Article:

Nkiaka, E, Nawaz, NR and Lovett, JC orcid.org/0000-0002-5839-3770 (2017) Using standardized indicators to analyse dry/wet conditions and their application for monitoring drought/floods: A study in the Logone catchment, Lake Chad basin. Hydrological Sciences Journal, 62 (16). pp. 2720-2736. ISSN 0262-6667

https://doi.org/10.1080/02626667.2017.1409427

Using standardized indicators to analyse dry/wet conditions and their application for monitoring drought/floods: A study in the Logone catchment, Lake Chad basin

E. Nkiaka[1], N.R. Nawaz[1] and J.C. Lovett[1]

[1]School of Geography, University of Leeds.

Correspondence to: E. Nkiaka (gyenan@leeds.ac.uk)

Abstract

The Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) were used in this study to analyse dry/wet conditions in the Logone catchment over a 50-year period (1951-2000). SPI analysis at different timescales showed several meteorological drought events ranging from moderate to extreme. SSI analysis showed that wetter conditions prevailed in the catchment from 1950-1970 interspersed with few hydrological drought events. Overall, results indicated that both the Sudano and Sahelian zones are equally prone to droughts and floods. However, the Sudano zone is more sensitive to drier conditions, while the Sahelian zone is sensitive to wetter conditions. Correlation analysis between SPI and SSI at multiple timescales revealed that the catchment has a low response to rainfall at short timescales, though this progressively changed as the timescale increased with strong correlations (≥0.70) observed after 12 months. Analysis using individual monthly series showed that the response time reduced to 3 months in October.

Keywords: standardized indicators; SPI; SSI; drought/floods monitoring; response time; Logone catchment; Lake Chad basin

1. Introduction

Large scale droughts are complex environmental phenomena with significant effects on agriculture, society and ecosystems. Generally, drought can be defined as a period of deficient rainfall over a long period of time and can be grouped into four main categories (meteorological, agricultural, hydrological and socioeconomic) (Wilhite and Glantz, 1985). In semi-arid areas in developing countries, such as the Sudano-Sahel region of Africa, rainfall plays a crucial role in the socio-economic wellbeing of the population because they depend on it for livelihood activities especially agriculture which is mostly rain-fed. However, in recent decades, food security in the region has been threatened following drought and rainfall variability (Gautam, 2006, Traore and Owiyo, 2013). In this region, drought can result in the loss of assets in the form of crops, livestock, and other productive capital as a result of low rainfall (meteorological droughts) which after extended periods can result in water shortages (hydrological droughts).

Despite a history of droughts, recent studies have, indicated a gradual increase in rainfall in the region (Odekunle et al., 2008, Nkiaka et al., 2017) but less attention has been given to extreme rainfall events compared to droughts probably because little information exists about floods and other damaging rainfall events in the Sudano-Sahel (Tschakert et al., 2010). The socio-economic impact of weather extremes, and predictions that extremes will become more frequent (Field et al., 2014), requires a change in paradigm so that equal attention is given to both droughts and floods in this region.

The Standardized Precipitation Index (SPI) (McKee et al., 1993) is a probability based indicator that indicates the degree to which accumulative precipitation for a specific period departs from the average state. This index is generally used to detect, monitor and assess dry and wet conditions and identify their variability at different spatial and temporal scales. Compared to other methods for calculating drought conditions e.g. the Palmer Drought Severity Index (PDSI), Standardized Precipitation Evapotranspiration Index (SPEI), the Surface Water Supply Index (SWSI), and the Standardized Anomaly Index (SAI), the SPI offers many advantages: (i) only a single input variable (precipitation) is necessary, (ii) provides a means of analyzing both wet and dry periods, (iii) it can be calculated for different time scales, (iv) it can allow the user to classify droughts into different categories, and (v) it is probability based and hence can be used in risk management and decision analysis. Due to its robustness and convenience, the SPI has been widely used to study droughts around the world (Roudier and Mahe, 2010, Du et al., 2013, Barker, 2016). It has also been used extensively to monitor wetness conditions (Seiler et al., 2002, Guerreiro et al., 2008), and to analyse both dryness and wetness conditions (Machado et al., 2011, Du et al., 2013, Ionita et al., 2015). Furthermore, the World Meteorological Organisation (WMO, 2012) recommends the use of the SPI to assess and monitor drought conditions and identify wet periods.

Despite its wide application, the SPI has been subjected to criticism by several authors e.g. (Lloyd-Hughes and Saunders, 2002). They argue that the use of the SPI for short time scale analysis (1, 2, 3-month) within regions characterized by low seasonal precipitation may result in over-estimation or under-estimation of the positive or negative SPI values. Golian et al. (2015) argue that using only a single index to monitor droughts may be misleading due to the complex nature of drought phenomena in both their causation and impact. As a result of these criticisms, the multivariate standardized drought index (MSDI) (Hao and AghaKouchak, 2013) was developed. Despite these advances, application of the SPI remains popular even though it requires a minimum of 30 years of monthly rainfall data which may limit its application in data-scarce regions and has been applied in many studies across the world (Seiler et al., 2002, Guerreiro et al., 2008, Roudier and Mahe, 2010, Machado et al., 2011, Cheo et al., 2013, Louvet et al., 2016).

Despite wide application of the SPI, the lack of understanding on how meteorological droughts are propagated to hydrological droughts is still a major obstacle to the development of a drought-focused monitoring and early warning system (Barker, 2016). However, Vicente-Serrano et al. (2011) developed and tested the standardized streamflow index (SSI), which can be used to obtain a hydrological drought index that is useful for making spatial and temporal comparisons over a wide variety of river regimes and flow characteristics. Many studies for gaining insight on how meteorological droughts are propagated to hydrological droughts using SPI and SSI have been published (Du et al., 2013, López-Moreno et al., 2013, Zhang et al., 2015, Barker, 2016). In Africa, although there are drought studies utilizing the SPI (Roudier and Mahe, 2010, Cheo et al., 2013, Louvet et al., 2016), the use of both SPI and SSI techniques for monitoring dryness and wetness conditions in the continent has not been reported.

Unlike the rest of the Sudano-Sahel region, studies on dryness and wetness conditions in the Lake Chad basin (LCB) are relatively few and largely undocumented. Insufficient research output from the basin may be attributed to limited rain gauge stations in Central Africa and the steady decline in the number of existing hydro-meteorological facilities in the region (Washington et al., 2006). Despite this decline, a number of studies analysing dryness and wetness conditions in the LCB have been carried out. Okonkwo et al. (2013) used the SPI to analyse monthly gridded rainfall and different satellite precipitation datasets for the period 2002-2011 and demonstrated that extreme wetness conditions prevailed in the basin in the year 2010; and Ndehedehe et al. (2016) applied independent component analysis (ICA) to reveal the prevalence of wetness conditions in the LCB during the period 2012 – 2014 by analysing different satellite precipitation datasets.

However, previous studies are generalized for the whole LCB, cover a short time horizon and may be misconstrued as insignificant in a particular location (i.e. at local or sub-catchment scale). The LCB covers an estimated area of $2.5x10^6$ km^2 (and a population of about 30 million and contains a range of ecological zones (hyper arid, arid, semi-arid and Sudano) with a high spatiotemporal variability in rainfall. Therefore, generalizing results from such studies as representative of smaller basins may not be useful for effective and robust planning of water resources management and development of adaptation strategies in the event of droughts and floods.

Reducing the spatial scale of such analysis enables to gain an insight into the likelihood of occurrence of extreme dryness and wetness conditions at sub-basin level and station locations. The Logone catchment was selected for this analysis for the following reasons: (i) the catchment covers two ecological zones (Sudano and semi-arid); (ii) it contributes a significant amount of inflow into Lake Chad; (iii) it is a transboundary catchment shared by three countries (Cameroon, Chad and Central Africa Republic); and (iv) it has extensive floodplains that contribute significantly to the livelihood of the local population.

The Logone catchment has experienced a series of floods in recent years with widespread socio-economic effects. However, even with the prevailing wetter climate, erratic rainfall means that water availability for agriculture, pastoral activities, ecosystem sustainability and inflow into Lake Chad is unpredictable. Yet there is limited detailed hydro-climatological documentation that can be used to enhance water resources management in the catchment. Analysing the characteristics of dryness and wetness conditions using long term data is an important step for establishing an effective and comprehensive monitoring and early warning system in the catchment. Understanding the context-specific nature of the likelihood of dryness/wetness conditions will facilitate the identification of policy interventions to enhance adaptation even in the context of climate change.

The main objectives of this study were to use the Standardized Precipitation Index (SPI) to: (i) calculate the frequency of occurrence and spatial distribution of dryness and wetness conditions, (ii) analyze their spatio-temporal characteristics, (iii) analyze the SPI and SSI trends in the catchment using the Mann-Kendall test, and (iv) use the two indicators to assess the relationship between rainfall and streamflow. This study is part of an on-going project aimed at understanding hydro-climatic variability in the Logone catchment that assesses vulnerability of the catchment to global climate change and the type of policy measures which can be put in place to improve water resources management and adaptation to climate change.

2. Study area and data

The Logone catchment is located in the south western part of the LCB. It covers an estimated area of 86,240 km^2 at the Logone Gana hydrometric station and lies between latitude 6˚ - 12˚ N and longitude 13˚ - 17˚ E (Figure 1). This is about 8% of the conventional LCB area of 1,053,455 km^2 (Adenle, 2001). The Logone is a major tributary of the Chari River, and the two rivers jointly contribute about 95% of inflow into Lake Chad (Loth and Acreman, 2004). The Logone has its source in Cameroon from the Mbere and Vina Rivers originating from the Adamawa Plateau. In Lai, it is joined by the Pende River from Central Africa Republic and flows in a south-north direction. The altitude ranges from about 1200 masl around the Adamawa Plateau in the south to 300 masl in Ndjamena in the north. It flows through three countries, Cameroon, Central Africa and Chad with a flat topography with average slope of less than 1.3%. The catchment is located in a Sudano-Sahelian climatic regime controlled by the tropical continental regime air mass (the Harmattan) and the oceanic regime equatorial air mass (monsoon) (Nkiaka et al., 2017). It has a strong north-south rainfall gradient with a single rainy season between May and October and an average annual rainfall varying between 500 mm/year in the north to about 1400 mm/year in the south. There is a strong spatio-temporal variability in rainfall (Nkiaka et al., 2017) and mean temperature in the catchment is 28° (Loth and Acreman, 2004).

