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Impact of Climate Variability on Groundwater Recharge: *A Case Study of Selected Regions in Nigeria*

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Abstract
The increasing impact of climate change on groundwater resources in Nigeria's ten selected locations presents a multifaceted challenge with far-reaching socio-economic implications. Urgent action is required to mitigate these impacts and build resilience among affected communities. A combination of hydrometrological data and geological knowledge was applied to scrutinize the factors that can impact on groundwater recharge in selected localities. Advanced statistical techniques using data from five models, based on the Coupled Muodel Intercomparison Project 6 dataset were employed to analyse hydro-meteorological parameters and their effects on groundwater recharge, particularly within the Shared Socio-economic Pathway 585 framework. The study combined historical data from 1971 to 2005 with future projections up to 2041. The research also delved into the impact of climate change on hydro-meteorological parameters in a flood-prone area known as the Auchi station, while also factoring in the underlying geological properties. Results showed substantial increases in these parameters, with projected annual values of 1400.47mm, 514.64mm, and 331.42mm, respectively. Revealing significant increases in mean annual precipitation, total runoff, and groundwater recharge, indicating greater water resource availability in the future. This study enhances the understanding of climate change's influence on groundwater, crucial for sustainable water management. The result shows that there is an increment in rainfall across Nigeria due to increasing temperature. There is a modest rainfall trend of 0.89mm/year, 0.91mm/year and 0.134 mm/year in the Southern stations of Auchi, Akure and Ossomala respectively while the Northern station of Yola, Katsina and Maiduguri exhibit high rainfall trend of 2.3mm/year, 2.87mm/year and 5.15mm/year respectively. The increasing rainfall however led to increasing groundwater recharge at Auchi (0.2mm/year), Akure (0.713mm/year), Ossomala (0.92mm/year), Yola (0.89mm/year), Katsina (0.65mm/year) while Maiduguri is having increasing groundwater recharge at 2.27mm/year. Areas characterized by significant elevation changes, such as the Jos Plateau, experience higher annual rainfall, total runoff, and groundwater recharge, surpassing that of neighbouring regions. Ultimately, the study recommends the implementation of tailored groundwater management strategies that consider the unique hydrogeological characteristics of each region and the potential effects of climate change. The cumulative findings significantly augment our comprehension of climate change's influence on groundwater resources, thus affording invaluable insights for the promotion of sustainable water resource management across the selected stations..

Keywords: *Climate change; Rainfall; Groundwater; Runoff; Geology*

Introduction

Climate change and variability exert a profound influence on every facet of life on Earth. This encompasses a wide array of elements, including water resources, energy, agriculture, vegetation, air quality, and sea levels (Myers, 2007). The dynamics of climate patterns play an indispensable role in shaping both natural ecosystems and the human economies that rely on them. According to (Khormi and Kumar, 2014); Kumar and Gautam, 2014) climate change refers to alterations in the statistical properties of the climate system, spanning decades or even longer, without regard to its specific origins. It encompasses shifts in temperature and weather patterns that can manifest at local or global scales. The Intergovernmental Panel on Climate Change (IPCC, 2014) describes climate change as modifications in climate conditions directly or indirectly attributable to human activities that modify the composition of the global atmosphere, exceeding the natural climate fluctuations observed over similar time spans (Bates *et al.*, 2008).

Climate change emerges from various sources and can be examined from diverse angles. Amidst natural factors, specific human actions have been pinpointed as pivotal or primary drivers of recent climate changes, often referred to as "global warming" (Ranjan *et al.*, 2006). As concentrations of greenhouse gases rise, so does the global surface temperature, a phenomenon recognized as "global warming" (Demargne et. al., 2014). As elucidated by Rummukainen (2012), climate change can alter the intensity and frequency of precipitation. This results from warmer oceans increasing moisture evaporation into the atmosphere, which, when concentrated within storm systems or transported over land, leads to heightened precipitation and heavier rainfall.

Given the intricate interconnectedness of natural systems with climate, climatic shifts can exert impacts across various dimensions of plant and animal life, food production, forest health, and groundwater resources (IPCC, 2014). One of the most severe repercussions of climate change pertains to the transformation of the hydrological cycle, influencing surface water levels and groundwater recharge into aquifers. This, in turn, affects both the quantity and quality of regional water resources (Dragoni and Sukhija, 2008). Nigeria, akin to numerous other nations worldwide, confronts the devastating ramifications of climate change, including rising temperatures, erratic rainfall patterns, and prolonged droughts. This convergence of challenges poses a significant threat to the country's groundwater resources, which serve as a lifeline for millions of Nigerians. With groundwater serving as the principal source of drinking water, irrigation, and industrial use, the repercussions of climate change on these resources demand earnest attention. However, groundwater systems are highly complex and interconnected, influenced by various factors such as geology, land use, and climate variability. Numerous communities find themselves without access to crucial information regarding the risks posed by changing groundwater conditions, along with the necessary resources for adapting to these shifts. This research aims to rectify this information deficit by offering tailored measures that suit each unique situation, thereby bridging the gap between knowledge and action. Efforts to comprehend the climate system's response to escalating greenhouse gas concentrations in the atmosphere have employed Global Climate Models (GCMs). These computer models are meticulously designed to replicate past climates with precision, thereby instilling confidence in their capacity to forecast future trends. Adopting this model will help in closing the gaps in our understanding and response to the impacts of climate change on groundwater resources. This is imperative for ensuring water security and sustainable development.

Most research solely relying on hydrometeorological data for climate change assessment, neglecting geological insights, might be insufficient, therefore this study delves into the intricate interactions among climate, groundwater dynamics, and geology, vital for comprehending recharge mechanisms and adapting to shifting climatic conditions, crucial for sustainable water management and development. The aim of this study is to investigate the impact of climate variability and change on groundwater recharge processes in selected regions. By examining the complex relationships between climatic factors and groundwater dynamics and geological impact, the study seeks to enhance our understanding of recharge mechanisms and their response to changing climatic conditions. The potential impacts of climate change on groundwater resources in the selected stations were assessed by analyzing the hydro-meteorological data to identify any climate trends. Aquifer characterization based on rock, soil, fracture systems and other geological properties that was previously overlooked, was carried out to evaluate the potential adaptation and mitigation strategies to address any negative impacts of climate change on groundwater resources and the recharge potential of soil formations in the study area with respect to observed climate trends.

Geology of Nigeria

Nigeria's geology is diverse and spans across an extensive region within West Africa, (Adegoke et.al., 2017) situated between latitudes 4° and 14° north and longitudes 3° and 14° east (Fig.1). Covering an area of approximately 923,768 square kilometers, Nigeria shares its borders with the Republic of Niger and Republic of Chad to the north, the Republic of Benin to the west, Cameroon to the east, and the Atlantic Ocean to the south (Tijani, 2023). This geographical expanse stretches from the Gulf of Guinea in the south to the Sahel, marking the edge of the Sahara Desert, in the north.

Within Nigeria, nearly half of the landmass is underlain by Precambrian basement rocks that have undergone deformation during the Pan-African orogeny. These rocks are predominantly metasediments, including gneisses, schists, migmatites, and calc-silicates, alongside amphibolites, and rare metamorphosed tuffs and volcanic rocks. Notably, banded iron formations rich in magnetite and hematite are prominent in the southeast, near Kabba and in north-central Nigeria (Adekoya, *et. al*., 2012). Additionally, Precambrian granitic intrusions are common in this basement region. Younger granites, originating from the Jurassic era, constitute a significant portion of the Jos Plateau in central Nigeria and are associated with tin (cassiterite) mineralization. Tertiary volcanic rocks, such as basalts and rhyolites, sporadically occur above the basement rocks on the Jos Plateau and eastern plateau regions.

The remaining parts of Nigeria are covered by Mesozoic and Younger sediments, distributed across various sedimentary basins, including the Benue Trough in the central region, Sokoto in the north-west, Chad in the north-east, Bida in the central region along the Niger valley, Dahomey in the south-west, Anambra in the south-east, and the Niger delta in the south coastal area (Nwajide and Reijers, 1996). The Benue Trough, characterized by a rifted basin running along the approximate line of the Benue River, is filled with Cretaceous sediments, with increasing thickness toward the south due to basin subsidence Ogungbesan and Akaegbobi, 2011). The sediments range from marine black shales in the lower part of the basin to fluvial-deltaic sandstones with occasional shale intercalations and conglomerate horizons in the upper part.

Similarly, other basins, such as the Bida Basin, Sokoto Basin, and Chad Basin, contain sediments of varying composition and thickness. The Lokoja and Patti formations within the Southern Bida Basin originated during the Campanian to Maastrichtian epochs, bearing resemblance to the Mamu and Nsukka formations in the neighbouring Anambra Basin. These basins are underlain by Precambrian basement rocks in an unconformable manner. (Auduson and Onuoha, 2020). Ossomala, is one of the stations of focus and is dominated by unconsolidated and poorly sorted sands of Benin formation (Ocheli *et. al.*, 2021; Anizoba, 2022). The Niger delta, situated in the coastal south, has been gradually extending into the Atlantic Ocean since the late Cretaceous period, accumulating Tertiary and Quaternary sediments of decreasing age toward the south. These sediments comprise various formations, including the Imo Shale, Ameki Formation, Ogwashi-Asaba Formation, and Benin Formation. They exhibit an upward transition from marine pro-delta shales to paralic intervals and continental sequences (Oboh-Ikuenobe *et.al.*, 2005). The thickness of these sediments can reach up to approximately 12,000 meters and contains economically significant hydrocarbon resources, primarily trapped within the Agbada Formation (Ilevbare and Imasuen, 2020).

The topography of the country ranges from lowlands along the coast and in the lower Niger valley to hills and plateaus (Tijani, 2023), including Jos Plateau in the center and predominantly high mountains in the southeast. The Sokoto Plains lies in the southwestern corner of the country, while the Borno Plains in the northeastern corner extend as far as the Lake Chad basin. The lowest elevation is 0 m near the Atlantic Ocean in the south while the highest elevation is 2419m at Chappal Waddi in the northeastern part of the country (Hayward and Oguntoyinbo, 1987; 2021). The Sokoto weather station sits within the Sokoto basin, also referred to as the Illumeden basin. This geological feature comprises two primary formations: the Illo and Gundumi Formations, primarily composed of grits and clay from the Maastrichtian age, resting unconformably atop the Pre-Cambrian Basement. The Illo and Gundumi Formations transition unconformably into the Dange and Gamba Formations, predominantly shales (Auduson and Onuoha, 2020).

