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

3  
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7  
8 **Abstract**

9 The Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) were used in  
10 this study to analyse dry/wet conditions in the Logone catchment over a 50-year period (1951-2000).  
11 SPI analysis at different timescales showed several meteorological drought events ranging from  
12 moderate to extreme. SSI analysis showed that wetter conditions prevailed in the catchment from  
13 1950-1970 interspersed with few hydrological drought events. Overall, results indicated that both the  
14 Sudano and Sahelian zones are equally prone to droughts and floods. However, the Sudano zone is  
15 more sensitive to drier conditions, while the Sahelian zone is sensitive to wetter conditions.  
16 Correlation analysis between SPI and SSI at multiple timescales revealed that the catchment has a  
17 low response to rainfall at short timescales, though this progressively changed as the timescale  
18 increased with strong correlations ( $\geq 0.70$ ) observed after 12 months. Analysis using individual  
19 monthly series showed that the response time reduced to 3 months in October.

20  
21 **Keywords:** standardized indicators; SPI; SSI; drought/floods monitoring; response time; Logone  
22 catchment; Lake Chad basin

23  
24 **1. Introduction**

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

34 capital as a result of low rainfall (meteorological droughts) which after extended periods can result  
35 in water shortages (hydrological droughts).

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

43 The Standardized Precipitation Index (SPI) (McKee et al., 1993) is a probability based  
44 indicator that indicates the degree to which accumulative precipitation for a specific period departs  
45 from the average state. This index is generally used to detect, monitor and assess dry and wet  
46 conditions and identify their variability at different spatial and temporal scales. Compared to other  
47 methods for calculating drought conditions e.g. the Palmer Drought Severity Index (PDSI),  
48 Standardized Precipitation Evapotranspiration Index (SPEI), the Surface Water Supply Index  
49 (SWSI), and the Standardized Anomaly Index (SAI), the SPI offers many advantages: (i) only a single  
50 input variable (precipitation) is necessary, (ii) provides a means of analyzing both wet and dry  
51 periods, (iii) it can be calculated for different time scales, (iv) it can allow the user to classify droughts  
52 into different categories, and (v) it is probability based and hence can be used in risk management  
53 and decision analysis. Due to its robustness and convenience, the SPI has been widely used to study  
54 droughts around the world (Roudier and Mahe, 2010, Du et al., 2013, Barker, 2016). It has also been  
55 used extensively to monitor wetness conditions (Seiler et al., 2002, Guerreiro et al., 2008), and to  
56 analyse both dryness and wetness conditions (Machado et al., 2011, Du et al., 2013, Ionita et al.,  
57 2015). Furthermore, the World Meteorological Organisation (WMO, 2012) recommends the use of  
58 the SPI to assess and monitor drought conditions and identify wet periods.

59 Despite its wide application, the SPI has been subjected to criticism by several authors e.g.  
60 (Lloyd-Hughes and Saunders, 2002). They argue that the use of the SPI for short time scale analysis  
61 (1, 2, 3-month) within regions characterized by low seasonal precipitation may result in over-  
62 estimation or under-estimation of the positive or negative SPI values. Golian et al. (2015) argue that  
63 using only a single index to monitor droughts may be misleading due to the complex nature of drought  
64 phenomena in both their causation and impact. As a result of these criticisms, the multivariate  
65 standardized drought index (MSDI) (Hao and AghaKouchak, 2013) was developed. Despite these

66 advances, application of the SPI remains popular even though it requires a minimum of 30 years of  
67 monthly rainfall data which may limit its application in data-scarce regions and has been applied in  
68 many studies across the world (Seiler et al., 2002, Guerreiro et al., 2008, Roudier and Mahe, 2010,  
69 Machado et al., 2011, Cheo et al., 2013, Louvet et al., 2016).

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

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

91 However, previous studies are generalized for the whole LCB, cover a short time horizon and  
92 may be misconstrued as insignificant in a particular location (i.e. at local or sub-catchment scale).  
93 The LCB covers an estimated area of  $2.5 \times 10^6$  km<sup>2</sup> (and a population of about 30 million and contains  
94 a range of ecological zones (hyper arid, arid, semi-arid and Sudano) with a high spatiotemporal  
95 variability in rainfall. Therefore, generalizing results from such studies as representative of smaller  
96 basins may not be useful for effective and robust planning of water resources management and  
97 development of adaptation strategies in the event of droughts and floods.

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

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

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

122

## 123 **2. Study area and data**

124 The Logone catchment is located in the south western part of the LCB. It covers an estimated  
125 area of 86,240 km<sup>2</sup> at the Logone Gana hydrometric station and lies between latitude 6° - 12° N and  
126 longitude 13° - 17° E (Figure 1). This is about 8% of the conventional LCB area of 1,053,455 km<sup>2</sup>  
127 (Adenle, 2001). The Logone is a major tributary of the Chari River, and the two rivers jointly  
128 contribute about 95% of inflow into Lake Chad (Loth and Acreman, 2004). The Logone has its source  
129 in Cameroon from the Mbere and Vina Rivers originating from the Adamawa Plateau. In Lai, it is  
130 joined by the Pende River from Central Africa Republic and flows in a south-north direction. The

131 altitude ranges from about 1200 masl around the Adamawa Plateau in the south to 300 masl in  
132 Ndjamena in the north. It flows through three countries, Cameroon, Central Africa and Chad with a  
133 flat topography with average slope of less than 1.3%. The catchment is located in a Sudano-Sahelian  
134 climatic regime controlled by the tropical continental regime air mass (the Harmattan) and the oceanic  
135 regime equatorial air mass (monsoon) (Nkiaka et al., 2017). It has a strong north-south rainfall  
136 gradient with a single rainy season between May and October and an average annual rainfall varying  
137 between 500 mm/year in the north to about 1400 mm/year in the south. There is a strong spatio-  
138 temporal variability in rainfall (Nkiaka et al., 2017) and mean temperature in the catchment is 28°  
139 (Loth and Acreman, 2004).