2.1. Data sources

Monthly rainfall and streamflow data were obtained from "Système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation" (SIEREM) (Boyer et al., 2006). According to Boyer et al. (2006), the SIEREM data was obtained using the POLLEN method adapted from the Object Modelling Technique. To increase robustness of our results, only stations that had monthly data covering the period 1951-2000 were selected; with missing data points of not more than 10%. Given that only 11 rain gauge stations located inside the catchment could fulfil these criteria, six additional rain gauge stations located outside the catchment, but within its immediate surroundings, were selected to increase the number of rain gauges. Stations 1-13 in Table 1 lie in the Sudano ecological zone (5° - 10°N) and stations 14-17 are located in the Sahelian ecological zone (10° - 12°N). These ecological zones represent simplified climatic zones based on the Köeppen Geiger climate classification for Africa (Peel et al., 2007). Streamflow time series were available for the period 1955-2000. The data was quality controlled using different homogeneity tests and all the time series were found to be homogeneous (Nkiaka et al., 2017). Gaps in the time series were infilled using Artificial Neural Network (ANN), Self-Organizing Maps (SOMs) techniques (Nkiaka et al., 2016).

A limitation of the study is the absence of rainfall data after the year 2000 so the influence of recent rainfall measurements on SPI values could not be evaluated. However for an insight into the recent characteristics of drought indices in the area covering the period 2002-2014, the reader can refer to Okonkwo et al. (2013) and Ndehedehe et al. (2016). A limitation of those studies is that only 10 years of satellite precipitation data was used in the SPI analysis. According to McKee et al. (1993), the application of the SPI for drought monitoring requires a minimum of 30 years data. Another limitation of those studies is that satellite precipitation analysis depends on the quality of gauge data used for satellite calibration, and are thus inevitably affected by the sparsity of gauge data or temporally incomplete gauge time series in the region under investigation.

3. Methodology

3.1. The Standardized Precipitation Index (SPI)

The methodology adopted in this study involves application of the SPI software (McKee et al., 1993) and fitting a gamma probability density function to a given frequency distribution of monthly precipitation totals for each station. Generally, the gamma distribution has been found to fit precipitation data quite well. The probability density function is calculated as:

$$G(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^c x^{\alpha-1} e^{\frac{-x}{\beta}} dx \qquad (1)$$

where, β is the scale parameter, α is the shape parameter, x is the monthly rainfall data, and $\Gamma(\alpha)$ is the gamma distribution function. The parameters of the gamma distribution function are estimated for each station for the chosen time scale (1, 3, 12-month, etc.). The gamma distribution parameters α and β are estimated using the maximum likelihood method. The gamma distribution is undefined for x = 0, but the precipitation may have zero value, so the cumulative probability distribution given a zero value is derived as follows:

$$H(x) = q + (1-q)G(x) \qquad (2)$$

where q is the probability of the zero precipitation value. The cumulative probability distribution is then transformed into the standard normal distribution to calculate SPI. A full description of the methodology on the calculation of SPI is available in Lloyd-Hughes and Saunders (2002).

According to McKee et al. (1993), the index has a normal distribution, so it can be used to estimate both dry and wet periods. A wet period according to the SPI value may be defined, for a time scale i, as the period during which the SPI is continuously positive and reaches a value of +1 or higher and a drought period begins when the SPI value is continuously negative and reaches a value of -1.0 or lower. SPI at different time scales, e.g. 3-month SPI of a particular month represents the deviation in precipitation totals for the same month and current plus previous two months, respectively. It indicates how the precipitation for a specific period compares with the complete record at a given station. In this study, analysis were conducted for multiple time-scales ranging from 1 to 24 months.

When interpreting SPI, one should bear in mind that dryness and wetness are relative to the historical average rather than the total of precipitation of a particular location. For example a given magnitude of precipitation at a dry station may produce a negative SPI value, while at a different extremely dry location within the same catchment the same precipitation magnitude may give a positive SPI value. Table 2 shows the classification scheme of SPI values according to WMO standards (WMO, 2012). SPI analysis were carried out for timescales of 1 to 24 months successively.

3.2. Standardized Streamflow Index (SSI)

Streamflow is an important variable used for monitoring both droughts and floods. To assess the best SPI timescale for explaining the temporal variability in the streamflow time series, a Pearson correlation analysis was performed between the monthly SSI and SPI series at timescales of 1 to 24 months. Given that streamflow is the integrated response of the catchment to rainfall from different parts of the catchment, SPI values used in the analysis were obtained by calculating the arithmetic average of SPI values from rain gauge stations located upstream of each gauging station. The arithmetic average was used on the basis that, once the rainfall data from the various stations have been converted to SPI values, the influence of "areal average rainfall" does not longer apply. This is because the transformation of SPI to the standard normal distribution with a mean of zero and a standard deviation of one makes the SPI comparable over time and space (Barker, 2016). The comparison between SSI and SPI provides an indication of the time taken for precipitation deficits to propagate through the hydrological cycle to streamflow deficits. This technique has been applied by several researchers for meteorological and hydrological drought analysis (López-Moreno et al., 2013, Barker, 2016). Note that rainfall data from 6 rain gauge stations located outside the catchment domain were not used because they do not contribute to streamflow measured inside the catchment. Table 2 is also valid for the classification of SSI.

Generally, the calculation of the SSI is mathematically similar to the SPI calculation shown in the preceding section and uses the same principle as the SPI, by aggregating streamflow data over selected accumulation periods. Given the heterogeneity in river and catchment characteristics (Vicente-Serrano et al., 2011), the most suitable probability distribution that can be used to fit individual streamflow series measured along the river may vary. Due to this variation, different probability distributions (lognormal, Pearson Type III, gamma distribution, Weibul, Generalized Pareto, General Extreme Value) have been applied to fit streamflow data for SSI calculation (Vicente-

Serrano et al., 2011). In this study the gamma distribution was used to fit streamflow. This distribution has extensively been used to fit global streamflow datasets in previous studies (Vogel and Wilson, 1996, McMahon et al., 2007, Du et al., 2013, Zhang et al., 2015).

SSI was calculated at two gauging stations along the Logone River; upstream at Bongor with an estimated drainage area of 73,000 km^2 and downstream at Logone Gana (outlet) with an estimated drainage area of 86,240 km^2. These stations were selected based on available river discharge records and also because Bongor is the only reliable station located downstream of the Sudano zone of the catchment while Logone Gana is located at the outlet in the semi-arid zone.

3.3. The Mann-Kendall trend test

The nonparametric Mann–Kendall test was applied to the SPI time series to examine the presence of trends. This test is widely used to detect trends in hydrology and climatology because it is robust against non-normal distributions and is insensitive to missing values. The null hypothesis H(0) states that there is no significant trend in the examined time series. The hypothesis is rejected if the p value of the test is less than the significance level (e.g. 0.05 indicating a 95% confidence level). The Mann–Kendall test has been used in several drought studies (Du et al., 2013, Golian et al., 2015, He and Gautam, 2016). Detailed information on the application of this test is widely available in the literature. In this study the results were calculated for the 95% confidence interval.

The catchment was divided into two parts; the northern part termed the Sahelian zone for stations located between latitudes 10°-12° N and the southern part termed the Sudano zone for stations located between latitudes 6°-10° N. The main difference between the two zones is an increase in annual rainfall total from stations located in the north to those in the south (Nkiaka et al., 2017). Table 1 gives the station name, coordinates, long term mean, maximum and minimum of the annual rainfall time series for each station.

4. Results

4.1. Frequency of dry/wet years

A 12-month SPI analysis was used for the 17 stations in order to show the prevalence and spatial distribution of dryness and wetness conditions across the catchment. Using the threshold values in Table 2, a particular year was considered dry if the SPI ≤ -1.0 and wet year if the SPI ≥ 1.0. Figure 2 shows the spatial distribution and frequency of occurrence of dry and wet years respectively. For example stations belonging to group 0.16 – 0.20 in Figure 2(a) experienced dry episodes in 16-20% of all the years used in the study, while stations belonging to group 0.18-0.20 Figure 2(b) experienced wet conditions in 18-20% of all years used (1951-2000). The analysis also showed that the frequency of occurrence of drought conditions was high for stations located in the Sudano zone of the catchment. For example stations like Ngaoundere, Baibokoum, Bongor and Bekao with high annual rainfall instead experienced the highest frequency of occurrence of severe dryness conditions.

Meanwhile, no drought conditions were observed in Massenya, the most northerly station located in the Sahelian zone of the catchment. This station instead witnessed the highest frequency of wetness conditions (35.0%) which is surprising. These results are consistent with the findings of Roudier and Mahe (2010) who observed in the Bani basin, located in the same latitudinal zone as the Logone catchment, that the semi-arid northern part of the basin was less prone to droughts compared to the southern part.

Overall the results indicated that both the Sudano and Sahelian zones of the catchment are prone to both droughts and floods as shown in Figure 2, although the average frequency of occurrence of floods is slightly higher (17.60%) compared to droughts (13.50%). Table 3 gives a detailed analysis of the results.

4.2. Analysis of dryness/wetness conditions at multiple time scales

Analysis of SPI at 1- and 3-month time-steps showed that SPI values frequently fluctuated above and below zero with no extended periods of dryness or wetness but short episodes of dry and wet conditions (Figure 3a&b). The results are consistent with the findings of Ndehedehe et al. (2016) in the southern part of the LCB covering the Logone catchment. Using the Effective Drought Index (EDI), Roudier and Mahe (2010) also reported that, droughts were more frequent but of shorter duration in the southern area of the Bani basin. SPI analysis at shorter time scale are mostly useful for monitoring past dryness and wetness conditions. This may be useful in reconstructing the flood history of a catchment.

