Analysis of Hydro-Meteorological Variables and Runoff Characteristics in the Sudano-Sahelian Ecological Zone of Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author SO designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors IPI and II managed the analyses of the study, managed the literature searches and English language editing. All authors read and approved the final manuscript.

Article Information

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ABSTRACT

This study examines the impact of climate change on hydrologic resources of selected rivers and lakes in the Sudano- Sahelian Ecological Zone of Nigeria. Climatologically data acquired were rainfall, temperature and evaporation from Nigeria Meteorological Agency, Oshodi, Lagos. Similarly, the hydrological data of river discharge and lake levels were obtained from Nigeria Hydrological Services, Kaduna. We used the Standardised Anomaly Index to test for fluctuations in rainfall, temperature, runoff and water level in lakes. Mann Kendall statistics were used to examine the trends in the climate variables. Pearman correlation was adopted to test the relationship between runoff and the rainfall variables. The findings revealed a general downward trend in rainfall amounts in the 1970s and 1980s. The findings also detected an upward trend in the amount of rainfall from 1990 to 2019. The correlation results of rainfall attributes and runoff showed significant relationships in annual rainfall (r= 0.61), annual rain-days (r=0.61), rain days of heavy rainfall (r= 0.57) and wet season rainfall (r=0.54). These attributed when combined, revealed a

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51% contribution to the overall regression with (r=0.51) at 95% probability level. The study concluded that the Sudano-Sahelian Ecological Zone of Nigeria experiencing an increase in the annual rainfall. The increase in rainfall point to the recovery of the rainfall from the great Sahelian drought of the 1970s and 1980s. The rise in the annual rainfall is a possible influencing factor to the frequent occurrences of flooding in recent time across the ecological zone.

1. INTRODUCTION

Scientific consensus suggested that climate change has potential impacts on water resources around the world. According to Ahmadi et al. [1], global runoff is increased by 4% with a rise of 1% temperature. One of the fundamental factors with applications in environmental, agricultural and economical is the climate change and its impacts on runoff occasion from changes in climate elements [2]. It has been averred that changes in climate elements of rainfall and temperature will largely determine the future runoff of a basin [3]. Therefore, research towards understanding climate characteristics concerning runoff is essential at this time.

Researches [4-7] have shown that for the past few decades, anthropogenic activities such as urbanisation, deforestation, population explosion have caused greenhouse gases to increase. These explained why the impacts of climate change on water resources are high on research agenda worldwide. Though several studies have been conducted, scientists are still worried about the frequency of future changes in overall flow magnitude, variability and timing of the main flow events. It is understood that these changes may have a high impact on transboundary river basin, for example, [8] averred that hydro-political tensions associated with water variability are concentrated mainly in northern and sub-Saharan Africa. Similarly, [9] established that 0.95–1.44 billion people are generally affected by water stress in transboundary river basins. The tension occurs as a result of the competition for water from stakeholders from different economic, political and social backgrounds.

Recent global studies of climate change, climate elements and runoff have revealed mixed trends. For example, [10] found that in China, Runoff is more sensitive to changes in precipitation than to changes in temperature [11] in Upper Heihe River Basin, analysed climate change scenario and found a positive correlation of change in a runoff with the change in precipitation. [12,13] in karst watershed south-west China found a trend of sustained decreasing and then an abrupt fluctuation in runoff trends. [1] found a negative trend in a future runoff in Kan watershed, [14] established that changes in atmospheric circulation induce a significant increase in storm flow in the Alzette River basin. [13] on their part established that significant effects climate change on the runoff decline in the Luan River basin. These mixed trends in rainfall and element of climate relationship are a pointer to the need to continue studies of runoff and climate variable at the regional and local level.

Global environmental change in Africa has brought on a sharper focus because changes in the environment, especially in the component of the hydrologic cycle brought by global warming as intensified land use particularly for food production and rapid urbanisation, will make the already vulnerable African society to be more prone. The vulnerability of African society to climate made the impact of climate change on water resources a topical issue since African countries primary economic activities and climate dependents. Findings from a previous study [15] in Africa indicates that the rainfall-runoff relationship varies significantly among different basins and countries. The variation rainfall-runoff relationship has been attributed to climatic conditions and its inter-annual variability. Similarly, while numerous studies exist in the other part of the world, little studies exist on runoff and climate variable relation in Africa.

