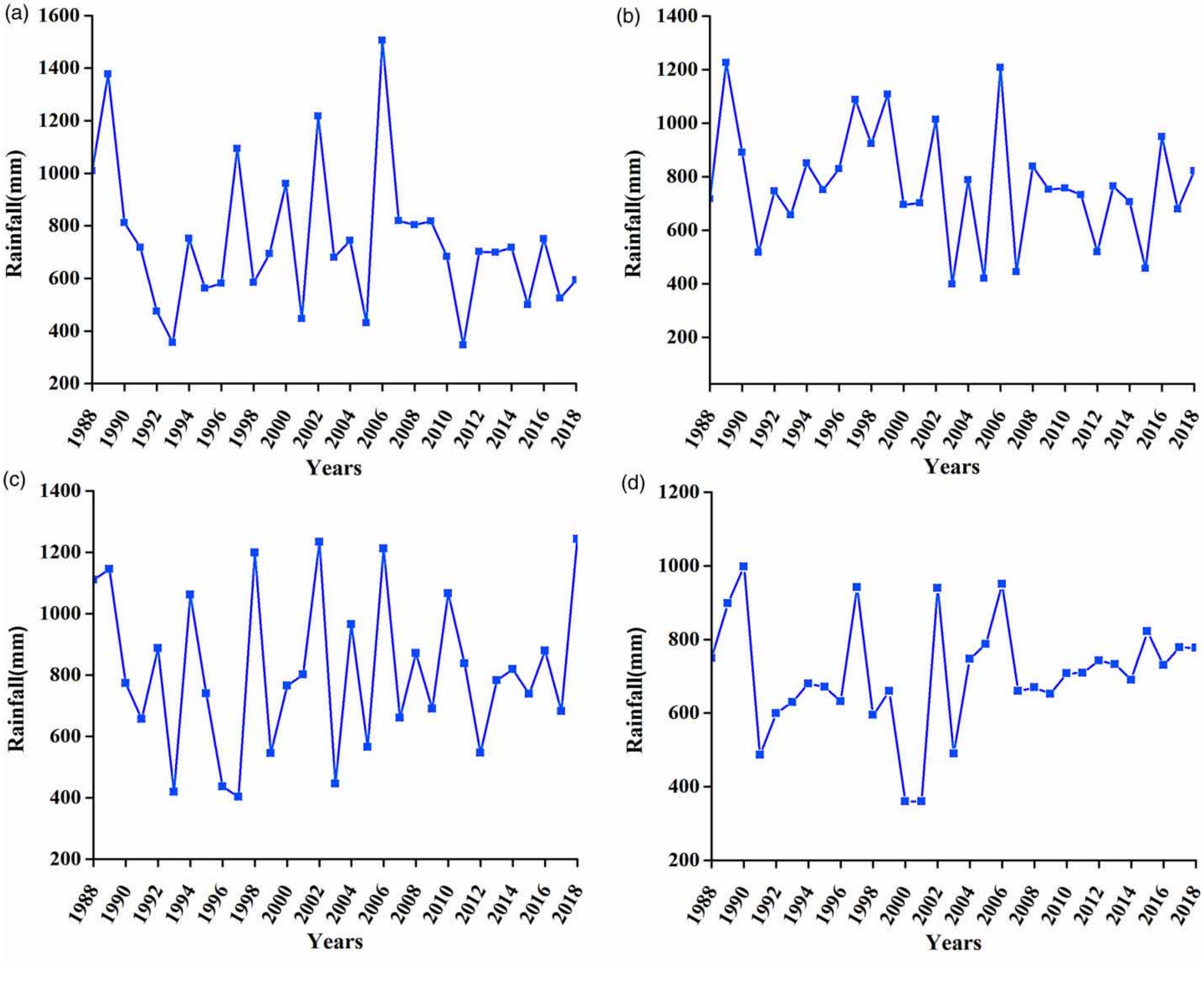

Figure 3 | Annual rainfall distribution for (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of entire catchment for the period 1988–2018.

