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Rainfall Analysis over the Niger Central Hydrological Area, Nigeria: Variability, Trend, and Change point detection

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ABSTRACT

Rainfall data are a vital meteorological input to agricultural modelling systems and water resources planning and management studies. In this study, CRU data (CRU_TS 4.01) was used to investigate spatiotemporal variability of rainfall at 33 sub-basins of the Niger Central Hydrological Area (NCHA), Nigeria, over 105 years (1911–2015). For Rainfall variability studies, rainfall variability index, precipitation concentration index, and linear regression model (LRM) were employed. Trend analysis and change point detection were done using nonparametric Mann-Kendall (MK) tests, Standard Normal Homogeneity Test (NSHT), and Pettitt's test (PT), and for spatial analysis of rainfall, kriging interpolation method was used. Rainfall variability index showed that 1983 and 1911 were the wettest and driest years, respectively, while 1921-1930 and 1981-1990 were the wettest and driest decades, respectively. Precipitation concentration index indicated that the NCHA had experienced 61% moderate rainfall and 39% high concentration rainfall. LRM showed that the change in the mean annual rainfall, early rainy season, and the main (or late) rainy season had occurred at the rate of -0.30 mm/year, -0.27 mm/year, and -0.23 mm/year, respectively. MK results showed that except for sub-basins 21 and 22 (which are positive), all other sub-basins have a negative trend signifying a decrease in trends of rainfalls. NSHT and PT suggested 1969 as the probable change point for the whole basin. The decrease in the amount of rainfall (after the change point) indicates a drier condition over the basin. Therefore, farmers and water resources personnel need to focus attention on the management of this vital resource by making the right choice of what and when to plant and managing the water crisis (drought and floods) which emanates from erratic rainfall.

1. Introduction

Rainfall and temperature are the most critical climatic variables relating to the impacts of climate change. More importantly, rainfall remains the principal factor in the choice of and change in crop types, and its intensity and frequency have

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been associated with extreme events (drought and flood) [18]. Various researches have shown that more significant spatial and temporal variations exist between different regions. Hence, the global-scale observations of historical climate are rendered non-viable for regional-scale planning of water resources or agricultural activities [50,57]. Therefore, regional-scale analysis of the historical data is fundamental. This will help to improve the certainty in the estimation about the future, which is a prerequisite for developing mitigation and adaptation plans against the adverse effects of climate change. This is particularly the case in Africa, which is a region characterized by extreme climatic variability including extreme weather events; the last 50 years (since 1969) have witnessed drastic reductions in average annual rainfall [43]. In comparison to previous years (1931 – 1960), a rainfall decrease of 29 – 49% was observed between 1968 and 1997 within the Sahel region [23,43].

The report of the Intergovernmental Panel on Climate Change asserted that while the rainfall amounts of some Africa countries is likely to decrease, there is a tendency that their rainfall variability will also increase [24]. The effect of this on the continent of Africa will be enormous due to its low adaptive capacity, high dependence on rain-fed agriculture, and high sensitivity of their socioeconomic system. In Nigeria, the impacts of climate change through change in rainfall amount and rainfall variability have been felt through droughts (of 1968 and 1973/74) and floods (of 1998, 1999, 2001, and 2005) [7]. While the droughts lead to the reduction of farm produce to between 12% and 14% of annual average and death of about 300,000 animals, the floods claimed several lives and properties [7].

Trend and mutation detection of rainfall time-series has gained popularity among researchers for their usefulness in tracking the extent and magnitude of climate change and variability [23]. Depending on the length and types (station or gridded) of the observed meteorological data available in different regions, trends of precipitation have been studied on different time scales (monthly, seasonal, yearly, decades, or century). The results of these studies have shown variations in both the direction (positive or negative) and magnitudes of the trend across the globe [8,39,58]. For instance, Longobardi and Villani [26] carried out a trend analysis of annual and seasonal rainfall time series in the Mediterranean area over 1919–1999. They observed that, aside from the summer period in which the trend was positive, the trend appears predominantly negative and the negative trend was significant for 97% of the total stations over the last 30 years. In a similar study, Tabari and Talaee [55] examined temporal variability of precipitation over Iran and noted a decreasing trend in annual precipitation at about 60% of the stations, with seven stations being significant at 95%, and the negative trends were most significant in the northwestern part of the country. Chen et al. [11] analyzed the annual and seasonal precipitation data for 49 stations in Liaoning province, China. They found that there was a decrease in precipitation over the 47-year period investigated, with annual, summer, autumn, spring, and winter precipitation decreasing by 96%, 92%, 84%, 63%, and 27%, respectively. An assessment of regional–level long–term (1901–2013) gridded rainfall variability over the Odisha State of India was done by Prabhakar et al. [49]. They found a mixed trend of positive and negative trends and detected a change point in the rainfall regime in 1945. They also noted that most of the districts showed positive trends before the change point, but showed a negative trend after it.

Several trend studies have also been reported across the continent of Africa and in Nigeria in particular. Maidment et al. [29] analyzed recent changes in precipitation over Africa and observed a mixed trend: a positive trend with an annual increase of up to 49 mm year^{-1} per decade, particularly at Central Africa and a negative trend having a decrease of below – 49 mm year^{-1} per decade in the month of March-May. Asfaw et al. [8] studied the variability and time series trend analysis of rainfall and temperature in Woleka sub-basin, north-central Ethiopia. Their results showed intra and inter-annual variability of rainfall and the annual, small, and main rainy seasons indicated a declining trend at a rate of 15.03, 1.93, and 13.12 mm per decade, respectively.

In Nigeria, Oguntunde et al. [39] examined the existence of a trend in rainfall over the 20th century and observed that about 90% of the entire nation showed decreasing trends and that change points occurred in rainfall regime in the agro-ecological zone between 1969 and 1971. They also noted a sharp difference between changes in rainfalls in 1931–1960 and 1961–1990 periods with annual rainfall reduction of 7% between the two periods. Further, Ogungbenro and Morakinyo [37] carry out change point analysis in rainfall pattern across the different climatic zones of Nigeria and found that there were common change points and transitions from dry to wet in all the zones between 1969 and 1972. In a more recent study, Ogunrinde et al. [38] assessed the climate change impact on rainfall and drought incidents across Nigeria. They observed an increasing trend for the standardized precipitation index SPI-12 series for all but one station. Their results also indicated that in the first 15 years of the 21st century, compared to the 20th century, Nigeria experienced more annual rainfall totals albeit with high variability within the rainy months of the year. The research of Oloruntade et al. [46] on rainfall trends between 1948 and 2008 in the Niger South Basin, Nigeria, showed that rainfall variability was generally low over the entire basin and the basin exhibited negative trends. Their study also showed that although the trend over 1948–1977 was negative, it was positive during 1978–2008, and that while the months of June, July, and August showed an insignificant positive trend, the trend of the remaining months was negative.

Based on the reports of the available studies on rainfall variability and trend analysis, particularly in Nigeria, little or no consideration has been given to sub-basins built from the hydrological response units (HRUs). Trend and variability studies of areas that are defined based on geographic and administrative function will likely lead to overgeneralization of results for areas under different HRUs and sub-basins. Moreover, the seasonality experienced in each locality is vital in seasonal rainfall studies. Still, available reviews have been adopting the four seasons (winter, summer, autumn, and spring) that are not typical of weather in Nigeria. Ogungbenro and Morakinyo [37] mentioned that early rainfall season in Nigeria consists of three months and Otache et al. [47] named April as the beginning of the rainy season in the Niger Central Hydrological

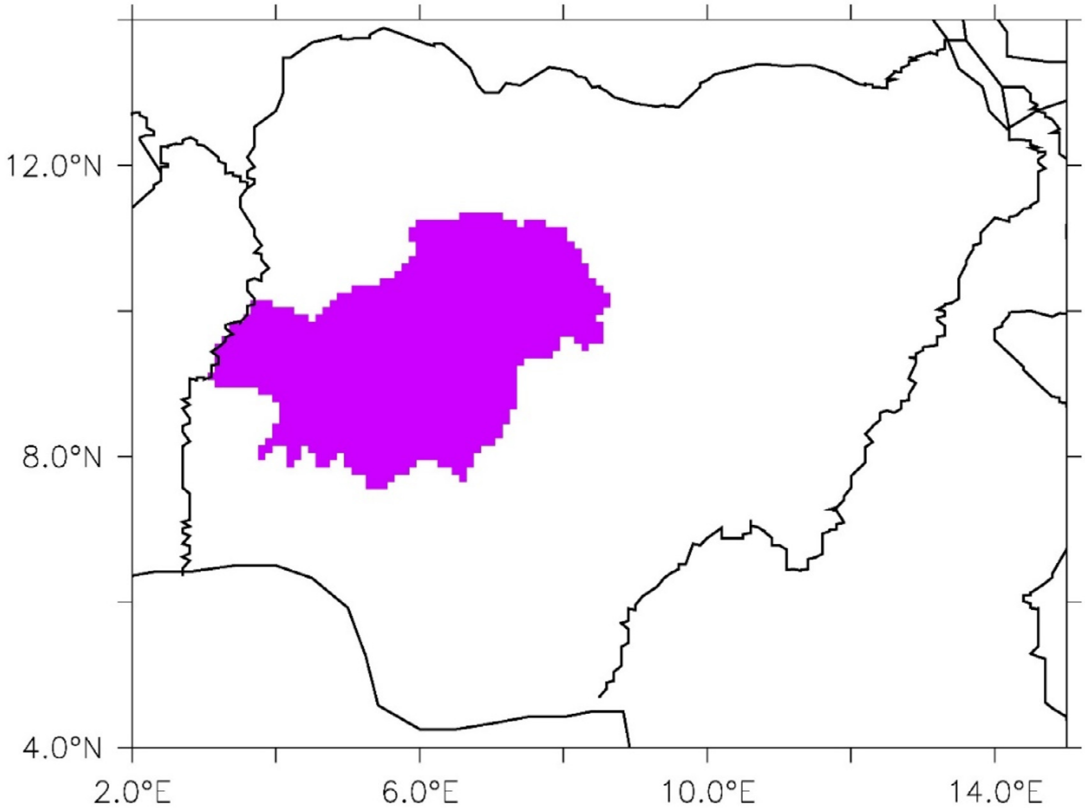


Fig. 1. Map of Nigeria showing the Niger Central Hydrological Area.