The clay-rich composition of these formations led to decreased water output from boreholes, consequently diminishing the overall quantity of groundwater available (Wali *et al.*, 2019). The Calabar Flank's sedimentation history began with the basal Aptian Awi Formation's fluvio-deltaic clastics (conglomerate, siltstone and sandstone), it transitioned to the mid-Albian Mfamosing Limestone and late Albian-Cenomanian-Turonian Ekenkpon Shale. The subsequent New Netim Marl featured thick marl with sparse dark shale. A brief hiatus in sedimentation occurred during the Santonian and Early Campanian, Sedimentation resumed in the Late Campanian-Maastrichtian with the Nkporo Shale, succeeded by Tertiary marine shales and regressive sandstones. The Mfamosing Formation signifies shallow marine carbonates, while the Ekenkpon and New Netim Formations denote rising sea levels, characterized by transgressive shales and marls. The Nkporo Shale, with dark-grey shale and inter-bedded sandy shale, siltstone, and mudstone, suggests shallow marine deposits. Overlying it, the Benin Formation contains lacustrine and fluvial materials like sands, pebbles, clay, lignite, and alluvium.Alpine age cretaceous sediments underlined by NE-SW faulted basement rocks dominate the Yola station (Ogunmola *et al.*2016). Kastina station is underlayed by crystaline basement rocks of Precambian age.

Methodology

The study areas for this research are the ten selected portions within Nigeria (Figure 1), located in the western part of Africa. The impacts of climate change and variability on any aspect of human livelihood and socioeconomic activities vary from global to local levels (Ajayi and Ilori, 2020); hence, ten (10) stations located in different parts of Nigeria used in this study were selected based on hydrological suitability, ecosystem vulnerability, climate change impacts such as flooding, increased precipitation, sea level rise, and data availability. Sophisticated statistical methodologies utilizing information from five models, derived from the Coupled Model Intercomparison Project 6 dataset, were utilized to scrutinize hydro-meteorological parameters and their implications on groundwater recharge, notably within the framework of the Shared Socio-economic Pathway 585. Integrating historical data spanning from 1971 to 2005 with future

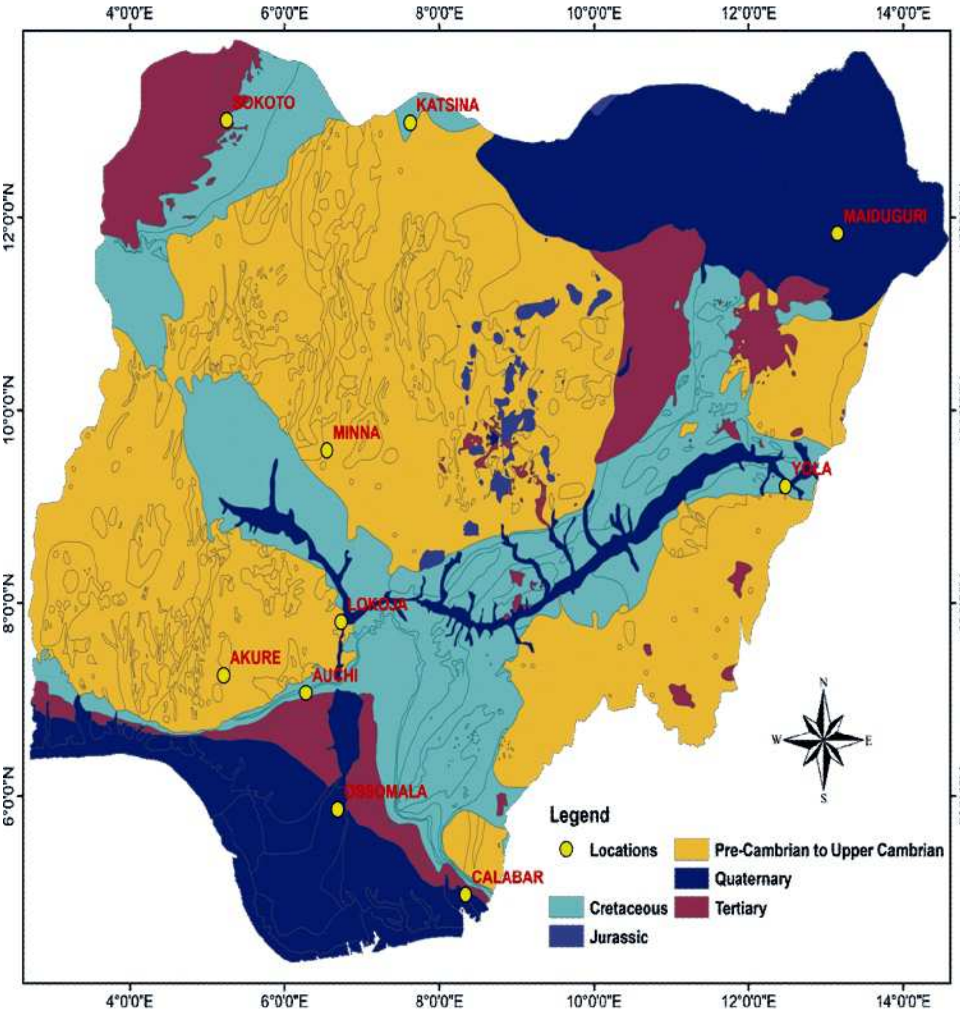

Fig. 1: Geological map of Nigeria showing the ten (10) selected stations used in this study (Modified from Obaje, 2009).

projections extending to 2041, the study offers comprehensive insights. Additionally, the investigation extends to the evaluation of climate change's impact on hydro-meteorological parameters in a flood-prone locale identified as the Auchi station, with due consideration given to the underlying geological characteristics. A review of the aquifer characterization using geophysical technique around Auchi area is included in later sections The selected sites are listed in Table 1. The physical characteristics of each of the ten stations are listed in Table 1.

Hydro-Meteorological Analysis

Data Sources

Climate models, like Global Climate Models (GCMs) or Regional Climate Models (RCMs), are crucial tools for projecting future climate variables under different scenarios. Accuracy depends on the model's ability to

Table 1: Description of Ten (10) selected stations used in this study.

S/N	Station Name	Longitude	Latitude	Elevation (m)
1	AUCHI	6.2748	7.0669	222.09
2	AKURE	5.2057	7.2571	351.41
3	OSSOMALA	6.6875	5.8611	24.62
4	YOLA	12.4782	9.2095	175.79
5	LOKOJA	6.7333	7.8023	88.00
6	CALABAR	8.3417	4.9757	58.00
7	MINNA	6.5463	9.5836	250.60
8	SOKOTO	5.2476	13.0059	284.88
9	KATSINA	7.6222	12.9816	513.33
10	MAIDUGURI	13.15096	11.8311	324.75

replicate past and present climate patterns (Ilori and Balogun, 2022; McMahon *et al.* 2015). This study utilized secondary data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) framework. ISIMIP offers trend-preserving bias-corrected climate datasets using a Multi-Model Ensemble (MME) covering various scenarios (Moss *et al.* 2010). The data were downloaded for analysis, focusing on impacts of climate change on groundwater resources in Nigeria over historical and future periods (1971-2041) under the socio-economic pathway of SSP585 (Hempel *et al.* 2013; Warszawski *et al.*, 2014). Rainfall, Runoff, and Groundwater Anomaly Indices were used to assess the impact of climate variability on groundwater resources in Nigeria. The future climatic/hydro-meteorological data (rainfall, total runoff and groundwater recharge) at yearly scale used in this study were obtained from the MME of five (5) coordinated international downscaling efforts, ISIMIP framework regional climate models (RCMs). The ISIMIP data are statistically downscaled from Coupled Model Inter-comparison Project Phase 6 (CMIP6). The anomaly was computed following Ajayi and Ilori (2020) and Alexander *et al.* (2006) methodologies, using historical long-term means of hydroclimatic variables to predict future deviations. Hydro-meteorological data sets that include monthly rainfall, runoff and groundwater recharge from the ISIMIP3b model were downloaded from http://data.isimip.org/download over the globe. These data were later subset over the ten (10) selected stations for the hisorical period of thirty-six years (1971 - 2005) and the future period of thirty-six years (2006-2041) under the socio-economic pathway of SSP585. The future period from 2006 to 2041 was chosen to examine the implications of exceeding a global warming level (GWL) of 2^{0}C on groundwater resources in Nigeria in the future relative to the historical period. A review of aquifer units characterization using a geophysical method over parts of Auchi area was carried out.

Spatial Pattern, Time-Series and Correlation between Rainfall and Groundwater/Runoff

Over the selected stations in Nigeria, the spatial patterns of rainfall, groundwater and runoff were plotted in to examine the mean spatial distribution and trends of all these hydro-climatic variables for the historical and future periods. However, an annual time series that gives the yearly variability and rate of change of rainfall, runoff and groundwater for all the stations was also adopted for the historical and future periods to ascertain the annual rate of increase or decrease (Fig. 2, 3 and 4). The correlation coefficient with values that range from -1 to 1 is a statistical measure of the strength of a linear relationship between two variables. The correlation coefficient was also employed to assess the degree of association between rainfall and groundwater/runoff for the historical period.

Results

Historical Hydro-Meteorological Change

Rainfall, runoff and groundwater anomaly indices were used to examine the impacts of climate variability and change on groundwater resources in Nigeria for the future under the SSP585. Following Ajayi and Ilori, (2020) and Alexander *et al.* (2006), in computing the anomaly, the historical long-term mean of each hydro-climatic variable is used to determine how these variables will deviate from the mean in the future relative to the historical.

Figure 2 shows the spatial pattern of annual rainfall, total runoff (qtot) and groundwater recharge (qr) over Nigeria for the historical period of 1971-2005. Annual rainfall pattern shows a northward decrease in mean annual rainfall from the coastal regions. It is observed that a maximum historical annual rainfall, total runoff and groundwater recharge of 2600 mm/yr over the coastal region of Nigeria decreased to about 600 mm/yr in the far northern part of Nigeria over the selected stations.

The influence of topography on hydrogeological parameters of a particular area evidenced by an increase/decrease in magnitude of annual rainfall, total runoff, and groundwater recharge of the area. Areas with high elevation and steep slopes tend to have higher runoff and rainfall than areas of low elevation (Wang et al., 2017). Regions with high topography like Jos Plateau, (Table 1) have higher annual rainfall, total runoff, and groundwater recharge amount more than 1200 mm/year compared to its immediate surroundings.

Tables 2, 3, and 4 depict the historical characteristics of annual rainfall, total runoff and groundwater recharge amount of all the selected stations.