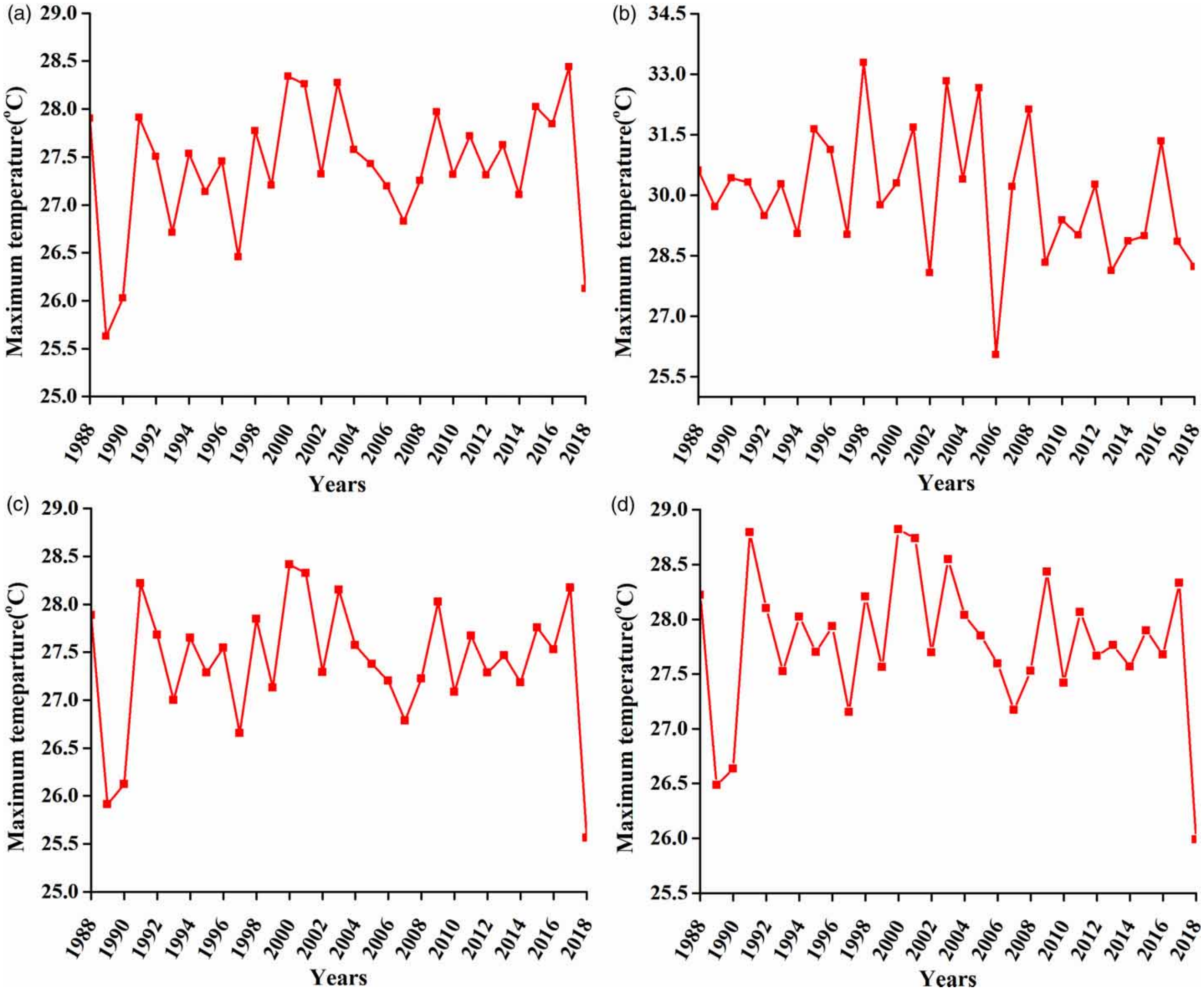

Figure 4 | Mean annual maximum temperature time series for (a) Babati, (b) Monduli, (c) Mbulu District office, and (d) the entire catchment for the period 1988–2018.

average of the annual minimum temperature showed an increasing trend at a rate of 0.025 °C/y compared to the maximum temperature which 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 & Bawoke 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 the case of temperature (Figure 7), the spatial distribution reveals that the 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 implications 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

