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Analysis of rainfall variability 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 socio-economic consequences posed by climate change in Africa are giving increasing emphasis to the need for trend analysis and detection of changes in hydro-climatic variables in data deficient areas. This study analyzes rainfall data from seventeen rain gauges unevenly distributed across the Logone catchment in the Lake Chad basin (LCB) over a fifty-year period (1951-2000). After quality control of the rainfall data using homogeneity tests, non-parametric MannKendall (MK) and Spearman rho tests were applied to detect the presence of trends. Trend magnitude was calculated using Sen's Slope Estimator. Results of the homogeneity test showed that rainfall was homogeneous across the catchment. Trend analysis revealed the presence of negative trends for annual rainfall at all the stations. Results of long term trend analysis at a monthly time scale revealed the presence of statistically insignificant positive trends at 32% of the stations. Spatially, the analysis showed a clear distinction in rainfall magnitude between the semi-arid and Sudano zones. The slope of the trend lines for annual rainfall averaged over the respective zones was higher in the semi-arid zone (-4.37) compared to the Sudano zone (-4.02). However, the station with the greatest reduction in annual rainfall (-8.06 mm) was located in the Sudano zone.

Keywords: Rainfall analysis, Mann-Kendall, Sudano-Sahel, Logone catchment, Lake Chad basin.

1) Introduction

Precipitation in the African Sudano-Sahel is highly variable both spatially and temporally, and experiences periods of prolonged drought such as that which affected the region in the 70s and 80s (Boyd et al., 2013; Nicholson, 2013). According to Nicholson (2013), rainfall in the Sudano-Sahel region is controlled by mesoscale convective systems (MCS). Its variability can be attributed to several factors. Firstly, as over the rest of Africa, annual rainfall variability can be attributed to global sea surface temperature (SST) anomalies (Giannini et al., 2008). Secondly, for the Sudano-Sahel, fluctuations in high altitude jet stream circulation is responsible for the spatiotemporal variability of rainfall in the region. This includes the African Easterly Jet (AEJ), the Tropical Easterly Jet (TEJ), the African Westerly Jet (AWJ), Low Level Jets, the West African Westerly Jet (WAWJ), the Nocturnal Low Level Jets (NLLJ), the Saharan Heat Low (SHL), and the Saharan Air Layer (SAL) (Nicholson, 2013).

Rainfall variability in the region is also strongly influenced by seasonal regime changes. The oceanic regime (monsoon), characterized by the progressive increase of moist air flow from the Atlantic Ocean into the continent up to about 11°N in May, is associated with seasonal migration of the Intertropical Convergence Zone (ITCZ) from its southern position in the boreal winter to its northern position in the boreal summer (Lebel et al., 2003). The continental regime (harmattan) is characterized by large convective systems during July to September embedded in the easterly circulation (Lebel et al., 2003), and also plays a key role in rainfall variability.

Decadal rainfall variability in the region has been associated with several possible causes. Jury (2010) attributed it to the interaction of Hadley Walker cells over Africa at decadal frequency through anomalous north-south displacement of the near-equatorial trough; Caminade and Terray (2010) linked it to atmospheric variability; Paeth and Hense (2004) attribute it to global warming while Zeng et al. (1999) attribute it to vegetation feedback processes.

Despite significant shrinkage in the size of Lake Chad in recent decades, research on rainfall variability over the Lake Chad basin (LCB) has received relatively little attention compared to other basins in the region (Ndehedehe et al., 2016; Karlson & Ostwald, 2016). Nevertheless, Okonkwo et al. (2014) used gridded gauge monthly time series (1970-2010) to show an increasing trend in annual rainfall over the LCB, while Niel et al. (2005) analyzed rainfall data from rain gauges covering the period 1950-2002 and reported a significant drop in annual rainfall in the central part of the basin (11° - 13°N). Armitage et al. (2015) also used paleo-climate records from the LCB to support the fact that the African monsoon responds to insolation forcing in a nonlinear manner and that Lake Mega-Chad exertd strong control on global biogeochemical cycles.

Given the numerous sub catchments that make up the LCB, the Logone catchment was selected for this analysis. This was motivated by the fact that: (i) the catchment covers two different ecological zones (Sudano and semi-arid); (ii) it contributes significantly to inflows into Lake Chad due to relatively high rainfall received in the Sudano zone; (iii) it is a transboundary catchment shared by three countries (Cameroon, Chad and Central Africa Republic); and (iv) it has extensive floodplains with great wildlife diversity and socio-economic value.

Floods have become frequent in recent years in the Logone catchment causing widespread socio-economic damage. Despite the floods, water availability for agriculture, pastoral activities, ecosystem sustainability and contribution as inflow into the lake, is still under threat due the erratic rainfall. Yet, there is limited hydro-climatological documentation about the catchment and future rainfall projections in the region based on recent climate models show considerable spread (Aloys et al., 2016; Haensler et al., 2013). Analysis of historical rainfall could therefore be a valuable source of information to gain insight into the sensitivity of the catchment to natural and human induced climate perturbations. This is important for informing water management and adaptation policies under climate change conditions.

The objective of this study was to: (i) check the spatial and temporal homogeneity of rainfall data in the Logone catchment; and (ii) analyse rainfall trends data in different space and time scales. Similar analysis at sub catchment scale have been conducted across many large basins in Africa, for example in the Bani, Kariba and Upper Blue Nile catchments, located in the Niger, Zambezi and Nile basins (Louvet et al., 2016; Muchuru et al., 2015; Tabari et al., 2015). A study limitation is the absence of gauge rainfall data after the year 2000, so the trends in recent rainfall variability after this period could not be explored. However, recent trends in rainfall within the LCB have been analysed using gridded gauge data (Okonkwo et al., 2014). Another limitation of this study is the use of rain gauge data, which are point measurements, to evaluate rainfall that is highly variable both in time and space. To be able to capture this variability a dense network of rain gauges equally distributed spatially across the catchment is needed, and this remains a major challenge in most hydro-climatic studies. Although this issue may be resolved by using satellite or reanalysis datasets, these too also need to be validated against in-situ rain gauge measurements (e.g. Nkiaka et al., in press). Accuracy, of satellite and reanalysis rainfall forecast models thus depends on the quality of gauge data used for calibration and are inevitably affected by the sparsity of gauge data or temporally incomplete gauge time series in the region under investigation.

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

2.1) Study area

The Logone catchment covers an area of about 86,240 km^2 at the Logone Gana hydrometric station and lies between latitude 6˚ - 12˚ N and longitude 13˚ - 16˚ E in the south western part of Lake Chad basin (Figure

1). It is a major tributary of the Chari River and the two rivers jointly contribute about 95% of the inflow into Lake Chad. It has its source in Cameroon from the Mbere and Vina Rivers rise in the Adamawa Plateau. In Lai, it is joined by the Pende River from the Central Africa Republic and flows in a south-north direction. Elevation ranges from about 1200 masl on the Adamawa Plateau in the south to 300 masl in Ndjamena in the north. The basin topography is relatively flat with an average slope of less than 1.3%. It flows through three different countries, Cameroon, Central Africa Republic and Chad. The catchment is located in a Sudano-Sahelian climatic regime under the tropical continental regime air mass (the Harmattan) and the oceanic regime equatorial air mass (monsoon). It has a strong north-south rainfall gradient with a single rainy season between April and October. Average annual rainfall varies between 600 mm/year in the north to about 1500 mm/year in the south. Landuse in the catchment is dominated by forest (53%) and agriculture (34%).