In west Africa and Nigeria in particular, an effort has been made to understand climate change and its implication on the various facet of lives. For example, Ojoye [16] assessed the impact of climate change on water resources in the Sudano-Sahelian ecological zone of Nigeria. He concluded that the volume of water in river Niger has dropped by 305 litres over the last 25 years and consecutive droughts have also reduced the numbers of wet zones. Others studies [14,18-20] have all shown an increasing trend in rainfall in the Sudano-Sahelian ecological zone and Lake Chad Basin. Though studies on rainfall trends exist in the study area, little is known of climate

change concerning runoff. The Sudano-Sahelian ecological zone is selected as a result of its strategic importance. The bulk of the inhabitants' socioeconomic activities are nature dependent [21]. Therefore any above or below normal in climate elements could lead to loss of agricultural productivity and earth building deterioration, leaking of the roof, and the collapse of buildings [22] with implications on life and properties. Hence, it is of great theoretical and practical significance to study the impacts of climate change on hydrologic characteristics at selected rivers in the Sudano-Sahelian ecological zone of Nigeria. The present study examines climate change and its impact on the hydrologic characteristics of the study area.

2. STUDY AREA

The Sudano-Sahelian Ecological Zone (SSEZ) of Nigeria is a large ecological zone that occupies almost one-third of the total landmass of the country. The area lies between longitudes 4^0E and 14^0E and latitudes 10^0N and 14^0N. It stretches from the Sokoto plains through the northern section of the high plains of Hausa land to the Chad basin. The climate of the zone is dominated by the influence of three major meteorological features, namely the Tropical Maritime (mT) air-mass, the Tropical Continental (cT) air-mass and the equatorial easterlies. The first two air masses meet along a slanting surface called the inter-tropical discontinuity (ITD).

The drainage systems of the Sudano-Sahelian Ecological Zone of Nigeria are dominated by the Komadougou-Yobe, Hadejia-Ja'amare and Sokoto-Rima river basins. The seasonal and long-term variations in the flow of these rivers have a range of seven-year means. The ratio of the 90% probable flow to the mean annual runoff is given as 1:65 for Sudan and 1:250 for Sahelian parts of the region, respectively. Eighty to ninety percent of flood flows are concentrated in three months of July to September. Most of the Sudano-Sahelian Rivers dried up during the 1972-1973 and 1984.
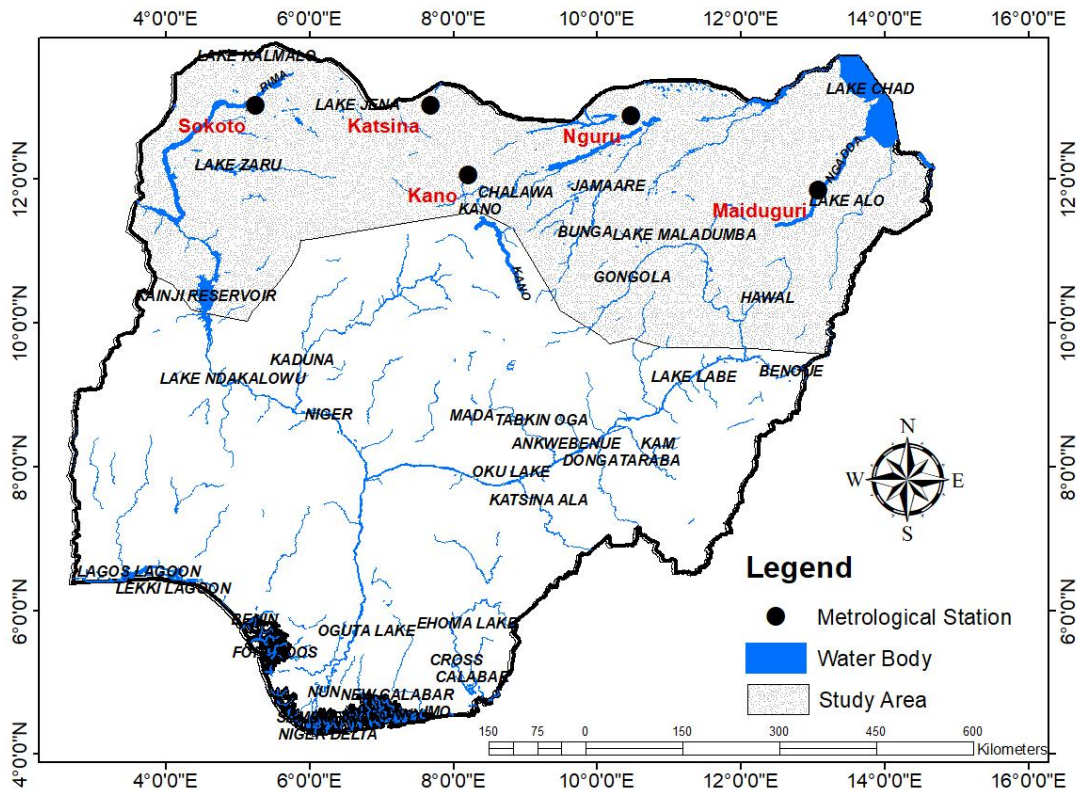