Stations like Calabar, Ossomala closer to the Atlantic Ocean (i.e., far south) recorded higher amount of annual rainfall, total runoff and groundwater recharge compared to Katsina and Sokoto stations in the far north. For example, the annual rainfall amount of 2722.47 mm observed over Calabar station for the historical period is higher than 534.75 mm and 502.79

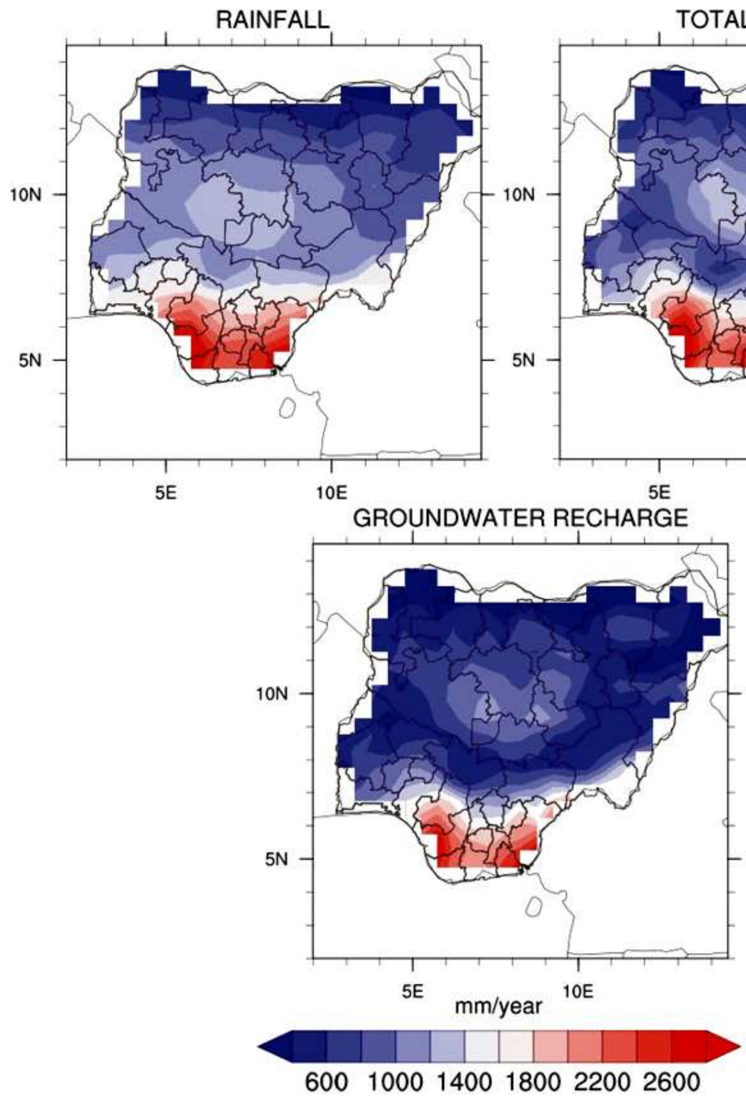

Fig. 2: Historical spatial pattern of annual rainfall, total runoff and groundwater recharge over Nigeria from 1971 to 2005 (data downloaded from Source: http://data.isimip.org/download)

mm mean annual rainfall recorded over Sokoto and Katsina, respectively. Similar pattern was also seen in total runoff (Table 3) and groundwater recharge (Table 4 and Figure 3, 4 and 5 respectively).

The correlation coefficient with values that range from -1 to 1 is a statistical measure of the strength of a linear relationship between two variables. For all ten stations, correlation values exist between rainfall and total runoff (Fig. 6) and between rainfall and groundwater recharge (Fig. 6). Highest and lowest correlation values of 0.93 and 0.83 between rainfall and total runoff were observed over Minna and Sokoto respectively while the maximum and minimum correlation value of 0.94 (Maiduguri) and 0.81 (Yola) were observed between rainfall and groundwater recharge. In all stations, there is strong relationship between annual rainfall and total runoff/groundwater recharge shown by the observed correlation values $\geq$ 0.81. The scatter plots show positive correlation, as an increase in rainfall equals an increase in qtot and qr.

The time series plot in Figure 3 shows the annual rainfall in the selected stations for a historical period (1971-2005). The regression line is used to interpret the time series plots. The direction and slope of the line shows the overall trend in the data. The regression line shows an increase in rainfall over time. The historical time-series plots of annual total runoff (qtot) and groundwater recharge (qr) for the period of 36 years also depicts an overall increase in qtot and qr in the selected stations over the years

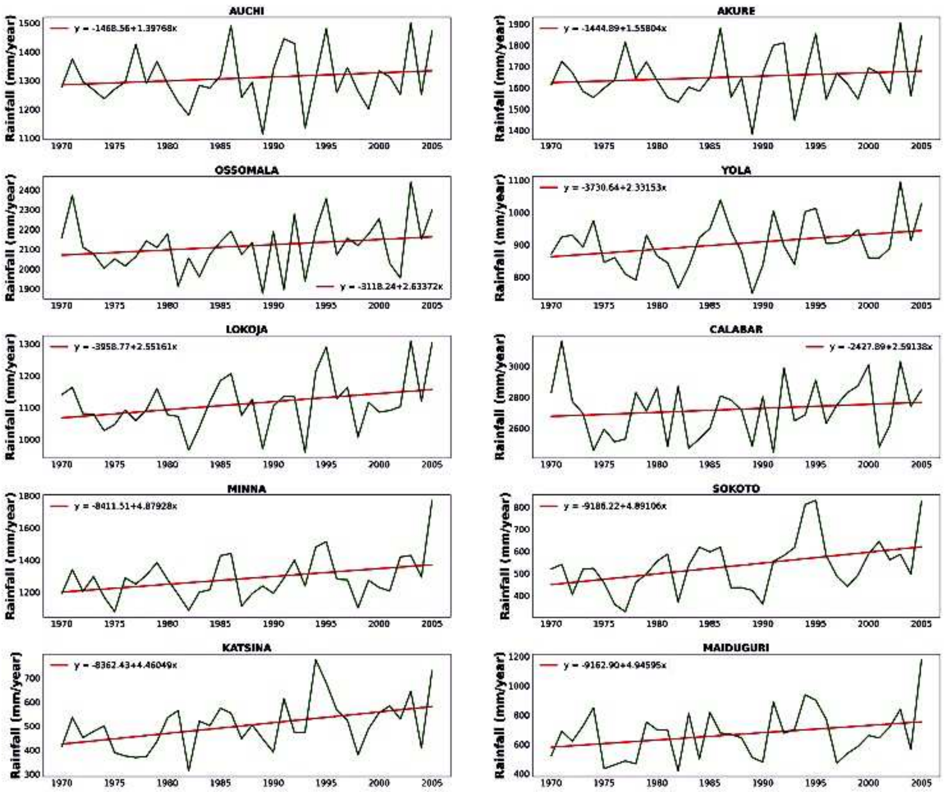

Fig. 3: Historical time-series of annual rainfall over ten selected stations in Nigeria from 1971 to 2005
(Data source: http://data.isimip.org/download)

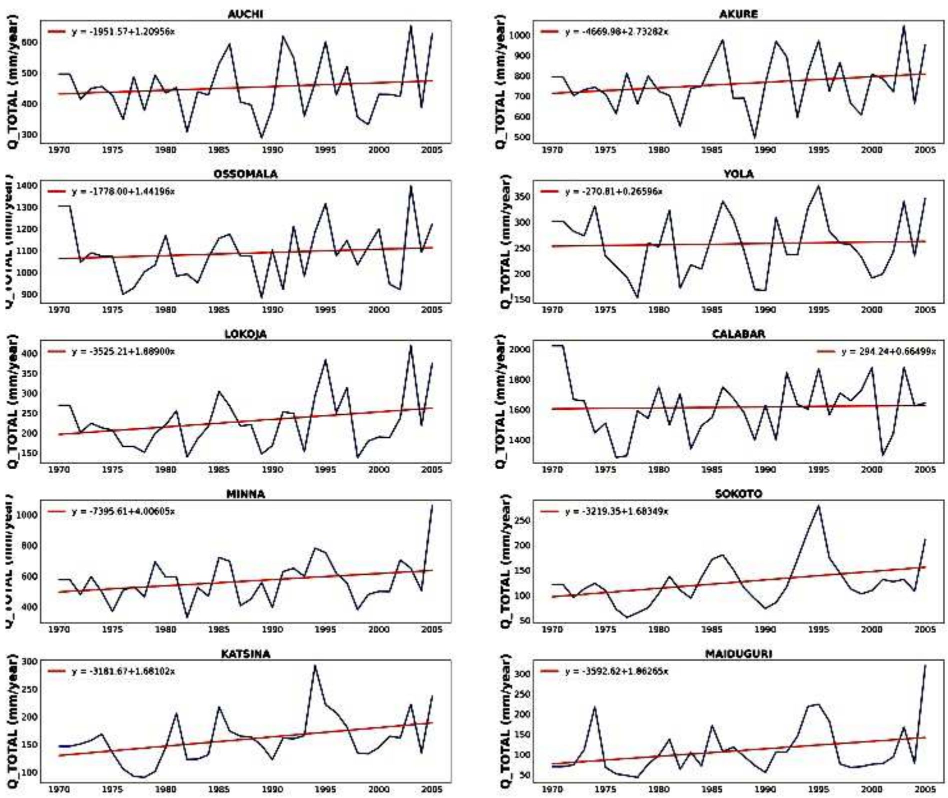

Fig. 4: Historical time-series of annual total runoff over ten selected stations in Nigeria from 1971 to 2005.
(Data source :http://data.isimip.org/download)

