HYDROCHEMICAL EVALUATION AND STABLE ISOTOPES STUDIES OF GROUNDWATER IN LOKOJA AREA, NORTH CENTRAL NIGERIA

BY

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ABSTRACT

Boreholes and wells are the most reliable sources of groundwater in Lokoja and its environs. Some aspects of hydrochemical properties of the groundwater resource have been assessed. However, stable isotopes characterisation to delineate recharge sources necessary for effective management of the groundwater system has not been undertaken. This work was designed to undertake an evaluation of hydrochemical and stable isotopes characteristics of groundwater in Lokoja, north central Nigeria in order to assess its quality and recharge sources.

Field geological mapping of Lokoja was carried out with rock samples collected and cut into slides for petrographic study. Physicochemical parameters were measured in the field using Hanna HI9861-3 digital meter. A total of 129 groundwater samples were collected during dry (65) and wet (64) seasons for hydrochemical analyses using inductively plasma emission spectrometry for cations and ion chromatography and titrimetry for anions. Thirty-nine samples were also collected and subjected to stable isotopes analyses using mass spectrometry. Data evaluation involving statistical correlation, estimation of Water Quality Index (WQI), Sodium Absorption Ratio (SAR) and hydrochemical plots for groundwater were carried out.

Migmatite-biotite gneiss, granite, sandstone and alluvium were the major rock units in the study area. Migmatite-biotite gneiss and granite were mostly composed of quartz, microcline, plagioclase and biotite. The water pH ranged from 5.5-10.6 and 5.4-9.1, while total hardness ranged from 4.11-472 and 1.2-260 mg/L in dry and wet seasons respectively. Electrical conductivity of 30-860 and 70-1,730 µS/cm, and total dissolved solids of 31-1,040 and 55-1,273 mg/L suggested low to moderately mineralised groundwater system. The concentrations of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} (mg/L) for dry and wet seasons were 1.12-103.52 and 0.1-79; 0.32-52.02 and 0.2-57.1; 1.61-122.27 and 3.4-157.7; and 0.55-107.17 and 1.5-72.2, respectively. The bicarbonate (HCO_3^-) was the dominant anion with values ranging from 5.16-128 and 10.3-398.7 mg/L, indicating recharge from CO_2 charged precipitation. The nitrate concentration ranged from 2.0-72.5 and 0.03-59.4 mg/L during dry and wet seasons.

The concentrations of As, Cr, Fe, Mn, Pb, Cu and Zn were <0.05 mg/L, indicating low background concentrations and hence no contamination with respect to trace elements. The analyses of stable isotopes revealed deuterium (δD) ranged from -23.9 to 11.7‰ and $\delta^{18}O$ -3.9 to -1.2 ‰, while deuterium excess (d-excess) of -6.3 and 16.2 ‰, indicated precipitation as the main recharge source with possible effects of kinetic evaporation. Positive correlations ($r>0.5$) exist between TDS and all major ions except HCO_3^-, indicating geogenic solute input to the overall mineralisation of the groundwater. Estimated WQI showed that 56.9 % of the samples fell within excellent class, while 35.4 and 7.7 % belonged to good and poor water classes, respectively. The estimated SAR revealed that 12.3, 70.8 and 16.9 % of the samples have low, medium and high salinity risk for irrigation. Hydrochemical characterisation revealed three dominant water types, which were Ca^{2+}-(Mg^{2+})-HCO_3^-, Ca^{2+-}-(Mg^{2+})-$Cl^{-}SO_4^{2-}$ and Na^{+}-(K^{+})-Cl^{-}-SO_4^{2-}, generally controlled by precipitation, weathering and dissolution of bedrocks.

The groundwater system in Lokoja and its environs has low to moderate mineralisation and limited migratory history. Recent precipitation was confirmed as the source of groundwater recharge.

Keywords: Water quality index, Sodium absorption ratio, Deuterium excess, Groundwater migratory history

Word count: 498

CERTIFICATION

I certify that this work was carried out by Mr. Rufai Ayuba (Matric. No.: 165745) in the Department of Geology, University Ibadan.

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DEDICATION

This work is dedicated to Almighty God for his blessings and to the memory of my late mother, Hajara Sani who died on June 1, 2014.

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LIST OF ABBREVIATIONS/ACRONYMS

asl = Above Sea Levels

BIS = Bureau of Indian Standards

CT = Complex Terminal

CIWA = Cooperation in International Waters in Africa

DWL = Depth to Water Level

EC = Electrical Conductivity

FMWR = Federal Ministry of Water Resource

GMWL = Global Meteoric Water Line

GPS = Global Positioning System

GSN = Geological Survey of Nigeria

ICP – MS = Inductively Coupled Plasma Mass Spectrometry

ICP – OES = Inductively Coupled Plasma Optical Emission Spectrometry

IC = Ion Chromatography

LMWL = Local Meteoric Water Line

m = Meters

mm = Millimeters

ml = Milliliters

Meq/L = Milliequivalents Per Liter

Mg/L = Milligrams Per Liter

NAFDAC = National Agency for Food and Drug Administration and Control

NOI = National Orientation Agency

PCA = Principal Component Analysis

PC = Principal Component

PQ = Plio-Quarternary

RBDAs = River Basin Development Authorities

SAR = Sodium Adsorption Ratio

SDGs = Sustainable Development Goals

SMOW = Standard Mean Ocean Water

SON = Standard Organisation of Nigeria

SWC = Saturated Water Column

TDS = Total Dissolved Solids

TDW = Total Depth of Well

TH = Total Hardness

UNESCO = United Nations Educational, Scientific and Cultural Organisation

UNICEF = United Nations Children's Fund

V-SMOW = Vienna Standard Mean Ocean Water

WQI = Water Quality Index

WHO = World Health Organisation

WL = Water Level

μS/cm = Microsiemens Per Centimeter

CHAPTER ONE

1.0 INTRODUCTION

1.1 General Statement

Groundwater is a significant source of potable water that is vital to life on earth. It offers a reliable source of water for household, agricultural and industrial uses. However, only a tiny portion of earth's water (about 2.5 percent) is fresh and suitable for human consumption. The remaining 97% plus are in the oceans and seas. However, groundwater alone constitutes about thirty percent (30.10 %) of the total 2.5 % of the world fresh water (Fig. 1.1) and it is a key drinking water source for many all over the world (Bachmat, 1994). In many places where state public water supply is not available, inhabitants of such places generally rely on groundwater as alternative source of low-cost high-quality domestic water supply (Talabi and Tijani, 2012). Nonetheless, abundant fresh water is tied up in glaciers and is essentially unavailable; the other reservoirs (for example, streams and lakes) have local importance but are far less essential on a worldwide scale compared to groundwater. The fact that groundwater is stored in the layers beneath the surface, and sometime at very high depths, helps protecting it from contamination and preserve its quality. Additionally, groundwater resource can often be found close to the final consumers and therefore does not require large investments in terms of infrastructure and treatment, as it is often necessary when harvesting surface water (CIWA, 2016).

A groundwater account in average for one third of the fresh water consumed by humans, but in some part of the world this percentage can reach up to 100% because groundwater is found almost everywhere and its quality is usually very good. It is also worthy of note that about 70% of groundwater withdrawn worldwide is used for agriculture. The groundwater quantity in aquifer is about 1,000,000 mi^3 compared to about 30,000 and 300 mi^3 in lakes and streams globally (Boswinkel, 2000).

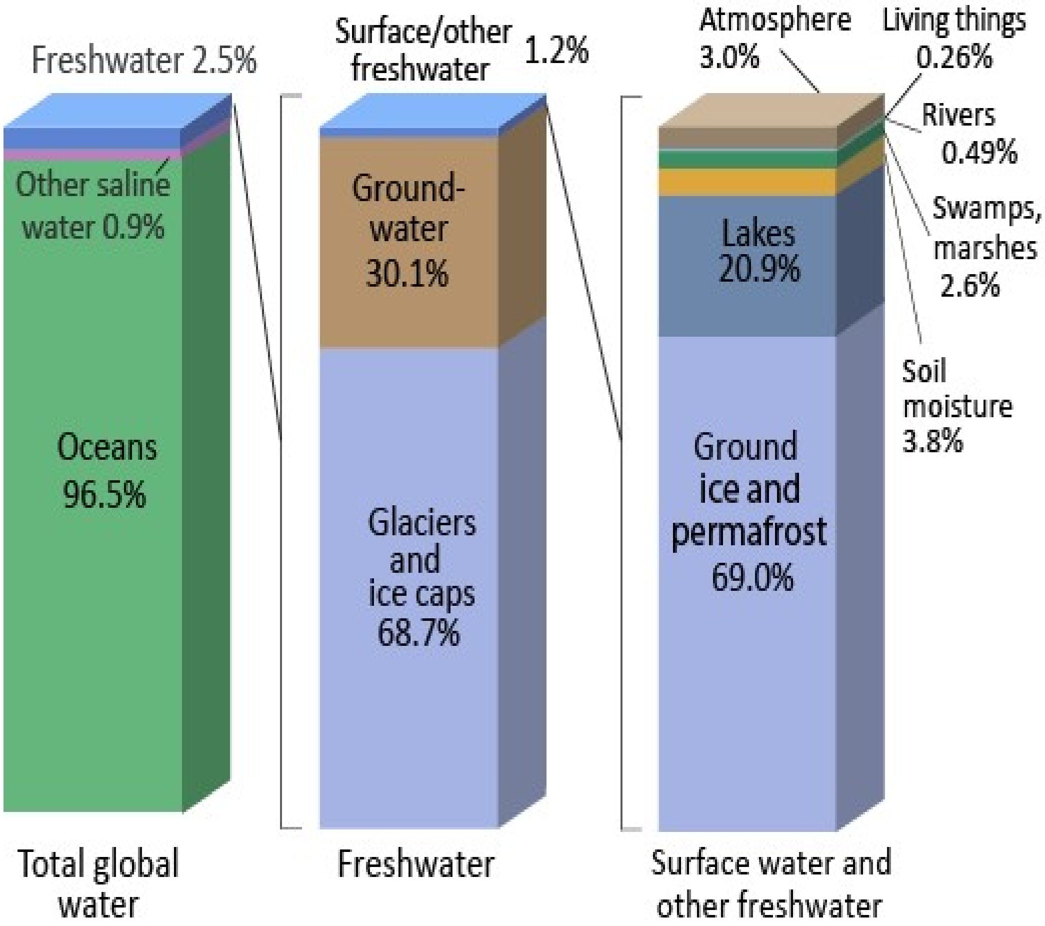

Fig. 1.1. World freshwater distribution.
(Source: Shiklomanov, 1993)

This means that the volume of groundwater is 30% greater than the volume in world fresh water lake and about 3,000 times more than the quantity in the streams (Boswinkel, 2000). On continental level, Africa has the largest groundwater storage of 5,500,000 km^3 in the world behind Asia with a total groundwater reserve of about 7,800,000 km^3 (UNESO, 1999). However, despite the abundant groundwater resources, lack of safe drinking water according to the World Health Organisation (WHO) and United Nation Children's Fund (UNICEF), is one of the world's leading problems affecting more than 1.1 billion people globally, meaning that one in every six people lacks access to safe drinking water. One third of all nations as at 2006 suffered from clean water scarcity, Sub-Saharan Africa had the largest number of water-stressed countries compared to any other region on the planet and of an estimated 800 million people who live in Africa; 300 million live in a water stressed environment (UNESCO, 2016). This alarming figure is projected to increase with the rise of global temperatures as a result of climate change. The United Nations World Water Development Report, 2016 estimated that by 2030, 75 to 250 million people in Africa will be living in areas of high water stress, which may likely displace between 24 million and 700 million people as conditions become increasingly unbearable. However, solutions to the challenges of water scarcity are hindered by shortcomings in water infrastructure, development, and management capacity to meet the demands of a rapidly growing population. This is compounded by the fact that Africa has the fastest urbanization rates in the world (UNESCO, 2016).

Nigeria scenario is not so different from that of the rest of Africa, as the country is blessed with abundant groundwater and surface water resources. Statistics from the Federal Ministry of Water Resources (FMWR), 2011, shows that Nigeria’s groundwater reserve is about 92 billion cubic meters while surface water is about 244 billion cubic meters. In spite of these enormous groundwater and surface water reserves, access to safe drinking water remains a challenge to majority of Nigerians, especially in the rural areas where many women and children spend hours daily searching for water. A latest progress report on drinking water by the WHO ranked Nigeria very low on the list of countries with elevated population density without access to enhanced drinking water. This challenge stemmed from the fact that 47 % of Nigerians have no access to clean water with 83% privately supply their own drinking water while approximately 9% are linked to the government supply scheme (National Orientation Agency (NOI) report, 2014). Clearly, Nigeria may likely fail to meet the Sustainable Development Goals (SDGs) target of universal access to safe and affordable drinking water for all citizens by 2030, as present interventions are clearly inadequate (WASHNorm, 2019). Consequently, instances of occasional waterborne diseases are not uncommon in several urban and rural areas in Nigeria due to lack of access to clean and safe drinking water. This is apparent in frequent reports of cholera outbreaks that have killed many individuals, especially children across the country. Report of the Nigerian Center for Disease Control (NCDC), 2014 confirmed a cholera outbreak in 14 states of the country, where 9,006 cases with 106 deaths were reported in the first quarter of 2014. The NCDC report indicates that Bauchi, with 6,910 cases recorded and 48 fatalities, is the most hit of the 14 States. Kano had 1,270 cases with 16 deaths, while three of the 28 cases in the Federal Capital Territory (FCT) resulted in deaths. In Kaduna State, 350 were reported with 19 fatalities, while four died from the 97 reported cases in Benue, six deaths in Taraba from the 190 reported cases, and six (6) fatalities in Ebonyi from 16 reported cases. In order to arrest this situation, government at all levels, international organizations such as the WHO and the UNICEF, Federal Ministry of Water Resources (FMWR), River Basin Development Authorities (RBDAs), communities and individuals have offered a number of boreholes to ameliorate the water challenge. However, in several areas of the country, the quality of water through these measures is sometimes of poor quality as these waters are tapped from shallow aquifers that are susceptible to contamination (Onwuka *et al.,* 2013).

Regarding the quality issue, the chemical constituents and dissolved solid contents is of considerable significance in determining the suitability of a given groundwater for a specific use (domestic, irrigation, industrial use etc.). Groundwater quality is the result of all processes and interactions that have occurred on the water from the moment it condenses in the atmosphere until it is discharged by a well or spring (Todd, 2005). There is constant interaction between groundwater and the subsurface medium where it stagnates or circulates, resulting in a balance between soil/rock composition and that of the water (i.e. water-rock interactions). Naturally the water that continues to infiltrate downward eventually becomes groundwater which react with the soil and rock materials in vadoze zone and the aquifer. These reactions primarily consist of solution of the solid phase in accordance with the solution chemistry of that particular mineral (Hem, 1970). The most efficient tool for distinguishing between different types of geochemical reaction and for inferring environmental variables that have impacts on groundwater quality and flow are isotopes and chemical characteristics of the water (Ayenew *et al.,* 2008). A wider range of components controls the chemical composition and mineralogy of groundwater circulating within rocks (aquifers) including precipitation composition, climate, topography and anthropogenic activity (Edmunds, 1992). Groundwater interactions with these factors contribute to the formation of various hydrochemical facies that may correlate with geology, climate, topography and land use activities.

In addition, isotope hydrological methods have been employed over the years in various hydrogeological investigations especially in respect of groundwater age dating and characterisation of groundwater system (Fritz and Fontes, 1980; Moser and Rauert, 1980). Isotopes are atoms of the same element which have the same atomic number but different mass number. Isotopes have different numbers of neutrons, which is responsible for the differences in the masses of various isotopes of an element. The differences in stable isotope proportions of natural compounds are governed by chemical interactions and phase changes, combined with the differences in the energy of chemical bonds associated with different isotopes of an element. The disparities in the bond energy are due to the relative mass difference between isotopes (Aggarwal *et al.*, 2009). Environmental isotopes can be divided into radioactive isotopes (e.g. ^{3}H and ^{14}C) and stable (^{2}H and ^{18}O). Stable isotopes of many different elements are applied in hydrological research but the most frequently used are the oxygen and deuterium isotopes. However, the use of stable isotopes in groundwater studies have the advantage of not only being components of water molecule itself, but they are also inert in the subsurface, hence serve as ideal tracer in hydrogeochemical evaluation of groundwater systems (Tijani and Abimbola, 2003). Therefore, the application of a stable isotope of O^{18} and D based on the concept of thermodynamic equilibrium (Drever, 1982) offers data on source of groundwater recharge and flow direction. The stable isotopes are also widely used as tracers to understand hydrogeological processes such as the direction of isotope exchanges and groundwater mineralisation within the subsurface which form the basis for understanding the level of rock-water interaction involving isotope exchanges.

In the light of the above, there is need for detail appraisal of groundwater resources in many areas of Nigeria, not only in terms of quantity but quality to ensure safe water for all by 2030. This forms the basis of this study aimed at assessing the hydrochemical and stable isotopes of groundwater in Lokoja area, north-central Nigeria. Lokoja, the study area has continued to record rapid expansion and population growth since becoming the capital of Kogi State. The population has been drawn to the city due to increased employment opportunities created by government departments and agencies as well as opening up of many business outlets. The population has grown astronomically from 77,516 in 1991 to an estimated 643,000 in 2019. Consequently, water demands for various uses in Lokoja and its environs have significantly increased with no corresponding increase in public water supply systems. The large volume of surface water from rivers Niger, Benue and Mimi, which would have been major sources of water supply in the study area has not been fully utilised because of contamination from untreated domestic, agricultural and industrial wastes; and the high cost involved in treatment to make it safe for various uses. Groundwater through shallow hand dug wells has therefore become most reliable and cost effective source to serve the water needs in many parts of the city. Most of these wells were poorly constructed and carelessly sited close to waste dumps, septic tanks, pit latrine and drainage systems (Ocheri and Mile, 2010, and Onwuka *et al.,* 2013). Water from such wells is extremely susceptible to contamination and the hazards of contaminated drinking water include diseases such as cholera, diarrhea, typhoid, parasitic worms. Generally, the human abuse of groundwater in the study area and many urban and rural communities in Nigeria comes from many different sources. Significant contamination is brought into groundwater through human activities such as the absence of an adequate household, municipal and industrial waste disposal schemes. Lack of sewage treatment facilities as a result of government negligence, poor hygiene practice such as building of septic tanks and pit latrines close to water wells and groundwater flow path, and application of chemical fertilizer and manure in agriculture are other ways in which contaminants are introduced into groundwater.

Based on the above background, this study is aimed at providing valuable hydrochemical and stable isotopes data about groundwater of Lokoja and its environs. This is expected to be helpful in understanding the groundwater system, recharge process as well as factors influencing the chemical composition, distribution of physicochemical properties and assessment of possible sources of contamination.

1.2 Aim and Objectives of the Study

The overall aim of this work is to evaluate the hydrochemical and isotopic characteristics of groundwater in Lokoja so as to determine its suitability as well as its origin and recharge processes. The detailed objectives of the study include to:

1. determine the physico-chemical (temperature, pH, EC and TDS, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, NO_3^{-} Cl^{-} and SO_4^{2-}) characteristics of groundwater in Lokoja
2. evaluate the factors influencing the chemical constituents of groundwater in the study area
3. identify possible sources of contamination and factors influencing groundwater chemistry, and
4. determine the stable isotope (^{2}H and ^{18}O) characteristics of groundwater in the study area in order to identify the source of recharge.

1.3 Justification of the Study

Groundwater is a key source of drinking water vital to life on earth. Groundwater occurred in the aquifers, which are rocks, with the ability to both store and transmit groundwater. Commonly, the large volumes of water stored in aquifers provide a reliable source of water for household, agricultural and in some cases industrial uses. Many residents of Lokoja and its environs depends largely on groundwater as a source of water for domestic, agricultural and industrial needs but owing to lack of proper domestic, municipal and industrial waste disposal and widespread poor hygiene practices, the groundwater in the area is highly susceptible to contaminations. Therefore, it is necessary to assess chemical characteristics and potability of the shallow groundwater in the study area through the evaluation of hydrochemical and stable isotope data from analyses of groundwater ssamples from the study area.

The quality of groundwater as determined by its chemical and biological constituents, total dissolved solids, and its temperature is of great importance in determining the suitability of a particular groundwater for a certain use. The quality of groundwater is the resultant of all processes and reactions that have acted on the water from the moment it condensed in the atmosphere to the time it is discharged by a well or spring. Examination of factors influencing the chemical composition of groundwater in the study area is very important owing to the role it plays in determining the quality of water. Water of good quality is said to be life and it is essential for the sustenance of life but it could also be carrier of diseases if made unsafe or unwholesome for consumption by any means. Safe water supply especially when complemented by good sanitation and hygiene practices are indispensable factors in the achievement of the Sustainable Development Goals (SDGs) and therefore, assessment of possible source(s) of contamination has become necessary in order to safeguard the water quality. Environmental isotope (Deuterium and Oxygen-18) was used to compliment hydrochemical evaluation in this study, which provides origin and flow patterns of groundwater in different hydrological cycle as well as generating evidence to the groundwater recharge in the study area. Therefore, identification of recharge source and flow pattern through isotope data helps in proper design and construction of wells as well as sewage pits to forestall anthropogenic pollution due to seepage/leakage that may arise from possible hydraulic connection with the shallow groundwater system in Lokoja area. Finally, this work tends to improve and update studies/researches by Omada *et al.,* 2009; Omali, 2014; Usman *et al.,* 2018 etc. in respect to hydrochemistry, stable isotope, groundwater resources management and evaluation in the study area.

1.4 Scope of the Study

This study covers Lokoja and its environs and involves a detailed assessment of physico-chemical and stable isotopic parameters of groundwater in the study area based on;

1. Preliminary studies, involves review of the existing literature, acquisition of topographic and geological maps and reconnaissance survey of the study area.
2. Geological mapping of the study area to delineate different rock units and their boundaries.
3. Well inventories (measurements of static water level, depth of wells and saturated water column) and hydrochemical sampling of groundwater involving in situ measurement of physicochemical parameters and collection of groundwater samples during the dry and wet seasons.
4. Data evaluation, interpretation and discussion of results of the analyses using qualitative and statistical approach.
5. Laboratory analyses of major cations, major anions and stable isotope (Deuterium or ^{2}H and ^{18}O) in standard laboratories.
6. Report writing to summarizes the data and provides explanation logically for easy references.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Location and Accessibility

Lokoja area falls within latitude 6^{o}39’ – 6^{o}46’N and longitude 7^{o}44’ – 7^{o}52’E (Fig. 2.1 and Fig. 2.2). The area covers segments of Mid-Niger (Bida) Basin west of the confluence of River Niger and Benue. Prominent towns and villages in the area include Lokoja, Ganaja, Otokiti and Filele. The area is accessible through a road from Abuja to Lokoja, Okene to Lokoja and the road from Ajaokuta to Lokoja. Several ethnic groups populate the area and it is thus a typical of the middle Belt region of Nigeria. The major ethnic groups include the Nupe, Kakanda, Ebira, Igala, Bassa, Okun, Oworo and the Hausas. The relief of Lokoja is made up of hills with low to moderate elevations ranging between 30 and 400 m above sea level.

2.2 Topography and Drainage

The topography of Lokoja is typically undulating with elevation ranging from several meters up to 400 m above sea level. Indurated and ferruginous sandstones cap Mount Patti and Agbaja hill, which are the two prominent hills in the area. Mount Patti is a linear northest-southeast ridge parallel to the Agbaja Plateau with an altitude of about 442.25 m. Both ridges follow the basin trend and are perpendicular to the main axis of the Benue Trough (Falconer, 1911). The area is drained by the Niger–Benue River system. The River Niger itself originated from the Fouta Djallon Highlands in west-central Guinea about 3,520 km away from its confluence with the River Benue at Lokoja where it continues as the lower Niger. Other minor rivers and streams like the Mimi River flow into the River Niger almost at the confluence. The drainage pattern of Lokoja is simply dendritic, where many tributaries join the major river in a tree-like manner.

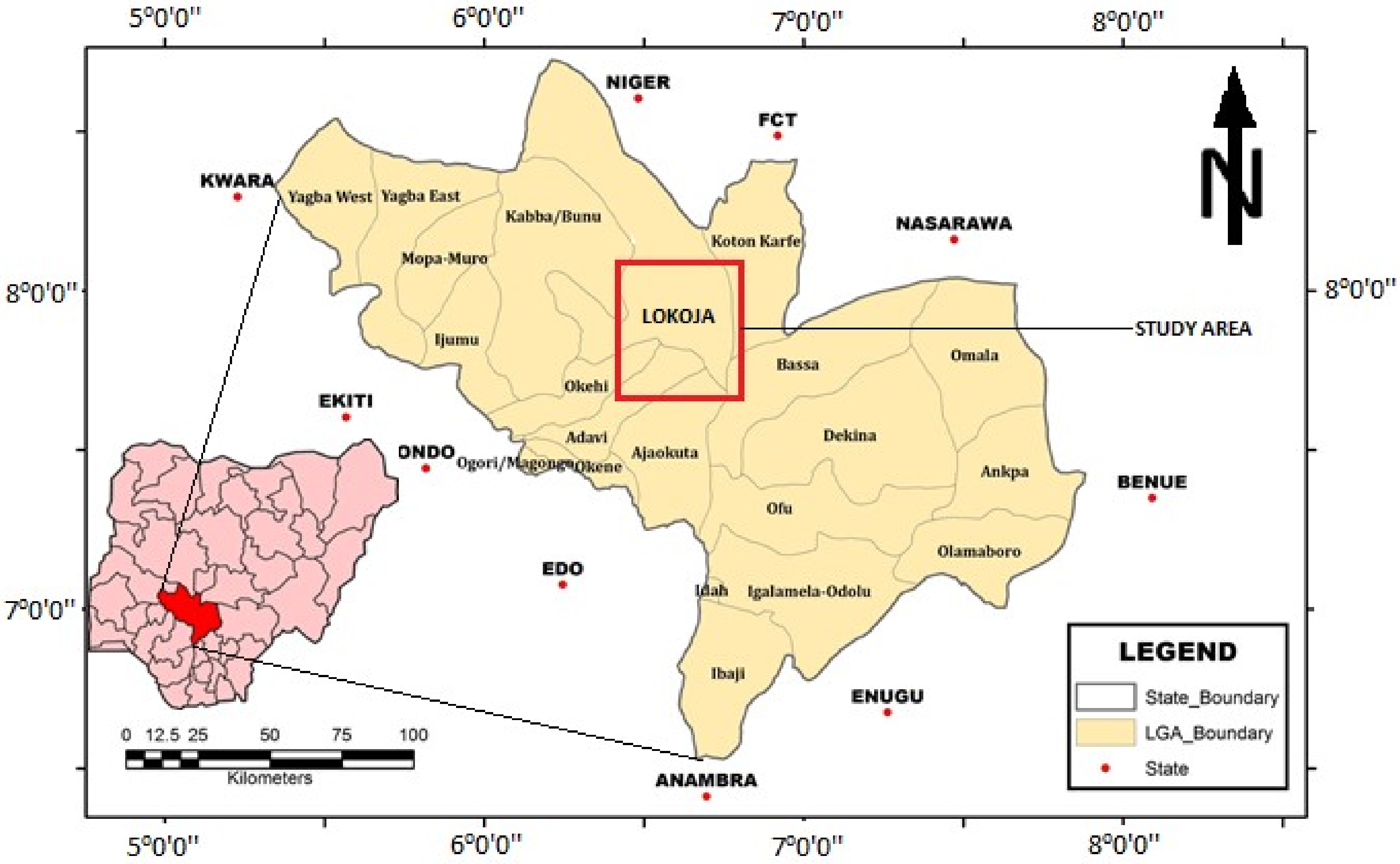

Fig. 2.1. Location map of Lokoja

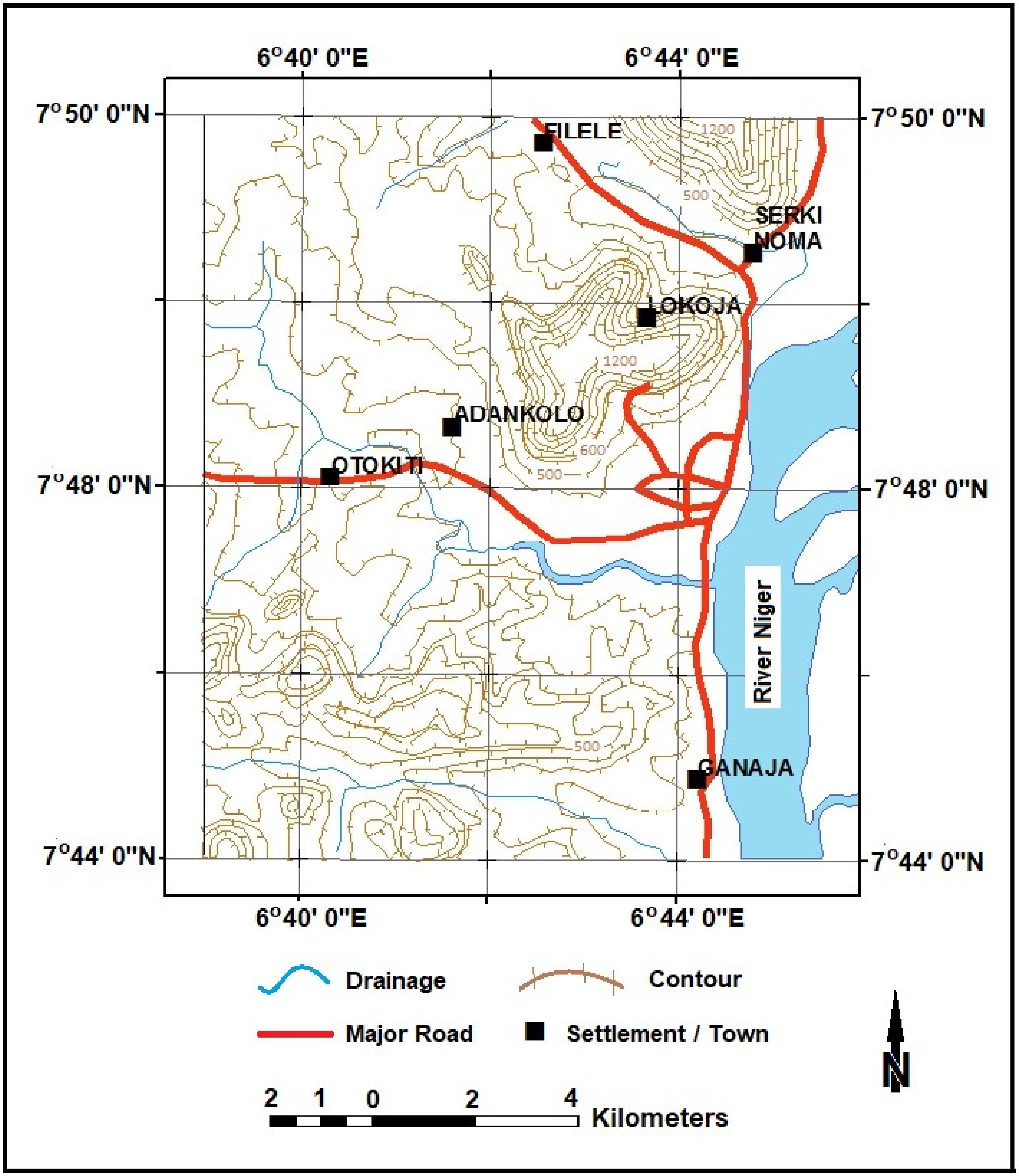

Fig. 2.2: Topographic map of Lokoja.
(Source: GSN, 1964)

2.3 Climate and Vegetation

Lokoja is characterised by two distinct seasons, namely; the rainy and dry seasons. The rainy season lasts from April to October while the dry season, which lasts from November to March, is very dusty and cold due to the northeasterly winds, which brings in the harmattan. The annual average temperature is 27^{o}C with annual average sunshine hour of 6.7 per day (Table 2.1). The area has annual average humidity of about 70 % (Table 2.2) and annual rainfall of between 1,000 and 1,500 mm (Table 2.3). A high temperature of 30-34^{o}C is experienced in the area during the dry season of between November and February (Meteorological Department of Federal Ministry of Aviation, 2007). The area has a vegetation type of guinea savannah, with dense trees bordering the rivers. The fringing forests are also found on steeper slopes formed by outcropping Cretaceous rocks that overlie the Basement. The vegetation is thick in areas covered by thick sedimentary succession and thin in areas with less overburden. The trees, which are taller in this area, are easily exploited due to accessibility over grassland terrain.

2.4 Review of Regional Geology of Nigeria

Nigeria is situated on a broad region west of the western African Craton (Ajibade and Woakes, 1989) and northeast of the Congo Craton. The ancient Precambrian rocks which were deformed during the period of the Pan-African Orogeny, about 550 million years ago, occupy about half of the land area of Nigeria outcropping in the west (Lokoja-Abeokuta-Babana), south-east (plateau bordering Cameroon) and in the north central (Bauchi-Kano-Anka-Kontongora) areas as shown in Fig. 2.3. Most of the rocks in the Basement are igneous and metamormphic rocks (gneisses, schists, migmatites and calc-silicates) along with amphibolites and rarer metamorphosed tuffs and volcanic rocks. Banded iron formations, rich in magnetite and hematite, also occur in the Basement Complex and one of the most prominent of these outcrops is at Itakpe southwest of Kabba in north-central Nigeria (Kogbe *et al.,* 1983). Intrusions of Precambrian granite i.e. older granite of 450-650 million are also prevalent in the basement areas (Wright, 1985). Jurassic younger granite and associated minor intrusions of between 145 and 190 million years old form a large part of the Jos Plateau of central Nigeria.

Table 2.1. Values of Average temperature (^{O}C) in Lokoja from 2001 to 2010

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
2001	26.6	28.8	31.4	30.2	29.5	27.5	26.7	26.2	26.6	28.4	29.2	29.4	28.4
2002	24.5	29.1	31.4	29.6	28.7	27.8	26.7	26.0	26.3	27.5	28.3	25.9	27.7
2003	26.7	27.3	30.0	31.0	30.2	29.9	26.8	26.4	28.6	28.3	28.1	25.8	28.3
2004	26.3	29.3	31.0	29.6	28.1	27.2	26.8	26.5	26.6	27.8	28.3	26.6	27.8
2005	25.6	30.6	31.3	28.6	28.6	27.4	27.3	27.1	27.3	27.8	28.3	27.7	28.1
2006	29.2	30.8	30.6	31.0	27.8	27.5	27.2	26.2	26.8	28.0	27.4	24.2	28.1
2007	25.1	30.1	30.9	30.3	28.3	27.3	26.8	26.3	26.4	27.1	28.5	26.5	27.8
2008	24.6	27.9	30.8	29.6	27.7	27.5	26.8	26.5	27.2	28.6	29.5	27.9	27.9
2009	27.6	30.3	31.4	29.4	23.7	27.0	26.9	26.6	27.1	27.1	27.9	26.5	27.6
2010	27.2	30.6	31.5	31.0	29.3	28.3	26.9	27.3	27.5	28.2	28.6	26.2	28.6

(Source: Meteorological Observation Station, Nigeria Meteorological Agency, Lokoja, Kogi State).