140

## 141 **2.1. Data sources**

142 Monthly rainfall and streamflow data were obtained from “Système d'Informations  
143 Environnementales sur les Ressources en Eau et leur Modélisation” (SIEREM) (Boyer et al., 2006).  
144 According to Boyer et al. (2006), the SIEREM data was obtained using the POLLEN method adapted  
145 from the Object Modelling Technique. To increase robustness of our results, only stations that had  
146 monthly data covering the period 1951-2000 were selected; with missing data points of not more than  
147 10%. Given that only 11 rain gauge stations located inside the catchment could fulfil these criteria,  
148 six additional rain gauge stations located outside the catchment, but within its immediate  
149 surroundings, were selected to increase the number of rain gauges. Stations 1-13 in Table 1 lie in the  
150 Sudano ecological zone (5° - 10°N) and stations 14-17 are located in the Sahelian ecological zone  
151 (10° - 12°N). These ecological zones represent simplified climatic zones based on the Köppen  
152 Geiger climate classification for Africa (Peel et al., 2007). Streamflow time series were available for  
153 the period 1955-2000. The data was quality controlled using different homogeneity tests and all the  
154 time series were found to be homogeneous (Nkiaka et al., 2017). Gaps in the time series were infilled  
155 using Artificial Neural Network (ANN), Self-Organizing Maps (SOMs) techniques (Nkiaka et al.,  
156 2016).

157 A limitation of the study is the absence of rainfall data after the year 2000 so the influence of  
158 recent rainfall measurements on SPI values could not be evaluated. However for an insight into the  
159 recent characteristics of drought indices in the area covering the period 2002-2014, the reader can  
160 refer to Okonkwo et al. (2013) and Ndehedehe et al. (2016). A limitation of those studies is that only  
161 10 years of satellite precipitation data was used in the SPI analysis. According to McKee et al. (1993),  
162 the application of the SPI for drought monitoring requires a minimum of 30 years data. Another  
163 limitation of those studies is that satellite precipitation analysis depends on the quality of gauge data

164 used for satellite calibration, and are thus inevitably affected by the sparsity of gauge data or  
165 temporally incomplete gauge time series in the region under investigation.

166

### 167 **3. Methodology**

#### 168 **3.1. The Standardized Precipitation Index (SPI)**

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

173

$$174 \quad G(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x t^{\alpha-1} e^{-\frac{t}{\beta}} dt \quad (1)$$

175

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

182

$$183 \quad H(x) = q + (1 - q)G(x) \quad (2)$$

184

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

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

195 record at a given station. In this study, analysis were conducted for multiple time-scales ranging from  
196 1 to 24 months.

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

203

### 204 **3.2. Standardized Streamflow Index (SSI)**

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

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



228 Serrano et al., 2011). In this study the gamma distribution was used to fit streamflow. This distribution  
229 has extensively been used to fit global streamflow datasets in previous studies (Vogel and Wilson,  
230 1996, McMahon et al., 2007, Du et al., 2013, Zhang et al., 2015).

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

236

### 237 **3.3. The Mann-Kendall trend test**

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

246 The catchment was divided into two parts; the northern part termed the Sahelian zone for  
247 stations located between latitudes 10°-12° N and the southern part termed the Sudano zone for stations  
248 located between latitudes 6°-10° N. The main difference between the two zones is an increase in  
249 annual rainfall total from stations located in the north to those in the south (Nkiaka et al., 2017). Table  
250 1 gives the station name, coordinates, long term mean, maximum and minimum of the annual rainfall  
251 time series for each station.

252

## 253 **4. Results**

### 254 **4.1. Frequency of dry/wet years**

255 A 12-month SPI analysis was used for the 17 stations in order to show the prevalence and  
256 spatial distribution of dryness and wetness conditions across the catchment. Using the threshold  
257 values in Table 2, a particular year was considered dry if the  $SPI \leq -1.0$  and wet year if the  $SPI \geq 1.0$ .  
258 Figure 2 shows the spatial distribution and frequency of occurrence of dry and wet years respectively.  
259 For example stations belonging to group 0.16 – 0.20 in Figure 2(a) experienced dry episodes in 16-  
260 20% of all the years used in the study, while stations belonging to group 0.18-0.20 Figure 2(b)

261 experienced wet conditions in 18-20% of all years used (1951-2000). The analysis also showed that  
262 the frequency of occurrence of drought conditions was high for stations located in the Sudano zone  
263 of the catchment. For example stations like Ngaoundere, Baibokoum, Bongor and Bekao with high  
264 annual rainfall instead experienced the highest frequency of occurrence of severe dryness conditions.

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

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

275

#### 276 **4.2. Analysis of dryness/wetness conditions at multiple time scales**

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

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

293

#### 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

327 and September, and were generally preceded by periods of moderate to severe drought conditions.  
328 The prevalence of extreme droughts conditions in the catchment during these months is consistent  
329 with the findings of Nkiaka et al. (2017) who reported that there was a general decline in July, August  
330 and September rainfall in catchment during the period 1951–2000.