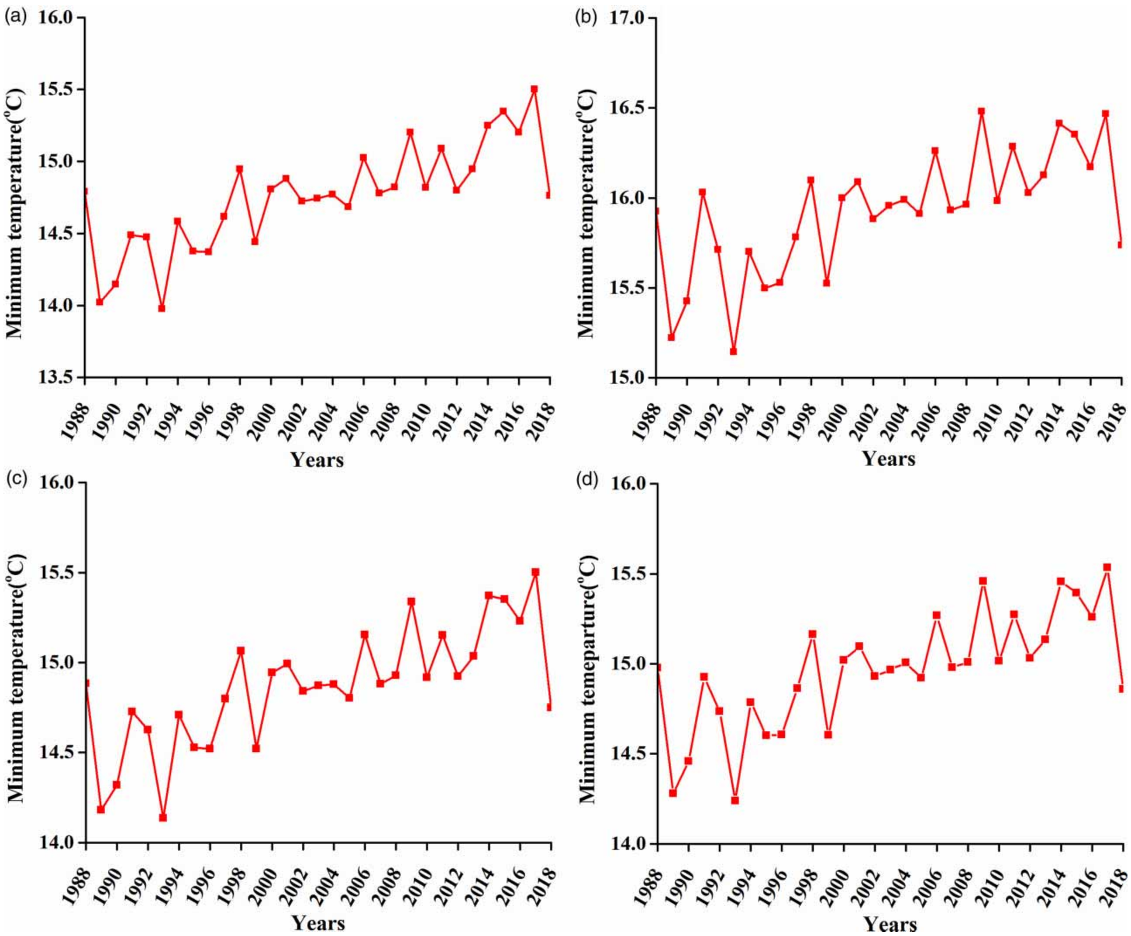

Figure 5 | Mean annual minimum temperature for (a) Babati, (b) Monduli, (c) Mbulu District office, and (d) the entire catchment from 1988 to 2018.