Table 2.2. Values of humidity (%) at Lokoja from to 2001 to 2010

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
2001	59	48	61	67	72	80	82	83	83	77	71	67	70.8
2002	50	55	63	70	76	78	83	85	83	81	74	65	71.9
2003	64	63	64	67	68	80	80	81	81	78	74	65	72.1
2004	62	54	55	69	77	79	80	81	81	78	73	69	71.5
2005	51	62	65	68	75	80	79	75	80	78	71	71	71.3
2006	79	62	65	67	77	79	81	83	82	79	69	68	74.3
2007	65	61	61	71	79	80	82	84	83	80	75	71	74.3
2008	60	51	61	71	79	79	80	84	83	81	77	69	72.9
2009	60	70	70	73	77	81	83	82	81	81	72	71	75.1
2010	67	65	63	69	76	76	79	79	78	80	73	70	72.9

(Source: Meteorological Observation Station, Nigeria Meteorological Agency, Lokoja, Kogi State).

Table 2.3. Values of rainfall in Lokoja from 2001 to 2010

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
2001	0.0	0.0	4.0	112.0	77.3	125.1	198.3	157.9	182.1	46.2	0.0	0.0	75.2
2002	0.0	0.0	2.9	162.2	79.6	93.2	325.9	298.0	196.4	139.0	1.8	0.0	108.3
2003	0.0	15.3	9.4	38.5	92.7	180.9	271.4	53.4	163.7	147.1	14.7	0.0	82.3
2004	0.0	0.0	3.4	157.5	246.0	168.4	255.5	78.6	252.9	203.1	0.0	0.0	124.1
2005	0.0	32.7	0.0	93.4	134.3	170.8	60.9	132.9	143.5	167.5	3.4	0.0	85.4
2006	12.4	19.3	40.9	61.8	370.0	62.1	303.9	352.8	290.6	163.2	0.0	0.0	139.8
2007	0.0	0.0	11.6	21.3	277.3	184.1	231.8	225.5	246.0	240.7	2.2	0.0	120.0
2008	0.0	0.0	21.8	163.6	161.6	166.3	213.8	274.7	170.2	87.8	0.0	3.9	105.3
2009	10.1	0.0	5.0	243.6	108.4	220.1	212.8	367.8	255.8	206.4	0.0	0.0	148.2
2010	0.0	0.0	2.2	132.8	125.0	104.4	255.6	133.2	148.2	0.0	0.0	0.0	100.2

(Source: Meteorological Observation Station, Nigeria Meteorological Agency, Lokoja, Kogi State).

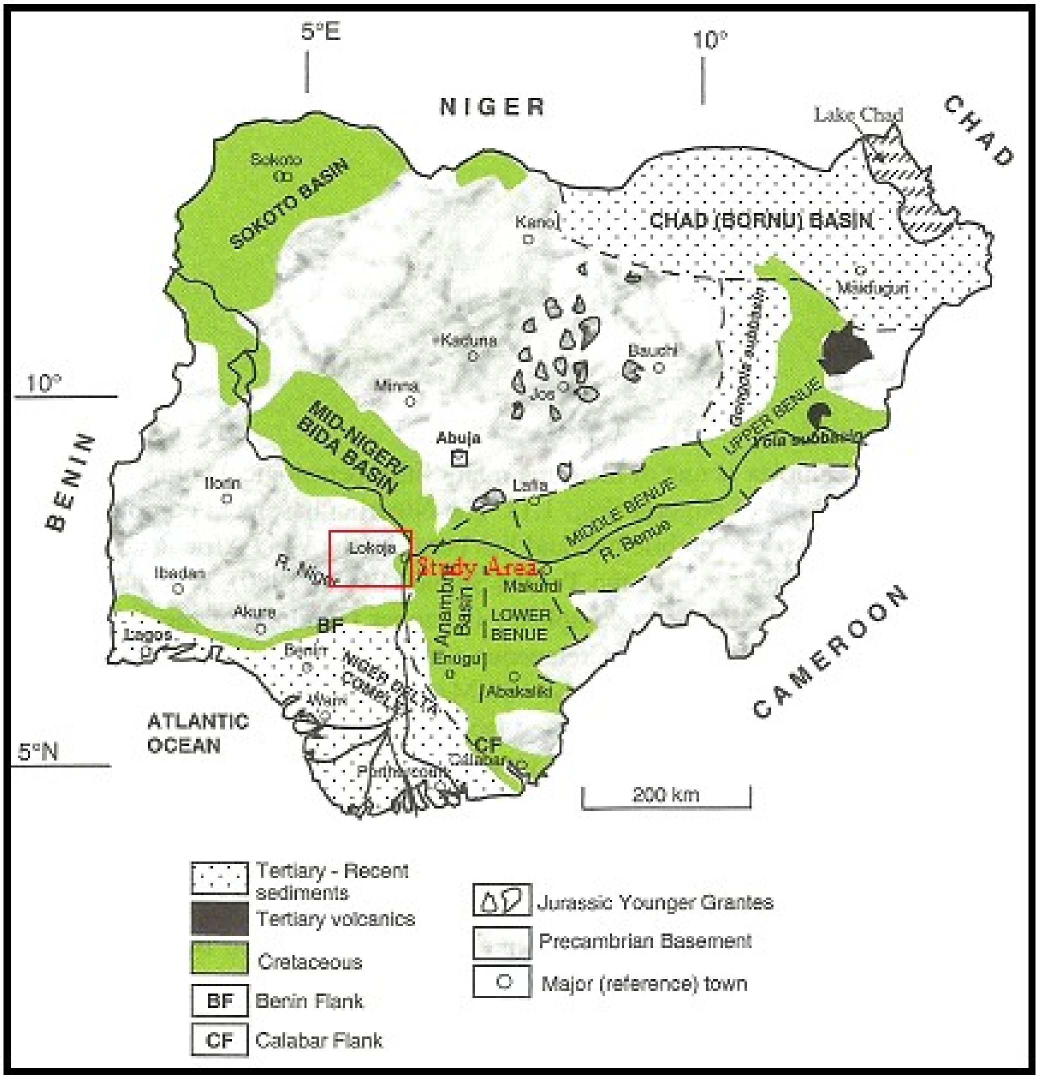

Fig. 2.3. Geology map of Nigeria showing Lokoja.
(Source: Obaje, 2009).

The younger granites are often associated with tin (cassiterite) minerization. Tertiary volcanic rocks (basalts and rhyolites) also occur sporadically above basement rocks on the Jos Plateau and the eastern plateau areas. The remaining sections of Nigeria are covered by a number of sediments, which are the Benue (central), Sokoto (north-west), Bida (central along the Niger Valley), Benin-Dahomey (south-west), Anambra (south) and the Niger-Delta (south coast), Wright (1985).).

2.5 Stratigraphic Setting of Mid-Niger Basin

The Mid-Niger Basin, otherwise known as the Bida Basin or the Nupe Basin, is an intracratonic NW-SE sedimentary basin that stretches from Kontagora in the northern section to Lokoja area to the south. The basin is delimited by the north-central and south-western Basement Complex as it merges with Anambra Basin to the south and Sokoto Basins at the north-western end (Adeleye, 1974). The basin is a somewhat depressed trough, whose origin can be heavily linked to Santonian orogenic movements in south-eastern Nigeria and the neighboring Benue Trough. The basin is an embayment trend NW – SE perpendicular to the key axis of the Benue Trough and the Niger Delta Basin (Obaje, 2009). It is often regarded as the northwestern extension of the Anambra Basin, both of which were important depocenters during the third major transgressive stage in Late Cretaceous in southern Nigeria (Obaje, 2009).

The Mid-Niger Basin stratigraphic succession, collectively known as the Nupe Group (Adeleye, 1973), includes a two-fold basins i.e. the Northern Bida Basin (Sub-basin) and Southern Bida (or Lokoja) Sub-basin. The Bida Sub-basin is said to be a northwestern extension of the Anambra Basin (Akande *et al.,* 2005) which comprises a north-west trending belt of Upper Cretaceous sedimentary units that were deposited as a result of block faulting, basement fragmentation, subsidence, rifting and drifting consequent to the Cretaceous opening of the South Atlantic Ocean (Petters, 1986). Major horizontal (sinistral) movements along the northeast–southwest axis of the adjacent Benue Trough appears to have been translated to the north-south and northwesterly trending shear zones to form the Mid-Niger Basin perpendicular to the Benue Trough (Benkhelil, 1989).

The Benue Trough's sedimentary fill though consists of three unconformity-bounded depositional successions; the geographic areas of Bida and Anambra were platforms up to the Santonian (Petters, 1978). The collapse of the platforms of Mid-Niger and Anambra resulted to the sedimentation of the Upper Cretaceous units / successions, which started with the marine shale of Nkporo and Enugu Formations that are regarded as lateral equivalent of Lokoja Formation in Bida Basin (Obaje, 2009). The sedimentary units of the Manu Formation, which overlie the Nkporo Formation, consist of shales, siltstones, sandstones and fluvio-deltaic coals to fluvio-estuarine environments whose lateral equivalents are the cross-bedded and poorly sorted sandstones and claystones of the Lokoja and Bida Formations in the southern Bida Basin. The exposures of Lokoja Formation (sandstones and conglomerates) which is about 300 m thick unconformably overlie the Pre-Cambrian to Lower Paleozoic basement gneisses and schists. The Mamu Formation in the Anamabra Basin is overlain by the Lower Maastrichtian Ajali sandstone Formation, which is laterally equivalent to Patti, Sakpe and Enagi Formations which overlain the Lokoja Formation in the Bida Basin. The Ajali sandstones are well sorted, quartz arenite frequently intercalated with siltstones and claystones, which in part are comparable to the lithologies of Patti and Enagi Formations. The Patti Formation (shales, siltstones, claystones and sandstones) is about 70-100 m thick in the Koton-Karfi and Abaji axis.

The Upper Maastrichtian Agbaja and Batati (lateral equivalents) overlain the Patti and Enagi Formations respectively; these formations consist of claystones, concretionary siltstones and oolitical, pisolitical and concretionary ironstones deposited in a shallow-marine continental environment. Compared to the earlier marine sedimentation established for the Campanian Nkporo Formation in the neighboring Anambra Basin during that transgressive phase, the Upper Cretaceous sedimentary sequences in the Bida Basin indicated that full marine conditions were not established (Obaje, 2009). Akande and Erdtmann (1998) opined that the successions of the Anambra Basin were up to 8 km thick compared to average 3.4 km thickness in the Bida Basin.

According to Adeleye and Dessauvagie (1972) the stratigraphy and sedimentation of the Upper Cretaceous sequence in the central part of the Bida Basin, included the Bida Sandstone (separated into the Doko and Jika member), the Sakpe Ironstone, the Enagi Siltstone and the Batati Formation as the four mappable stratigraphic units. These stratigraphic units correlate with the other lithostratigraphic units in the Southern Bida Basin (Fig. 2.4).

2.6 Geology of the Study Area

Lokoja area is a segment of the Basement Complex of Southwestern Nigeria and the Mid-Niger (Bida) Basin where both crystalline and sedimentary rocks are represented (Fig 2.5). The Basement complex comprises mainly granites, migmatite-biotite gneisses and schists, which are intruded by the NE-SW trending pegmatite dykes and covered by the Cretaceous-Recent coarse-medium grained sands to the east forming the bank of River Niger. The coarsely porphyritic granite with biotite and hornblende generally form the major ferromagnesian mineral content as evident around Ganaja area of Lokoja (Hochey and Sachi, 1986). The gneisses are characterised by regular banding, leading from mineral segregation, where predominantly light bands alternate with predominantly dark bands. Individual bands differ between a few millimeters and several centimeters in thickness. The mineral contents of these rocks from field observations are biotite, quartz and feldspar. The rocks are broadly oriented in the north-south direction and marked by a sub-parallel alignment of elongated and closely packed feldspar phenocrysts, mainly microcline and a corresponding preferred orientation of biotite (Hockey and Sachi, 1986).

The sedimentary portion consists of Quaternary-Recent river alluvium and Cretaceous false-bedded sandstone of Lokoja Formation. The Lokoja Sandstone is the basal unit overlying the basement complex unconformably. The formation is the lateral equivalent of the Bida sandstone, consisting of subangular to sub-rounded quartz pebbles in clay matrix. Lithologic units range from conglomerates, coarse to fine grained sandstones, siltstone and claystones, varying in colour from milky to purple and massive to cross stratified.

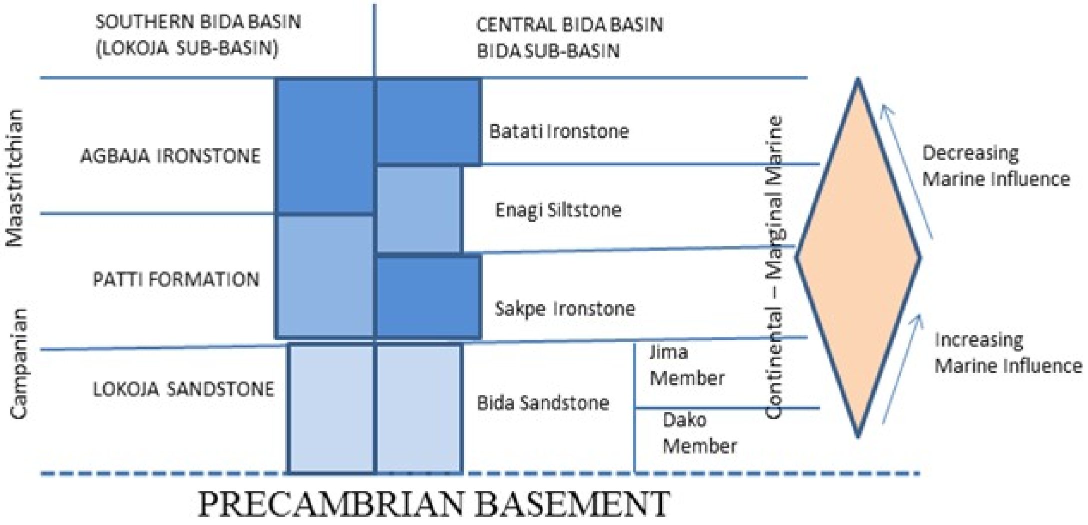

Fig. 2.4. Stratigraphy of Mid-Niger Basin.
(Source: Obaje, 2009).

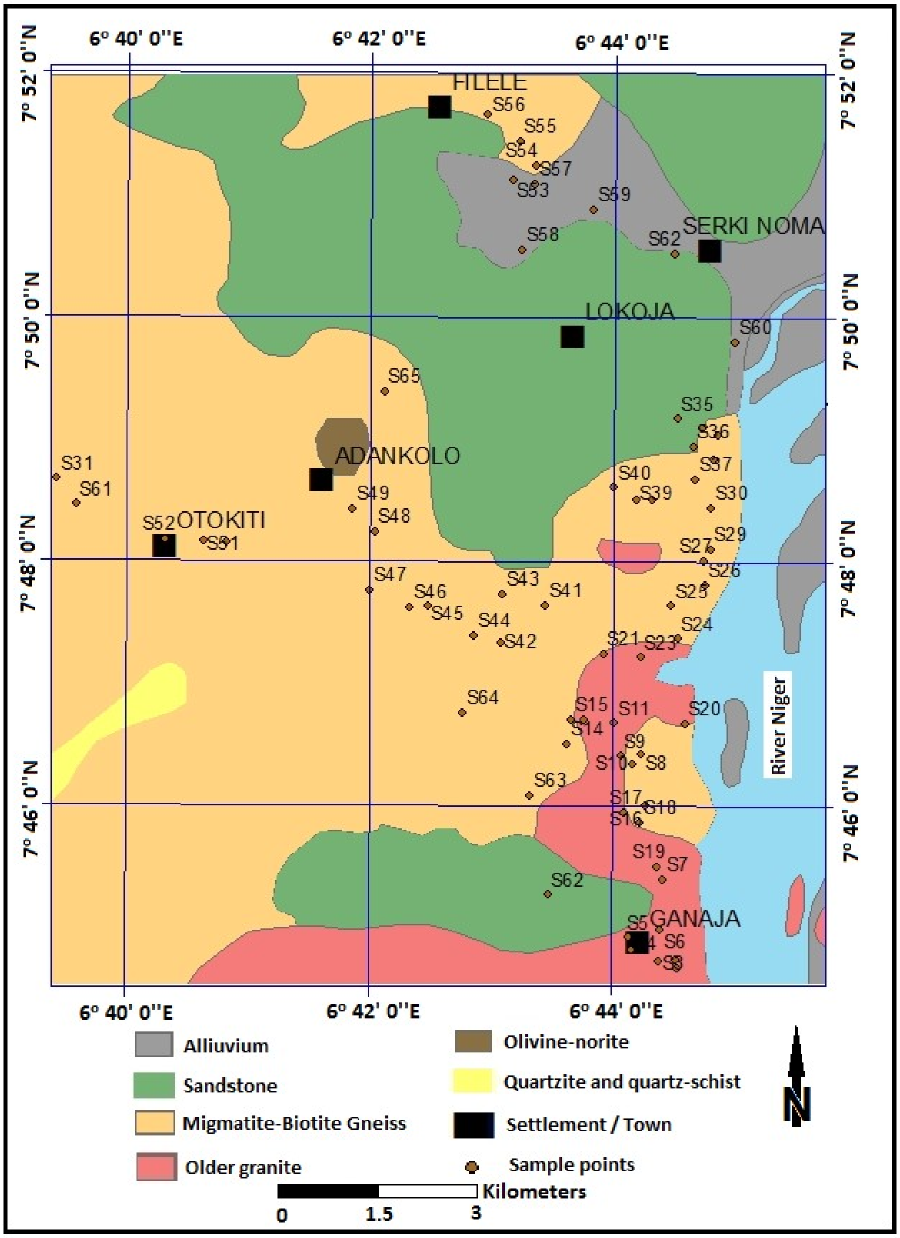

Fig. 2.5. Geological map of the Lokoja area.
(Source: GSN, 1986)

The prevailing units are generally poorly sorted and composed mainly of quartz and feldspar thus texturally and mineralogically immature (Ojoh, 1992). This Formation is exposed between Lokoja and Koton-Karfi and has been interpreted as continental (alluvial fan) deposit (Braide, 1992); the upper part of which have been inundated by marine conditions (Ladipo *et al.,* 1994). Sedimentary structures including cross stratification and biogenic structures are well defined. The Patti Formation which overlain the Lokoja Formation consists of sandstones, siltstones, claystones and shales interbedded with bioturbated ironstones.

The siltstones of the Patti Formation are commonly parallel stratified with occasional soft sedimentary structures (e.g. slumps), and other structures such as wave ripples, convolute laminations, load structures (Braide, 1992; Gebhardt, 1998; Akande *et al.,* 1992). The Patti Formation therefore appears to have been deposited in marginal shallow marine to brackish water condition identical to the depositional environments of similar lithologic units of the Mamu and Ajali Formations in the Anambra Basin (Ladipo, 1988; Adeniran, 1991; Nwajide and Reijers, 1996). The Agbaja Formation forms a persistent cap over the Campanian-Maastrichtian sediments in the Southern Bida Basin consists of sandstones and claystones interbedded with oolithic, concretionary and massive ironstone beds as observed in top of Patti and Agbaja ridges. The sandstones and claystones are interpreted as abandoned channel sands and overbank deposits influenced by marine reworking to form the massive concretionary and oolitic ironstones (Ladipo *et al.,* 1994; Braide, 1992; Olaniyan and Olobaniyi, 1996).

2.7 Hydrogeological Setting of Nigeria

Hydrogeology of an area is usually controlled by such factors as geology and climate of that area. This is because of the fact that geology formations underlying the area and the structure contained in them determine the types of aquifer to be encountered and how the aquifers are recharged while the climate determines the amount and rate of recharge of the aquifer by precipitation water (Todd, 2005). Generally, aquifer distribution in Nigeria is categorised into two systems (Fig. 2.6): Basement fluvio-volcanic aquifers characterized by fissures and consolidated or unconsolidated sedimentary aquifers characterised by intergranular pore-spaces (Eduvie, 2006; Tijani *et al*., 2016). Details on these types of aquifers are summarised below:

a) **Fissures/fractured Crystalline Aquifers:** Groundwater availability in areas underlain by crystalline basement rocks depends on the development of thick overburden unit (overburden aquifers) and/or the presence of fractures in the fresh bedrock (fractured bedrock aquifers). This is characteristic of areas underlain by the basement blocks of the west, north central and the eastern parts of Nigeria. Usually, the storage of groundwater is confined to fractures and fissures in the weathered zone of igneous, metamorphic and volcanic rocks, the thickness of which range from <10-60 m in semi-arid and humid tropical rain forest zones. The groundwater resources here are usually limited (Eduvie, 2006), except in areas with intensive fracturing, especially in tropical humid setting with active recharge.

b) **Consolidated/Unconsolidated Sedimentary Aquifers**: The occurrence of groundwater in consolidated/unconsolidated sedimentary aquifers is dependent on the presence of intergranular pore-spaces in sedimentary formations. This is characteristic of all the sedimentary basins in Nigeria with interaction of shale/claystone and sandy aquifers of Cretaceous-Tertiary-Quaternary units. These aquifers varied from unconfined to confined aquifers in the different sedimentary basins. In addition, the pore-type aquifer is also found in alluvial deposits, which collectively form primary unconsolidated aquifers.

There are four main aquifer scenario characterised by different hydrogeological settings and groundwater conditions in Nigeria (MacDonald *et al.* 2011 and Tijani, *et al.* 2016). These include:

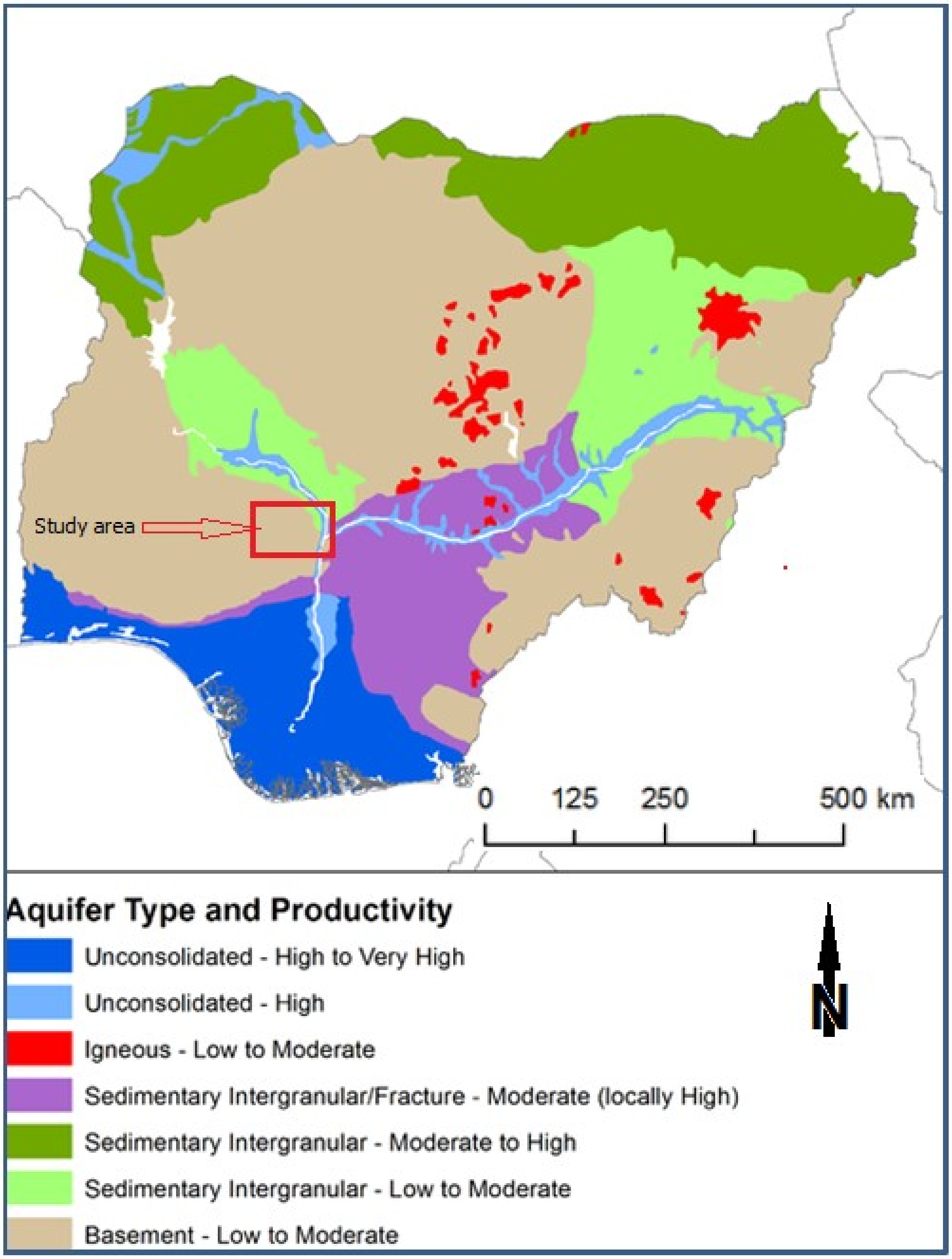

Fig. 2.6. Hydrogeological map of Nigeria with main aquifer type and productivity showing Lokoja.
(Source: Tijani *et al.,* 2016).

i) Precambrian crystalline basement rocks: These rocks occupy about 50% of Nigeria and characterised by very low primary permeability or porosity. Groundwater occurrences are within the weathered overburden or fractured bedrock. Typical yield of boreholes is usually 0.1–1 l/s, but can occasionally be as high as 10 l/s (Fig. 2.7a).

ii) Consolidated sedimentary rocks: The consolidated sedimentary rocks occupy 35% of Nigeria and characterized most of the inland sedimentary Basins (Sokoto, Borno, Bida, Anambra, eastern Dahomey Basin and Benue Trough, etc). Sandstone units in the basins can store considerable volumes of groundwater and support high yielding boreholes of 10–50 l/s. However, low permeability mudstones and shale units (especially in SE-Nigeria) support low yields of less than 0.5 l/s (Fig. 2.7b).

iii) Unconsolidated sediments: The rocks cover about 10% of Nigeria. These are usually productive with high porosity/storage and are characteristics of the coastal zone (Coastal Plain Sands), including the Tertiary Niger Delta with yields of 5–50 l/s, depending on the depth of individual boreholes (Fig. 2.7c).

iv) Unconsolidated alluvial sediments: The unconsolidated alluvial sediments in river valleys constitute about 1% and usually underlain most river valleys. These vary in thickness from few meters to 100 m, and have a high porosity with yield of about 1–10 l/s (Fig. 2.7d).

2.7.1 Hydrogeology of North-Central Nigeria

The hydrogeology of north-central Nigeria is characterised by both sedimentary and basement aquifers (Adelana *et al.,* 2008). The Mid-Niger Basin extends northwestwards along the River Niger from the confluence with the River Benue River in Lokoja. Crystalline Basement rocks adjoin the area on all sides except to the southeast where it has a common boundary with the Cretaceous sediments of the Lower Benue Basin (Du Preez and Barber, 1965). The Lower Niger Basin area is drained by minor rivers flowing SW-NE, and N-S from the Kabba and Jos Highlands in the south and the north respectively (Adelana *et al.,* 2008).

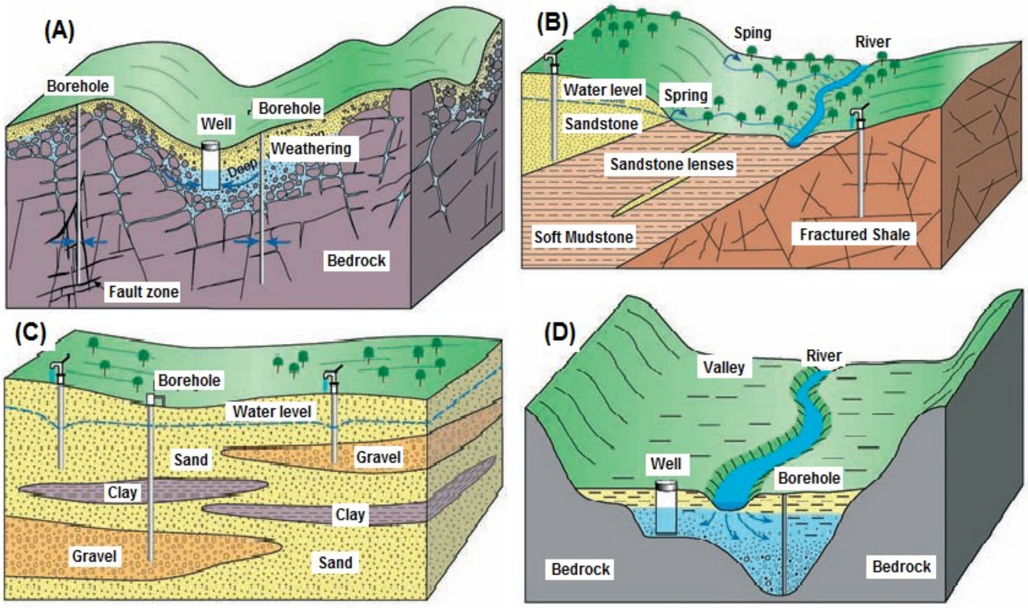

Fig. 2.7. Diagrammatic illustration of the four main hydrogeological environments in Nigeria (a) Precambrian crystalline basement rocks (b) Consolidated sedimentary rocks (c) Unconsolidated sediments (e) Unconsolidated alluvial sediments.
(Source: MacDonald *et al.* 2011).

The Patti Formation has a maximum thickness of about 100 m, and is composed of fine to medium-sized sandstones, some claystones and carbonaceous siltstones. Inclusions of oolithic ironstones were observed towards the top of the formation. The formation has distinctively lower hydraulic conductivities than those of the deeper Lokoja Formation; hence not a primary target for groundwater exploration. Additionally, intercalated clay and shale layers may reduce the productivity of wells, as vertical recharge may be obstructed. The sandstones of the Lokoja Formation rest directly on the granitic to quartzitic basement rocks. The whole sequence consists of pebbly, clayey grits and sandstones with a minimum thickness of 250 m. Due to their higher hydraulic conductivity values; groundwater exploration tends to focus on the Lokoja Formation. Three pumping tests situated within the sedimentary series of the Bida Basin as reported by Mands (1992), which were performed at Shashi Dama, Gaba and Etsugaie (near Bida) showed that transmissivity values are in the range of 5.5-29.3m^2/d.

The hydraulic conductivities were reported as 6x10^{-2} to 3x10^{-5} m/s (0.5-2.6 m/d), which are similar to values obtained by Vrbka *et al.,* (1999). The work of Kehinde (1990) indicates lower transmissivity for sediments of the Bida Basin (mainly <1-50 m^2/d) presented in Vrbka *et al.,* (1999). The variations between these results may partly be due to the fact that the latter examined mainly sandy sediments. Furthermore, pumping wells are usually not fully penetrating and the screens may have been positioned in zones with relatively low hydraulic conductivities. Thus, transmissivity values from pumping tests are based on relatively short screen sections of some meters. Whereas Adelana *et al.,* 2008 calculated the bulk transmissivity for a sediment thickness of 500 m. Based on the mean value for screen lengths of 3-10 m, a transmissivity in the range of 10-33m^2/d would result (Vrbka *et al*., 1999), to some extent confirming the findings of Kehinde (1990) and Mands (1992). Based on the thickness data of Ojo and Ajakaiye (1989) of 500 m for the Lokoja-Abaji section and a void space of 12–18%, the entire groundwater resource (sedimentary cover of about 60 km × 80 km = 4,800 km^2) was estimated to be in the range of 290-430 km^3.

The Basement Complex rocks underlain areas in west-central Nigeria, which include part of Niger, Kwara, Kaduna, Kogi, Benue and Plateau States (Adelana *et al.,* 2008). These basement areas are composed mainly of granitic and migmatitic gneisses and granites. There are also extensive areas of schists, phyllites occurring in Kaduna and Kwara states. Both the older and younger granites of these areas are poor aquifers. Whereas, over most of these areas occur thin, discontinuous mantle of weathered rocks or joint and fracture systems in the unweathered basement provide secondary reservoir. The decomposed mantle is sometimes too thin to harbor large quantities of water and is usually clayey to be highly permeable. The crystalline basement of Nigeria generally represents the deeper, fractured aquifer and is noted as a poor source of groundwater. This area is partly overlain by a shallow, porous aquifer within the lateritic soil cover as described by Annor and Olasehinde (1996). Streams and rivers rise quickly during and after precipitation, thus indicating a rather low storage capacity of the soil and underlying rocks. Offodile (1992) from a borehole situated on the southern outskirts of Ilorin on a major fracture in migmatitic granite, reports a yield of about 7.2 m^3/h (2 l/s). Yields between 1-2 l/s are considered good, and yields are more commonly below 1 l/s.

2.7.2 Local Hydrogeology

Lokoja is a segment of the Mid-Niger (Bida) Basin and Basement Complex of southwestern Nigeria. Hydrogeologically, the Quaternary-Recent sediment of Lokoja Formation and river alluvium constitute the shallow sedimentary aquifers while weathered/fractured Precambrian crystalline rocks and thick sapprolites form the aquifers in the basement part of the study area. In sedimentary part of the study area, the sandstones of Lokoja Formation constitute the major aquifers due to its higher hydraulic conductivity values (Adelana *et al.,* 2008). Factors controlling an aquifer's porosity, permeability, and specific yield in these rocks include particle size, particle distribution, particle shape, and particle cementation state. Highly angular and rounded particles generally produce high values, while subangular particles tend to be compacted and offer very low values of porosity and permeability. Potential aquifer may be isotropic or anisotropic, homogeneous or heterogeneous or a combination of the types, and exhibiting variable sizes, shapes of particles and distribution. A completely isotropic homogenous material, high porosity will tend to result from completely fine or completely coarse-grained (Offodile, 2002). Groundwater within the shallow alluvium aquifer occurs largely under water table conditions and is found to outcrops and in some places as spring. Alluvium aquifer is recharged directly by precipitation or the adjurning flood water of Rivers Niger-Benue system (Offodile, 2000; Omada *et al.,* 2009).

Groundwater in Basement Complex terrain of the study area like the rest of southwestern Basement Complex occurs in the weathered mantle/regolith and in the fractures within the unweathered crystalline rocks. The yields of wells/boreholes in such basement setting are directly proportional to the thickness of weathered overburden and/or with the extent of fracturing in underlying fresh bedrocks (Tijani, *et. al.,* 2010). Generally, the development of secondary porosities and permeability resulting from shearing, jointing, and deep weathering, and fracturing give rise to the occurrence of groundwater in basement area of Lokoja (Oyinloye and Ademilua, 2005). However, the weathered regolith unit and sapprolite serve as the main local source of water for the shallow boreholes and hand dug-wells in many parts of the study area. The abstraction of groundwater is primarily through boreholes, hand dug wells, and springs. Static water level in well varied between 0.5 and 10.1m with an average of 3.21 m, total depth of well varies between 3.0 and 10.5 m and saturated water column varies between 0.5 and 4.2 m. According to Lower Niger River Basin Development Authority (LNRBDA), 2003 report, the average yield is between 70 m^3/day and 130 m^3/day.

