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Research Article

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Posted Date: March 5th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-272000/v1>

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Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on March 26th, 2021. See the published version at <https://doi.org/10.1007/s00704-021-03586-0>.

Spatio-temporal analysis of droughts in the Lake Chilwa Basin, Malawi

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Abstract

Drought phenomena are attributed to water availability deficit that is caused by low precipitation. However, droughts are quite complex and cannot simply be defined on the basis of precipitation as other factors may have an influence. In this study, we investigated the spatio-temporal patterns of droughts in Lake Chilwa Basin, an endorheic lake basin that has recently experienced major recurrent lake recessions. The standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) at six- and twelve-month timescales were used to evaluate drought severity variations from 1970 to 2018, in relation to the recessions. The stationarity difference in rainfall between 1973 to 1995 and 1996 to 2018 and climatological trends were tested using Mann-Whitney and Mann-Kendall tests, respectively. The El Niño Southern Oscillation (ENSO) influence on rainfall was also investigated. In general, the results show a statistically insignificant decreasing rainfall trend, coupled with statistically significant temperature increase ($\alpha=0.05$). In addition, both indices broadly detected droughts within similar category ranges and variation patterns, suggesting minimal influence of temperature on droughts compared to rainfall. The study also reveals that not every ENSO event leads to low rainfall in the basin. It is further shown that unlike past major recessions e.g., 1994/95, recent lake dry-ups of 2012 and 2015 were as a result of milder droughts. Moreover, the trigger threshold of lake dry-ups is shown to have shifted; such that average annual rainfall below 1000mm is likely to yield a dry-up in recent times than before, which may be attributable to anthropogenic pressure.

Keywords: Droughts, hydrological drought, Standardised Precipitation Index, Standardised Precipitation Evapotranspiration Index, Lake Chilwa Basin

1.0 Introduction

Drought phenomena are associated with water availability deficit that is caused by low precipitation compared to a long term average (Dubrovsky et al., 2009). Drought events however are quite complex (Vicente-serrano, 2007) and cannot simply be defined on the basis of precipitation as other factors such as evapotranspiration and soil moisture may have an influence. Due to their complex characteristics, droughts can be categorised as either agricultural, meteorological, hydrological or socioeconomic depending on their specific area of impact and driving factors (Leng et al., 2015). Droughts have in recent years become more frequent and intense globally (Zhang & Jia, 2013), more so in Africa (Wambua et al., 2018). The IPCC (2007) predicts that the southern African region specifically will become drier unlike the equatorial region where it is expected to be mostly wetter.

For Malawi, being in the transition zone between two climate regions (Shongwe et al., 2009) of the tropical savanna and the warm temperate - hot summer as per Köppen-Geiger classification (Peel et al., 2007), climate projections have sometimes presented conflicting findings (Nicholson et al., 2014). Some models predict future drier conditions while others predict the opposite (Shongwe et al., 2009). What is always clear though is that droughts are costly and damaging to societies and ecosystems more than any other natural disaster (Sheffield et al., 2009; Wang et al., 2015; Wilhite, 2000) especially when an occurrence leads to extreme low flows in rivers and abnormal low levels in lakes, reservoirs, and groundwater (Loon, 2015). Irrespective of their impacts, droughts do not receive much of publicity and scientific attention as compared to other disasters such as floods, often because they are not as dramatic (Loon, 2015). Droughts generally develop slowly and are considered a “creeping disaster” which makes their onset and cessation hard to notice.

The detection and monitoring of droughts have over the years relied on the application of drought indices. Indices such as the standardized precipitation index (SPI) (McKee et al., 1993), standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010), Palmer drought severity index (PDSI) (Palmer, 1965) and effective drought index (EDI) (Byun & Wilhite, 1999) have over the years been used in drought analyses. The application of these indices has at times presented some uncertainties; for example, the magnitude of a drought can vary depending on the index used. Similarly, the direction of change can differ depending on the timescale applied (Dai, 2011). Some shortcomings can arise due to a mismatch between index parameters and prevailing conditions of a region (Kirono & Kent, 2011).

For a better representation of drought events, multivariate indices have recently been developed to incorporate a wider range of hydro climatic variables such as precipitation, soil moisture, evaporation, runoff, and geomorphologic parameters (Anderson et al., 2011; Hao & Aghakouchak, 2013). These multivariate indices though are often data intensive (Wang et al., 2015) and may not be suitable for data scarce regions such as the sub-Saharan Africa. Thus, drought indices whose hydro-meteorological variables can easily be obtained (e.g., precipitation and temperature) are usually widely accepted. Among the drought indices, the SPI is commonly applied in global and regional drought monitoring because it only takes in precipitation as input (Byun & Kim, 2010), and for most regions precipitation data is mostly available and for longer periods than any other meteorological variable (Byun and Wilhite 1999).

Other commonly applied indices include the SPEI and PDSI. These two incorporate the reference evapotranspiration which can be a critical parameter in drought severity assessment, particularly for warmer environments where temperature can be an important variable. Of these two though, the SPEI has often shown to be more robust due to its multi-scalar nature that enables it to identify various drought types and drought impacts on diverse systems (Vicente-serrano, 2007; Vicente-serrano et al., 2013); and is fairly simple to compute and interpret compared to the PDSI (Beguiría et al., 2014). Since each index has its own advantages and limitations, drought studies often employ at least two indices in order to identify the most appropriate for a particular region.

In this study, we analysed the spatio-temporal patterns of droughts in the Lake Chilwa Basin using the SPI and SPEI; and examined climatological patterns and trends in relation to the lake recessions. The Chilwa Basin is located in the Southern Malawi and has in recent years experienced frequent episodes of droughts which have led to a couple of major recessions in the past decade (Chiotha et al., 2017). The basin, with a population of at least 2 million people (GoM, 2018), is of great importance as it encompasses a Ramsar classified wetland that sustains livelihoods through fishing and rice cultivation. Besides, most rivers/streams in the basin are a source of water for domestic and irrigation and hence drought implications are always immense to the people living within the basin. Although drought occurrences are not completely new in the history of the basin (Agnew & Chipeta, 1979;

Lancaster, 1979; Njaya, 2009), the recent rate of recurrence prompted further investigation. This study aimed at revealing patterns and underlying causal factors of droughts as a prerequisite for effective water resource planning and drought preparedness.

2.0 Study Site

Lake Chilwa Basin (**Figure 1**) is an endorheic lake basin located in southern Malawi within latitudes 14° 40' S and 15° 55' S and longitudes 35°15' E and 35° 45' E. It is a trans boundary lake basin with a total watershed area of 8,349 km²; of which 5669 km² (68%) is in Malawi and 2680 km² (32%) in Mozambique (Agnew & Chipeta, 1979). The basin is situated in a tectonic depression and is the second largest lake in Malawi with an area of approximately 2284 km² (Rebello et al., 2011). The lake area however fluctuates annually and within season. The Lake Chilwa basin has a radial drainage pattern with streams converging from the surrounding watershed, most of which originate from the mountains on the Malawi side. The basin altitude ranges from about 500 m above mean sea level (a.m.s.l) close to the lake shores to about 2650 m (a.m.s.l) around mountainous areas of Zomba and Mulanje.

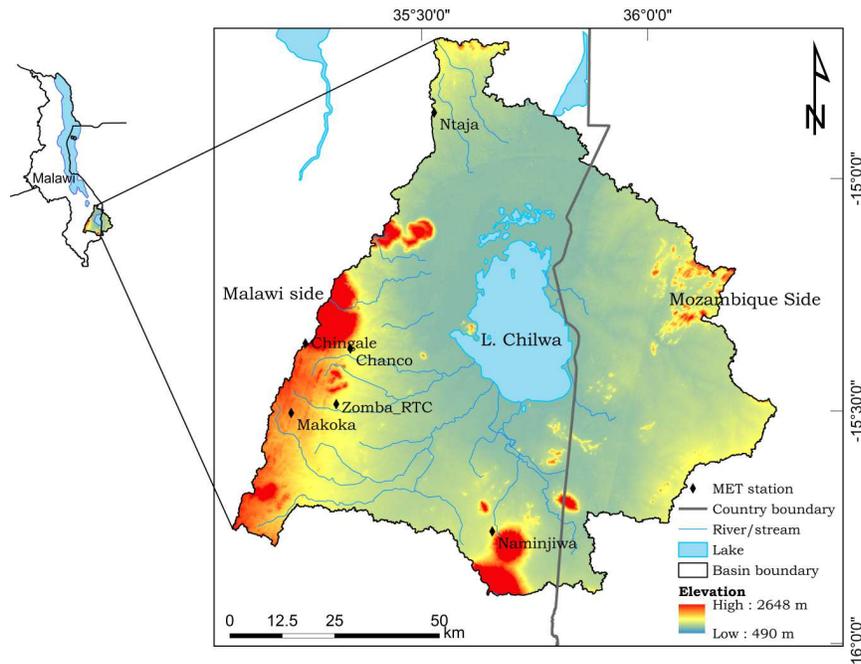


Figure 1: Map of the Lake Chilwa Basin showing the locations of weather stations

The basin receives average rainfall ranging between 1100 and 1600 mm per year, reaching up to more than 2,500 mm in Zomba and Mulanje Mountains, while in the lowland plains the average annual rainfall can be as low as 700 mm (Mvula et al., 2014). The rainfall pattern in the basin is unimodal with most rainfall (80%) occurring in the months of November to April. According to Ngongondo et al. (2011), from the months of May to August there are sporadic winter rainfall locally known as “*chiperone*”, experienced in the highlands due to an influx of cool moist south-easterly winds through Mozambique. The climate in the Chilwa Basin is tropical wet and dry, commonly known as Savanna climate and the rainfall regime is strongly influenced and controlled by the Inter-Tropical Convergence Zone (ITCZ), where the north easterly monsoon and south easterly trade winds converge. The mean annual temperature for the Chilwa basin varies between 21 °C and 24 °C (Chavula, 2000).

3.0 Methods and data

The SPI and SPEI were applied to evaluate the spatio-temporal pattern of drought in the Lake Chilwa Basin from the year 1970 to 2018, a period that includes some of the most severe droughts historically recorded in the Chilwa Basin leading to complete lake dry-ups. In addition, the study explored the influence of El Niño Southern Oscillation (ENSO) anomaly on rainfall over the Lake Chilwa region.

3.1 Data and processing

The daily precipitation and daily air temperature were obtained from the Climate Change and Meteorological Services Department of Malawi, as recorded at six stations in the Chilwa Basin over the period of 1970 to 2018. The stations included Chancellor College/ or Chanco, Chingale, Makoka, Naminjiwa, Ntaja and Zomba RTC and the station details are summarized in **Table 1**. The daily datasets of precipitation and temperature (maximum and minimum) for the period of 1970 to 2018 were later converted to monthly datasets for the SPEI and SPI computations.