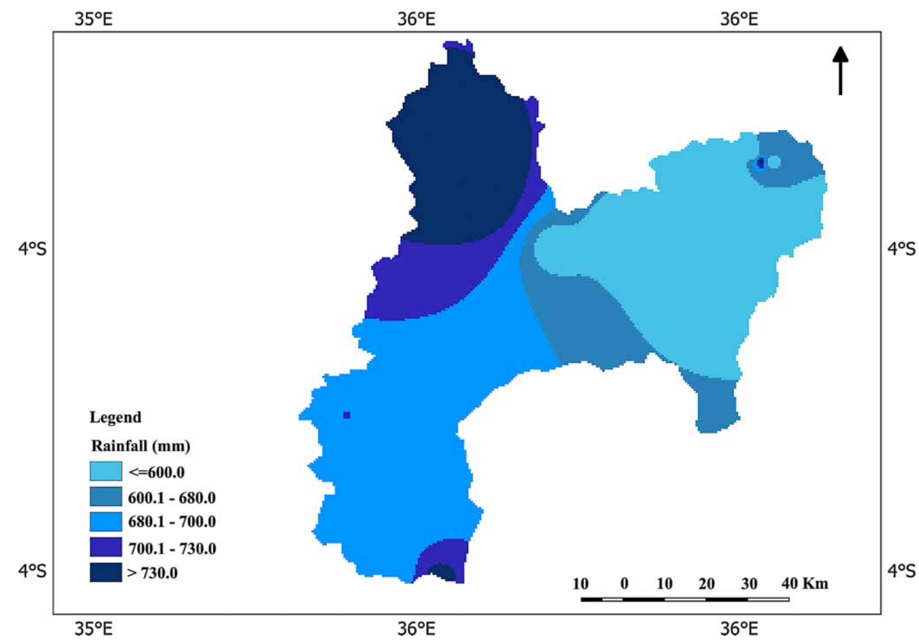

Figure 6 | Spatial distribution of mean annual rainfall temperature at the Manyara catchment for the period 1988–2018.

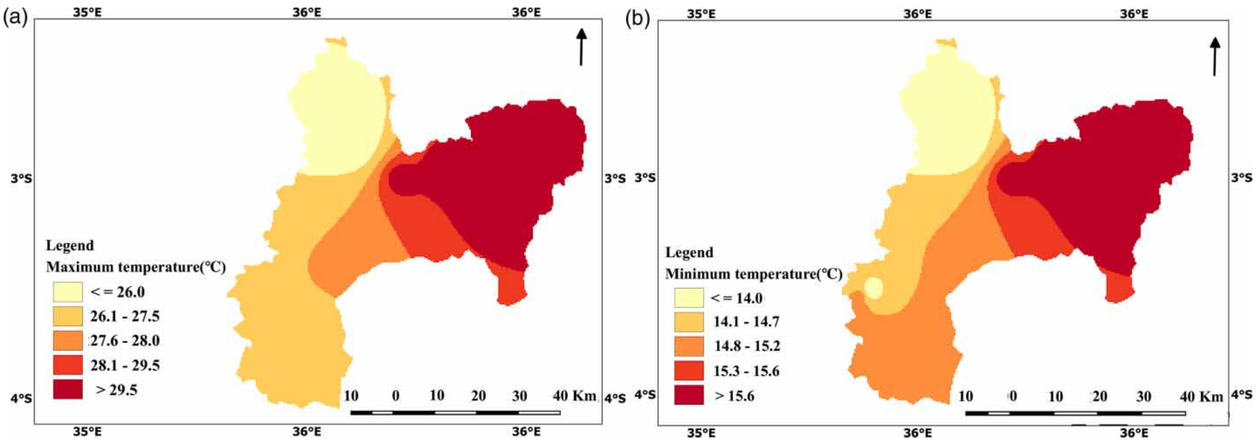

Figure 7 | Spatial distribution of mean annual (a) maximum temperature (b) minimum temperature at the Manyara catchment for the period 1988–2018.

Table 2 | Mann-Kendall and Sen's slope result for annual (a) rainfall (b) maximum temperature (c) minimum temperature