331

#### 332 **4.2.2. Spatio-temporal variation of wetness conditions**

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

344 Temporal analysis using 12-month SPI values showed that the wettest period in the catchment  
345 was recorded during the 1950 decade with the highest SPI value observed in Moundou (3.58). A close  
346 examination of Figures 3-5 revealed that, wetness conditions prevailed in most stations during the  
347 1990 decade ranging from moderate to extreme wetness with different durations across individual  
348 station locations. These results are consistent with those of other studies that reported on the  
349 prevalence of extensive floods in the region during this period (Odekunle et al., 2008, Tschakert et  
350 al., 2010, Okonkwo et al., 2014, Louvet et al., 2016).

351

#### 352 **4.3. Evaluation of hydrological droughts**

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

358 Prolonged hydrological droughts prevailed in the catchment from 1980 to mid-1990 with the  
359 drought categories ranging from mild to severe (Figure 4). Meanwhile, from mid-1990 stretching into

360 the year 2000, humid conditions dominated in the catchment. Similar observations were made using  
361 the SPI at different station locations across the catchment which correspond to previous studies in the  
362 region as mentioned in the preceding section.

363

#### 364 **4.4. Results of trend analysis**

365 The results of Mann-Kendall trend test indicated that across the catchment and at all time  
366 scales considered, negative trends in SPI were obtained with different significant levels indicating  
367 that the null hypothesis of no trend was rejected (Table 4). It can be observed that 7, 14 and 17 stations  
368 showed statistically significant negative trends at the 5% significant level for 1-month, 3-month and  
369 12-month time scales respectively (Table 4). These negative trends in SPI values follow the general  
370 decline in rainfall over the catchment and are consistent with reported trends in the region (Odekunle  
371 et al., 2008, Nkiaka et al., 2017). Although no drought conditions were observed at Massenya station,  
372 it is worth noting that there was a significant negative trend in rainfall at this station during the period  
373 under study.

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

378

#### 379 **4.5. Relationship between SPI and SSI**

380 Results of Pearson correlation analysis between monthly SSI and SPI at different timescales  
381 (1–24 months) showed that all correlations were positive although strong correlations were observed  
382 only at longer timescales (Figure 5). The correlations showed that the Logone River has a low  
383 response to rainfall at short timescales from weak correlations obtained. However, this progressively  
384 changed as the timescale increased with strong correlations ( $\geq 0.70$ ) observed after 12 and 15 months  
385 at Bongor and Logone Gana gauging stations respectively. López-Moreno et al. (2013) observed  
386 similar strong correlations between SSI and SPI at longer timescales across catchments in southern  
387 Spain where catchments had permeable limestone headwaters. Barker (2016) also reported similar  
388 findings across several catchments underlain by major aquifers in England.

389 Figure 6a&b show the result of monthly correlations between SSI and SPI for selected  
390 months. It can be observed from the figure that the correlations changed seasonally according to SPI  
391 timescale but generally became very strong ( $\geq 0.70$ ) after 12 months. During the month of March, the  
392 correlation values dropped to minimum after 4 and 5 months at Bongor and Logone Gana respectively

393 before rising steadily to become very strong ( $\geq 0.70$ ) after eight months. The same phenomenon was  
394 observed during the month of July where the correlation values decreased to 0.20 after 9 months  
395 before increasing rapidly ( $\geq 0.70$ ) within 3 months. The correlations for each month were summarized  
396 using contour plots for the two gauging stations (Figure 7a&b). From the figure, it can be observed  
397 that the response time of the catchment is 5-6 months at the beginning of the rainy season (June/July).  
398 Meanwhile, towards the end of the rainy season (September/October) the response time reduces to 3  
399 months as indicated by very strong correlation values ( $\geq 0.70$ ).

400

## 401 **5. Discussion**

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

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

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

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

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

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

439         The reasons why strong correlations occur at the outlet of the catchment (Logone Gana) after  
440 15 months compared to 12 months upstream can be attributed to the fact that; after the Bongor  
441 gauging station, the wetland area increases significantly compared to the upstream area thereby  
442 increasing the volume of water stored in the wetlands. Furthermore there is a dam that captures and  
443 store water from the Logone during peak flow periods, further delaying the propagation of floodwater  
444 downstream. The influence of dams in delaying the response time of river catchments have also been  
445 reported in other studies (López-Moreno et al., 2013).

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

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

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

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

487 Although the whole catchment experienced many periods of wetness conditions with varying  
488 severity and duration across individual station locations, wetter conditions prevailed longer in in the  
489 Sahelian zone. This implies that this part of the catchment may be more prone to extreme wetness



490 and hence floods especially because of the low surface gradient. Policy orientation here may seek to  
491 reduce flooding risk through effective implementation of building regulations to prevent people from  
492 constructing houses on flood prone zones and develop/improve flood control infrastructure.  
493 Government through decentralized structures could also seek to provide weather forecasting  
494 information to the local population through community radios or SMSs given that many such radio  
495 stations exist in the area, and mobile telephone network coverage is high. Meanwhile, understanding  
496 the response time of a catchment can enhance disaster preparation.

497

## 498 **6. Conclusion**

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

503 Analysis using 12-month SPI values showed that annual rainfall was very variable in the  
504 catchment as there was a strong variation between SPI values from year to year. However, rainfall in  
505 the catchment during the period under study could be described as near stable given that near normal  
506 (-0.99 to 0.99) conditions dominated in most the rain gauge stations with an average frequency of  
507 occurrence above 65%.

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

516  
517 This study has permitted us to identify localities within the catchment that are prone to  
518 dryness/wetness conditions using available rainfall data. Results obtained can help farmers to decide  
519 which crops to cultivate in which part of the catchment e.g. drought resistant crops in areas prone to  
520 droughts. Furthermore, the identification of the drought/flood-prone areas can enhance management  
521 planning to improve the socioeconomic conditions of the population living in these localities e.g.  
522 through the protection of assets of small-scale farmers and herders.