2.2) Data sources

Monthly rainfall data was obtained from "Système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation" (SIEREM) (Boyer et al., 2006). To improve reliability of analysis, only stations that had monthly data covering the period 1950-2000 with missing data points of not more than 10% were selected. Using these criteria, only 11 rain gauge stations located inside the catchment were acceptable, so six rain gauge stations located outside the catchment with the same climatic conditions were included in order to increase the data available.

Gaps were filled using the Artificial Neural Network (ANN) Self-Organizing Map (SOM) technique (Nkiaka et al., 2016). The time series were further screened and comparisons between stations made using statistical metrics including coefficient of variation (C_v), skewness (C_s) and actual excess kurtosis (K_u).

The monthly time series were aggregated to annual and seasonal time series for each station. The rainy season in the catchment generally lasts from April to October, aggregation was done for the months of April, May and June to correspond with the pre-monsoon season; then July, August and September (JJAS) for the monsoon season. Table 1 shows the station name, coordinates, long term mean, maximum, minimum, C_v, C_s, and K_u of the annual rainfall time series for each station. The C_v of annual rainfall varies between 0.10 - 0.24; rainfall is slightly positively skewed (C_s=0.36) and leptokurtic (K_u=0.34) (higher and sharper central peak with longer and flatter tails) compared to a normal distribution where C_s=0 and K_u=0. Long term mean annual rainfall varies between 642 mm/year (Massenya) in the semi-arid zone to 1514 mm/year (Ngaoundere) in the Sudano zone.

3) Methodology

The catchment was divided into two parts. The northern part was termed "semi-arid" for stations located between latitude 10° -12° N and the southern part termed "Sudano" for stations located between latitude 6° - 10° N. Stations 1-13 lie in the Sudano zone and 14-17 are located in the semi-arid area (Table 1). Annual rainfall from stations located in each of the zones was averaged and plotted as shown in Figure 2. Different statistical tests were used for homogeneity and trend testing. (Sonali and Kumar, 2013).

3.1 Homogeneity test

The importance of the homogeneity test is to ensure that the data is not affected by non-climatic factors such as station location, station environment, observation practices and instruments. According to Yozgatligil and Yazici, (2015) homogeneity testing is a critical quality control method in hydro-climatological studies and underpins the reliability of any inferences drawn from the data. For homogeneity testing, the standard normal homogeneity test (SNHT), Buishand Range (BR), Pettitt and Von Neumann ratio tests were applied (Yozgatligil and Yazici, 2015; Buishand et al., 2013; Wijngaard et al., 2003). Under the null hypothesis, all four tests assume that the annual values of the variable under investigation are independent and identically distributed while under the alternative hypothesis, SNHT, BR and Pettit tests assume there is a break or step-wise shift in the mean of the variable. The first three tests can locate the year in which the break occurred. SNHT is useful for detecting inhomogeneity at the beginning or end of the time series while BR and Pettitt tests are useful for detecting inhomogeneity at the middle of the time series. While the SNHT and BR tests assume that the variable is normally distributed, the Pettitt test does not use this assumption because it is a non-parametric test based on the ranks of the observations in the series rather than on the values themselves. Finally, under the alternative hypothesis, the Von Neumann ratio test assumes that the series is not randomly distributed. Generally, a combination of different statistical methods is recommended to be most effective to track down inhomogeneities in hydro-climatic time series (Wijngaard et al., 2003). Critical values for all these tests are available in Wijngaard et al. (2003).

3.2 Trend test

After testing and ascertaining the homogeneity of the data, the time series was deseasonalized using the Seasonal Trend Decomposition procedure based on Loess (STL) (Cleveland et al., 1990). This technique was used to decompose the time series into three components: trend, seasonal, and the remainder component. STL is widely used for deseasonalizing hydro-climatic data (Buma et al., 2016; Aguilera et al., 2015).

Trend tests were used to detect if the trend component of the deseasonalized rainfall time series monotonically increased or decreased with time. The non-parametric tests used for trend testing included MannKendall (MK) and Spearman rho tests while Sen's Slope estimator was used to calculate the magnitude of the trend (Onyutha et al., 2015; Sonali and Kumar, 2013; Kumar et al., 2010). Only the trend component was used for analysis to avoid distortion due to seasonality or irregularity in the data. The deseasonalized monthly rainfall time series were further aggregated into annual and seasonal time scales to check for potential changes that could have occurred at these time scales. Note that for analysis at monthly time scale, the rainfall data was not deseasonalized.

Because the ability to detect trends in a time series using the MK test can be influenced by the presence of autocorrelation, Yue et al. (2002) proposed the use of trend-free pre-whitening (TFPW) to remove autocorrelation. However, many authors have criticized the use of TFPW for this purpose (Sonali and Kumar, 2013; Kumar et al., 2010; Bayazit and Önöz, 2007). These authors argue that, when the sample size is large ($n \geq 50$) and the slope of the trend is high (≥ 0.01), pre-whitening is not needed because there will be negligible effect of serial correlation especially for a type-I error, and could also result in significant power loss of the test. Given that the sample size of data used in this study is large ($n \geq 50$) and the MK test was not the only test used for trend testing, TFPW was not applied.

Although most trend analysis consider only long term time series, short significant events may also exist within data series that do not have any significant influence on the overall long term time series, but could have profound impact on livelihoods, ecosystems and infrastructure. For this reason, trend analysis was also conducted at monthly and seasonal time scales.

4) Results

4.1 Homogeneity analysis

Results obtained using the different homogeneity tests were not in total agreement with each other. While SNHT and BR tests produced similar results, the Pettitt test produced different results and the changes observed did not occur in the same year. However, according to Wijngaard et al. (2003), the different tests could have different sensitivities to changes in rainfall series explaining the differences in results.

In this study, a time series was considered homogenous if the critical values of SNHT, Pettitt test and Von Neumann ratio test statistics were less than 11.38, 293 and 1.36 respectively. Since SNHT and BR tests produced identical results, only the results of SNHT are shown in Table 2. These results were further grouped into classes A, B and C using the criteria proposed by Wijngaard et al. (2003) at the 1% significance level. The results are grouped into: class A (useful) zero or one rejection; class B (doubtful) two rejections; and class C (suspect) three or more rejections. From Table 2, 47% of the stations fall under class A classified as homogeneous; 29% of the stations fall under class B meaning that these time series are doubtful, thus results of trend analyses should be regarded critically due to the possible existence of inhomogeneities; and 24% of the stations were grouped under class C suggesting that the results of the trend analysis should be rejected due to the existence of inhomogeneities.

However, the dates of the breaks observed in classes B and C fall mostly within the period of drought or its onset in the region, so we considered that these breaks were as a result of natural climate variability. None of the time series exhibited significant break points at the 99% confidence interval, so we assumed that the data were free from any artefacts that could cause artificial trends in the rainfall time series, and that these time series could be regarded as homogeneous and thus qualify for trend analysis.

Furthermore, despite the smoothing effect caused by averaging over large areas, the trend in annual rainfall still shows a general downturn in rainfall beginning around the mid-1960s for all stations as shown in Figure 2. Figures 3a&b also confirm the homogeneity in the time series as the mean monthly range is the same for stations located in each of the zones with no outlier detected.

4.2 Trend analysis

The results obtained using the various statistical trend tests are elaborated in the following sub sections divided into annual, seasonal and monthly rainfall trend analysis.