SPI analysis at a 12-month time-step demonstrated a strong variation in annual rainfall fluctuating between wet and dry years (Figure 3c). Generally, results showed that drought events were frequent at shorter time-scales but lasted for shorter durations at longer timescales, droughts were less frequent but persisted for longer periods (Figure 3a, b & c). Furthermore, the period of occurrence and duration of dry and wet years vary from one station to another. These results are consistent with the findings of Cheo et al. (2013). Cheo et al. (2013) using SPI analysis at a 12-month time-step reported that, there was a significant spatial variability in drought occurrence and intensity across the northern regions of Cameroon located adjacent to the Logone catchment.

4.2.1. Spatio-temporal variation of dryness conditions

Analysis of 12-month SPI across all the stations showed that all but one station in the catchment experienced a minimum of three periods of drought. These droughts could be categorised as ranging from moderate to extreme with different durations beginning as early as the mid-1960s at some station before becoming very noticeable at most station locations after 1970. Drought episodes with extended durations occurred around (1971-1973), (1981-1984) and (1991-1993). Nevertheless, the total duration, severity and period of occurrence of the drought episodes varied from one station location to another.

Based on Table 2 and using 12-month SPI to analyze drought categories showed that, the Sahelian zone experienced extreme droughts of averagely longer duration (20 months) compared to 14 months in the Sudano zone. Meanwhile, severe droughts lasted for almost the same duration (24 months) in both parts of the catchment. Moderate droughts persisted longer in the Sudano zone with an average duration of 52 months compared to 47 months in the Sahelian zone. The results follow the findings of Ndehedehe et al. (2016) who reported that the Sudano zone of the LCB was more vulnerable to drought conditions compared to the Sahelian zone. Roudier and Mahe (2010) also reported that the duration of droughts was slightly longer in the southern zone of the Bani basin compared to the extreme north part.

Further scrutiny of 12-month SPI time series revealed that, apart from 1980 decade when most severe to extreme droughts seemed to concentrate in the middle of the decade, severe and extreme drought conditions appear to be mostly concentrated around the beginning or end of a decade interspersed with moderate drought conditions. Results also show that moderate/severe droughts were mostly intra-annual and lasted for shorter time-scales while extreme droughts were inter-annual and persisted for longer periods (e.g. September 1971-April 1972, October 1983- May 1985, September 1999-July 2000) for Baibokoum, Ngaoundere and Bousso stations respectively.

The temporal and spatial evolution of drought variability using a 12-month SPI further indicated that, the driest months in the catchment were recorded in the 1980 and 1990 decades with varying degrees of severity. In the Sahelian zone the driest months were recorded in Bailli (SPI = -2.78) in April 1980 and Bongor (SPI= -3.30) in May 1985. Meanwhile, in the Sudano zone the driest months were observed in Deli (SPI= -4.38) in August 1992, Kello (SPI= -3.85) in May 1985, Baibokoum (SPI= -3.77) in June 1984 and Ngaoundere (SPI= -3.22) in August 1984. These values further indicate that droughts were more severe in the Sudano zone where the lowest SPI value was observed (-4.38) compared to (-3.30) in the Sahelian zone. Analysis also showed that extreme droughts prevailed during the period of rainy season especially around the months of July, August and September, and were generally preceded by periods of moderate to severe drought conditions. The prevalence of extreme droughts conditions in the catchment during these months is consistent with the findings of Nkiaka et al. (2017) who reported that there was a general decline in July, August and September rainfall in catchment during the period 1951–2000.

4.2.2. Spatio-temporal variation of wetness conditions

Analysis of 12-month SPI also revealed that, all stations witnessed periods of wetness conditions with different durations which can be classified as ranging from moderate to extreme (Table 2). The average duration of extreme wetness conditions was slightly longer (16 months) for the Sudano zone compared to the Sahelian zone (11 months). Severe and moderate wetness conditions persisted longer (39 and 70 months) in the Sahelian zone compared to (27 and 56 months) in the Sudano zone respectively. Although the whole catchment experienced many periods of wetness with varying durations across individual station locations, wetter conditions prevailed longer in the Sahelian zone (120 months) compared to the Sudano zone (96 months). Surprisingly, Massenya station located in the Sahelian zone continuously experienced repeated periods of wetness ranging from moderate to extremely wet conditions stretching into the year 2000. This suggest that the Sahelian zone may be more prone to floods than the Sudano zone.

Temporal analysis using 12-month SPI values showed that the wettest period in the catchment was recorded during the 1950 decade with the highest SPI value observed in Moundou (3.58). A close examination of Figures 3-5 revealed that, wetness conditions prevailed in most stations during the 1990 decade ranging from moderate to extreme wetness with different durations across individual station locations. These results are consistent with those of other studies that reported on the prevalence of extensive floods in the region during this period (Odekunle et al., 2008, Tschakert et al., 2010, Okonkwo et al., 2014, Louvet et al., 2016).

4.3. Evaluation of hydrological droughts

Results of SSI at different timescales are generally similar to those of SPI at equivalent timescales (Figure 4). Unsurprisingly, more hydrological drought events were observed at shorter timescales but as the timescales increased, the number of drought events reduced but the duration increased. The results indicated that wetness conditions prevailed in the catchment from 1950-1970 decades even though interspersed with few episodes of hydrological droughts during the 1970 decade.

Prolonged hydrological droughts prevailed in the catchment from 1980 to mid-1990 with the drought categories ranging from mild to severe (Figure 4). Meanwhile, from mid-1990 stretching into the year 2000, humid conditions dominated in the catchment. Similar observations were made using the SPI at different station locations across the catchment which correspond to previous studies in the region as mentioned in the preceding section.

4.4. Results of trend analysis

The results of Mann-Kendall trend test indicated that across the catchment and at all time scales considered, negative trends in SPI were obtained with different significant levels indicating that the null hypothesis of no trend was rejected (Table 4). It can be observed that 7, 14 and 17 stations showed statistically significant negative trends at the 5% significant level for 1-month, 3-month and 12-month time scales respectively (Table 4). These negative trends in SPI values follow the general decline in rainfall over the catchment and are consistent with reported trends in the region (Odekunle et al., 2008, Nkiaka et al., 2017). Although no drought conditions were observed at Massenya station, it is worth noting that there was a significant negative trend in rainfall at this station during the period under study.

Results of Mann-Kendall trend analysis also show the presence of statistically significant negative trends for all SSI time series (Table 4). Our results are consistent with findings in region whereby a deficit in rainfall led to a corresponding drop in streamflow in most rivers across the Sudano-Sahel region (Paturel et al., 2003).

4.5. Relationship between SPI and SSI

Results of Pearson correlation analysis between monthly SSI and SPI at different timescales (1–24 months) showed that all correlations were positive although strong correlations were observed only at longer timescales (Figure 5). The correlations showed that the Logone River has a low response to rainfall at short timescales from weak correlations obtained. However, this progressively changed as the timescale increased with strong correlations (≥0.70) observed after 12 and 15 months at Bongor and Logone Gana gauging stations respectively. López-Moreno et al. (2013) observed similar strong correlations between SSI and SPI at longer timescales across catchments in southern Spain where catchments had permeable limestone headwaters. Barker (2016) also reported similar findings across several catchments underlain by major aquifers in England.

Figure 6a&b show the result of monthly correlations between SSI and SPI for selected months. It can be observed from the figure that the correlations changed seasonally according to SPI timescale but generally became very strong (≥0.70) after 12 months. During the month of March, the correlation values dropped to minimum after 4 and 5 months at Bongor and Logone Gana respectively before rising steadily to become very strong (≥0.70) after eight months. The same phenomenon was observed during the month of July where the correlation values decreased to 0.20 after 9 months before increasing rapidly (≥0.70) within 3 months. The correlations for each month were summarized using contour plots for the two gauging stations (Figure 7a&b). From the figure, it can be observed that the response time of the catchment is 5-6 months at the beginning of the rainy season (June/July). Meanwhile, towards the end of the rainy season (September/October) the response time reduces to 3 months as indicated by very strong correlation values (≥0.70).

5. Discussion

Results from this study show that stations located in both parts of the catchment (Sudano and Sahelian) are prone to droughts of all categories that could last for different durations. However, stations located in the Sudano zone are more likely to experience extreme droughts of shorter duration, while those in the Sahelian zone experience droughts of slightly lesser intensity but longer durations. Furthermore, the Sahelian zone of the catchment may be more prone to floods than the Sudano. The significant negative trends in SPI and SSI values suggest that there has been a significant change in the processes that influence rainfall and streamflow in the catchment. This indicates that the catchment is sensitive to natural climate perturbations and could thus be vulnerable to anthropogenic climate change.

Reasons why the Sudano zone may be more sensitive to extreme droughts compared to the Sahelian zone are not clear. Generally, the position and strength of ITCZ strongly influences the processes that generate rainfall over the region (Nicholson, 2013).

Causes of droughts have mostly been attributed to changes in global Sea Surface Temperatures (SST) in particular the warming of the Pacific and the Indian Oceans, which led to changes in atmospheric circulation over the region (Giannini et al., 2008). In addition, droughts over the Sudano-Sahel have also been attributed to the occurrence of El Niño Modoki and canonical El Niño events which are known to cause below average rainfall over the northern latitudes, especially over this region (Preethi et al., 2015). Furthermore, in the LCB, (Okonkwo et al., 2014) asserts that, during the period under study, El Niño Southern Oscillation (ENSO) events may have contributed to a decrease in rainfall over the Southern portion of the LCB where the Logone catchment is located.

Rainfall recovery in the region have been attributed to several effects: Giannini et al. (2013) associates it with warming of the Northern Atlantic Ocean and asserts that, if this warming continues to exceed that of the global tropics, rainfall will intensify in the region. Dong and Sutton (2015) attributed it to rising levels of greenhouse gases (GHGs) in the atmosphere, while Evan et al. (2015)

linked it to an upward trend in the Saharan heat low (SHL) temperature resulting from atmospheric greenhouse warming by water vapour.