Area (NCHA). However, seasonal rainfall based on early and main rainy seasons has not been reported. The three seasons having early and main rainy seasons have nevertheless been reported elsewhere (e.g. [8]) in Africa. Thus, this study aims to assess the trend, mutation point, and change in rainfall pattern at sub-basin levels of the NCHA on annual and seasonal timescales.

2. Materials and methods

2.1. Study Area

The Niger River Basin (NRB) is a basin delineated by the unusual flow of the river Niger through ten countries. It is the second-largest in Africa covering an area of 2.27 million km^2 and is located between latitudes 5° N and 24° N and longitudes 12° W and 17° E [42]. Out of the active river basins, those located in Nigeria have 562,372 km^2 accounting for 44.2% of the total active basins [36,40]. The basin experiences high variability in rainfall that ranges from 250-750 mm/yr at the Sahelian zone to over 2,000 mm/yr close to the river mouth in the Guinean zone [6,42]. A vital portion of this basin in Nigeria will be considered for this study, and the portion is called the NCHA. It is one of eight hydrological areas in Nigeria and lies in the intermediate zone between the semi-arid climate in the north and sub-humid climate in the south; the climate is influenced by the seasonal movement of the Intertropical Convergence Zone resulting in wet and dry seasons [47]. The NCHA is located between Latitudes 7.5 ° N – 12° N, Longitudes 3.0 ° – 9.0 ° E and has an altitude ranging between 10 and 650 m (Fig. 1). The report of Japan International Cooperation Agency (JICA) mentioned that NCHA spreads over a 158,000 km^2 area, having a river and groundwater discharge of 208 mm/year and 52 mm/year, respectively (JICA, 2011) [25]. The area spans over the Tall Grass Savanna agro-ecological zone of Nigeria and very few parts of the Rain Forest. Additionally, Nigeria has about 60 large dams, with the most prominent three (Kanji, Jebba and Shiroro) having a total water storage of 34,800 MCM located in the area under study (JICA, 2011). The area is characterized significantly by the dry and wet seasons; nevertheless, the two seasons can be grouped into three (early, main, and dry seasons) to give a true reflection of the seasons experienced in the region. Rain starts in April, attaining its peak in September and ends in October, while the dry season lasts between November and March [47]. The dry season is characterized by low humidity and high temperatures (>35°C towards the northern part of the area) while the wet season is characterized by high humidity and low temperatures

Table 1
Geographical characteristics of the stations with available data length for Rainfall.

Station	Latitude (N)	Longitude (E)	Altitude (m)	Period
NCHA*	7.5-12^0	3-10°	9.6-650.20	1911-2015
Lokoja	7.47'	06^0 44'	62.50	1971-2015
Ilorin	8.29'	04^0 35'	307.40	1971-2015
Bida	9^0 06'	06^0 01'	144.30	1970-2014
FCT	9^0 15'	07^0 00'	343.10	1982-2014
Minna	9^0 37'	06^0 32'	256.40	1970-2014
Kainji	9^0 51'	04^0 36'	65.00	1987-2016
Shiroro	9^0 57'	6^0 50'	398.00	1990-2017
Kaduna	10.36'	07^0 27'	645.40	1971-2015
Zaria	11^0 06'	07^0 41'	110.90	1970-2014
Gusau	12^{0}10'	06^0 42'	451.00	1971-2015

*Data obtained from CRU 4.01 FCT is Federal Capital Territory.

(<30°C). The NCHA is a basin which has an inlet into it in Kainji and the outlet at Lokoja, which are important stations on Niger River Basin.

2.2. Details of data and methods

The observation data (station and gridded) used for rainfall variability and trend analysis were obtained from different sources. The station data collected from Kainji and Shiroro Hydroelectric power stations and the Nigerian Meteorological Agency (NIMET) consist of daily and monthly rainfall data. The Gauge stations and the available data length are presented in Table 1. The gauged stations are synoptic weather stations in Nigeria that are within the area of study. The gauged station for Gusau is outside the NCHA, the NCHA however extends to Gusau. The data cleanining was implemented to exclude years with missing data, and the remaining data were processed to ensure homogeneity and quality control. The quality control was done using double- mass curve analysis [28]. The area of study was delineated into 33 sub-basins using the Soil and Water Assessment Tool (SWAT), and each of the sub-basins was considered a data point. The SWAT takes into consideration spatial heterogeneity of the study area finding information from the Digital elevation model (Fig. 2) [53].

Gridded monthly rainfall data from the Climate Research Unit (CRU_TS 4.01) with 0.5 by 0.5 latitude and longitude resolution over the periods 1911 - 2015 was obtained and used for trend analysis. Conway and Mahe [12] and New et al. [34] gave detailed information on CRU data quality control and interpretation. The use of CRU data in Africa is becoming popular with hydrological scientists and engineers due to the problems of missing data, limitation in data lengths, and spatial coverage associated with station data. The use of CRU in Nigeria has been reported in several long-term trend studies [1,39]. Hughes and Slaughter [22] argued that there are regional differences in the success of using CRU datasets; however, Abiodun et al. [1] reported a good correlation of CRU data with data from Nigeria weather stations. While the CRU data was used for the temporal analysis of trend, the station data were used for the spatial analysis.

The NIMET daily data collected were converted to monthly data to determine the correlation with CRU monthly. The CRU data were added to generate seasonal and average annual data for each data point in the study area [62]. The mean values at the corresponding data points were considered to determine the rainfall across the entire study area [2,18]. In order to allow for a reasonably fair assessment of the seasonal trend and spatial analysis, the seasons were defined as “early rainy season” which extends from April to June, “main (or late) rainy” season which starts in July and ends in October, and “dry season” (November – March). This weather definition was based on the opinion (which was sought through a questionnaire) of water resource experts and local farmers.

2.3. Data analysis techniques

Different statistical techniques have been adopted for the analysis of rainfall variability and trend in this study. For the preliminary and variability analysis, the mean, standard deviation, skewness, kurtosis, coefficient of variation (CV), rainfall variability Index (δ_i), Precipitation Concentration Index (PCI), and the linear regression model were all employed. Mann Kendall (MK) and Sen Slope estimator were applied to determine the trend direction and magnitude [39]. To assess the homogeneity of the time-series, Standard Normal Homogeneity Test (NSHT) and Pettitt’s test were both applied at 5% significant level. The tests were used to determine the year in which abrupt change occurs. The rainfall deviation map was then created to explore spatial distribution and deviation. Data analysis was done using excel spreadsheet, XLSTAT, MAKESENS, ArcGIS 10.3.1, and ArcSWAT. The details of the statistical techniques are given in the sections below

2.3.1. Measure of central tendency

The mean was computed as the sum of all values divided by the sample size. This was done to understand the central tendency of the time series [31]. For this, the arithmetic means were estimated for monthly, seasonal, and annual time-series.

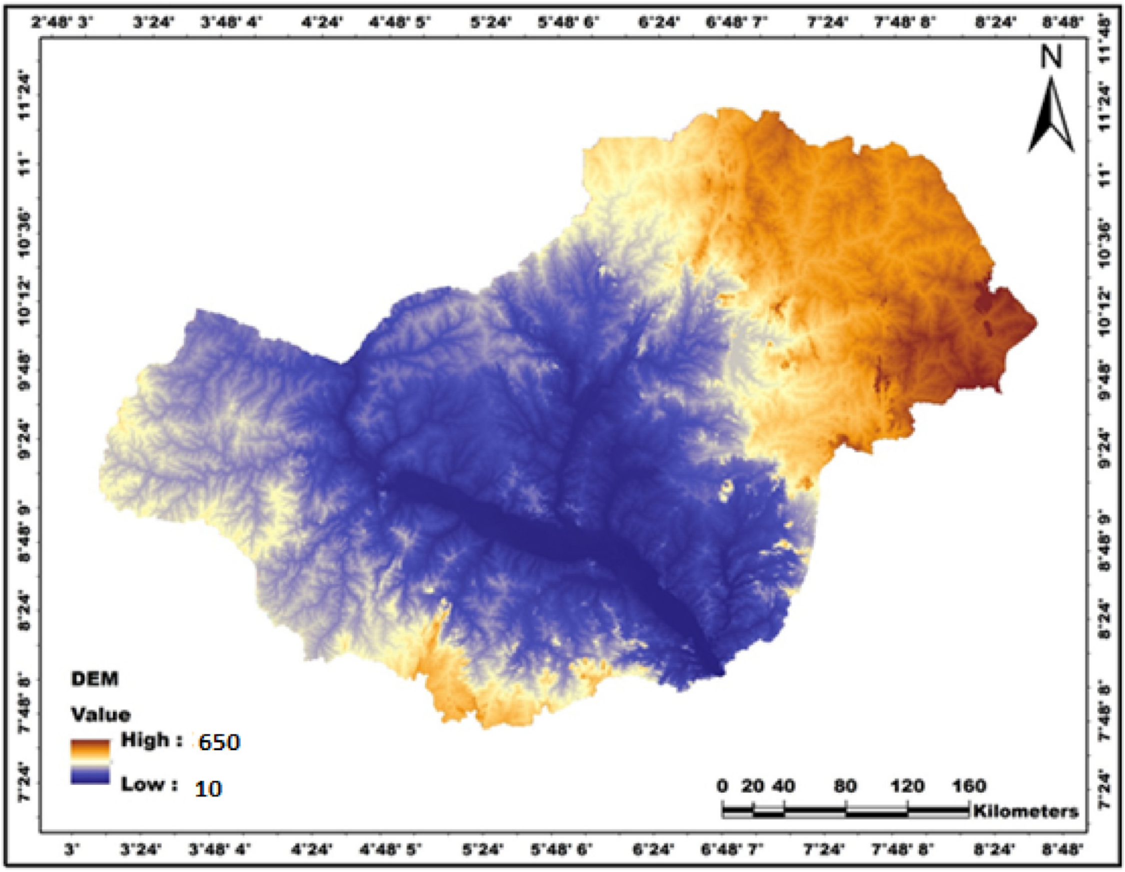


Fig. 2. Digital elevation model (DEM) of the study area.