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

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

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

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

545

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551

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

Station No	Location Station name	Geographic coordinates		Elevation (m)	Annual rainfall (mm/year)			Catchment zone
		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	Bouso	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	

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Table 2: SPI values

SPI value	Category
$\geq 2.00$	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
$\leq -2.0$	Extremely dry

Table adapted from (WMO, 2012)

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

<b>Frequency of occurrence of droughts and floods (%)</b>									
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
Bouso	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

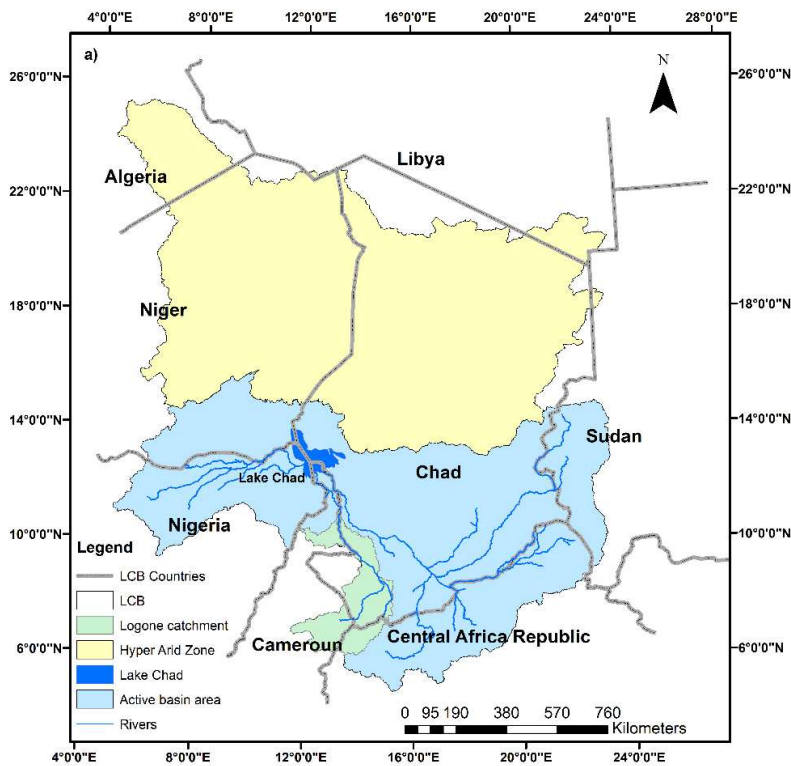


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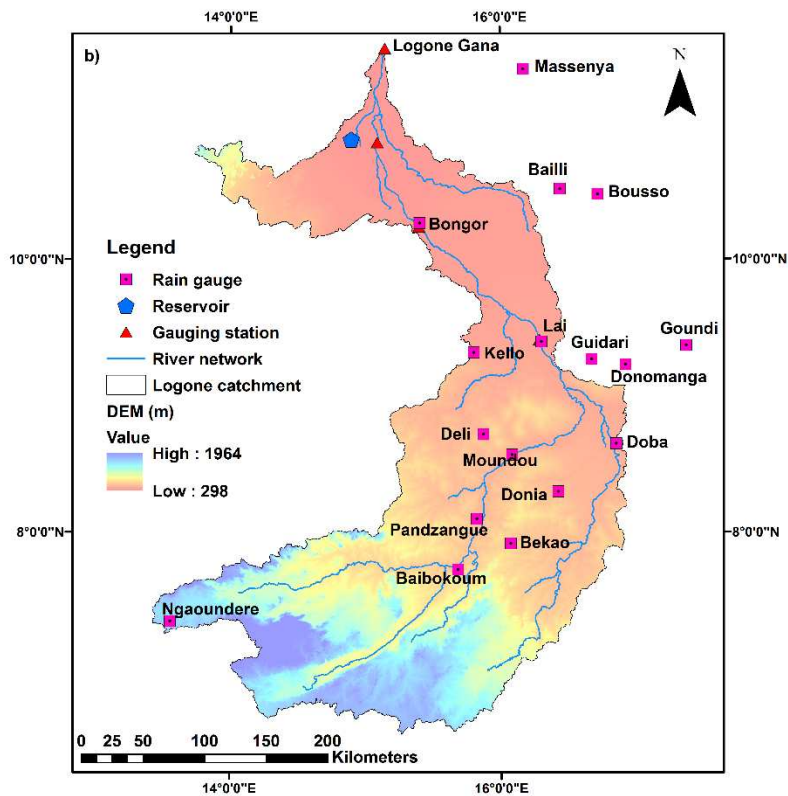
Table 4: Results of Mann-Kendall trend test for 1-month, 3-months and 12-months SPI and SSI time series