Fig. 1. The sudano-sahelian ecological zone of Nigeria

3. MATERIALS AND METHODS

3.1 Collection of Data and Analysis

The data for the study were meteorological and hydrological data. The meteorological Data are rainfall, temperature and evaporation while the hydrological data is the stream Flow. Climatologically data acquired were rainfall, temperature and evaporation from Nigeria Meteorological Agency, Oshodi, Lagos. Similarly, the hydrological data of river discharge and lake levels were obtained from Nigeria Hydrological Services, Kaduna. All the parameters were subjected to statistical analyses, Mann-Kendall, Regression and anomalies indexes.

For this study, the runoff series of selected rivers were collected monthly and summed up to have the annual runoff series. These annual runoff series were examined for fluctuations using the standardised runoff anomaly index given by:

$$x_{ij} = \frac{1}{N_j} \sum (a_{ij} - a_i) \delta$$

Where,

x_{ij} = runoff departure for the jth year
a_{ij} = the year's runoff totals at a river i
a_i = the mean of the rivers' totals for the base period
δ = standard deviation of the river's total for the based period
N_j = number of years when data are available

Two types of runoff attributes were analysed to study runoff trends over time; changes in annual runoff totals, in wet and dry seasons. The period for this was sub-divided into decades (Pre-1980, 1981-1990, 1991-2000,2001-2010,2010-2019), and their means were calculated. The calculated value was compared with the long-term mean to determine their deviation from the mean. Trend analysis was used to compute the trend of the rivers.

The water levels in each of the selected lakes in the selected lakes were computed on an annual basis from the daily water level values and tested for fluctuations over the period 1980-2019 using the standardised anomaly index. The water levels in the selected lakes were tested for trend using the trend analysis. Trend analysis was tested for both the dry season (November to March/April) and wet season (April to October).

3.2 Climate Variables - Runoff Relationships

The rate of change between runoff and the climate variables of rainfall, temperature and evaporation were computed using simple percentages. The changes in a runoff with the climate variable were computed as a function of the total annual runoff, rainfall, temperature and evaporation for both the dry and wet years at the hydrological basin. The equation used for computation is given as:

$$\frac{(x_i - x_m)}{N}$$

Where:

x_i = total annual value for a variable (rainfall, temperature, evaporation, runoff)
x_m = mean annual value for a base period
N = number of years when data is available

3.2.1 Rainfall characteristics –runoff correlations

The correlation between rainfall characteristics such as annual rainfall, wet season rainfall, heavy rainfall, annual rain days and rain days of heavy rainfall and runoff was carried out for each of the selected rivers using the multiple correlations.

3.2.2 Prediction of water levels and runoff

Water levels in lakes and runoff from rivers were predicted using the rainfall characteristics that were found to correlate strongly with water levels from the selected lakes and runoff from the selected rivers. The multiple regression models were used. This was given as:

$$Y = a1 + b1X1 + b2X2 + \cdots bnXn$$
Y= Runoff
X_1-X_n= rainfall characteristics
a_1, b_1 - b_n =constant of multiple regression

3.2.3 Mann- kendall statistics

Recent studies [23-26] suggested that Mann Kendall tau statistic developed by Mann [27] and modified by Kendall [28] is an excellent tool for trend detection in different applications. Mann-Kendall statistics was adopted for this study at an alpha level of 0.5.