The slow response of streamflow to rainfall in the Logone River could partly be attributed to the physical characteristics of the catchment given the low surface gradient (≤1.3%) and the length of the river, which is almost 1000 km from the upper parts of catchment to the outlet at Logone Gana. The influence of topography and catchment size on the response times of river catchments have been reported in several studies (López-Moreno et al., 2013, Soulsby et al., 2006). Soulsby et al. (2006) reported that small and mountainous catchments have short and steep flow paths, which are generally associated with a fast hydrological response to rainfall events. The Logone catchment is an extensive medium-size lowland catchment; its size and gradient may significantly contribute to increase the response time from different parts of catchment after rainfall. The slow response could also be attributed to extensive wetlands in the catchment so runoff is generated only after all depressions in the wetlands area filled.

The reasons why strong correlations occur at the outlet of the catchment (Logone Gana) after 15 months compared to 12 months upstream can be attributed to the fact that; after the Bongor gauging station, the wetland area increases significantly compared to the upstream area thereby increasing the volume of water stored in the wetlands. Furthermore there is a dam that captures and store water from the Logone during peak flow periods, further delaying the propagation of floodwater downstream. The influence of dams in delaying the response time of river catchments have also been reported in other studies (López-Moreno et al., 2013).

Given that the highest rainfall in the catchment is recorded in the Sudano zone located upstream, the slow response of the catchment to rainfall also suggest that most of the rainfall received upstream infiltrates into the groundwater aquifer as observed by Nkiaka et al. (in review). Indeed, Candela et al. (2014) reported that the kinds of soils found in the southern portion of the LCB covering the Sudano zone of the Logone catchment where rainfall is high favour aquifer recharge through rainfall infiltration and that groundwater contribution to total streamflow in the Logone River was significant. Nkiaka et al. (in review) also observed that groundwater contribution to streamflow was significant in the catchment. Given that these previous studies indicate a major role played by groundwater in the hydrology of the catchment; the delay in the response time of the catchment may also be attributed to groundwater storage from rainfall infiltration. Indeed, previous studies have identified groundwater storage as a major reason for delays in the response times of catchments (López-Moreno et al., 2013, Barker, 2016).

The decrease in correlation values between SSI and SPI during the dry season may be attributed to the depletion of the water table due to high evapotranspiration rates in the catchment during this period. This suggest that as the water table drops, the contribution of groundwater to streamflow reduces. This can explain why the response time of the catchment increases to 5-6 months. At the onset of the rainy season, the water table starts to rise due to increased infiltration from rainfall. Towards the end of the rainy season, the water table becomes saturated and groundwater contribution to streamflow becomes significant thus reducing the catchment response time to about three months. The reduced response time towards the end of the rainy season could also be attributed to high runoff coefficient resulting from wet antecedent soil moisture conditions as the soil moisture threshold becomes exceeded which reduces the infiltration capacity of the soil (Penna et al., 2011). Therefore, as the water table becomes saturated and soil moisture threshold is exceeded, any rainfall received in the catchment during this period directly contributes to runoff generation thus, reducing the catchment response time.

Although flood events typically occur in time steps of hours to days, positive SPI values at longer timescale may not necessarily translate to flood(s) but may give information on the antecedent moisture conditions of the soil. Furthermore, positive SPI in the Logone catchment in particular will not translate directly to flood events in the river given the considerable lag between rainfall and streamflow as observed in this study. Apart from that, SPI peaks at longer time scale(s) are not suitable for detecting flood peaks because the averaging effect of long-term accumulated precipitation may obscure the signal of extreme precipitation events over a short period (Du et al., 2013). On the other hand, SPI at longer timescales like 12-month are suitable for representing droughts because these event usually take a longer time to manifest as SPI responds more slowly to short-term precipitation variation.

The aim of spatiotemporal assessment of dryness/wetness conditions and their duration was to provide a weighted assessment for each zone and individual station location. From the drought severity ranking, it is possible for policy makers to focus attention to localities that are very prone to droughts by creating coping strategies such as developing irrigation and water storage infrastructure, improving soil water conservation techniques and diverting water to ensure environmental flows for wetlands ecosystem sustainability.

Although the whole catchment experienced many periods of wetness conditions with varying severity and duration across individual station locations, wetter conditions prevailed longer in in the Sahelian zone. This implies that this part of the catchment may be more prone to extreme wetness and hence floods especially because of the low surface gradient. Policy orientation here may seek to reduce flooding risk through effective implementation of building regulations to prevent people from constructing houses on flood prone zones and develop/improve flood control infrastructure. Government through decentralized structures could also seek to provide weather forecasting information to the local population through community radios or SMSs given that many such radio stations exist in the area, and mobile telephone network coverage is high. Meanwhile, understanding the response time of a catchment can enhance disaster preparation.

6. Conclusion

The aim of this study was to use the standardized indicators to calculate the frequency of occurrence of drought/flood events and the spatial distribution of dryness and wetness conditions; analyze their spatio-temporal characteristics and trends and use the standardized precipitation index and standardized streamflow index to assess the relationship between rainfall and streamflow.

Analysis using 12-month SPI values showed that annual rainfall was very variable in the catchment as there was a strong variation between SPI values from year to year. However, rainfall in the catchment during the period under study could be described as near stable given that near normal (-0.99 to 0.99) conditions dominated in most the rain gauge stations with an average frequency of occurrence above 65%.

Analysis of SPI at different timescales showed several periods of meteorological droughts ranging from moderate to extreme. SSI analysis also showed that while wetter conditions prevailed in the catchment from the 50s to 70s decades interspersed with episodes of hydrologic droughts in the 1970s; hydrological droughts persisted in the catchment from 1980 to mid-1990. Our findings also indicate that, both the Sudano and Sahelian zones are equally prone to drought and flood conditions although the Sudano zone is more sensitive to drier conditions while the Sahelian zone is sensitive to wetter conditions. Rainfall and streamflow analysis show that the catchment response very slowly to rainfall at short timescales but the situation changes at longer timescales.

This study has permitted us to identify localities within the catchment that are prone to dryness/wetness conditions using available rainfall data. Results obtained can help farmers to decide which crops to cultivate in which part of the catchment e.g. drought resistant crops in areas prone to droughts. Furthermore, the identification of the drought/flood-prone areas can enhance management planning to improve the socioeconomic conditions of the population living in these localities e.g. through the protection of assets of small-scale farmers and herders.

However, given the considerable small number of rain gauge stations used for analysis compared to the catchment size, these results should be regarded with caution as they may not represent the actual situation in the catchment especially in the semi-arid zone where only four rain gauges were used. Furthermore, given that rainfall data was not available from the year 2000 onwards, the results presented in this study may no longer represent the recent situation prevailing in the catchment given that the time lapse is >16 years.

SPI and SSI analysis at longer time scale can give an idea on the duration of either the wet or dry periods in the catchment given that SPI responds more slowly as the time scale increases so the cycles of positive or negative SPI values become more visible. This can give an indication of the abundance of water resources over a given time period or shortage of water which is usually manifested by the occurrence of droughts.

Using this study, it was possible to show that in catchments with physical, climatic and hydrological regimes that vary, the SPI and SSI can be effectively used to analyse droughts and floods conditions. By using both indicators, it is possible to show how physical catchment characteristics e.g. surface gradient, wetlands and man-made structures (e.g. dams) and soil types that influence surface and groundwater movement can significantly affect the catchment response time.

Application of SPI and SSI can be used to enhance the understanding of the hydrological behaviour of catchments, which is indispensable for developing water management policies for adaptation in the context of climate change. This can be used for disaster preparation in remote areas where modern facilities for disaster risk preparation are often absent, thereby allowing preventative measures to be implemented, and so reducing vulnerability of the local population to climate related disasters.

Acknowledgement

The first author is sponsored by the Commonwealth Scholarship Commission in UK. The authors are grateful to SIEREM for making available data used in this research free on their website. The authors wish to thank two anonymous reviewers and editor(s) whose insightful comments helped to improve the quality of the manuscript.

References

ADENLE, D. 2001. Groundwater resources and environmental management in Niger Basin Authority and Lake Chad Basin Commission agreements. UIPO, Ibadan, Nigeria.

BARKER, L. J. 2016. From meteorological to hydrological drought using standardised indicators. *Hydrology and Earth System Sciences,* 20**,** 2483.

BOYER, J.-F., DIEULIN, C., ROUCHE, N., CRES, A., SERVAT, E., PATUREL, J.-E. & MAHE, G. 2006. SIEREM: an environmental information system for water resources. *IAHS publication,* 308**,** 19.

CANDELA, L., ELORZA, F., TAMOH, K., JIMÉNEZ-MARTÍNEZ, J. & AURELI, A. 2014. Groundwater modelling with limited data sets: the Chari–Logone area (Lake Chad Basin, Chad). *Hydrological Processes,* 28**,** 3714-3727.

CHEO, A. E., VOIGT, H.-J. & MBUA, R. L. 2013. Vulnerability of water resources in northern Cameroon in the context of climate change. *Environmental earth sciences,* 70**,** 1211-1217.

DONG, B. & SUTTON, R. 2015. Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall. *Nature Climate Change,* 5**,** 757-760.

DU, J., FANG, J., XU, W. & SHI, P. 2013. Analysis of dry/wet conditions using the standardized precipitation index and its potential usefulness for drought/flood monitoring in Hunan Province, China. *Stochastic environmental research and risk assessment,* 27**,** 377-387.

EVAN, A. T., FLAMANT, C., LAVAYSSE, C., KOCHA, C. & SACI, A. 2015. Water vapor–forced greenhouse warming over the Sahara Desert and the recent recovery from the Sahelian drought. *Journal of Climate,* 28**,** 108-123.

FIELD, C. B., BARROS, V. R., MACH, K. & MASTRANDREA, M. 2014. *Climate change 2014: impacts, adaptation, and vulnerability*, Cambridge University Press Cambridge and New York.

GAUTAM, M. 2006. Managing drought in sub-Saharan Africa: Policy perspectives. *Invited paper prepared for presentation at the International Association of Agricultural Economists, Gold Coast, Australia*.

GIANNINI, A., BIASUTTI, M., HELD, I. M. & SOBEL, A. H. 2008. A global perspective on African climate. *Climatic Change,* 90**,** 359-383.

GIANNINI, A., SALACK, S., LODOUN, T., ALI, A., GAYE, A. & NDIAYE, O. 2013. A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environmental Research Letters,* 8**,** 024010.