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

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



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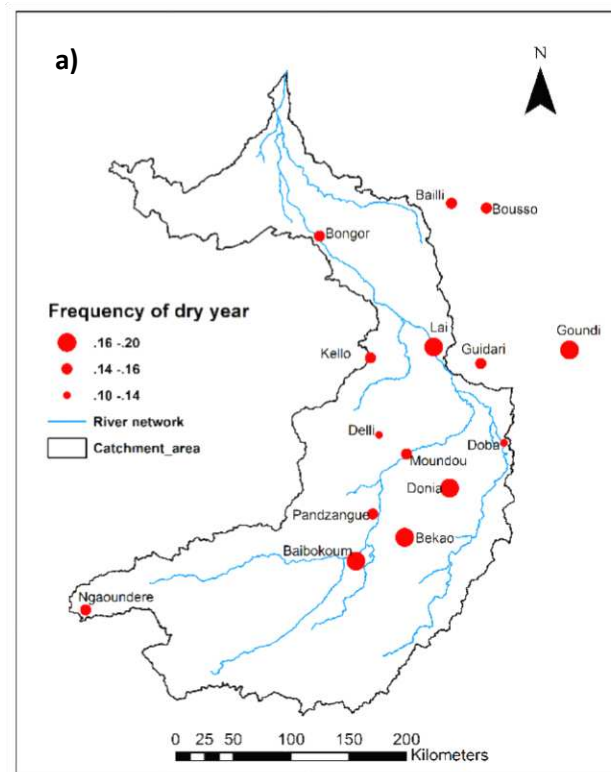
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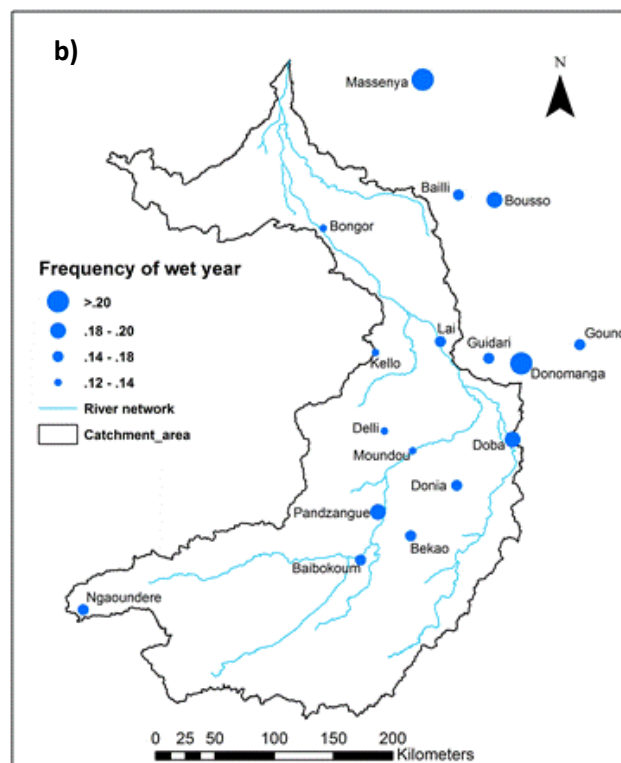
802 Figure 1: Lake Chad basin showing the position of the Logone catchment (a), Logone catchment showing

803 the location of rain gauges (b). (DEM: Digital Elevation Model)

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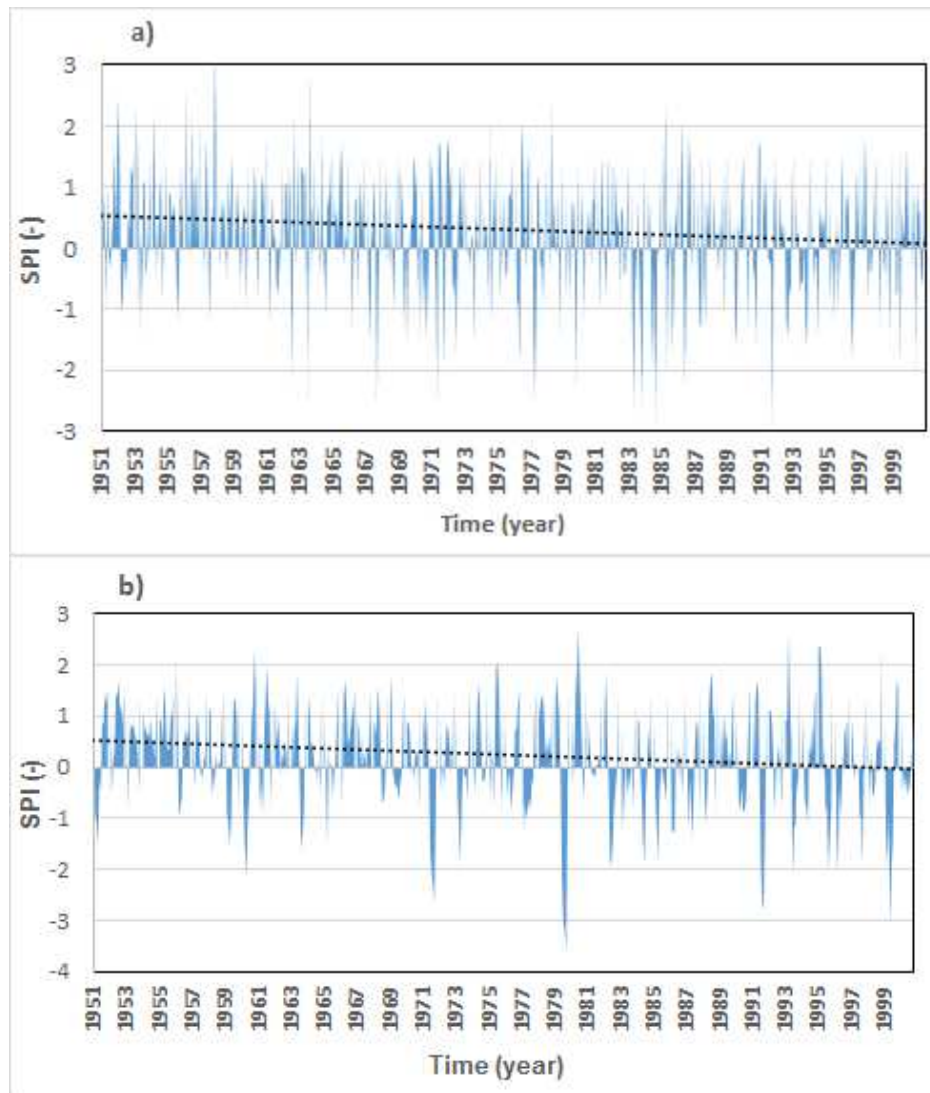