4.2.1 Annual rainfall

Figure 2 shows the trend component of the annual rainfall averaged over the semi-arid and Sudano areas of the catchment. From the figure it can be observed that there was a general decline in annual rainfall over the two ecological zones. Although the trend remained negative during the period under study, the figure shows a general recovery in rainfall beginning from mid-1980 but has not yet reached the level observed before the drought. The figure also shows that although the trend was generally negative, annual rainfall was very variable in both parts of the catchment during the period under study. Table 3 shows the results of MK, Spearman Rho and Sen's Slope tests at 5% significance level. Results from both tests indicate the presence of negative trends for annual time series, therefore the null hypothesis was rejected for all stations. The magnitude of Sen's Slope further indicated that annual rainfall reduced by 1-9 mm/year across stations with a maximum drop observed at Goundi (-8.06 mm/year), while the minimum was observed at Pandzangue (-1.48 mm/year). Apart from Bousso which is located in the semi-arid area, the decrease in annual rainfall was more severe for stations located in the Sudano area of the catchment.

4.2.2 Seasonal rainfall

Analysis of seasonal rainfall using both tests revealed negative trends during the pre-monsoon and monsoon seasons with almost equal severity in both zones as the drop varied from -0.27 to 2.25 mm/season. The magnitude of the Sen's Slope showed that Goundi station witnessed the most dramatic drop in both the pre-monsoon and monsoon rainfall (-2.25 mm/season). Stations with statistically significant negative trends were recorded only in the Sudano area during the pre-monsoon and monsoon seasons even at annual time scale.

The negative trends in annual and seasonal rainfall observed in the Logone catchment correspond to the onset of the Sahelian drought that lasted from the mid-1960s-1980s and was associated with a significant drop in rainfall throughout the region. Similar trends in annual rainfall in the LCB were reported by Niel et al. (2005) and elsewhere in the region by Ifabiyi and Ojoye, (2013), Sarr (2012), and Conway et al. (2009). Meanwhile for seasonal rainfall, Sarr (2012) reported a general decline in seasonal July, August and September (monsoon) rainfall throughout the 1961–1990 period in the Sudano-Sahel zone of Nigeria.

4.2.3 Monthly rainfall

Results of long term trend analysis at a monthly time scale shown in Table 4 revealed that, apart from negative trends, statistically insignificant positive trends were also observed at some stations. Positive trends were observed in July at 35% of the stations while April, May and June recorded positive trends at 29% of the stations. The increase in monthly rainfall was random with no station observing a systematic increase during all the months. Furthermore, positive trends were observed across the catchment in August at only two stations (Pandzangue and Kello) and a statistically significant positive trend was observed at one station (Deli) in September. This finding is important as hitherto the highest rainfall was recorded in the catchment during August and September (Loth, 2004).

The increase in rainfall in the months of April, May, June and July with little or no increase in August and September suggest that there might have been a backward shift in the occurrence of rainfall in the catchment. However, further analysis is needed using daily rainfall data extending into the recent decade to confirm this. Lebel and Ali, (2009) also reported the disappearance of peak rainfall previously observed in August in the Central Sahel region, and Sarr (2012) asserted that there was a general decline in July, August and September rainfall throughout the 1961–1990 period in the region. The backward shift in rainfall could increase crop production in the catchment as it coincides with the planting season.

Following Ma et al. (2013), Table 5 summarises the differences between annual, seasonal and monthly decadal mean rainfall data in the catchment from their long-term means. In this table, the values represent the decadal means minus the long-term mean 1951-2000. From the table it can be observed that higher than normal rainfall was recorded across the catchment during the 1950 and 1960 decades. This was followed by a general drop during the 1970 and 1980 decades which correspond to the period of drought in the region. Although decadal rainfall in 1990 was still generally low compared to 1950 and 1960 decades in most stations, positive values were observed in 24% of the stations (Lai, Pandzangue, Deli and Massenya).

Analysis further revealed that, between 1980 and 1990 decades, pre-monsoon (April, May and June) rainfall increased in 65% of the stations. Three stations (Baibokoum, Pandzangue and Massenya) recorded a decadal increase of more than 120 mm/decade during the monsoon season in the 1990 decade. Generally, decadal rainfall was very variable across the catchment because the difference between the long term and decadal means oscillated between high and low values from decade to decade (Figures 4a&b and 5a&b). Furthermore, the difference between mean decadal rainfall for 1990 and 1980 showed that decadal rainfall increased by an average of 15 mm across the catchment during the 1990 decade compared to the previous decade.

The increase in decadal rainfall during 1990 decade suggest that the catchment may be recovering from drought, as is the case in other Sudano-Sahel catchments. Increasing rainfall trends in the region have been widely reported (Louvet et al., 2016; Mertz et al., 2012; Lebel and Ali, 2009; Mahé and Paturel, 2009; Odekunle et al., 2008). Maidment et al. (2015) in their analysis observed a positive trend in rainfall in the LCB covering the semi-arid zone of the Logone catchment while Okonkwo et al. (2014) also reported a similar trend in the southern part of LCB covering the Sudano zone of the catchment. In a recent study, Ndehedehe et al.

(2016) also reported an increasing trend in rainfall over the LCB since 1990. In addition, the positive trends in rainfall observed in the catchment are reported to be a global trend (Westra et al., 2013).

4.3 Spatial variability in rainfall

The first evidence of spatial rainfall variability in the catchment is in the difference in annual and monthly means between stations located in semi-arid zone and those located in Sudano zone. As shown in Table 2, mean annual rainfall varies between 600 – 900 mm/year for stations located in the semi-arid zone and 900 – 1500 mm/year for station in the Sudano zone. It can also be observed from Figures 3a&b that monthly rainfall varies between 200-300 mm/month in the semi-arid and 250-350 mm/month in the Sudano zones. Additional proof of spatial variability of rainfall in the catchment is evident in the strong north-south gradient in rainfall over the catchment with rainfall increasing in a southward direction as shown in Table 1.

The coefficient of variation (C_v), which measures dispersion around the mean, was also calculated to analyze the spatial variability of annual precipitation for each station. As shown in Table 1, this coefficient varied from 10% in Ngaoundere to 24% in Bousso. Average annual variability was 18%, 17% and 21% for the whole catchment, the Sudano, and the semi-arid zones respectively. This indicates that stations located in the semi-arid zone displayed a higher degree of rainfall variability compared to stations located in Sudano zone.

Furthermore, the slope of the trend lines for annual rainfall averaged over the respective zones is steeper for the semi-arid zone (-4.37) compared to the Sudano zone (-4.02) (Figure 2). This implies that the semi-arid zone witnessed a more severe drop in rainfall compared to the Sudano zone during the period under study. At the level of individual stations, results in Table 3 show that the most significant drop in rainfall was registered in Goundi (-8.06 mm/year) located in the Sudano zone compared to Bousso (-7.55 mm) in the semi-arid zone. These results are similar to those obtained in other catchments in the region (Mertz et al., 2012; Conway et al., 2009; Mahé et al., 2009). As shown in Figure 3b and Table 1, Massenya, the most northerly station, recorded the lowest long term mean annual and monthly rainfall; while Ngaoundere which is the most southerly station has the highest of both.

Results of trend analysis further indicated that, although negative trends were recorded across all the stations in the catchment, statistically significant negative trends were observed only in the Sudano zone.

Although there are significant differences in total rainfall over the zones, there are common characteristics among them, including a single rainy season and a high variability in rainfall across individual stationsFrom year to year all stations show a severe drop in rainfall around 1984 and a general recovery observed after 1985 (Fig. 2).

5) Discussion

The significant negative trends in annual and seasonal rainfall recorded across the catchment suggest that there has been a significant change in the processes that influence rainfall. This indicates that the catchment is sensitive to natural climate perturbations and could thus be vulnerable to anthropogenic climate change.