Station	*Z*	Sen's slope	*S*	*Var (S)*	Kendall's *tau*	*P*-value	α	
Babati	−0.85	−4.32	−51	3,461.67	−0.11	0.4	0.05	
Monduli	−0.85	−5.08	−51	3,461.67	−0.11	0.4	0.05	(a)
Mbulu District office	−1.36	−11.97	−81	3,461.66	−0.17	0.17	0.05	
Catchment	1.557	4	97	3,801.67	0.2	0.12	0.05	
Babati	1.02	0.01	61	3,439.67	0.13	0.31	0.05	
Monduli	−1.82	−0.05	−108	3,441.33	−0.24	0.07	0.05	(b)
Mbulu District office	0.07	0.03	5	3,443	0.01	0.9	0.05	
Catchment	−0.46	−0.006	−29	3,779.67	−0.06	0.65	0.05	
Babati	4.82	0.03	281	3,380.33	0.63	0	0.05	
Monduli	4.07	0.03	238	3,394.67	0.53	0	0.05	(c)
Mbulu District office	4.39	0.03	259	3,461.67	0.56	0	0.05	
Catchment	4.07	0.024	248	3,682	0.53	0	0.05	

climate stations and the entire catchment. A decreasing trend in the annual rainfall at the rate of 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, the temperature increased significantly due to the release of longwave radiation. The minimum temperature showed an increasing trend at a rate of 0.024 °C/y compared to the maximum temperature which showed a slight yearly decreasing trend in all stations 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 maximum temperatures (Tesso *et al.* 2012; Chang'a *et al.* 2017).

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]	(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	Extreme drought	1	1	0

[a]*Source*: McKee *et al.* (1993).

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 years 2002 and 2006, whereas the more negative values obtained in the years 1993 and 2003. Also, the SPI results revealed that in the catchment, drought conditions were more sustained compared to wet