2.8 Review of Previous Work

There are several detailed published works on hydrogeology and hydrogeochemistry in the study area and several numbers of similar relevant studies exist in other parts of Nigeria and the rest of the world. Therefore, the review of literature is based on works carried out on hydrochemistry/hydrogeochemistry and stable isotopes, which were targeted at assessing groundwater quality and source of recharge. Olarewaju *et al.,* (1997), Idowu and Ajayi (1998), Abimbola *et al.,* (1999), Bala and Onugba (2001), Tijani and Abimbola (2003), Appelo and Postma (2005), Tood (2005) Talabi and Tijani (2013) and others worked on hydrochemistry, hydrogeochemistry and contamination of groundwater in different parts of Nigeria. Tijani, (1994) identified that mineral dissolutions are related to slow weathering process and limited migratory history of the CO_2 charged precipitation water recharging the weathered regolith aquifer. Olarewaju *et al.,* (1997) evaluated groundwater chemical properties in some parts of central Nigeria's basement complex and found that groundwater from the areas is usually of excellent quality and therefore potable. However, they suggested that regular chemical analysis of water samples be undertaken to detect if there was any deterioration in the quality of the water, particularly in the pollution-prone urban regions. Idowu and Ajayi, (1998) investigated the occurrence of groundwater in two geological environments in southwestern Nigeria. They concluded that water from basement aquifers is slightly-moderately hard.

In the basement complex area within Bunsuru and Gagere sub-basins of northern Nigeria, Bala and Onugba (2001) carried out preliminary chemical assessments of the groundwater. The study involved laboratory assessment of the chemical quality of groundwater within the rocks of the sub-basins of the Sokoto-Rima drainage basin. The study identified $Ca^{2+}(Mg^{2+}) – Cl^{-} – SO_4^{2-}$ and $Ca^{2+}(Mg^{2+})\text{-}HCO_3^{-}$ as the two types of water within the basin though the general grouping would tend towards the $Ca^{2+}(Mg^{2+}) – Cl^{-} – SO_4^{2-}$ water type. In assessing patterns in groundwater chemistry resulting from groundwater flow, Stuyfzand, 1999 found that groundwater flow influences hydrochemical patterns because flow reduces mixing by diffusion, carries the chemical imprints of biological and anthropogenic changes in the recharge area, and leaches the aquifer system.

A lot of other researchers such as Helena et al., (2000), Nosrat and Asghar (2010), Talabi and Tijani (2012), *Ayuba et al.,* (2013) and others have also employed hydrogeological characterization and quality assessment techniques to study groundwater. Abimbola and Tijani, (1999) assessed the groundwater in Abeokuta and its environs and the Ca^{2+} and HCO_3^{-} were recognized as the prevailing groundwater ions. The water is of low TDS and $Ca\text{-}HCO_3^{-}$ type of water. Olatunji *et al.,* (2001) evaluated Hydrochemistry of water resources of Oke-Agbe Akoko, southwestern Nigeria. They found several water samples to be chemically potable when compared to the specified standard for drinking water by World Health Organization (WHO) and they equally identified low sodium hazard. Ofoma *et al.,* (2005) carried out the physico-chemical analysis of groundwater in parts of Portharcourt city, eastern Niger Delta Nigeria. Their analytical findings were contrasted with WHO, 2006 drinking water standards and determined that after treatment the water was appropriate for drinking. They further suggested that legislation be provided for quarterly biological and physico-chemical examination of borehole water in the area. This should be enforced by the necessary agencies/authorities such as National Agency for Food and Drug Administration and Control (NAFDAC), Local and National Environmental Agencies, and other relevant ministries, parastatals and agencies saddled with such responsibility.

Ariyo *et al.,* 2005 in their contributions to geochemical characterization of aquifers in the Basement Complex-sediment transition zone around Ishara Southwestern Nigeria noted that the difference in aquifer is reflected in the chemistry of the groundwater resources found in them. As such, they concluded that there is a strong relationship between the geology of an area and the water chemistry found within the area. The authors suggested the bacteriological evaluation to assess both surface and groundwater pollution levels which cannot be identified by their physical and chemical analysis. They also found that the area's groundwater is essentially normal earth alkaline water type Ca^{2+}- (Mg^{2+}) – SO_4^{2-} - Cl^- and predominantly of Ca^{2+}- (Mg^{2+}) - HCO_3^- water type. Tijani *et al.,* 2006 studied heavy metals contamination of stream waters and bottom sediments of urban drainage systems in Abeokuta area, southwestern Nigeria and concluded that geology and anthropogenic activities are the principal factors controlling the environmental quality of both water and sediments in the study area. The study further revealed that metal concentrations in the sediments are a reflection of the geogenic input (flux) through weathering and erosion with limited anthropogenic inputs, while the contamination in the stream waters could be mainly due to human inputs as direct discharge of domestic sewage into the stream channels. Olobaniyi *et al.,* (2007), investigated the hydrogeochemical and bacteriological characteristics of groundwater in Agbor area, South-South Nigeria and concluded that the water types encountered include the bicarbonate and chloride types. While the bicarbonate type indicates areas of recent water recharge with Base Exchange processes, the chloride type suggests influence saline water intrution accompanied by some cations exchange activities. Nton *et al.,* (2007) assessed the surface and groundwater quality in Agbowo – Orogun area of Ibadan, Southwestern Nigeria and concluded that the surface water in particular is slightly alkaline, unfit for drinking but could be developed to supplement existing ones while the groundwater was generally fresh and potable though minor treatment such as boiling and filtration would be required for some locations.

In evaluation of shallow aquifer in Wadi Marwani, western Saudi Arabia, El-Ahmadi and El-Fiky, 2009 indicated the presence of anthropogenic sources of contamination in Wadi Maradi with higher concentrations in agricultural and residential areas. The groundwater chemistry in Piper's diagram indicated that Ca^{2+}+Mg^{2+} are the dominant cations in the hydrochemical facies, however, it changes widely from a Ca^{2+}- (Mg^{2+}) - HCO_3^- type (in the upstream part) to a Ca^{2+}- (Mg^{2+}) – Cl^-–SO_4^{2-} type (downgradient), suggesting that increase in Cl^- and NO_3^- concentrations is typical of anthropogenically contaminated groundwaters. In India, Vasanthavigar et al., 2010 applied water quality index for groundwater quality assessment of Thirumanimuttar sub-basin. The results of the study indicated that the groundwater of the study area was strongly influenced by effective weathering and leaching action of feldspars and magnesium calcite found in the litho units of the study area along with anthropogenic activities like industrial effluents, automobile emissions, and phosphatic fertilizers in urban environments. Talabi and Tijani (2012) evaluated the chemical composition and quality of shallow groundwater in crystalline basement complex area of Ekiti, Southwest Nigeria. The investigation indicated that the order of major cations abundance was $Ca^{2+} > K^+ > Na^+ > Mg^{2+}$ while that of anions was $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$. They also concluded that overall drinking quality assessment indicates that most of the hydrochemical parameters satisfied World Health Organisation (WHO) and Standard Organisation of Nigeria (SON) standard values for drinking water except in few locations where Pb, Fe and Mn exceeded the standard values; and majority of the samples were under normal conditions ideal for irrigation purposes.

In a related work, Onwuka *et al.,* 2013 evaluated hydrochemical characteristics and quality assessment of regolith aquifers in Enugu metropolis, southeastern Nigeria and found that groundwater of the area is acidic to slightly alkaline and varies from soft water to moderately hard water. Cl^-, HCO_3^-, K^+, Na^+ and SO_4^{2-} showed an increase in concentrations during the dry season which was attributed to effective weathering of the lithological units of rocks and anthropogenic activities. Groundwater quality was generally poor during the rainy season than that of the dry season due increased leachate of solutes from geogenic and anthropogenic sources during the season. Dedzo *et al.,* 2017 examined the importance of rocks and their weathering products on groundwater quality in Central-East Cameroon. Their study revealed that the water samples were generally slightly acidic to neutral ($5.3 < pH < 6.7$), fresh (Total Dissolved Solids < 1000 mg/L), soft and moderately hard ($2.54 <$ Total Hardness < 136.65 mg/L). The Ca^{2+} (Mg^{2+})-HCO_3^- type were the most dominant water variety in the study area, whereas the Ca^{2+} (Mg^{2+}) SO_4^{2-} types were less represented. They also concluded from petrographic and geochemical studies, coupled with soil and hydrogeochemical results that the dominant factors controlling the water chemistry in the area are anthropogenic activities, water-rock interactions (chemical weathering) and ion exchange.

Haritash *et al.,* 2017 undertook hydrochemical characterization and suitability assessment of groundwater and identified that groundwater in Baga–Calangute area was found to be fit for drinking except for slightly elevated values of chlorides and nitrates. Therefore, it is likely that agriculture in Calangute–Baga stretch has had an impact on groundwater quality. An assessment of groundwater quality data suggests rock–water interactions in the form of direct base exchange reactions and silicate weathering primarily govern the quality of groundwater. Hallouche et al., (2017) assessed geochemical and qualitative assessment of groundwater of the High Mekerra watershed of northwestern Algeria. This study identified that groundwater resource is currently under heavy pressures to meet the growing needs of drinking water and irrigation and therefore assessed the geochemical characteristics of groundwater of the High Mekerra watershed at 21 points distributed across the two main aquifers (Ras El Ma and Mouley Slissen) in the region. They reported that the hydrochemical facies of Ras El Ma groundwater are dominantly MgCl and CaCl type, while those of Mouley Slissen groundwater are of $CaHCO_3^-$ type. Principal component analysis shows a strong correlation between groundwater mineralization and Ca^{2+}, Na^+, Cl^- and SO_4^{2-} ions stemming from the dissolution of carbonates, gypsum and anhydrite. Groundwater mineralization evolves from south to north. Geochemical modeling shows that the High Mekerra groundwater is saturated with respect to calcite and dolomite and undersaturated with respect to gypsum and anhydrite. Nitrate concentrations that exceed the WHO standard (50 mg/L) at several points are linked to the agro-pastoral activities in this region.

Some researchers have used stable isotopes techniques and sometimes with hydrochemistry to study surface and groundwater systems. Tijani and Abimbola, (2003) on the assessment and evaluation of the chemical data from Oke-Ogun Area South-western Nigeria provides an insight into the hydrochemical and isotope evolution of groundwater system in weathered basement aquifer. The stable isotope research shows meteoric origin of groundwater recharge with limited degree of kinetic evaporation. Onugba and Eduvie, (2005) worked on the hydrogeochemistry and environmental isotopes of the aquifer systems in the Upper Benue area of Nigeria and concluded that the groundwater in the Basement Complex at relatively shallow depth was vulnerable to pollution. Their findings revealed that over 40% of the samples from boreholes in the communities located in the Basement Complex contained excessive nitrate from anthropogenic sources. Consequently, there was need for groundwater/aquifer protection measures to ensure good quality water supply for the people. Isotope data revealed that groundwater in Basement Complex contain water of recent recharge while in the sandstone area, there is mixed origin, old and recent recharge. The authors concluded that the recharge mechanism in both the Basement Complex and sedimentary aquifers is clearly understood. The fractures in the Basement Complex can facilitate rapid recharge. They further recommended more investigations on the trace elements in groundwater which were not usually analysed in routine monitoring of water quality. Tijani, (2008) on Hydrochemical and stable isotope compositions of saline groundwater in Benue trough observed that Hydrochemical characteristics indicated that the original marine chemistry has been modified by rock-water interactions, involving dolomitisation and enrichment of Ca^{2+} through cation exchange process.

Yeh et al., 2009 employed stable isotopes for assessing the hydrologic characteristics and sources of groundwater recharge. This study showed that the stable isotopes compositions of precipitation decrease with increasing rainfall amount and air temperature because the amount effect of precipitation is pronounced. The amount effect is clear but there was no temperature effect. The isotopic ranges of the river waters are relatively smaller and more depleted than those of precipitation. This indicated that the river water mainly came from upstream precipitation. The study also showed that the plot of $\delta^{18}O$ vs. δD of the groundwater of the Chih-Pen Creek Basin are both closely distributed along the LMWL line, suggesting that the watersheds have little evaporation. It was estimated that the groundwater is a mixture of river water and precipitation, and that the effect of the river water recharge is greater than that of the infiltration. Mckenzie *et al.,* 2010 conducted a hydrogeochemical survey of Kilimanjaro to determine water source and age of groundwater. The study inferred that bivariate plot of δ2H vs. $\delta^{18}O$ showed groundwater samples plot along on a line with the same slope as Global Meteoritic Water Line (GMWL). However, with a higher intercept than the GMWL and that there is an older groundwater system that is disconnected from the surface water system and a river system that is closely connected to some groundwater and precipitation. The study also showed that there is a small but identifiable contribution from the deeper groundwater system to the surface water system. Obiefuna and Orazulike (2011) found groundwater in semi-arid area of Yola as mildly acidic to neutral, while groundwater chemistry indicated the alkaline earth metal (Ca^{2+}+Mg^{2+}) significantly exceeded the alkalis (Na+K) and weak acids exceeded the strong acids (Cl^{-} + SO_4^{2-}) suggesting the dominance of carbonate weathering followed by silicate weathering. Srinivasamoorthy *et al.,* 2011a used hydrochemistry and stable isotopes as tools for groundwater evolution and contamination investigations. The study concluded that the $\delta^{2}H$ versus $\delta^{18}O$ diagram shows that the groundwater data plot to the right of the Global Meteoric Water Line (GMWL) and Local Meteoritic Water Line (LMWL). The water types were categorized into 5 spatial Groups. Group 1 represents indicates recharge waters with low EC and highly depleted isotopes.

Group 2 are the intermediate between recharge and discharge areas with intermediate EC and moderately depleted isotopes. Group 3 represents higher EC values and enriched isotope values. Group 4 is highly affected by pollution with very higher EC and more enriched isotopic composition. The Group 5 represents very high EC and highly enriched stable isotopic composition showing deep circulation and longer residence time.

Tarki *et al.,* 2012 studied major ions and stable isotopes in groundwaters of the Plio-Quaternary (PQ) shallow aquifer of the Djerid Oases, southern Tunisia to investigate and elucidate the origin of groundwater recharge and the mineralization processes. The study found that oxygen and hydrogen isotopic data for all samples from the PQ shallow aquifer that fall well below the GMWL suggested that groundwater derive from air masses different from those of the present day. These data revealed that there is a shift toward heavy $\delta^{18}O$ values and low $\delta^{2}H/\delta^{18}O$ slope, indicating evaporation effects. The large negative d-excess values characterizing these groundwaters suggest a secondary evaporation of recharge water caused by the irrigation return flow. The comparison of the PQ isotope contents with previously published data from the underlying Complex Terminal (CT) aquifer, identified as a fossil groundwater reservoir, show an obvious overlap of a large number of samples. This overlap indicates that the PQ shallow aquifer is mainly recharged by return flow of the CT palaeoclimatic groundwater after their evaporation in the flood irrigated areas. Talabi and Tijani (2013) investigated hydrochemical and stable isotopic characterization of the shallow groundwater system in the Ekiti crystalline basement terrain and discovered that the stable isotope analysis revealed a meteoric source of groundwater recharge (i.e. latest precipitation with slight degree of kinetic evaporation recharging the related shallow basement aquifer). Saka *et al.,* 2013 worked on hydrogeochemistry and isotope studies of groundwater in the Ga West Municipal Area, Ghana and concluded that the isotopic compositions of oxygen and hydrogen for rainwater and groundwater samples suggest that the main source of groundwater recharge is by direct rainfall infiltration. The isotopes also suggest that the shallow wells in particular are recharged by evaporated rainwater either on the ground surface or in the unsaturated zone. The d-excess values in both rainfall and groundwater have average values of 14.2 and 10.2, respectively and this shows that the d-excess in groundwaters of the study area may be inherited from the rainfall.

Saxena *et al.,* 2014 studied isotopic-chemical framework of groundwater aquifer recharge to study the pollution dynamics at Delhi, India. This study concluded that the groundwater, which is recharged by precipitation, vary from location to location and pumping induced groundwater intermixing through different flow pathways. This results in wide range of spatial variations in stable isotope (^{18}O) signature of groundwater, with $\delta^{18}O$ values as depleted -10.2664 to -1.248 ‰ during 2010-11; from -8.5872 to -2.736 ‰ in the groundwater of Najafgarh drain basin area during 2011-12, and -8.979 to -1.248 ‰ during 2010-11; from -8.131 to -2.736‰ in the groundwater of south-western part of Najafgarh drain basin area during 2011-12. Gonzalez-Trinidad et al., 2017 attempted identification of groundwater recharge sites through environmental stable isotopes in an alluvial aquifer in Mexican state of Zacatecas. The objective of this study was to achieve the isotopic characterization of rainfall and groundwater and to report the comprehensive understanding of groundwater flow processes around and within the Calera aquifer and, consequently, its potential recharge sites. This study concluded that the δD of precipitation ranged between -110.20‰ and 10.11‰, with a mean of -55.67‰ ± 27.81‰. The $\delta^{18}O$ ranged between -17.80‰ and 2.74‰, with a mean of -9.44‰ ± 4.74‰. The δD of groundwater ranged between -81.92‰ and -36.45‰, with a mean of -66.05‰ ± 8.58‰. The $\delta^{18}O$ ranged between -18.26‰ and -8.84‰, with a mean of -12.35‰ ± 2.12‰. The local meteoric water line of the Zacatecas state is $\delta D = -2.03 + 5.68\ \delta^{18}O$. The groundwater samples were clustered into four groups. The clustering of the samples led to the finding that stream flows play a significant role in the hydrological balance as a source of local recharge to the aquifer.

In general, natural groundwater receives dissolved constituents by dissolving aquifer gasses, minerals, and salts. Soil and aquifer gasses and the most soluble minerals and salts in an aquifer usually determine the groundwater chemical composition in an aquifer. Most groundwater systems are usually recharged through soil zones containing partial pressures of carbon dioxide gas that are higher than the atmosphere. Recently recharged groundwater therefore generally contains high inorganic carbon concentrations. Minor and trace element compositions of natural groundwater depend on the availability of minor and trace elements in easily soluble phases or on sorption sites, and the redox state of the water in the aquifer (Graham *et al.,* 1996). Due to the comparative insolubility of crystalline rocks, groundwater passing through igneous rocks dissolved only a very tiny amount of mineral matter. Rainwater percolating through these rocks is charged with atmospheric carbon dioxide leading to the formation of weak carbonic acid, which enhances the water's solvent action. The dissolution of silicate minerals from igneous rocks lead to silica being added to the groundwater. Sedimentary rocks are more soluble than igneous rocks "because of their high solubility, combined with their great abundance in the earth's crust; thus, they furnish a major portion of the soluble constituents of groundwater. Sodium and calcium are commonly added cations; bicarbonate and sulphate are corresponding anions. Chloride occurs to only a limited extent under normal conditions; important sources of chloride, however, are from sewage, connate water, and intruded seawater. Occasionally nitrate may be a critical component of groundwater composition; high concentrations may indicate sources of past or present pollution. In limestone terrains, calcium and bicarbonate ions are added to the groundwater by dissolution (Todd, 2005).

Based on the previous hydrogeochemical and stable isotopes research works reviewed, many except few of these authors employed hydrochemistry and stable isotopes in groundwater studies. This work however, employed both hydrochemistry and stable isotopes hydrology to evaluate the groundwater resources of Lokoja and its environs North-central Nigeria in terms of its suitability for drinking and irrigation purposes as well as to assess the source of groundwater recharge and flow process. The database generated is expected to serve as useful guide for the exploration and sustainable development of groundwater in the study area.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Preliminary Studies and Data Acquisition

Preliminary studies involved review of literature, maps collation, research design and reconnaissance survey and inventories of available wells and boreholes in the study area. Review of literature involves review of previous research works carried out by various authors on hydrochemistry/hydrogeochemistry, and stable isotopes assessments. The focus of the review was to serve as guide in the design and execution of this present work. Topographical and drainage maps of Lokoja area were prepared from existing topographical map (Sheet 62) while geological map of the area was re-produced from GSN Lokoja Sheet 62 using ArcGIS. Meteorological data (Rainfall, Humidity and Temperature data) for the study area were acquired from Meteorological Department, Ministry of Aviation. Reconnaissance visits were made to the study area to take the inventory of existing wells and boreholes as well as mapping of geological units within the localities of wells and boreholes. Finally, field geological mapping of Lokoja and its environs were undertaken with emphasis on rock types and their boundaries, texture, composition and structures of the rocks.

3.2 Field Activities

Field activities employed in this study include field geological mapping, well inventories and determination of groundwater flow direction, in situ measurement of physical parameters and groundwater sampling. The details of the specific activities are presented in the following sections.

3.2.1 Field Geological Mapping

Field geological mapping involved traversing across the study area to determine the various rock types, contacts between the rocks with references to lithological and mineralogical composition, structural features and the orientation of the features. At every outcrop/exposure, fresh rock sample was collected using sledge hammer and chisel where necessary. The fresh sample for each location was labeled and the GPS readings were taken and recorded. For this research, three rock units i.e. migmatite-biotite gneiss, older granite and sandstone were sampled for petrographical studies.

3.2.2 Well Inventories and Determination of Groundwater Flow Directions

With the aid of level meter, depths to the water level, total depth of wells and saturated water column were measured and recorded from existing wells. The Global Positioning System (GPS) *Germin etress* 20 was used to measure longitude, latitude and surface elevation of each well with respect to mean sea level. The water level is critical in groundwater flow mapping as it represents the energy level (hydraulic heads) in moving water from one point to another. The depth to water level varies depending on the local topography and the prevailing climate. The water level was generally established by a long term balanced between recharge and discharge despite seasonal climatic fluctuations. However, water levels in groundwater systems are generally a reflection of land surface as the water level is more or less a subdued replica of the land surface. Hydraulic head was determined by subtracting depth to water level from ground surface elevation (Fig. 3.1). The hydraulic head at well locations were contoured for the study area using Arc GIS sofware to produce the groundwater level map. From Fig. 3.1, hydraulic head is mathematically expressed as;

$$H_H = P_H + E_H = E - SWL$$

Where H_H = hydraulic head, P_H = pressure head, E_H = elevation head, E = Elevation, SWC = static water level.

3.2.3 In-situ Measurements of Physical Parameters

Sensitive physical parameters such as temperature, pH, conductivity and Total Dissolved Solids (TDS) were measured in the field using a digital conductivity meter (Hanna HI9861-3) that was calibrated with buffer solutions having pH values of 4 and 7. In situ measurements of these parameters during the sampling operation were necessary in order to obtain on-the-spot physico-chemical data, which may not be accurately determined in

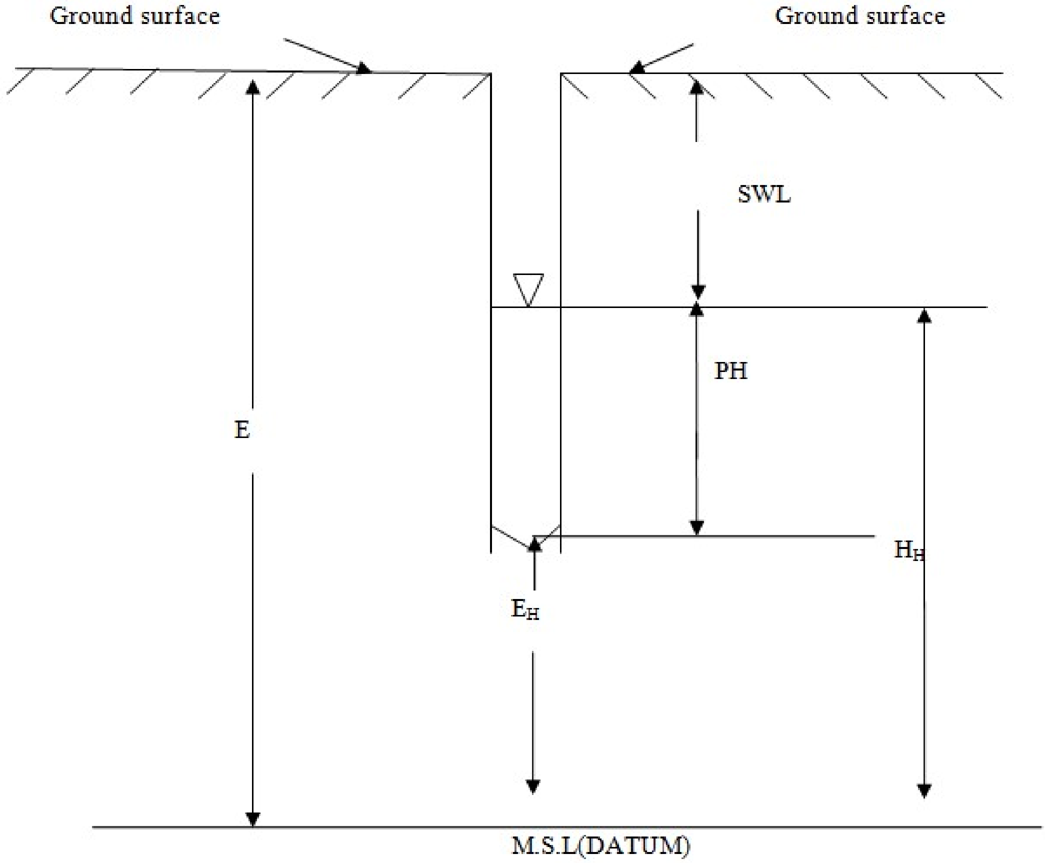

Fig. 3.1. A schematic diagram showing distribution of head in a borehole.

the laboratory due to possible change during transportation (Tijani and Abimbola, 2003). Moreover, such field measurements are said to serve as quick control checks for the subsequent laboratory results (Lloyd and Heathcote, 1985).

3.2.4 Groundwater Sampling

A total of sixty-five (65) and sixty-four (64) groundwater samples were collected from different locations, and sources (boreholes and hand dug wells) in Lokoja and its environs during the dry season (month of February 2015) and the wet season (month of July, 2016), respectively for hydrochemical analyses. A pair of samples was collected from each location for both dry and wet seasons; one for anions and the other for cations analysis. Samples for cations and trace elements analyses were filtered using 0.45 μm membrane filter and acidified to pH of < 2.0 with concentrated (ultra-pure) nitric acid on the field. This was done in order to maintain stability of the oxidation state of the various elements in solution and to prevent precipitation (Tijani, 1994). In addition, thirty-nine (39) groundwater samples were collected for stable isotope analyses during the wet season. To ensure a representative sample, groundwater samples were collected using a bailer which was emptied into a pre-cleaned, 120 ml HDPE plastic bottles that was rinsed with sample water three times prior to use based on the methods described by APHA (1995) and GPS reading was taken and recorded at every location. The samples were stored in refrigerator at $4^{O}C$ before transportation for laboraratory analyses in order to prevent microbial activities which may affect the result of the analyses.

Samples were collected and grouped based on four (4) major rock types that overlain the study area; five (5) samples from alluvium, seven (7) from sandstone, thirty-five (35) from biotite-migmatite gneiss and seventeen (17) from older granite were collected during the dry season. In wet season, three (3) samples from alluvium, five (5) from sandstone, thirty-two (32) from biotite-migmatite gneiss and twenty-four (24) from older granite were collected.

3.3 Laboratory Studies

Laboratory studies for this work involved petrographical (thin-section) analysis of rocks, hydochemical analyses for the determination of cations, anions and trace elements, and stable isotopes analysis for the determination of deuterium and oxygen-18. The details of these studies are presented in the following sections.

3.3.1 Petrographical Analysis

For the purpose of this research, twenty fresh rocks (nine migmatite-biotite gneisses, seven older granites and four sandstones) were sampled from the study area for petrographical analyses. Initially, the samples were megascopically studied in the field as hand specimen before preparation for laboratorary petrographical (thin sections) studies. The slides were prepared and photomicrographs were taken at the petrology laboratory, Kogi State University, Anyigba. The following three steps were involved in thin section analysis;

a) Cutting of rock samples: Rock samples were cut with the saw arm of Hillquist machine into slices of not less than 8mm thick along marked orientations and trimmed to dimensions to fit into glass slides. With the aid of a 45-micron full coated diamond lap on the Hillquist thin section grinder, each specimen was grinded on the surface to be cemented until all disturbed structures and saw marks were removed and absolutely flat. Checks for flatness were made by reflecting light off the prepared surface. For each of the specimen, the glass slide was frosted to brush off the oily surface and to make the thickness of the glass slide uniform using fine mesh silicon carbide (800 grit) on a glass plate. After frosting, a heat-controllable hot plate set to 80^{o}C and covered with aluminum foil was used to heat each specimen and remove moisture.

b) Mounting of specimen on glass slide: With the use of epoxy syringes, 7 ml of epoxy A and 3 ml of epoxy B were measured and mixed thoroughly in a small potric dish container. The mixed epoxy was spread generously on the prepared surface of each sample. Then, each specimen was cemented on a glass slide. All bubbles were removed by pressing the specimen against the glass slide firmly.

The specimens were allowed to cool naturally for at least 24 hours. The saw arm of the Hillquist machine was then used to reduce the thickness of the cemented specimens to about 1.5 mm thickness. Then, each specimen was then grinded using the Lap arm and dial gauge indicator as control by sweeping the specimen back and forth across the wheel cup to a thickness of between +0.06 and +0.07 mm. This will leave the specimen between 40 and 50 microns thick while 30-micron plate was installed as the grinder to remove scratches which then brought each specimen's thin section to transparent thickness of 30 microns (0.03 mm).

c) Microscopic observation: Finally, the prepared slides were studied under microscope with cross polarized light (with analyzer) and plane polarized light (without analyzer) with magnification of X10. The photomicrographs of the samples were taken under the microscope at the same magnification.

3.3.2 Hydrochemical Analyses

The hydrochemical analyses of dry season samples for major ions and trace elements were carried out at ACME Analytical Laboratory in Vancouver, Canada while those of wet season samples along with stable isotope samples were analysed at Water Science Laboratory, University of Nebraska, Lincoln, USA. The concentrations of major cations: calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}); trace elements: arsenic (As), iron (Fe), manganese (Mn), lead (Pb), zinc (Zn), chromium (Cr) and cadmium (Cd); major anions: Bicarbonate (HCO_3^-), Nitrate (NO_3^-), Sulphate (SO_4^{2-}) and Chloride (Cl^-) and; stable isotopes: ^2H or D and ^{18}O were analysed for groundwater samples in the study area.

During the dry season, major cations and trace elements were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) was used to confirm higher concentrations. Solutions containing a high amount of total dissolved solids were diluted 10X prior to analysis with a corresponding increase in detection limits. Detection limit of major cations is presented in Table 3.1. While the concentrations of chloride (Cl^-), nitrate (NO_3^-) and bicarbonate

Table 3.1. Detection limit of major cations

Parameters	Detection limit (no dilution)	Detection limit (≥10 dilution)
Ba^+	0.05 ppb	80 ppb
Ca^+	0.05 ppb	0.4 ppm
Fe^+	10 ppb	10,000 ppb
K^+	0.05 ppm	1 ppm
Mg^+	0.05 ppm	1 ppm
Na^+	50 ppb	1000 ppb
Sr	0.01 ppb	1 ppb
As	0.5 ppb	3000 ppb
Cd	0.05 ppb	700 ppb
Cr	0.5 ppb	300 ppb
Fe	10 ppb	10000 ppb
Mn	0.05 ppb	50 ppb
Pb	0.1 ppb	*

*Not reported

(Source: ACME Laboratory, 2015).

(HCO_3^-) were determined by the calorimetric technique and sulphate (SO_4^{2-}) was analysed by the Turbimetry method during the dry season.

During the wet season, the concentrations of major cations were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS); the anions (Cl^-, NO_3^- and SO_4^{2-}) were analysed using Ion Chromatography (IC). In IC analysis, a small aliquot of sample (0.1 ml) was measured using a sample loop, injected into a stream of carbonate/bicarbonate eluent and pumped through an ion exchange column. The anions were separated on the basis of their relative affinities for the low capacity, strongly basic, ion exchange resin comprising the column. Separated ions were converted to their highly conductive acid forms in a membrane suppressor and detected in the eluent as they pass through a conductivity detector. Ions were identified by their retention time and quantified by measurement of peak area. Bicarbonate was determined by titration.

The major ions data were subjected to internal consistency tests to account for the differences that may arise from use of different laboratories and methods of determination of ions in groundwater samples. The concentrations of the major anions and cations were compared to ensure that these concentrations were within ± 5% of each other, using the charge balance error formula (Appelo and Postma 2005).

$$\frac{\sum cations - \sum anions}{\sum cations + \sum anions} x100 \qquad 3.1$$

where the concentrations of the anions and cations were expressed in meq/L. All the 65 and 64 samples for dry and wet seasons respectively passed the internal consistency test and were used for the next stage of the research.

3.3.3 Stable Isotopes Analysis

Stable isotopes (^2H or D and ^{18}O) were determined at the Water Science Laboratory, University of Nebraska Lincoln USA using Mass Spectrometry method. Deuterium (^2H) was determined by placing water samples in 1 ml glass vials and septa sealed. The vials were placed in an auto-sampler and subsequently injected into a pyrolizing furnace set at 1040^0C. Helium carried the resultant sample gases through a Gas Chromatograph to separate the carbon monoxide peak from H_2 peak. Samples were then pushed to the mass spectrometer where hydrogen isotope ratios were determined at masses 1, 2 and 3. For O^{18}, water samples were equilibrated using the automated fill mode on the sample preparation module on the GV 2003. Once equilibrated, the samples were pressurised with helium and then let through a water trap and into sample loop. The sample loop was moved into the continuous flow of helium and water sample was pushed through a Gas Chromatograph column to the mass spectrometer where the carbon and oxygen isotope rations were determined at masses 44, 45, 46.

3.4 Data Evaluation

Hydrochemical and isotope results were subjected to several data evaluations. The details of the methods employed in this study are presented in the section below.

3.4.1 Multivariate Statistical Analyses

Two statistical analyses were used to evaluate the hydrogeochemical data i.e. correlation analysis and principal component analysis. The data were processed using GenStat 10.3.0.0. Correlation coefficient is commonly used to measure and establish the relationship between two variables (parameters) and it is a simplified statistical tool to show the degree of dependency of one variable (parameter) with respect to others to the other. Principal component analysis however, is a multivariate statistical analysis and it is commonly used to reveal patterns in large data set. The goal when using principal component analysis is to determine few linear combinations of original variables that can be used to summarize the data set without losing much information. Principal component analysis operates on sums of squares and products, or a correlation matrix, or a matrix of variance and covariance formed from variates. According to Davis (1986), principal component analysis helps to reduce the intricacy of data sets on a big scale and thus identify the prevalent geochemical processes. For the principal component analysis, 14 parameters in 65 groundwater samples were used. On the principle of the Kaisier criterion, the number of major PCs for interpretation was chosen with an Eigen value higher than one and all explained percentage variation equal to or greater than 70%. The test statistics is:

$$n - \frac{(2p + 11)}{6}\left[\log\left(1/k \sum_{i>k} l_i\right) - 1/k \sum_{i>k} \log\, l_i\right] \qquad 3.2$$

Where n is the number of units and p is the number of variables. Asymptotically, the statistics have a chi-square distribution with $(k+2)\ (k-1)/2$ degrees of freedom. If any latent roots are zero, GenStat software excludes them from the calculation of the test statistic; the effective value of p is reduced accordingly.