A positive value of Mann Kendall tau statistic is an indicator of an increasing trend; a negative

value indicates a decreasing trend, while 0 indicates no trend.

4. RESULTS AND DISCUSSION

Fig. 2. represent the fluctuations in the runoff in the Sudano-Sahelian Zone of Nigeria. Runoff series during the period 1958-2019 contains several phases of low and high water. Results show a drastic and continuous decline in runoff from 1978 to 2006. The decline in runoff corresponds to the drought years as reported by Usman & Abdulkadir [21]. The duration of persistently low and high-water phases does not exceed 10 years. In general, four phases of low and high water can be observed. Above-average runoff occurred during the pre-1970s and 1987-90 while below-average runoff was observed during 1970-1975 and 1980-1990 periods. The below-average runoff, which commenced in 1970 was less severe as compared to the 1980s. The positive runoff anomalies are stronger than the negative ones.

The runoff series of river Hadejia has been divided into two periods. The period 1969-76 was dominated by above-average runoff. The years 2003-2008 were exceptionally high-water years in the series. Apparent low stream flow anomalies which commence in 1981 continued unabated till 1992. The high flow was pronounced particularly from 2003-2008 and 2012-2018. The positive deviations are very pronounced. The negative anomalies are more striking in the 1980s as compared to preceding and proceeding years. This result corroborates the findings of Dami [29,17,18] that since the 1969-73 drought, rivers in Northern Nigeria may never return to their pre-1970 levels and size. The regulating effect of the Sokoto, Hadejia-Ja'amare lakes is hardly detectable.

4.1 Fluctuations in Annual Runoff in the SSEZ of Nigeria

Table 1 presents the runoff series of the selected rivers were sub-divided into pre-1970 and post-1970 periods. The table is reflecting the major rainfall anomalies that have afflicted the basin in recent years. The 1971-2019 periods were further sub-divided into 1971-1980, 1981-1990, 1991-2000, 2001-2010 and 2-011-2019 to evaluate the consistency of the observed changes. The results revealed the deviation of the mean Runoff from the long-term mean. The deviation of the mean value for the pre-1970 period ranges from -8.42 for river Kano

to +13.82 percent for river Hadejia. The mean variation reflects a below mean runoff for Kano and above mean runoff for the other rivers in the basin. For 1971-80 period, all the sampled rivers experienced a below-average runoff, and only river Sokoto experienced a positive deviation of 0.45 percent, for the 1981-1990 period, all the rivers experienced a below mean runoff between -22.9 percent for river Ebeji and -17.7 percent for river Ja'amare while rivers Kano and Sokoto had an above-average runoff of +0.87 percent and +1.06 percent respectively. The trend in the mean Runoff between 1991-2000 is similar to 1971-1980. The period of 1991-2000 showed all the rivers recorded a below-average runoff in the river Sokoto river Ngadda. River Kano recorded a positive deviation of +0.36 percent.

The 2001-2019 period showed total deviation from previous observed years when all the rivers sampled recorded an above-average runoff that ranged from +1.55 for the Sokoto river to +40.20 for river Ngadda. Results showed a similarity in runoff decreased and rainfall decline from 1971-2000.

4.2 Trend in the Stage of Streams in the SSEZ of Nigeria

The results of the trend of stages in the selected rivers revealed that water level in the sampled rivers changes significantly in the period under study in sympathy with the changes in runoff observed in Table 2. The decline in water level is more marked in rivers Ebeji and Ngadda as compared to other rivers.