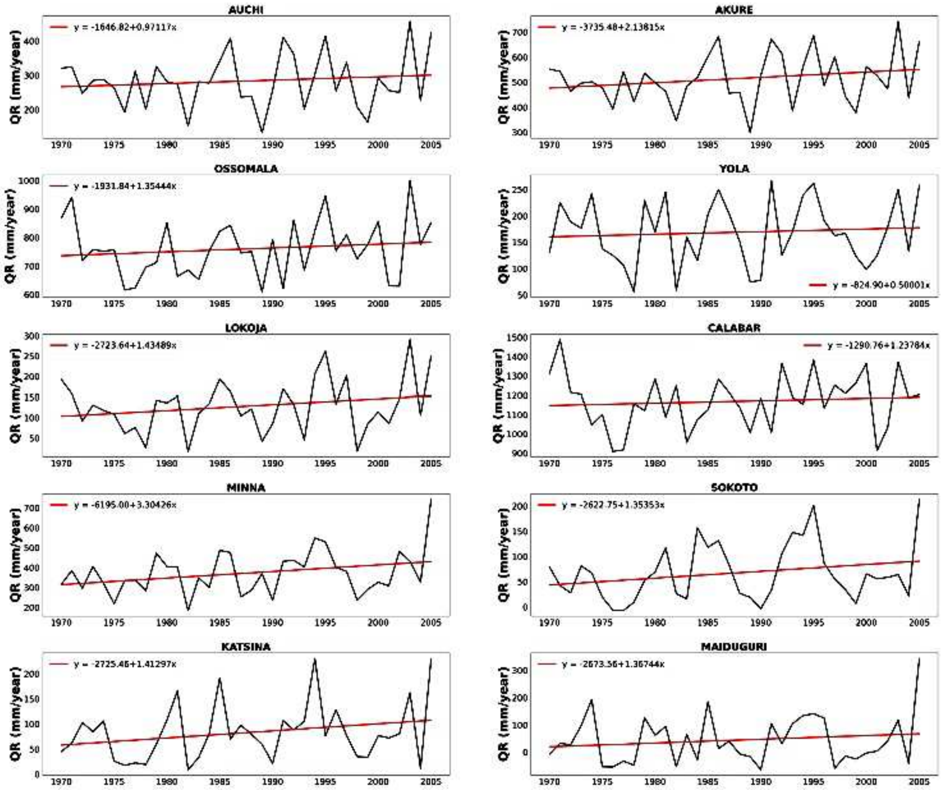

Fig. 5: Historical time-series of annual groundwater recharge over ten selected stations in Nigeria from 1971 to 2005 (Data source: http://data.isimip.org/download)

Table 2: Statistical description of historical annual rainfall

	AUCHI	AKURE	OSSOMALA	YOLA	LOKOJA	CALABAR	MINNA	SOKOTO	KATSINA	MAIDUGURI
count	36	36	36	36	36	36	36	36	36	36
mean	1309.33	1651.72	2116.28	903.28	1112.56	2722.47	1286.06	534.75	502.79	667.17
std	94.96	118.42	132.5	77.56	83.74	182.83	137.64	120.34	104.19	167.81
min	1114	1383	1877	749	959	2444	1079	326.9	313.1	419
25%	1256.5	1570.75	2045.5	855.5	1075	2579.25	1198.25	453.2	429.75	519.25
50%	1292	1641	2114.5	900	1104	2729.5	1275.5	530.65	501.1	672.5
75%	1350.25	1701	2180.25	943.25	1145.75	2835.5	1352	587.62	557.48	757.5
max	1501	1906	2440	1095	1309	3162	1771	830.2	776.5	1178

Table 3: Statistical description of historical Total runoff

	AUCHI	AKURE	OSSOMALA	YOLA	LOKOJA	CALABAR	MINNA	SOKOTO	KATSINA	MAIDUGURI
count	36	36	36	36	36	36	36	36	36	36
mean	452.43	761.5	1087.89	257.79	229.17	1615.92	566.42	126.58	159.35	109.39
std	89.86	124.79	126.97	57.23	68.2	190.24	139.45	46.6	42.87	61.1
min	289.2	496	884	153.2	137.9	1282	330	55.9	90.4	43.3
25%	393.7	690.75	989.75	216.18	183.95	1496.5	480	101	134.2	69.97
50%	432.6	741	1075	254.1	217.9	1626.5	557	115.75	154	86
75%	496.2	814.5	1171.25	302.65	258.5	1714.75	634.5	139.43	169.95	122.9
max	652	1045	1397	370.2	419.3	2023	1059	278.7	292.5	320.3

Projected Hydro-Meteorological Data Change

Figure 8 shows the spatial pattern of annual rainfall, total runoff (qtot) and groundwater recharge (qr) over Nigeria for the projected period of 2006-2041. Annual rainfall pattern shows a southward increase in mean annual rainfall from inland regions. It is observed that a maximum projected annual rainfall, total runoff and groundwater recharge of 3000 mm/yr over the coastal region of Nigeria decreases to about 600 mm/yr in the far northern part of Nigeria.Regions with high topography, such as the Jos Plateau, exhibit projected

Table 4: Statistical description of historical Groundwater recharge

	AUCHI	AKURE	OSSOMALA	YOLA	LOKOJA	CALABAR	MINNA	SOKOTO	KATSINA	MAIDUGURI
count	36	36	36	36	36	36	36	36	36	36
mean	283.38	514.08	760.11	168.88	128.21	1169.44	372.22	67.39	82.82	44.22
std	77.56	100.24	99.73	61.34	65.49	140.81	108.82	56.43	56.9	89.53
min	133.2	298.9	610	56.1	17	909	184.3	-7	9.2	-63.5
25%	238.78	458.5	686	124.95	85.5	1085	299.75	25.6	34.95	-25.22
50%	279.25	500.2	753.5	168.3	126.15	1185	359.35	57.4	77.05	29.6
75%	324.92	562.65	828.75	226.42	159.38	1254.75	431.85	91.5	105.55	104.75
max	456.5	742.6	1000	267.1	290.8	1488	742.9	213.4	230.5	343.6

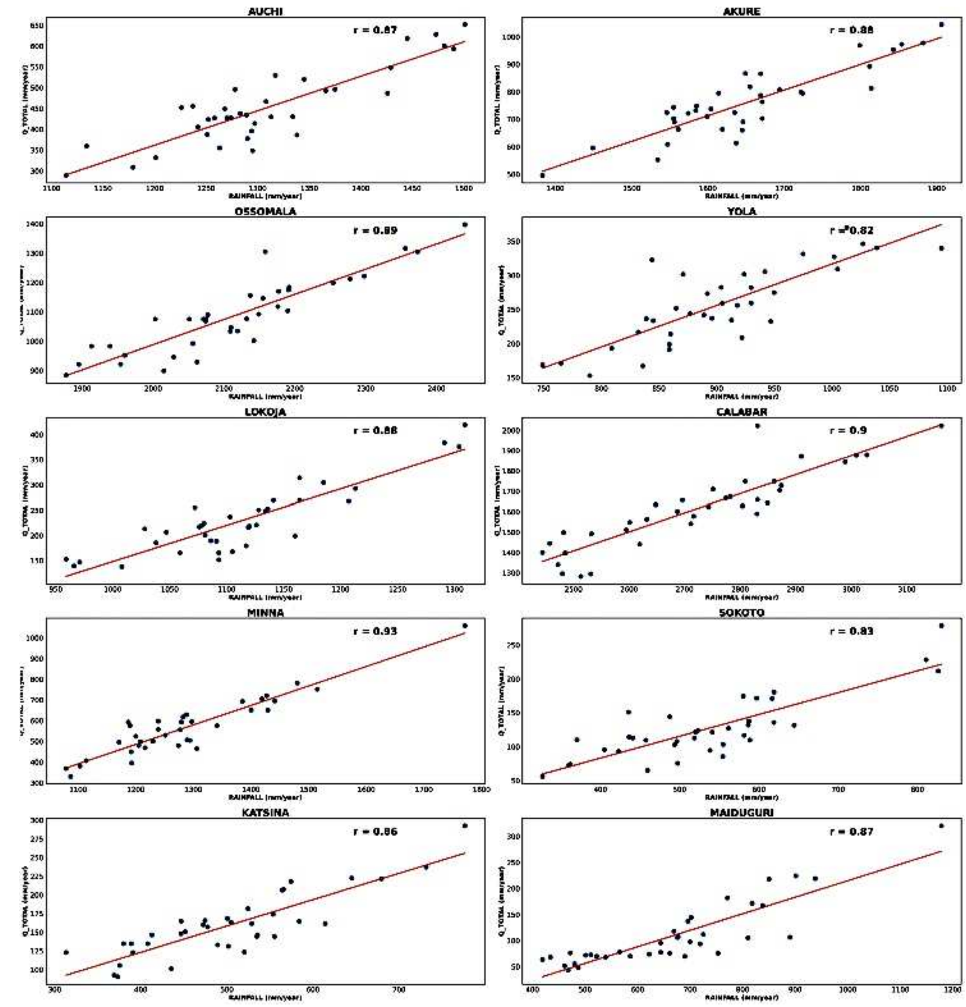

Fig. 6: Correlation between annual rainfall and annual total runoff of ten selected stations over Nigeria

annual rainfall, total runoff, and groundwater recharge amounts exceeding 1300 mm/year, which is higher than that of their immediate surroundings.

Tables 5, 6, and 7 depict the projected characteristics of annual rainfall, total runoff and groundwater recharge amount of all the selected stations. The stations like Calabar, Ossomala record a projected higher amount of annual rainfall, total runoff and groundwater recharge mean values of 2790.31mm, 1632.19mm, and 1183.72mm respectively. Sokoto and Katsina show the lowest projected mean annual rainfall amount of 716.83mm and 729.03mm respectively. The lowest projected total runoff and groundwater recharge amounts are observed in Sokoto and Lokoja with means values of 223.3mm, 298.2mm and 135.96mm, 181.01mm respectively.