Table 1: Summary information on weather stations used in the study

| Station name | Longitude | Latitude | Elevation - a.m.s.l (m) | Mean annual rainfall (mm) | Mean annual temperature (°C) | Period (years) |
|--------------|-----------|----------|----------------------------|------------------------------|---------------------------------|----------------|
| Chanco | -15.38 | 35.35 | 886 | 1290 | 21.6 | 1970 to 2018 |
| Chingale | -15.37 | 35.25 | 610 | 908 | 21.9 | 1970 to 2018 |
| Makoka | -15.52 | 35.22 | 1029 | 970 | 21.1 | 1970 to 2018 |
| Naminjiwa | -15.77 | 35.67 | 773 | 1005 | 22.5 | 1970 to 2018 |
| Ntaja | -14.87 | 35.53 | 731 | 857 | 23.6 | 1970 to 2018 |
| Zomba RTC | -15.50 | 35.32 | 915 | 1238 | 21.4 | 1970 to 2018 |

3.2 Drought index computation

This study employed two timescales for both the SPI and SPEI; the six (6) month time step (SPI-6 and SPEI-6) effective for representing agricultural drought and a twelve (12) month time step (SPI-12 and SPEI-12) which best represents the hydrological droughts.

The SPI

The Standardised Precipitation Index is used to quantify water deficit for the different time durations in the studied stations. The SPI represents the departure of a drought event from the long-term mean, expressed as a z-score in standard deviation units. The first step in calculating the SPI involves fitting the precipitation data into a probability distribution function and then computing the SPI values as recommended by McKee et al. (1993). Since precipitation is usually not normally distributed for the time scales of 12 months or less, the long-term record is fitted to a probability distribution (gamma) and transformed into a normal distribution so that the mean SPI for a location is zero (0), standardized deviation of the precipitation is adjusted to one (1) and skewness of the existing data is readjusted to zero (0). In our study, the SPI was calculated for each station at 6- and 12-month timescales; according to the Pearson III distribution and the parameters were calculated following the L-moment method (Sankarasubramanian & Srinivasan, 1999).

The SPEI

Unlike the SPI which only takes in precipitation as input, the SPEI also includes temperature and the index is based on the water balance methodology developed by Thornthwaite (1948), known as the Thor parameterization. The monthly PET (Vicente-Serrano et al., 2010) is calculated by:

$$PET = 16K \left(\frac{10T}{I} \right)^m \quad (1)$$

Where; PET is the potential evapotranspiration (mm), K is a correction coefficient derived from the latitude and month i , T is the monthly average temperature, I is the heat index and m is a coefficient based on heat index. The values of I , m and K are calculated by:

$$I = \sum_{i=1}^{12} \left(\frac{T}{5} \right)^{1.514} \quad (2)$$

$$m = (6.75e0.7)I^3 - (7.71e0.5)I^2 + (1.179e0.2)I + 0.492 \quad (3)$$

$$K = \left(\frac{n}{12}\right) \left(\frac{NDM}{30}\right) \quad (4)$$

Where; NDM is the number of days of the month and n is the maximum number of sun hours for month i , computed by:

$$n = \left(\frac{24}{\pi}\right) \times \arccos(-\tan \varphi \tan \delta) \quad (5)$$

Where; φ is the latitude of the station and δ is the solar declination in radians, calculated by:

$$\delta = 0.403 \operatorname{sen} \left(\frac{2\pi J}{360} - 1.405 \right) \quad (6)$$

Where; J is the average Julian day of the month i

Once the value of PET is determined, the water deficit or surplus for the month i is calculated using:

$$D_i = P_i - PET_i \quad (7)$$

Where, D_i is the water deficit or surplus for the month i , P_i is precipitation and PET_i is the potential precipitation for the month i . The calculated D_i values are aggregated at different time scales (months) as:

$$D_n^k = \sum_{i=0}^{k=1} P_{n-1} - (PET)_{n-1} \quad (8)$$

Where; k is the timescale (months) of the aggregation and n is the calculation month. For this study, $k = 6$ and 12 for 6 month and 12 month

The probability density function of a Log-logistic distribution is given as:

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} \left(1 + \left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right)^{-2} \quad (9)$$

Where; α , β , and γ are the scale, shape and origin parameters respectively for $\gamma > D < \infty$. The probability distribution function for D series is then given as:

$$f(x) = \left[1 + \left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \quad (10)$$

With $f(x)$, the SPEI can be obtained as the standardized values of $F(x)$ according to the method of Abramowitz and Stegun (1965), computed as:

$$SPEI = W - \left(\frac{c_0 + c_1 w + c_2 w^2}{1 + d_1 w + d_2 w^2 + d_3 w^3}\right) \quad (11)$$

Where; $w = \sqrt{-2 \ln(P)}$ for $P \leq 0.5$, P is the probability of exceeding a determined value of D_i and is given as; $P = 1 - f(x)$; while the constants are given as; $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$

The categorization of drought in terms of severity in this study was based on index categories (Guttman, 1998) as shown in **Table 2**. Typical drought events were identified and further investigated, the spatial distributions of the typical drought events were plotted and their possible driving forces were explored.

Table 2: Drought category ranges for SPI and SPEI (Guttman, 1998)

| Drought category | Range of drought categories | | Typical severity of event |
|--------------------------------|-----------------------------|----------------|---------------------------|
| | SPI | SPEI | |
| Extremely moist (<i>EM</i>) | 2.00 > | 2.00 > | |
| Severe moist (<i>SM</i>) | (1.50, 2.00] | (1.50, 2.00] | |
| Normal (<i>N</i>) | (1.00, 1.50] | (1.00, 1.50] | |
| Mild drought (<i>MD</i> *) | (-0.99, 1.00] | (-0.99, 1.00] | 1 in 3 years |
| Moderate drought (<i>MD</i>) | (-1.00, -1.50] | (-1.00, -1.50] | 1 in 10 years |
| Severe drought (<i>SD</i>) | (-1.50, -2.00] | (-1.50, -2.00] | 1 in 20 years |
| Extreme drought (<i>ED</i>) | -2.00 < | -2.00 < | 1 in 50 years |

3.3 Analysis of climatic trends

The rank-based nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975) recommended by the World Meteorological Organisation (WMO, 1988) was used to test monotonic trends of the annual rainfall and mean temperature for the six stations. The magnitude of monotonic trends in climatological record was quantified using the Kendall's slope (β) which requires a time-series of equally spaced data.

3.4 Drought comparison between two periods

This study compared the relative frequency of droughts between two periods of 1973 to 1995 (representing the past) and 1996 to 2018 (representing the present), based on their severity categories. In addition, the annual rainfall between these periods were compared using the Mann-Whitney U test. The Mann-Whitney U test is a non-parametric test that assumes that the two distributions are similar in shape, with a null hypothesis that no significant differences exist between the two samples and are stochastically equal. The Mann-Whitney test was computed as;

$$E(U) = n_u (N + 1) / 2 \quad (12)$$

Where $E(U)$ is the expectation of U , n_u is the sample size of the sample being tested, and N is the total sample size $N = n_1 + n_2$. The difference between the observed and the expected rank is then approximated using the normal distribution, thus the area under the curve of a z -distribution which is calculated as;

$$z = \frac{U - E(U)}{\sqrt{n_1 n_2 (N + 1) / 12}} \quad (13)$$

The test establishes confidence intervals around the median of the differences between the two test samples called the point estimate.

4.0 Results and discussion

4.1 Rainfall variability

Figure 2 shows a time-series plot of the average annual rainfall for the basin from 1970 to 2018 based on the six weather stations. Of particular interest were the average rainfall amounts in the years preceeding a dry-up events of Lake Chilwa; thus the years 1995, 2012 and 2015. As shown in **Figure 2**, the lake recession of 1995 was preceeded by a record low average annual rainfall of less than 700 mm for the basin in 1994/95. In contrast, Lake Chilwa in the years 2011/12 and 2015 dried up as a result of annual rainfall within 700 mm and 1000 mm; amounts which were also recorded for the past period but never resulted to the complete drying of the lake, for example in 1979/80 and 1982/83. While low rainfall is certainly a contributing factor to the drying of lake, this study reveals that the triggering threshold has shifted up. It implies therefore that the average rainfall amounts below 1000 mm in recent years are likely to cause a serious lake recessions.

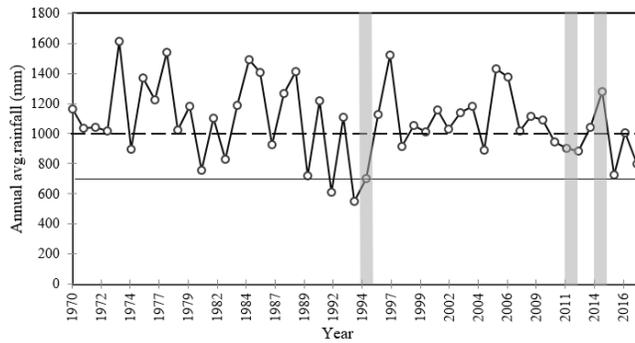


Figure 2: Time series plot of average annual rainfall for the basin (1970-2018)

Figure 3 shows the average lake levels for Lake Chilwa for the recent period of 2011 to 2016. As shown, the Lake Chilwa in the recent years dry-up in 2012 and 2015, which presented an opportunity to analyse the magnitude of drought events and rainfall amounts that led to drying of the lake in recent times. The drying of Lake Chilwa has negative consequences on fishing as it does not only render fishing impossible, but also leads to complete loss of some species (Njaya, 2001).