2.3.2. Variability Analysis

Kurtosis and skewness were employed to describe the distribution features of the rainfall in the NCHA. These two statistics were used by Cao et al. [10] for precipitation study in China. Skewness is a dimensionless value that measures the asymmetry in a distribution. It essentially measures the relative size of the two tails. The coefficient of skewness (Cs) is a common measure of skewness; a right-skewed distribution has a positive Cs while a left-skewed distribution has a negative Cs [17]. Hydro-meteorological data are usually skewed, and highly skewed data restrict the ability to use hypothesis tests that assume the data have a normal distribution. Hence, it is important to evaluate the skewness of the data. The formula for computing the skewness is given below:

$$\text{skewness} = \frac{n}{(n-1)(n-2)} \sum \frac{(X_i - X_{mn})^3}{s^3} \tag{1}$$

where n is the sample size, X_i is the i^{th} X value, Xmn is the average, and s is the sample standard deviation.

Kurtosis is also a dimensionless value defined as a measure of the combined weight of the tails relative to the rest of the distribution. Thus, if a dataset has a positive kurtosis, it has more weight in the tails than the normal distribution, but if it has a negative kurtosis, it has less weight in the tails than the normal distribution.

$$kurtosis = \left\{ \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum \frac{(X_i - X_{mn})^4}{s^4} \right\} - \frac{3(n-1)^2}{(n-2)(n-3)} \tag{2}$$

The definition of the parameters is the same as in skewness. A time-series is said to be normally distributed if it has values of the coefficients of skewness and kurtosis of 0 and 3, respectively.

The CV was computed (as in equation 3) to evaluate the variability of the rainfall. The degree of variability is a function of the indicator, which implies that the higher the value of CV, the higher the variability and vice versa [8]. The value of CV obtained is used to categorize the degree of variability of rainfall events as less (CV < 20), moderate (20 < CV < 30), and high (CV > 30):

$$CV = \frac{\sigma}{\mu}\ x\ 100 \tag{3}$$

where CV is the coefficient of variation, σ is standard deviation, and μ is the mean rainfall.

Moreover, rainfall variability index was computed. The index assists in examining the nature of the trend by separating the wet and dry years from the available rainfall time series [39]. It is usually computed as the standardized precipitation anomaly using equation 4 below:

$$\delta_i = (P_i - \mu)/\sigma \tag{4}$$

where δ_i is rainfall variability index for the year i, Pi is annual rainfall for the year i, μ is the mean annual rainfall, and σ is the standard deviation. It is used to assess the severity and frequency of drought [19,39]. The severity classes are extreme drought ($\delta_i < -1.65$), severe drought ($-1.28 > \delta_i > -1.65$), moderate drought ($-0.84 > \delta_i > -1.28$), and no drought ($\delta_i > -0.84$) [3].

Furthermore, PCI was computed to examine the variability of rainfall for the year 1911 – 2015 using the Oliver [44] modified equation by De Luis et al. [14]:

$$PCI_I = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100 \tag{5}$$

where P_i is the amount of the ith month.

PCI values less than 10 signify low precipitation concentration, values between 11 and 15 indicate moderate concentration, values between 16 and 20 signify high concentration, and values of 21 and above indicate very high concentration (Oliver; 1980).

2.3.3. Trend Analysis

Linear regression is one of the simplest and vital methods for analyzing the trend of data in time series. It has been used in hydrological studies as it allows for estimation of the slope of a specific trend under study [21,38]. The slope defines the trend, whether positive or negative, and when the slope assumes a positive value, it shows an increasing trend, while a negative value signifies a decreasing trend.

The equation of the linear regression shown hereafter was used to estimate the temporal changes in rainfall

$$y = a + bx + \varepsilon \tag{6}$$

where y is the dependent variable (which is rainfall in this study), a is a constant, b is the regression coefficients, x is the independent variable (the years), and ε is the error term.

Trend analysis was also carried out using the Mann-Kendall (MK) trend test. Mk is a non-parametric trend test that has been widely used to detect trends of rainfall time series [16,20,56,58,61]. In this study, the MK test has been used to detect the presence of monotonic (increasing or decreasing) trends and to determine whether or not the trend is significant. The test was carried out on monthly, seasonal, and annual bases. Before applying the Mann-Kendall MK test, pre-whitening of the original time series was done. This is to eliminate the effect of significant positive serial correlation.

The MK test statistic 'S' is calculated based on Mann [30] and Kendall [27] using the formula below

$$S = \sum_{i=1}^{n-1} \sum_{j=i-1}^{n} sign\ (xj - xi) \tag{7}$$

where xi and xj are the sequential data values, n is the data set record length, and

$$Sign = \begin{cases} +1 & \theta > 0 \\ 0 & if\ \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{8}$$

indicates positive differences, no differences, and negative differences, respectively, and S is computed as the sum of the integers. The expected value of S equals zero (E[S] = 0) for series without trend and the variance is computed as below:

$$\sigma^2(s) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \tag{9}$$

where q is the number of tied groups and t_p is the number of data values in $\boldsymbol{p^{th}}$ group. The test statistics Z is then given as:

$$Z = \begin{cases} \frac{s-1}{\sqrt{\sigma^2(s)}} & S > 0 \\ 0 & if\ S = 0 \\ \frac{s+1}{\sqrt{\sigma^2(s)}} & S < 0 \end{cases} \tag{10}$$

The Z statistic is used to test the null hypothesis, H_0, that the data are randomly ordered in time, with the alternate hypothesis, H_1, indicating an increasing or decreasing monotonic trend.

2.3.4. Change Point Detection

Pettitt's test and the Standard Normal Homogeneity Test (NSHT) statistics were both adopted for detecting the change point in rainfall data. The two methods have been reported in several studies (e.g. [57]). The change point test, developed by Pettitt [48], is a nonparametric test which is useful for assessing the existence of abrupt changes in climatic records [54]. The statistics used for Pettitt's test have been reported in earlier studies [15,57]. It is computed using the following steps:

Uk statistic was calculated using the following formula

$$U_k = 2\sum_{i=0}^{n} r_i - k(n+1) \tag{11}$$
$$K = 1, 2 \cdots n$$

where *mi* is the rank of the *i*th observation when the values *x*1, *x*2,... ., *xn* in the series are arranged in ascending order, and *k* takes values from 1, 2,... ., *n*.

Then, the statistical change point test (SCP) was determined as:

$$K = {}^{max}_{1\le k\le n}|U_k| \tag{12}$$

When U_k attains the maximum value of *K* in a series, a change point will occur in the series. The critical value is obtained by:

$$K_\alpha = \left[-ln\alpha\left(n^3+n^2\right)/6\right]^{1/2} \tag{13}$$

Standard Normal Homogeneity Test (NSHT) is a widely used homogeneity test for change detection [51]. SNHT is more sensitive to the breaks at the beginning and the end of the time series [13]. Alexandersson and Moberg [5] proposed a statistic T(k) to compare the mean of the first k years of the record with that of the last (n - k) years:

$$T(K) = k\hat{Z}_1^2 + \ (n-k)\hat{Z}_2^2 \tag{14}$$
$$k = 1, 2 \cdots n$$

$$\hat{Z}_1 = \frac{1}{n}\frac{\sum_{i=1}^{k}\left(Y_i - \bar{Y}\right)}{s} \tag{15}$$

$$\hat{Z}_2 = \frac{1}{n-k}\frac{\sum_{i=k+1}^{k}\left(Y_i - \bar{Y}\right)}{s} \tag{16}$$

$$S = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right) \tag{17}$$

n is the data set length, Yi is the i^{th} element of the data set, and $\bar{Y}$ is the mean value of the data set. If a break is located at the year K, then T(k) reaches a maximum near the year k = K. The test statistic T_0 is defined as

$$T_0 = {}^{max}_{1\le k\le \mathrm{n}}\ T(K) \tag{18}$$

The p-value has been computed using 10000 Monte Carlo simulations at a 99% confidence interval for the two statistics.

2.3.5. Spatial Analysis of rainfall series

In order to explore the spatial distribution of trends on an annual and seasonal basis, rainfall deviation was interpolated using ArcGIS 10.3.1 based on rainfall deviation of each sub-basin in reference to the entire basin. The computation of rainfall deviation was done using the equation below (equation 19), and the interpolation was done with ordinary kriging (exponential semivariogram) method. Ordinary kriging of a single variable is claimed to be the most common and robust geostatistical method used for the prediction of the variables at an unknown location [59]. Since rainfall is the only variable, the ordinary kriging method was adopted, and the method has been used for rainfall mapping in previous studies (e.g. [33]). The analysis was done for the entire time-series (1911-2015), pre-change point period (1911-1969), and post-change point period (1970-2015) as reported in Duhan and Pandey [18].

$$D = (X - \ \mu)\ X\ \frac{100}{\mu} \tag{19}$$

Where D is the rainfall deviation, x is annual rainfall mean, and μ is the long-term mean value. The result of the computation was used for interpolation using ordinary kriging (exponential semivariogram) method.