GOLIAN, S., MAZDIYASNI, O. & AGHAKOUCHAK, A. 2015. Trends in meteorological and agricultural droughts in Iran. *Theoretical and applied climatology,* 119**,** 679-688.

GUERREIRO, M. J., LAJINHA, T. & ABREU, I. 2008. Flood analysis with the standardized precipitation index (SPI). *Revista da Faculdade de Ciência e Tecnologia* 4**,** 8 - 14.

HAO, Z. & AGHAKOUCHAK, A. 2013. Multivariate standardized drought index: a parametric multi-index model. *Advances in Water Resources,* 57**,** 12-18.

HE, M. & GAUTAM, M. 2016. Variability and trends in precipitation, temperature and drought indices in the state of California. *Hydrology,* 3**,** 14.

IONITA, M., SCHOLZ, P. & CHELCEA, S. 2015. Spatio-temporal variability of dryness/wetness in the Danube River Basin. *Hydrological Processes,* 29**,** 4483-4497.

LLOYD-HUGHES, B. & SAUNDERS, M. A. 2002. A drought climatology for Europe. *International journal of climatology,* 22**,** 1571-1592.

LÓPEZ-MORENO, J., VICENTE-SERRANO, S., ZABALZA, J., BEGUERÍA, S., LORENZO-LACRUZ, J., AZORIN-MOLINA, C. & MORÁN-TEJEDA, E. 2013. Hydrological response to climate variability at different time scales: A study in the Ebro basin. *Journal of hydrology,* 477**,** 175-188.

LOTH, P. E. & ACREMAN, M. C. 2004. *The return of the water: restoring the Waza Logone Floodplain in Cameroon*, IUCN.

LOUVET, S., PATUREL, J., MAHÉ, G., ROUCHÉ, N. & KOITÉ, M. 2016. Comparison of the spatiotemporal variability of rainfall from four different interpolation methods and impact on the result of GR2M hydrological modeling—case of Bani River in Mali, West Africa. *Theoretical and Applied Climatology,* 123**,** 303-319.

MACHADO, M., BENITO, G., BARRIENDOS, M. & RODRIGO, F. 2011. 500 years of rainfall variability and extreme hydrological events in southeastern Spain drylands. *Journal of Arid Environments,* 75**,** 1244-1253.

MCKEE, T. B., DOESKEN, N. J. & KLEIST, J. The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology, 1993. American Meteorological Society Boston, MA, 179-183.

MCMAHON, T. A., VOGEL, R. M., PEEL, M. C. & PEGRAM, G. G. 2007. Global streamflows–Part 1: Characteristics of annual streamflows. *Journal of Hydrology,* 347, 243-259.

NDEHEDEHE, C. E., AGUTU, N. O., OKWUASHI, O. & FERREIRA, V. G. 2016. Spatio-temporal variability of droughts and terrestrial water storage over Lake Chad Basin using independent component analysis. *Journal of Hydrology,* 540, 106-128.

NICHOLSON, S. E. 2013. The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteorology,* 2013.

NKIAKA, E., NAWAZ, N. & LOVETT, J. 2016. Using self-organizing maps to infill missing data in hydro-meteorological time series from the Logone catchment, Lake Chad basin. *Environmental monitoring and assessment,* 188, 1-12.

NKIAKA, E., NAWAZ, N. R. & LOVETT, J. C. 2017. Analysis of rainfall variability in the Logone catchment, Lake Chad basin. *International Journal of Climatology,* 37, 3553-3564.

ODEKUNLE, T. O., ANDREW, O. & AREMU, S. O. 2008. Towards a wetter Sudano-Sahelian ecological zone in twenty-first century Nigeria. *Weather,* 63, 66-70.

OKONKWO, C., DEMOZ, B. & GEBREMARIAM, S. 2014. Characteristics of Lake Chad level variability and links to ENSO, precipitation, and river discharge. *The Scientific World Journal,* 2014.

OKONKWO, C., DEMOZ, B. & ONYEUKWU, K. 2013. Characteristics of drought indices and rainfall in Lake Chad Basin. *International journal of remote sensing,* 34, 7945-7961.

PATUREL, J.-E., OUEDRAOGO, M., SERVAT, E., MAHE, G., DEZETTER, A. & BOYER, J.-F. 2003. The concept of rainfall and streamflow normals in West and Central Africa in a context of climatic variability. *Hydrological sciences journal,* 48, 125-137.

PEEL, M. C., FINLAYSON, B. L. & MCMAHON, T. A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.,* 11, 1633-1644.

PENNA, D., TROMP-VAN MEERVELD, H., GOBBI, A., BORGA, M. & DALLA FONTANA, G. 2011. The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences,* 15, 689.

PREETHI, B., SABIN, T., ADEDOYIN, J. & ASHOK, K. 2015. Impacts of the ENSO Modoki and other tropical Indo-Pacific climate-drivers on African rainfall. *Scientific reports,* 5.

ROUDIER, P. & MAHE, G. 2010. Study of water stress and droughts with indicators using daily data on the Bani river (Niger basin, Mali). *International Journal of Climatology,* 30, 1689-1705.

SEILER, R., HAYES, M. & BRESSAN, L. 2002. Using the standardized precipitation index for flood risk monitoring. *International journal of climatology,* 22, 1365-1376.

SOULSBY, C., TETZLAFF, D., RODGERS, P., DUNN, S. & WALDRON, S. 2006. Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: an initial evaluation. *Journal of Hydrology,* 325, 197-221.

TRAORE, S. & OWIYO, T. 2013. Dirty droughts causing loss and damage in Northern Burkina Faso. *International Journal of Global Warming,* 5, 498-513.

TSCHAKERT, P., SAGOE, R., OFORI-DARKO, G. & CODJOE, S. N. 2010. Floods in the Sahel: an analysis of anomalies, memory, and anticipatory learning. *Climatic Change,* 103, 471-502.

VICENTE-SERRANO, S. M., LÓPEZ-MORENO, J. I., BEGUERÍA, S., LORENZO-LACRUZ, J., AZORIN-MOLINA, C. & MORÁN-TEJEDA, E. 2011. Accurate computation of a streamflow drought index. *Journal of Hydrologic Engineering,* 17, 318-332.

VOGEL, R. M. & WILSON, I. 1996. Probability distribution of annual maximum, mean, and minimum streamflows in the United States. *Journal of hydrologic Engineering,* 1, 69-76.

WASHINGTON, R., KAY, G., HARRISON, M., CONWAY, D., BLACK, E., CHALLINOR, A., GRIMES, D., JONES, R., MORSE, A. & TODD, M. 2006. African climate change: taking the shorter route. *Bulletin of the American Meteorological Society,* 87, 1355-1366.

WILHITE, D. A. & GLANTZ, M. H. 1985. Understanding: the drought phenomenon: the role of definitions. *Water international,* 10**,** 111-120.

WMO 2012. Standardized precipitation index user guide. *In:* SVOBODA, M., HAYES, M. & WOOD, D. (eds.) *World Meteorological Organization* Geneva, Switzerland.

ZHANG, Y., YOU, Q., LIN, H. & CHEN, C. 2015. Analysis of dry/wet conditions in the Gan River Basin, China, and their association with large-scale atmospheric circulation. *Global and Planetary Change,* 133**,** 309-317.

Table 1: Overview of rainfall gauge stations and annual rainfall properties

Station No	Location	Geographic coordinates		Elevation (m)	Annual rainfall (mm/year)			Catchment zone
	Station name	Lat	Long		Max	Min	Mean	
1	Ngaoundere	7.35	13.56	1113	1864	1152	1514	Sudano
2	Baibokoum	7.73	15.68	1323	1672	881	1277	
3	Bekao	7.92	16.07	528	1630	853	1181	
4	Pandzangue	8.1	15.82	345	1892	919	1242	
5	Donia	8.3	16.42	414	1782	796	1085	
6	Moundou	8.57	16.08	410	1843	783	1103	
7	Doba	8.65	16.85	387	1475	680	1057	
8	Delli	8.72	15.87	427	1539	705	1064	
9	Donomanga	9.23	16.92	370	1519	681	982	
10	Guidari	9.27	16.67	369	1562	629	1005	
11	Kello	9.32	15.8	378	1413	503	980	
12	Goundi	9.37	17.37	368	1519	681	982	
13	Lai	9.4	16.3	358	1491	669	1022	
14	Bongor	10.27	15.4	328	1070	400	790	semi-arid
15	Bousso	10.48	16.72	336	1365	423	844	
16	Bailli	10.52	16.44	330	1146	463	797	
17	Massenya	11.4	16.17	328	977	410	641	

Table 2: SPI values

SPI value	Category
≥ 2.00	Extremely wet
1.5 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤ -2.0	Extremely dry

Table adapted from (WMO, 2012)

Table 3: Frequency of occurrence of drought and flood episodes in the Logone catchment

	Frequency of occurrence of droughts and floods (%)								
Station	Extreme wet	Very wet	Moderately wet	Near normal	Moderate drought	Severe drought	Extreme drought	Total Flood episodes	Total Drought episodes
Ngaoundere	1.53	3.06	11.04	69.95	6.79	3.90	3.74	15.62	14.43
Baibokoum	0.51	5.09	10.02	66.89	10.02	3.74	3.74	15.62	17.49
Bekao	1.70	5.10	9.69	63.78	13.78	4.93	1.02	16.50	19.73
Pandzangue	3.90	3.40	11.54	65.70	12.05	3.40	0.00	18.85	15.45
Donia	2.04	2.72	10.02	68.76	12.56	2.89	1.02	14.77	16.47
Moundou	2.55	3.40	6.96	71.99	7.30	6.11	1.70	12.90	15.11
Doba	3.72	5.49	9.20	70.27	6.73	2.30	2.30	18.41	11.33
Delli	3.74	4.75	4.92	75.72	6.45	2.04	2.38	13.41	10.87
Donomanga	3.57	11.04	16.47	68.93	0.00	0.00	0.00	31.07	0.00
Guidari	4.24	2.72	7.81	70.63	7.64	4.24	2.72	14.77	14.60
Kello	2.21	1.36	9.68	72.67	4.92	6.28	2.89	13.24	14.09
Goundi	2.72	7.64	6.96	65.03	11.04	4.58	2.04	17.32	17.66
Lai	2.04	4.41	9.68	67.74	8.32	4.24	3.57	16.13	16.13
Bongor	0.68	4.41	8.32	70.29	8.15	3.90	3.90	13.41	15.96
Bousso	1.87	1.70	14.77	66.38	7.64	4.75	2.89	18.34	15.28
Bailli	1.53	7.30	5.94	69.61	8.49	3.57	3.57	14.77	15.62
Massenya	3.39	13.39	18.31	64.92	0.00	0.00	0.00	35.08	0.00