3.4.2 Hydrochemical Plots

Piper trilinear diagram, Gibbs diagram, stiff diagram and Schoeller diagram were drawn using computer software Aquachem. Piper trilinear diagram (Piper, 1944) conveniently reveals similarities and differences among groundwater samples, as water samples with similar qualities will tend to plot together as a group i.e. it is used to inferred hydrogeochemical facies. The hydrochemical facies concept was developed to identify and understand the water composition in different classes. Facies are recognisable parts of different characters belonging to any genetically related system (Rajendra Prasad et al. 2009). The diagram is useful in bringing out chemical relationships among groundwater samples in more definite terms compared to other convectional plotting methods. A piper plot is comprised of three components: a ternary diagram in the lower left representing cations (magnesium, calcium, and sodium + potassium), a ternary diagram in the lower right representing anions (chloride, sulfate, and carbonate + bicarbonate), and a diamond plot in the middle which is a matrix transformation of the two ternary diagrams. Each sample is normalised (sum of cations = 100 and sum of anions = 100), so the relative concentrations are on a percentage basis from which inference is drawn based on hydrogeochemical facies concept (Back and Hanshaw 1965).

Stiff (1951) proposed a pattern which uses parallel horizontal axes extending on each side of a vertical zero axes. In this pattern, concentrations of cations are plotted, one on each axis to the left of zero, and likewise anions concentrations can be plotted, one on each axis to the right of zero; the ions being plotted in the same sequence. The resulting points are connected to give an irregular polygonal shape or pattern in which waters of a similar quality define a distinctive shape from other of different quality. The stiff patterns can be a relatively distinctive method of showing water composition differences and similarities. The width of the pattern is an approximate indication of total ionic content of a particular groundwater sample.

The Schoeller diagram (Shoeller, 1962) is one of the graphical representations of hydrochemistry of groundwater samples and it shows the total concentration of major ions in log-scale which allow the major ions of many samples to be represented on a single graph and the concentrations are typically expressed in milli equivalent per liter. The diagram also allows visual comparison of the composition of different water type. Multiple samples from different wells may be plotted on a single diagram to distinguish similar patterns in the ratios of particular anions and cations. Water concentrations are a function of the groundwater chemistry and the chemical composition of the aquifer rock material. These patterns may be used to distinguish common or disparate source areas of water drawn from multiple wells. Gibbs diagram (Gibbs, 1970), a plot of TDS against $Na^+/(Na^+ + Ca^{2+})$ ratio usually assessed the functional source of dissolved ions in waters as evaporation dominance, rock dominance (dilution and weathering) and precipitation dominance, which controls the water chemistry. Gibbs diagram is widely used to establish the relationship of water composition and aquifer lithological characteristics (Kumar *et al.,* 2014).

3.5 Water Quality Assessment

Assessment of water quality for drinking purpose involved estimation of Water Quality Index (WQI) while quality assessment for irrigation involved Sodium hazard, Sodim Adsorption Ratio (SAR), Magnesium hazard, Residual Sodium Carbonate (RSC) and Permeability Index. The details of these assessments are presented in the section below.

3.5.1 Drinking Quality Indices

1) Total Hardness (TH): TH is the presence of divalent metallic cations (calcium and magnesium) in groundwater. These ions react with with soap to form precipitates and with certain anions present in the water to form scale. Total hardness is usually expressed as the calcium carbonate equivalent.

Thus,

$$H_T = Ca \times \frac{CaCO_3}{Ca} + Mg \times \frac{CaCO_3}{Ca} \qquad 3.3$$

These parameters (H_T, Ca and Mg) are expressed in mg/L and the ratios in the equivalent weights equation. The above equation is reduced to

$$H_T = 2.5\,Ca + 4.1\,Mg \qquad 3.4$$

2) Water Quality Index (WQI): One of the best methods for the communication of the water quality information to the public and policymakers is the Water quality index (WQI) (Mishra and Patel, 2001; Singh, 1992). WQI has become significant parameters for assessing and managing groundwater (Naik and Purohit, 2001 and Tiwari and Mishra 1985). WQI is a rating method reflecting the composite influence of different water quality parameters and it is estimated from the point of view of the suitability of groundwater for human consumption. For WQI, three steps were involved as follows:

a) Assignmet of weight (wi): Weights (wi) were allocated to each of the 12 chosen assessment parameters according to their comparative significance in the general drinking water quality (Table 3.2). Due to its important role in water quality assessment, the maximum weight of 5 was been allocated to the nitrate while weight 2, was however allocated to TH due to relative harmless nature of its concentration in water. Depending on their significance in determining water quality, other parameters were allocated weights between 1 and 5.

b) Estimation of relative weight (Wi): Using the following equations, the relative weight (Wi) is calculated:

$$W_i = \frac{w_i}{\sum_i^n} \qquad 3.5$$

Where, Wi is the relative weight, wi is the weight of each parameter and n is the number of parameters. Calculated relative weight (Wi) values of each parameter were also given in Table 3.2.

Table 3.2. Relative weights of assessment parameters (mg/L)

Parameters	SON Standard	Weight (w_i)	Relative weight $W_i = \frac{w_i}{\sum_i^n}$
TDS	500	5	0.0980
TH	150	2	0.0392
Ca	75	3	0.0588
Na^+	200	3	0.0588
NO_3^-	50	5	0.0980
SO_4^{2-}	100	4	0.0784
Cl^-	250	5	0.0980
Fe^{2+}	0.03	4	0.0784
Mn	0.2	5	0.0980
Pb	0.01	5	0.0980
Cr	0.05	5	0.0980
Zn	3.0	5	0.0980
		$\sum w_i = 51$	$\sum W_i = 0.9996$

SON (Standard Organisation of Nigeria)

c) Assignment of quality rating scale (qi)**:** A quality rating scale (qi) is assigned to each parameter by dividing the concentration in each water sample by the respective standard (Standard Organization of Nigeria, 2007) in accordance with the guidelines laid down in the BIS, 1991 followed by multiplication of the result by 100:

$$q_i = (C_i / S_i) X100 \qquad 3.6$$

where qi is the quality rating, Ci is the concentration of each chemical parameter in each water sample in mg/L, and Si is the SON standard for drinking water for each chemical parameter in mg/L.

For computing the WQI, the Sub-Index (SI) of ith parameter was first determined for each chemical parameter, which is then used to determine the WQI as per the following equation;

$$SI_i = W_i \times q_i \qquad 3.7$$

$$WQI = SI_i \qquad 3.8$$

SI_i is the sub-index of ith parameter; q_i is the rating based on concentration of ith parameter and n is the number of parameters. According to Chartterji and Rajiuddin (2002), the computed WQI values can be categorized into five groups, 0-25 excellent water quality, 26-50 good water quality, 51-75 poor water quality, 76-100 very poor water quality, and > 300 water inappropriate for drinking.

3.5.2 Irrigation Quality Indices

The following irrigation quality parameters were employed for assessing irrigation quality status of groundwater in Lokoja and its environs.

a) Sodium Hazard: In the classification of irrigation water, sodium concentration is of excellent importance because soil reacts with sodium to decrease its permeability (Janardhana, 2007). Soils containing a high proportion of sodium with carbonate as the predominant anion are referred to as alkali soil and those with chloride or sulphate as the predominant as anion are saline soils. Either type of sodium-saturated soil ordinarily will support little or no plant growth. Sodium percentage was calculated using equation;

$$\% \ Na = \frac{(Na + K)100}{Ca + Mg + Na + K} \qquad 3.9$$

All of the ionic concentrations are presented in milliequivalents per liter.

b) Sodium Adsorption Ratio (SAR): According to Jafar *et al.,* (2013), sodium adsorption ratio may show the degree to which irrigation water tends to enter cation – exchange reaction in soil. Calcium and magnesium adsorbed by sodium is a risk because it damages the structure of the soil and becomes rigid and impervious. The salinity laboratory of the U.S. Department of Agriculture, (1954) recommends the sodium absorption ratio because of its direct relation to the adsorption of sodium by soil. The sodium adsorption ratio was calculated using the equation 6 (Richards 1954);

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}} \qquad 3.10$$

All the concentrations of the constituents are expressed in milliequivalents per liter

c) Magnesium Hazard (MH): Magnesium is an indicator to assess the quality of water for irrigation purposes (Szabolcs and Darab, 1964). MH describes the connection between concentration of magnesium and calcium in groundwater. Magnesium risk was calculated using equation 7:

$$\mathrm{MH} = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100 \qquad 3.11$$

d) Residual Sodium Carbonate (RSC): The residual sodium carbonate (RSC): RSC index of irrigation water or soil is used to indicate the alkalinity hazard for soil. The RSC index is used to find the suitability of the water for irrigation in clay soils which have a high cation exchange capacity. When dissolved sodium in comparison with dissolved calcium and magnesium is high in water, clay soil swells or undergoes dispersion, which drastically reduces its infiltration capacity. Clay soils irrigation with high RSC index water leads to fallow alkali soils formation (USSL, 1954). The RSC is expressed as the sum of the values of bicarbonate and carbonate ions minus the sum of the values of calcium and magnesium where ions are represented in meq/L.

$$\text{RSC} = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+}) \qquad 3.12$$

Permeability Index (PI): Permeability of the soil is affected by high sodium as well as carbonate and bicarbonate contents in water. A part of CO_3^- and HCO_3^- is precipitated as $CaCO_3$ or $MgCO_3$ removing Ca^{2+} and Mg^{2+} from irrigation water and leads to increased proportion of solution (Doneen, 1961). Permeability risk of groundwater was determined using:

$$\text{PI} = \frac{(Na^{+} + (\sqrt{HCO_3^{-}})}{(Ca^{2+} + Mg^{2+} + Na^{+})} \times 100 \qquad 3.13$$

CHAPTER FOUR

4.0 RESULTS INTERPRETATION AND DISCUSSION

4.1 Petrography

Petrographic (thin section) analysis was undertaken to determine the modal compositions of the rocks through visual estimation under the microscope. In hand specimen, older granite I is light coloured and coarse to very coarse grained texture with elongate feldspars, biotite flakes and rounded quartz. In thin section (Fig. 4.1a), quartz, biotite, microcline and hornblende with modal composition of 38.70, 25.81 and 27.42 % respectively (Table 4.1a) constitute of major minerals and ferromagnesian mineral like hornblende (4.84 %) and opaque (3.23 %) were the accessory minerals. Quartz was xenomorphic in shape, microcline exhibiting cross hatched twining and biotite was shade of brown. Older granite II in hand specimen is made up of creamy-white feldspar and quartz and dark minerals. The dark minerals are arranged in a streaky banding, giving the rock a gneissic texture. This comprised mineralogically of quartz, feldspars and biotite with biotite-defined foliation (Fig. 4.1b). The modal compositions in thin section (Table 4.2) were 54.76, 11.90, 30.95 and 2.38 % for quartz, biotite, microcline and opaque minerals respectively (Table. 4.1a).

Migmatite-biotite gneisses I in hand specimen are dark grey in colour and are generally medium grained. The mineral compositions are quartz, biotite, plagioclase and some accessories with quartz as the dominant mineral in hand specimen. In thin section (Fig. 4.2a), the modal compositions of migmatite-gneiss (Table 4.2a) are quartz (46.15 %), biotite (28.21 %), plagioclase (12.82 %), opaque (5.13 %) and others (7.69 %). The modal compositions of Migmatite-biotite gneisses II in thin section (Fig.4.2b) were 36.05, 11.63, 6.98, 30.23, 4.65, 3.49 and 6.98 % for quartz, biotite, hornblende, microcline, opaque and accessory minerals respectively (Table 4.2b).

The sandstone samples in hand specimen are generally fine to coarse grained varying in colour from milky to purple and massively cross stratified. The modal compositions of sandstones in thin section (Fig. 4.3 and Table 4.3) were quartz (67.25 %), plagioclase (5.17 %), opaque (20.69 %) and other minerals (6.9 %). The analyses of photomicrographs of the migmatite-biotite gneisses, older granites and sandstone samples from the study area revealed the abundance of quarts, microcline, mica (of which biotite was dominant) and plagioclase. The weathering and dissolution of these minerals especially plagioclase, microcline, mica to a lesser extent quartz were possibly responsible for groundwater mineralisation in Lokoja and its environs. The atmospheric and biogenic carbon (IV) oxide charged surface permeate into the ground which strongly react with these minerals liberating into the water cations such as calcium, magnesium, sodium and potassium (equation 4.1 to 4.5 while leaving clay minerals as residue. The result of this reaction gives rise to groundwater of different compositions.

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3 \tag{4.1}$$

$$2NaAlSi_3O_8 + 2CO_2 + 3H_2O \leftrightarrow 4siO_2(OH)_4 + 2Na^+ + 2HCO_3^- \tag{4.2}$$

$$Ca_2Mg_5Si8O_{22}(OH)_2 + 14CO_2 + 22H_2O \rightarrow 2Ca^{2+} + 5Mg^{2+} + 14HCO_3 + 8Si(OH)_4 \tag{4.3}$$

$$CaMg(Si_2O_6) + 4CO_2 + 6H_2O \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3 + 2Si(OH) \tag{4.4}$$

$$2KAlSi_3O_8 + 11H_2O \rightarrow Si_2O_5Al_2(OH)_4 + Si(OH)_3 + 2K^+ + 2)OH \tag{4.5}$$

4.2 Well Inventories and Groundwater Flow Directions

The summary of well inventory is presented in Table 4.4 while the detailed data are presented in Appendix I and II. Well inventory revealed that the depth to water level (DWL) during the dry season varied between 0.5 and 10.1 m with an average of 3.21m while that of wet season from 0.06 to 8.55 m, the total depth of well (TDW) varies between 3.0 and 10.5 m for both seasons, and saturated water column (SWC) in dry season ranged between 0.5 and 4.2 m and 1.3 and 6.4 for wet season.

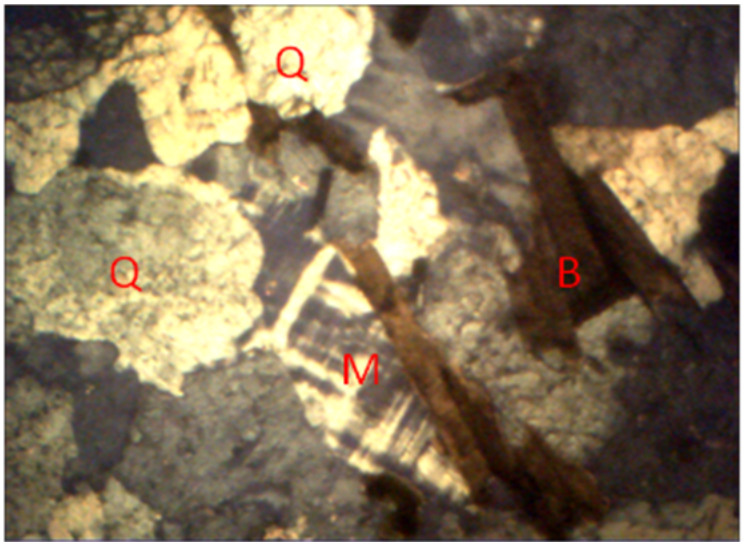

Fig. 4.1a. Photomicrograph of granite I (Q = quartz, M = Microcline, B = Biotite)

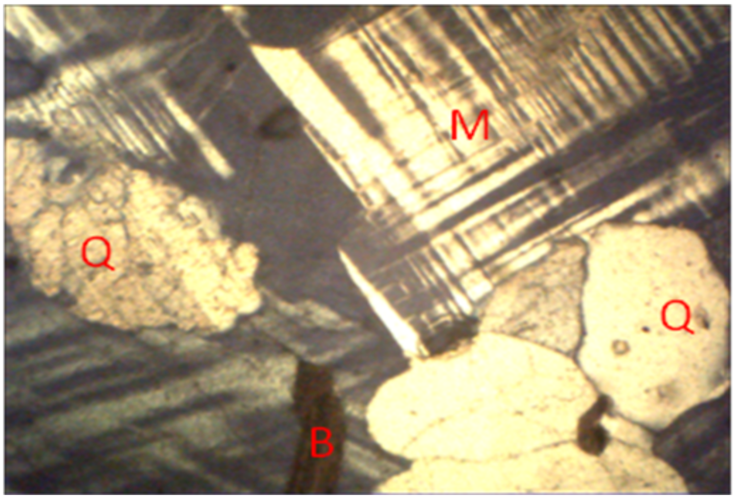

Fig. 4.1b. Photomicrograph of granite II (Q = quartz, M = Microcline, B = Biotite)

Table 4.1a. Modal composition of granite I

Sample R2	
Minerals present	Percentage
Quartz	38.70
Biotite	25.81
Microcline	27.42
Hornblende	4.84
Opaque	3.23
Total	100.00

Table 4.1b. Modal composition of granite II

Sample R4	
Minerals present	Percentage
Quartz	54.76
Biotite	11.90
Microcline	30.95
Opaque	2.39
Total	100.00

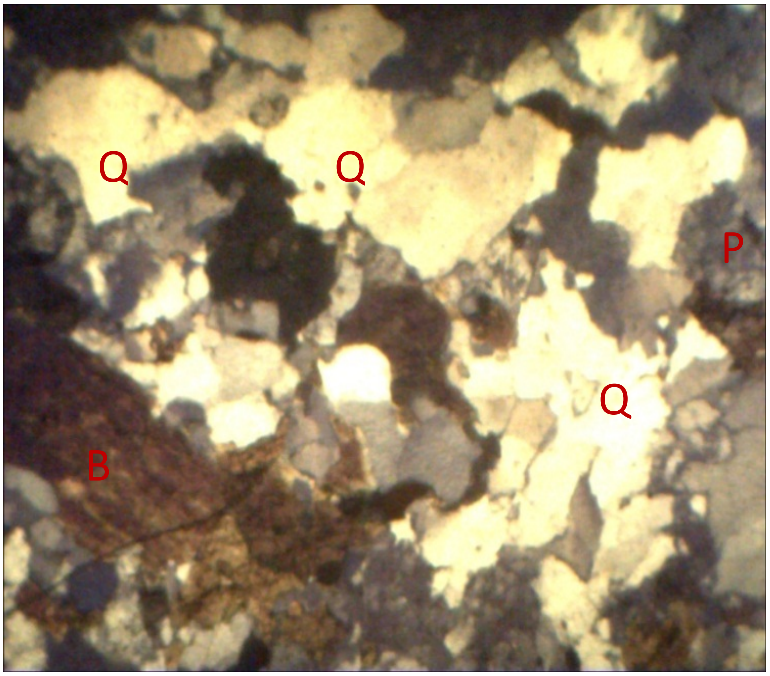

Fig. 4.2a. Photomicrograph of migmatite gneiss I (Q = quartz, B = Biotite, P = Plagioclase)

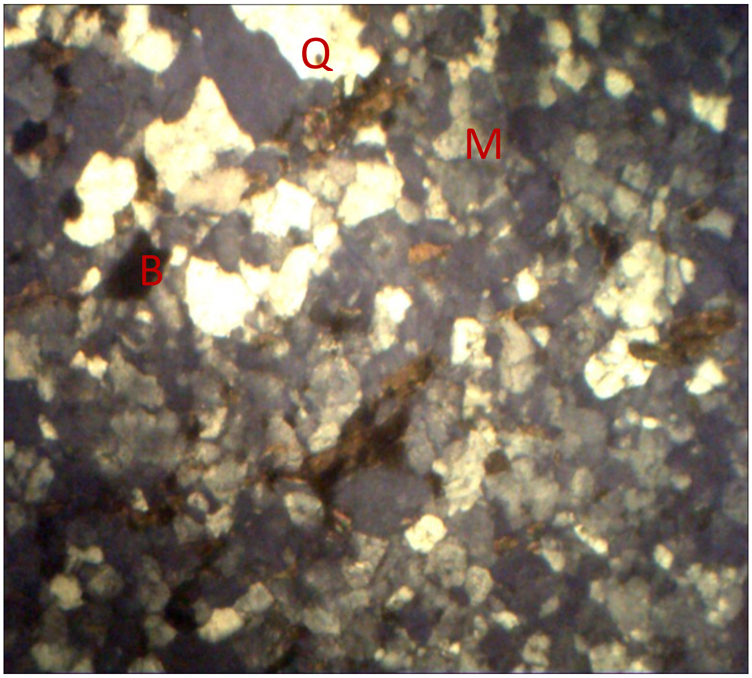

Fig. 4.2b. Photomicrograph of migmatite gneiss II (Q = quartz, M = Microcline, B = Biotite)

Table 4.2a. Modal composition of migmatite gneiss I

Sample R7	
Minerals present	Percentage
Quartz	46.15
Biotite	28.21
Plagioclase	12.82
Opaque	5.13
Others	7.69
Total	100.00

Table 4.2b. Modal composition of migmatite gneiss II

Sample 11	
Minerals present	Percentage
Quartz	36.05
Biotite	11.63
Hornblende	6.98
Microcline	30.23
Opaque	4.65
Accessories	3.49
Others	6.97
Total	100.00

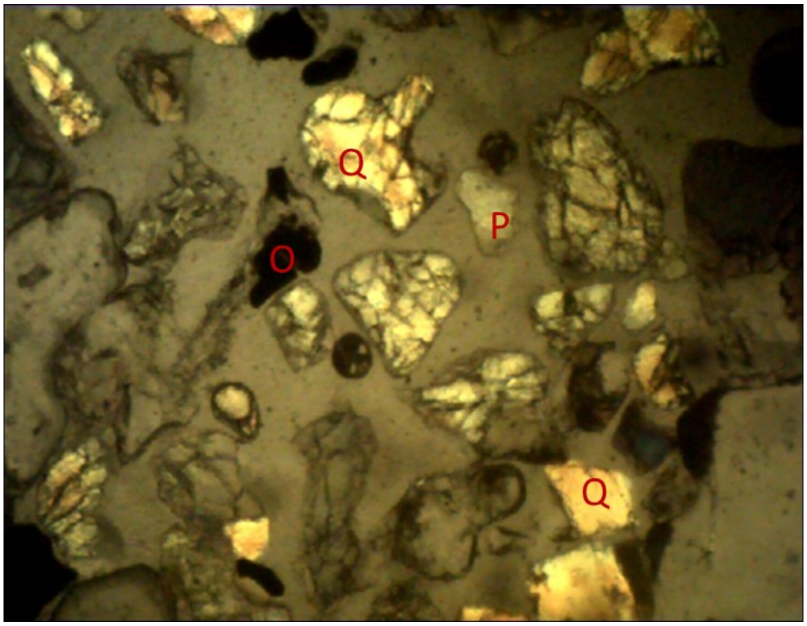

Fig. 4.3. Photomicrograph of sandstone (Q = quartz, P = Plagioclase, O = Opaque)

Table 4.3. Modal composition of sandstone

Sample L16	
Minerals present	Percentage
Quartz	67.25
Plagioclase	5.17
Opaque	20.68
Others	6.90
Total	100.00

Table 4.4. Summary of well inventory for dry and wet seasons

Parameters	Min	Max	Mean
Dry Season			
DWL (m)	0.5	10.1	3.21
TDW (m)	3.0	10.5	4.71
SWC (m)	0.5	4.2	1.56
WL (m)	22.8	112.0	70.5
Wet Season			
DWL (m)	0.06	8.55	1.88
TDW (m)	3.0	10.5	4.71
SWC (m)	1.3	6.4	1.05
WL (m)	45.2	201	73.5

KEY

DWL (Depth to Water Level)
TDW (Total Depth of Well)
SWC (Saturated Water Column)
WL (Water Level)

The wells were generally shallow across the study area but were slightly deeper in sedimentary terriains (3.0 – 10.5 m) than the basement terrains (3.0 – 9.6 m). The water levels of most wells in both seasons vary significantly (0.5 – 10.1 m) from one well to another and this is a clear indication of localised and disconnected shallow weathered aquifers typical of basement terrain. The depth to water level is shallower in wet season due to precipitation recharging the aquifer than in dry season when some wells dried off as recharge into aquifers was absent due to lack of precipitation.

A plot of saturated water column (SWC) versus total depth of well revealed a weak correlation in dry (0.15) and wet (0.45) seasons (Fig. 4.4a and 4.4b). These confirmed the localised nature of the weathered aquifer, which is assumed to be controlled by different bedrock lithology, and intensity of weathering in basement setting (Talabi and Tijani, 2013). The dry season plot (Fig. 4.4a) showed that SWC does not have any correlation with TDW, though even with shallow TDW of less 5.0 m there is still higher SWC. This may be an indication that the yield of water in some wells may be fracture controlled because even when the wells are of shallow depth they still exibit higher yield. The wet season plot (Fig. 4.4b) on the other hand showed slight correlation between SWC and TDW which can be attributed to possible influence of recharge from precipitation. Therefore, with higher recharge during wet season, it is obvious that the deeper wells will have higher storage space, which translated to higher SWC hence the slight correlation. The plot of total depth of well versus total dissolved solids (Fig. 4.5a and Fig 4.5b) showed that there is less number of wells with TDS >700 mg/L due to reduced dissolution and chemical weathering during dry season. Whereas, there is higher number of wells with TDS >700 mg/L during wet season implying the contribution of dissolution and leaching of solutes through active vertical recharge during wet season (Idowu and Ajayi, 1998).

Groundwater level map was produced to determine flow direction in the study area. Hydraulic heads, which was determined by subtracting static water level from surface elevation from sample points, was used to produce groundwater level map. Well inventories revealed that water level (WL) i.e. hydraulic head of wells varied between

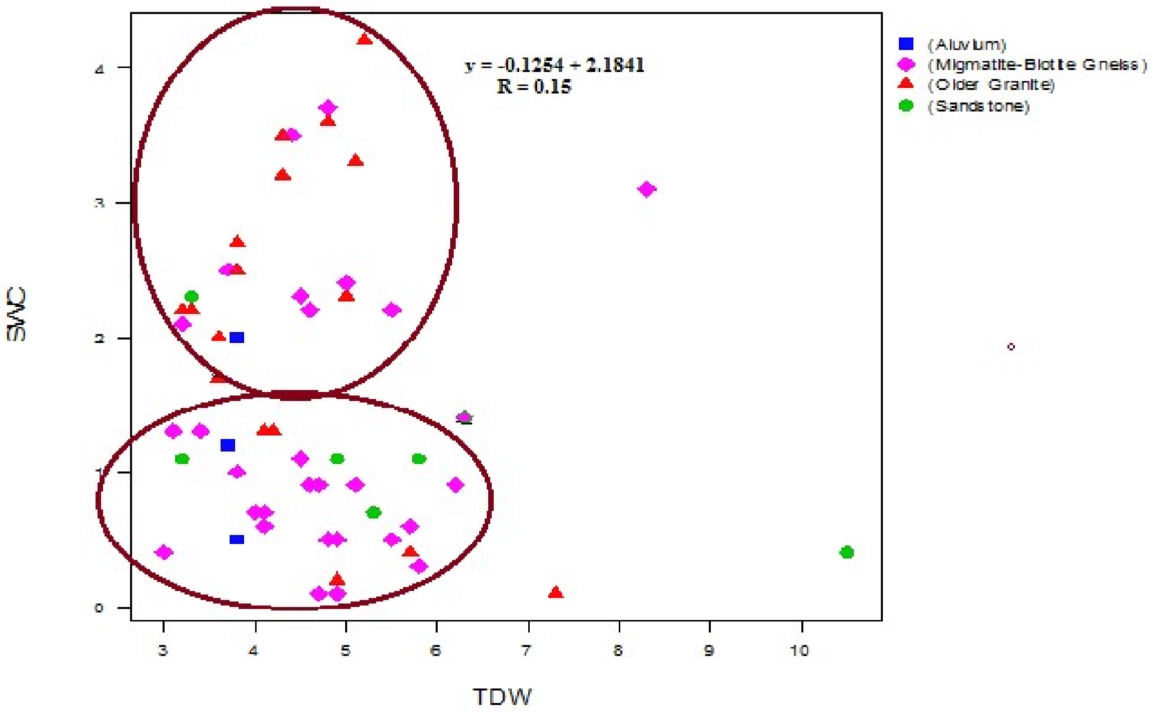

Fig. 4.4a. Saturated water column vs. Total depth of well (dry season)

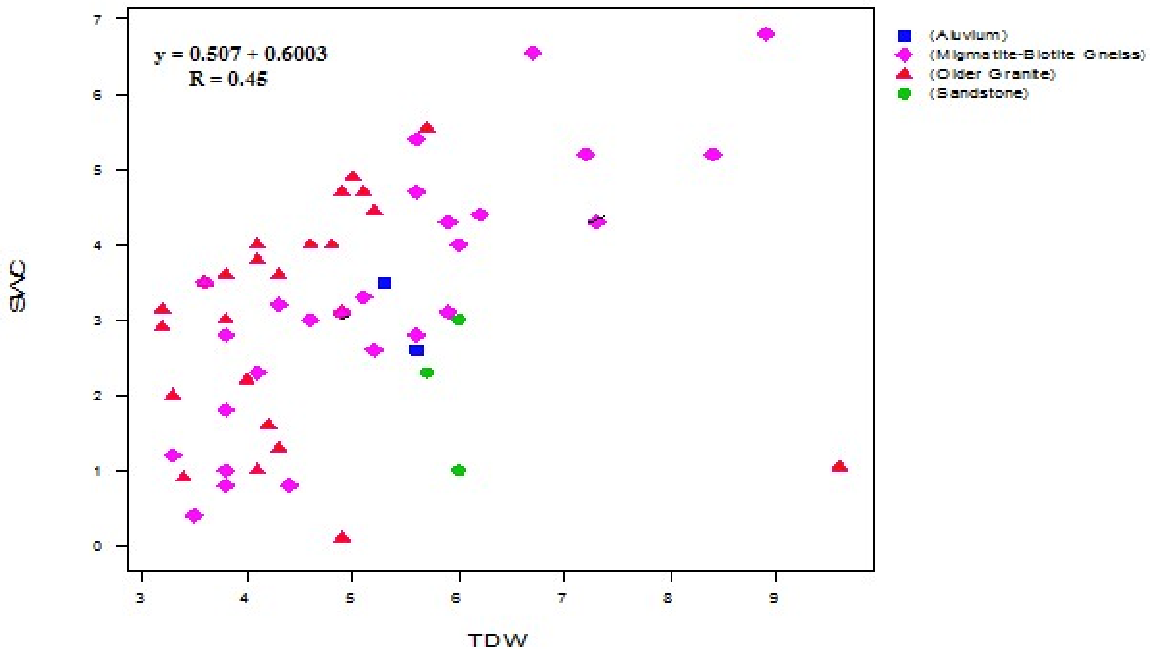

Fig. 4.4b. Saturated water column vs. Total depth of well (wet season)

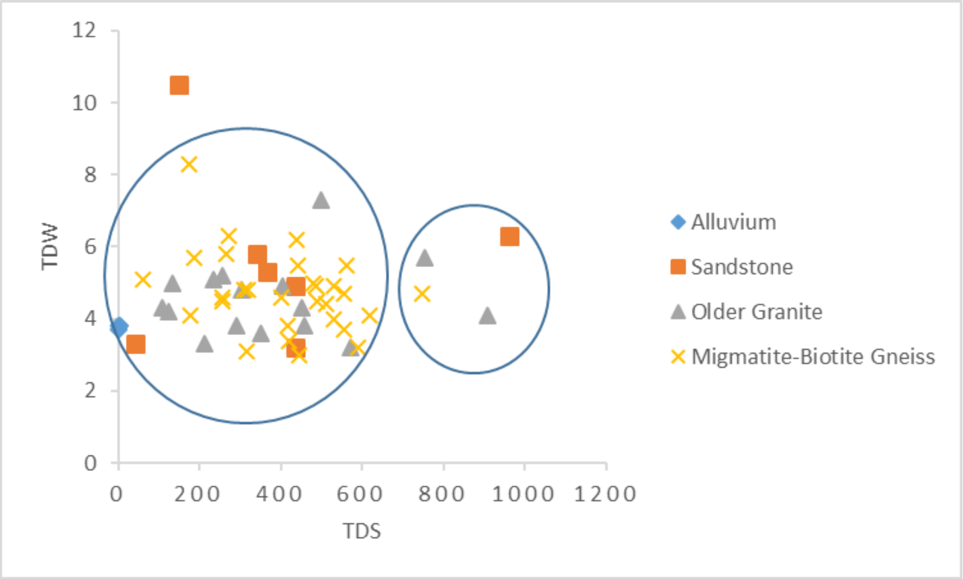

Fig. 4.5a. Plot of TDW vs. TDS for dry season

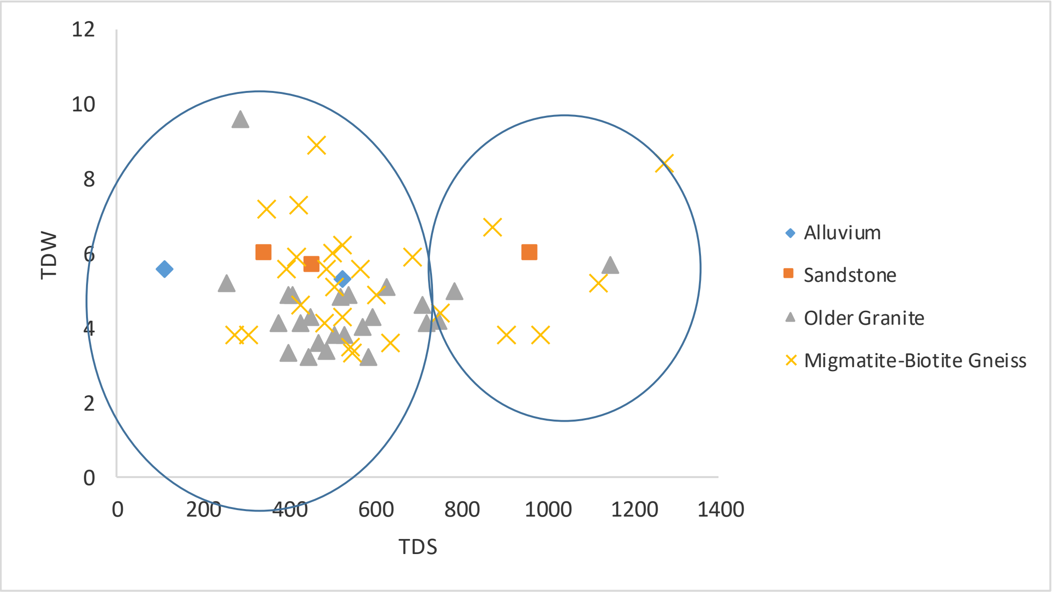

Fig. 4.5b. Plot of TDW vs. TDS (wet season)

22.8 and 112 m above sea level (a.s.l.) with an average of 70.8 m (a.s.l.) as presented in Table 4.5. The map shows that groundwater generally flows towards the central part of Lokoja from Mount Patti and Adankolo (North-Eastern) and Otokiti (South-Western) part of the area. The map also shows groundwater flow from Mount Patti towards Felele towards to Agbaja hill (Fig. 4.6). It was observed that the average TDS of 441.7 mg/L from lower elevations did not differ greatly from those of higher elevations with values of 372.8 mg/L. This suggests the localised (non-continuous) nature of aquifer in the study area typical of basement terrians (Stuyfzand, 1999).