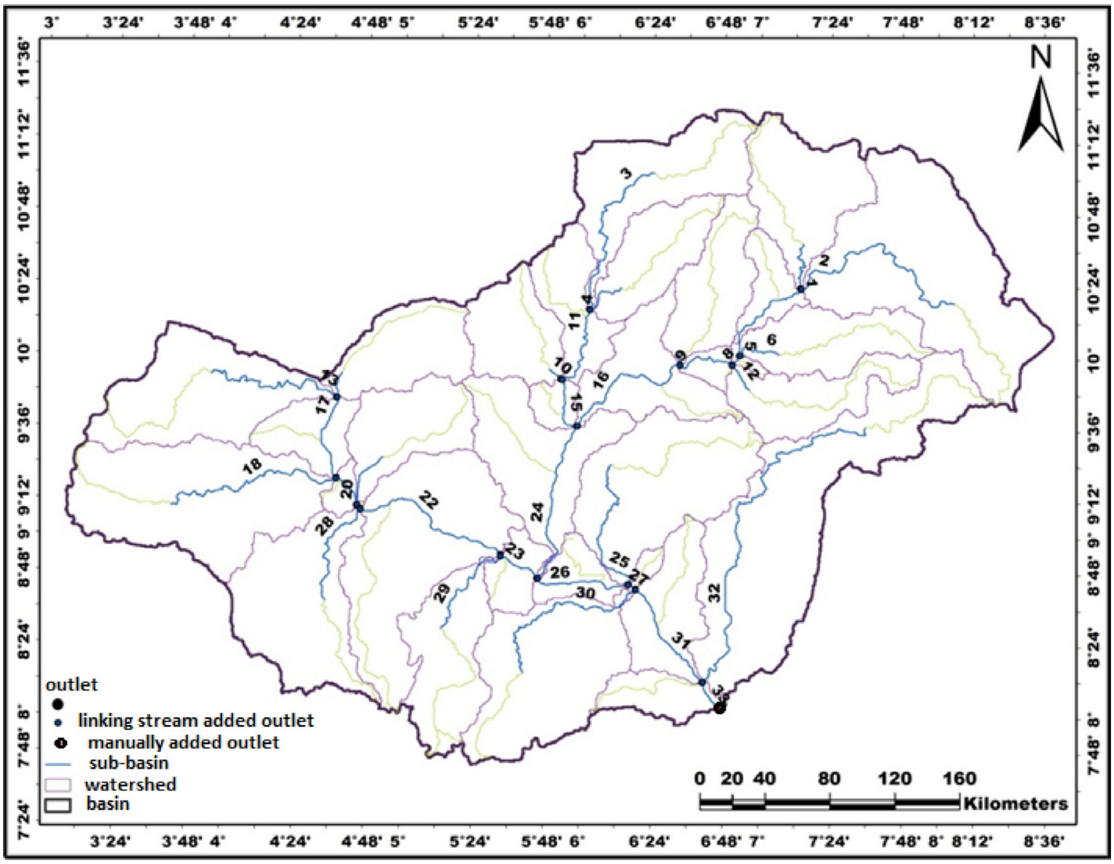


Fig. 3. NCHA and its sub-basins as delineated by SWAT.

3. Results and Discussion

3.1. Descriptive statistics and variability analysis

In the present study, the spatial and temporal variability of rainfall has been investigated at the NCHA (Fig 3), over 105 years (1911–2015) on monthly, seasonal, and annual bases. The result of the correlation analysis showed that CRU data was strongly correlated (0.68-0.82) with available station data across the basin. The mean value of all the station data for 1990-2014 was found to have a better correlation (0.86) with CRU data. The results of the statistical analyses for the 105-year time series of rainfall (1911-2015) are presented in Table 2. The mean annual rainfall was 1194.30 $mmyr^{-1}$ having a standard deviation of 117.87 $mmyr^{-1}$. The minimum annual rainfall experienced within the basin was 910.61 mm while the maximum was 1452.49 mm. The coefficients of kurtosis and skewness were -0.45 and -0.04, respectively, which suggest that the data is negatively skewed and not normally distributed [2]. The coefficient of variation shows that the temporal variability of annual rainfall in the basin was 9.87%. Mk-test shows that it has a declining annual trend that is significant ($P < 0.05$).

The results of the coefficient of skewness and kurtosis for the seasonal scale show that both the early rainy season (April -June) which contributed 32.11% of the total annual rainfall and the late rainy season (July- October) which has a higher seasonal contribution (63.99%) are not normally distributed. Most of the rainfall events was experienced in the month of September followed by August, both of which contribute 60.4% and 38.6% to the total main (JASO) and annual rainfall, respectively. The main (or late) rainy season has a higher seasonal contribution (63.99%). The inter-annual variability was higher in the early rainy season having the CV of 14.51% than in late rainy season which has a CV of 11.73%. General observation shows that except for the dry season which can be classified as having a high degree of variability (CV >30), the degree of variability of annual and seasonal rainfall events are considered less (i.e. CV <20).

For instance, of the main rainy season, the month of September has the highest contribution (30.85%), which was closely followed by August (29.44%). The dry season, having five months (November, December, January, February, and March), contributed a comparatively insignificant percentage (3.9%) to the total annual rainfall. The highest value of the coefficient of variability (43.03%) was noted for the dry season followed by early rainy season (14.51). The two rainy seasons have

Table 2
Descriptive Statistics of monthly (mm/month), seasonal (mm/month), and annual (mm/year) rainfall over the NCHA (1911-2015).

Months	Min	Max	Mean	SD	Ck	Cs	CV%	Z-value	Slope
Jan	0	14.25	1.95	2.53	5.82	2.15	130.2	−0.18	0.001
Feb	0	25.41	7.05	6.35	0.21	0.97	90.14	−1.03	−0.016
Mar	1.4	72.8	28.56	16.09	−0.03	0.6	56.34	−3.76***	−0.220
Apr	7.33	188.2	73.12	30.8	0.94	0.67	42.12	−1.51	−0.167
May	66.83	228.27	138.77	30.9	0.48	0.32	22.27	−1.58	−0.176
Jun	101.49	228.03	171.57	25.97	−0.55	−0.21	15.13	−1.24	−0.133
Jul	79.62	325.91	201.76	41.87	0.69	−0.04	20.75	0	0.001
Aug	120.94	387.74	225.48	49.3	0.48	0.25	21.86	0.71	0.118
Sep	141.74	316.78	235.84	33.43	−0.08	−0.21	14.17	−2.22*	−0.270
Oct	28.04	211.06	101.17	35.6	0.20	0.56	35.19	−0.05	−0.005
Nov	0.15	24.9	7.38	5.89	−0.14	0.83	79.81	−3.66***	−0.067
Dec	0	8.82	1.45	1.9	4.71	2.21	131.67	−1.25	−0.003
AMJ	267.59	530.26	383.46	55.63	0.01	0.22	14.51	−2.74**	−0.477
JASO	543.39	964.71	764.25	89.66	−0.36	0.01	11.73	−0.26	−0.098
NDJFM	9.63	92.03	46.58	20.04	−0.44	0.30	43.03	−4.24***	−0.322
Annual	910.61	1452.49	1194.30	117.87	−0.45	−0.04	9.87	−2.00*	−0.879

*** trend at 0.001 level of significance
** trend at 0.01 level of significance
* trend at 0.05 level of significance
Ck is coefficient of kurtosis
Cs is coefficient of skewness

Table 3
Descriptive Statistics of annual and seasonal rainfall at some gauged stations.

	Annual			AMJ			JASO		
Statistics	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)
Lokoja	1228.35	238.8	19.44	434.38	106.79	24.58	749.38	168.97	22.54
Ilorin	1221.58	284.35	23.27	443.36	125.67	28.35	701.42	198.19	28.26
Bida	1158.86	184.63	15.93	380.69	104.43	27.43	757.80	168.44	22.23
FCT	1451.28	184.32	12.70	415.69	103.61	24.93	995.10	144.92	14.56
Minna	1208.18	159.13	13.70	354.09	105.15	29.69	840.71	137.53	16.36
Kainji	1039.59	154.91	14.90	330.77	84.18	25.45	688.26	104.1	15.13
Shiroro	1320.10	183.43	13.90	374.18	93.97	25.11	938.19	137.44	14.65
Kaduna	1213.57	161.46	13.37	336.96	76.8	22.79	861.11	133.81	15.54
Zaria	1020.55	151.77	14.87	282.39	94.97	33.63	732.79	109.76	14.98
Gusau	892.23	204.92	22.97	212.55	63.13	29.7	677.56	175.67	25.92

SD: standard deviation; CV: coefficient of variation.

declining trends. However, while the early rainy season was significant ($P < 0.01$), the late rainy season was not significant. The results suggest that there is more inter-annual variability in the early rainy season than in the late.

On the monthly timescale, the rainfall varied from 14.17% to 131.67%, while the highest was in December (131.67%,) followed by January (130.2%); the least was in September (14.17%). This result is in agreement with the submission of Oloruntade et al. [45] who identified December to February as the months with the highest variability in Onitsha, Nigeria. All the months except July and August had a decreasing trend at a varying level of significance. The slope showed the same pattern as the Z-value (MK-test).

The results generally show that the rainfall varied more on monthly and seasonal timescales than inter-annually over the study area. This has implications both on rain-fed agriculture and the freshwater system as not only will the produce from farms be affected but also the quantity and quality of freshwater will be compromised [45,60]. Hence, there is a need for better water resources management strategies.