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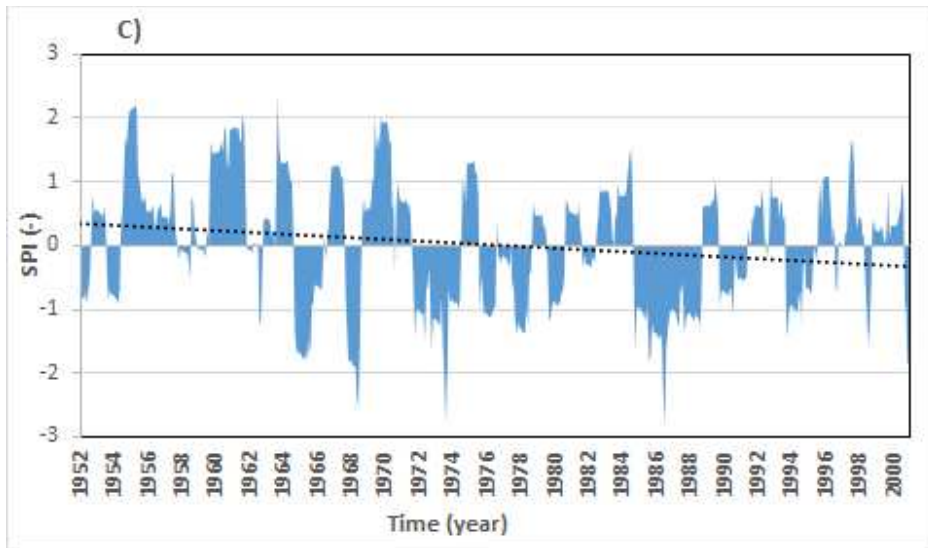
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810 Figure 2: Frequencies of occurrence and spatial distribution of dry and wet years in Logone catchment for  
811 the 1951–2000 period. The frequency was calculated as percentage according to the 12-month SPI for each  
812 year; a dry year a) was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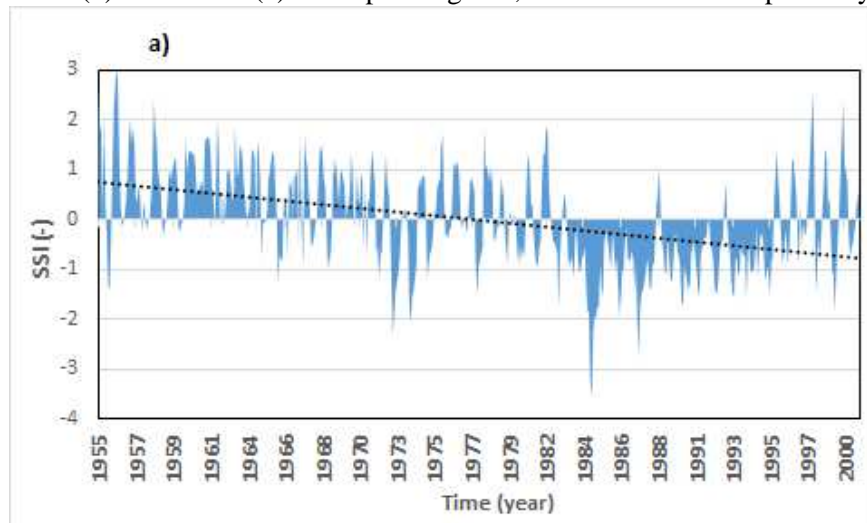


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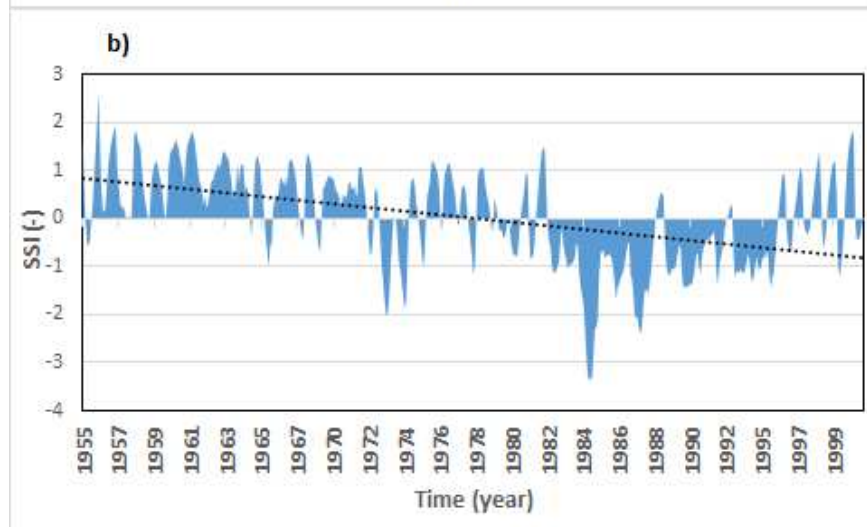
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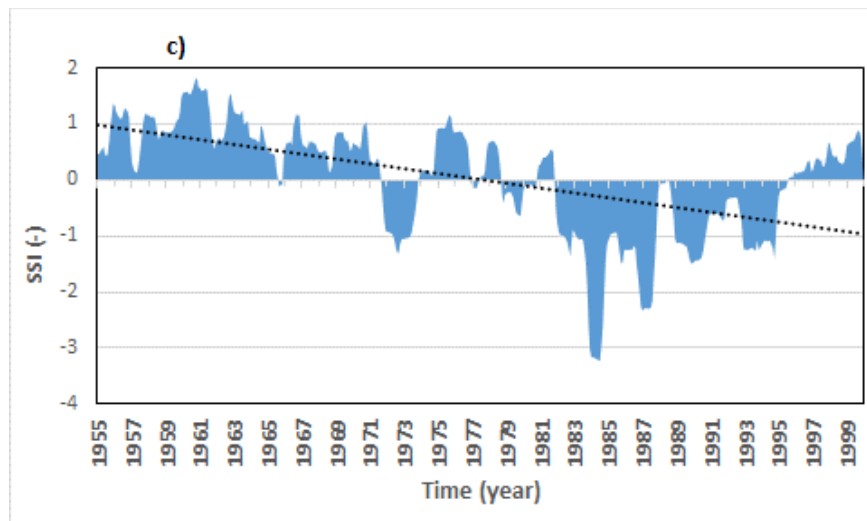
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 819 Figure 3: SPI time series for selected accumulated periods at different rain gauge stations: Ngaoundere (a)  
 820 Bailli (b) and Bekao (c) corresponding to 1, 3 and 12 months respectively.