Generally, rainfall variability in the Logone catchment can be attributed to the seasonal north-south movement of the intertropical convergence zone (ITCZ) as its strength and position strongly influence the processes that generate rainfall over the region (Nicholson 2013). Furthermore, given the location of the catchment (6˚-12˚N), the spatiotemporal variability in rainfall can also partly be attributed to the AWJ and WAWJ. These jet streams develop around this latitudinal zone from May to September coinciding with the period of peak rainfall in the catchment (Nicholson, 2013). The Northern African Easterly Jet (AEJ-N) and Southern African Easterly Jet (AEJ-S), which blow over the Logone catchment in August, also play a major role in influencing rainfall variability in the catchment (Fainsworth et al., 2011).

Factors such as topography also influence the spatial variability of rainfall in the Logone catchment. For example the southern flank of the Adamawa Plateau in Cameroon acts like a shield that prevents the progress of the oceanic regime (monsoon winds) towards the north around the month of March when the southern part of Cameroon is experiencing rain. This causes the displacement of the ITCZ towards the Western Highlands of Cameroon, so the continental regime (harmattan) with its dryness continues to prevail in the catchment (Molua and Lambi, 2006). During the month of May, the wetter oceanic regime pushes the continental regime northwards and displaces the ITCZ towards the north into the Logone catchment. Rainfall amounts recorded in the catchment during this period are indicative of the strength of the monsoon and position of ITCZ (Molua and Lambi, 2006).

The differences in rainfall between the semi-arid and Sudano zones can also be attributed to the kind of regime (oceanic or continental) that prevail in each of the zones at a given period of the year. In the Sudano zone the oceanic regime from the Atlantic Ocean dominates, causing high annual rainfall, while in the semi-arid area the continental regime from the Sahara Desert dominates resulting in low annual rainfall. High rainfall in the Sudano zone can also be attributed to orographic effects due to the high altitude of Adamawa Plateau in Cameroon and the Karre Mountains in the Central Africa Republic.

At the decadal time scale, Okonkwo et al. (2014) reported that El Niño Southern Oscillation (ENSO) events occurring around the months of July, August and September usually lead to a decrease in rainfall over the LCB so the absence of positive trends in rainfall during August and September across the catchment could be attributed to ENSO events. In addition, Okonkwo et al. (2015) reported that the current warm phase of Atlantic Multi Decadal Oscillation (AMO) could play a major role by influencing the increasing trends in decadal precipitation in the region as observed in this study.

The increase in monthly rainfall during the 1990 decade could be attributed to an increase in the intensity of localised rainfall as observed by Panthou et al. (2014) and Giannini et al. (2013) in other areas across the region. For example, after analysing rainfall trends in the Sudano-Sahel zones of Nigeria, Ifabiyi and Ojoye (2013) concluded that increasing rainfall trend was responsible for the frequent floods observed in the area recently. Furthermore, Okonkwo et al. (2015) have reported that there is a slow recovery in Lake Chad level as a response to recent increases in rainfall in the basin.

Giannini et al. (2003) attribute increasing rainfall trends in the region to a rise in SST of the Northern Atlantic Ocean. Meanwhile, Dong and Sutton (2015) have attributed this increase to the rising levels of greenhouse gases (GHGs) in the atmosphere and the consequent increase in atmospheric temperature. In a separate study, Evan et al. (2015) partly attribute this rainfall recovery in the region to an upward trend in the Saharan heat low (SHL) temperature resulting from atmospheric greenhouse warming by water vapour.

Temporal changes observed in rainfall patterns, with increasing trend in pre-monsoon rain earlier, could increase crop production in the catchment as it coincides with the planting season. However, more advanced forecasting techniques are needed so that information on the early onset of rainfall can be communicated to farmers in real time and with certainty. In general, the observed increase in rainfall could be beneficial to biodiversity, agriculture and pastoral activities, but floods also have negative socio-economic consequences such as destruction of property and crops. Flooding could also increase the risk of water related diseases such as malaria, diarrhoea, cholera and typhoid fever. Spatial rainfall analysis is important because it enables local authorities to know where to focus attention for developing water conservation measures and develop infrastructure to prevent damage due to floods.

6) Conclusion

Rainfall time series in the Logone catchment were analysed at monthly, seasonal, annual and decadal time scales with the aim of finding trends and variability using data from 17 rain gauge stations unevenly distributed across the catchment and beyond. Based on available data, the following conclusions can be drawn:

- Annual rainfall was homogeneous but very variable from year to year across the catchment.
- While negative trends were observed for annual rainfall in all the stations, statistically insignificant positive trends were obtained in all but one station at a monthly time step for some months.
- The negative trends in precipitation observed in the catchment correspond to the onset of the Sahelian drought in the mid-1960s to the 1980s that led to a significant drop in rainfall across the region.
- Although the statistically insignificant monthly positive trends in rainfall did not have any influence on the long term trend, it highlighted the importance of conducting trend analysis at shorter time scale.
- Increase in catchment rainfall observed during the 1990 decade indicate that the Logone catchment could be recovering from drought similar to catchments across the region.
- Analysis at monthly time scales revealed a backward shift in rainfall during the 1990 decade as more rainfall was observed during the pre-monsoon season, while the monsoon season witnessed a significant drop.
- These results indicate that the Logone catchment is sensitive to natural climate perturbations and could thus be vulnerable to anthropogenic climate change.

Results from this study may be useful to water managers and farmers for planning monthly and seasonal management of water resources, and to policy makers for informing adaptation policies under anticipated climate change given the highly sensitive nature of the catchment to climate perturbations. Nevertheless, due to natural climate variability in the region, it is difficult to predict if observed positive trends in rainfall will continue in the future. We acknowledge that the results of trend analysis obtained in this study might yield different results if gauge data beyond the year 2000 were available because this would have added another 1.5 decades to the length of the available gauge records.

Future research in the catchment will seek to analyse dry/wet conditions in the catchment using the standardized precipitation index and other relevant drought analysis indices and their application for monitoring droughts/floods.

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Table 1: Overview of meteorological stations and annual rainfall properties

Station No	Rain gauge station		Location		Elevation (m)	Annual rainfall (mm/yr)					
	Station ID	Name of locality	Lat	Long		Max	Min	Mean	C_v	C_s	K_u
1	1050042800	Ngaoundere	7.35	13.56	1113	1864	1152	1514.32	0.10	-0.16	-0.06
2	1460009500	Baibokoum	7.73	15.68	1323	1672	881	1277.36	0.15	-0.14	-0.69
3	1460017500	Bekao	7.92	16.07	528	1630	853	1180.98	0.17	0.32	-0.62
4	1460072500	Pandzangue	8.10	15.82	345	1892	919	1242.44	0.18	1.00	0.67
5	1460034500	Donia	8.30	16.42	414	1782	796	1085.42	0.19	0.83	1.13
6	1460066000	Moundou	8.57	16.08	410	1843	783	1102.72	0.17	1.26	4.22
7	1460033000	Doba	8.65	16.85	387	1475	680	1057.18	0.18	0.44	-0.21
8	1050630400	Deli	8.72	15.87	427	1539	705	1064.04	0.17	0.56	0.11
9	1460035000	Donomanga	9.23	16.92	370	1519	681	981.60	0.17	0.50	0.81
10	1460044500	Guidari	9.27	16.67	369	1562	629	1005.16	0.20	0.57	0.36
11	1460041500	Kélo	9.32	15.80	378	1413	503	979.68	0.18	-0.28	0.23
12	1460049000	Goundi	9.37	17.37	368	1519	681	981.60	0.17	0.50	0.81
13	1460053000	Lai	9.40	16.30	358	1491	669	1021.92	0.16	0.25	0.29
14	1460025500	Bongor	10.27	15.40	328	1070	400	789.86	0.18	-0.32	0.37
15	1460027000	Bousso	10.48	16.72	336	1365	423	844.24	0.24	0.19	-0.39
16	1460010000	Bailli	10.52	16.44	330	1146	463	797.32	0.19	0.3	-0.07
17	1460060500	Massenya	11.40	16.17	328	977	410	641.48	0.21	0.34	-0.2