Spatial distributions of annual, early, and main rainy seasons are presented in Table 3. The annual rainfall ranged from 892 mmyr−1 in Gusau to 1451 mmyr−1 in Federal Capital Territory. The rainfall in the early rainy season (AMJ) ranged from 212 $mmyr^{-1}$ in Gusau to 443.36 $mmyr^{-1}$ in Ilorin, and in the main rainy season, it ranged from 677.56 $mmyr^{-1}$ in Gusau to 995.10 mmyr−1 in Federal Capital Territory. The highest annual and seasonal rainfalls were experienced in Federal Capital Territory, and Ilorin, Gausau, recorded the least. This shows that rainfall decreased with increasing latitude. This observation is in agreement with the findings in earlier studies (e.g. [4,35,41]). On the other hand, the spatial pattern of the coefficient of variation (CV) showed that the variability of the rainfall increases with increase in latitude as also indicated in earlier studies of Ogunrinde et al. [38] and Oguntunde et al. [39]. For instance, Gusau which is the northernmost part of the area under study consistently had high CV on annual (22.97%) and seasonal (29.70% for AMJ and 25.9219.44 for JASO) timescales. However, Lokoja and Ilorin have annual CV values of 19.44% and 23.27%, respectively. The two locations are on the least latitude, but both have a comparatively high amount of rainfall. This suggests that latitude is not the only factor responsible

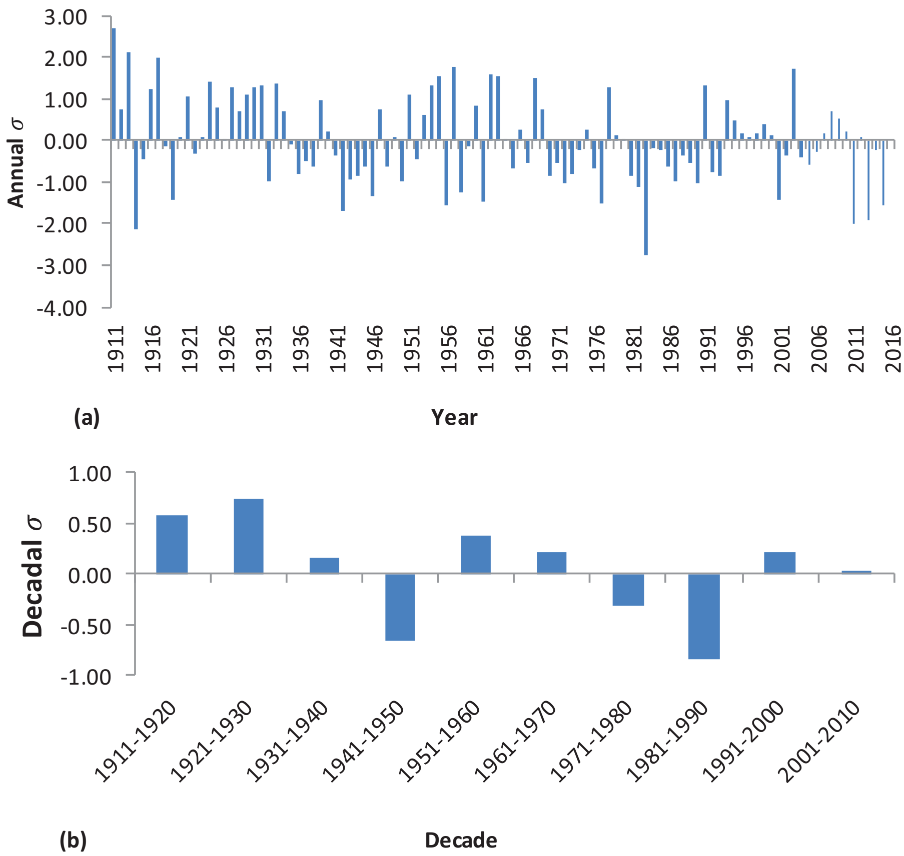


Fig. 4. Annual and decadal rainfall variability indices for the NCHA.

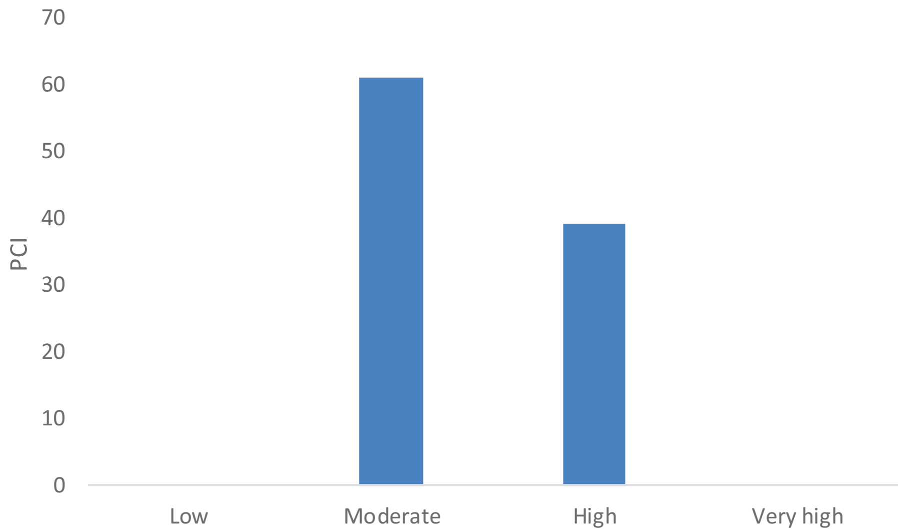


Fig. 5. Precipitation concentration Index (PCI) of NCB (1911 – 2015).

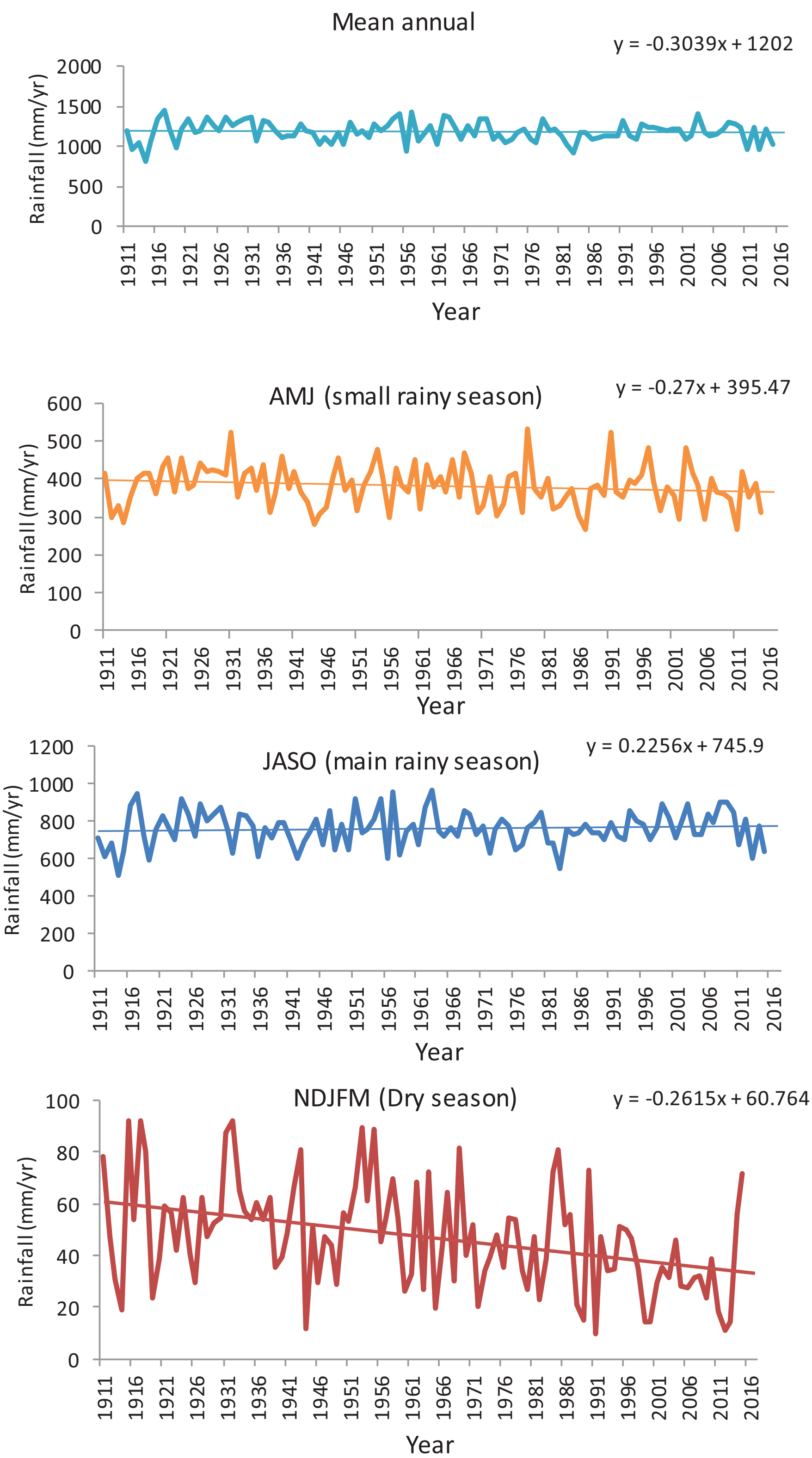


Fig. 6. Annual and Seasonal rainfall pattern over the NCHA (1911–2015).

Table 4
Trend Analysis and Mutation Point (1911-2015).