The time series plot in Figure 9 shows the annual rainfall in the selected stations for the projected period, the

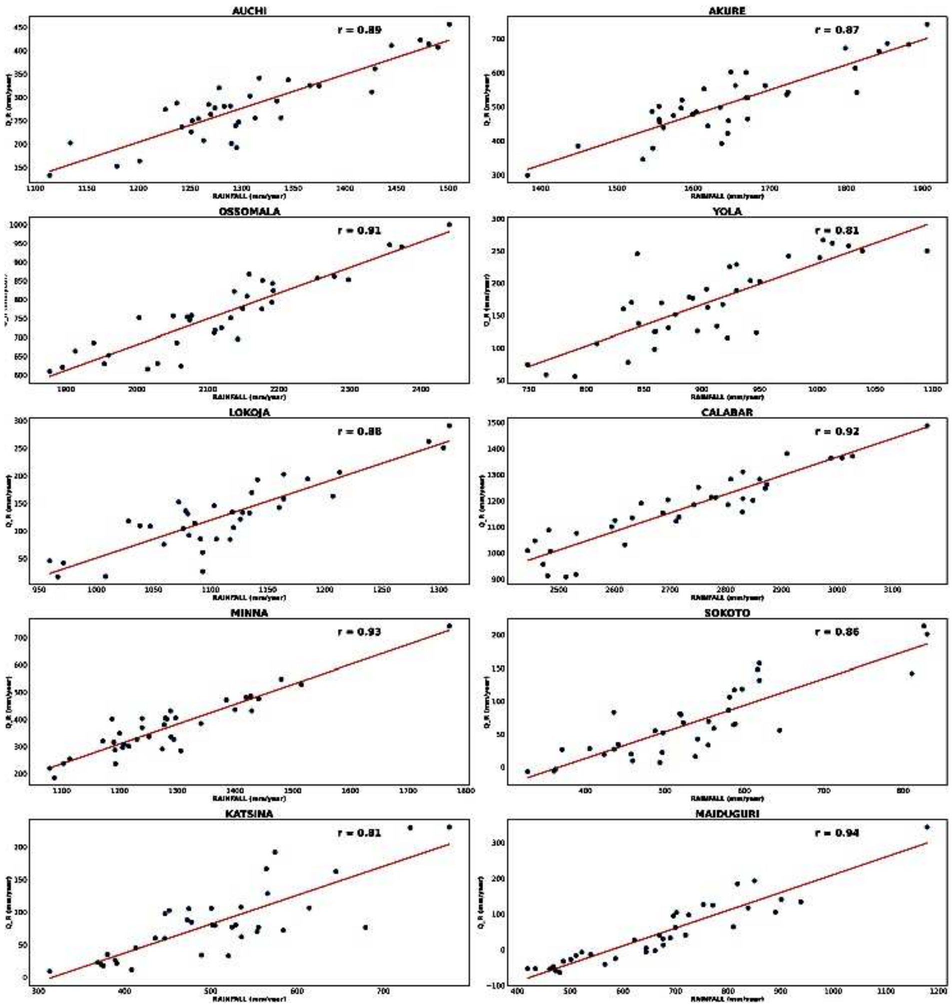

Fig. 7: Correlation between annual rainfall and annual groundwater recharge of ten (10) selected stations over Nigeria

regression line shows an increase in rainfall in stations like Yola, Katsina, Maiduguri, Sokoto and Lokoja. The regression line with negative slope indicates a decrease in rainfall trend in some stations (Calabar, Minna) and a close to zero value indicating no significant change in rainfall trend for some stations (Akure, Auchi, Ossomala) from 2006-2041. A comparison between the historical and projected plots suggests a high likelihood of increased annual rainfall in some stations over the next decade. A projected decrease in total runoff is observed in Calabar and Ossomala. Maiduguri shows a significant increase in the total runoff and groundwater recharge trend for the projected period. Annual total runoff and groundwater recharge derived from observed historical and projected time series records of the ten (10) selected stations in Nigeria are strongly correlated to annual rainfall.

Figures 12, 13, and 14 represent future annual rainfall, total runoff, and groundwater recharge anomalies over selected stations relative to the historical mean. The anomaly, which refers to the deviation from the mean, represents the projected difference between the future and historical mean for annual rainfall, total runoff, and groundwater recharge. The red curves on each plot represent a non-linear trend obtained by a two-year moving average. Positive anomalies on each plot are marked by points where the anomaly value is above zero, indicating an above-average amount of rainfall, total runoff, and groundwater recharge relative to the historical mean. Conversely, the anomaly is negative if the projected future values are lower than their respective historical means.

The plots show that stations in Sokoto, Maiduguri, Katsina, Ossomola, and Akure will experience an increase in rainfall, total runoff, and groundwater recharge amounts between 2025 and 2030, as obtained by a two-year moving average. This increase is attributed to climate change

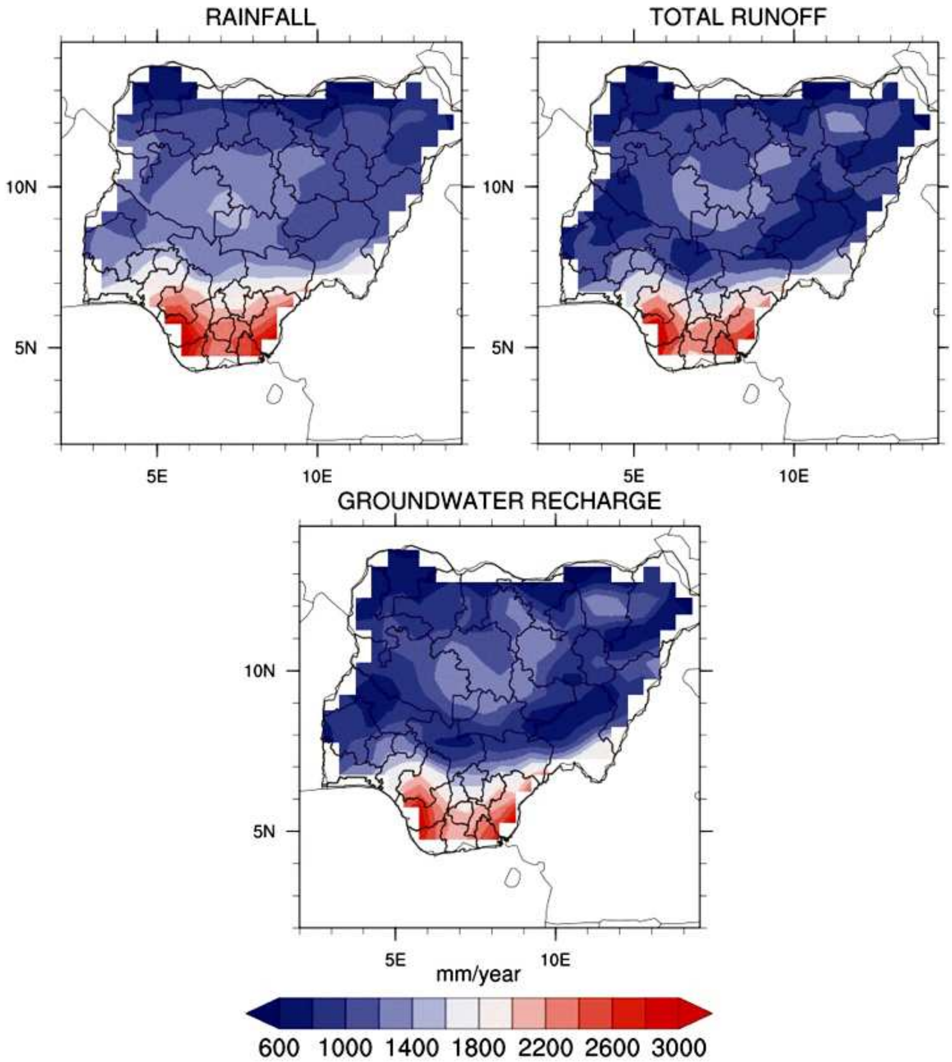

Fig. 8: Projected (future) spatial pattern of annual rainfall, total runoff and groundwater recharge over Nigeria from 2006 to 2041.

Table 5: Statistical description of projected annual rainfall

	AUCHIs	AKURE	OSSOMALA	YOLA	LOKOJA	CALABAR	MINNA	SOKOTO	KATSINA	MAIDUGURI
count	36	36	36	36	36	36	36	36	36	36
mean	1400.47	1764.17	2217.58	1023.92	1211.25	2790.31	1379.53	716.83	729.03	920.31
std	111.4	135.66	152.55	98.2	109.49	192.67	170.36	154.75	146.04	194.35
min	1201	1530	1908	801	947	2499	1054	450	455	529
25%	1308	1677.25	2141	954.5	1148.5	2641.75	1238.5	606.25	650.5	789.25
50%	1384.5	1729.5	2196	1010.5	1194.5	2765	1367	721	713.5	900.5
75%	1452.5	1834.5	2267.25	1086.75	1258.5	2884.5	1485.25	832.75	821.5	1054.25
max	1660	2092	2599	1214	1458	3295	1809	1081	1118	1394

Table 6: Statistical description of projected total runoff

	AUCHI	AKURE	OSSOMALA	YOLA	LOKOJA	CALABAR	MINNA	SOKOTO	KATSINA	MAIDUGURI
count	36	36	36	36	36	36	36	36	36	36
mean	514.64	842.81	1142.89	325.34	298.2	1632.19	635.08	223.3	303.49	256.74
std	119.14	146.69	153.58	86.06	92.48	189.17	184.52	99.48	132.76	134.81
min	338.4	624	851	189.7	126.3	1347	272	101.8	125	97
25%	423.65	751.25	1048	266.3	234.02	1486.25	509.5	170.35	219.95	151.9
50%	488.8	813.5	1134	312.05	291.15	1592	620.5	187.4	285.7	214.25
75%	577.45	915.5	1199.5	377.4	339.1	1719.5	757.75	257.48	339.62	337.9
max	775.5	1167	1525	552.3	510.1	2127	1101	606.1	757.1	663.4

Table 7: Statistical description of groundwater recharge

	AUCHI	AKURE	OSSOMALA	YOLA	LOKOJA	CALABAR	MINNA	SOKOTO	KATSINA	MAIDUGURI
count	36	36	36	36	36	36	36	36	36	36
mean	331.42	575.01	800.14	221.68	181.01	1183.72	425.15	135.96	183.89	137.55
std	98.86	115.81	120.19	81.43	80.72	146.98	143.87	115.54	150.63	133.66
min	187.7	392.8	582	58.4	3.7	951	118.1	-19.9	-33.8	-86.2
25%	251.1	496.55	737	162.1	126.38	1061	326.05	62.8	57.85	53.68
50%	309.55	559.55	787	212.75	180.2	1157.5	417.9	108.5	168.2	105.8
75%	388.2	637.25	844.5	277.98	217.4	1242.5	522.83	180.55	260.5	218.3
max	548.9	834.6	1102	427.7	356.2	1567	763.9	541.2	611.5	487.9