Lat. and Long.: Latitude and Longitude in degrees respectively. C_v: Coefficient of variation; C_s: Skewness and K_u: Actual excess kurtosis

Table 2: Results of homogeneity tests for annual rainfall (1951-2000)

Station name	SNHT		Pettitt		Von Neumann	Test Class
	Statistics	Break	Statistics	Break	Statistics	
Ngaoundere	11.04	1966	340		1.44	B
Baibokoum	5.42		240		2.10	A
Bekao	6.42		239		2.00	A
Pandzangue	3.51		192		1.45	A
Donia	9.05		331	1982	1.66	B
Moundou	9.13		254		2.03	A
Doba	11.89	1970	317		1.43	C
Deli	3.95		205		2.26	A
Donomanga	16.25	1955	350		1.51	C
Guidari	12.55	1964	310		1.74	C
Kélo	4.86		205		1.97	A
Goundi	18.31	1962	453	1976	0.97	B
Lai	4.43		234		1.86	A
Bongor	12.24	1969	367	1969	1.30	B
Bousso	14.77	1961	394	1971	1.38	C
Bailli	9.5	1962	342		1.87	B
Massenya	7.98		290		1.41	A

Critical values of SNHT, Pettitt and Von Neumann are <11.38, <293 and <1.36 respectively

Table 3: Results of annual and seasonal rainfall analysis using MannKendall's Tau (Z_{MK}), Spearman's Rho (*SR*) and Sen Slope (SE)

Station	Annual rainfall			Pre-monsoon			Monsoon		
	Z_{MK}	SR	SE	Z_{MK}	SR	SE	Z_{MK}	SR	SE
Ngaoundere	-0.32	-0.47	-4.00	-0.26	-0.39	-1.15	-0.28	-4.30	-1.16
Baibokoum	**-0.24**	**-0.35**	-4.11	**-0.24**	**-0.34**	-1.15	**-0.20**	**-0.30**	-0.98
Bekao	-0.16	-0.26	-3.00	-0.13	-0.21	-0.70	-0.15	-0.24	-0.95
Pandzangue	-0.10	-0.16	-1.48	-0.07	-0.12	-0.27	-0.07	-0.12	-0.37
Donia	-0.30	-0.43	-5.31	-0.29	-0.43	-1.44	-0.28	-0.40	-1.37
Moundou	**-0.23**	**-0.33**	-3.12	**-0.20**	**-0.30**	-0.78	-0.18	-0.24	-0.72
Doba	-0.25	-0.36	-4.31	**-0.23**	**-0.33**	-1.03	**-0.24**	**-0.34**	-1.12

Deli	-0.12	-0.15	-1.87	-0.13	-0.17	-0.59	-0.10	-0.14	-0.33
Donomanga	-0.37	-0.49	-6.02	-0.36	-0.44	-1.45	-0.33	-0.44	-1.57
Guidari	**-0.25**	-0.37	-5.04	**-0.25**	**-0.34**	-1.39	-0.18	-0.25	-1.59
Kello	-0.16	-0.23	-2.84	-0.13	-0.18	-0.54	-0.12	-0.18	-0.51
Goundi	-0.40	-0.59	-8.06	-0.40	-0.58	-2.07	-0.39	-0.57	-2.25
Lai	-0.13	-0.19	-1.96	-0.08	-0.13	-0.37	-0.10	-0.16	-0.52
Bongor	-0.31	-0.47	-3.34	-0.27	-0.41	-0.87	-0.28	-0.43	-0.95
Bousso	-0.40	-0.56	-7.55	-0.38	-0.52	-0.87	-0.37	-0.52	-1.94
Bailli	-0.40	-0.58	-4.66	-0.35	-0.52	-1.18	-0.35	-0.51	-1.40
Massenya	-0.15	-0.21	-2.11	-0.16	-0.21	-0.55	-0.14	-0.19	-0.57

*Bold values indicate that the trend is statistical significant at 5% level as per the 2 tail test (+ for increasing and - for decreasing) pre-monsoon season (April, May and June) while monsoon season (July, August and September)

Table 4: Results of monthly rainfall analysis using MannKendall's Tau (Z_{MK}), Spearman's Rho (*SR*) and Sen Slope (SE)

Station	March		April			May			June		
	SR	SE	ZMK	SR	SE	ZMK	SR	SE	ZMK	SR	SE
Ngaoundere	-0.14	-0.34	0.07	0.15	0.48	-0.13	-0.21	-0.70	-0.19	**-0.28**	-1.19
Baibokoum	-0.20	0.00	**-0.20**	-0.28	-0.74	-0.09	-0.14	-0.45	-0.13	-0.19	-0.79
Bekao	**0.15**	0.00	-0.04	-0.07	-0.18	-0.01	-0.02	-0.05	0.03	0.06	0.14
Pandzangue	-0.25	0.00	-0.15	-0.24	-0.47	0.00	-0.02	0.00	-0.09	-0.13	-0.38
Donia	**-0.38**	0.00	-0.25	-0.37	-0.67	0.09	-0.12	-0.30	-0.18	-0.26	-0.82
Moundou	-0.37	0.00	**-0.20**	-0.30	-0.68	-0.13	-0.20	-0.43	-0.06	-0.08	-0.27
Doba	**-0.10**	0.00	**-0.22**	-0.29	-0.53	0.00	-0.02	0.00	-0.11	-0.15	-0.56
Delli	-0.35	0.00	**-0.22**	-0.35	-0.50	-0.26	**-0.36**	-1.22	-0.05	**-0.07**	-0.21
Donomanga	0.03	0.00	0.00	0.00	0.00	-0.01	-0.03	-0.04	0.04	0.05	0.24
Guidari	-0.26	0.00	-0.04	-0.08	-0.08	-0.05	-0.06	-0.24	-0.03	-0.03	-0.23
Kello	**-0.12**	0.00	-0.16	-0.25	-0.37	0.03	0.04	0.13	0.07	0.11	0.29
Goundi	**-0.28**	0.00	-0.08	-0.13	-0.20	-0.15	-0.22	-0.78	0.01	0.01	0.03
Lai	-0.23	0.00	0.04	0.02	0.09	-0.01	0.03	0.00	0.02	0.02	0.08
Bongor	-0.30	0.00	-0.14	-0.18	-0.18	-0.08	-0.12	-0.30	**-0.22**	-0.31	-1.04
Bousso	-0.15	0.00	-0.17	-0.24	-0.25	0.03	0.04	0.10	-0.18	-0.23	-0.86
Bailli	-0.19	0.00	0.02	0.02	0.00	0.00	0.00	0.00	-0.14	-0.22	-0.64
Massenya	-0.16	0.00	0.09	0.14	0.03	**-0.22**	**-0.32**	-0.43	-0.11	-0.16	-0.36