Sub-basin	Latitude	Longitude	Test Z	Q	Pettit's test	SNHT test
1	10.94	7.24	−3.52***	−1.577	**1969**	1957
2	10.49	7.95	−3.35***	−1.463	**1969**	1931
3	11.00	6.42	−4.39***	−1.94	**1969**	**1969**
4	10.58	6.40	−3.70	−1.585	**1969**	**1969**
5	10.41	7.04	−1.48	−0.737	**1969**	1931
6	10.11	7.40	−2.71**	−1.275	**1969**	1931
7	10.41	6.74	−0.67	−0.356	**1969**	1931
8	9.98	6.93	−2.77**	−1.308	1969	1931
9	9.96	6.72	−2.77**	−1.308	1968	1931
10	10.14	5.62	−3.12**	−1.39	**1969**	1931
11	10.31	5.95	−2.81**	−1.317	**1969**	1931
12	9.80	7.30	−2.65**	−1.297	**1934**	1931
13	9.78	3.86	−1.79+	−1.046	**1969**	1931
14	10.04	5.02	−3.12**	−1.39	**1969**	1931
15	9.74	5.85	−2.25*	−1.117	1934	1934
16	9.91	6.38	−2.59**	−1.303	1931	1934
17	9.57	4.49	−2.00*	−1.116	**1969**	**1969**
18	9.20	3.84	−1.79+	−1.046	1968	1917
19	9.24	4.67	−1.54	−0.835	**1969**	1934
20	9.61	5.03	−2.47*	−1.201	1944	1934
21	9.17	4.77	0.56	0.357	1969	1934
22	8.90	5.09	0.31	0.214	1987	2013
23	8.80	5.64	−1.15	−0.64	1934	1934
24	9.45	5.75	−1.96*	−0.995	1934	1934
25	9.30	6.45	−2.06	−1.1	1934	1934
26	8.79	5.98	−1.15	−0.64	1931	1934
27	8.84	6.38	−2.06*	−1.097	**1934**	**1934**
28	8.61	4.44	−0.67	−0.356	1934	1931
29	8.33	5.27	−0.19	−0.114	1931	1931
30	8.25	5.81	−0.44	−0.285	1934	1931
31	8.62	6.50	−0.49	−0.291	1934	1934
32	9.11	7.25	−2.62**	−1.219	**1934**	1931
33	8.16	6.35	−0.94	−0.521	1934	1931

*** trend at 0.001 level of significance
** trend at 0.01 level of significance
* trend at 0.05 level of significance
+ the trend at 0.1 level of significance
bold years depicts Ha (i.e there is a date at which there is a change in the data)

for the degree of variability in rainfall. This is in line with the claim of Nnaji et al. [35] and Ayanlade et al. [9] that attributed rainfall variability to the variation in the amount of rainfall recorded across Nigeria.

3.2. Rainfall variability index

The annual and decadal rainfall variability indices for the NCHA are shown in Fig. 4 (a and b).

The annual timescale of the indices shows that the series is characterized by a random succession of different drought severity level. Five years (1914, 1942, 1983, 2011 and 2013) recorded extreme drought with 1983 been the driest year. Severe droughts were experienced in seven years (1919, 1946, 1956, 1961, 1977, 2001, and 2015), moderate drought occurred in nine years (1932, 1943-44, 1950, 1958, 1972, 1982, 1987, and 1990), and the remaining years were devoid of drought. Among the years with no drought, the wettest year was 1911. On a decadal time-scale, no drought was experienced; however, while, 1981-1990 was the driest (-0.83), the wettest decade was 1921-1930 (0.74). These results are in agreement with the finding of Oguntunde et al. [39] and Ogunrinde et al. [38] whose work extends over the region that housed the NCHA.

3.3. Precipitation Concentration Index

The result of the precipitation concentration index is presented in Fig. 5. The result shows that the rainfall over the entire basin falls under two classes of moderate and high concentration. The larger percentage (61%) is moderate while the remaining percentage (39%) falls into the class of high concentration.

The rate of change in trend is shown on a linear regression model (Fig 6.) The slope of the regression line defines the rate of change in the trend of the time series. Hence, the mean annual rainfall, early rainy season, late rainy season, and dry season have a rate of change of -0.304 mm/year, -0.27 mm/year, 0.226 mm/year, and -0.262 mm/year, respectively. The slope shows that except for the major rainy season (which shows a positive trend), declining trends had been witnessed over the NCHA on different timescales at a varying level of magnitude. This implies a decline in rainfall over the study

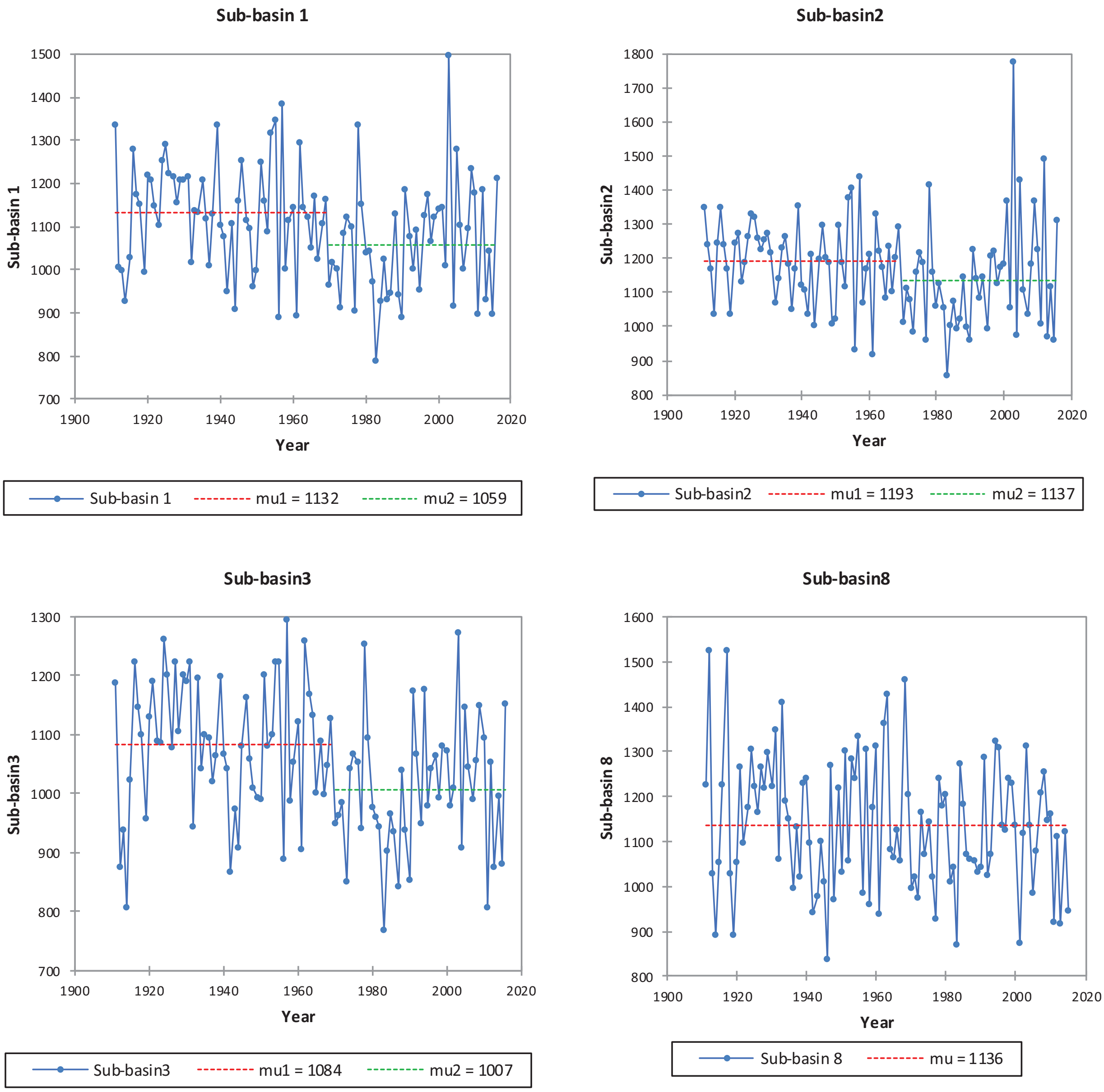


Fig. 7. Change year in annual mean rainfall series in sub-basins 1-3 and 8 mu1 and mu2 denote the mean rainfall before and after the change point.

area on an annual basis and a probable drying condition causing a reduction in the amount of water available for rain-fed agricultural, hydro-power generation, and municipal water supplies. Muhire et al. [32] opined that the consequence of such reduction would be felt in the agricultural sector through a decrease in farm produce. Likewise, the decreasing trend in the early rainy season (AMJ) suggests a probable delay in onset of rainfall in the study area. This is in line with the submission of Okpara et al. [43] who attributed drought witnessed in Nigeria to late starts of the rainy season and drastic reductions in the length of the rainy season and subsequently the length of the growing season. Also, [45] attributed late resumption of farming activities in a region in Nigeria to the late onset of rainfall.

There has, however, been an increase in the main rainy season (JASO), leading to more surface water availability and probably also resulting in the flood witnessed recently. A similar claim had been reported by Oloruntade et al. [46] who submitted that increase in summer rainfall exacerbates flooding in a region in Nigeria. The negative trend in the dry season (NDJFM) suggests that the season is getting drier and water is getting scarcer. This could be a result of early cessation of rain leading to a lesser amount of rainfall experienced in the season. The reduction is most pronounced on an annual timescale, followed by the early rainy season, and several studies have reported such reduction in the region (e. g [39,52]).