Table 4: Results of Mann-Kendall trend test for 1-month, 3-months and 12-months SPI and SSI time series

Rainfall Station	**1-month**		**3-month**		**12-month**	
	Z_{MK}	*p*-value	Z_{MK}	*p*-value	Z_{MK}	*p*-value
Ngaoundere	-0.08	**7.00E-03**	-0.16	**1.05E-08**	-0.99	**2.22E-16**
Baibokoum	-0.05	9.40E-02	-0.12	**1.86E-05**	-0.99	**2.22E-16**
Bekao	-0.03	3.49E-01	-0.04	1.04E-01	-0.99	**2.22E-16**
Pandzangue	-0.02	4.70E-01	-0.04	1.70E-01	-0.99	**2.22E-16**
Donia	-0.09	**2.00E-03**	-0.15	**1.07E-07**	-0.99	**2.22E-16**
Moundou	-0.07	**1.30E-02**	-0.12	**1.67E-05**	-0.99	**2.22E-16**
Doba	-0.86	**2.00E-03**	-0.16	**5.38E-08**	-0.99	**2.22E-16**
Deli	-0.03	2.46E-01	-0.07	**8.00E-03**	-0.99	**2.22E-16**
Donomanga	-0.06	4.50E-02	-0.12	**4.10E-05**	-0.99	**2.22E-16**
Guidari	-0.07	**1.20E-02**	-0.12	**1.65E-05**	-0.99	**2.22E-16**
Kello	-0.03	2.36E-01	-0.05	1.06E-01	-0.99	**2.22E-16**
Goundi	-0.09	**2.00E-03**	-0.19	**1.58E-11**	-0.99	**2.22E-16**
Lai	-0.02	3.80E-01	-0.05	8.15E-02	-0.99	**2.22E-16**
Bongor	-0.07	**8.00E-03**	-0.11	**8.52E-11**	-0.99	**2.22E-16**
Bousso	-0.09	**2.00E-03**	-0.17	**2.89E-09**	-0.99	**2.22E-16**
Bailli	-0.05	9.90E-02	-0.11	**1.43E-04**	-0.99	**2.22E-16**
Massenya	-0.07	1.18E-02	-0.05	6.30E-01	-0.99	**2.22E-16**
Gauging station						
Bongor	-0.33	**2.22E-16**	-0.36	**2.22E-16**	-0.46	**2.22E-16**
Logone Gana	-0.31	**2.22E-16**	-0.33	**2.22E-16**	-0.43	**2.22E-16**

*Bold values indicate that the trend is statistical significant at 5% level as per the 2 tail test for SPI and 1% for SSI

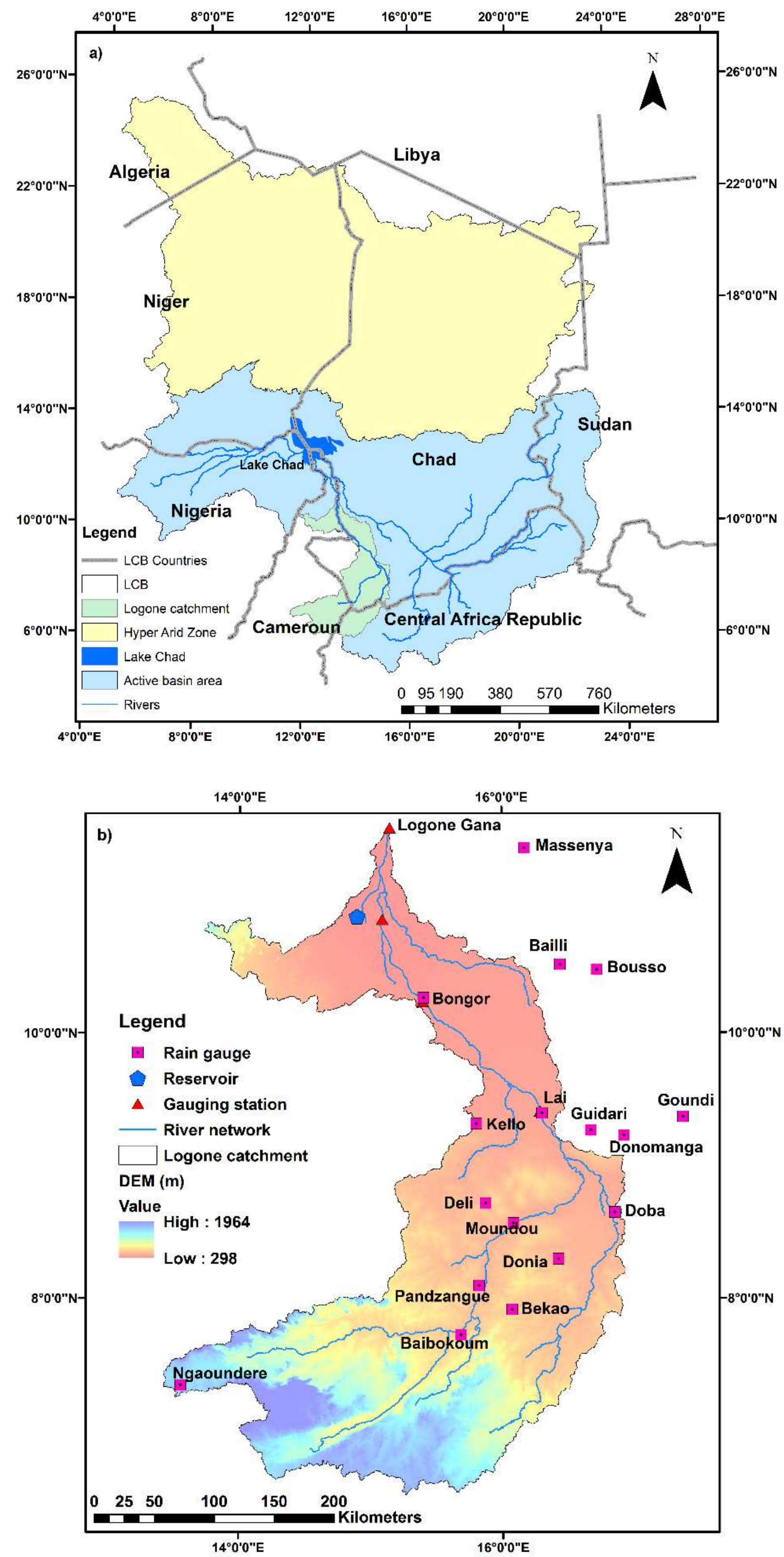
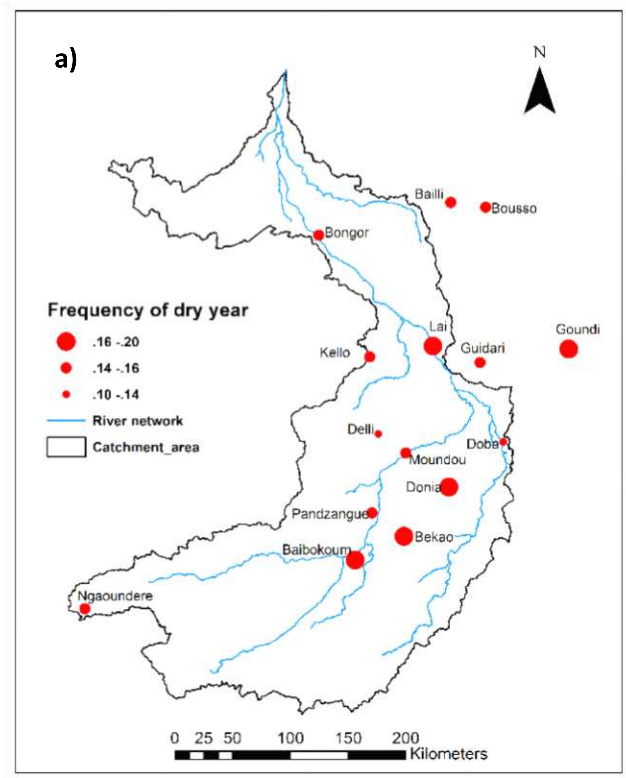


Figure 1: Lake Chad basin showing the position of the Logone catchment (a), Logone catchment showing the location of rain gauges (b). (DEM: Digital Elevation Model)


a)
N
Bailli
Bousso
Bongor
Frequency of dry year
.16 -.20
.14 -.16
.10 -.14
River network
Catchment_area
Goundi
Lai
Guidari
Kello
Delli
Doba
Moundou
Donia
Pandzangue
Bekao
Baibokoum
Ngaoundere
0 25 50 100 150 200
Kilometers