4.3 Physical Parameters

Summary of results of the measured physical parameters during the dry and wet seasons are presented in Table 4.6 while the detailed data are presented in Table 4.7 and 4.8. The temperature measured in the dry season ranged from 25.3 to 33.7°C while the wet season values ranged from 24.7 to 31.6°C. In general, cool water is more palatable than warm water, and the effect of temperature on the availability of a number of inorganic constituents and chemical contaminants that may influence taste of the water. High water temperature according to WHO (2006) increases microorganism growth and may raise concerns with taste, odour, colour and corrosion. The measured temperature in the dry season were all above the 25°C, the value proposed by WHO as suitable temperature of water quality whereas only one sample had temperature of 24.7°C in wet season, an ambient temperature (local temperature of Lokoja which is usually high) was thought to be responsible for the elevated values of temperature. The pH of water is a measure of its reactive properties i.e. low pH values, especially below 4, implies corrosive water which tends to dissolve metals and other substances with which it comes into contact. High pH, particularly above 8.5, indicates alkaline water, which on heating will tend to form a scale and it also affect considerably the water treatment and use (Todd, 2005). In Lokoja area, the pH of the groundwater ranged from 5.5 to 8.5 in dry season and 5.4 and 9.1 in wet season. The groundwater was generally neutral in both seasons (Talabi and Tijani, 2013) but were slightly acidic in locations S14 (5.9) and S57 (5.7) during the dry season and locations L28 (6.3), L48 (6.0), L68 (5.4) and L69 (6.3) for wet season possibly

Table 4.5. Parameters for the determination of water level

S/ID	Latitude	Longitude	Elevation (m)	DWL (m)	WL (m)
S1	N07044’40.2’’	E006044’32.6’’	67	1.2	65.8
S2	N07044’44.4’’	E006044’31.9’’	41	1.1	39.9
S3	N07044’43.4’’	E006044’23.1’’	56	1.4	54.6
S4	N07044’49.2’’	E006044’10.0’’	58	1.6	56.4
S5	N07044’55.2’’	E006044’08.6’’	59	2.1	56.9
S6	N07044’59.3’’	E006044’23.6’’	63	2.4	60.6
S7	N07045’23.8’’	E006044’25.2’’	57	3.4	53.6
S8	N07046’25.2’’	E006044’14.0’’	69	4.3	64.7
S9	N07046’24.3’’	E006044’04.0’’	70	5.3	64.7
S10	N07046’20.6’’	E006044’10.2’’	80	3.7	76.3
S11	N07046’40.5’’	E006044’01.0’’	74	1.0	73
S12	N07046’46.7’’	E006043’59.8’’	64	0.8	63.2
S13	N07046’42.0’’	E006043’45.6’’	55	4.7	50.3
S14	N07046’30.4’’	E066043’37.2’’	75	3.4	71.6
S15	N07046’42.1’’	E006043’39.6’’	70	3.3	66.7
S16	N07046’00.2’’	E006044’16.7’’	59	4.8	54.2
S17	N07045’46.6’’	E006044’06.0’’	30	7.2	22.8
S18	N07045’51.6’’	E006044’13.8’’	68	2.9	65.1
S19	N07045’30.1’’	E006044.22.4’’	66	1.1	64.9
S20	N07046’40.3’’	E006044’35.8’’	53	3.5	49.5
S21	N07047’14.5’’	E006043’55.5’’	54	0.5	53.5
S22	N07047’16.1’’	E006044’03.4’’	59	0.5	58.5
S23	N07047’12.9’’	E006044’13.7’’	68	2.7	65.3
S24	N07047’22.2’’	E006044’32.0’’	65	1.9	63.1
S25	N07047’38.2’’	E006044’28.7’’	78	2.1	75.9
S26	N07047’48.4’’	E006044’45.3’’	54	2.8	51.2
S27	N07048’00.6’’	E006044’44.8’’	53	1.9	51.1
S28	N07048’05.9’’	E006044’47.9’’	48	0	48
S29	N07048’26.6’’	E006044’48.3’’	65	0	65
S30	N07048’41.6’’	E006044’51.8’’	60	0	60
S31	N07048’50.4’’	E006044’49.6’’	53	1.1	51.9
S32	N07049’02.3’’	E006044’51.3’’	58	4.6	53.4
S33	N07049’06.0’’	E006044’43.6’’	73	5.7	67.3

Table 4.5. Cont'd. Parameters for the determination of water level

S/ID	Latitude	Longitude	Elevation (m)	DWL (m)	WL (m)
S34	N07049'10.3''	E006044'31.4''	115	0	115
S35	N07048'56.7''	E006044'39.2''	86	4.9	81.1
S36	N07048'40.4''	E006044.40.4''	49	3.7	45.3
S37	N0704'.30.7''	E006044'18.8''	87	1.2	85.8
S38	N07048'30.6''	E006044'11.3''	96	5.1	90.9
S39	N07048'36.5''	E006044'00.1''	112	0	112
S40	N07047'38.5''	E006043'26.0''	80	2.2	77.8
S41	N07047'19.6''	E006043'04.8''	68	0	68
S42	N07047'43.7''	E006043'05.5''	86	2.4	83.6
S43	N07047'23.5''	E006042'51.6''	72	1.1	70.9
S44	N07047'38.0''	E006042'29.0''	72	5.4	66.6
S45	N07047'37.0''	E006042'19.7''	91	2.6	88.4
S46	N07047'45.6''	E006041'59.9''	70	5.3	64.7
S47	N07048'14.4''	E006042'02.3''	99	3.8	95.2
S48	N07048'25.5''	E006041'51.5''	104	0	104
S49	N07048'08.6''	E006040'49.0''	103	0	103
S50	N07048'09.6''	E006040'38.0''	88	2.6	85.4
S51	N07048'10.4''	E006040'19.3''	92	2.9	89.1
S52	N07051'07.5''	E006043'09.9''	106	1.8	104.2
S53	N07051'14.6''	E006043'21.3''	84	0	84
S54	N07051'26.6''	E006043'13.2''	98	4.3	93.7
S55	N07051'39.7''	E006042'57.2''	105	4.2	100.8
S56	N07051'05.3''	E006043'20.6''	84	1.9	82.1
S57	N07050'33.0''	E006043'14.6''	100	1	99
S58	N07050'52.9''	E006043'49.8''	81	10.1	70.9
S59	N07049'47.9''	E006044'59.6''	59	3.3	55.7
S60	N07048'29.9''	E006039'35.5''	78	4.9	73.1
S61	N07050'31.5''	E006044'30.5''	66	5.1	60.9
S62	N07045'18.7''	E006043'28.5''	71	3.8	67.2
S63	N07046'07.4''	E006043'19.6''	88	4.6	83.4
S64	N07046'47.9''	E006042'46.3''	83	5	78
S65	N07049'25.9''	E006042'06.9''	93	3.4	89.6

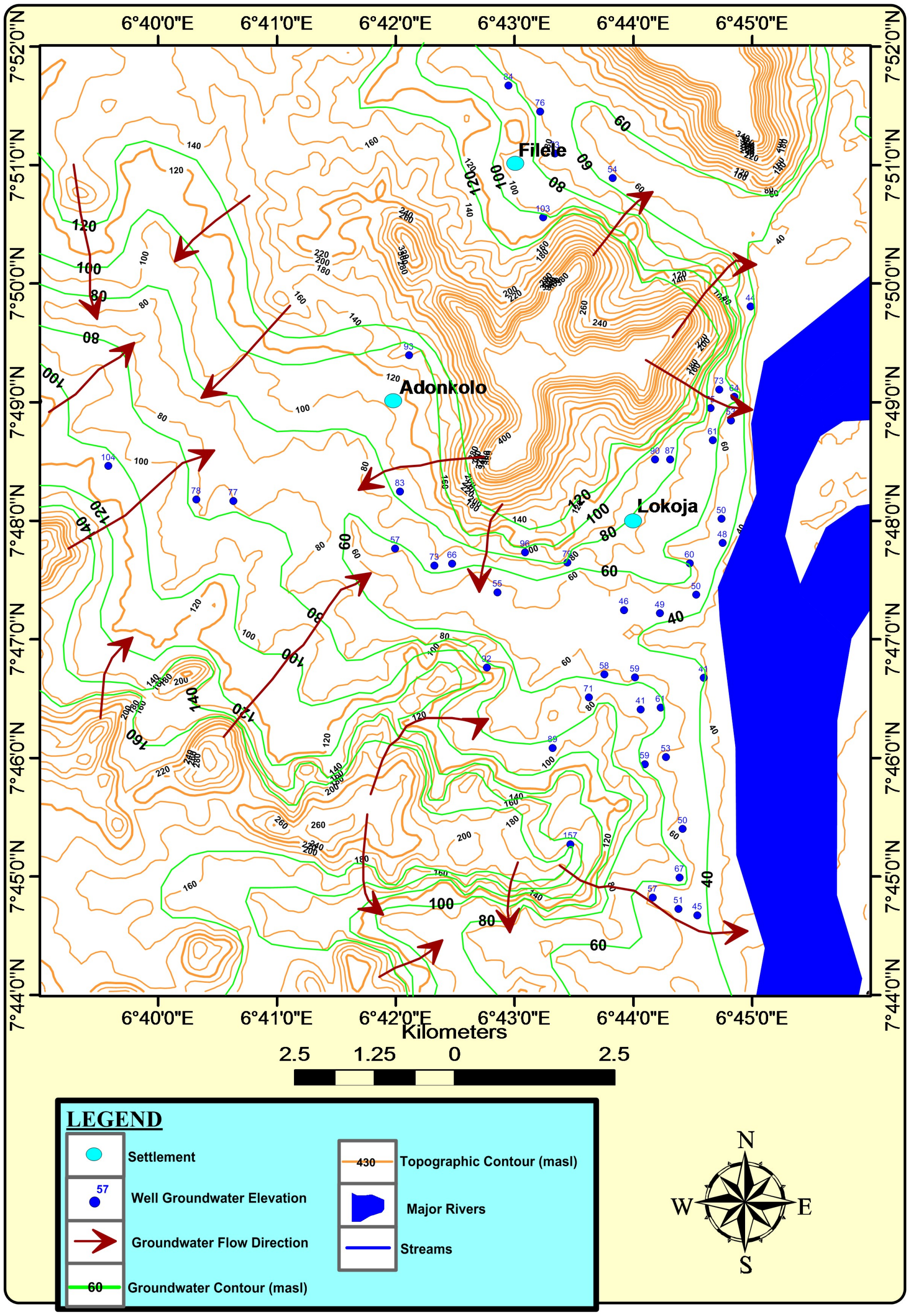

Fig. 4.6. Contour map of hydraulic heads showing flow directions in Lokoja

Table 4.6. Summary of physical parameters for dry and wet seasons

Parameters	Min	Max	Mean	WHO (2006)	SON (2007)
Dry Season					
T°C	25.3	33.7	30.20	25	-
pH	5.5	10.6	7.39	6.5-8.5	6.5-8.5
EC (µcm)	30	860.0	527.28	1000	1000
TDS (mg/L)	31	1040.0	379.80	1000	500
TH (mg/L as $CaCO_3$)	4.11	472.0	151.47	100	150
Rainy Season					
T°C	24.7	31.6	28.96	25	-
pH	5.4	9.1	7.15	6.5-8.5	6.5-8.5
EC (µcm)	70	1730	783.44	1000	1000
TDS (mg/L)	55	1273	558.45	1000	500
TH (mg/L as $CaCO_3$)	1.2	360	138.39	100	150

Table 4.7. Results of physical parameters for the dry season samples

Location Name	Sample ID	ELEV (m)	T°C	pH	EC (µS/cm)	TDS (mg/L)	TH (mg/L $CaCO_3$)
Ganaja 1	S1	67	29.7	08.3	420	303	92.8
Ganaja 2	S2	41	28.9	06.7	630	451	174
Ganaja 3	S3	56	28.2	08.1	350	255	87
Ganaja 4	S4	58	28.8	08.2	490	351	152
Ganaja 5	S5	59	29.6	08.6	610	436	185
Ganaja 6	S6	63	29.4	07.2	320	235	113
Lokoja 1	S7	57	26.2	07.5	1250	909	235
Lokoja 2	S8	69	25.3	07.5	680	486	302
Lokoja 3	S9	70	27.9	08.4	1040	755	240
Lokoja 4	S10	80	29.5	06.8	560	400	169
Lokoja 5	S11	74	29.8	07.8	790	570	255
Lokoja 6	S12	64	30.0	07.1	140	108	44.5
Lokoja 7	S13	55	31.9	07.8	560	403	160
Lokoja 8	S14	75	30.5	05.9	130	178	17.9
Lokoja 9	S15	70	29.3	06.6	240	530	64.8
Lokoja 10	S16	59	31.3	07.3	730	530	313
Lokoja 11	S17	30	29.6	07.3	690	499	244
Lokoja 12	S18	68	30.8	10.1	160	124	56.6
Lokoja 13	S19	66	30.8	07.1	400	292	128
Lokoja 14	S20	53	29.1	07.4	860	620	299
Adankolo 1	S21	54	31.9	07.8	290	213	121
Adankolo 2	S22	59	30.3	07.5	640	458	235
Adankolo 3	S23	68	31.9	09.1	180	133	65.6
Adankolo 4	S24	65	31.7	07.6	1390	1040	472
Adankolo 5	S25	78	32.3	07.2	580	419	188
Adankolo 6	S26	54	28.7	07.0	580	416	147
Lokoja 15	S27	53	30.4	08.7	710	511	156
Lokoja 16	S28	48	29.1	07.3	570	406	216
Lokoja 17	S29	65	28.9	07.1	510	365	213
Lokoja 18	S30	60	30.9	06.8	710	509	246
Lokoja 19	S31	53	29.0	07.3	820	589	150
Lokoja 20	S32	58	30.2	07.4	1030	748	178
Lokoja 21	S33	73	29.8	08.4	1330	962	242

Table 4.7. Cont'd. Results of physical parameters for the dry season samples

Location NAME	Sample ID	ELEV. (m)	T°C	pH	EC (μS/cm)	TDS (mg/L)	TH (mg/L $CaCO_3$)
Lokoja 22	S34	115	30.1	05.5	30	31	5.02
Lokoja 23	S35	86	31.4	07.1	470	341	94.5
Lokoja 24	S36	49	32.2	06.5	610	442	94.5
Lokoja 25	S37	87	27.0	07.2	770	555	130
Lokoja 26	S38	96	32.1	06.7	360	265	79.4
Lokoja 27	S39	112	32.1	07.2	280	208	41.2
Lokongoma 1	S40	80	29.7	08.0	360	257	127
Lokongoma 2	S41	68	30.2	07.4	510	371	300
Lokongoma 3	S42	86	30.3	07.2	440	316	154
Lokongoma 4	S43	72	33.3	07.4	440	320	146
Lokongoma 5	S44	72	31.2	08.4	240	174	95.2
Lokongoma 6	S45	91	30.2	07.5	670	479	206
Lokongoma 7	S46	70	27.6	07.3	610	439	234
Lokongoma 8	S47	99	31.8	08.0	770	555	254
Lokongoma 9	S48	104	31.6	06.8	270	194	109
Otokiti 1	S49	103	30.2	06.9	700	505	313
Otokiti 2	S50	88	28.4	07.3	620	444	219
Otokiti 3	S51	92	30.4	07.2	350	256	4.11
Filele 1	S52	106	32.7	05.9	140	110	32.9
Filele 2	S53	84	33.7	07.2	580	415	208
Filele 3	S54	98	31.9	10.6	430	309	75.6
Filele 4	S55	105	32.5	07.0	80	62	24.3
Filele 5	S56	84	30.4	06.6	300	220	95.4
Filele 6	S57	100	30.0	05.7	50	42	172
Filele 7	S58	81	32.2	07.0	200	148	36.7
Lokoja28	S59	59	31.4	06.3	460	367	143
Lokoja29	S60	78	28.9	06.7	357	272	28.1
Lokoja30	S61	66	28.9	06.8	255	187	137.4
Lokoja31	S62	71	29.4	07.6	614	436	21.1
Lokoja32	S63	88	29.6	07.4	473	367	63.9
Lokoja33	S64	83	29.8	07.5	786	563	146.5
Lokoja34	S65	93	29.8	07.3	658	490	92.6

Table 4.8. Results of physical parameters for the wet season samples

Sample Location	Sample ID	Elev. (m)	pH	EC (µS/cm)	TDS (mg/L)	Temp. (^oC)	TH (mg/L $CaCO_3$)
Ganaja 1	L1	82	9.1	390	290	27.7	21.6
Ganaja 2	L2	75	5.9	350	254	27.7	35
Ganaja 3	L4	71	8.3	680	470	27	114
Ganaja 4	L5	78	7.5	630	447	26.4	92.2
Ganaja 5	L6	79	6.9	870	629	29.6	144
Ganaja 6	L8	77	7.6	1020	721	29.5	212
Ganaja 7	L10	66	7.3	560	400	26.6	110
Ganaja 8	L11	56	6.7	1570	1148	29	309
Ganaja 9	L12	56	7.5	980	710	27	246
Ganaja 10	L14	57	7.1	780	586	29.3	208
Ganaja 11	L15	71	6.7	640	452	29	108
Ganaja 12	L16	55	8.1	750	541	31	133
Ganaja 13	L17	58	7.2	570	378	25.2	63.9
Lokoja 1	L18	54	7.1	900	572	27.9	90.1
Lokoja 2	L19	63	7.1	570	410	30.4	112
Lokoja 3	L20	53	8	580	422	28.7	121
Lokoja 4	L21	69	7.1	1030	748	29.2	220
Lokoja 5	L22	66	7.6	440	274	29.4	87.6
Lokoja 6	L23	74	7.4	600	428	30.2	99.9
Lokoja 7	L24	66	7.2	560	400	29.8	82.9
Lokoja 8	L25	73	7	710	508	28.2	150
Lokoja 9	L26	50	7.3	730	522	28.9	166
Lokoja 10	L27	70	7.7	830	594	28	191
Lokoja 11	L28	64	6.3	430	306	30.1	25.9
Lokoja 12	L29	69	6.8	730	481	29.2	96.5
Lokoja 13	L30	60	7.4	760	549	28.5	193
Lokoja 14	L31	52	7.8	730	528	28.4	131
Adankolo 1	L32	52	8.1	1090	786	28.5	174
Adankolo 2	L33	56	7.3	880	637	28	180
Adankolo 3	L34	56	8.3	670	486	29	130
Adankolo 4	L36	48	7.8	1250	905	30.6	197
Adankolo 5	L37	76	8.4	1050	753	28.2	136

Table 4.8. Cont'd. Results of physical parameters for the wet season samples

Sample Location	Sample ID	Elev. (m)	pH	EC (µS/cm)	TDS (mg/L)	Temp. (^oC)	TH (mg/L $CaCO_3$)
Adankolo 6	L38	54	7.2	1350	984	29.2	323
Lokoja 15	L39	57	7	750	542	29.8	140
Lokoja 16	L40	56	7.3	810	568	29.9	184
Lokoja 17	L41	51	7.5	790	526	31.6	177
Lokoja 18	L42	67	6.9	800	569	30.1	118
Lokoja 19	L43	55	7.2	1060	767	30.5	232
Lokoja 20	L44	59	8	1210	876	29.6	158
Lokoja 21	L45	59	6.7	1730	1273	26.5	176
Lokoja 22	L46	80	7.8	1320	960	29.8	142
Lokoja 23	L47	71	8	1540	1122	31.3	216
Lokoja 24	L48	98	6	580	417	30.7	82.7
Lokongoma 1	L49	201	7.6	70	55	30	1.21
Lokongoma 2	L50	77	6.6	700	505	24.7	124
Lokongoma 3	L51	72	7	910	605	29.6	125
Lokongoma 4	L52	53	6.8	810	503	29.7	167
Lokongoma 5	L53	85	6.8	640	464	28.7	96.4
Lokongoma 6	L54	60	7.5	730	524	29.2	155
Lokongoma 7	L55	70	7	950	687	28.9	171
Lokongoma 8	L56	66	8.1	480	347	28.8	83.3
Lokongoma 9	L57	103	7.2	550	396	30.2	74.7
Lokongoma 10	L58	77	7.2	590	426	28.4	159
Lokongoma 11	L59	98	6.9	400	293	28.9	59.2
Otokiti 1	L60	82	6.7	950	659	29.1	223
Otokiti 2	L61	90	0.71	1580	1150	29.8	360
Otokiti 3	L62	153	8	700	487	28.8	103
Otokiti 4	L63	119	6.8	510	362	29.4	75.1
Filele 1	L64	108	7.3	730	525	29.1	170
Filele 2	L65	101	7.1	150	112	30.6	18.8
Filele 3	L66	75	6.7	690	500	30.8	124
Filele 4	L67	89	6.6	480	342	26.6	96.3
Filele 5	L68	73	5.4	570	405	28.2	78.8
Lokoja 25	L69	50	6.3	680	455	28.8	62.9

through biogeochemical process caused by soil respiration (giving carbonic acid), dissolution of humic acid, oxidation of nitrogen compound and hydrolysis of ferrous iron in the soil (Todd, 2005). Samples from locations S18 (10.1), S23 (9.1), S27 (8.7) and S54 (10.6) were slightly alkaline during the dry season and location L1 (9.1) during the wet season possibly through carbondioxide from atmosphere or dissolution of aluminosilicate minerals in the bedrocks. Electrical Conductivity (EC) measured during dry season sampling ranged from 30 to 860 µS/cm and 70 to 1,730 µS/cm during wet season. All the values of EC in the dry season were <1,000 µS/cm and water samples from locations L8, L11, L21, L32, L36, L37, L38, L43, L44, 45, L46, L47 and L67 from migmatite-biotite gneiss and older granite in the wet season had concentrations of >1,000 µS/cm. The higher concebtration of EC measured in these locations indicates the contribution and leaching of solutes through active vertical recharge during the wet season (Onwuka *et al.,* 2013). Most water-dissolved substances dissociate into ions capable of conducting electrical current.

Consequently, the quantity of metals dissolved in water is a useful measure of electrical conductance. The greater the conductivity, the more the water is mineralised. Total Dissolved Solids (TDS) is a measure of the total quantity of dissolved ions in water and is therefore considered a very important parameter in water quality and chemical assessment (Todd, 2005). The measured TDS values ranged from 31 to 1,040 mg / L in dry season while that of wet season ranged from 55 to 1273 mg/L. Water potability with a TDS level below 600 mg/L is usually regarded as good for domestic use and many industrial processes but becomes more and more unfit for drinking at TDS concentrations above 1000 mg/L (WHO, 2006). The low TDS levels (< 1,000 mg/L) recorded in this study except for S24 = 1,040 mg / L in the dry season and L11 = 1148 mg/L, L45 = 1273 mg/L, L47 = 1122 mg/L and L61= 1,150 mg/L during the wet season suggested low to moderate mineralisation with limited migratory episode and rock water interactions. High TDS measured from samples in some of these locations were probably from dissolved geologic materials because of weathering and dissolution especially during wet season. Similarly, concentrations of samples from migmatite-biotite gneiss and older granite were generally higher than those from alluvium and sandstone because of chemical weathering and dissolution of aluminosilicate minerals in these rocks. The classification of water based on total dissolved solids indicates that the water in the study area is fresh (Onwuka *et al.,* 2013). During the dry season, the measured total hardness (TH) ranged from 4.11 to 472 mg/L while the wet season values ranged from 1.2 to 360 mg/L. Thirty-nine samples representing 60 % of the samples during the dry season exceeded SON, 2007 highest permissible drinking quality standard of 150 mg/L and 26 samples representing 40 % exceeded WHO, 2006 standard of 100 mg/L. Twenty samples representing 31.2 % of the total samples exceeded SON, 2007 maximum permissible drinking quality standard and thirty-eight samples representing 59.4% exceeded that of WHO, 2006 standard during the wet season. The lithology of the aquifer matrix, which is mainly made of weathering products of basic and intermediate igneous rocks, may relate to the elevated values of total hardness. The dissolution of these rock which are rich in calcium and magnesium produce high $Ca^{2+}$and Mg^{2+} concentrations that increase the groundwater's total hardness (Appelo and Postma, 2005). The reaction of these ions with soap form precipitates and with some ions in water to form scale. As a result of their adverse action with soap, for household cleaning applications, hard water is unsatisfactory, so water softening procedures are required to remove hardness. From Table 4.9, the total hardness of groundwater in Lokoja area varies between 'moderately hard' and 'hard' categories as most values fell within 75 – 130 mg/L and 150 – 300 mg/L in both seasons.

4.4 Hydrochemical Profiles

Generally, several factors control groundwater chemistry and quality. These factors include the geological environment in which the water flows, groundwater flow rate, groundwater source, and human activities. Lithology of the rocks, type of geochemical reactions, and solubility of the rocks in which the water interacts with usually control dissolved ions concentration in groundwater (Nosrat and Asghar, 2010). Furthermore, cation-anion exchange and mixing are other processes that may significantly influence the chemistry of groundwater (Tijani and Abimbola, 2003). Examination of factors influencing the chemical composition of groundwater in the study area is very important owing to the role it plays in determining the quality of water.

Table 4.9. Classification of water hardness

Hardness, $Mg/CaCO_3$	Class	Sample number		Percentage (%)	
		Dry	Wet	Dry	Wet
<75	Soft	2	4	3.10	6.25
75-150	Moderately Hard	27	34	41.54	53.13
150-300	Hard	27	24	41.54	37.50
60-80	Very Hard	9	2	13.85	3.13

(Source: Sawyer and McCarty, 1967)

The detailed results of chemical composition of groundwater for dry and wet seasons in Lokoja area are presented in Table 4.10 and 4.11 while the summary of the results along with WHO (2006) and that of SON (2007) drinking water quality standard are presented in Table 4.12.

4.4.1 Results of Cations Analyses

The concentration of calcium (Ca^{2+}) during the dry season varied from 1.12 mg/L to 103 mg/L while that of wet season 0.1 mg/L to 79 mg/L. The concentration of magnesium (Mg^{2+}) in the dry season ranged from 0.32 mg/L to 52.02 mg/L while it ranged from 0.2 mg/L to 57.1 mg/L in the wet season. Magnesium is generally less abundant than calcium in groundwater owing to the fact that it less soluble and magnesium-rich minerals naturally dissolves slowly as compared to those of calcium, which have high dissolution and are more abundant in the crust as compared with magnesium. Calcium and magnesium values were all within the maximum allowable limits of 75 mg/L and 50 mg/L for WHO, 2006 and SON, 2007 standards for calcium and magnesium, respectively; barring two locations (locations S20 = 80.07 mg/L and S24 = 103.52 mg/L) for calcium in dry season samples and location L38 (79.042 mg/L) for calcium and location L61 (57.12 mg/L) for magnesium in wet season. Weathering and dissolution of basement rock materials especially plagioclase (anorthite end member) and microcline (Dedzo *et al.,* 2017) was believed to have played a role in calcium and magnesium contents of the groundwater in Lokoja area as expressed in equations 4.1 and 4.3 The concentrations of sodium (Na^{+}) generally ranged from 12.56 to 244.27 mg/L during dry season sampling and 15.0 to 157.7 mg/L for wet season sampling. The concentrations for all locations during the dry season were within the WHO and SON maximum permissible limit of 200 mg/L except one location (location S7 = 244.27 mg/L) while no sample had concentration above the standards in the wet season and this could be as a result of dilution on concentration during the wet season (Haritash *et al.,* 2017). The average sodium taste threshold at room temperature is about 200 mg/L. Dissolution of silicate minerals especially plagioclase (albite end member) is probably the source of groundwater in the study area as expressed in the equation 4.2. Potassium (K^{+}) ranged from 0.55 to 107.17 mg/L for the dry season and 1.5 to 72.2 mg/L for wet season.

Table 4.10. Results of chemical parameters of dry season sample (mg/L)

Location Name	Sample ID	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	NO_3^{-}	SO_4^{2-}	Cl^{-}
Ganaja 1	S1	29.47	4.66	46.51	10.24	67.6	6	50.9	26
Ganaja 2	S2	47.77	13.22	55.89	7.45	42.3	39	24.7	58
Ganaja 3	S3	29.24	3.39	40.14	4.8	134.4	9.7	17.7	30
Ganaja 4	S4	29.27	19.11	59.04	5.81	86.9	2.8	20.0	12
Ganaja 5	S5	34.26	24.6	91.71	3.58	12.0	<2.0	14	14
Ganaja 6	S6	29.95	9.3	23.71	8.49	201.1	6.8	26.9	21
Lokoja 1	S7	23.32	43.04	244.27	6.61	57.3	9.7	19.8	33
Lokoja 2	S8	46.93	45.04	50.03	1.7	23.7	10.6	11.9	21
Lokoja 3	S9	70.92	15.21	131.88	16.51	117.6	72.5	55.5	97
Lokoja 4	S10	50.9	10.2	58.03	4.33	46.2	18	14	78
Lokoja 5	S11	63.8	23.4	75.12	4.12	138.5	35.6	50.6	98
Lokoja 6	S12	12.14	3.44	8.9	3.94	85.0	2.9	17.6	3.6
Lokoja 7	S13	39.91	14.67	59.87	8.05	158.2	20.4	29.4	40
Lokoja 8	S14	5	1.31	22.61	3.53	121.4	7.1	1.76	19
Lokoja 9	S15	15.22	6.52	31.65	4.26	102.6	<2.0	16.1	25
Lokoja 10	S16	72.39	32.13	58.11	1.98	102.2	16.4	30.4	59
Lokoja 11	S17	43.07	33.16	84.51	7.38	80.8	2	7.84	13
Lokoja 12	S18	20.74	1.15	6.69	8.83	190.0	<2.0	20.5	3.1
Lokoja 13	S19	33.4	10.96	42.09	6.51	46.2	6.7	31.8	21
Lokoja 14	S20	80.07	24	74.06	17.93	113.4	67.5	34.8	110
Adankolo 1	S21	40.25	4.87	19.3	11.63	124.4	<2.0	26	6.1
Adankolo 2	S22	72.2	13.36	50.82	9.29	87.5	4.5	38.6	47
Adankolo 3	S23	19.33	4.21	13.25	3.9	5.86	17.9	1.21	19
Adankolo 4	S24	103.52	52.02	133.26	14.15	27.4	70.4	70.8	170
Adankolo5	S25	60.76	8.86	47.5	10.79	118.0	22.3	39	54
Adankolo 6	S26	42.23	10.12	57.05	35.17	17.8	22	44.8	53
Lokoja 15	S27	44.96	10.74	97.2	26.35	14.6	14.5	68	60
Lokoja 16	S28	36.19	30.66	46.62	11.08	5.16	<2.0	8	27
Lokoja 17	S29	36.69	29.64	39.78	12.17	48.2	<2.0	13.7	38
Lokoja 18	S30	63.96	20.99	53.6	15.23	21.9	3.4	31.1	88
Lokoja 19	S31	41.65	11.13	75.7	60.89	63.9	42.6	43.7	84
Lokoja 20	S32	49.48	13.24	122.77	54.72	10.6	34.8	55.7	140
Lokoja 21	S33	64.61	19.51	145.9	107.17	16.7	28.9	52.8	180

Table 4.10. Cont'd. Results of chemical parameters of dry season sample (mg/L)

Location NAME	Sample ID	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	NO_3^-	SO_4^{2-}	Cl^-
Lokoja 22	S34	1.4	0.37	4.21	1.84	33.4	<2.0	7.36	3
Lokoja 23	S35	25.71	7.37	48.39	24.77	54.0	22.6	10.8	74
Lokoja 24	S36	42.79	7.54	53.99	38.66	83.6	28.9	42.1	63
Lokoja 25	S37	24.85	16.48	24.3	2.26	162.7	19.8	20.5	25
Lokoja 26	S38	23.58	4.98	40.56	14.6	218.6	<2.0	10.6	17
Lokoja 27	S39	12.58	2.39	57.26	3.74	105.6	<2.0	5.43	6.7
Lokongoma 1	S40	42.99	4.65	37.02	4.36	72.0	4.9	9.39	11
Lokongoma 2	S41	66.1	32.93	19.06	4.94	16.7	5.2	16.5	17
Lokongoma 3	S42	36.1	15.63	47.65	2.94	110.1	7	20.7	28
Lokongoma 4	S43	46.24	7.52	33.02	9.89	110.7	20.2	34.8	28
Lokongoma 5	S44	30.57	4.58	21.11	1.65	72.6	2.1	21.2	8.2
Lokongoma 6	S45	62.74	11.91	72.8	6.99	63.1	22.9	40	40
Lokongoma 7	S46	21.86	43.75	45.46	7.3	44.9	8.2	6.38	52
Lokongoma 8	S47	61.54	24.32	89.3	8.05	62.0	8.3	43	86
Lokongoma 9	S48	18.79	15.01	16.94	7.17	140.2	<2.0	3.06	4
Otokiti 1	S49	56.89	41.6	35.49	11.28	89.6	<2.0	9.35	57
Otokiti 2	S50	43.18	27.03	46.49	8.99	210.4	7.4	18.4	49
Otokiti 3	S51	1.12	0.32	1.61	0.55	156.2	<2.0	1.22	1.4
Filele 1	S52	9.35	2.32	15.49	5.5	60.1	3.5	6.1	22
Filele 2	S53	53.25	18.36	46.99	4.86	8.56	<2.0	17.4	78
Filele 3	S54	26.08	2.54	18.67	17.78	187.2	23	9.05	23
Filele 4	S55	6.61	1.89	6.31	3.85	34.0	7.6	0.62	4.7
Filele 5	S56	28.3	6.01	21.13	11.54	67.2	<2.0	4.59	19
Filele 6	S57	52.72	9.73	65.65	55.06	156.3	7	45.2	68
Filele 7	S58	12.54	1.30	33.57	3.33	93.3	<2.0	3.28	4.6
Lokoja28	S59	44.54	7.84	47.06	17.66	75.5	21.3	26.8	51
Lokoja29	S60	8.16	1.87	56.34	4.74	139.0	13.5	5.7	8
Lokoja30	S61	47.34	4.67	12.56	16.05	217.5	4.8	8.9	5
Lokoja31	S62	4.08	2.66	8.34	1.67	76.3	8.0	17.5	57
Lokoja32	S63	3.97	13.11	23.23	24.21	32.9	19.0	27.6	22
Lokoja33	S64	46.23	7.54	9.12	2.16	123.8	3.9	5.7	7
Lokoja34	S65	34.12	1.80	17.51	2.86	89.3	7.7	2.9	16

Table 4.11. Results chemical parameters for wet season samples (mg/L)