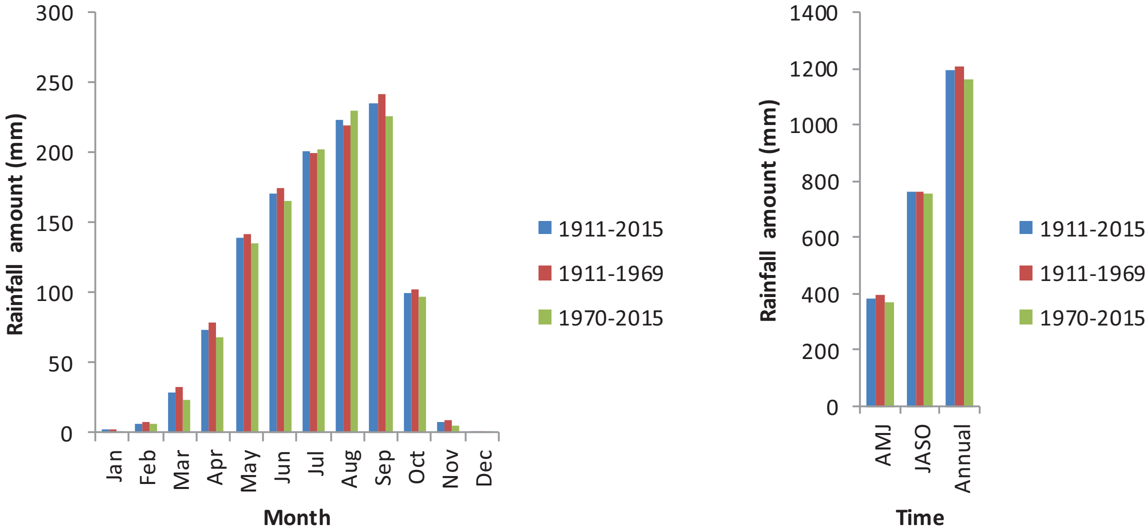


Fig. 8. Comparison of the mean monthly, seasonal, and annual rainfall over the NCHA.

3.4. Trend Analysis and change point Detection at Sub-basin levels

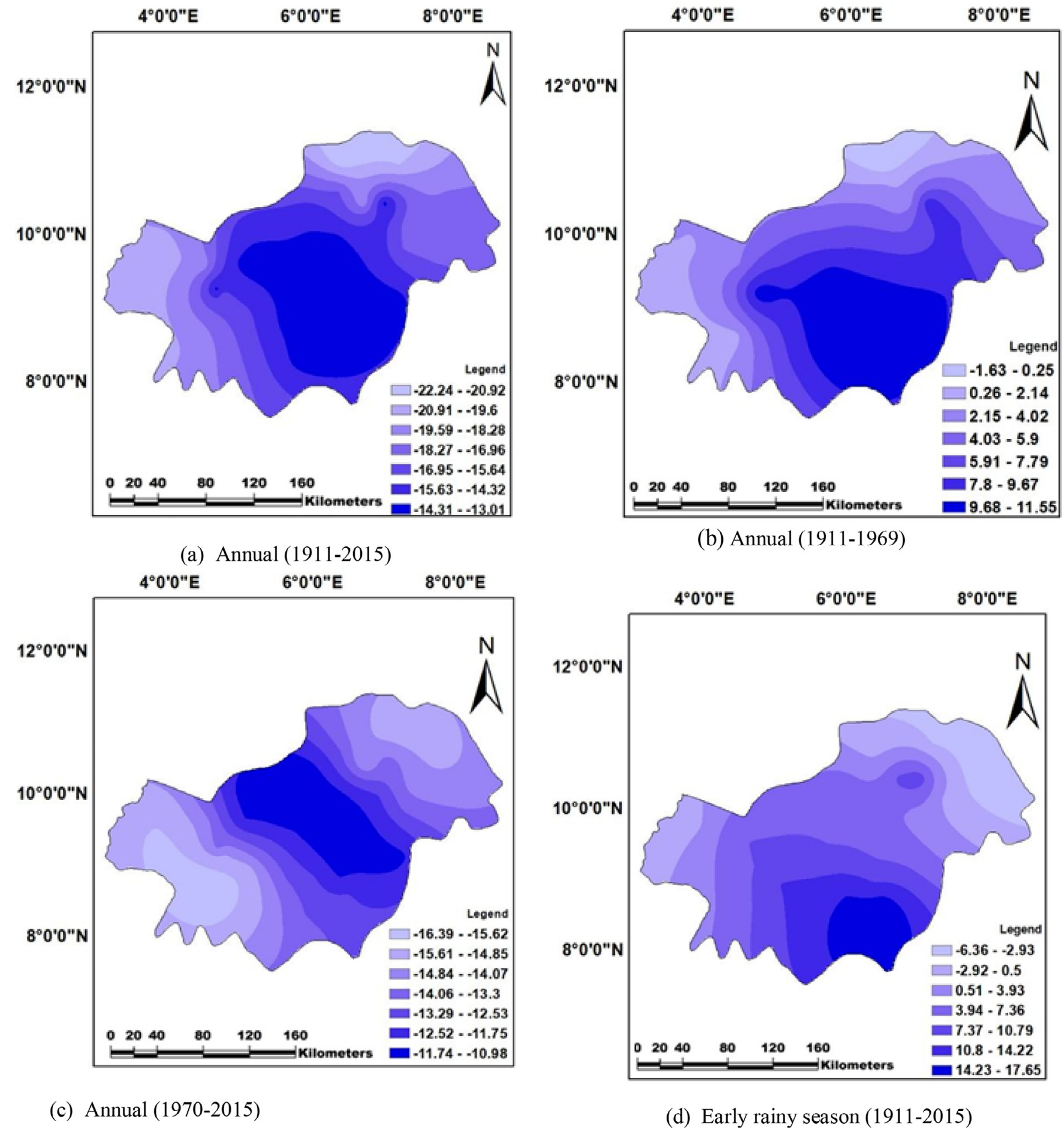
The results of monotonic trends, slope estimates, and change points detection in annual rainfall are presented in Table 4. The results show that significant changes have occurred at most of the sub-basin levels. The Z-statistic varied spatially from -4.39 to +0.56, while the slope varied across the sub-basin through -1.94 and 0.357. Only two (sub-basin 21 and 22) out of 33 sub-basins show a positive trend. Sub-basins 1, 2, and 3 recorded a change that is significant at 0.1% (i.e. $p < 0.001$). Nine (9) sub-basins showed a change that is significant at 1%, and five (5) showed a significant change at 5%. Only one (1) sub-basin experienced a change that is significant at 10%, while the changes in the remaining sub-basins are not significant.

The change point analysis in annual rainfall at each of the 33 sub-basins, which was computed using Pettitt's test and SNHT test, was also presented on the same table. Pettitt's test and SNHT test for homogeneity show that 13 and 3 sub-basins have heterogeneous annual rainfall series around the year 1969, respectively. This suggests a significant change in the mean before and after the year 1969. Though the year 1934 was also detected as a change point in about 13 sub-basins, only two are heterogeneous. The existence of two different heterogeneous change points suggests the uniqueness of each of the sub-basins as the delineation is based on the topography of each sub-basin. Taxak et al. [57] opined that variation in change year could be attributed to change in elevation.

The results for the whole basin and some of the sub-basins show that the year 1969 is likely to be the change year, which is in agreement with the earlier findings of Oguntunde et al. [39] and Ogungbenro and Morakinyo [37] wherein they opined that the change point in the region that housed the study area occurred around 1969. However, some of the sub-basins experienced a change point before the year, and this indicates that generalizing a change point for a large area or areas under different hydrological response units and sub-basins is error-prone. Fig. 7 shows the change in the mean value of some of the sub-basins with heterogeneous series as depicted by Pettitt's test.

3.5. Distribution of rainfall during pre- and post-change point period

The rainfall distribution pattern over the basin in the three time-series (1911-2015, 1911-1969, and 1970-2015) considered shows that April is consistent with adequate rainfall for the start of farming activities (Fig. 8). Similar findings have been reported by Ogungbenro and Morakinyo [37]. The mean rainfall amounts of 73.6 mm, 78.15 mm, and 67.78 mm recorded in April for the respective period of 1911-2015, 1911-1969, and 1970-2015 show a decline in rainfall amount after the change point. The highest mean was in the years 1911 to 1969, followed by the years 1911 to 2015. The least value was after the change point (1970-2015). This suggests a comparatively dry condition over the area and, if the trend continues, the month of April may no longer be appropriate for the start of farming activities for most of the sub-basins. The trend was consistent for all the months except July and August in which the post-change point period received the highest rainfall of 202 mm and 229 mm, respectively. This high rainfall could be responsible for floods witnessed in recent times in some of the areas within the basin. This finding is similar to the research by Oloruntade et al. [45] who reported a decreasing trend for all the months except for June to August and attributed positive trends in the two months to the flood witnessed in Onitsha, Nigeria. The percentage decrease in the amount of rain (after the change point) in early and late rainy seasons are 3.81% and 1.18%, respectively, while annually is 2.70%. This implies a drier seasonal and annual condition of rainfall. The change in



(a) Annual (1911-2015)

(b) Annual (1911-1969)

(c) Annual (1970-2015)

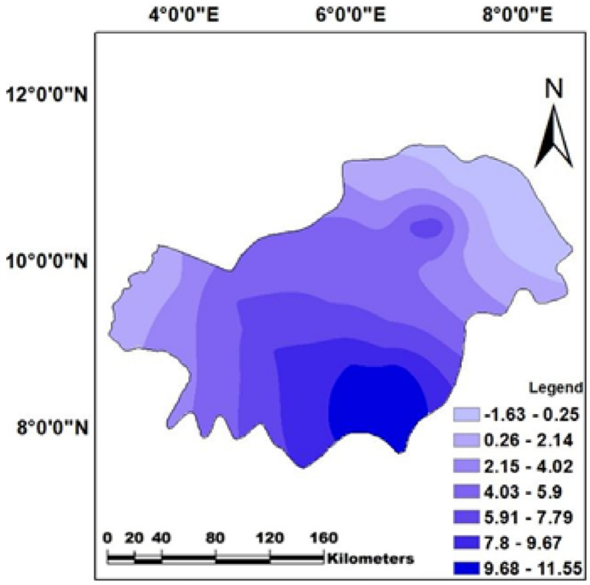
(d) Early rainy season (1911-2015)

Fig. 9. (a-i): Spatial patterns of Rainfall in annual and seasonal precipitations from 1911 to 2015, 1911 to 1969, and 1970 to 2015.