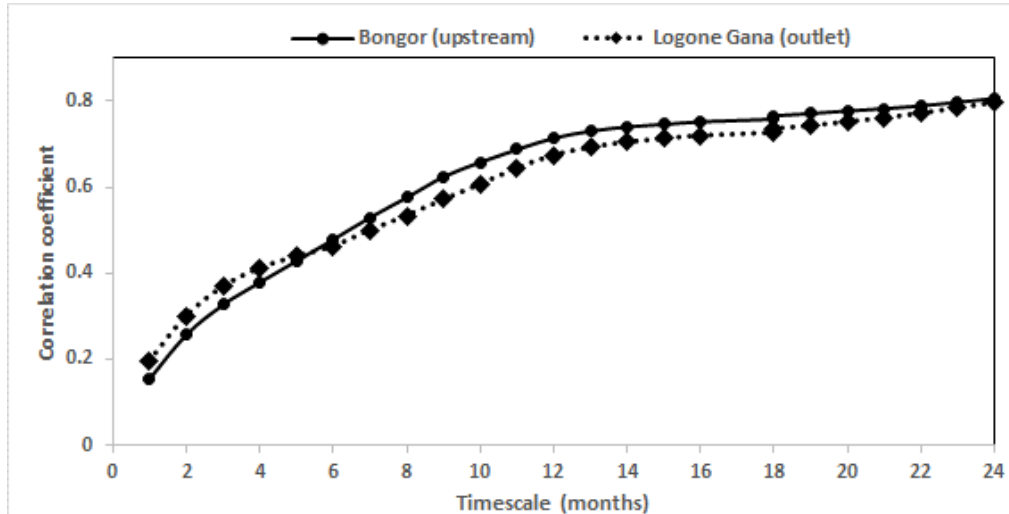
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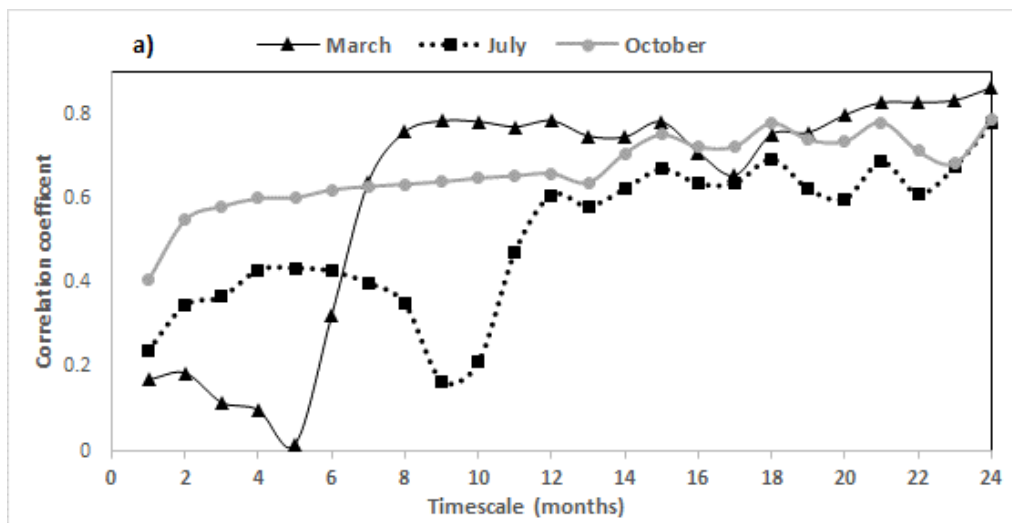
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 824 Figure 4: SSI time series for selected accumulated periods at the outlet of the Logone Gana gauging station.  
 825 a, b, and c correspond to 1,6 and 12 months respectively.  
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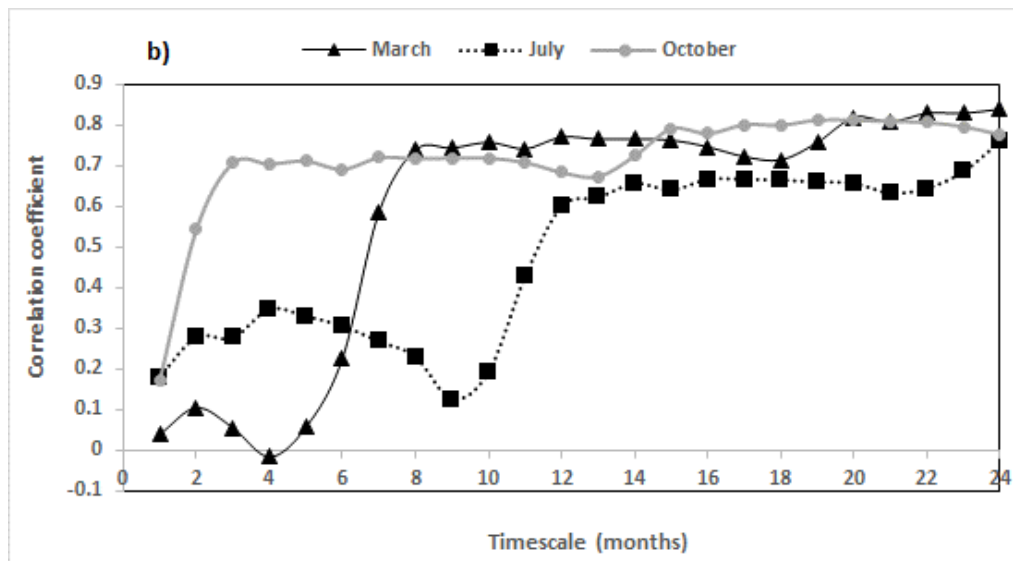