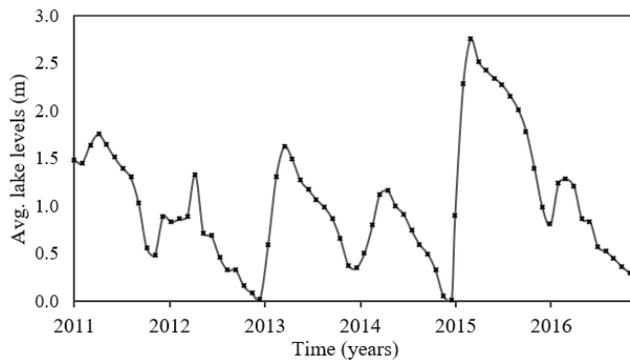
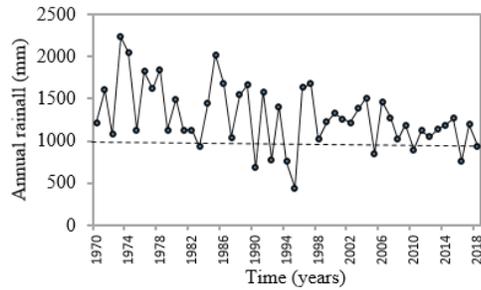
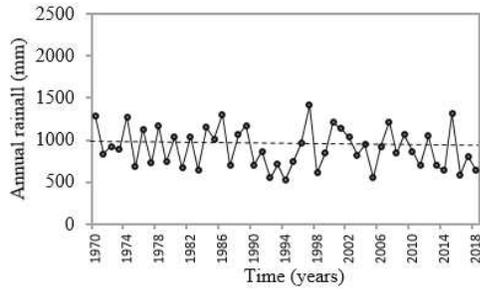


Figure 3: Average lake levels for the Lake Chilwa for the period of 2011 to 2016

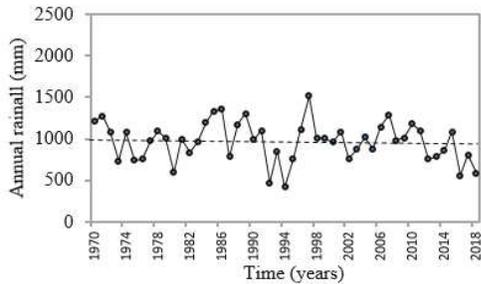
Figure 4 displays time-series plots of annual rainfall for each of the six weather stations highlighting the 1000 mm threshold. Based on the plots, it is evident that highest rainfall amounts are recorded within the montaneous areas of the basin as shown in **Figures 4a** and **4f** for Chanco and Zomba RTC, respectively. The biggest hydrological contribution in terms of rivers and streams in the basin also emanates from these mountaneous areas. On the otherhand, lowland plain areas for example Ntaja (**Figure 4e**) record the lowest annual rainfall, mostly below 1000 mm. Reduced annual rainfall due to climate variability within the mountaneous areas therefore can therefore have significant hydrological implications in the basin unlike in the low-lying plains.



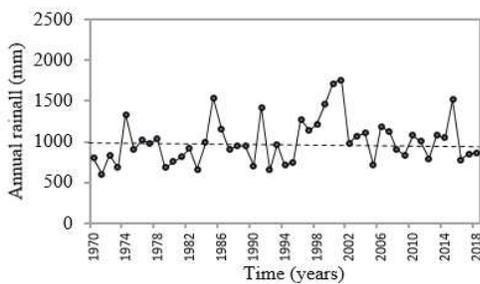
(a) Chanco



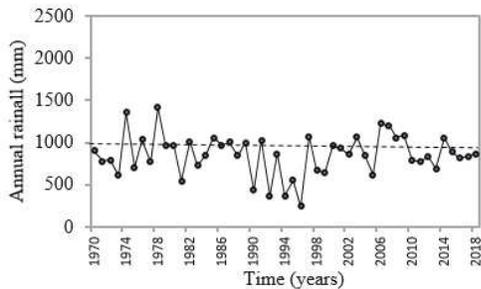
(b) Chingale



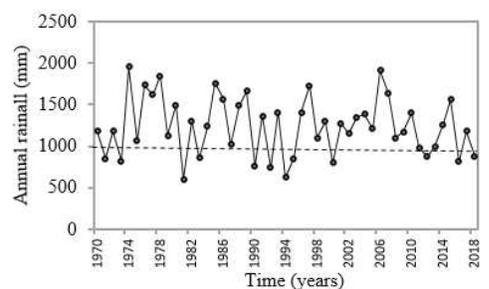
(c) Makoka



(d) Naminjiwa



(e) Ntaja



(f) Zomba RTC

Figure 4: Time series plot of annual rainfall for the six stations in the basin (1970-2018)

4.1.1 El Niño influence on rainfall basin

Relating rainfall variability in the Chilwa Basin to the El Niño Southern Oscillation (ENSO) anomaly, it is noted that the major recorded ENSO events had minimal effect on rainfall in the basin. As shown in **Figure 5**, the Oceanic Niño Index (ONI) computations by Wang et al. (2019) depict 1972/73, 1982/83, 1997/98 and 2014/15 as having a ‘Strong basin-wide’ El Niño events. However, rainfall in the Lake Chilwa Basin was not as extremely low in those years; particularly 1997/98 which registered fairly good rainfall amounts in the basin as observed at most stations such as at Chanco, Makoka, Naminjiwa and Zomba RTC. Nonetheless, the extreme low rainfall event of 1994/95 was as a result of ‘moderate Central Pacific (CP)’ El Niño anomaly, which is more common in recent years unlike the moderate Eastern Pacific (EP). The general indication is that not all El Niño phenomena lead to low rainfall; and not all the years with extreme low rainfall are due to the ENSO effect. A similar observation was made by Clay et al. (2003) in the Southern Africa region that despite the existence of a significant relationship between ENSO and inter-annual variations in rainfall, not every ENSO event results into low rainfall in the Southern Africa. Other oceanic-atmospheric interactions in the Indian Ocean and Southern Atlantic may have major influence on extreme rainfall events.

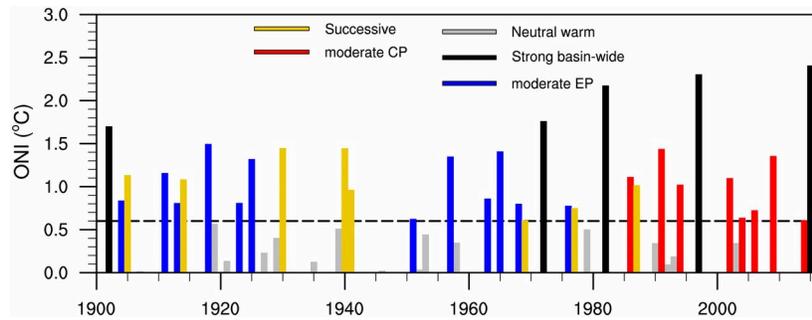


Figure 5: Changing El Niño types from 1901 to 2017 (Wang et al., 2019)

4.2. Climatological trends

Taking the significance level (α) as 0.05, monotonic trends of annual rainfall and temperature were generally different as shown in **Table 3**. Except for Ntaja and Naminjiwa weather stations, rainfall trends showed a decreasing tendency in the Lake Chilwa Basin during the 1970 to 2018 period as presented by the Kendall's slope (β); however, the negative trends were only significant at one station (Chanco). At basin level, an insignificantly decreasing rainfall trend was broadly observed based on MK trend test results of basin annual rainfall means of the analysed stations. Air temperature on the other hand tended to increase at all weather stations during the study period, significantly so at three stations of Chanco, Makoka and Ntaja. The overall significant increase in air temperature, coupled with an insignificant declining rainfall trend suggests that the Lake Chilwa Basin is becoming warmer and drier.

These findings are largely consistent with what Zuzani et al. (2019) observed for the southern Malawi that temperature tended to increase between 1961 to 2015 while rainfall tended to decrease. Similarly, Ngongondo et al. (2011 & 2015) noted that between 1971 and 2000, rainfall in Malawi generally decreased insignificantly while air temperature significantly increased. Previous studies also revealed statistically increasing air temperature in Malawi, e.g. McSweeney et al. (2008) observed that mean annual air temperatures in Malawi increased by +0.9 °C between 1960 and 2006. The implication of this on the water balance is that Malawi may slowly descend into a water-limited situation.

Table 3: Mann-Kendall trend test results for annual rainfall and annual mean temperature (1970 - 2018)

| Station name | Rainfall | Mean temperature |
|--------------|----------|------------------|
| | β | β |
| Chanco | -0.279* | 0.447* |
| Chingale | -0.132 | 0.094 |
| Makoka | -0.097 | 0.301* |
| Naminjiwa | 0.013* | 0.156 |
| Ntaja | 0.012 | 0.345* |
| Zomba_RTC | -0.083 | 0.045 |
| Basin mean | -0.163 | 0.300* |

* Significant ($\alpha = 0.05$)

Relating rainfall trends to SPI and SPEI trends in **Table 4**, it is shown that even though some stations i.e. Chingale, Makoka and Zomba_RTC presented an insignificant decrease in rainfall, the corresponding SPI and SPEI values showed a significantly decreasing tendency at both 6- and 12-month timescales. This suggests that drought conditions significantly increased within these stations despite just an insignificant decrease in rainfall. For Naminjiwa station which portrayed a significant increase in rainfall trend, SPI and SPEI trends equally showed a significantly increasing tendency for both 6- and 12-month timescales, suggesting wetter conditions within the area. Ntaja station however, with an insignificant increase in rainfall showed no significant trend for both SPI and SPEI over the study period.

Table 4: Mann-Kendall trend test results for SPI and SPEI at 6- and 12-month timescales (1970 - 2018)

| Station name | SPI_6 trend | SPI_12 trend | SPEI_6 trend | SPEI_12 trend |
|--------------|-------------|--------------|--------------|---------------|
| | β | β | β | β |
| Chanco | -0.0019* | -0.0025* | -0.0022* | -0.0026* |
| Chingale | -0.0012* | -0.0011* | -0.0014* | -0.0014* |
| Makoka | -0.0010* | -0.0007* | -0.0013* | -0.0010* |
| Naminjiwa | 0.0012* | 0.0010* | 0.0016* | 0.0014* |
| Ntaja | 0.0003 | 0.0000 | 0.0000 | 0.0000 |
| Zomba_RTC | -0.0009* | -0.0007* | -0.0011* | -0.0009* |

* *Significant* ($\alpha = 0.05$)

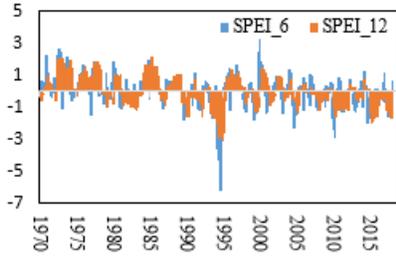
Although the rainfall tendency is inclined towards a decline, the results of Mann-Whitney test (**Table 5**) on annual rainfall compared between the periods of 1973 to 1995 and 1995 to 2018 show no significant differences in rainfall amounts between the two periods at $\alpha = 0.05$. This could suggest that the basin experienced more of climate variability and not climate change, although the annual rainfall generally showed a decreasing tendency.