The apparent overriding control of rainfall fluctuations on changes in water resources in the SSEZ of Nigeria notwithstanding, other factors such as geology and man's activity are also very important and accounts for the anomalies observed in the annual runoff and stage height of streams. For instance, the selected sub-basins are underlain by the impermeable basement complex rock which reduces the amount of water in the rivers that goes into underground water and thus enhance the correlation between runoff/stage and rainfall. There are none of the sub-basins where man's activity is not felt. Man's activity such as urbanisation and deforestation on the one hand and reservoir regulations, irrigation, municipal and industrial uses of water, on the other hand, manifest contrasting effect on runoff.
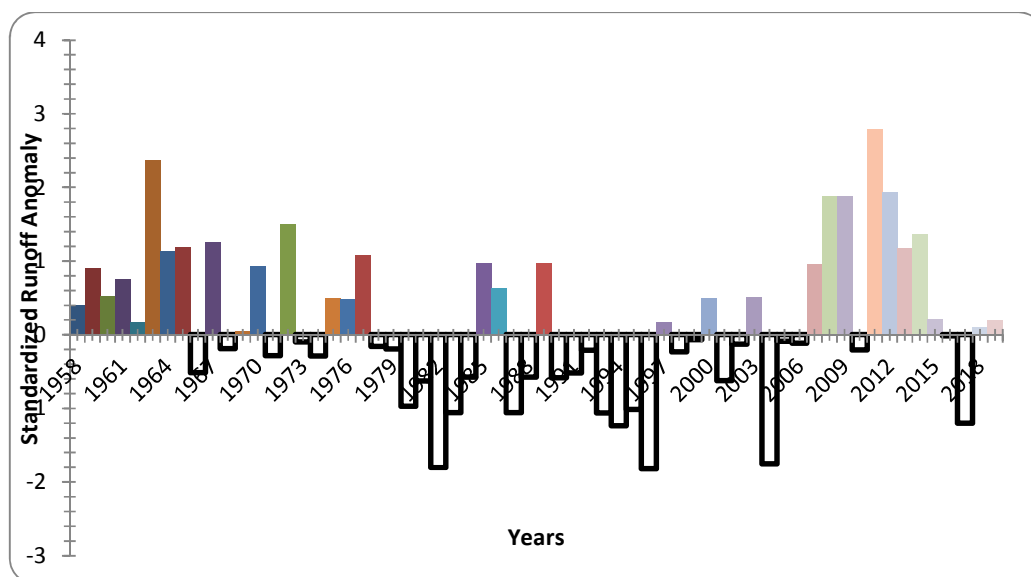
Fig. 2. Runoff anomalies in the sudano-sahelian ecological zone of Nigeria

Table 1. Decadal deviation of the mean runoff

Rivers	Pre-1970	1971-1980	1981-1990	1991-2000	2001-2010	2011-2019
Sokoto	0.14	0.45	1.06	-2.79	1.55	3.72
Kano	-8.42	-0.64	0.87	0.36	2.42	20.53
Hadejia	13.82	-3.14	-20.42	-2.57	27.49	34.74
Rima	13.12	-2.99	-19.4	-2.44	26.11	28.62
Ja'amare	9.56	-4.21	-17.68	-1.87	26.11	23.21
Ebeji	9.42	-4.17	-22.99	-1.82	32.7	40.2
Ngadda	9.05	-4.01	-22.07	-1.75	31.39	34.65

4.3 Fluctuations of Water Level in Selected Lakes in the SSEZ

For this study, the major lakes in the study area with a consistent and long period of records were selected. These were; Tiga, Challawa and the Nigeria portion of Lake Chad. The fluctuations in water level in these lakes were as shown in Fig. 2. The annual water level series contain few periods of persistently low and high-water levels. The variations in water level in these lakes bear a remarkable relation with rainfall change in the study area. The explanation to this is not far-fetched because the region is ravaged by lower-than-normal rainfall at these periods. It may also be attributed to the fact that agricultural development, rapid urbani sation and industrialization growth are increasingly modifying the natural runoff process and exerting growing demands on the water supply. Goes, [30] and Ojoye, [16] have shown that Tiga and Challawa dams' level correlate closely with rainfall over a wide area.

4.4 Trend of Water Level in the Selected Lakes

The results of the trend in water level at the selected lakes were revealed in Table 3. The results revealed that water level in the lakes increased (at 99% significance level) in the period 1991-2019. Increasing rainfall over the years played an essential role in the increasing level of water recorded in the various lakes in the zone. The lake level will continue to increase due to a progressive rainfall increase in the area.

4.5 Runoff Response to Long-Term Changes in Rainfall conditions in the SSEZ of Nigeria

The observed fluctuations in both rainfall and runoff Runoff were correlated to determine and explain the nature and magnitude of their relationships. Six rainfall attributes were correlated with the runoff for each of the sub-basins selected for the study using multiple

regression analysis. These attributes include; annual rainfall, dry season rainfall, wet season rainfall, heavy rainfall, annual rain-days and rain-days of heavy rainfall (Table 4).