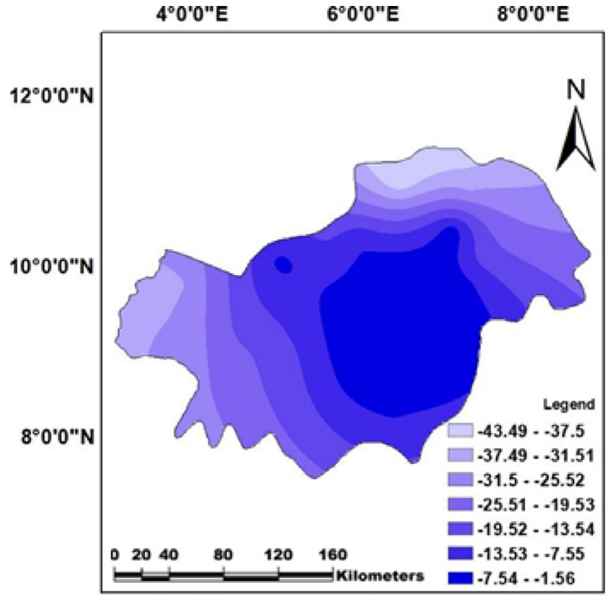
rainfall distribution after the change points has been attributed to the role of different climatological and dynamical features of the study area and that of West Africa at large [37].

3.6. Spatial analysis of Rainfall pattern

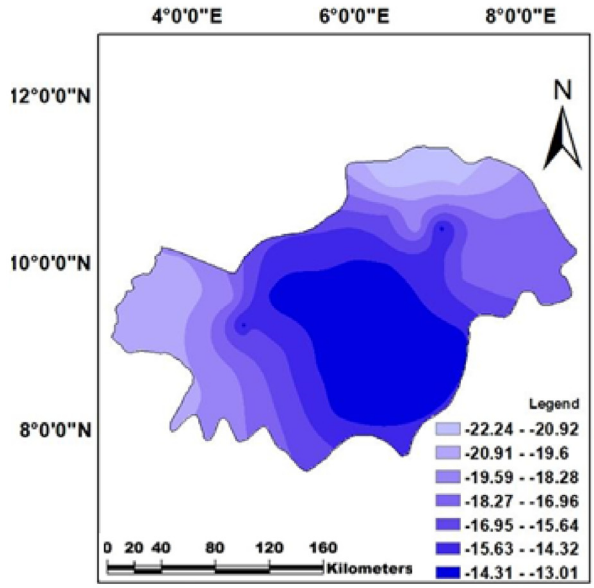
Farming is the main activity or occupation of the large percentage of rural dwellers in the study area. Hence, information on rainfall patterns for the pre- and post-change point period is essential. The results of the spatial analysis are shown in Figs. 9(a-i). The rainfall deviation map for the annual rainfall from 1911-2015 (Fig. 9a) shows a deviation through -22.24 and -13.01, indicating a negative deviation across the 33 sub-basins. The deviation map for annual rainfall from 1911-1969 (Fig. 9b) shows a deviation through -1.63 and 11.55, while the deviation map for 1970-2015 (Fig. 9c) varied through -16.39 and -10.98. The rainfall map for the post-change point period (1970) followed the same pattern with 1911-2015 as both



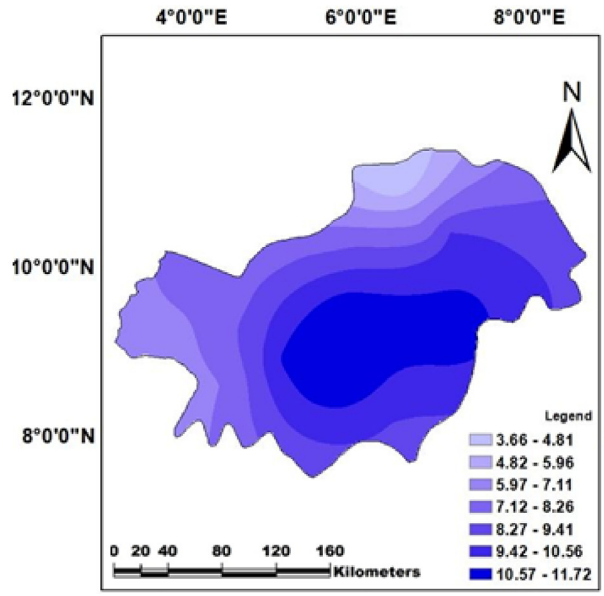
(e) Early rainy season (1911-1969)



(f) Early rainy season (1970-2015)



(g) Late rainy season (1911-2015)

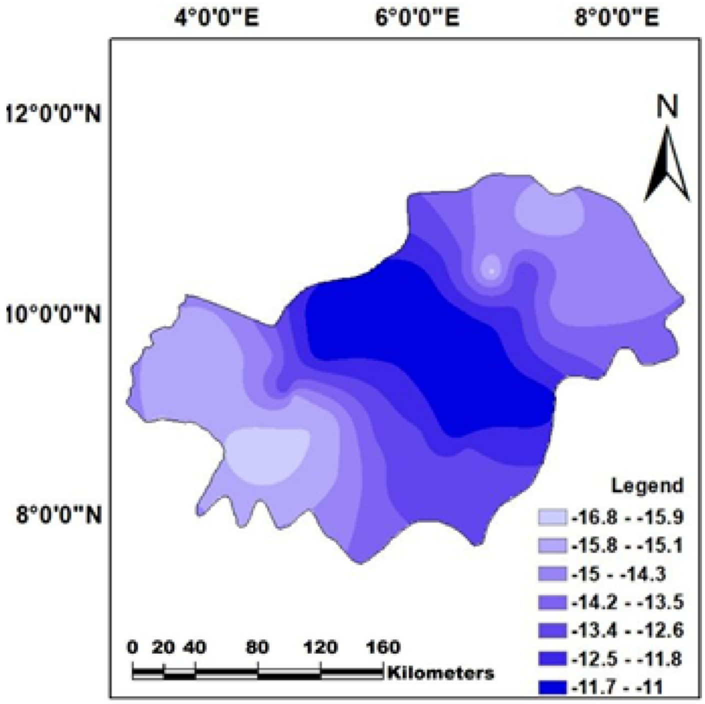


(h) Late rainy season (1911-1969)

Fig. 9. Continued

have a negative deviation for all of the sub-basins. However, the pre-change point period (1911-1969) only has a negative deviation at the uppermost part of sub-basin 3. The negative deviation of the annual rainfall for 1911-2015 and 1970-2015 is of SE-NW direction, while the positive deviation for the year 1911-1969 is of NW-SE direction.

A positive deviation dominates the early rainy season for the years 1911-2015 and years 1911-1969, and only about two sub-basins (sub-basins 2 and 3) deviated negatively (Fig. 9d and e). However, during the years 1970-2015 (Fig. 9f), the entire sub-basins experienced a negative deviation (-43.49 to -1.56). In the late rainy season, the map showed a negative deviation for the years 1911-2015 and 1970-2015 (Fig. 9g and i) while the years 1911-1969 (h) showed positive deviation for the all sub-basins (Fig. 9i). The spatial patterns for the year 1911-2015 and 1970-2015 experienced negative deviations across the 33



(i) Late Rainfall (1970-2015)

Fig. 9. Continued

sub-basins while the year 1911-1969 experienced positive deviations (3.66-11.72). The maps give more explicit and detailed pictures of the spatial distribution of rainfall which were hitherto discussed under Table 3. Similar to Table 3, the maps indicate that both the latitude and volume of rainfall received in a region determine the rainfall variability; however, the role of latitude is more pronounced. With the exception of 1911-1969, the annual and seasonal timeline over the NCHA show a severe declining trend in the order of SE – NW orientation. This is what probably manifests in the persistence of drought over the NCHA, mostly at the northern part, and the migration of desertification towards the South.

4. Conclusion

In this study, the spatiotemporal variability of rainfall has been investigated at 33 sub-basins of the NCHA for a data length of 105 years (1911-2015). Trend and homogeneity test were analyzed for monthly, seasonal, and annual timescales. The trend was significant in early rainy season ($p < 0.01$) and on an annual basis ($p < 0.05$). A decreasing trend at varying levels of significance was also recorded across the sub-basins except for sub-basins 21 and 22. The rainfall experienced over the area varied from moderate (61%) to high (39%). The most probable year of the change point in the basin was 1969. The rainfall over the area post-change point has been on the decrease for the rainy seasons, and annual rainfall indicates probable drier period than wet in the future. However, the months of July and August are characterized by increasing rainfall amounts while the remaining months follow the same decreasing trend with annual and seasonal timelines. Consequently, the drought and flood might likely be on the increase and in succession over the basin. The spatial analysis also indicates a change in rainfall pattern in the annual, early, and late rainy season after the change-point across the sub-basins. The shift in rainfall pattern may have adverse effects on the economy of the region as fluctuation in rainfall intensity and duration, as well late-onset, affects the farming activities. This adverse effect may be attributed to the impact of climate change on the climatology of the NCHA, resulting in a reduction in water resources availability and duration of planting activities. Hence, it is suggested that the local farmers should consider early-maturing plants during the rainy season. Besides, more dams should also be constructed to store the high-intensity rainfall, which has been leading to flooding in September. This will not only help to mitigate recurrent flooding but also make available water for irrigation during the dry season.

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