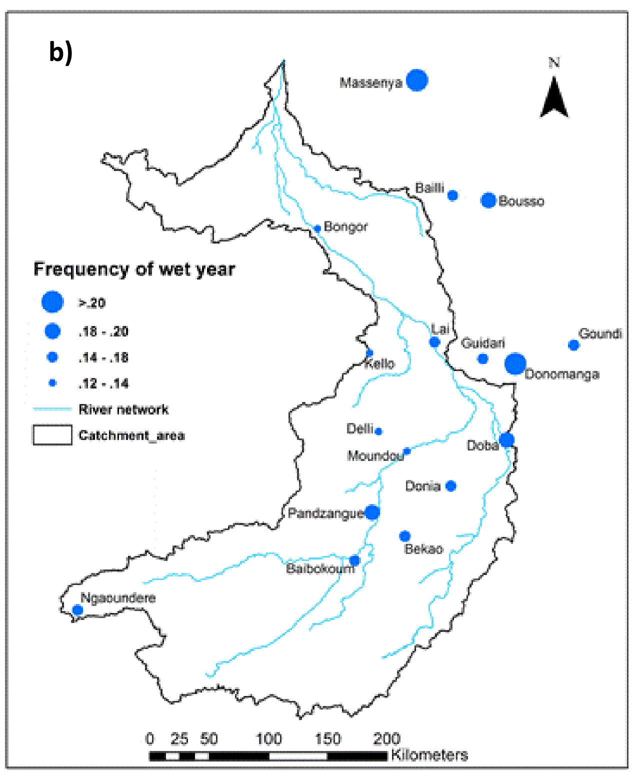
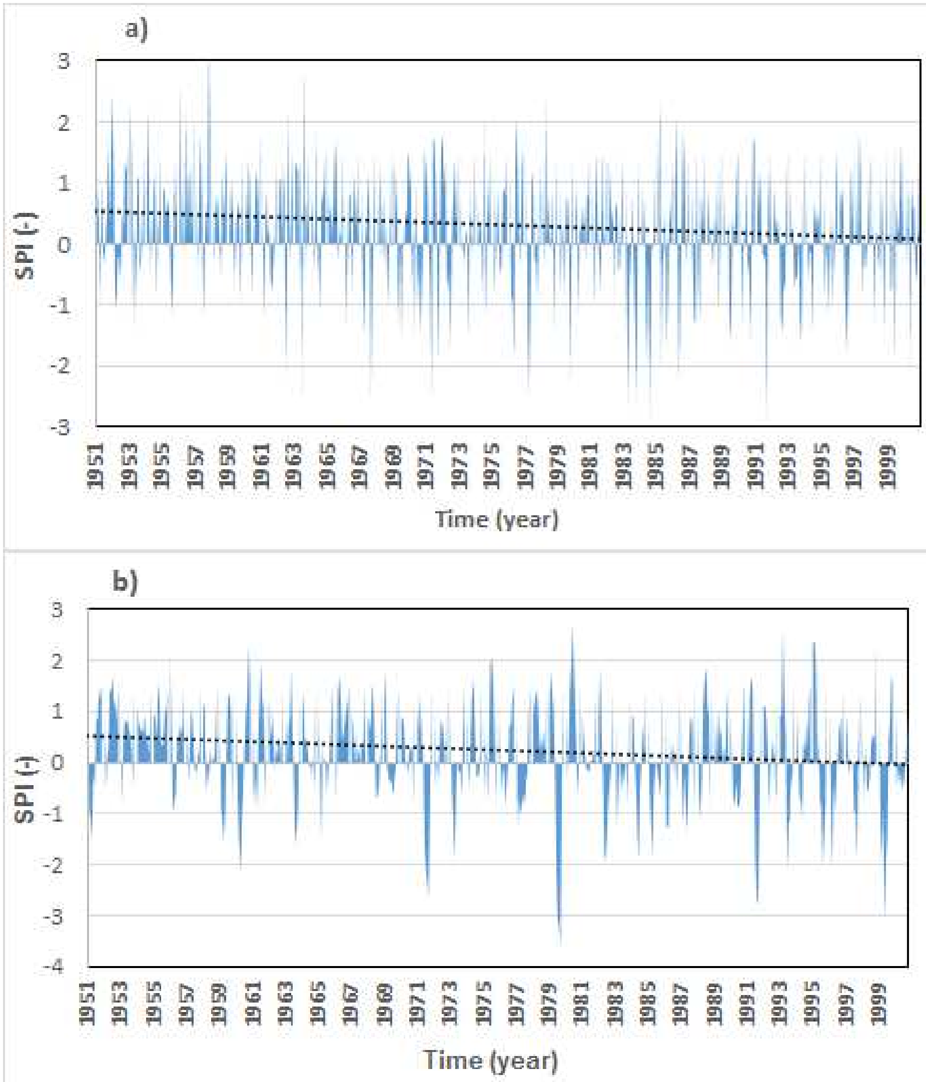

b)
N
Massenya
Bailli
Bousso
Bongor
Frequency of wet year
>.20
.18 - .20
.14 - .18
.12 - .14
River network
Catchment_area
Lai
Guidari
Goundi
Donomanga
Kello
Delli
Moundou
Doba
Donia
Pandzangue
Bekao
Baibokoum
Ngaoundere
0 25 50 100 150 200
Kilometers

Figure 2: Frequencies of occurrence and spatial distribution of dry and wet years in Logone catchment for the 1951–2000 period. The frequency was calculated as percentage according to the 12-month SPI for each year; a dry year a) was defined when SPI ≤-1.0 and b) wet year when SPI ≥ 1.0



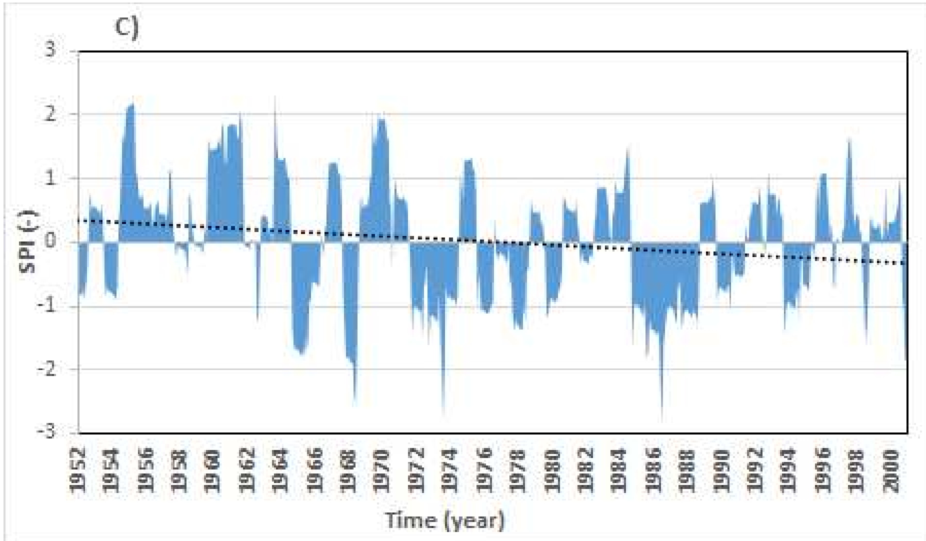
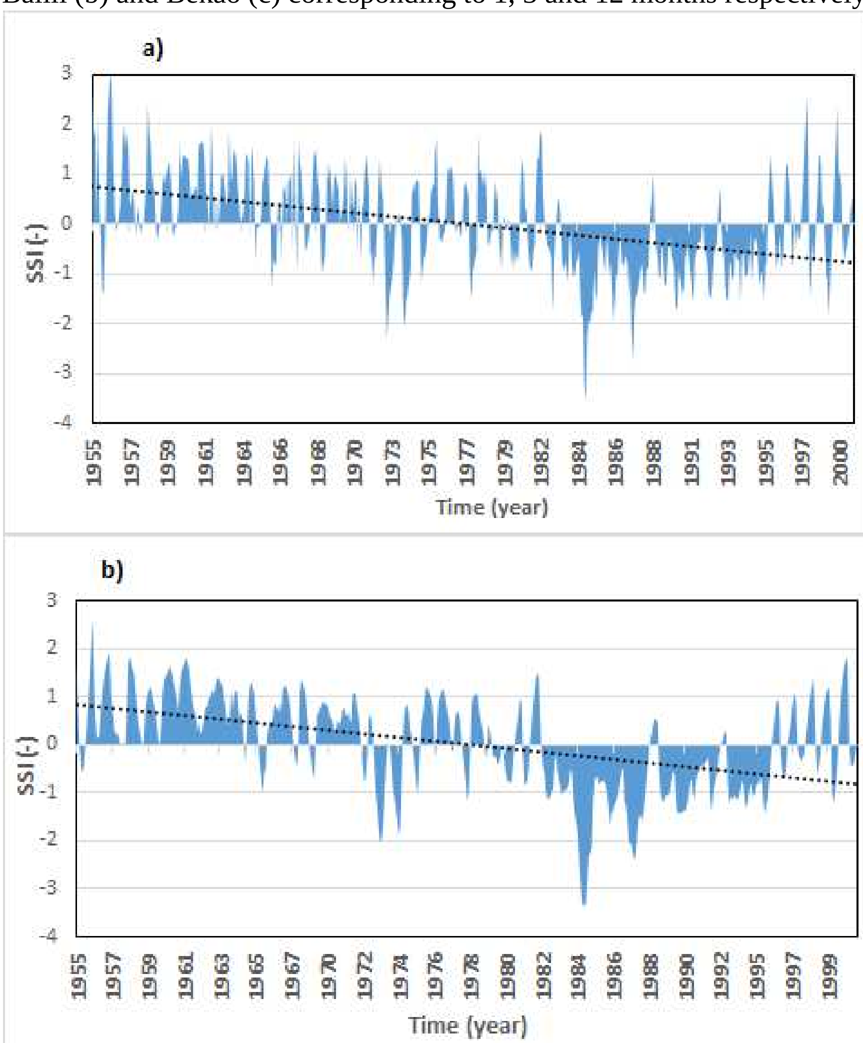


Figure 3: SPI time series for selected accumulated periods at different rain gauge stations: Ngaoundere (a) Bailli (b) and Bekao (c) corresponding to 1, 3 and 12 months respectively.