Sample Location	Sample ID	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	NO_3^-	SO_4^{2-}	Cl^-
Ganaja 1	L1	4.803	2.34	29.63	22.161	88.8	13.7	12.5	8.6
Ganaja 2	L2	7.564	3.917	18.92	13.792	35.5	15.8	20.6	15.1
Ganaja 3	L4	32.008	8.196	37.13	8.034	53.3	33.2	33.4	41.9
Ganaja 4	L5	15.897	12.79	45.24	6.596	77.3	12	14	80.8
Ganaja 5	L6	32.981	14.97	72.26	17.088	122.9	32.4	31	80.3
Ganaja 6	L8	58.899	15.85	57.94	11.799	96.4	40.8	40.6	95.2
Ganaja 7	L10	30.196	8.524	26.85	5.548	86.2	11.7	36.2	45
Ganaja 8	L11	60.836	38.28	109.2	23.021	284.2	23.4	62.7	151.5
Ganaja 9	L12	71.683	16.17	67.96	10.366	248.7	15.2	85.2	59.9
Ganaja 10	L14	68.376	9.138	30.72	12.788	207.9	9.3	38.3	62.1
Ganaja 11	L15	24.462	11.53	37.49	5.965	73.5	19	34.6	54.6
Ganaja 12	L16	24.28	17.73	59.73	22.596	309.5	5.5	26.8	4.6
Ganaja 13	L17	14.304	6.873	30.74	4.367	55.9	11.2	42.3	37.5
Lokoja 1	L18	19.181	10.27	44.5	8.342	88.8	16	45.2	47.3
Lokoja 2	L19	30.479	8.784	35.65	10.838	103.9	15.6	40.2	37
Lokoja 3	L20	20.729	16.99	38.64	2.606	230.8	0.2	25.6	27.8
Lokoja 4	L21	40.759	28.83	60.03	5.145	299.2	16.6	42.3	66.3
Lokoja 5	L22	14.984	12.22	15.0	9.357	121.7	2.3	31.5	8.2
Lokoja 6	L23	21.92	11.01	39.17	7.287	93.9	16.6	50	37.1
Lokoja 7	L24	17.117	9.789	25.71	3.61	55.8	17.4	56.8	31.4
Lokoja 8	L25	32.926	16.58	33.2	6.549	102.7	25.7	42	49.1
Lokoja 9	L26	22.94	26.43	30.63	1.794	185.3	10.7	51.2	37.6
Lokoja 10	L27	44.089	19.63	31.44	1.849	271.3	3.408	49.6	39.3
Lokoja 11	L28	5.788	2.79	29.4	4.345	34.2	18.262	6	26.9
Lokoja 12	L29	23.595	9.152	38.07	7.032	172.6	2.049	35.2	35.5
Lokoja 13	L30	42.355	21.17	31.45	1.495	254.9	1.847	55.9	37.5
Lokoja 14	L31	34.35	10.89	52.53	5.814	235.8	10.2	43.8	43.9
Adankolo 1	L32	16.071	32.7	124	1.922	398.3	4.4	39.9	52.7
Adankolo 2	L33	49.627	13.74	48.59	10.808	195.3	19.7	54.5	53.5
Adankolo 3	L34	34.001	10.9	42.63	4.817	131.9	14.7	55.4	39.4
Adankolo 4	L36	46.307	19.79	91.69	28.376	121.9	55.4	74.5	98.4
Adankolo 5	L37	34.816	11.83	32.32	13.222	154.7	25.9	62.8	73.9

Table 4.11. Cont'd. Results chemical parameters for wet season samples (mg/L)

Sample Location	Sample ID	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	NO_3^-	SO_4^{2-}	Cl^-
Adankolo 6	L38	79.042	30.56	67.98	26.536	278.9	39.5	75.6	108.4
Lokoja 15	L39	35.176	12.7	43.85	15.957	96.5	31.6	48	48.9
Lokoja 16	L40	21.402	31.95	42.42	10.582	319.7	0.5	7.8	34.5
Lokoja 17	L41	30.144	24.88	40.2	12.512	223.3	14.5	44	38.9
Lokoja 18	L42	26.419	12.59	47.6	21.429	66.1	33.2	43	73
Lokoja 19	L43	48.065	27.18	55.41	14.379	251.1	8.9	36.6	128.7
Lokoja 20	L44	41.177	13.48	98.1	61.316	126.8	48.3	54.2	11.7
Lokoja 21	L45	41.087	17.86	157.7	60.665	111.7	42.2	70.5	191.7
Lokoja 22	L46	37.487	11.66	110.2	57.157	114.2	34.5	37.9	139.8
Lokoja 23	L47	62.886	14.36	102.9	72.225	111.6	59.4	77.9	43.8
Lokoja 24	L48	23.105	6.072	34.28	15.578	28	25.2	15.1	43.8
Lokongo 1	L49	0.1	0.234	3.35	1.893	12.7	0.03	1.9	1.1
Lokongoma 2	L50	24.633	15.23	42.56	2.09	98.9	21.4	40.3	51.5
Lokongoma 3	L51	33.956	9.867	55.23	19.441	152.2	15.8	58.5	50.8
Lokongoma 4	L52	21.631	27.47	36.39	4.968	213.1	7.7	41.3	42.4
Lokongoma 5	L53	12.05	16.16	54	2.652	175.1	13.4	27.1	31.7
Lokongoma 6	L54	34.362	16.96	38.7	2.48	158.5	13.6	32.5	49.5
Lokongoma 7	L55	51.616	10.33	63.46	18.751	119.2	29.2	51.5	75.6
Lokongoma 8	L56	20.178	8.008	19.71	4.213	107.8	9	28.4	16.4
Lokongoma 9	L57	14.022	9.672	34.18	12.669	43.2	20.4	24.8	28.2
Lokongoma 10	L58	17.467	28.12	24.42	67.007	202.9	7.5	22.7	29.4
Lokongoma 11	L59	2.654	12.83	20.33	7.328	167.5	0.8	5.3	7.4
Otokiti 1	L60	21.408	41.25	33.44	10.935	289.2	3.4	10.4	70.1
Otokiti 2	L61	50.171	57.13	74.91	15.146	254.9	24.8	52.4	180.1
Otokiti 3	L62	22.608	11.38	50.48	6.574	10.3	33.9	30.2	55.9
Otokiti 4	L63	11.975	11.01	31.93	4.811	183.5	1.8	5.5	17.8
Filele 1	L64	36.722	19.04	38.19	12.59	116.7	19.4	12.1	51.9
Filele 2	L65	5.103	1.467	5.98	3.431	22.9	6.7	0.7	3.3
Filele 3	L66	20.049	17.92	47.66	6.499	190.3	4.3	16.5	75.7
Filele 4	L67	21.626	10.29	22.14	9.313	50.7	20.4	8.4	32.8
Filele 5	L68	21.87	5.894	54.26	8.12	22.9	29	5	62.3
Lokoja 25	L69	15.086	6.144	58.26	18.982	56.8	28.1	22.3	62.9

Table 4.12. Summary of results of chemical parameters for dry and wet season

Parameters (mg/L)	Min	Max	Mean	WHO (2006)	SON (2007)
Dry season					
Ca^{2+}	1.12	103.52	37.69	75	75
Mg^{2+}	0.32	52.02	14.12	50	50
Na^{+}	1.61	244.27	49.91	200	200
K^{+}	0.55	107.17	12.92	-	-
HCO_3^-	5.16	128	87.03	200	-
NO_3^-	2.00	72.5	17.44	50	50
SO_4^{2-}	0.62	70.8	22.99	250	100
Cl^-	1.40	180	41.59	250	250
Wet season					
Ca^{2+}	0.1	79	29.74	75	75
Mg^{2+}	0.2	57.1	15.62	50	50
Na^{+}	3.4	157.7	48.1	200	200
K^{+}	1.5	72.2	14.18	-	-
HCO_3^-	10.3	398.7	146.41	200	-
NO_3^-	0.03	59.4	18.26	50	50
SO_4^{2-}	0.7	85.2	36.72	250	100
Cl^-	1.1	191.7	53.75	250	250

Potassium in groundwater in the study area was suggested to be sourced from leaching of microcline (orthoclase) in the bedrocks or weathered regoliths as expressed in equation 4.5. There are no proposed standards for potassium, but values greater than 50 mg/L of sodium and potassium in the presence of suspended matter results in scale and corrosion in boilers (Todd, 2005). During the two seasons, the order of cations concentration was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$.

4.4.2 Results of Anions Analyses

The concentration of bicarbonate (HCO_3^-) in the dry season ranged between 5.16 and 128 mg/L and 10.3 to 398.7 mg/L with an average of 146.41 mg/L in the wet season. The values of bicarbonate analysed in the dry season were well below the threshold limit of 200 mg/L set by WHO, 2006 while those in wet season have eighteen samples representing 28.13 % of the total samples were higher than WHO standards (200 mg/L). This can can be attributed to CO_2 charged precipitation which reacts to produced weak carbonic acid that subsequently dissociates into hydrogen ions and bicarbonate ions as expressed in the equations 4.6 and 4.7 (Tijani, 1994; Vasanthavigar *et al.,* 2010);

$$CO_2(g) + H_2O \longrightarrow H_2CO_3(aq) \tag{4.6}$$

$$H_2CO_3(aq) \longrightarrow H^+(aq) + HCO_3^-(aq) \tag{4.7}$$

Bicarbonate concentrations in wet season were a lot higher than those of dry season and this was clearly due to interaction of precipitation and CO_2 present in the atmosphere and in the soil zone.

The concentration of nitrates in groundwater is usually low, but due to leaching or runoff from agricultural fields where inorganic fertilizers are used or contamination from human or animal waste, it can rise to high levels (Onugba and Eduvie, 2005). Water that contains high amounts of nitrate (>100 mg/L) is bitter and can cause physiological distress (WHO, 2006). Water from shallow wells with more than 45 mg/L has been noted to cause methamoglobinemia in children (Todd, 2005). In the study area, nitrate (NO_3^-) concentrations in dry season generally varied between 2.0 and 42.6 mg/L (15.3 mg/L) while that of wet season varied from 0.03 to 48.3 mg/L (11.2 mg/L) reflecting similar concentrations is both seasons. However, locations (S9 = 72.4 mg/L, S20 = 67.5 mg/L and S24 = 70.4 mg/L) for dry season and locations (L36 = 55.4 mg/L and L47 = 59.4 mg/L) for wet season had values that exceeded permissible limits of 50 mg/l for both WHO and SON standards. The higher concentrations in these locations were attributed to leachates from refuse dumps and pit latrines within 5 to 10 meters' proximity of these sample points and along flow paths, for example, in areas around Maigari palace in Lokoja and Lokongoma.

Sulphates are discharged along with industrial wastewater and through atmospheric deposition; though, the concentrations normally found in groundwater are from natural sources mainly from oxidation of sulphide ores and dissolution of gypsum and anhydrite (Abimbola and Tijani, 1999). Sulphate is typical anion in groundwater and traditionally neglected as pollution but excessive uptake could result in condtions such as diarrhea, dehydration and gastrointestinal disorders (Leslie and Lyons, 2018; Wang and Zhang, 2019). In this study, sulphate (SO_4^{2-}) in the dry season varied between 0.6 mg/L and 70.8 mg/L while in the wet season it ranged from 0.7 to 85.2 mg/L. All values for both seasons were bellow WHO, 2006 and SON, 2007 maximum permissible limits of 250 and 100 mg/L respectively. The source of sulphate in the study area is assumed to be natural (i.e. atmospheric deposition).

The concentration of chloride (Cl^-) in the study area ranged between 1.4 and 180 mg/L in dry season while those of the wet season varied from 1.1 to 191.7 mg/L. The concentrations of chloride in both seasons were below 250 mg/L of WHO, 2006 and SON, 2007 maximum permissible limits. Chloride in groundwater usually can come from natural sources, sewage and industrial effluents, urban runoff comprising de-icing salt and industries. However, the concentration of chloride in groundwater in the study area may have been sourced from chemical weathering of rocks, evapotranspiration of the runoff or leaching of salts from domestic wastes. Depending on the alkalinity of water, excessive concentration of chloride increases the rate of metals corrosion in the distribution system. This can lead to elevated concentrations of metals especially iron in water supply system (Ofoma *et al.,* 2005, Olobaniyi *et al.,* (2007). In addition, chloride exceeding 250 mg/L can cause taste in the water. The order of major anions concentrations during both seasons were $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$.

In summary, hydrochemical profile indicated that the groundwater system in the study is low to moderately mineralised with limited migatory history (i.e low rock-water interaction). The concentrations of major cations and anions for both dry and wet seasons with few exceptions were within the recommended standard values of WHO, 2006 and SON, 2007. The distribution of major ions during the dry and wet seasons is illustrated using bar graphs (Fig. 4.7a and 4.7b). The examination of the graphs shows seasonal variations in major ionic concentations in that the concentrations of most ions for wet season were higher compared to those of dry season. The higher values of the ions during the wet season as observed earlier imply the contribution of dissolution and leaching of solutes through active vertical recharge during wet season.

4.4.3 Results of Trace Elements

The results of trace elements analysed in groundwater from Lokoja area are presented in Table 4.13 and the summary is presented in Table 4.14. Trace elements in groundwater are chemical elements dissolved in water in minute quantities and in concentration less than 1.0 mg/L (U.S.G.S., 1993). Even though they are present in small concentrations, their desirable intake is necessary for proper functioning of human body. While at the same time their deficiency or excess or both may be a health risk. In the study area, the concentrations of iron ranges from 0.01 – 0.094 mg/L which indicated that iron levels were within permissible limit of WHO, 2006 and SON, 2007 standards. However, concentrations at locations S14 (0.315 mg/L) and S16 (0.37 mg/L) which were slightly higher than the permissible limits may have resulted from the corrosion of iron materials used for well completion in these locations. Iron is often present in water and is vital component that all living organisms require in minute amounts. Concentrations of iron in groundwater is usually naturally occurring as precipitation which infiltrate the regolith and the underlying geologic formations dissolves iron, moving it to aquifer which serves as source of groundwater but industrial effluent, acid mine drainage, sewage and waste leachate can also add iron to local groundwater.

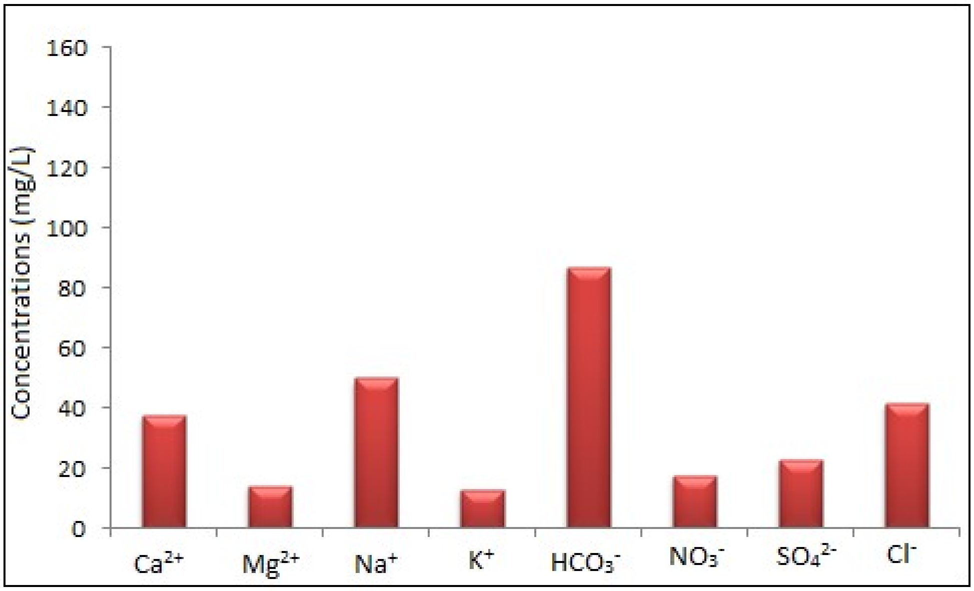

Fig. 4.7a. The mean concentration of major ions during the dry season

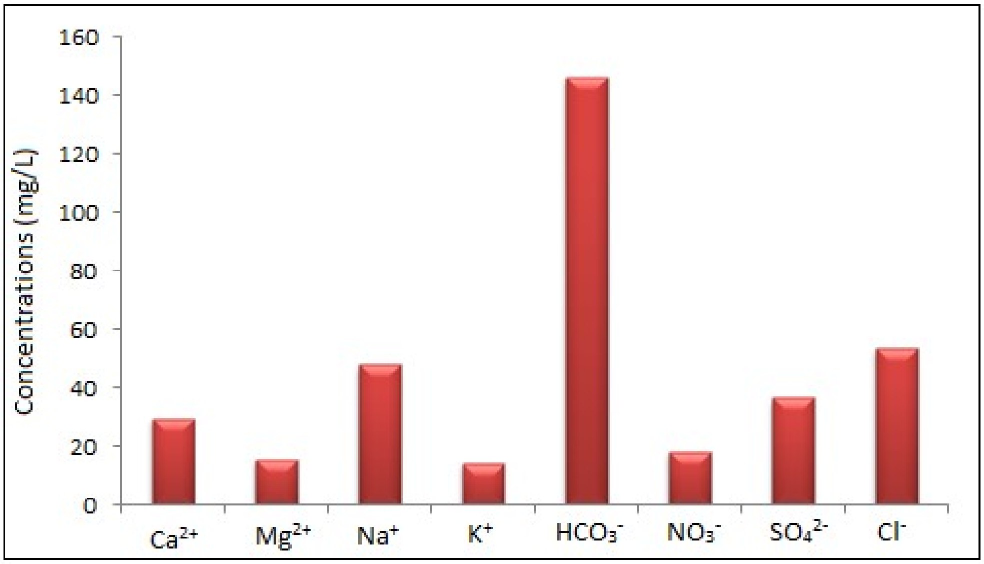

Fig. 4.7b. The mean concentration of major ions for wet season

Table 4.13. Results of trace element concentration of groundwater (mg/L)

Sample Location	Sample ID	As	Cr	Fe	Mn	Pb	Cu	Zn
Ganaja 1	S1	0.0005	0.0235	0.01	0.02034	0.0059	0.0069	0.0024
Ganaja 2	S2	0.0005	0.0033	0.01	0.01827	0.0001	0.0021	0.0014
Ganaja 3	S3	0.0006	0.0049	0.01	0.00031	0.0001	0.0013	0.0022
Ganaja 4	S4	0.0005	0.0041	0.01	0.00123	0.0001	0.0005	0.0006
Ganaja 5	S5	0.0005	0.0056	0.01	0.0005	0.0001	0.0005	0.0005
Ganaja 6	S6	0.0005	0.0082	0.01	0.00005	0.0001	0.0007	0.0121
Lokoja 1	S7	0.0005	0.0129	0.01	0.00017	0.0001	0.0005	0.0023
Lokoja 2	S8	0.0005	0.0073	0.01	0.00025	0.0002	0.0035	0.0014
Lokoja 3	S9	0.0006	0.0179	0.01	0.00025	0.0001	0.0014	0.0017
Lokoja 4	S10	0.0005	0.0154	0.01	0.0003	0.0001	0.0006	0.0012
Lokoja 5	S11	0.0014	0.0105	0.01	0.00008	0.0001	0.0019	0.0046
Lokoja 6	S12	0.0007	0.0065	0.01	0.00007	0.0001	0.0007	0.0043
Lokoja 7	S13	0.0011	0.006	0.01	0.00027	0.0001	0.0008	0.0059
Lokoja 8	S14	0.0005	0.0025	0.315	0.00046	0.0001	0.0008	0.0012
Lokoja 9	S15	0.0005	0.0065	0.01	0.00029	0.0001	0.0016	0.0028
Lokoja 10	S16	0.0005	0.0016	0.37	0.00132	0.0001	0.0002	0.0008
Lokoja 11	S17	0.0005	0.0049	0.01	0.00028	0.0001	0.0012	0.0014
Lokoja 12	S18	0.0008	0.0092	0.01	0.00045	0.0001	0.0005	0.0015
Lokoja 13	S19	0.0005	0.0132	0.01	0.00018	0.0001	0.0004	0.0005
Lokoja 14	S20	0.0005	0.0056	0.01	0.00015	0.0001	0.0008	0.0061
Adankolo 1	S21	0.0005	0.0068	0.01	0.00033	0.0001	0.0005	0.0097
Adankolo 2	S22	0.0011	0.0049	0.01	0.00415	0.0001	0.0007	0.0516
Adankolo 3	S23	0.0006	0.0069	0.01	0.00043	0.0001	0.0012	0.0066
Adankolo 4	S24	0.0007	0.0087	0.01	0.00072	0.0001	0.0013	0.0241
Adankolo 5	S25	0.0005	0.0019	0.01	0.00374	0.0001	0.0003	0.0098
Adankolo 6	S26	0.0014	0.0138	0.01	0.00052	0.0001	0.0019	0.0099
Lokoja 15	S27	0.0012	0.0068	0.01	0.00034	0.0001	0.0006	0.0085
Lokoja 16	S28	0.0005	0.0073	0.01	0.00099	0.0001	0.0018	0.0211
Lokoja 17	S29	0.001	0.0117	0.01	0.00008	0.0001	0.0022	0.0028
Lokoja 18	S30	0.0005	0.0163	0.01	0.04181	0.0003	0.0205	0.0026
Lokoja 19	S31	0.0005	0.0141	0.01	0.01599	0.0001	0.0012	0.0025
Lokoja 20	S32	0.0007	0.0127	0.01	0.39993	0.0001	0.0035	0.0037
Lokoja 21	S33	0.0006	0.0047	0.01	0.00153	0.0001	0.0007	0.0209

Table 4.13. Cont'd. Results of trace element concentration of groundwater (mg/L)

Sample Location	Sample ID	As	Cr	Fe	Mn	Pb	Cu	Zn
Lokoja 22	S34	0.001	0.0084	0.01	0.00025	0.0001	0.0007	0.0143
Lokoja 23	S35	0.0019	0.016	0.01	0.0006	0.0001	0.0023	0.0151
Lokoja 24	S36	0.0005	0.0011	0.094	0.02652	0.0001	0.0002	0.0055
Lokoja 25	S37	0.0005	0.0027	0.01	0.00052	0.0001	0.0004	0.0141
Lokoja 26	S38	0.0005	0.0044	0.01	0.0007	0.0001	0.0006	0.036
Lokoja 27	S39	0.0005	0.0052	0.01	0.00032	0.0001	0.002	0.0549
Lokongoma 1	S40	0.0005	0.002	0.01	0.00588	0.0001	0.0004	0.0116
Lokongoma 2	S41	0.0006	0.0067	0.01	0.00023	0.0001	0.0001	0.0046
Lokongoma 3	S42	0.0008	0.0056	0.01	0.00041	0.0001	0.0005	0.0008
Lokongoma 4	S43	0.0005	0.0046	0.01	0.00312	0.0001	0.0005	0.0006
Lokongoma 5	S44	0.0005	0.0052	0.01	0.005	0.0001	0.002	0.0046
Lokongoma 6	S45	0.0005	0.0002	0.01	0.0001	0.0001	0.0005	0.0023
Lokongoma 7	S46	0.0005	0.0053	0.01	0.00132	0.0001	0.0006	0.0006
Lokongoma 8	S47	0.0008	0.0038	0.01	0.0043	0.0001	0.0022	0.0011
Lokongoma 9	S48	0.0006	0.0001	0.01	0.0024	0.0001	0.0005	0.0022
Otokiti 1	S49	0.0009	0.0145	0.01	0.00024	0.0001	0.001	0.002
Otokiti 2	S50	0.0005	0.009	0.01	0.00278	0.0001	0.0013	0.0292
Otokiti 3	S51	0.0005	0.0167	0.01	0.2438	0.0001	0.001	0.2823
Filele 1	S52	0.0005	0.0131	0.01	0.4964	0.0001	0.0009	0.0112
Filele 2	S53	0.0005	0.0005	0.01	0.00211	0.0001	0.0008	0.0053
Filele 3	S54	0.0005	0.0016	0.01	0.01371	0.0001	0.0005	0.0005
Filele 4	S55	0.0007	0.0108	0.001	0.62272	0.0001	0.0022	0.0034
Filele 5	S56	0.0005	0.011	0.01	0.00142	0.0001	0.0005	0.0046
Filele 6	S57	0.0005	0.0005	0.01	0.00208	0.0001	0.0001	0.0163
Filele 7	S58	0.0005	0.0073	0.01	0.00056	0.0001	0.0006	0.004
Lokoja28	S59	0.0005	0.0073	0.01	0.00046	0.0001	0.0003	0.0118
Lokoja29	S60	0.0007	0.006	0.01	0.00025	0.0001	0.0007	0.0377
Lokoja30	S61	0.0005	0.0066	0.01	0.00015	0.0001	0.0004	0.003
Lokoja31	S62	0.0007	0.0059	0.01	0.00073	0.0001	0.0004	0.0006
Lokoja32	S63	0.0004	0.0062	0.01	0.00075	0.0001	0.0004	0.0006
Lokoja33	S64	0.0005	0.0082	0.01	0.00005	0.0001	0.0007	0.0116
Lokoja34	S65	0.0005	0.0092	0.01	0.00005	0.0001	0.0007	0.0114

Table 4.14. Summary of result of trace elements

Parameters	Min	Max	Mean	WHO (2006)	SON (2007)
As (mg/L)	0.0004	0.0019	0.000629	0.01	0.01
Cr (mg/L)	0.0005	0.0235	0.008457	0.05	0.05
Fe (mg/L)	0.001	0.37	0.014046	0.3	0.3
Mn (mg/L)	0.00005	0.62272	0.03014	0.4	0.2
Pb (mg/L)	0.0001	0.0059	0.000278	0.01	0.01
Cu (mg/L)	0.0001	0.0205	0.001355	2.0	1.0
Zn (mg/L)	0.0005	0.2823	0.012902	3.0	3.0

However, iron dissolved in groundwater is in the reduced iron II form (ferrous Iron) which is soluble and stable under anerobic condition and normally does not cause any problem by itself in water. Iron II is oxidised to iron III (ferric iron) on contact with oxygen in the air which forms insoluble ferric hydroxide ($Fe(OH)_3$) in water. Groundwater with high levels of iron can cause damage to skin and can lead to hemochromatosis which results in liver and heart damage. The range concentrations of other trace elements were; As ranged between 0.0004 and 0.0019 mg/L with a mean of 0.00063 mg/L, Mn varied from 0.00005 to 0.622 mg/L with an average of 0.03014 mg/L, Cr ranged from 0.0005 to 0.023 mg/L with an average of 0.0085 mg/L, Pb ranged 0.0001 to 0.0059 mg/L with an average of 0.00028 mg/L, Cu ranged from 0.0001 to 0.02 mg/L with a mean value of 0.0014 mg/L and Zn varied between 0.0005 to 0.28 mg/L with an average of 0.013 mg/L. The concentration of As, Cr, Pb, Cu and Zn were below the permissible limits (Table 4.14), indicating possible natural source of these elements. The order of trace element concentration was Mn > Fe > Zn > Cr > Cu > As > Pb.

4.5 Bedrocks Control on Hydrochemistry

The influence of bedrock types on groundwater chemistry in the study area is assessed in this section. The concentrations of various parameters analysed are discussed based on the rock types underlying the study area so as to determine the influence of bedrock units on groundwater chemistry. The rocks are alluvium, sandstone, migmatite-biotite gneiss and older granite. The results of physico-chemical parameters based on these rock types for dry and wet seasons are presented in Appendix VI – VIII and the results are summarised in Tables 4.15 to 4.17. The temperature during the dry season ranged from 30.4^{o}C to 33.7^{o}C with a mean value of 32.14^{o}C and 29.1^{o}C to 30.8^{o}C during wet season in groundwater samples from alluvium bedrock. Temperature in groundwater samples from alluvium was greater than any other rock types in the area with average values of 32.14^{o}C and 30.2^{o}C for dry and wet season respectively. The slightly higher values of temperatures recorded in alluvium bedrock setting could be attributed to ambient atmospheric temperature radiating through unconsolidated alluvium materials to shallow aquifers which border rivers Niger and Benue where temperature is always highest due possible micro climatic effects through circulation of air between land and water. The slightly higher temperature recorded in samples from alluvium could also be attributed to higher heat absorption capacity of silica which constitude bulk of alluvial aquifer materials where absorbed heat is transferred to the water in the aquifer. There were little temperature variations among other rock types and for the fact that increase in temperature increase the solubility of solids, the effects of temperature on the dissolution of rocks in the study area were likely to be uniform across all rock types.

The mean values of pH of the groundwater were all within the range of 6.5 – 8.5 in both seasons but slightly lower in alluvium and sandstone due to little or no dissolution of minerals in these rocks while it was slightly higher in migmatite-biotite gneiss and older granite because of effective weathering and dissolution. The EC values for the dry season were all less than 1,000 μS/cm in groundwater samples from alluvium, while sample location S33 (1,330) from sandstone, location S32 (1030 mg/L) in migmatite-biotite gneiss, locations S7 (1,250 mg/L) and S9 (1,040 mg/L) in older granite were slightly greater than 1,000 μS/cm. Whereas, sample location L46 from sandstone, locations L36, L37, L38, L43, L44, L45, L47 and L61 from migmatite-biotite gneiss and locations L8, L11, L21 and L38 from older granites in wet season had values above 1,000 μS/cm. The number of samples with EC >1,000 μS/cm were higher during the wet season than the dry season signifying the input of dissolution and leaching of solute during the wet season.

The groundwater in the study area was generally low to moderately mineralised with little rock-water interactions and short residence time. However, the recorded high values of EC in few locations could be attributed to the effects of anthropogenic activities such as waste dumps close to these locations. The measured values of TDS were all less than 1,000 mg/L across all rock types during both seasons except location S24 from older granite bedrock during dry season and locations L45, L47 and L61 from migmatite-biotite gneiss and location L11 from older granite during wet season. The observed high TDS concentrations in these locations were thought to be the effects of dissolution by infiltrating or recharging water and effective weathering of bedrocks during wet season (Talabi and Tijani, 2012).

Table 4.15a. Summary of results of physical parameters based on rock types for dry season

Bedrock	Statistics	Temp. (°C)	pH	EC (µS/cm)	TDS (mg/L)	TH (mg/L $CaCO_3$)
Alluvium	Min	30.4	5.9	80	62	24.3
	Max	33.7	7.2	580	515	208
	Mean	32.1	6.6	312	235	101
Sandstone	Min	29.4	5.5	30	31	5
	Max	32.2	8.6	1330	962	242
	Mean	30.1	7.2	472	346	104
Migmatite-biottite gneiss	Min	25.3	5.9	130	174	4.11
	Max	33.3	10.6	1030	784	313
	Mean	30.0	7.3	546	407	159
Older granite	Min	26.2	6.7	140	108	44.5
	Max	31.9	10.1	1390	1040	472
	Mean	29.9	7.9	579	418	169

Table 4.15b. Summary of results of physical parameters based on rock types for wet season

Bedrock	Statistics	Temp. (°C)	pH	EC (µS/cm)	TDS (mg/L)	TH (mg/L $CaCO_3$)
Alluvium	Min	29.1	6.7	150	112	18.8
	Max	30.8	7.3	730	525	170
	Mean	30.2	7.0	523.3	379	104.3
Sandstone	Min	26.6	5.4	70	55	1.21
	Max	30	7.8	1320	960	142
	Mean	28.7	6.7	624	443.4	76.2
Migmatite-biottite gneiss	Min	24.7	0.7	400	274	25.9
	Max	31.6	8.4	1730	1273	360
	Mean	29.3	7.0	850.3	604.6	149.7
Older granite	Min	25.2	5.9	350	254	21.6
	Max	31	9.1	1570	1148	309
	Mean	28.5	7.4	763.6	545.8	140.9

Table 4.16a. Summary of results of major cations based on rock types for dry season

Bedrock	Statistics	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)
Alluvium	Min	6.61	1.89	6.31	3.85
	Max	53.25	18.36	47.06	17.66
	Mean	28.41	7.28	27.40	8.68
Sandstone	Min	1.40	0.37	4.21	1.69
	Max	64.61	25.6	145.9	107.17
	Mean	24.80	10.18	53.23	28.12
Migmatite-biottite gneiss	Min	1.12	0.32	1.61	0.55
	Max	80.07	45.04	122.8	60.89
	Mean	39.61	15.03	45.54	12.83
Older granite	Min	12.14	1.15	6.69	3.9
	Max	103.52	52.02	244.27	16.51
	Mean	41.66	15.83	64.43	8.101

Table 4.16b. Summary of results of major cations based on rock types for wet season

Bedrock	Statistics	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)
Alluvium	Min	5.10	1.47	5.98	3.43
	Max	36.72	19.04	47.66	12.59
	Mean	20.62	12.81	30.61	7.51
Sandstone	Min	0.1	0.23	3.35	1.89
	Max	37.49	11.66	110.2	57.16
	Mean	19.23	6.84	49.64	19.09
Migmatite-biottite gneiss	Min	2.65	2.79	15	1.49
	Max	79.04	57.13	157.7	72.21
	Mean	30.19	18.10	49.90	17.96
Older granite	Min	4.80	2.34	18.92	1.79
	Max	71.68	38.28	124.00	23.02
	Mean	32.39	14.63	47.68	9.32

Table 4.17a. Summary of results of major anions based on rock types (dry season)

Bedrock	Statistics	HCO_3^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)
Alluvium	Min	8.56	2	0.62	4.7
	Max	75.5	21.3	26.8	78
	Mean	49.07	7.28	11.10	34.94
Sandstone	Min	12	7	3.28	3
	Max	156.3	28.9	52.8	180
	Mean	60.13	15.73	23.96	49.8
Migmatite-biottite gneiss	Min	5.16	2.1	1.22	1.4
	Max	218.6	67.5	68	140
	Mean	92.77	16.77	21.07	41.16
Older granite	Min	5.86	2	1.21	3.1
	Max	201.1	72.5	70.8	170
	Mean	97.12	20.46	30.62	41.05

Table 4.17b. Summary of results of major anions based on rock types (wet season)

Bedrock	Statistics	HCO_3^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)
Alluvium	Min	22.87	4.34	0.733	3.328
	Max	190.32	19.44	16.525	75.7
	Mean	109.95	10.17	9.778	43.651
Sandstone	Min	12.68	0.03	1.984	1.134
	Max	114.25	34.49	37.942	139.765
	Mean	51.48	22.41	15.113	59.776
Migmatite-biottite gneiss	Min	10.27	0.17	5.324	7.396
	Max	319.66	59.4	77.918	191.715
	Mean	157.44	19.74	38.579	56.077
Older granite	Min	35.50	3.41	12.471	4.58
	Max	398.27	40.80	85.235	151.463
	Mean	156.10	16.57	41.968	50.862

The mean values of Total Hardness (TH) in groundwater from alluvium, sandstone, migmatite-biotite gneiss and older granite bedrocks during the dry season were 100.72 mg/L, 103.7 mg/L, 159.5 mg/L and 169.1 mg/L respectively. While the values in the wet season were 104.3 mg/L, 76.2 mg/L, 149.7 mg/L and 140.9 mg/L for alluvium, sandstone, migmatite-biotite gneiss and older granite setting respectively. In migmatite-biotite gneiss rock type, 23 samples (63.9 %) and 17 samples (47 %) exceeded the maximum permissible limits of 100 and 150 mg/L for WHO, 2006 and SON, 2007 standards, respectively during dry season while 21 samples (63.6 %) and 15 samples (45.6 %) exceeded the standards during the wet season. However, TH for few locations from alluvium and sandstone and several locations from older granite had values in excess of maximum permissible limits of SON and WHO standards. Higher values recorded in migmatite-biotite gneiss and older granite was probably due to dissolution of calcium and magnesium ions in these bedrocks (Al-Ahmadi and El-Fiky, 2009).