The results in Table 4 show that there is a high correlation (95% probability level) between annual rainfall and annual runoff in all the selected sub-basin, a correlation of 0.75 was observed for Ngadda rivers, and Sokoto rivers recorded 0.69 and the least in the series was recorded in Ja'amare river. The findings is consistent with the study of [15,14,31,3] who found significance relationship between runoff and climate elements in their study areas. The explanation for the high correlation of runoff with the annual rainfall was because the rivers in the study area are fed exclusively by rain. Therefore, much of the variation in runoff is determined by changes in total annual rain. The rainfall-runoff correlations result in Table 4 also revealed that there is a low positive correlation between dry-season rainfall and runoff in all the sub-basin. The wet season rainfall was found to correlates significantly with runoff in all the selected rivers.

4.6 Predicting Runoff and Water Levels in Selected Lakes

Rainfall attributes that have a significant correlation with runoff and lake levels were used in the prediction. This is based on the fact that runoff and water level in lakes are highly sensitive to changes in rainfall and other climatic variables. A multiple regression performed on these rainfall attributes revealed that annual rainfall (ANRF), wet season rainfall (WSRF), annual rain days (ANRD), heavy rainfall (HRF) and rain days of heavy rainfall (RDHRF) are significant in the prediction of runoff and water level in lakes in the selected rivers and lakes of the study area. The model and the correlation values were as shown in Table 5.

Table 6 shows the predictive equations for water levels in the selected dams of the study area. The coefficient of multiple determinations (R^2) for all the dams was found to be significant at 95% confidence level. The highest value of 0.96 was obtained at the Challawa dam, 0.94 at the Tiga and Lake Chad, while 0.88, 0.85, 0.79 and 0.75 were obtained for Jibiya, Bakolori, Zobe and Goronyo dam respectively.

Table 2. Trends in the stage of streams in the SSEZ

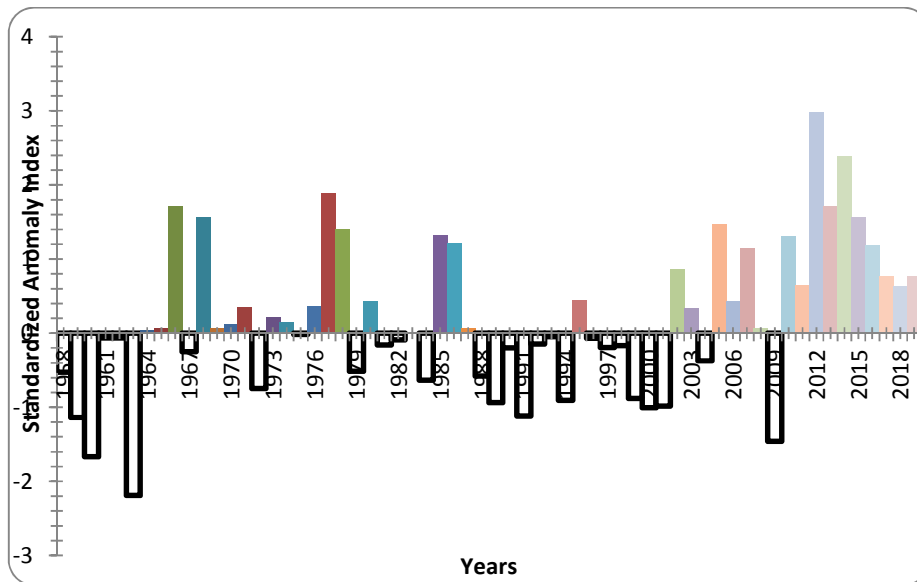| Rivers	Period	Stage
Sokoto	1968-2019	-0.578
Kano	1968-2019	-0.829
Hadejia	1968-2019	-0.401
Rima	1968-2019	-0.225
Ja'amare	1968-2019	-0.761
Ebeji	1968-2019	-0.654
Ngadda	1968-2019	-0.678

Fig. 3. Fluctuations in water levels at lakes in the SSEZ

Table 3. Trends in water level in lakes in the SSEZ

Lake	Tiga	Challawa	Bakolori	Goronyo	Jibiya	Zobe	Lake Chad
Water level Trend	0.15	0.21	1.2	1	0.05	0.35	0.02