Table 5: Mann-Whitney test results on annual rainfall between 1973-1995 and 1996-2018 ($\alpha=0.05$)

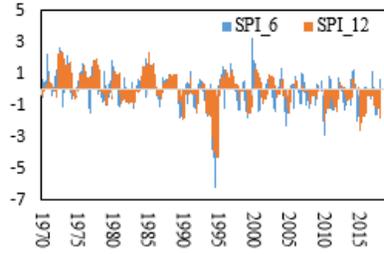
| Weather station | U (standardized) | <i>p</i> -value |
|-----------------|------------------|-----------------|
| Chanco | 1.698 | 0.089 |
| Chingale | 0.961 | 0.337 |
| Makoka | 0.960 | 0.337 |
| Naminjiwa | 0.960 | 0.337 |
| Ntaja | -0.140 | 0.888 |
| Zomba_RTC | 1.692 | 0.091 |
| Basin mean | 0.000 | 0.870 |

4.2 Drought events based on the SPI and SPEI

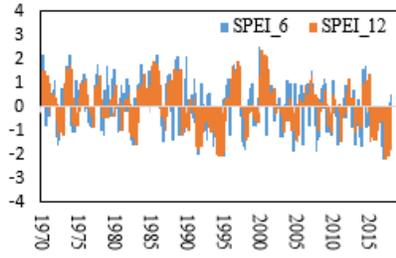
Figure 6 shows the temporal variations of drought in the Lake Chilwa Basin for the period of 1970 to 2018 as detected by the SPEI and SPI at 6- and 12- months for all the six weather stations in the basin. The plots depict a similar variation pattern in the long term for both indices and timescales. It is noted that both indices detected an extreme drought event during the 1994 to 1995 period at all six weather stations for both the 6- and 12- month time-step. The drought of 1994/95 was most severe recorded for the entire study period; and was more pronounced at the Chancellor College/Chanco station (**Figures 6a** and **6b**). The plots further reveal that the extreme drought of 1994/95 was a climax of rather a prolonged moderate to severe drought that started in 1992; significantly manifested at Chingale (**Figures 6c** and **6d**), Makoka (**6e** and **6f**), Naminjiwa (**6g** and **6h**) and Ntaja (**6i** and **6k**). The hydrological implication of such a prolonged and extreme drought was that Lake Chilwa completely dried in the year 1995 (Njaya, 2001).



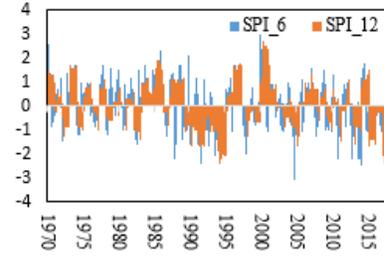
(a) Chanco: SPEI 6- and 12- months



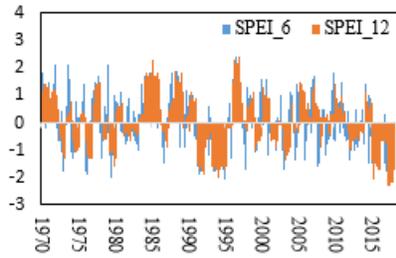
(b) Chanco: SPI 6- and 12- months



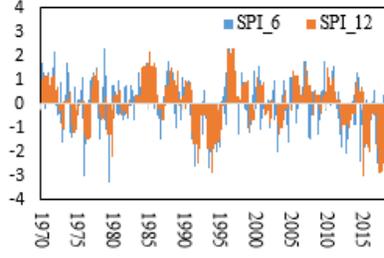
(c) Chingale: SPEI 6- and 12- months



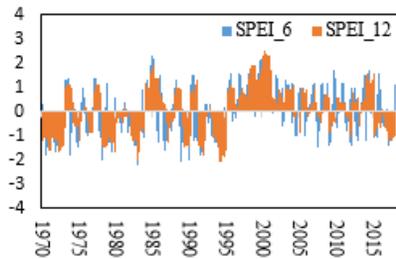
(d) Chingale: SPI 6- and 12- months



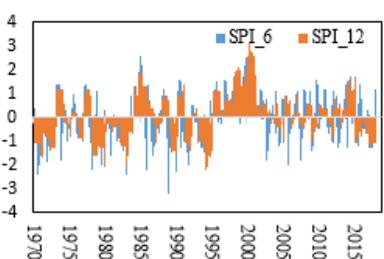
(e) Makoka: SPEI 6- and 12- months



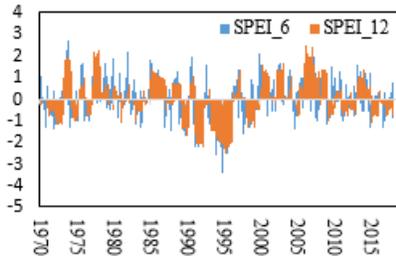
(f) Makoka: SPI 6- and 12- months



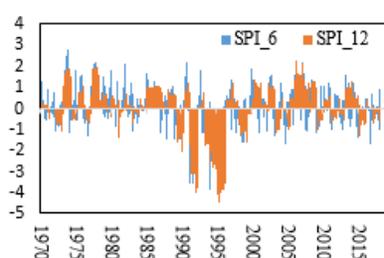
(g) Naminjiwa: SPEI 6- and 12- months



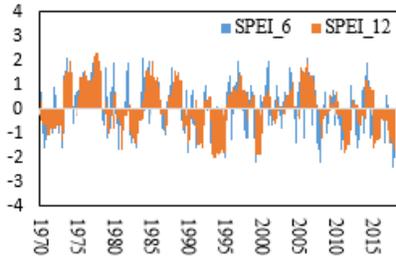
(h) Naminjiwa: SPI 6- and 12- months



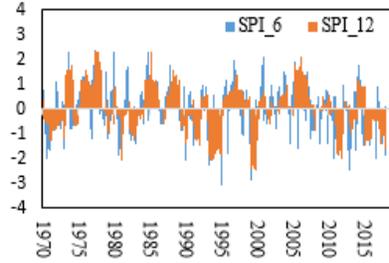
(i) Ntaja: SPEI 6- and 12- months



(j) Ntaja: SPI 6- and 12- months



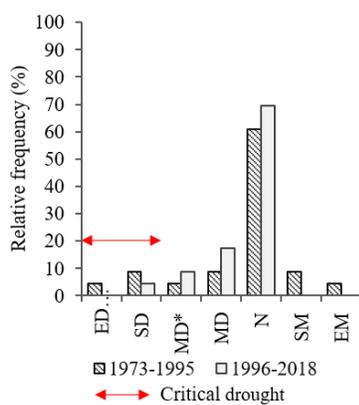
(k) Zomba_RTC: SPEI 6- and 12- months



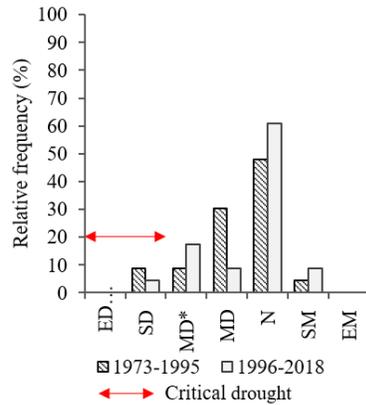
(l) Zomba_RTC: SPI 6- and 12- months

Figure 6: Temporal variations of SPEI and SPI at 6- and 12- month time-step for the six stations

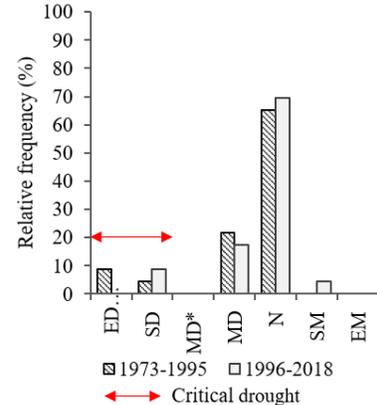
Figure 7 illustrates the relative frequency of drought occurrence compared between the two periods of 1970-1995 (the past) and 1996-2018 (the recent) for all the stations. From the histograms, it is evident that the relative frequency of the most extreme drought (ED) events occurred during the past period as detected at Chanco (**Figure 7a**), Makoka (**Figure 7c**), Ntaja (**Figure 7e**) and Zomba RTC (**Figure 7f**). Similarly, severe droughts (SD) were also more frequent during that same period (1973-1995), quite noticeable at Chanco, Chingale, Ntaja and Zomba RTC weather stations. Remarkably, no single extreme drought event was recorded at any weather station during the recent period of 1996 to 2018, yet the lake dried-up twice in this latter period. This suggests that moderate droughts are now causing serious lake recessions than before, a scenario likely to be associated with increased water exploitation causing a decrease in river flow and groundwater amount recharging the lake system.



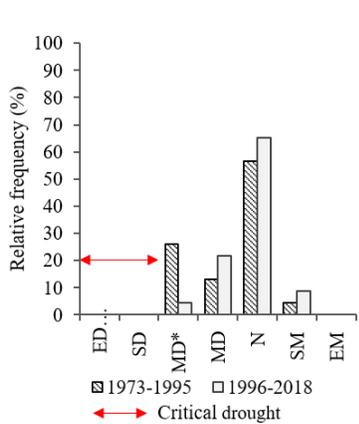
(a) Chanco: Drought frequency



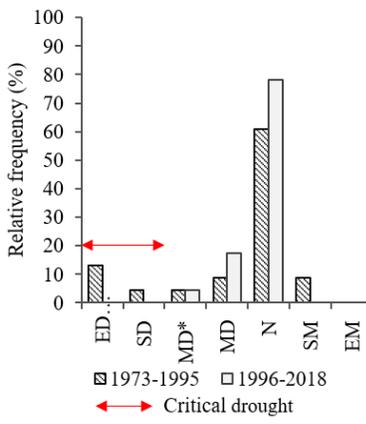
(b) Chingale: Drought frequency



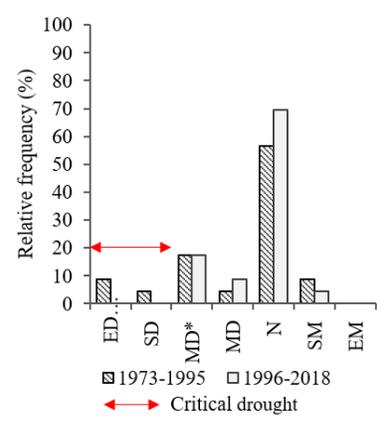
(c) Makoka: Drought frequency



(d) Naminjiwa: Drought frequency



(e) Ntaja: Drought frequency



(f) Zomba_RTC: Drought frequency

Figure 7: Relative drought frequency comparison between 1973 to 1995 and 1996 to 2018 for the six stations

4.3 SPI and SPEI performance

Figure 8 is a box-and-whisker plot of SPEI and SPI at 6- and 12- months timescale for all the six stations, which depicts the drought detection variability between the indices and the timescales. As shown in the plots, there was not much variation in terms of drought detection for the two indices, as they were both able to detect droughts within the same category ranges. The SPI however at times exaggerated the magnitude of drought severity at some stations when compared with SPEI as in the outlier case at Chanco for both SPI-6 and SPI-12 (**Figures 8b** and **8d**); and also at Ntaja comparing SPI-12 and SPEI 12. This could imply that air temperature was quite an important factor at these two stations since SPEI incorporates precipitation and temperature as input while SPI only precipitation. Regardless of the exaggeration however, both the SPI and SPEI were able to detect drought events within the same category range at both the 6- and 12- month timescales. drought detection within similar severity ranges by the two indices indicates that precipitation and not temperature is the dominant factor of droughts in the basin; such that the contribution of temperature to drought occurrences in the Lake Chilwa Basin was quite minimal.