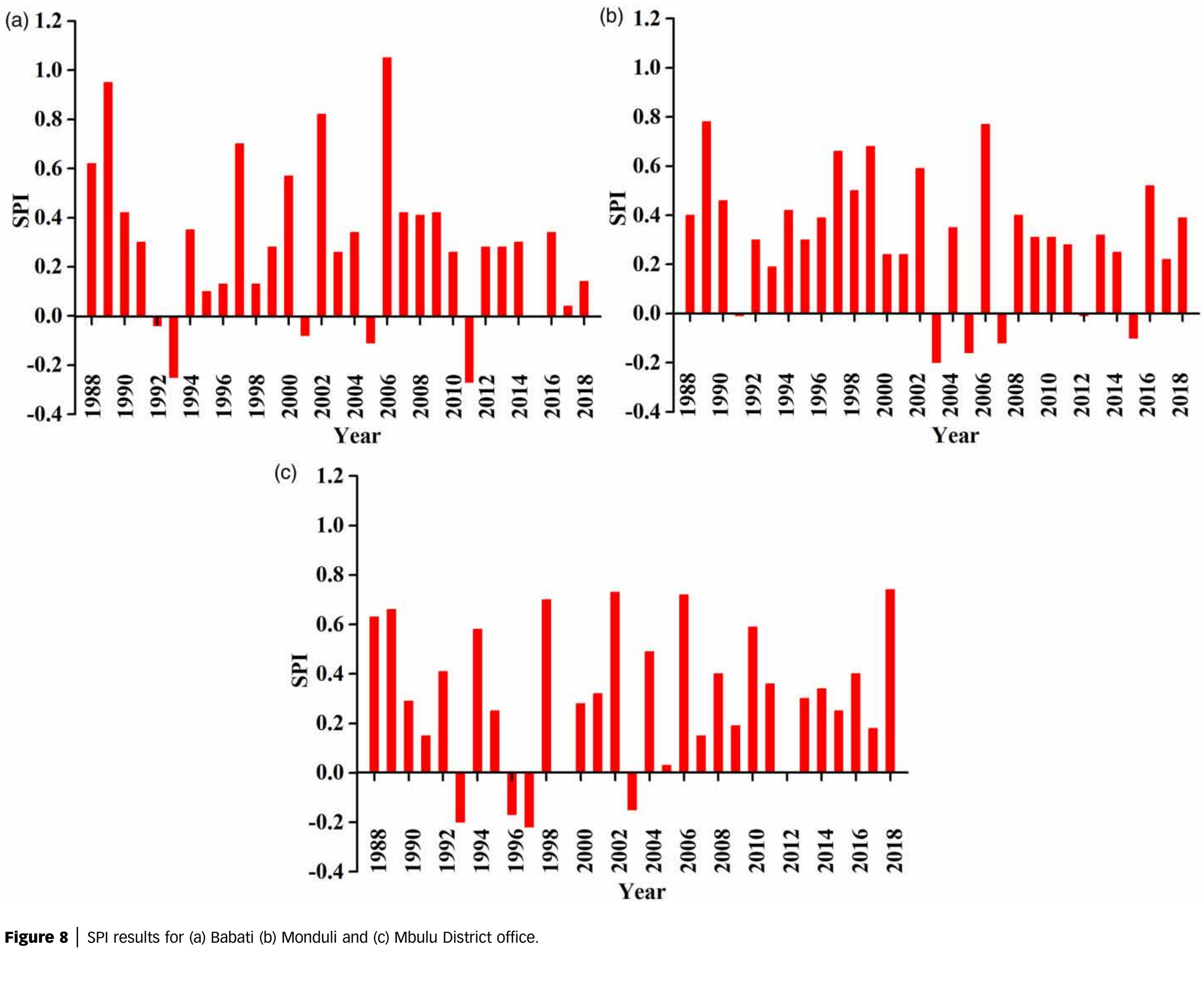

Figure 8 | SPI results for (a) Babati (b) Monduli and (c) Mbulu District office.

Table 4 | Onset and cessation patterns of rainfall for 30 years in the Lake Manyara catchment

	Onset				Cessation			
Year	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	21-Nov	15-Apr	19-Apr	15-Apr	03-May
2002	28-Oct	06-Nov	21-Nov	22-Oct	15-Apr	15-Apr	25-Apr	01-May
2003	29-Oct	06-Nov	06-Nov	23-Oct	15-Apr	21-Apr	15-Apr	15-Apr
2004	23-Nov	09-Dec	05-Jan	03-Feb	15-Apr	15-Apr	01-May	02-May
2005	18-Dec	21-Nov	26-Nov	25-Dec	30-Apr	21-Apr	22-Apr	02-May
2006	23-Nov	28-Nov	02-Dec	16-Oct	03-May	15-Apr	22-May	19-May
2007	12-Oct	06-Nov	01-Nov	21-Oct	06-May	18-Apr	15-Apr	15-Apr
2008	01-Jan	19-Nov	16-Jan	22-Mar	16-Apr	07-May	03-May	08-May
2009	12-Nov	29-Nov	08-Nov	06-Dec	09-May	29-Apr	26-Apr	24-Apr
2010	08-Nov	07-Nov	22-Nov	10-Dec	17-Apr	15-Apr	03-May	12-May
2011	24-Nov	07-Dec	14-Nov	14-Feb	22-Apr	15-Apr	24-Apr	21-Apr
2012	02-Nov	09-Nov	14-Nov	24-Nov	15-Apr	15-Apr	18-Apr	18-May
2013	06-Dec	13-Dec	11-Dec	12-Nov	15-Apr	15-Apr	26-Apr	27-Apr
2014	28-Nov	21-Jan	05-Feb	03-Nov	13-May	15-Apr	29-Apr	01-May
2015	03-Nov	18-Nov	15-Nov	03-Nov	15-Apr	20-May	15-Apr	15-Apr
2016	15-Nov	09-Jan	08-Jan	17-Nov	25-May	15-Apr	11-Apr	09-May
2017	04-Nov	12-Nov	18-Nov	19-Nov	21-May	15-Apr	15-Apr	16-Apr
2018	18-Oct	05-Jan	22-Dec	01-Jan	15-Apr	09-May	15-Apr	15-Apr

conditions. Furthermore, the SPI trends showed an increase in the intensity of drought in many stations 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 multi-scalar, 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 exhibits 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 of the rainy season for the different locations. On average, the rainy season starts in November and ends in April or

May, although the catchment location seems to have both unimodal and bimodal modes of rainfall. The results also show that the rainy season mostly starts early in the areas with high altitude around Karatu and Mbulu Agriculture stations and later 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 the possible influence of climate change in these areas which may have implications for 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 rainy season over the past 30 years for the Lake Manyara catchment in Tanzania. From this study, the climate status