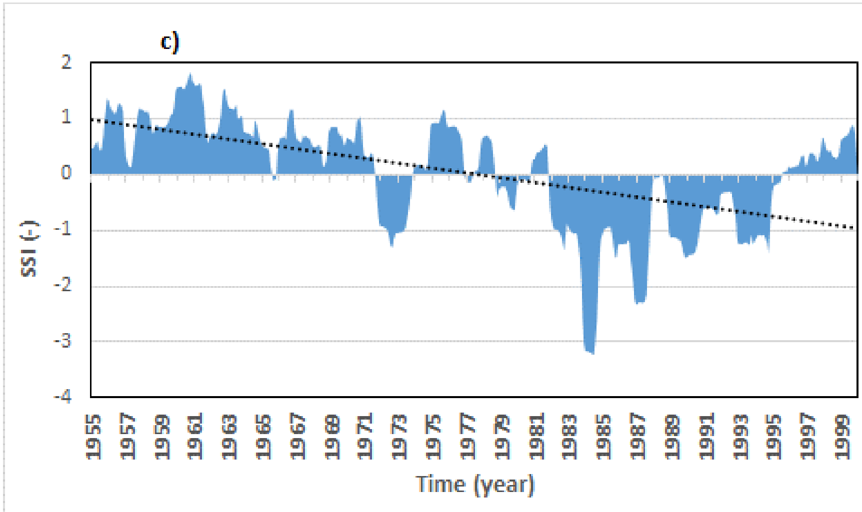


Figure 4: SSI time series for selected accumulated periods at the outlet of the Logone Gana gauging station. a, b, and c correspond to 1,6 and 12 months respectively.

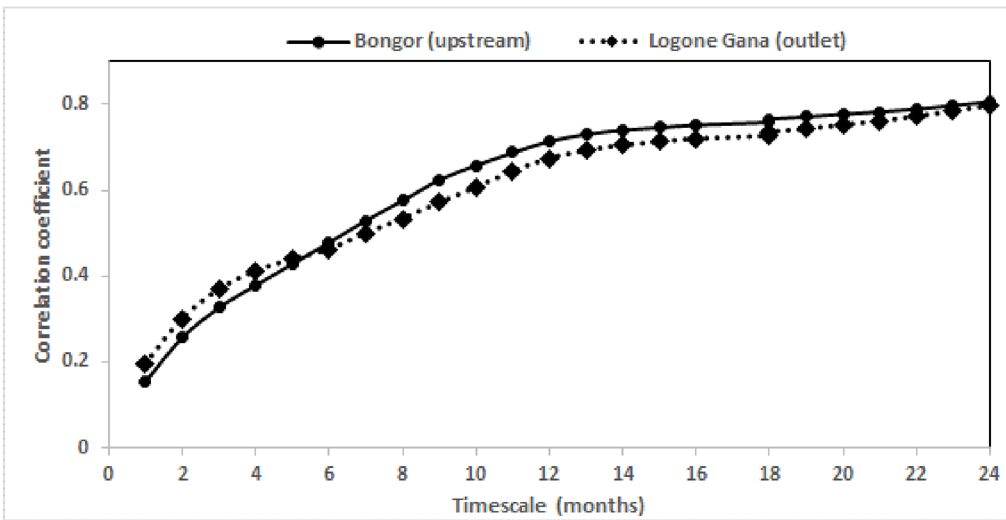
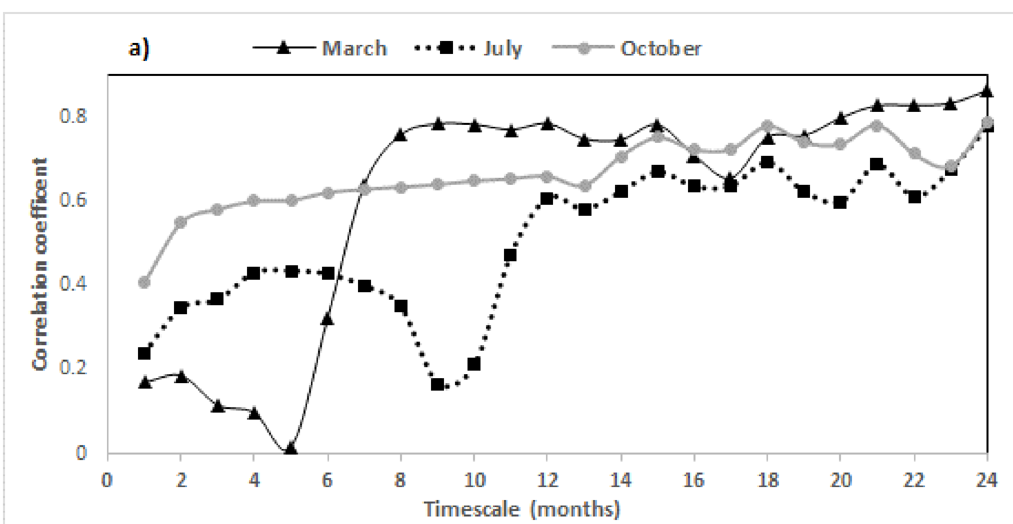


Figure 5: Correlation coefficients between the monthly SSI and the 1- to 24-month SPI



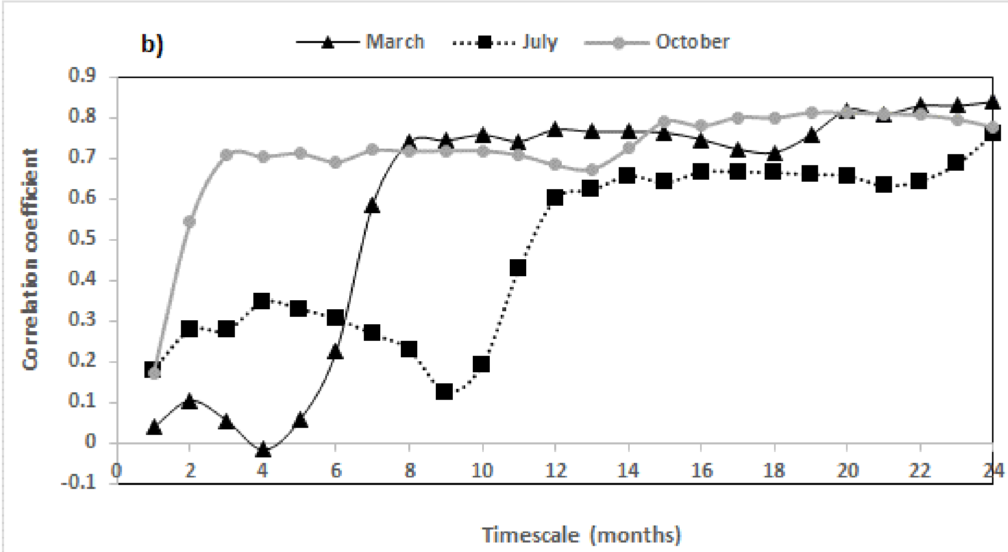


Figure 6: Correlation coefficients between the monthly SSI and SPI for different individual months: a) Logone Gana and (b) Bongor. The X-axis indicates the timescale of SPI.

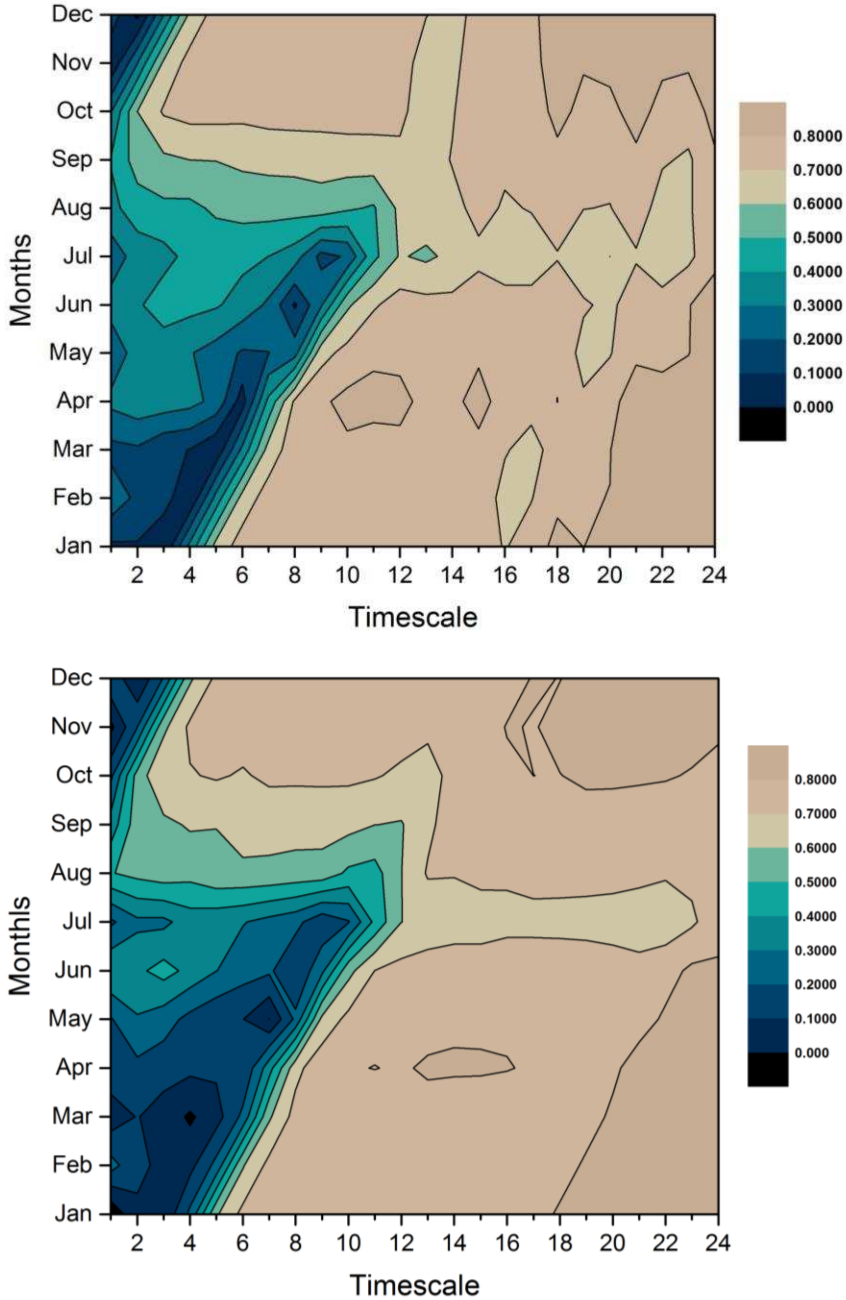


Figure 7: Contour plots summarizing monthly correlation coefficients (top Bongor, bottom Logone Gana). The X-axis indicates the timescale of SPI.