Station name	July			August			September			October		
	ZMK	SR	SE	ZMK	SR	SE	ZMK	SR	SE	ZMK	SR	SE
Ngaoundere	0.01	0.01	-0.11	-0.09	-0.13	-0.50	-0.06	-0.10	-0.43	-0.10	-0.13	-0.71
Baibokoum	-0.12	-0.15	-0.86	-0.02	0.02	-0.19	-0.06	-0.09	-0.57	-0.16	-0.21	-1.02
Bekao	-0.08	-0.13	-0.58	-0.17	-0.24	-1.43	**-0.19**	**-0.30**	-1.41	-0.08	-0.10	-0.43
Pandzangue	0.08	0.12	0.57	0.11	0.18	1.08	-0.11	-0.18	-1.12	-0.01	0.00	0.00
Donia	-0.11	-0.14	-0.89	**-0.22**	-0.33	-1.29	-0.14	-0.21	-1.03	-0.10	-0.15	-0.38
Moundou	-0.02	-0.05	-0.14	-0.16	-0.24	-1.00	**-0.09**	-0.12	-0.62	0.02	0.02	0.13
Doba	0.02	0.03	0.17	**-0.22**	-0.32	-1.59	**-0.29**	**-0.40**	-1.61	-0.06	-0.08	-0.21
Delli	-0.09	**-0.13**	-0.68	-0.30	-0.43	-2.08	**0.07**	**0.13**	0.56	0.09	**0.13**	0.61
Donomanga	-0.17	-0.23	-1.31	**-0.21**	-0.32	-1.32	**-0.23**	**-0.34**	-1.50	-0.25	-0.37	-0.92
Guidari	-0.13	-0.20	-1.00	**-0.21**	-0.29	-1.84	-0.18	-0.26	-1.71	**-0.20**	**-0.28**	-0.85
Kello	-0.15	-0.21	-1.12	0.09	0.14	0.66	**-0.15**	**-0.23**	-1.11	-0.16	-0.21	-0.58
Goundi	**-0.22**	**-0.31**	-1.79	-0.17	-0.26	-1.82	-0.29	-0.43	-2.06	-0.17	-0.24	-0.83
Lai	0.19	**0.28**	1.78	-0.11	-0.18	-0.85	-0.29	-0.41	-2.45	**-0.23**	**-0.30**	-0.69
Bongor	0.08	0.11	0.49	-0.10	-0.15	-1.07	**-0.19**	**-0.27**	-1.20	-0.04	-0.06	-0.03
Bousso	**-0.20**	**-0.31**	-1.43	**-0.22**	-0.34	-2.00	-0.19	-0.25	-1.71	-0.10	-0.16	-0.24
Bailli	-0.15	-0.23	-0.89	-0.12	-0.18	-1.27	**-0.21**	-0.31	-1.63	-0.11	0.12	-0.20
Massenya	0.00	0.02	0.00	-0.04	-0.06	-0.31	-0.15	-0.20	-0.57	0.05	0.05	0.10

*Bold values indicate that the trend is statistical significant at 5% level as per the 2 tail test (+ for increasing and - for decreasing). January, February, November and December are excluded from the table.

Table 5: The difference between mean decadal rainfall and the long-term mean (1951 - 2000). Differences represent the decadal mean minus the long-term mean (mm)

	Decade	Ngaoundere	Baibokoum	Bekao	Pandzangue	Donia	Moundou	Doba	Deli	Donomanga	Guidari	Kélo	Goundi	Lai	Bongor	Bousso	Bailli	Massenya
Annual rainfall	1951-1960	**128.68**	**100.24**	**105.22**	**56.46**	**95.28**	**71.98**	**96.02**	**49.36**	**135.6**	**130.54**	**65.02**	**197.32**	**31.28**	**108.24**	**192.66**	**102.58**	**99.32**
	1961-1970	**19.08**	**28.64**	**46.12**	**-34.74**	**86.88**	**78.18**	**142.52**	**38.86**	**38**	**81.64**	**31.72**	**29.52**	**70.98**	**54.64**	**59.46**	**36.58**	**20.02**
	1971-1980	**25.88**	**5.54**	-78.78	**64.36**	**14.48**	**2.28**	-53.28	-49.84	-46.5	-20.06	**1.32**	**24.82**	-20.12	-32.66	-24.14	**3.78**	-37.48
	1981-1990	-86.22	-102.86	-71.18	-122.44	-115.12	-120.12	-98.78	-47.24	-90.8	-144.6	-89.48	-180.08	-98.92	-120	-138.34	-53.22	-103.98
	1991-2000	-87.42	-31.56	-1.38	**36.36**	-81.52	-32.32	-86.48	**8.86**	-36.3	-47.56	-8.58	-71.58	**16.78**	-10.26	-89.64	-89.72	**22.12**
Monthly	1951-1960	**10.75**	**8.36**	**8.78**	**4.71**	**7.99**	**6**	**8.05**	**4.11**	**11.31**	**10.89**	**5.47**	**16.44**	**2.65**	**9.02**	**16.06**	**8.55**	**8.28**
	1961-1970	**1.48**	**2.35**	**3.78**	**-2.9**	**7.05**	**6.52**	**11.66**	**3.24**	**3.12**	**6.75**	**2.44**	**2.46**	**5.74**	**4.55**	**4.96**	**3.05**	**1.67**
	1971-1980	**2.18**	**0.47**	-6.55	**5.36**	**1.26**	**0.19**	-4.39	-4.15	-3.86	-1.66	**0.16**	**2.07**	-1.63	-2.72	-2.01	**0.32**	-3.12
	1981-1990	-7.16	-8.56	-5.92	-10.2	-9.55	-10.01	-8.18	-3.94	-7.55	-12.03	-7.41	-15.01	-8.2	-10	-11.53	-4.44	-8.67
	1991-2000	-7.26	-2.62	-0.1	**3.03**	-6.75	-2.69	-7.15	**0.74**	-3.01	-3.95	-0.66	-5.97	**1.44**	-0.86	-7.47	-7.48	**1.84**
pre-monsoon	1951-1960	**42.90**	**25.43**	-6.41	-15.86	-0.49	**27.63**	**5.29**	**37.57**	**43.73**	-22.49	**9.72**	**46.25**	**29.03**	-5.18	**30.05**	-5.20	**22.05**
	1961-1970	**55.90**	**21.83**	**35.19**	**33.94**	**24.01**	**14.03**	**3.69**	**48.27**	**9.33**	**37.21**	**45.22**	**34.05**	**28.83**	**24.02**	**18.05**	**50.30**	**2.75**
	1971-1980	-15.30	-4.17	**7.39**	**0.84**	-37.19	**4.53**	**19.19**	-16.13	**34.23**	-2.89	**10.42**	-26.85	**4.83**	-23.08	-8.25	-20.20	**23.85**
	1981-1990	-59.00	**18.43**	-29.81	-51.86	-2.09	-46.07	**5.59**	-48.53	**17.13**	-36.69	-42.88	-17.85	-22.67	-35.88	-63.35	-47.80	-14.95
	1991-2000	-13.30	-68.97	-3.11	**37.74**	**8.61**	-7.97	-43.31	-24.73	-98.67	**15.81**	-12.28	-24.45	-44.57	**38.22**	**24.55**	**20.80**	-30.05
Monsoon	1951-1960	**40.1**	**32.85**	**41.95**	**85.13**	**23.63**	**86.78**	**6.85**	**24.18**	**55.95**	**31.48**	**53.17**	**163.85**	**40.48**	**33.99**	**108.43**	**120.67**	**94.27**
	1961-1970	**13.2**	-22.55	**3.55**	**0.23**	**22.43**	**24.78**	**80.85**	-44.72	**7.45**	**75.18**	**3.17**	**2.55**	**109.98**	**70.29**	**7.73**	**22.17**	**26.97**
	1971-1980	**88.7**	**68.35**	-10.75	**0.83**	-12.17	-59.32	**17.05**	**43.18**	-20.15	-47.32	**7.37**	-28.25	-12.92	**18.39**	-25.27	**23.47**	-5.63
	1981-1990	-41.4	-17.65	-93.75	-14.17	-35.67	-50.22	-55.45	-92.52	-60.65	-24.22	-54.73	-85.05	-48.82	-66.21	-48.87	-94.23	-78.43
	1991-2000	-100.6	-53.95	**38.25**	-94.07	-14.87	-26.12	-44.25	**52.58**	**12.25**	-31.72	-12.43	-78.65	-79.82	-72.31	-74.57	-99.73	-70.43