Table 4. Rainfall-Runoff correlations in the SSEZ (mm)

Rivers	Annual rainfall	Dry season rainfall	Wet season rainfall	Heavy rainfall days	Annual rain days	Heavy rainfall days
Sokoto	0.69	0.31	0.58	0.6	0.68	0.68
Kano	0.67	0.24	0.6	0.58	0.64	0.57
Hadejia	0.54	0.27	0.49	0.45	0.62	0.61
Rima	0.56	0.23	0.52	0.35	0.63	0.51
Ja'amare	0.46	0.23	0.4	0.42	0.4	0.53
Ebeji	0.61	0.35	0.52	0.5	0.53	0.42
Ngadda	0.75	0.32	0.65	0.72	0.78	0.68

Table 5. He predictive equations for runoff in each of the selected rivers

S/N	Rivers	Predictive Equations	R^2	*SE
1	Sokoto	Y = -6.649E6-0.237ANRF+0.598WSRF+0.734ARD-0.201RDHRF+0.078HRF	0.98	4.40E+05
2	Kano	Y = +5774.822+0.491ANRF+0.371WSRF-0.200ARD+370RDHRF-0.022HRF	0.98	6.30E+05
3	Rima	Y = +6997E6-0.09ANRF+0.38WSRF-0.488ARD+0.366RDHRF+0.692HRF	0.96	1.00E+06
4	Hadejia	Y = -3.416E7+0.674ANRF-0.065RDHRF	0.63	5.00E+06
5	Ja'amare	Y=-3.743E7-0.068ANRF+0.957WSRF-0.132ARD+0.099HRF	0.94	8.90E+05
6	Ebeji	Y=-2.152E7+0.447ANRF+0.391WSRF+0.224ARD-0.040RDHRF	0.98	2.50E+05
7	Ngadda	Y=4.700E6+1.101ANRF-0.214WSRF+0.093ARD+0.001HRF	0.96	4.00E+05

Table 6. The predictive equations for runoff in each of the selected dams

S/N	Lakes	Predictive Equations	R^2	*SE
1	Tiga	Y=1.649+0.969RDHRF+0.548ANRF-0.415WSRF+0.659ARD-0.181HRF	0.94	0.08
2	Challawa	Y= 2.457+0.733RDHRF+0.3HRF-0.492ANRF+0.053WSRF-0.538ARD	0.96	0.06
3	Bakolori	Y=-8.153+0.935WSRF-0.295ANRF+0.149ARD+0.449RDHRF+0.096HRF	0.85	0.28
4	Goronyo	Y=8.104-0.205ANRF+0.024ARD+0.324RDHRF+0.080HRF	0.75	0.33
5	Jibiya	Y=-5.509+0.938WSRF-0.151ARD+0.092RDHRF-0.010HRF	0.88	0.48
6	Zobe	Y=-0.064+0.889WSRF-0.276ARD+0.126RDHRF+0.199HRF	0.79	0.23
7	L.Chad	Y=-6.495+0.968ANRF-0.504WSRF+0.486ARD+0.397RDHRF-0.243HRF	0.94	0.16

5. CONCLUSION

This study investigates hydro-meteorological variables and their runoff relationship in the Sudano- Sahelian Ecological Zone of Nigeria. Water levels in Sokoto-Rima, Hadejia-Ja'amare and Yobe-Komadougou basins, Tiga and Challawa lakes for the period 1968-2019 were also collected. The dry and wet season rainfall series were computed and analysed for fluctuations and trend using the standardised rainfall anomaly index and the Mann Kendall Statistics respectively. The annual runoff, stage and water levels in lakes were also analysed for fluctuations. A general mixed trend of upward and downward in runoff was observed across the rivers in the study area. The trend results suggest that local microclimate influences the runoff in the study area. The runoff showed fluctuation in the ecological zone. The runoff fluctuation was more pronounced in the 1970s and 1980s drought years as compared to other years. It is evident from the study that the runoff anomalies are a reflection of the rainfall regime in the Northern part of Nigeria. The findings provide information on the hydro-meteorological and runoff relationship in the Sudano-Sahelian Ecological Zone of Nigeria.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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