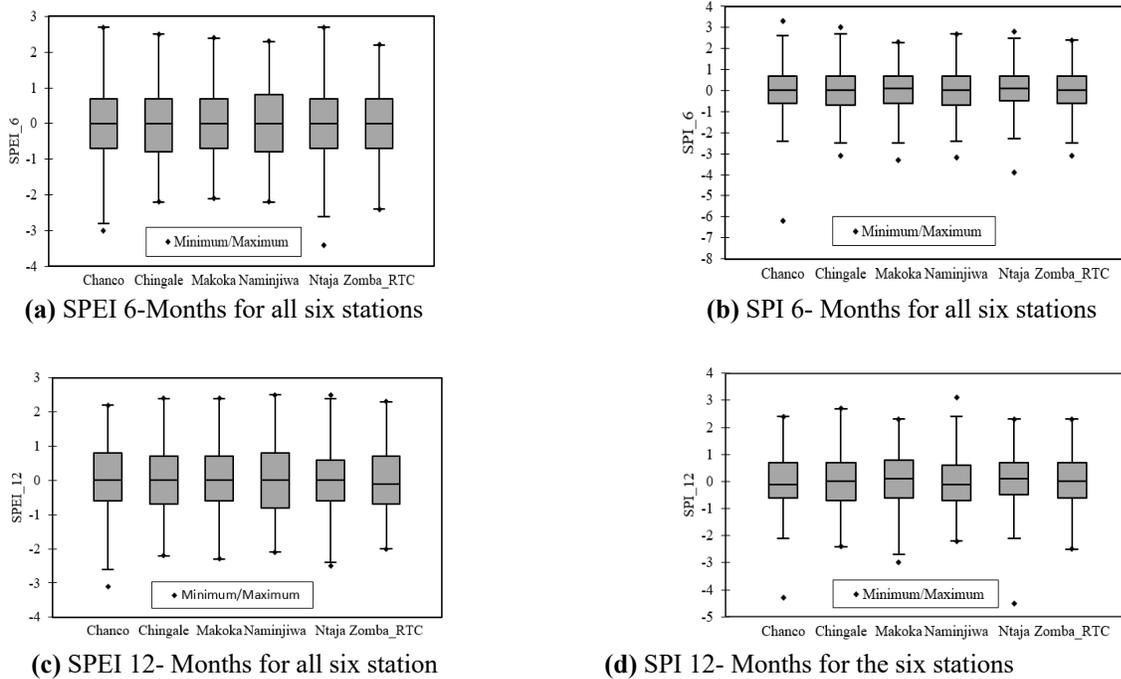
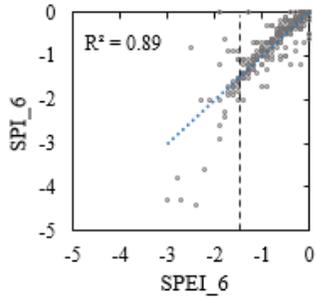
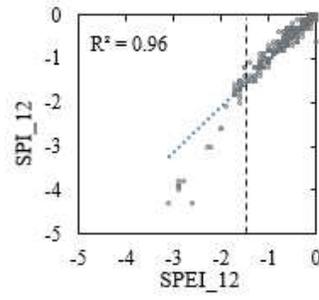


Figure 8: Box-and-whisker plot of the SPEI and SPI at 6- and 12- months timescale

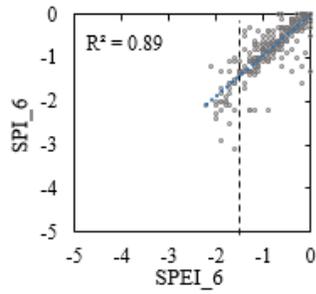
Figure 9 shows scatter plots of SPEI vs SPI at 6- and 12- months timescale for the six weather stations in the Lake Chilwa Basin. As shown, the correlation between the SPI and SPEI in terms of drought detection in the Chilwa Basin was quite high, with the coefficient of determination (R^2) ranging between 0.87 to 0.94 at 6-month timescale; and even improved significantly at a longer timescale of 12 months for all stations except at Ntaja station which registered the lowest R^2 of 0.87 and 0.88 at 6 and 12 months timescales, respectively. This might suggest that air temperature was quite an important factor at Ntaja; nevertheless, the level of correlation is still very high suggesting that both indices are reliable although SPEI shows to be a better index of the two.



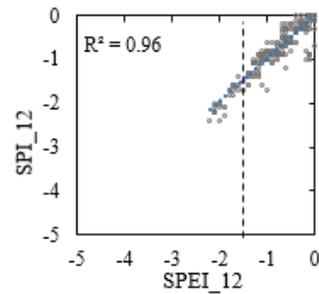
(a) Chanco: SPEI 6 vs SPI 6



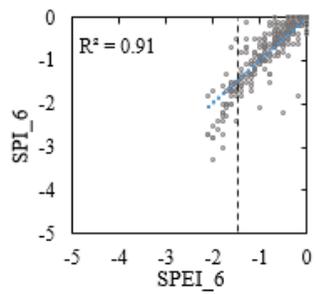
(b) Chanco: SPEI 12 vs SPI 12



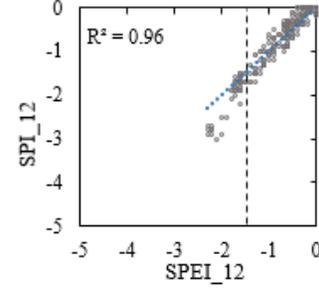
(c) Chingale: SPEI 6 vs SPI 6



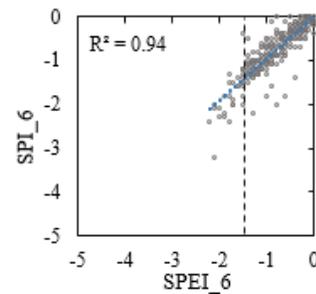
(d) Chingale: SPEI 12 vs SPI 12



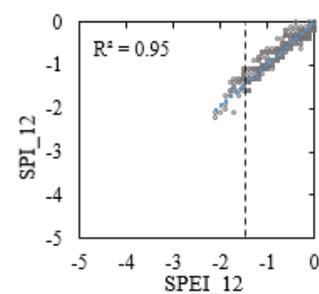
(e) Makoka: SPEI 6 vs SPI 6



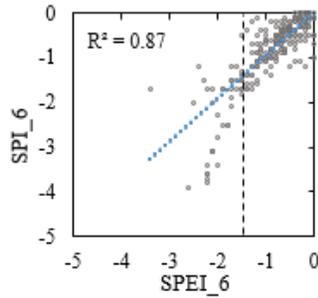
(f) Makoka: SPEI 12 vs SPI 12



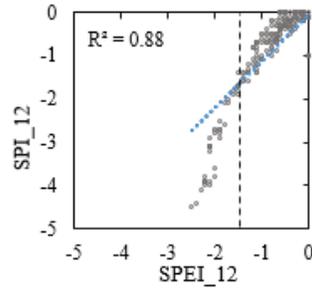
(g) Naminjiwa: SPEI 6 vs SPI 6



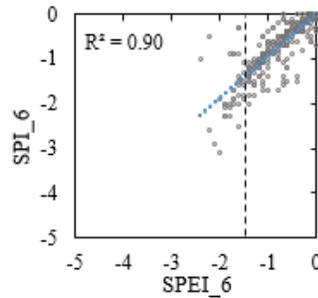
(h) Naminjiwa: SPEI 12 vs SPI 12



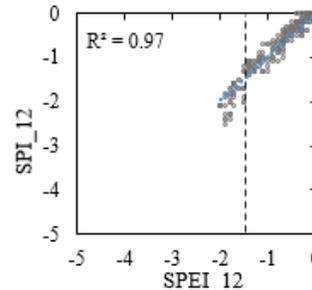
(i) Ntaja: SPEI 6 vs SPI 6



(j) Ntaja: SPEI 12 vs SPI 12



(k) Zomba_RTC: SPEI 6 vs SPI 6



(l) Zomba_RTC: SPEI 12 vs SPI 12

Figure 9: Scatter plot of SPI and SPEI compared at 6- and -12 monthly scales for each station

5.0 Conclusion

This study has found that both the SPI and SPEI had similar capabilities in detecting droughts of the Lake Chilwa Basin. Overall, the most extreme low rainfall events were recorded more in the previous years (1973 to 1995) compared to recent period of (1996 to 2018). In general, rainfall in the Lake Chilwa basin displayed a decreasing tendency although such decrease was not generally significant based on MK test at alpha level (α) of 0.05. The insignificant decreasing tendency perhaps explains why the stationarity difference test using Mann-Whitney test failed to detect significant differences in annual rainfall between periods of 1973 to 1995 and 1996 to 2018. Temperature on the other hand shows to be increasing in the basin, with MK test detecting significant increasing tendency at three of six weather stations analysed in the basin. Based on SPI and SPEI results nevertheless, the contribution of the increasing temperature to drought occurrences in the basin is quite insignificant, and therefore the drying episodes of Lake Chilwa are largely attributed due to low rainfall amounts received in a preceding year. Nonetheless, while low rainfall is certainly an important factor to lake recessions, this study reveals that the threshold level of low rainfall leading to complete drying of Lake Chilwa has changed, such that average annual rainfall below 1000mm in the basin are likely to trigger a lake recession in recent years.. This is indicative of anthropogenic effect associated with water abstractions as human population increases in the basin; or a disturbance to runoff flow regime due to changes in land use and or land cover. Considering that rainfall displays a decreasing tendency generally, this study envisages more dry-up episodes in the near future.

Acknowledgements

This work was financially supported by the project 'Building REsearch Capacity for sustainable water and food security In dry lands of sub-saharan Africa' (BRECCIA) which is supported by UK Research and Innovation as part of the Global Challenges Research Fund, grant number NE/P021093/1. We further acknowledge the Malawi Department of Climate Change and Meteorological Services (DCCMS) for kindly providing the climate data.