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 829 Figure 5: Correlation coefficients between the monthly SSI and the 1- to 24-month SPI  
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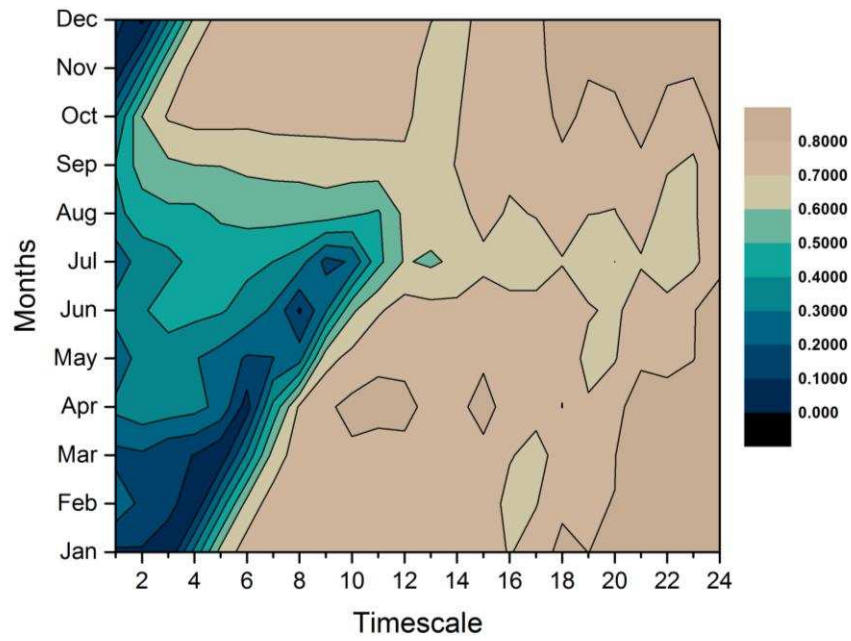
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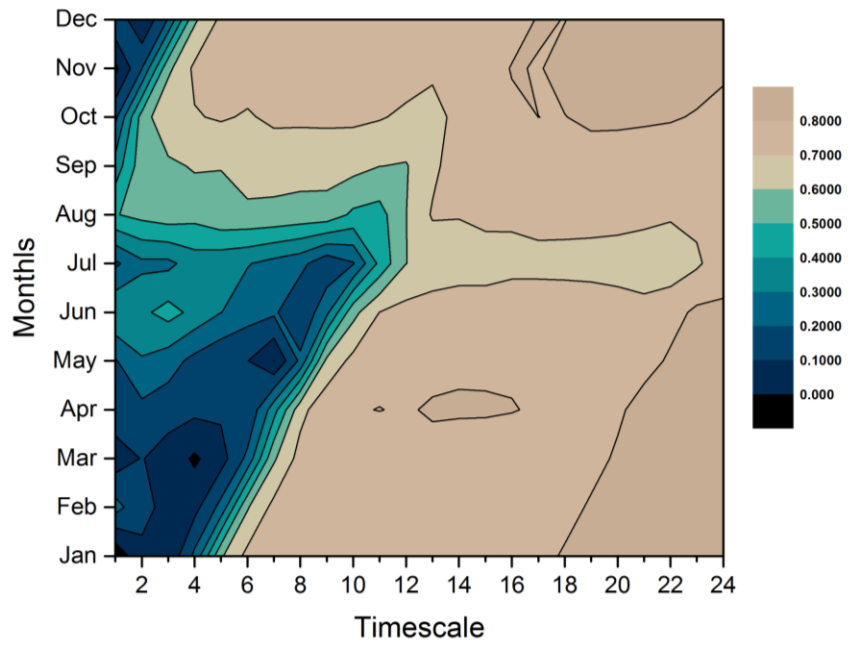


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Figure 6: Correlation coefficients between the monthly SSI and SPI for different individual months: a) Logone Gana and (b) Bongor. The X-axis indicates the timescale of SPI.



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