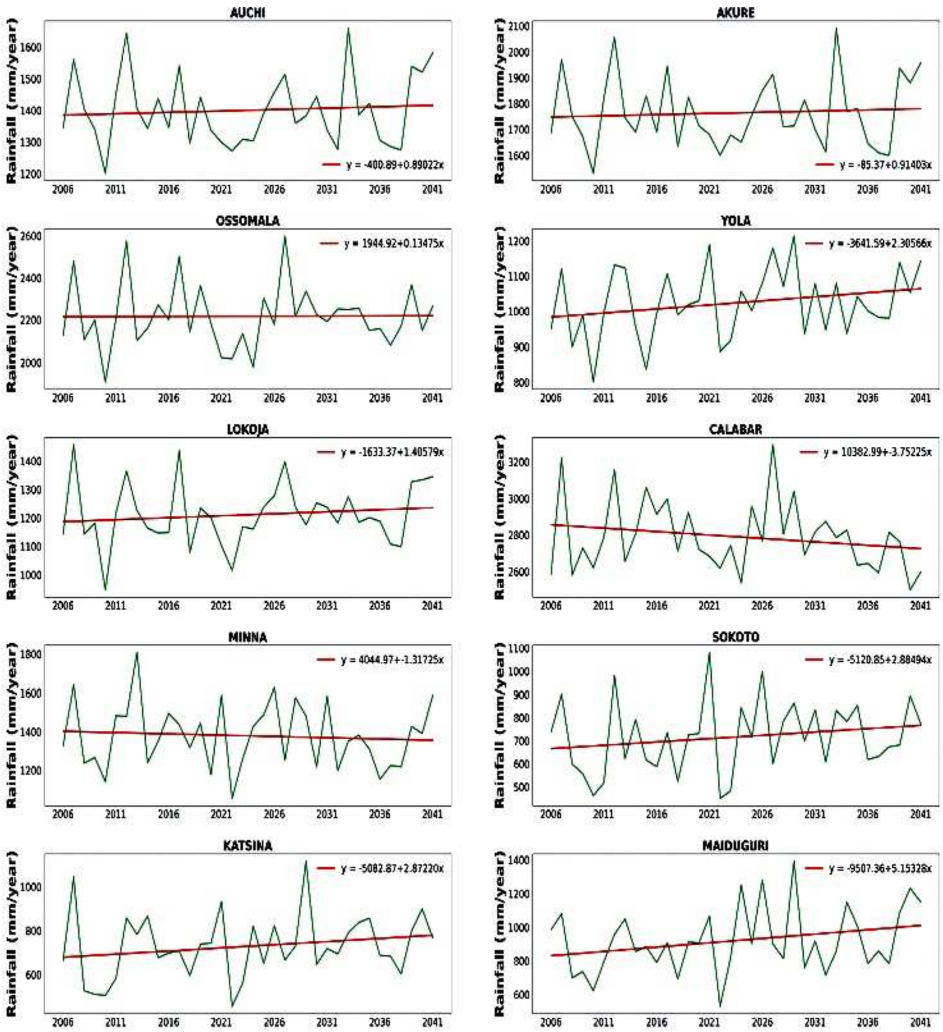

Fig. 9: Future time-series of annual rainfall over ten selected stations in Nigeria from 2006 to 2041

Auchi Station

Auchi lies within Latitude 07° 03' 42.2"and Longitude 006° 16' 14.7". This area experiences the humid tropical climate, which is characterized by wet and dry seasons. Auchi is one of the flood prone local government areas in Nigeria where the cause of flooding is not only due to climate change and anthropogenic reasons but also due to the geology and topography in the area. The area also suffers acute groundwater shortage. The topography is relatively undulating with a rugged relief, and it slopes from the north of the area to the south. The area is characterized by detritic drainage system and is drained mainly by River Orle and River Niger with their tributaries. The hydrogeological properties of the subsurface formations in Auchi and their potential impact on groundwater recharge in the context of climate change is investigated.

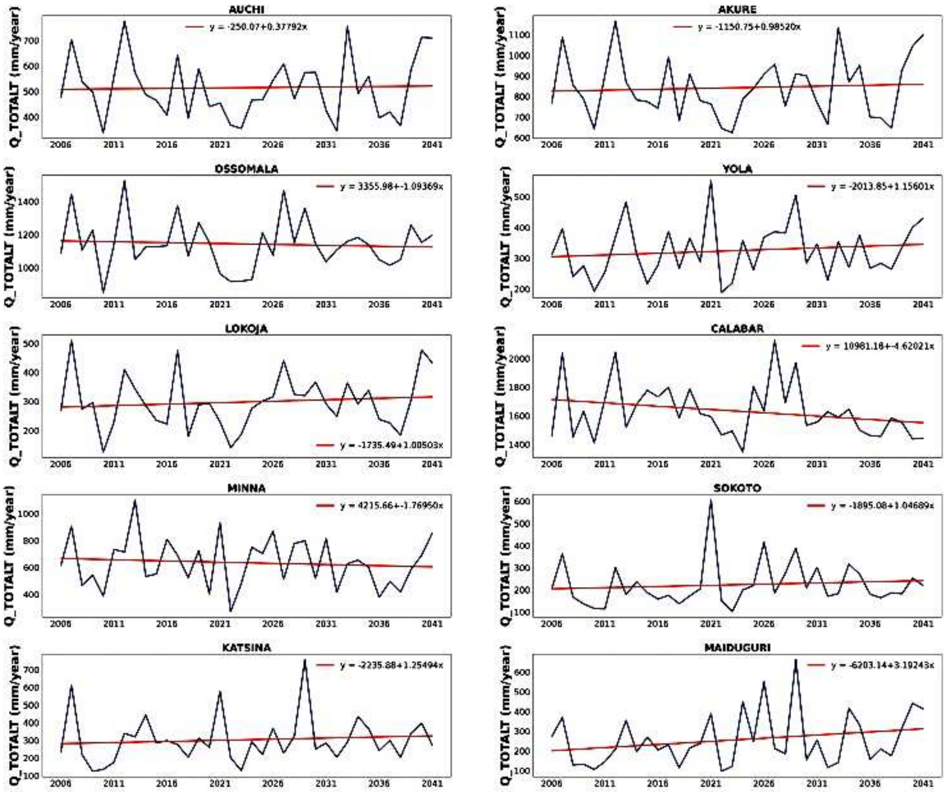

Fig. 10: Future time-series of annual total runoff over ten selected stations in Nigeria from 2006 to 2041

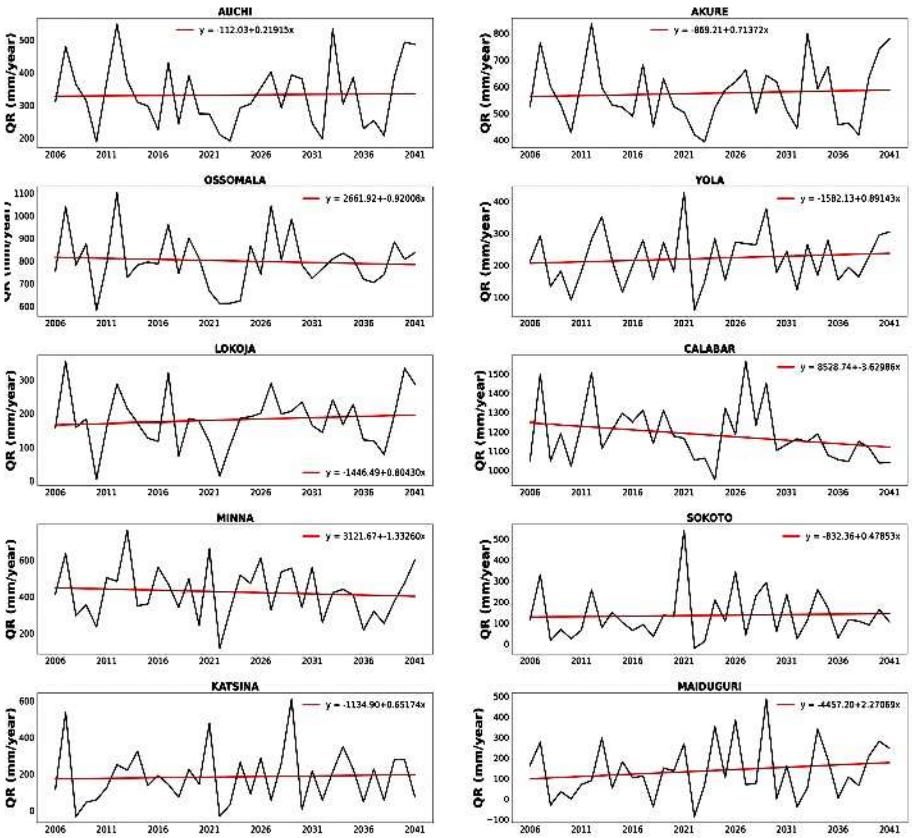

Fig. 11: Future time-series of annual groundwater recharge over ten selected stations in Nigeria from 2006 to 2041

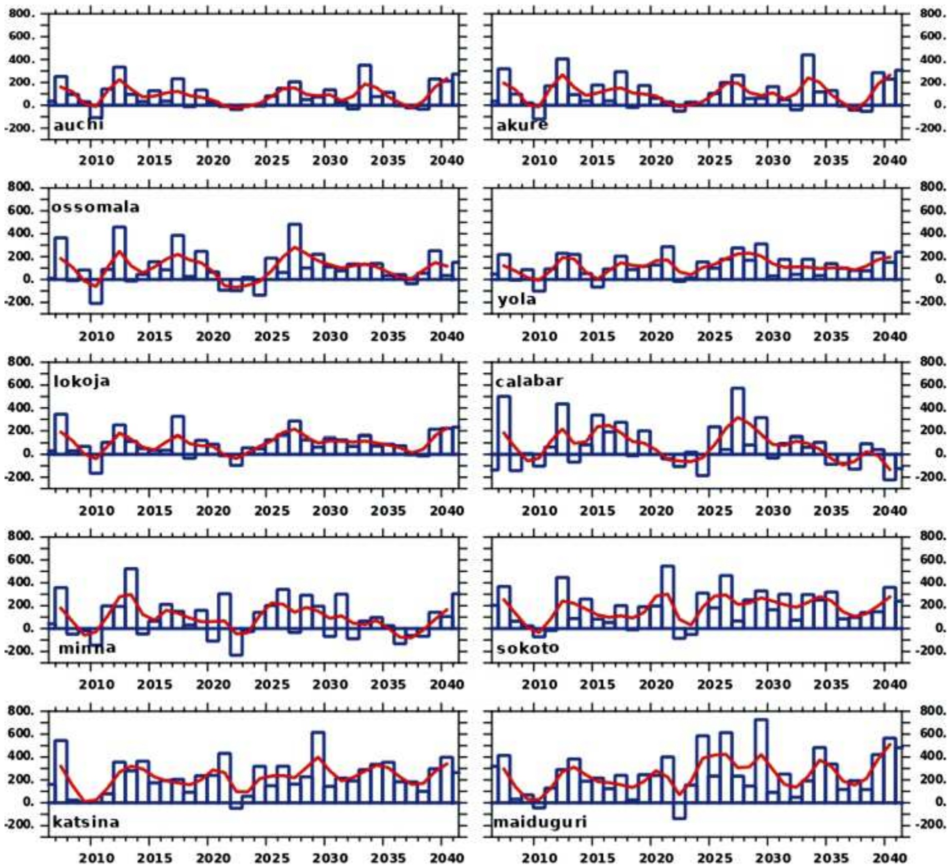

Fig. 12: Future annual rainfall anomaly over ten selected stations relative to historical (1971–2005) mean.