Declarations

- **Conflict of Interest**

There are no any direct or indirect conflicts of interest that we are aware of regarding this work.
- **Funding Statement**

This work was financially supported by the project 'Building REsearch Capacity for sustainable water and food security In dry lands of sub-saharan Africa' (BRECCIA) which is supported by UK Research and Innovation as part of the Global Challenges Research Fund, grant number NE/P021093/1.
- **Author's Contribution**

O. Kambombe took lead of the research, analysed, did literature review and drafted the initial manuscript.
C. Ngongondo took lead in the supervision, guided research direction, assisted in the writing and editing of the manuscript.
L. Eneya contributed in the supervision, provided research direction, assisted in the writing and editing of the manuscript.
M. Monjerezi contributed in the supervision, provided research direction, and assisted in the writing and editing of the manuscript.
C. Boyce provided most of the meteorological data used for the study, assisted in the writing and editing of the manuscript.
The listed authors have made a significant contribution to warrant their being part of authorship and have approved the work.
- **Data, material and code availability**

Meteorological data used for this study can be accessed through the link provided below. Additional data, material or code used can be provided upon request to the authors if needed
https://drive.google.com/drive/folders/1kUSuzJ1dXpoTtDc_6sCBw3Gaw73oYIcK?usp=sharing
- **Ethics approval**

The study followed all necessary ethical and professional conduct. Since no human or animal subjects were involved, a special waiver was provided by the university to go ahead with the study.
- **Consent to participate**

No human subjects were involved and hence consent to participate was not applicable.
- **Consent for publication**

The authors affirm that all the relevant data provided for this research was consented for publication.

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Figures

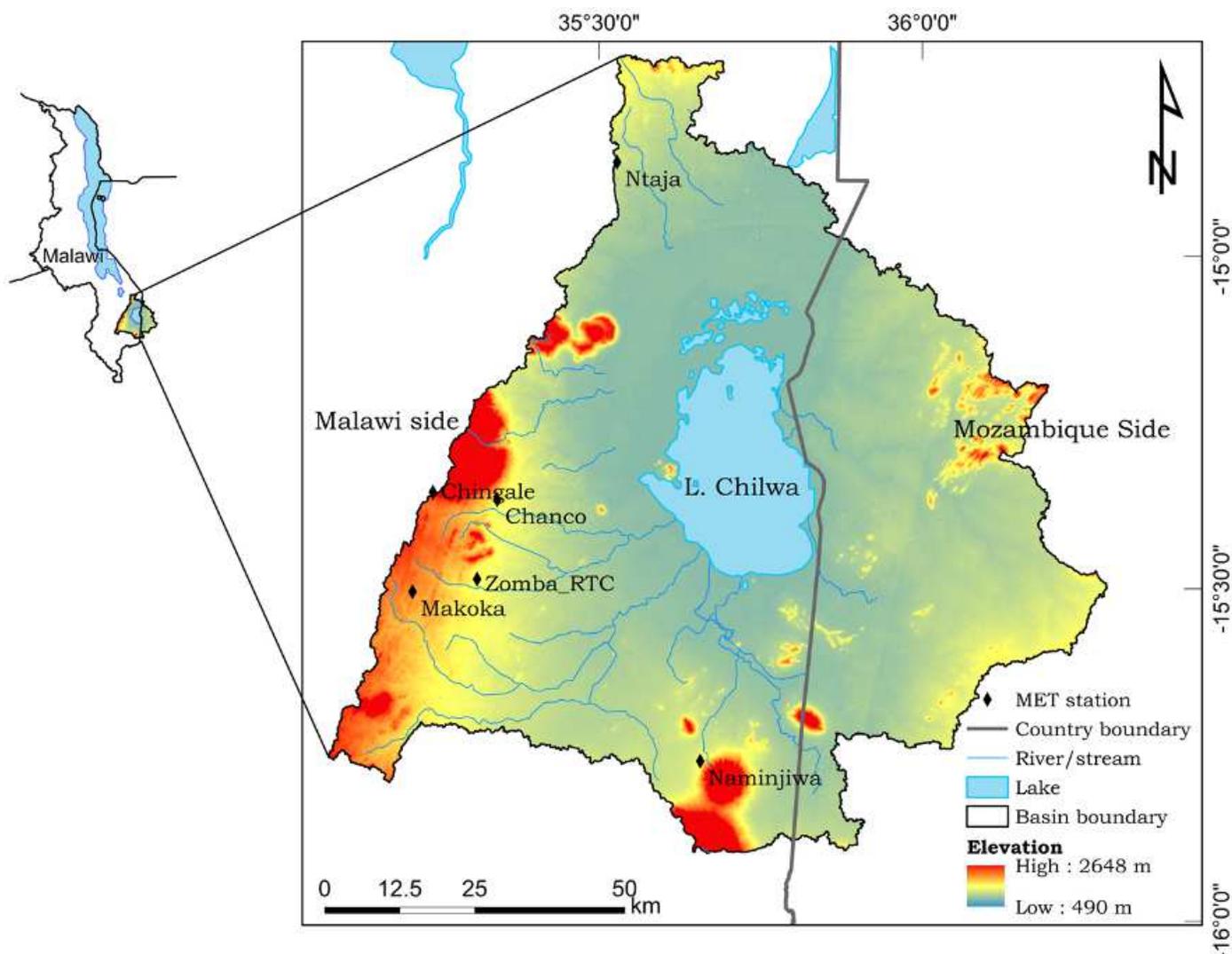


Figure 1

Map of the Lake Chilwa Basin showing the locations of weather stations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

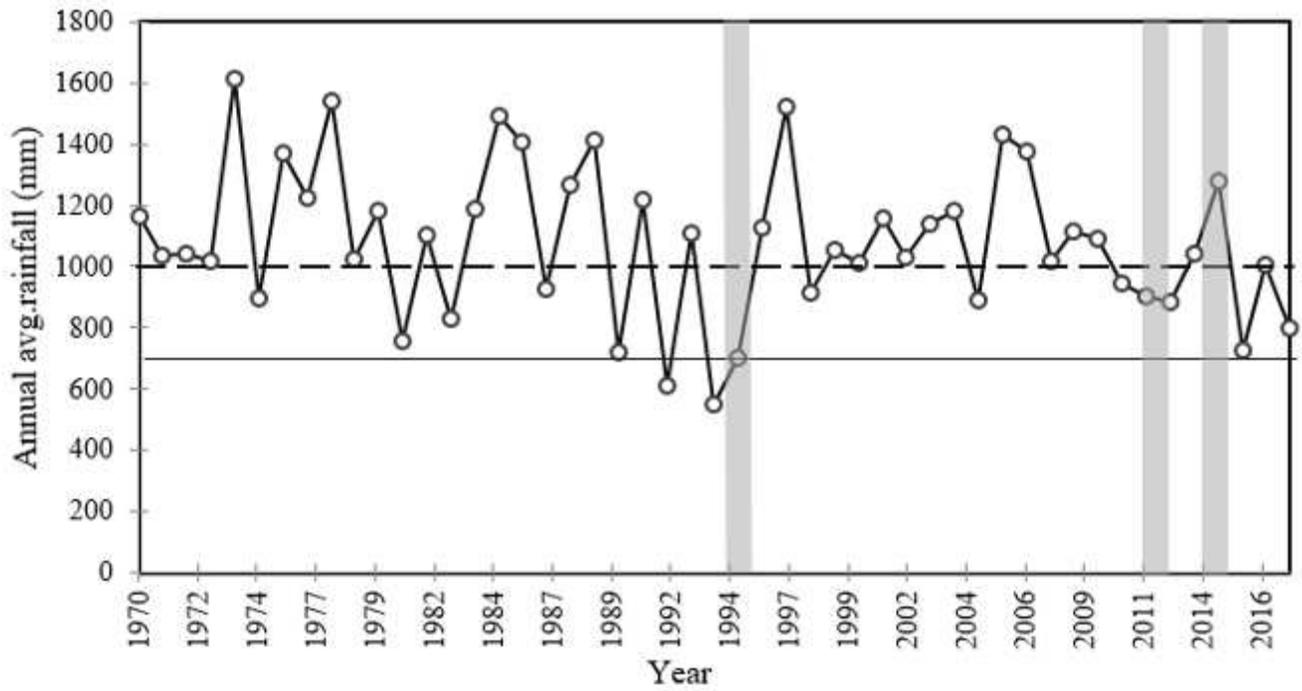


Figure 2

Time series plot of average annual rainfall for the basin (1970-2018)

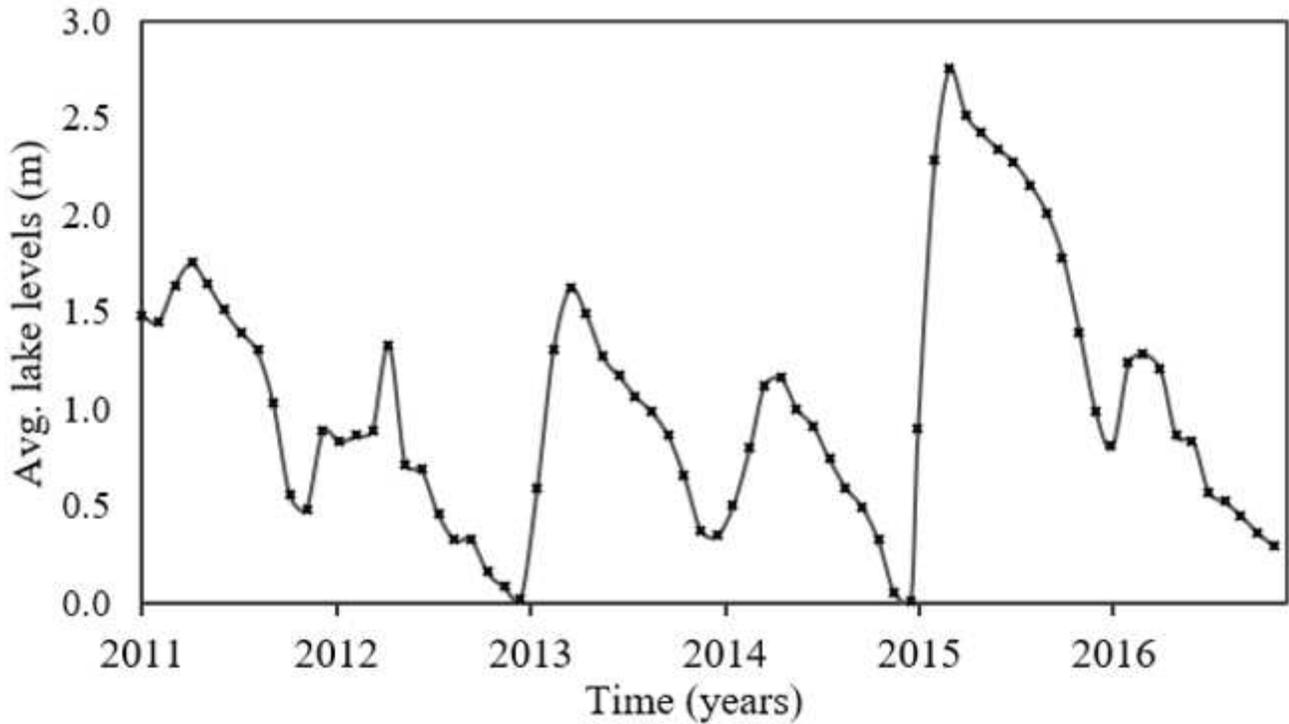
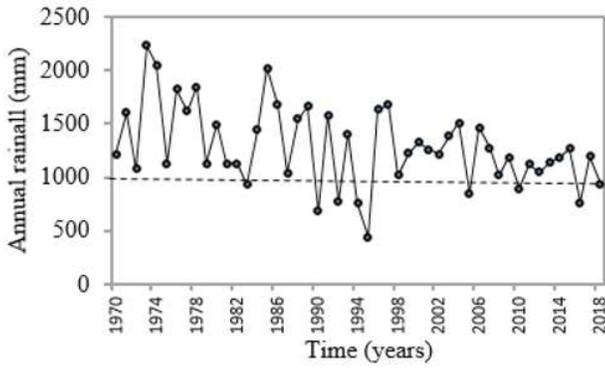
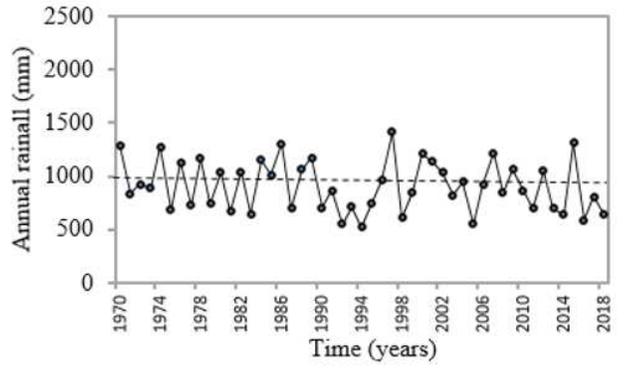