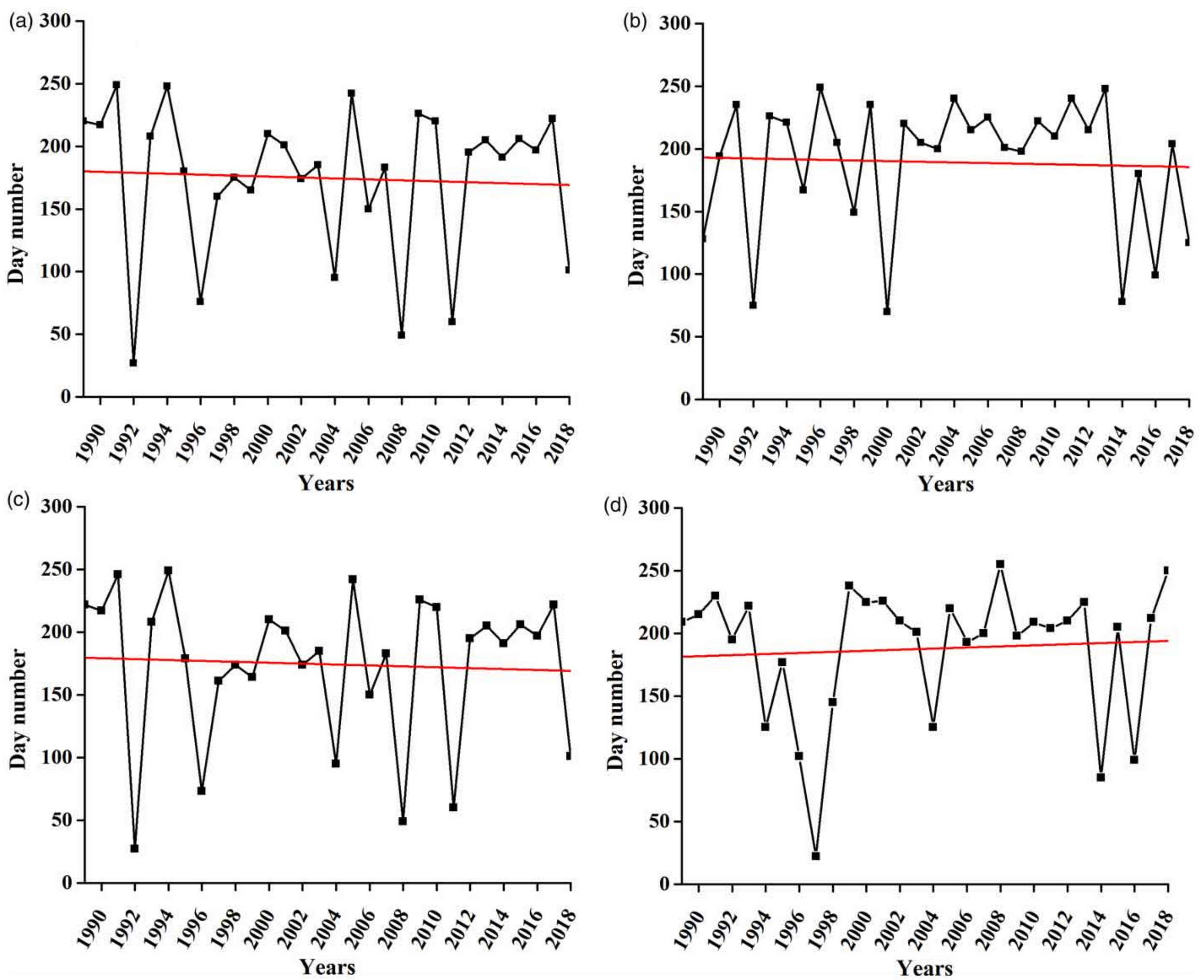

Figure 9 | Length of seasonal rainfall in days for (a) Karatu (b) Babati (c) Monduli and (d) Mbulu District office.

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.

ACKNOWLEDGEMENTS

We acknowledge financial support from the Water Infrastructure and sustainable Energy Futures (WISE-Features) and the Tanzania Meteorological Authority (TMA) their support throughout this study. Professor Alfred N. N. Muzuka, who passed away during the course of this work – Alfred, you will always be remembered for your diligence and adherence to standards. Thank you!

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wcc.2020.197.

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First received 17 September 2019; accepted in revised form 18 February 2020. Available online 6 April 2020