Further evaluation of physico-chemical results based on rock types for both dry and wet seasons using bar charts (Fig. 4.8) show that the EC, TDS and TH exibit similar trends indicating lower values for alluvium and sandstone as compared to migmatite-biotite gneiss and older granite bedrock settings. The implication is that there is less or no dissolution of minerals in alluvium and sandstone bedrock settings because the compositions of the two rocks/formations are predominantly quartz and sandy materials which can not be easily weathered further, hence low EC, TDS and TH (Idowu and Ajayi, 1998, Ariyo *et al.,* 2005). The higher dissolved solids for migmatite-biotite gneiss and older granite can be attributed to the dissolution of silicate minerals in those rock units as earlier determined from petrographical studies as expressed in equation 4.1-4.5. Cations concentration in groundwater from the study area showed little variations across all rock units. The Ca^{2+} concentrations in dry season had average concentrations of 28.41 mg/L, 24.80 mg/L, 39.6 mg/L and 41.66 mg/L in alluvium, sandstone, migmatite-biotite gneiss and older granite respectively and during the wet season, Ca^{2+} had average concentration of 20.62 mg/L,

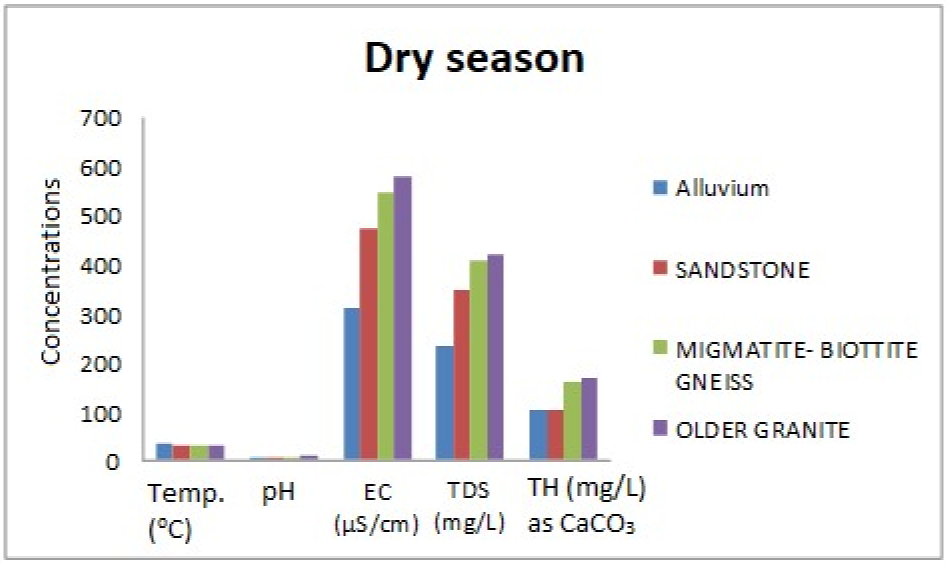

Fig. 4.8a. Concentration of physical parameters based on rock types (dry season)

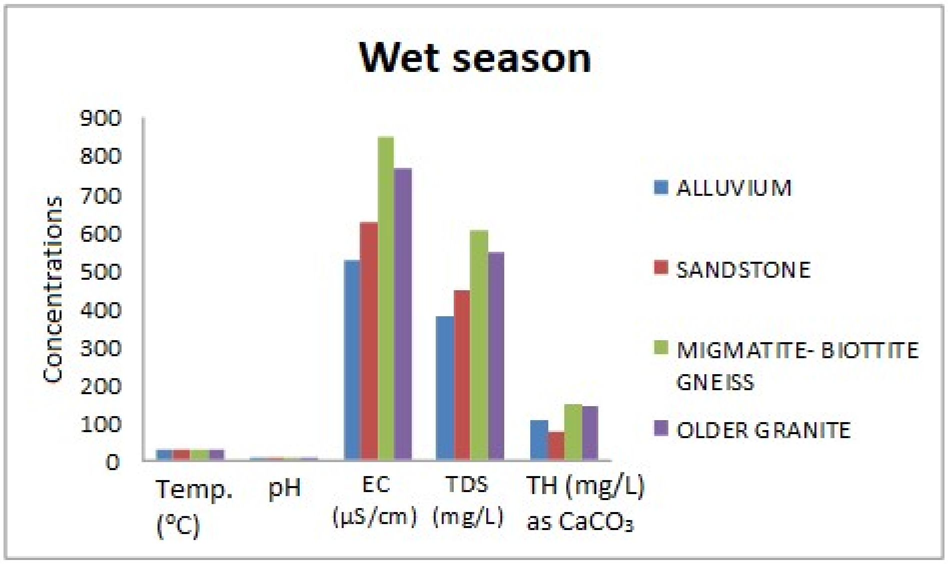

Fig. 4.8b. Concentration of physical parameters based on rock types (wet season)

19.23 mg/L, 30.19 mg/L and 32.39 mg/L for alluvium, sandstone, migmatite-biotite gneiss and older granite respectively. The average concentration of Mg^{2+} during the dry season for alluvium, sandstone, migmatite-biotite gneiss and older granite settings were 7.28 mg/L, 10.8 mg/L, 15.03 mg/L and 15.83 mg/L respectively while that of wet season were 12.81 mg/L, 6.84 mg/L, 18.10 mg/L and 14.63 mg/L from alluvium, sandstone, migmatite-biotite gneiss and older granite settings respectively. Calcium and magnesium analysed in both seasons follow similar trend as EC, TDS and TH as the values were higher in migmatite-biotite gneiss and older granite rock units than those of alluvium and sandstone bedrock settings (Fig. 4.9). This is indication that the higher dissolved solids for migmatite-biotite gneiss and older granite can be attributed to the dissolution of calcium amd magnesium in those rock units. Whreas there is less or no dissolution of minerals in sandstone and alluvium because the compositions of the two rocks are predominantly quartz and sandy materials which can not be easily dissolved or weathered. The average concentration of Na^+ in groundwater from alluvium, sandstone, migmatite-biotite gneiss and older granite were 27.40 mg/L, 53.23 mg/L, 45.54 mg/L and 64.43 mg/L respectively during dry season and 30.61 mg/L, 49.64 mg/L, 49.90 mg/L and 47.68 mg/L during wet season. Na^+ concentrations were higher in sandstone, migmatite-biotite gneiss and older granite rock units than alluvium in both seasons. The average concentration of K^+ in groundwarer during the dry season were 8.68 mg/L, 28.12 mg/L, 12.85 mg/L and 8.10 mg/L for alluvium, sandstone, migmatite-biotite gneiss and older granite respectively and 7.51mg/L, 19.09 mg/L, 17.96 mg/L and 9.32 mg/L respectively during the wet season. K^+ was dominant in sandstone than those in other rock units.

Furthermore, the concentration of cations especially those of Ca^{2+} Mg^{2+} and Na^+ showed relatively higher values in migmatite-biotite gneiss and older granite rock units than that in alluvium and this was an indication of weathering and dissolution of aluminosilcate minerals from migmatite-biotite gneiss and older granite rock units but higher in sandstone bedrock setting probably due to ion exchange process where sodium replaces alkaline earth metals.

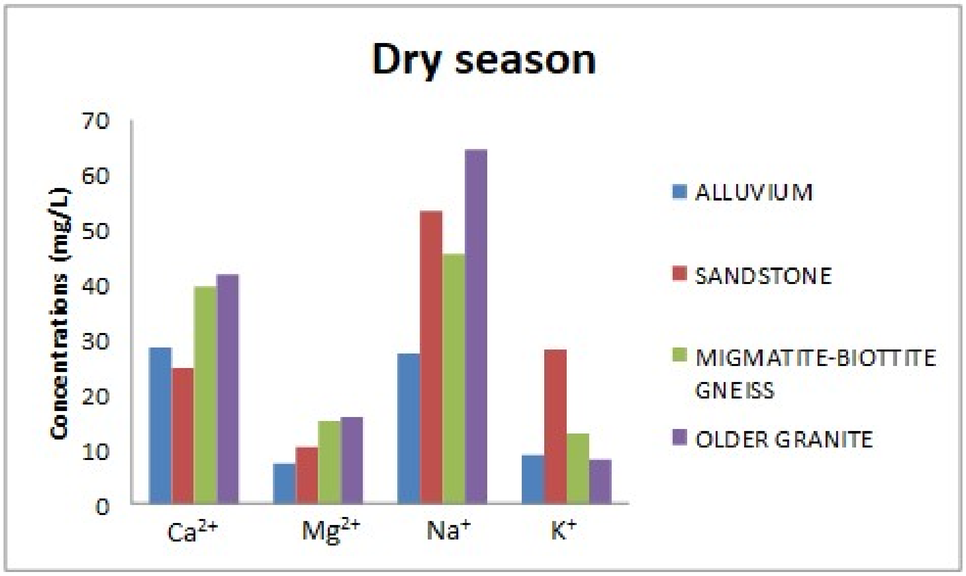

Fig. 4.9a. Concentration of cations based on rock types (dry season)

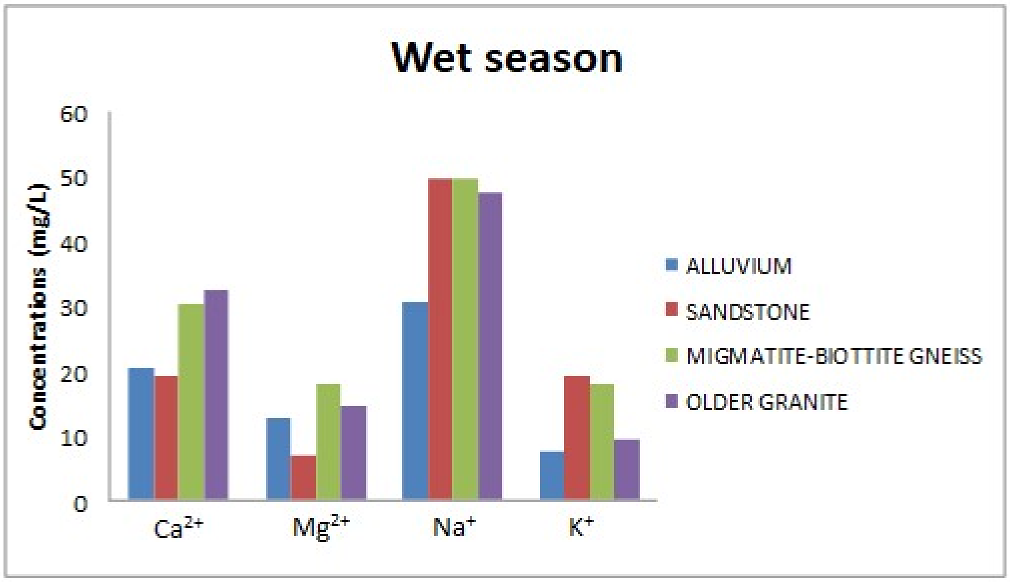

Fig. 4.9b. Concentration of cations based on rock types (wet season)

The major anions in the study area showed systematic variations in their concentrations among all the rock types. The average concentration of HCO_3^- in groundwater samples from alluvium, sandstone, migmatite-biotite gneiss and older granite settings were 49.07 mg/L, 60.13 mg/L, 92.77 mg/L and 97.12 mg/L during the dry season and 109.95 mg/L, 51.48 mg/L, 157.44 mg/L and 156.10 during the wet season respectively. The mean concentration of NO_3^- were 7.28 mg/L, 15.73 mg/L, 16.77 mg/L and 20.46 mg/L during the dry season and 10.17 mg/L, 22.41 mg/L,19.74 mg/L and 16.57 mg/L during the wet season for groundwater samples from alluvium, sandstone, migmatite-biotite gneiss and older granite settings respectively. The mean values of SO_4^{2-} for alluvium, sandstone, migmatite-biotite gneiss and older granite were 11.10 mg/L, 23.96 mg/L, 21.07 mg/L and 30.62 mg/L during the dry season and 9.778 mg/L, 15.113 mg/L, 38.579 mg/L and 41.968 mg/L during the wet season respectively. The mean values of Cl^- were 34.94 mg/L, 49.8 mg/L, 41.16 mg/L and 41.05 mg/L during the dry season and 43.651 mg/L, 59.776 mg/L, 56.077 mg/L and 50.862 mg/L during wet season for alluvium, sandstone, migmatite-biotite gneiss and older granite respectively. However, HCO_3^- concentration was the dominant among the major anions in all the rock units and this dominance could be as result of CO_2 charged precipitation that recharges the aquifer in the study area. This CO_2 charged precipitation produces weak acid that will eventually dissociated into hydrogen ion and bicarbonate ion as expressed in equations 4.6 and 4.7.

The values of HCO_3^- in groundwater samples from migmatite-biotite gneiss and older granite rock units were higher than those from alluvium and sandstone settings (Fig. 4.10) and this is consistent with trends of EC, TDS, TH, Ca^{2+} and Mg^{2+}. NO_3^- values were generally low in the groundwater samples across all the rock units indicating little effects of agricultural and anthropogenic waste on groundwater system.

4.6 Multivariate Statistical Analyses

Pearson correlation and principal component analysis were used to carry out statistical analyses of geochemical data. The Pearson correlation matric is helpful because it can indicate the connection between factors (parameters) that can demonstrate the general consistency of the data set and indicate the contribution of the individual chemical

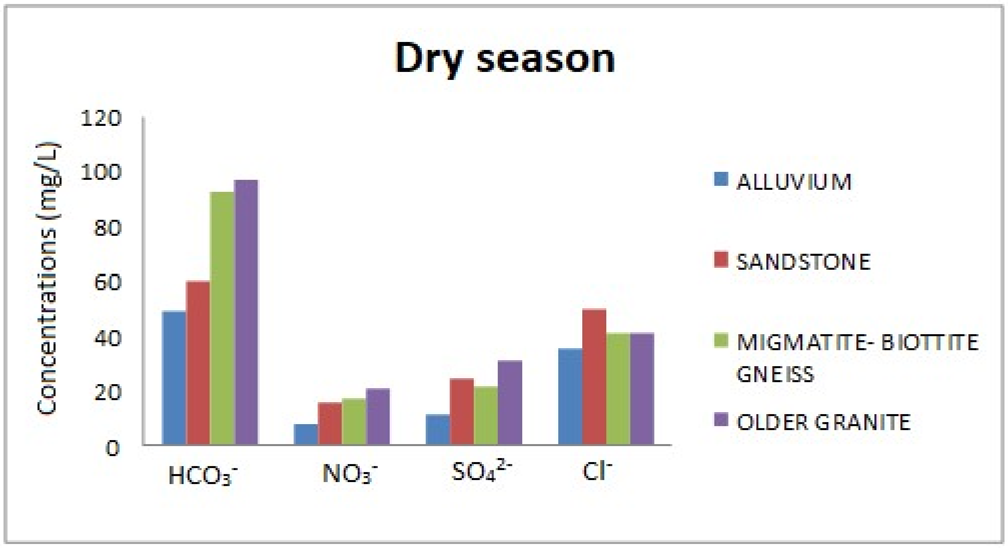

Fig. 4.10a. Concentration of anions based on rock types (dry season)

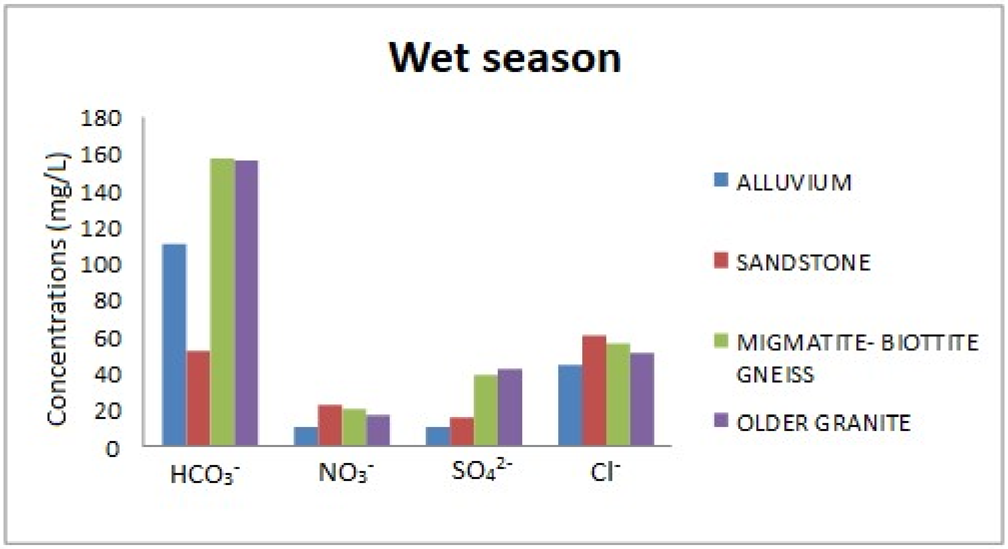

Fig. 4.10b. Concentration of anions based on rock types (wet season)

parameters in several hydrochemical influencing factors (Helena *et al.,* 2000). Table 4.18a and 4.18b presents the correlation matrix for major ions and physical parameters. Total Dissolved Solids (TDS) predicts spatial control of major ion levels as a helpful indicator of groundwater chemistry and anthropogenic contamination. With the exception of some samples, concentrations of all major ions examined tend to increase with increased TDS except where anomalous high values were determined. TDS was positively correlated with all major ions; Ca^{2+} (0.6223), Mg^{2+} (0.6222), Na^+ (0.7631), K^+ (0.3625), SO_4^{2-} (0.5620), Cl^- (0.7392), and NO_3^- (0.5970) except HCO_3^- with correlation coefficient of -0.2653 during the dry season while TDS was positive correlated with Ca^{2+} (0.7471), Mg^{2+} (0.6035), Na^+ (0.8618), K^+ (0.5696), HCO_3^- (0.4441), SO_4^{2-} (0.6933), Cl^- (0.8019) and NO_3^- (0.5793) during wet season. The positive correlation between these major ions and the TDS in the study area is an evidence of geogenic input to the overall mineralisation of the groundwater system. The positive correlation may also suggest the effect on groundwater chemistry by agricultural operations through leaching of soluble salts from the soil, where these salts are precipitated under the influence of elevated evaporation rates (El-Ahmadi and El-Fiky, 2009). The negative correlation between TDS and HCO_3^- during the dry season was probably due absence of precipitation while positive correlation during the wet season suggested an influence of CO_2 charged precipitation recharging the aquifers in the study area.

Principal component analysis (PCA) is a multivariate statistical analysis and it is commonly used to reveal patterns in large data set. The goal when using principal component analysis is to determine few linear combinations of original variables that can be used to summarize the data set without losing much information. PCA helps to reduce the intricacy of data sets on a big scale and thus identify the prevalent geochemical processes (Davis, 1986). In this study, twelve factors (parameters) were used for the principal component analysis in 65 water samples and four principal components (PCs) were obtained covering 70.54 % (dry season) and 88.29 % (wet season) of the total variance.

Table 4.18a. Correlation coefficients of physicochemical parameters in dry season

Parameters	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	NO_3^{-}	pH	TH	EC	TDS
Ca^{2+}	1.000											
Mg^{2+}	0.5317	1.000										
Na^{+}	0.4567	0.5202	1.000									
K^{+}	0.2678	0.0107	0.4040	1.000								
HCO_3^{-}	-0.1353	-0.2999	-0.2725	-0.1632	1.000							
SO_4^{2-}	0.6428	0.2042	0.5567	0.5216	-0.1641	1.000						
Cl^{-}	0.6777	0.3968	0.6086	0.6247	-0.2959	0.7123	1.000					
NO_3^{-}	0.5450	0.2115	0.4707	0.3563	-0.0851	0.6155	0.7024	1.000				
pH	0.1255	0.0380	0.1379	0.0284	0.0422	0.1896	0.0464	0.1428	1.000			
TH	0.8754	0.8719	0.5554	0.1510	-0.2452	0.4788	0.6112	0.4280	0.1012	1.000		
EC	0.6538	0.6386	0.7684	0.3732	-0.2733	0.5693	0.7427	0.6034	0.2268	0.7347	1.000	
TDS	0.6223	0.6222	0.7631	0.3625	-0.2653	0.5620	0.7392	0.5970	0.1880	0.7074	0.9761	1.000

Table 4.18b. Correlation coefficients of physicochemical parameters in wet season

Parameters	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	pH	TH	EC	TDS
Ca^{2+}	1.000											
Mg^{2+}	0.3788	1.000										
Na^+	0.4941	0.3649	1.000									
K^+	0.3232	0.1032	0.5910	1.000								
HCO_3^-	0.3797	0.7525	0.2988	-0.0139	1.000							
SO_4^{2-}	0.7353	0.2701	0.5297	0.3185	0.2663	1.000						
Cl^-	0.5720	0.5200	0.6832	0.3255	0.2090	0.4337	1.000					
NO_3^-	0.4812	-0.0433	0.5797	0.5899	-0.3469	0.484	0.4486	1.000				
pH	-0.0316	-0.3924	-0.0421	0.0676	0.0082	0.0916	-0.4072	-0.0309	1.000			
TH	0.8359	0.8246	0.5183	0.2588	0.6781	0.6100	0.6588	0.2686	-0.2522	1.000		
EC	0.7363	0.6107	0.8549	0.5588	0.4459	0.6995	0.7962	0.5720	-0.1718	0.8125	1.000	
TDS	0.7471	0.6035	0.8618	0.5696	0.4441	0.6933	0.8019	0.5793	-0.1699	0.8148	0.9966	1.000

Based on Kaisier criterion, the number of significant PCs for the interpretation was selected with an Eigen value higher than one and a total described percentage variation equal to or greater than 70 %. Table 4.19a (dry season) and Table 4.19b (wet season) presents the factor loading, latent root, Eigen value and percentage variation in PC. The parameters selected for each PC were based on their latent roots; PC 1 = 5.749, PC 2 = 1.683, PC 3 = 1.283 and PC 4 = 1.150 for dry season and PC 1 = 6.5, PC 2 = 2.064, PC 2 = 1.209 and PC 4 = 0.822 for wet season. The first PC described 41.06 % of the total sample variance for dry season data and loaded for Ca^{2+}, Cl^-, Electrical Conductivity (EC), K^+, Na^+, Total Dissolved Solids and Total Hardness while the first PC for wet season described 54.17 % and loaded for all parameters. Chloride was believed to be released from chemical weathering of rocks, atmospheric deposition and evapotranspiration of the runoff or leaching of salts from domestic wastes. Calcium (Ca^{2+}), Na^+, Total dissolved solids (TDS) and total hardness (TH) were assumed to be indicative of the natural processes and water-rock interaction which leads to weathering and leaching of these ions and parameters into the groundwater. The second PC (PC 2) which explained 12.09 % of the total variance had high loading for K^+ for dry season while PC 2 for dry season showed 17.20 % of the total variance and had high loading for HCO_3^- and Mg^{2+}. PC 3 and PC 4 of dry season data respectively accounted for 9.17 % and 8.22 % of all the variance, and PC 3 had a high NO_3^- loading, while PC 4 had a high K^+ loading.

PC 3 and PC 4 of the wet season data showed 10.07 % and 6.85 %, respectively of the total variance. PC 3 had loading for Cl^- while PC 4 had loading for K^+ and Na^+. Precipitattion dissolution and leaching of silicate minerals accounted for PC 2 while anthropogenic activities, atmospheric deposition and rock-water interactions were asummed to account for PC 3 – PC 4.

Table 4.19a. Factor loading for variances (dry season)

n=12	PC 1	PC 2	PC 3	PC4
Ca^{2+}	0.336	-0.021	-0.093	-0.197
Cl^-	0.356	0.177	0.116	0.159
EC	0.382	-0.107	-0.013	-0.001
HCO_3^-	-0.135	0.237	0.089	-0.619
K^+	0.212	0.482	0.055	0.358
Mg^{2+}	0.288	-0.448	0.061	-0.122
NO_3^-	-0.039	-0.049	0.563	-0.371
Na^+	0.333	0.009	0.041	0.052
SO_4^{2-}	0.144	0.128	-0.317	0.023
TDS	0.364	-0.129	0.042	0.021
TH	0.355	-0.271	-0.020	-0.190
pH	0.078	0.124	-0.538	-0.424
Latent Roots	5.749	1.693	1.283	1.15
% Variation	41.06	12.09	9.17	8.22

n= Number of parameters

Table 4.19b. Factor loading for variances (Wet season)

n=12	PC1	PC2	PC3	PC4
Ca^{2+}	0.320	0.008	-0.135	-0.484
Cl^-	0.310	-0.046	0.363	-0.053
EC	0.385	-0.037	0.041	0.082
HCO_3^-	0.193	0.551	-0.117	0.208
K^+	0.213	-0.355	-0.072	0.535
Mg^{2+}	0.253	0.437	0.181	0.186
NO_3^-	0.219	-0.516	0.005	-0.128
Na^+	0.322	-0.172	0.065	0.336
SO_4^{2-}	0.290	-0.081	-0.320	-0.420
TDS	0.386	-0.042	0.037	0.087
TH	0.346	0.264	0.025	-0.186
pH	0.054	0.045	-0.829	0.211
Latent Roots	6.500	2.064	1.209	0.822
% Variation	54.170	17.200	10.070	6.850

n = Number of parameters

4.7. Hydrochemical Facies

The concept of hydrochemical facies is used to study the distribution of water type and identify the origin of the chemical character of groundwater system. Hydrochemical facies classify cation and anion concentrations of groundwater into similar composition categories. However, the chemical composition of groundwater varies with respect to variations in geological medium through which the water flows, groundwater flow rate and anthropogenic activity. Therefore, in order to characterise the hydrochemical facies of the groundwater system in the study area, Piper trilinear diagrams, Schoeller diagrams and Stiff diagrams were employed. Piper trilinear diagrams (Piper, 1953) based on chemical parameters i.e. anion and cation concentrations were used to catigorised groundwater in the study area. A piper diagram is a convenient way to categorise water types by using the ionic compositions of different samples of water (Al-Omran *et al.,* 2012; Al-Ahmadi, 2013). There are two triangles in the plots, one for cations and the other for anions plottings. The respective point plots of cations and anions are projected to the diamond-shaped field and respective points of interception represents the data plot points for the different samples; thus signifying the hydrochemical facie of the different water samples (Back and Henshaw, 1965). The plotting of Piper diagram is based on the content of major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and anions (HCO_3^-, SO_4^{2-} and Cl^-). The plots (Fig. 4.11 and Fig. 4.12) revealed four (4) different types of facies in both dry and wet seasons. They are; $Ca^{2+}(Mg^{2+}) – HCO_3^-$; $Na^{+}(K^{+}) – Cl^- – SO_4^{2-}$; $Ca^{2+}(Mg^{2+}) – Cl^- – SO_4^{2-}$ and $Na^{+}(K^{+}) – HCO_3^-$ facies. These facies along with the number of samples in each facies and their percentage are presented in Table 4.20.

(I) $Ca^{2+}(Mg^{2+}) – HCO_3^-$ facie

From the piper plots, 21 out of 65 water samples representing 32.3 % during the dry season and 22 out of 64 samples (34.4 %) in the wet season investigation belong this facie (I). This facie is described as bicarbonate groundwater from near surface mineral weathering and it is the dominant facies in the study area for both seasons. The facie represents the initial stage of groundwater evolution and shows groundwater of recharge area.

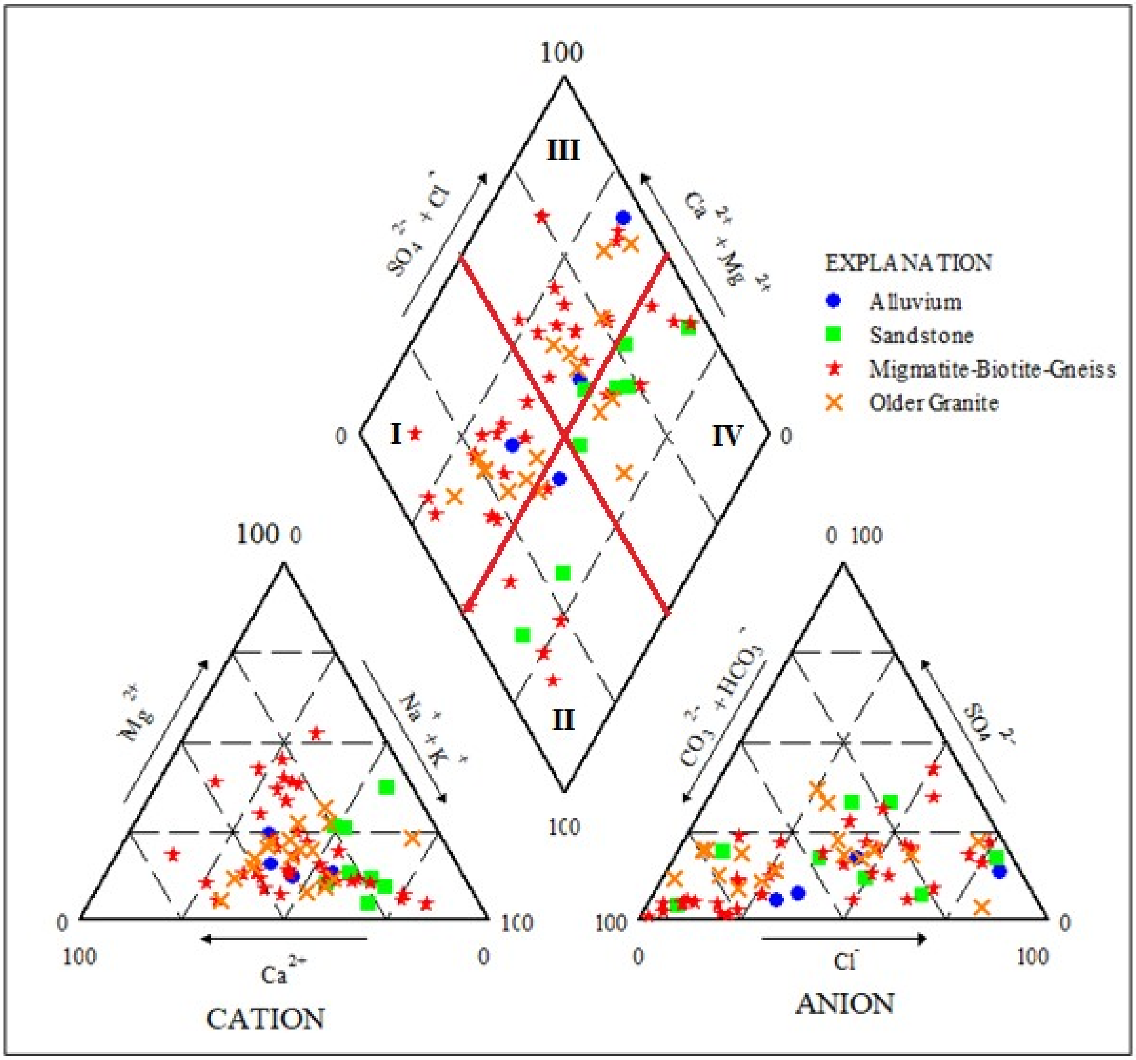

Fig. 4.11. Piper diagram of groundwater samples (dry season)

Legend/Hydrochemical Facies

I = $Ca^{2+}(Mg^{2+}) – HCO_3^-$

II = $Na^+(K^+) – HCO_3^-$

III = $Ca^{2+}(Mg^{2+}) – SO_4^{2-} - Cl^-$

IV = $Na^+(K^+) – SO_4^{2-} - Cl^-$

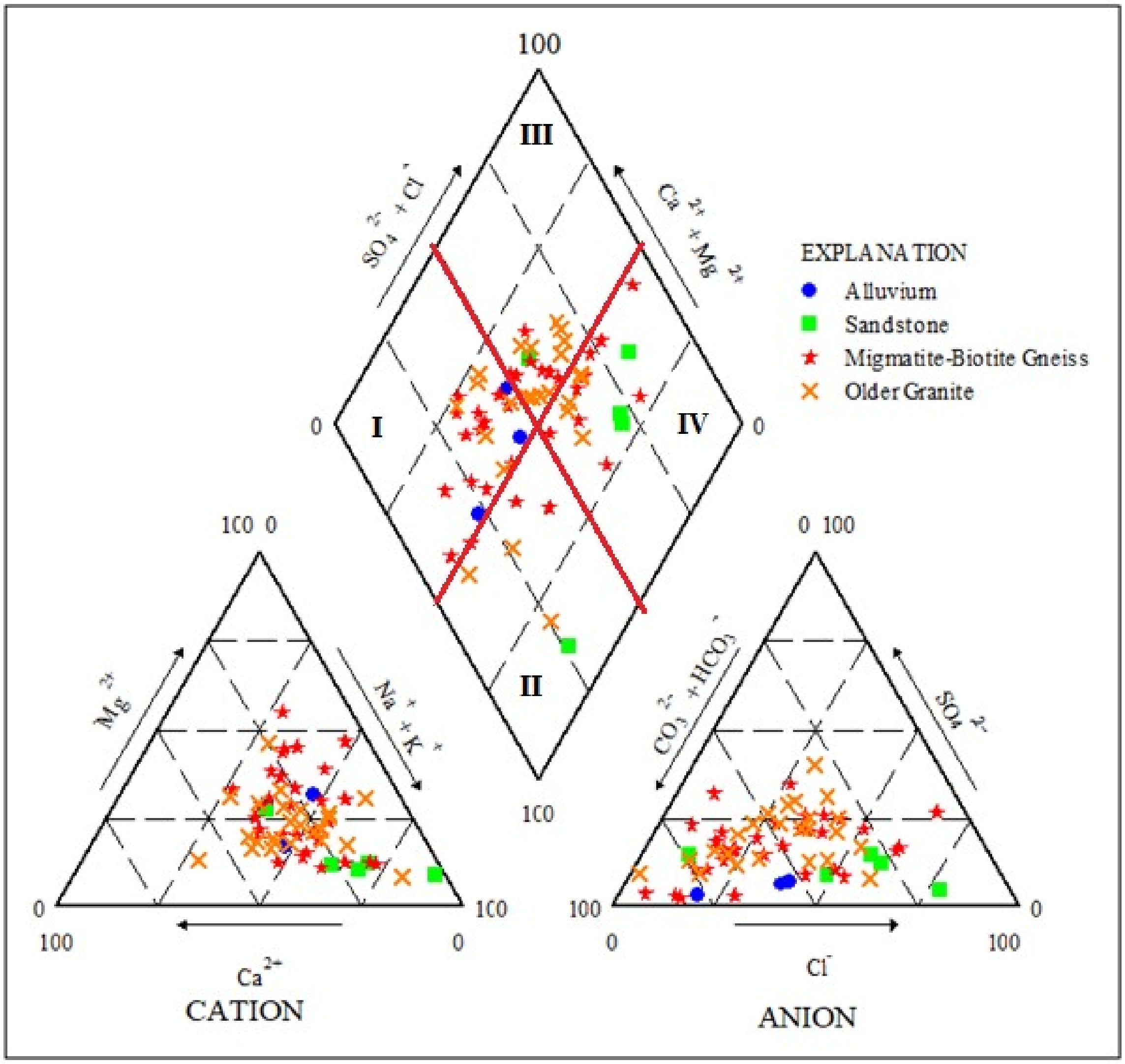

Fig. 4.12. Piper diagram of groundwater samples (wet season)

Legend/Hydrochemical Facies

I = $Ca^{2+}(Mg^{2+}) – HCO_3^-$

II = $Na^+(K^+) – HCO_3^-$

III = $Ca^{2+}(Mg^{2+}) – SO_4^{2-}$ - Cl^-

IV = $Na^+(K^+) – SO_4^{2-}$ - Cl^-

Table 4.20. Facie types of the study area

Facies	Sample number		Percentage (%)	
	Dry	Wet	Dry	Wet
$Ca^{2+}(Mg^{2+}) – HCO_3^-$ (I)	21	22	32.3	34.4
$Na^{+}(K^{+}) – HCO_3^-$ (II)	10	7	15.4	10.9
$Ca^{2+}(Mg^{2+}) – SO_4^{2-}$ - Cl^- (III)	21	18	32.3	28.1
$Na^{+}(K^{+}) – SO_4^{2-}$ - Cl^- (IV)	13	17	20.0	26.6

Dissolution of silicates (feldspar) in the bedrock and interactions with aluminosilicates in the weathered regolith were likely responsible for the chemical composition of this facie and are characteristics of the Nigerian Basement Complex with little or no mixing (Tijani, 1994). Samples from migmatite-biotite gneiss (13 for dry and 12 for wet season) and older granite (7 each for both dry and wet seasons) bedrocks settings were mostly plotted in this facie and weathering and dissolution of plagioclase and microcline from these bedrocks as determined by petrographical analysis could be responsible for this facie as expressed equation 4.1.