Figure 3

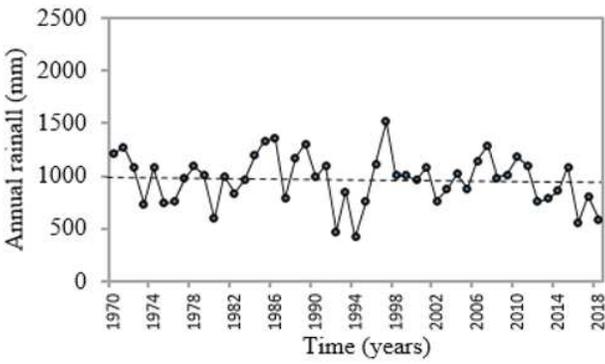
Average lake levels for the Lake Chilwa for the period of 2011 to 2016



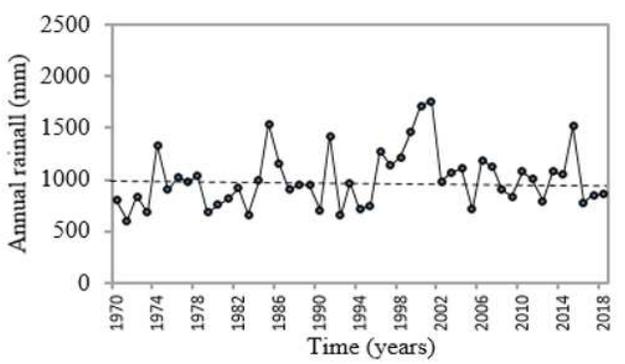
(a) Chanco



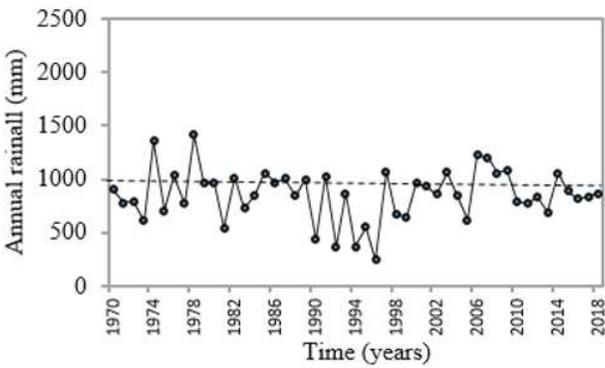
(b) Chingale



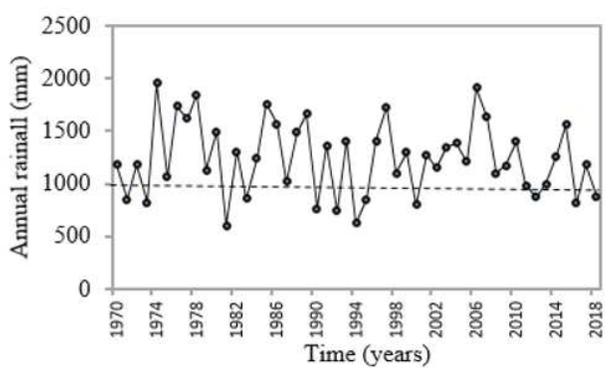
(c) Makoka



(d) Naminjiwa



(e) Ntaja



(f) Zomba RTC

Figure 4

Time series plot of annual rainfall for the six stations in the basin (1970-2018)

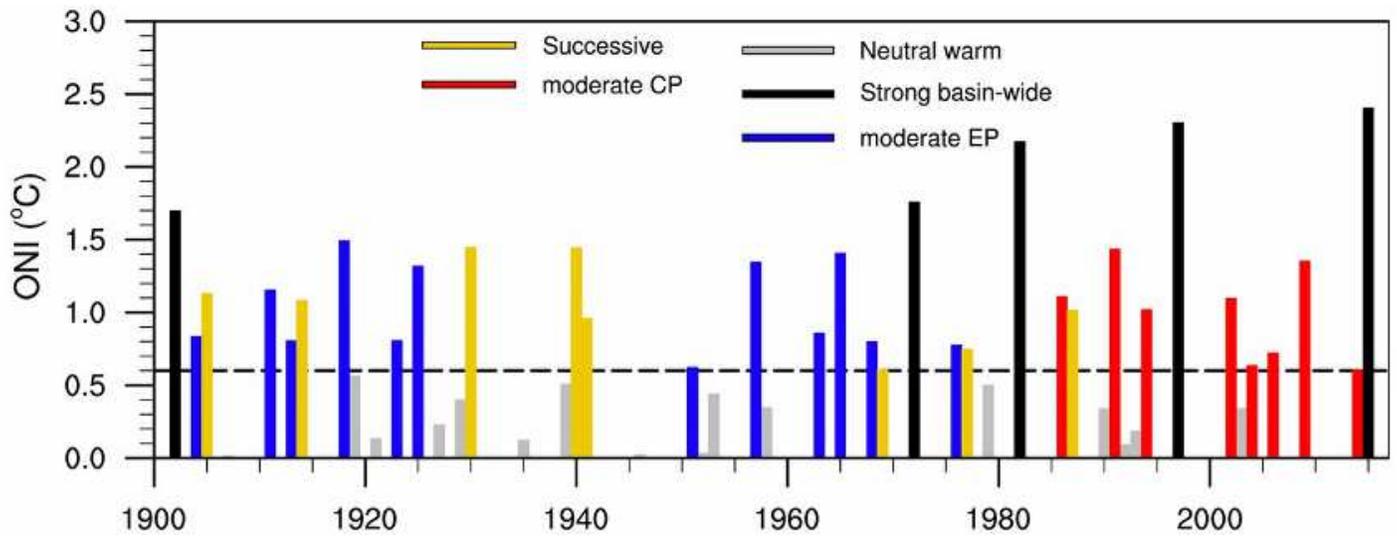
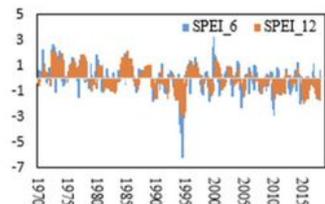
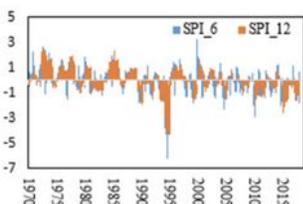


Figure 5

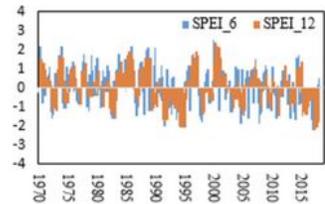
Changing El Niño types from 1901 to 2017 (Wang et al., 2019)



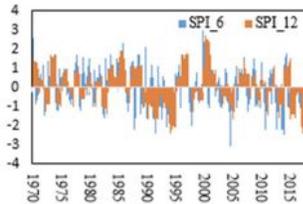
(a) Chanco: SPEI 6- and 12- months



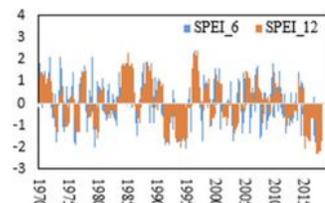
(b) Chanco: SPI 6- and 12- months



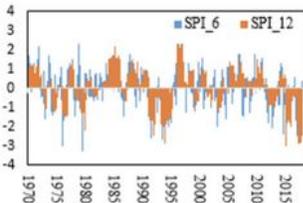
(c) Chingale: SPEI 6- and 12- months



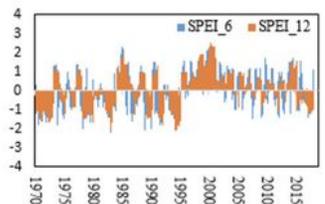
(d) Chingale: SPI 6- and 12- months



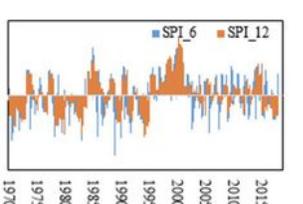
(e) Makoka: SPEI 6- and 12- months



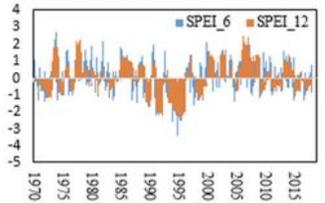
(f) Makoka: SPI 6- and 12- months



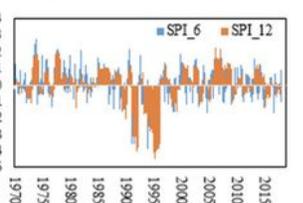
(g) Naminjiwa: SPEI 6- and 12- months



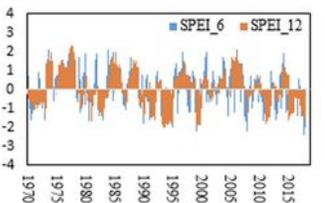
(h) Naminjiwa: SPI 6- and 12- months



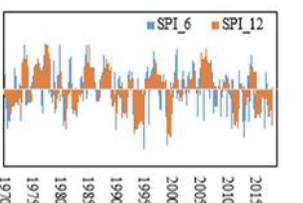
(i) Ntaja: SPEI 6- and 12- months



(j) Ntaja: SPI 6- and 12- months



(k) Zomba_RTC: SPEI 6- and 12- months



(l) Zomba_RTC: SPI 6- and 12- months

Figure 6

Temporal variations of SPEI and SPI at 6- and 12- month time-step for the six stations