Figures in bold represent increases

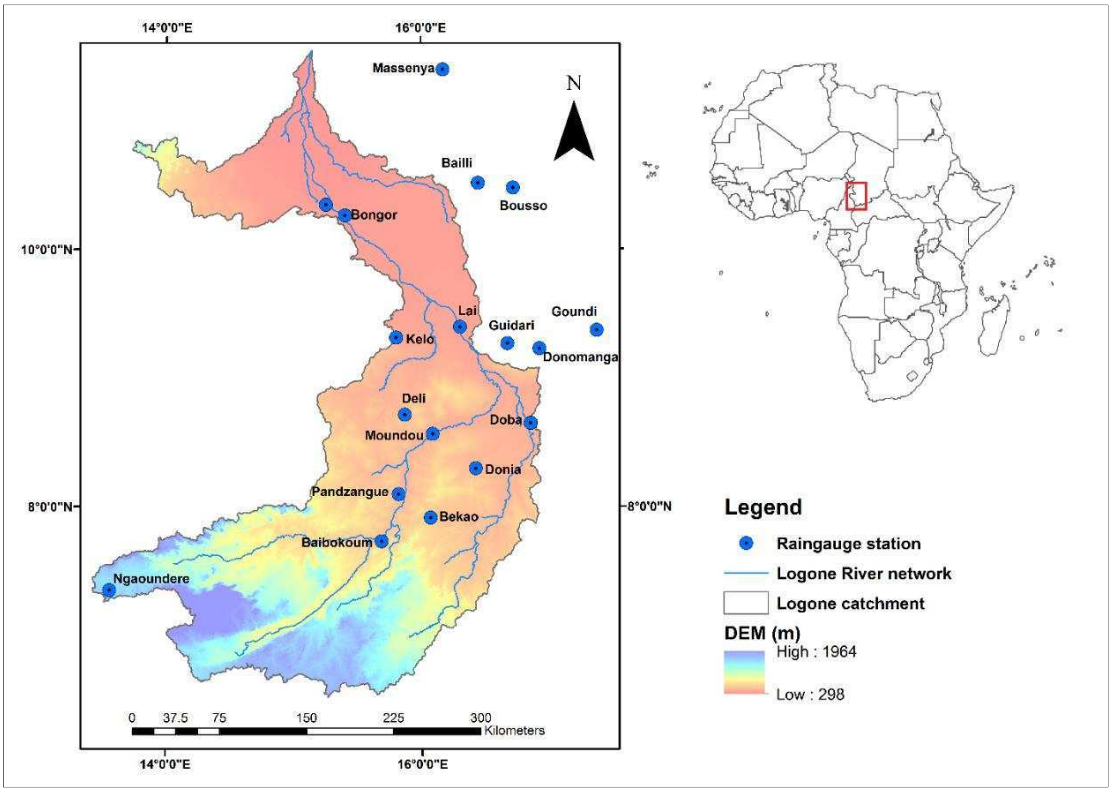


Figure 1: Map of study area. DEM: Digital Elevation Model at mean sea level

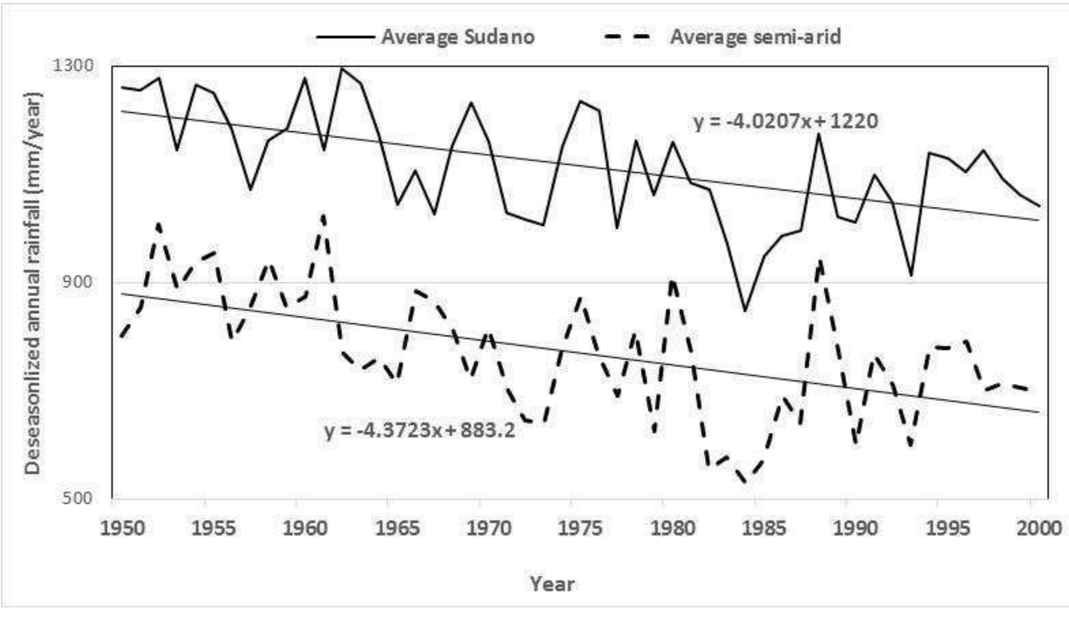
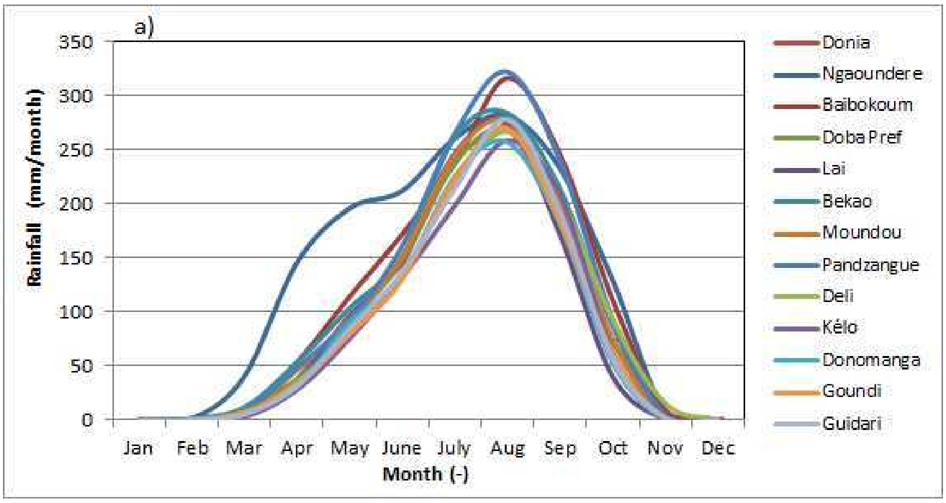