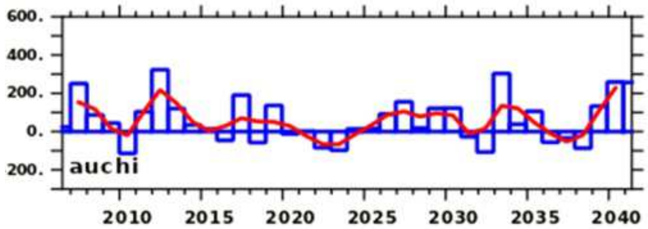

Fig. 13: Future annual total runoff anomaly over ten selected stations relative to historical (1971–2005) mean.

Climate Change Data and Impact Assessment in Auchi

Climate change is manifesting in Auchi through extreme weather events like heavy rainfall, flooding, and droughts, which are affecting groundwater recharge. Greenhouse gas emissions from fossil fuels are altering rainfall patterns, posing serious implications for freshwater in aquifers. These changes have adverse effects on socio-economic activities, agriculture, and water resources.

Historical data from 1971 to 2005 in Auchi shows an upward trend in annual rainfall, total runoff, and groundwater recharge, with mean values of 1309.33mm, 452.43mm, and 283.38mm, respectively. The projected period from 2006 to 2041 indicates an increase in annual rainfall, with a mean of 1400.47mm, as well as higher total runoff and groundwater recharge, with mean values of 514.64mm and 331.42mm, respectively, during the same period.

The overall increase in these parameters in the projected period compared to the historical period is predicted, implying greater water resources availability in Auchi. This could have mixed effects on socio-economic activities and agriculture in the region. A thorough study of the climate data and impact assessment in Auchi is therefore, necessary as these events lead to adverse impacts on socio-economic activities, agricultural production, and water resources. The historical time series of annual rainfall, total runoff, and groundwater recharge (1971-2005) in Auchi indicate an upward trend, with mean values of 1309.33mm, 452.43mm, and 283.38mm, respectively (Figures 3-5). The projected period of 2006-2041 shows an increase in annual rainfall, with a mean amount of 1400.47mm (Figure 9). Additionally, there is a projected increase in annual total runoff and groundwater recharge with slightly above

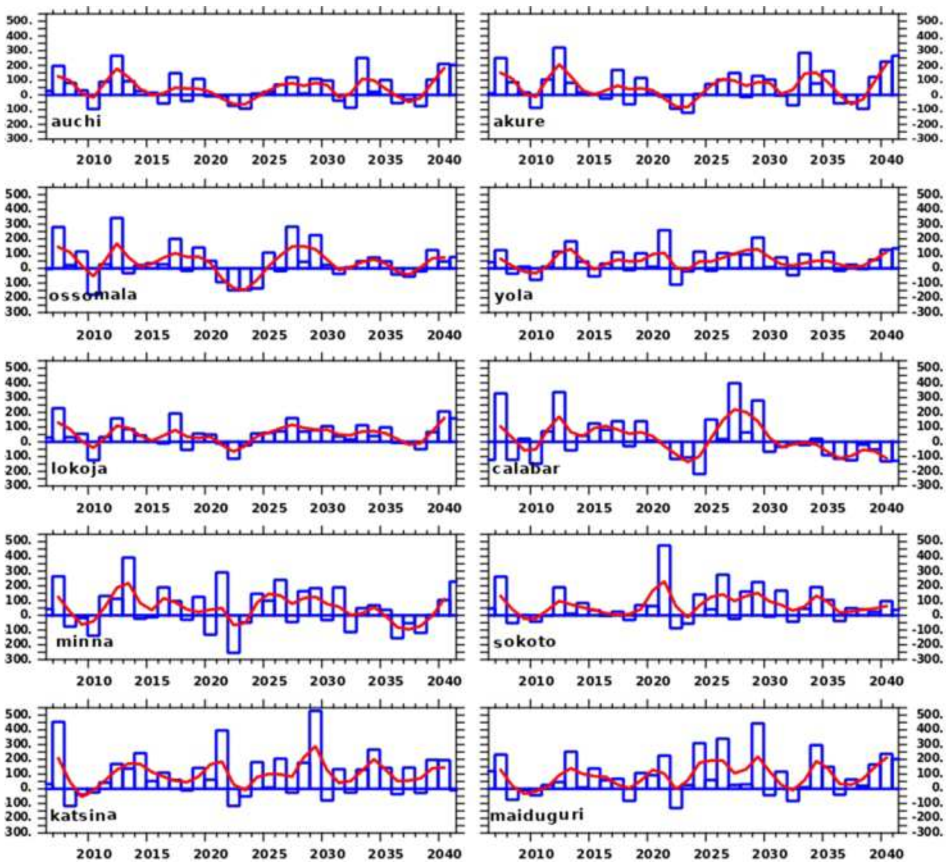

Fig. 14: Future annual groundwater recharge anomaly over ten selected stations relative to historical (1971–2005) mean.

zero slopes and mean values of 514.64mm and 331.42mm, respectively, for the same period, as represented in Figures 10 and 11.

The correlation graphs (Fig. 6 and 7) indicate a strongly positive correlation between these hydro-meteorological parameters in Auchi for both the historical and projected periods.it can be inferred from Figures 12, 13 and 14 that the study area will experience an increase in rainfall, total runoff, and groundwater recharge amounts between 2025 and 2035, as obtained by a two-year moving average. This increase can be attributed to climate change. The table below provides a clear summary of the mean annual values of the hydro-meteorological parameters over Auchi for the historical and projected periods. It shows that all three parameters are expected to increase in the projected period compared to the historical period. This suggests that there will be a greater availability of water resources in Auchi in the projected period, which could have both positive and negative impacts on the socio-economic activities and agricultural production in the region

Table 10: Mean Annual Values of Hydro-meteorological Parameters in Auchi for Historical (1971-2005) and Projected (2006-2041) Periods.

Description	Historical (1971-2005)	Projected (2006-2041)	Projected Change
Mean annual Rainfall(mm)	1309.33	1400.47	91.14
Mean annual Total runoff(mm)	452.43	514.64	62.21
Mean annual Groundwater recharge (mm)	283.38	331.42	48.04

Aquifer Delineation and Characteristics in Auchi

The sandstones and siltstones layers of the Ajali formation in the Benin flank (western flank of Anambra Basin) in Auchi are generally porous and permeable, making them good aquifers for the storage and movement of groundwater. However, the shales and clays in the formation are generally impermeable and act as confining layers, limiting the movement of groundwater Babaiwa *et al.* (2020).

Geology and Hydrogelogy of Auchi and Environ

Auchi is located in southwestern Nigeria (Fig. 15), and its geology is characterized by sedimentary rocks of the Ajali Formation (Obaje *et al.* 2004). The Ajali Formation is composed of dry sand, sandstones and clay, with occasional clay and limestone layers. The formation is believed to have been deposited during the Lower Cretaceous period, around 120-130 million years ago. The Anambra hydrogeological Basin comprises an, almost, triangular shaped embayment covering an area of about 30,000km^2 with a sedimentary pile of approximate thickness of 9 km (Iheanacho 2016). It stretches from the area just south of the confluence of the River Niger and Benue across to areas around Auchi, Okene, Agbo and Asaba, west of the river, and Anyangba, Idah, Nsukka, Onitsha and Awka area, east of the river. From an elevation of about 300m, the Udu – Idah escarpment slopes gently towards the southwest into the flood plain of the River Niger and across, to the west. The basin is drained mainly by the Anambra River and its main tributaries, the Mamu and Adada (Offodile, 2002). Field observations and desktop study show that Auchi is underlain by geologic materials belonging to the Ajali formation (Obaje, 2009). The Ajali formation is successively underlain by materials belonging to the Nsukka and Mamu formations. The Nsukka formation hitherto called the upper coal measure, bears sandstone, shale and coal while the underlying Mamu formation which has compositional similarity with the Nsukka,

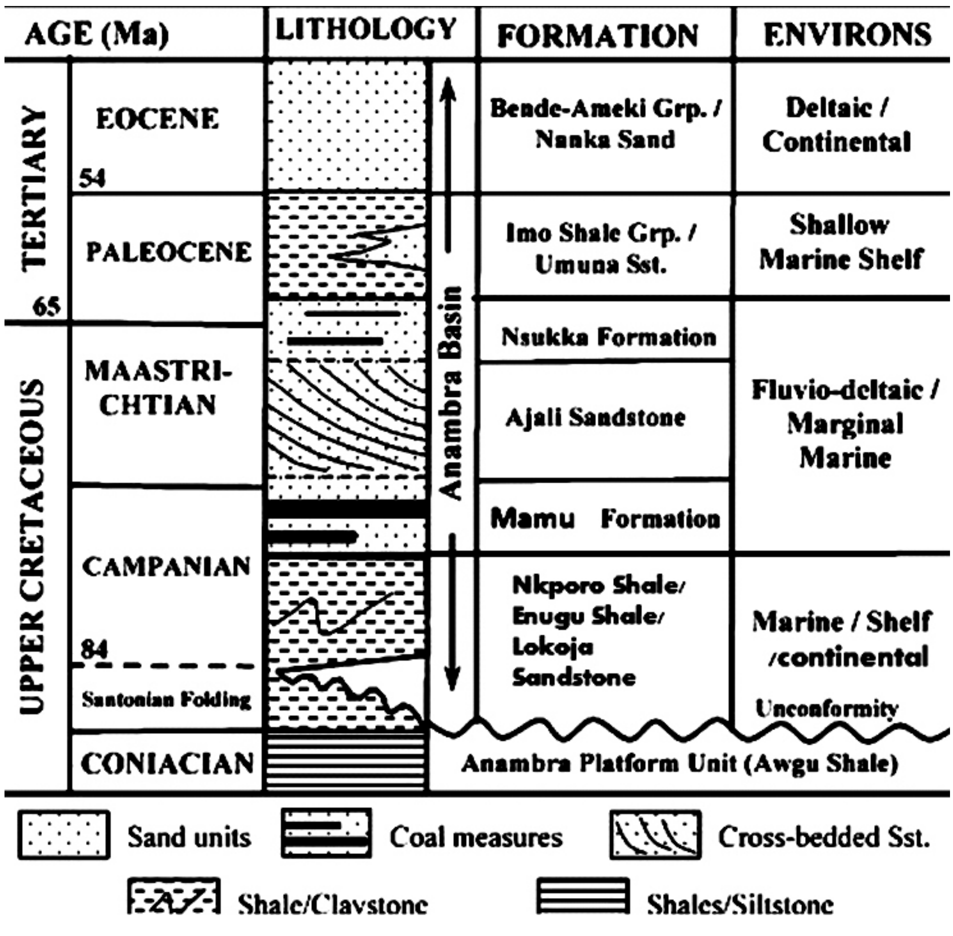

Fig. 15: Stratigraphy and Gross Depositional Environment Anambra Basin (modified from Tijani et al., 2010)a

offers a higher frequency of coal occurrence. Hydrogeologically, the Ajali formation constitutes a heterogeneous lithological sequence, with a generally deep-water table conditions ranging from 30m to over 170m in places (Offodile, 2002). The sandy aquifers within the formation are friable, poorly sorted and typically whitish at depth (Ilegieuno *et al.* 2020,). Three lithofacies belonging to two different lithostratigraphic units are recognized in Auchi area, namely shale unit overlain by cross-bedded, burrowed sandstone which is then overlain by ferruginize sandstone (Adekoya *et al.* 2011). Also, the aquifers are often overlain by highly resistive (dry) sandy/sandstones/ clayey layer and deep down, the groundwater is ferruginous.