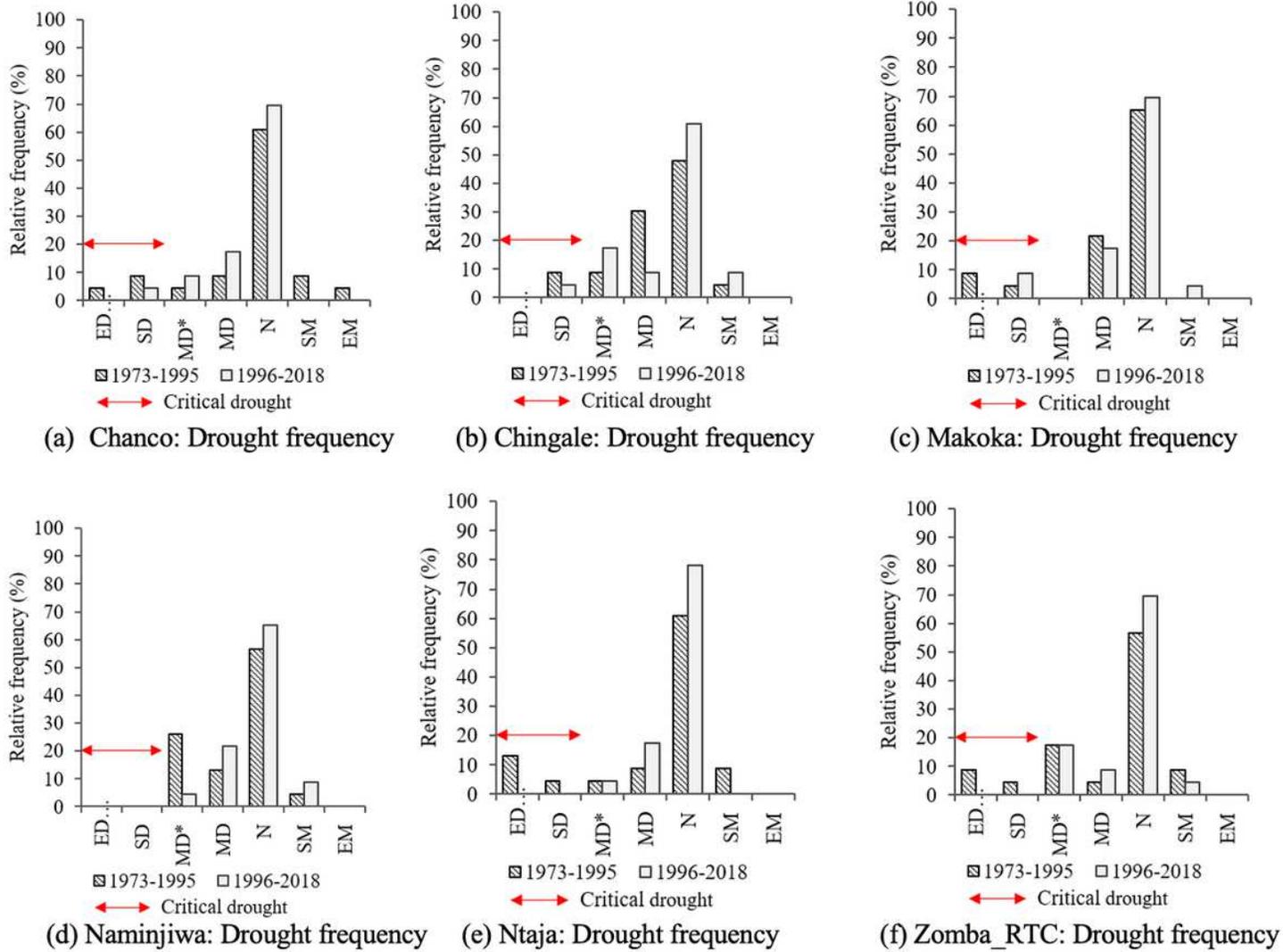
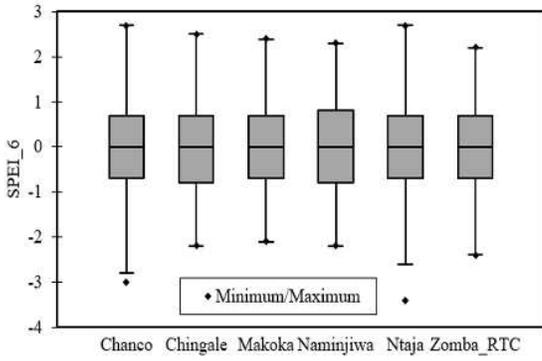
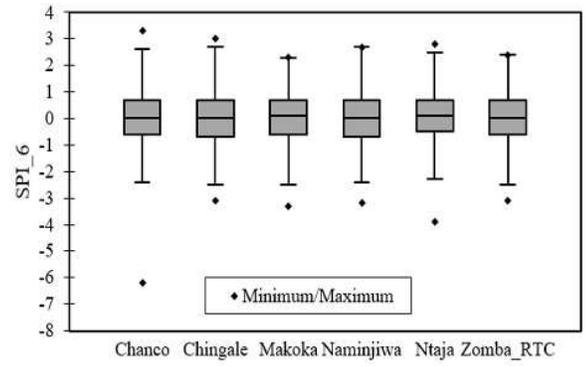


Figure 7

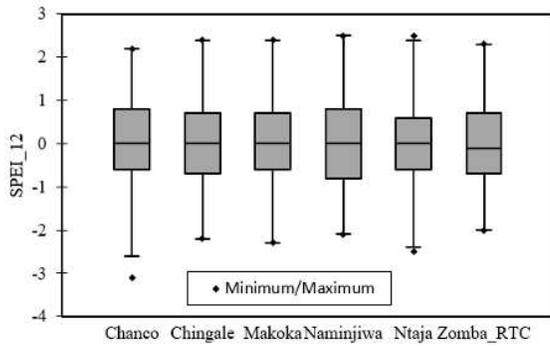
Relative drought frequency comparison between 1973 to 1995 and 1996 to 2018 for the six stations



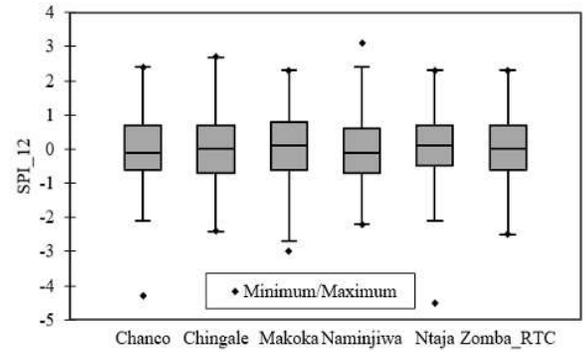
(a) SPEI 6-Months for all six stations



(b) SPI 6- Months for all six stations



(c) SPEI 12- Months for all six station



(d) SPI 12- Months for the six stations

Figure 8

Box-and-whisker plot of the SPEI and SPI at 6- and 12- months timescale

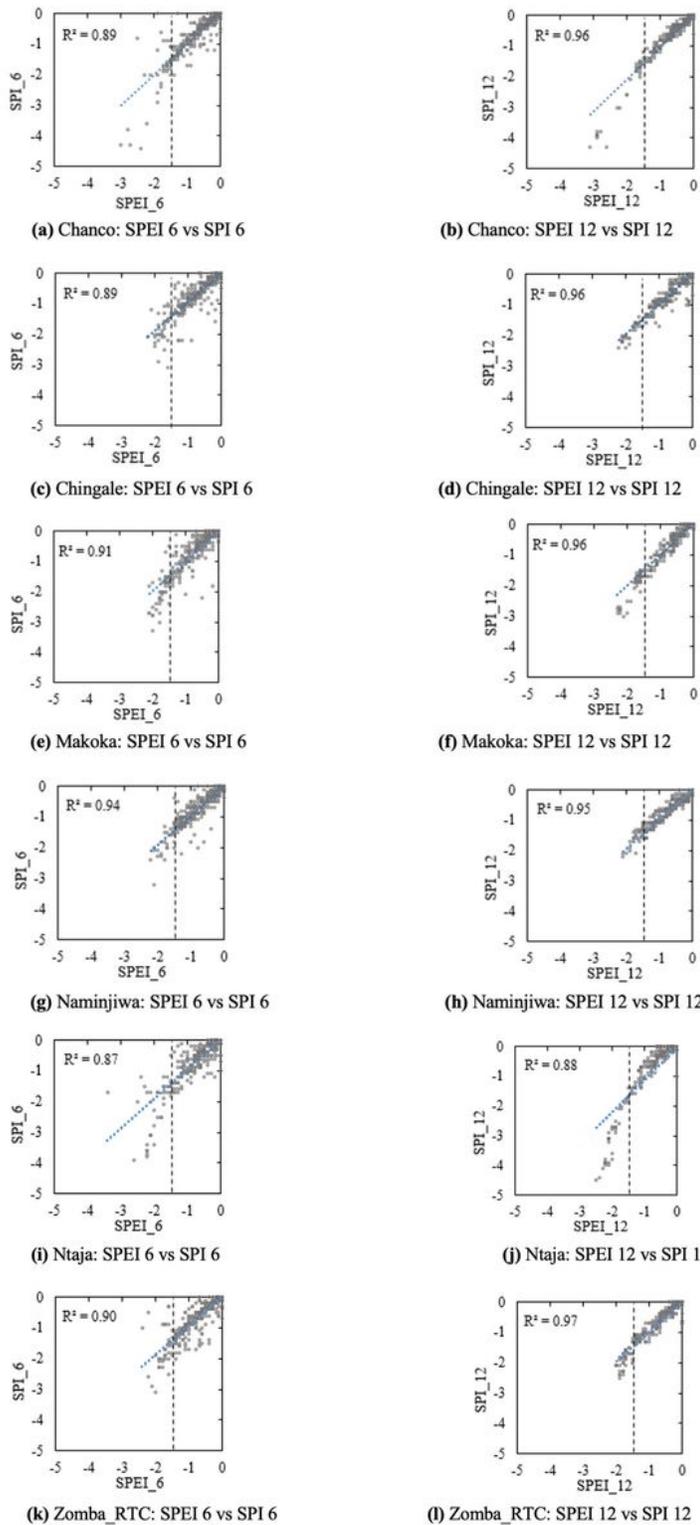


Figure 9

Scatter plot of SPI and SPEI compared at 6- and -12 monthly scales for each station