Figure 2: Annual rainfall trend in the Logone catchment



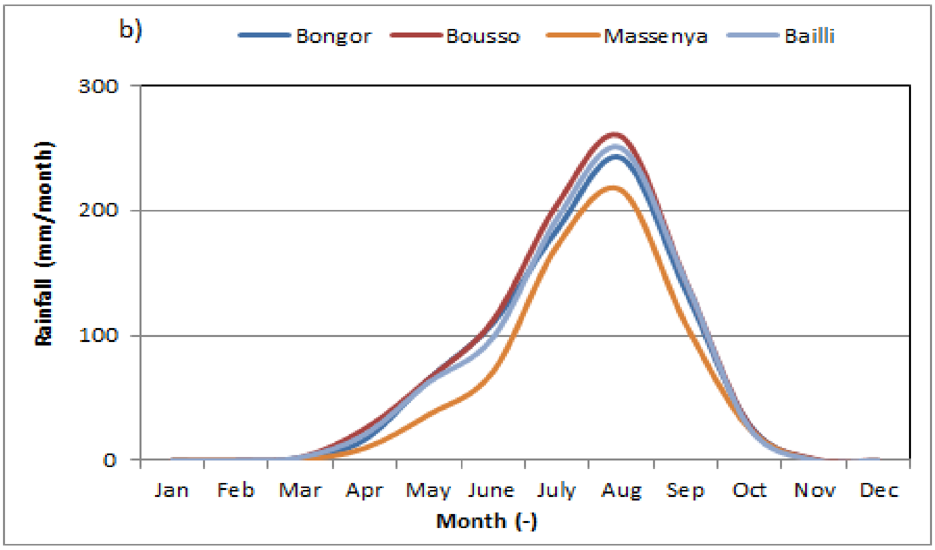
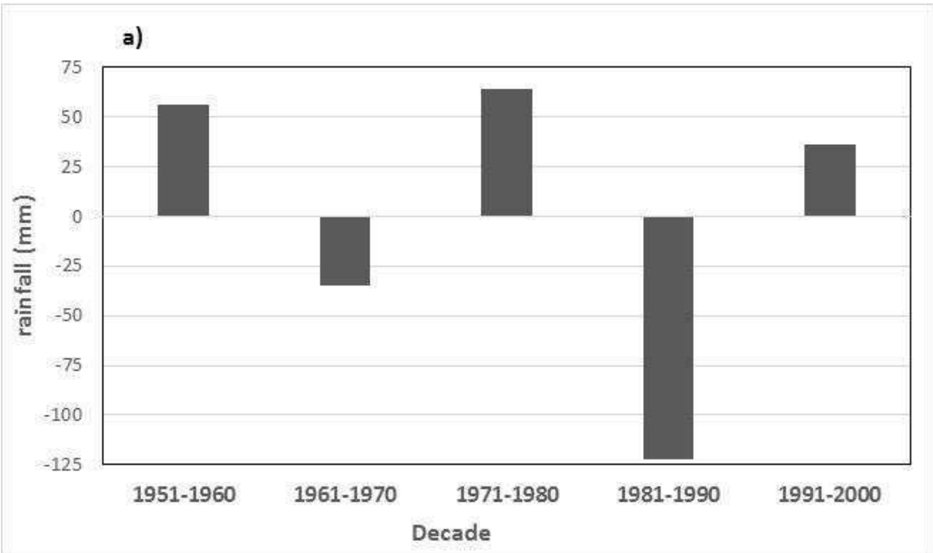


Figure 3: Long term mean monthly rainfall for (a) Sudano zone, (b) semi-arid zone



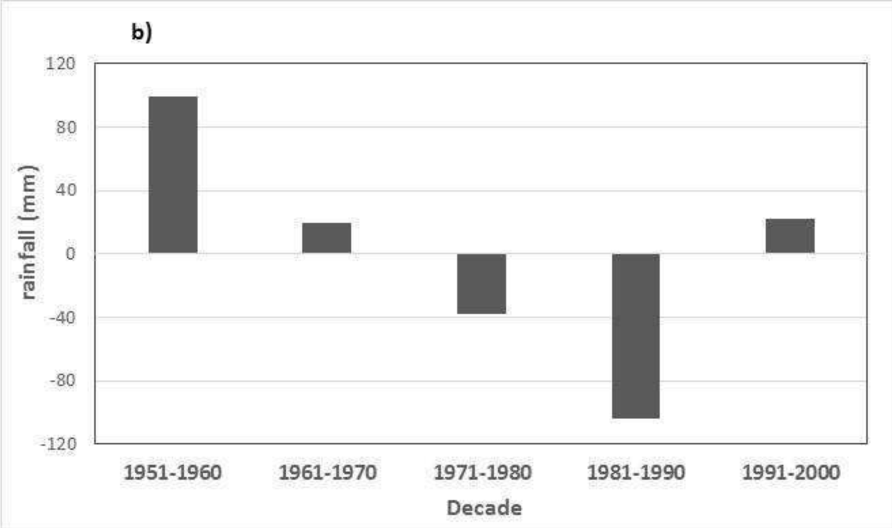
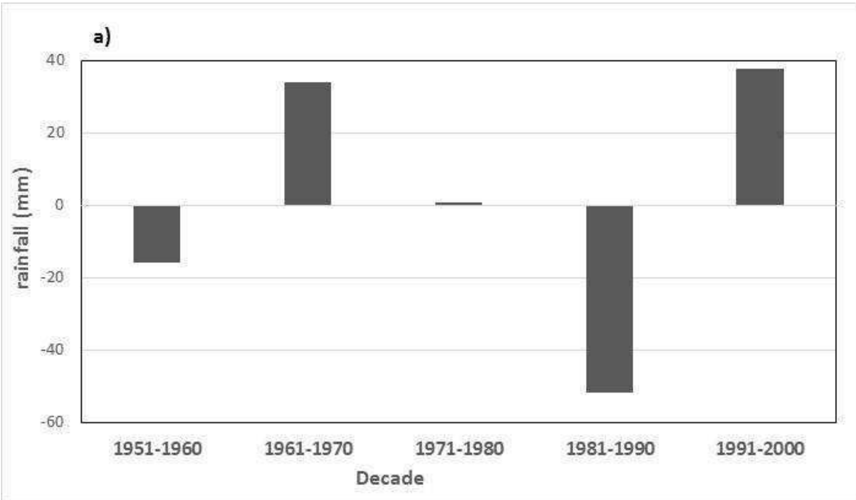


Figure 4: Difference between decadal mean and long term mean (1951-2000) for annual rainfall in a) Sudano area (Pandzangue) b) semi-arid area (Massenya)



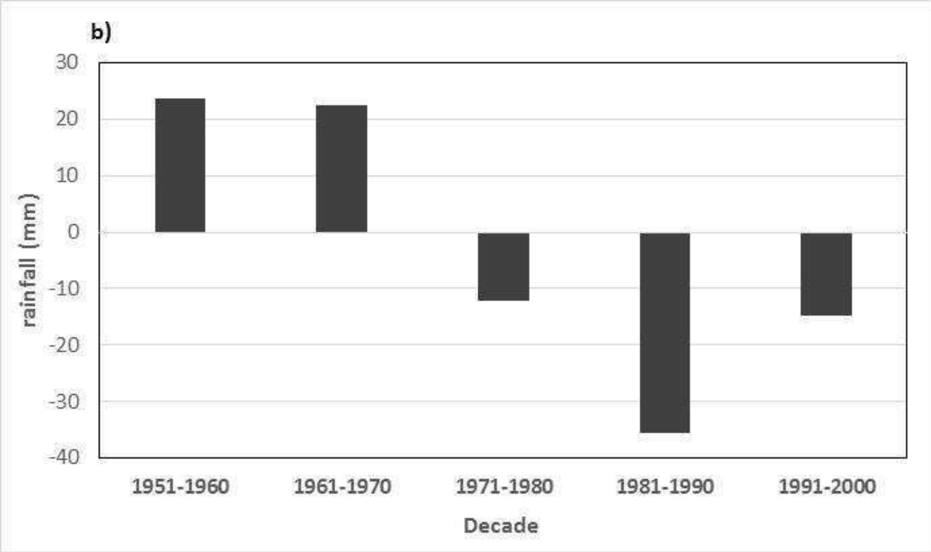


Figure 5: Difference between decadal mean and long term mean (1951-2000) for seasonal rainfall in Lai (a) Pre-monsoon (b) Monsoon