The geophysical survey carried out by of Babaiwa *et al.* (2020) using Vertical Electronic Sounding (VES) reveals six (6) to seven (7) subsurface layers in VES 1 and 2 namely:
Layer 1: Topsoil (0-5 meters),
Layer 2: Clayey sand and sandy clay (5 to 15 meters)
Layer 3: Dry sand (encountered at depth (30 to 35 meters) indicating the absence of groundwater,
Layer 4: Wet sandstone and saturated sandstone

These layer classification was adapted in this study to investigate the subsurface geology and aquifer characteristics. The ability of the various soil lithologies in Auchi to allow for the percolation and storage of groundwater depend on a number of factors, including the porosity, permeability, and thickness of the different layers. However, the presence of impermeable confining layers creates conditions for the formation of confined aquifers.

Discussion

The study focused on assessing the impact of climate change, specifically changes in rainfall and total runoff, as well as lithology on groundwater recharge in ten stations in Nigeria. The assumption was made that land use and other biophysical factors would remain constant in the future. Future climatic and hydro-meteorological data, including rainfall, total runoff, and groundwater recharge, were obtained from a multi-model ensemble (MME) of regional climate models (RCMs) through the Inter-sectoral Impact Model Inter-comparison Project (ISIMIP) framework. The study used the RCP 8.5 emission scenario, representing a business-as-usual scenario, to evaluate the potential impact on groundwater recharge if immediate mitigation and adaptation strategies are not implemented. The results estimated mean annual values for rainfall, total runoff, and groundwater recharge over the selected stations for both historical and projected periods.

The predicted mean annual values for rainfall, total runoff, and groundwater recharge for the ten selected stations between 2006 and 2041 are presented. The results revealed significant variations across the stations. For instance, Sokoto, located in the far north, exhibited the lowest predicted mean annual rainfall, total runoff, and groundwater recharge values. According to Wali *et al.*, (2019) groundwater within the basement complex area of the Sokoto basin typically exists in limited quantities. While boreholes drilled into the unweathered basement rock, tend to yield only a small amount of water, those in the weathered basement section, known as regolith, like the one at Yandu, offer more promise. In these areas, characterized by coarse sand, gravel, and clay, groundwater can be extracted in substantial quantities from the regolith aquifer. In the Central Sokoto basin, the lithological composition of boreholes includes clay with sand, laterites, clay, limestone, and basal sand, indicating a significant groundwater potential. However, this potential is under threat from decline in the water table during prolonged dry periods. Floodplain and shallow groundwater reservoirs have been tapped for agricultural irrigation and domestic purposes (Hamidu *et al.*, 2017). Additionally, the general lowland topography of this area might be responsible for the minimal runoff, as indicated in Table 3.

The hydro-meteorological parameters at Calabar station exhibit the highest values among the studied locations. Situated atop a pile of Cretaceous sediments spanning over 3 kilometers, including carbonate, clastic, sandstone, and shale formations, the Calabar area boasts distinctive characteristics. It features shallow aquifers and maintains a high groundwater table for much of the year, attributed to extended wet seasons and occasional rainfall during shorter dry periods. This abundance of groundwater resources potentially remains underutilized, with excess water cascading into rivers and streams (Uchenna *et al.*, 2023). The region's prolonged periods of heavy precipitation, coupled with surplus groundwater and its relatively flat terrain, along with the susceptibility of its lithology to weathering, may exacerbate continuous land degradation through gully erosion and flooding.

In the Ossomala region, groundwater conforms to the local topography, flowing in a northeast to southwest direction and lying deeper beneath the aquifer (Anizoba, 2022). However, the area grapples with flooding and gully erosion (Arinze, 2023), exacerbated by the loose sediment composition, prolonged rainfall, proximity to the River Niger, and its topography . Projections indicate that Ossomala is expected to experience heightened precipitation, runoff, and groundwater recharge (as indicated in Tables 5, 6, and 7, respectively). This underscores the urgent need to address the threats of flooding and erosion to prevent future devastation.

The study provided valuable insights into the potential impact of climate change on groundwater recharge in the selected stations in Nigeria. It demonstrated the importance of considering future climatic scenarios and their implications for groundwater resources, emphasizing the need for proactive measures to mitigate and adapt to changing conditions.

Around Auchi and its environ the presence of a layer that is characterized by dry sand with a resistivity of 1943.4 Ωm and a thickness of 19.4 m in VES 1 of Babaiwa et.al., 2020 survey result and the absence of this dry layer in the VES 2 (Babaiwa et.al., 2020) shows that the formation is not present or continuous everywhere, or the hydrological characteristics varies from place to place. The Dry layer without groundwater overlying a saturated basal layer indicates that the dry layer is acting as an impediment to water percolation from the surface and as an impermeable layer to ascending underground water. The saturated layer at the base of the VES indicates that this layer allows the ascending groundwater to rise through it.

The presence of such subsurface impervious sedimentary layer will resist or impede the vertical movement of water due to their impermeable nature leading to the development of artesian aquifers, pressurized groundwater systems. This type of aquifer occurs along Uzzeba-Osiffo road, while the closest settlement suffers from scarcity of groundwater.

The layer can take various forms due to the varying presence of clay, siltstone, shale, or compacted silt and sand. Since this layer is interbeded with more permeable layers, their distribution is highly variable, they can be regionally extensive or localized as observed in VES 1 and 2. The impermeability of this layer inhibits the recharge of groundwater from the surface. This reduction in recharge rates can have significant consequences for sustainable groundwater management in affected areas. Dependence on groundwater from aquifers beneath impervious formations can lead to declining water tables. The clay-rich composition of the formations within the Sokoto basin too is responsible for the diminished water yield in boreholes and consequently adversely affecting the quantity of groundwater. Consequently, Wali *et al.* (2019), utilizing geochemical analysis of surface water, verified the existence of harmful bacteria in the surface water within this basin. They advocated for thorough treatment of the water prior to consumption as a precautionary measures. While, balancing water supply demands with the limitations posed by impervious layers is a critical challenge in some areas such as Auchi, some areas are affected by unconsolidated loose sediments that easily gives way to flooding. Impervious layers hinder the infiltration of rainwater into the groundwater system. This reduced infiltration capacity can contribute to surface runoff and increase the risk of flooding during heavy rainfall events (as indicated from the predicted years). This situation increases the susceptible to flash floods and urban flooding due to rapid runoff in most of the coastal areas. Akure like most areas underlained by basement rocks, access groundwater through handdug wells, by drilling through the weathered zone and the fractures zones Afolabi *et al.*(2022). Hand dug well within the basement usually dries up at the peak of the dry season while most boreholes with less than 40 meters depth barely survive during such dry seasons.

Although, rainfall and groundwater recharge is not expected to change significantly in the coming years around Akure, Minna, and Kastina regions, (the aquifer in Yola area due to the presence of Bima formation can only be reached beyond 80m-200m depth), therefore, care must be taken to prevent over pumping of groundwater during the dry seasons. It is recommended that hand-dug wells are further deepened to improve yield during severe and prolonged dry spells. Water conservation measures and water recycling measures should be considered. New boreholes are expected to be drilled deeper than previously done to tap into deeper prolific fractures, while tapping into weathered overburden aquifers should be minimised to maintain sufficient water during the dry seasons.

Conclusions

The findings of this study shed light on the intricate dynamics of hydro-meteorological parameters and lithological influences on groundwater recharge across various stations in Nigeria. The stark disparities observed between southern coastal areas and far northern regions underscore the need for region-specific water management strategies tailored to address the diverse challenges posed by climate variability and geological conditions. Southern stations like Calabar and Ossomala exhibit significantly higher annual rainfall, total runoff, and groundwater recharge compared to their northern counterparts such as Katsina and Sokoto. This spatial gradient in precipitation patterns is closely linked to proximity to the Atlantic Ocean, with coastal regions experiencing greater moisture influx and subsequent recharge of groundwater resources. The strong positive correlation observed between rainfall and total runoff/groundwater recharge underscores the intimate relationship between these variables, emphasizing the pivotal role of precipitation in sustaining water availability.

Projections for the period 2006-2041 highlight a continuation of these trends, with coastal regions expected to maintain higher levels of rainfall and groundwater recharge compared to inland areas. However, the study also predicts an increase in rainfall, total runoff, and groundwater recharge for select stations between 2025 and 2030, attributed to climate change. These findings underscore the urgency of implementing proactive measures to mitigate the potential impacts of climate variability on water resources. Moreover, the study underscores the significance of considering lithological characteristics in groundwater management efforts. The presence of impermeable sedimentary layers poses challenges to groundwater recharge by inhibiting vertical water movement and contributing to surface runoff, increasing the risk of flooding in affected areas. Understanding the hydrogeological properties of these formations is crucial for developing effective strategies to sustainably manage groundwater resources and mitigate flood risks.

Recommendations stemming from this research include the deepening of hand-dug wells to enhance groundwater yield during dry spells, implementation of water conservation and recycling measures, and drilling of new boreholes to tap into deeper aquifers. Additionally, further research on the hydrogeological characteristics of subsurface formations is warranted to inform more robust management strategies and enhance resilience to climate variability and flooding.

Finally, this study provides valuable insights into the complex interplay between climate change, lithology, and groundwater recharge in Nigeria. By integrating scientific findings with practical interventions, stakeholders can work towards building climate-resilient water systems capable of meeting the evolving needs of communities while safeguarding precious water resources for future generations.

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