(II) Na^+ (K^+) – HCO_3^- facie

This facie constitutes 15.4 % (10 samples) during the dry season and 10.9 % (7 samples) of total facies in the study area. Seven groundwater samples from migmatite-biotite gneiss, two from sandstone and one from alluvium bedrock settings plotted in this facie during the dry season while three samples each from migmatite-biotite gneiss and older granite and a sample from sandstone terrain plotted in this facie during the wet season. This facies is softened bicarbonate water, where alkalis replace alkaline earth metals. Due to geochemical evolution through exchange processes, this facie is generally referred to as exchange water (Lohnert, 1970 and 1973; Nton *et al.,* 2007). The presence of substantial amounts of clay material as cation exchanger in Lokoja area as overburden units and flow rate promote active cation exchange and reaction as expressed in equation 4.8.

$$\frac{1}{2} Ca^{2+} – HCO_3 + Na – X \rightarrow \frac{1}{2} Ca^{2+} – X_2 + NaHCO_3 \qquad (4.8)$$

(III) Ca^{2+}(Mg^{2+}) – SO_4^{2-}– Cl^-

Twenty-one groundwater samples (32.3 %) and 18 samples (28.1 %) for dry and wet seasons respectively belong to Ca^{2+}(Mg^{2+}) – SO_4^{2-}– Cl^- facies. Twelve samples from migmatie-biotite gneiss, six from older granite, 2 from sandstone and one from alluvium bedrocks during the dry season and seven from migmatite-biotite gneiss, 10 from older granite and one from sandstone bedrock settings during the wet season were plotted in this facie. The facie is the second most dominant in the study area and this demonstrates the dominance of alkaline earth metals over alkalis (i.e. Ca+Mg > Na+K) and strong acid anions over weak acid anions (i.e. Cl+SO_4 > HCO_3) (Ravikumar *et al.,* 2015). This facie is characterised by release of Ca^{2+} and Mg^{2+} through the dissolution of aluminosilicate minerals in the weathered regolith and bedrock by carbondioxide charged precipitation water. This is consistent with results obtained by Tijani, 1994 and Nton *et al.,* 2007 in similar basement terrain.

(IV) $Na^+(K^+) – SO_4^{2-} – Cl^-$

Thirteen samples (20.0 %) and 17 samples (26.6 %) during the dry and wet season respectively were categorised as $Na^+(K^+) – SO_4^{2-} – Cl^-$ facie. In this facie, five samples from migmatite-biotite gneiss, three from older granite and five from sandstone bedrock settings during the dry season were plotted while eight samples from migmatite-biotite gneiss, six from older granite and three from sandstone terrains plotted in this facie during the wet season. This facie is dominated by sodium-alkali and its source is thought to be Lokoja Formation which comprises of quartz and feldspar (plagioclase) that are texturally immature. This assertion is proved as most of the samples from sandstone bedrock were plotted in this facie. The sodium-alkali component of this facie is the product of reaction as expressed in equation 4.3. The chloride which may have come from leachate from waste dumps and sulphate from atmospheric source may have also influenced this facie.

Furthermore, Schoeller diagram is another data plot approach which is usually used to represent the concentrations of major ions of many samples in log-scale on a single graph (Shoeller, 1962). The diagrams show the major cations and anions on the horizontal axis, whereas the log scale vertical axis shows the concentrations in milliequivalent per liter. The plots are usually used to distinguish common or disparate source areas of water drawn from multiple wells or rock types. The plot showed that cation concentrations were in the sequence of $Ca^{2+} > Na^++K^+ > Mg^{2+}$ during the dry season, and $Na^++K^+ > Ca^{2+} > Mg^{2+}$ in wet season for samples from alluvium terrain, $Na^++K > Ca^{2+} > Mg^{2+}$ in both seasons for samples from sandstone terrain. In migmatite-biotite gneiss bedrock setting, the order was $Na^++K^+ > Ca^{2+} > Mg^{2+}$ for dry and wet season, and $Na^++K^+ > Ca^+ > Mg^{2+}$ in samples from older granite terrain for both seasons (Fig. 4.13 and Fig. 4.14). The anions concentrations of groundwater samples from the study area was in the order of Cl^- > HCO_3^- > SO_4^{2-} during the dry season and HCO_3^- > Cl^- > SO_4^{2-} for samples from alluvium, Cl^- > HCO_3^- > SO_4^{2-} in both seasons in samples from sandstone; in migmatite-biotite gneiss and older granite bedrock, the order was HCO_3^- > Cl^- > SO_4^{2-} in dry and wet seasons. The difference between ionic composition lines of groundwater on the Schoeller diagrams indicated the dominance of $Ca^{2+}(Mg^{2+}) – HCO_3^-$, $Na^+(K^+) – HCO_3^-$ and $Na^+(K^+) – Cl^- - SO_4^{2-}$ hydrochemical facies across the rock types for both seasons. These hydrochemical facies delineated from the Schoeller diagrams agree with those delineated from Piper trilinear diagrams.

Stiff diagrams were also used to depict the ionic concentrations of major cations and anions. The technique of plotting stiff diagram is that it uses four parallel horizontal axes extending on each side of a vertical zero axis. On each axis, concentrations of four cations were plotted to the left of zero and that of anions plotted to the right of zero. The concentrations were in milliequivalents per liters (meq/L). Stiff diagrams plotted for the dry and wet season data are presented in appendix VXI. The interpretation of Stiff diagrams indicated the dominance of Ca^{2+} and Na^+ among cations in both dry and wet season across all rock types while HCO_3^- showed dominance among the anions. The $Ca^{2+}(Mg^{2+}) – HCO_3^-$ water type was the predominant facie in the study area. During the dry season, two samples from alluvium, four samples from sandstone, nine samples from biotite-migmatite gneiss and five samples from older granite bedrocks belong to this water types while three samples from alluvium, a samples from sandstone, 19 samples from biotite-migmatite gneiss and 11 sapmples from older granite terrains during the wet season belong to this water type. $Na^+(K^+) – HCO_3^-$ water type which is the second most dominant facie had a sample from alluvim, three samples from sandstone, nine samples biotite-migmatite gneiss and seven from older granite bedrocks belong to the facie during the dry season while 6 samples from biotite-migmatite gneiss, 5 samples from older granite bedrocks belong to the facie during the wet season.

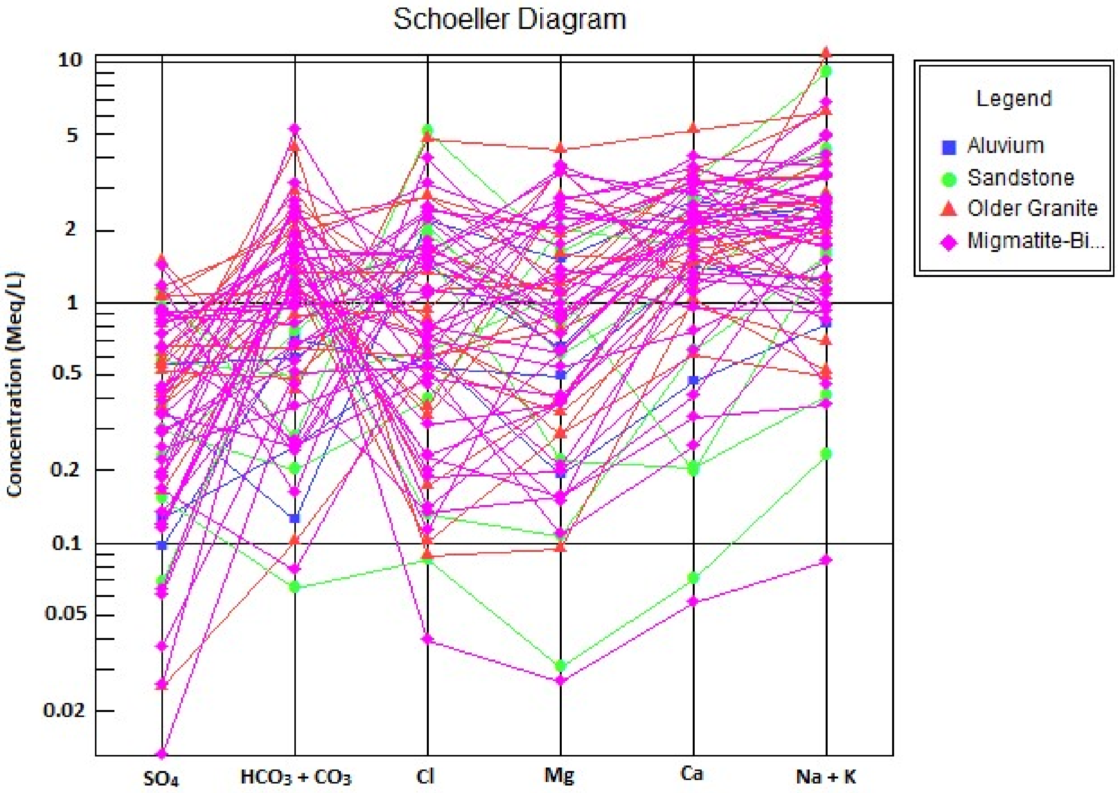

Fig. 4.13. Schoeller diagram of groundwater samples (dry season)

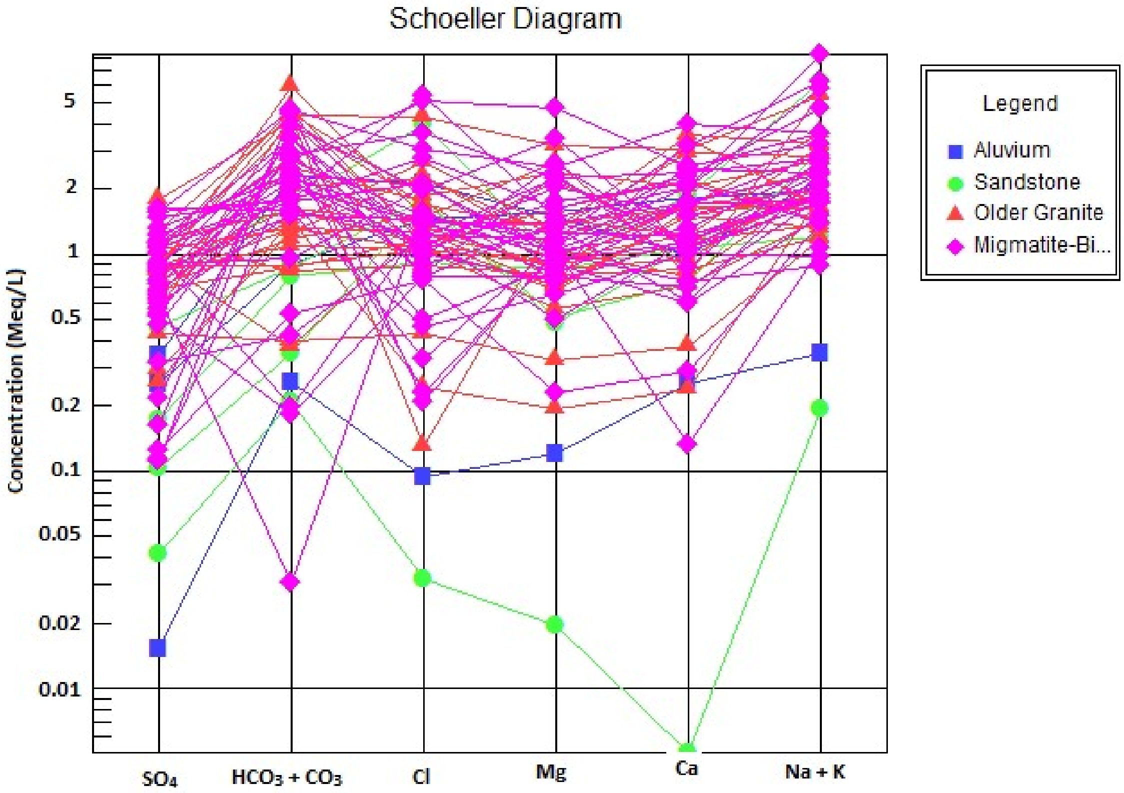

Fig. 4.14. Schoeller diagram of groundwater samples (wet season)

Na^++(K) – SO_4^{2-}-Cl^- water type which is the third dominants facie in the study area had seven groundwater samples from migmatite-biotite gneiss, two from sandstone and one from alluvium bedrock settings plotted in this facie during the dry season while three samples each from migmatite-biotite gneiss and older granite and a sample from sandstone terrain plotted in this facie during the wet season. The dissolution and leaching of aluminosilicate minerals by carbondioxide charged precipitation water infiltrating through migmate-biotite gneiss and older granite bedrocks were possibly responsible the dominance of $Ca^{2+}(Mg^{2+}) – HCO_3^-$ and $Na^+(K^+) – HCO_3^-$ water types in the study area.

Furthermore, Durov diagram was also used to plot the major ions analysed in groundwater samples from Lokoja area (Fig. 4.15 and Fig. 4.16). Durov diagram defines the hydrological processes affecting the groundwater chemistry. However, hydrochemical processes acting on the groundwater system and evolutionary trend along with an indication of mixing of various water types, ion exchange and reverse ion exchange processes were interpreted using Durov diagram (Al-Barakah *et al.,* 2017). Fields 1, 4, and 7 define ion exchange process, Fields 7, 5 and 3 define simple dissolution or mixing and Fields 3, 6, and 9 define reversed ion exchange process. The plots showed that most of the samples fall in fields 7, 5 and 3 in both dry wet season seasons, suggesting that simple dissolution as the major process influencing groundwater chemistry. The results also show that the mixing of two or more facies in the groundwater system may be a possibility. In addition, the functional source of dissolved ions in the groundwater was evaluated by plotting TDS against $Na^+ / (Na^+ + Ca^{2+})$ as evaporation, rock (dilution and weathering), and precipitation dominance (Gibbs, 1970). The physic-chemical data of groundwater from the study area for both seasons were plotted within the rock dominance zone (Fig. 4.17 and 4.18). This suggests that rock–water interaction is the major source of dissolved ions in groundwater. The rock–water interaction process includes the chemical weathering of rocks, dissolution–precipitation of secondary carbonates, and ion exchange between water and clay minerals.

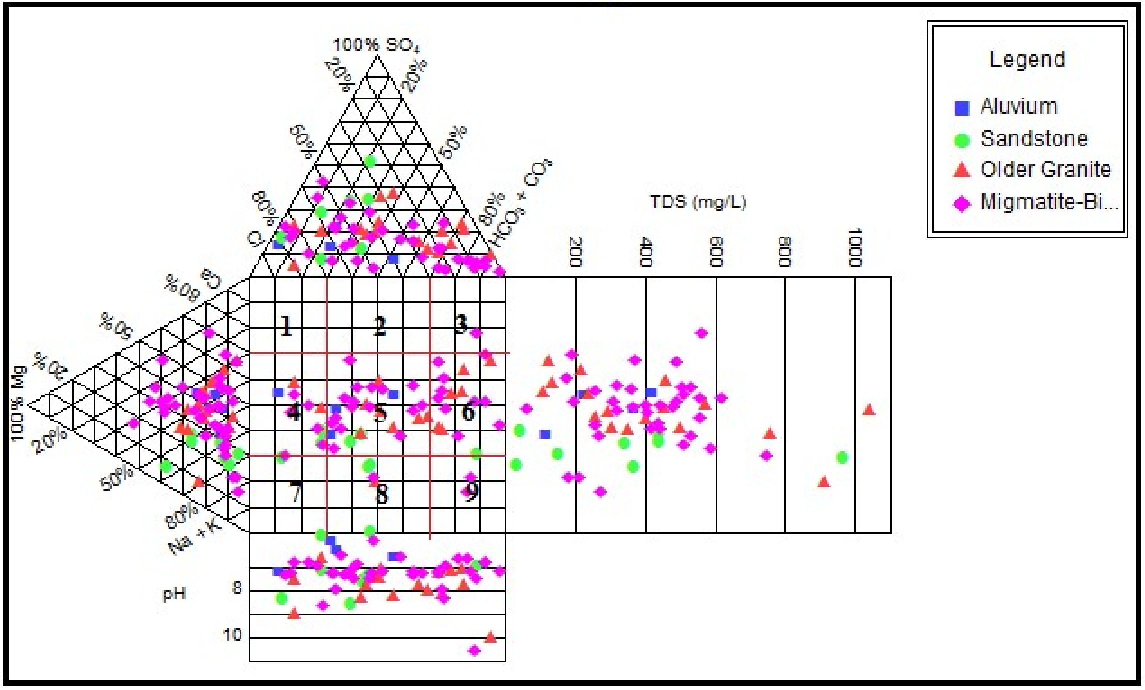

Fig. 4.15. Durov Diagram showing hydrological processes (dry season)

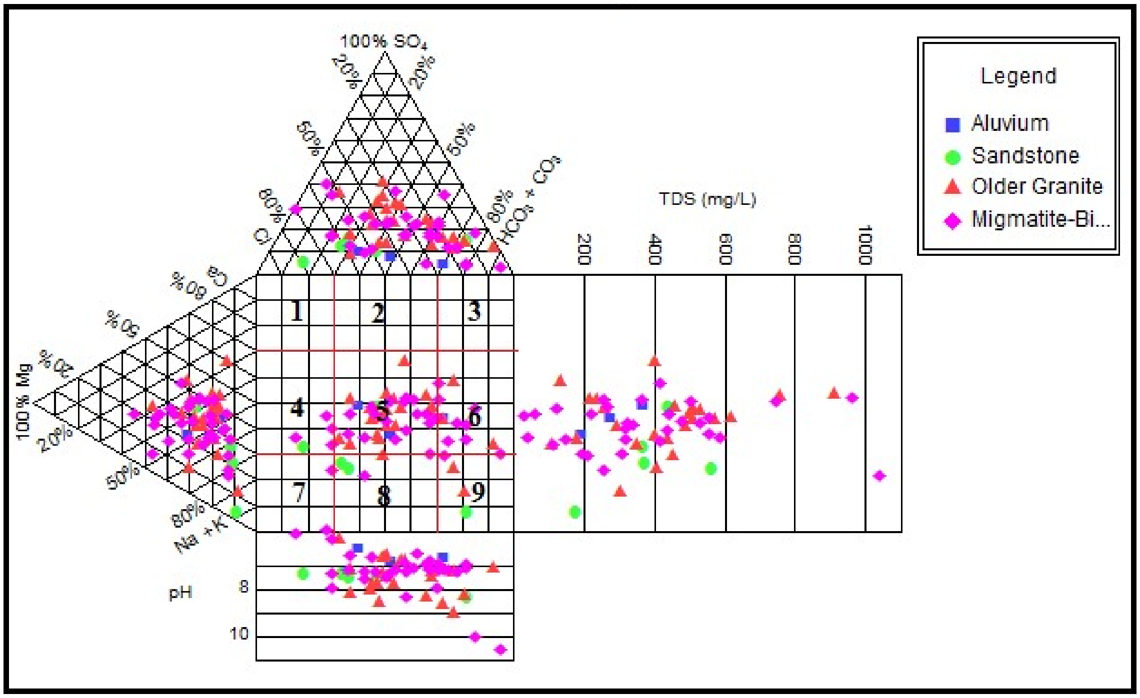

Fig. 4.16. Durov Diagram showing hydrological processes (wet season)

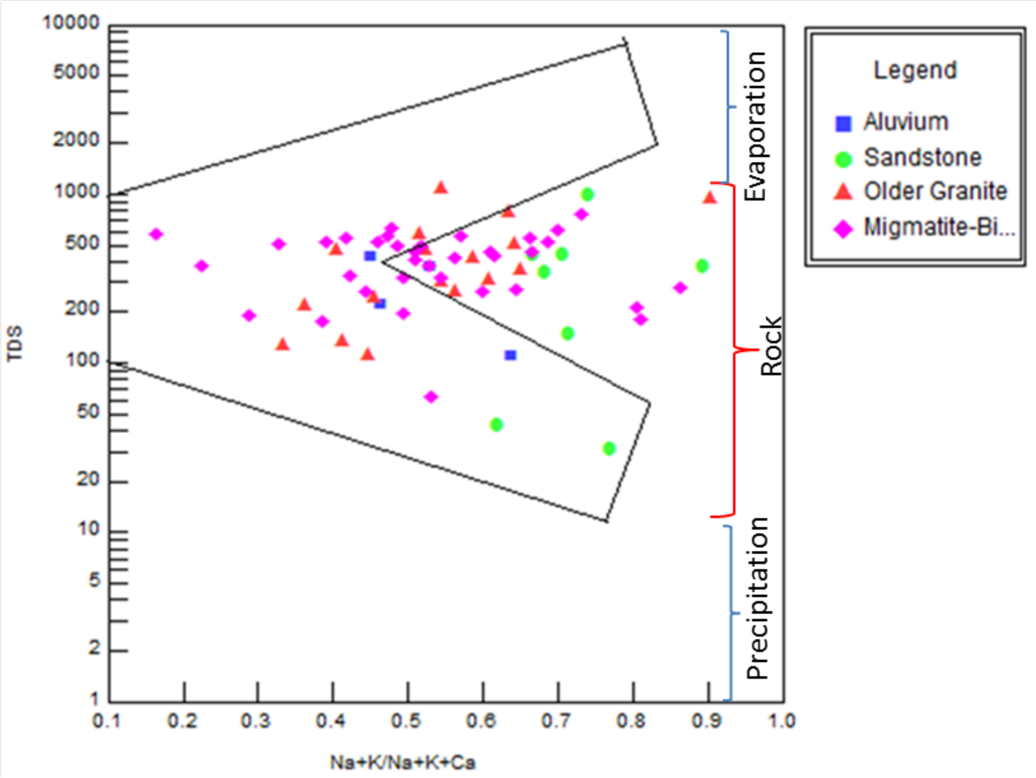

Fig. 4.18. Gibbs diagram of groundwater samples (dry season)

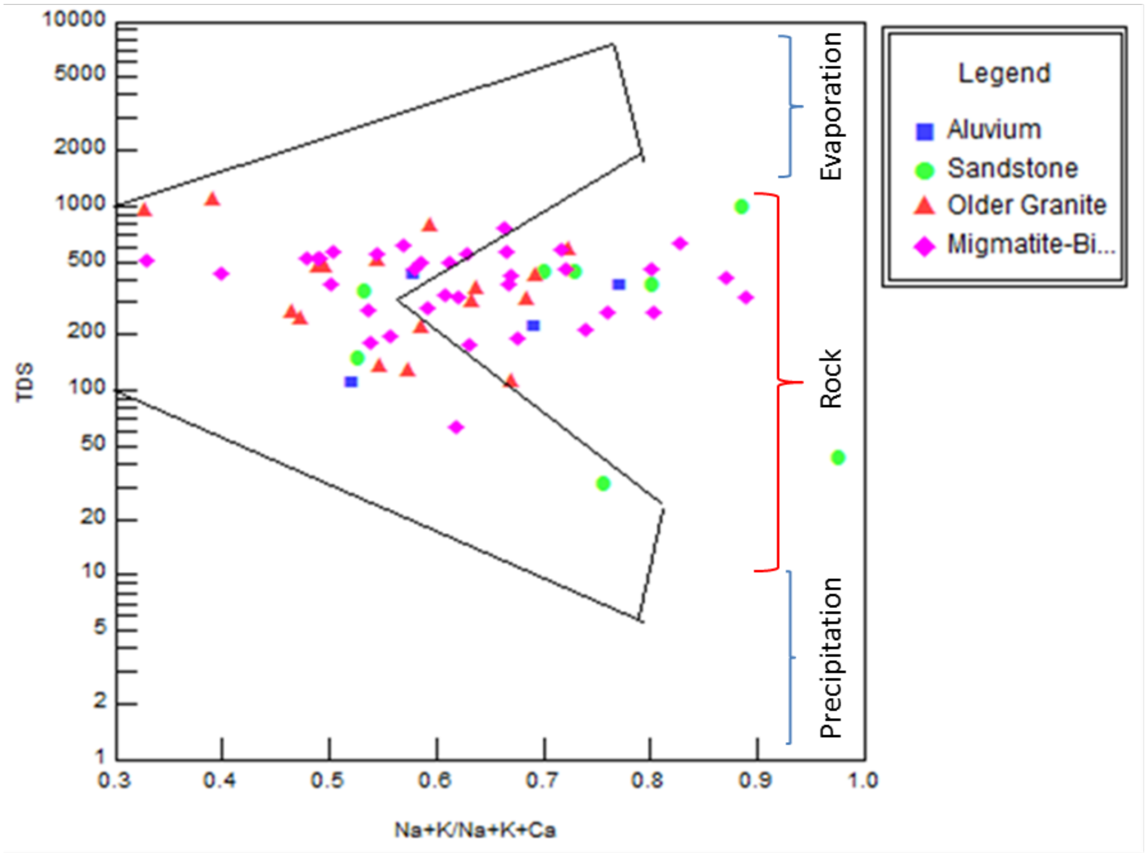

Fig. 4.18. Gibbs diagram of groundwater samples (wet season)

4.8 Mechanism Controlling Ionic Constituents of Groundwater in Lokoja Area

The dissolution of a broad range of different elements in groundwater is generally governed by the lithology, nature of geochemical reactions and solubility of aquifers materials (Nosrat and Asghar, 2010). The concentrations of many of the dissolved constituents tends to be higher in groundwater than that of surface water, and shallow groundwater tends to have less concentrations than deep groundwater which have been in contact with bedrocks over a longer time. The rate of evaporation, chemical composition of rocks and that of rainwater generally control the chemistry of groundwater. During precipitation, atmospheric and biogenic carbon dioxide combine with water to form weak acid (carbonic acid) that later dissociated into hydrogen ion and bicarbonate ion (equation 4.6 and 4.7). The carbonic acid then percolates through the ground from the surface, where it reacts with feldspars, carbonates and other minerals, which dissolve them and form an aqueous solution of calcium, sodium and bicarbonate ions as expressed in equations 4.1 to 4.5

A bivariate plot was also used to investigate silicate weathering, carbonate dissolution and evaporate dissolution (Halim *et al.,* 2010, Srinivasamoorthy *et al.,* 2011b, Hallouche *et al.,* 2017). Bivariate plots of major ions provide additional information about the groundwater chemistry of the study area. The relative importance of weathering processes and ion exchange were examined using a plots of Ca^{2+} + Mg^{2+} versus HCO_3^- + SO_4^{2-} (Fig. 4.19a and 4.19b). The excess of Ca^{2+} + Mg^{2+} over SO_4^{2-} + HCO_3^- results in ion exchange and the points on the plot are shifted to the left and if the points shift rightward as a result of a large excess of Ca^{2+}+ Mg^{2+} over SO_4^{2-} + HCO_3^-, the reverse ion exchange is the process (McLean *et al.,* 2000; Hallouche *et al.,* 2017). In ion exchange, both Ca^{2+} and Mg^{2+} in the aquifer matrix are substituted by sodium ions at suitable exchange locations owing to the dissolution of minerals and release of elements (Alkali earth) while anions remain unchanged. Reverse ion exchange on the hand involves the release of calcium and magnesium and a descrease in sodium concentration. An exchange between alkalis in the liquid phase of the aquifer with alkali earth metals in the aquifer solid phase will result in a positive index indicating reverse exchange reactions (Lloyd and Heathcote, 1985).

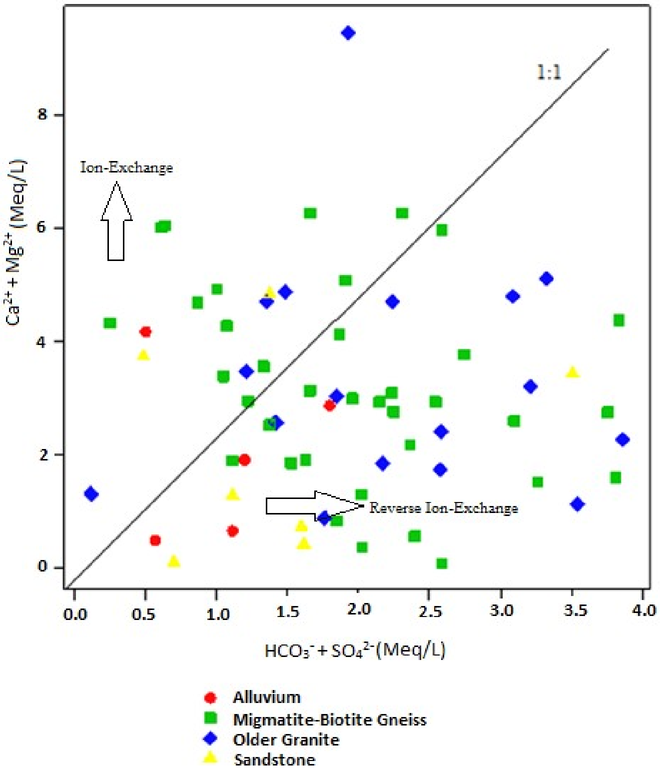

Fig. 4.19a. Plot of $Ca^{2+} + Mg^{2+}$ vs. $HCO_3^- + SO_4^{2-}$ of groundwater samples (dry Season)

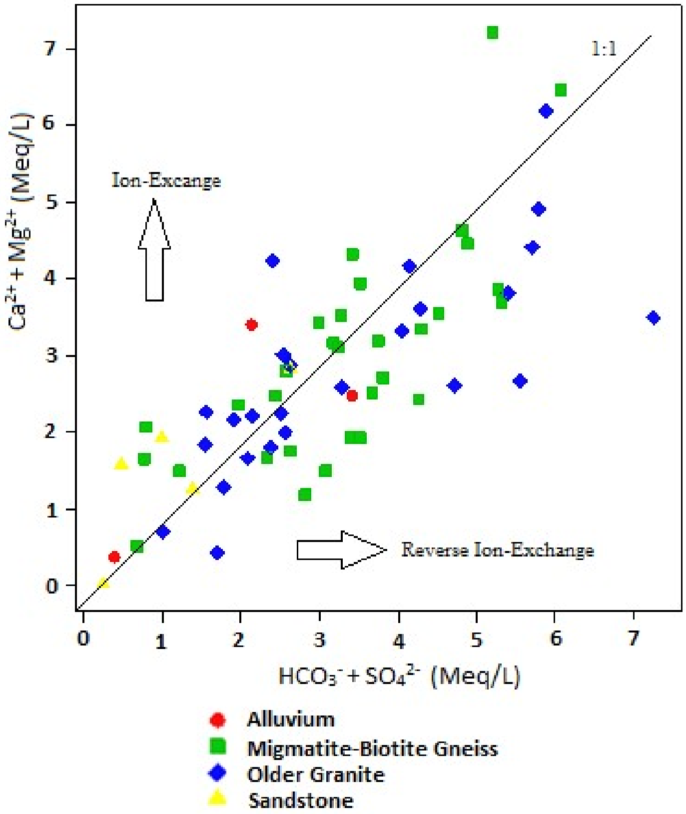

Fig. 4.19b. Plot of $Ca^{2+} + Mg^{2+}$ vs. $HCO_3^- + SO_4^{2-}$ of groundwater samples (wet season)

This process is majorly responsible for the increase of calcium and magnesium ions over sodium ion. The plots indicated that 45 (69.2 %) and 34 (53.1 %) of groundwater samples for dry and wet season respectively of the total samples scattered below the 1:1 line indicating reverse ion exchange (i.e. the high concentration of Ca^{2+} + Mg^{2+} relative to SO_4^{2-} + HCO_3^-) while 20 (30.8 %) and 30 (46.9 %) samples for dry and wet seasons respectively were scattered above the line suggesting an ion exchange and in this process, Na^+ and K^+ in clay material must balance part of the HCO_3^- + SO_4^{2-} (McLean *et al.,* 2000). The reverse ion exchange dominates over ion exchange in the study area because of the weathering and dissolution of calcium and magnesium from migmatite-biotie gneiss and older granite that underlie major part of the area. The wet season plot showed higher linear correlation than that of dry season due increased dissolution and leaching of solutes from the bedrocks.

The plots of alkaline earth metals Ca^{2+} + Mg^{2+} versus HCO_3^- (Fig. 4.20a and 4.20b) showed that samples were scathered and not clustered along 1:1 equiline indicating that silicate weathering and weathering of amphiboles and pyroxene minerals from the basement rocks were possibly responsible for HCO_3^- composition of groundwater in the study area and not from dissolution of carbonates ((Srinivasamoorthy *et al.,* 2011b; Hallouche, 2017). In addition, if the weathering of silicate minerals such as pyroxenes and amphiboles are the only source of calcium and magnesium in groundwater, the ratio of $Ca+Mg:HCO_3$ should be > 0.5 (Sami 1992). A ratio of < 0.5 could be a result of depletion of Ca^{2+} and Mg^{2+} relative to HCO_3^- due to ion exchange or enrichment of HCO_3^-. However, in this present study, the ratio of > 0.5 was estimated for all samples for both dry and wet seasons and this is an indicative of silicate weathering.

Similarly, the plots of Ca^{2+} versus HCO_3^- (Fig. 4.21a and 4.21b) of groundwater samples from the study area showed that the estimated $Ca:HCO_3$ ratio of 1.3 and 1.6 for dry and wet season respectively is an indicator of simple dissolution of silicates (Zhang *et al.,* 1995). The high molar ratio (>0.5) of $Ca:HCO_3$ observed in groundwater samples from the study area indicated reverse ion exchange source for calcium and magnesium, which is present in hard rock formations with an increase in salinity (Drever, 1997).

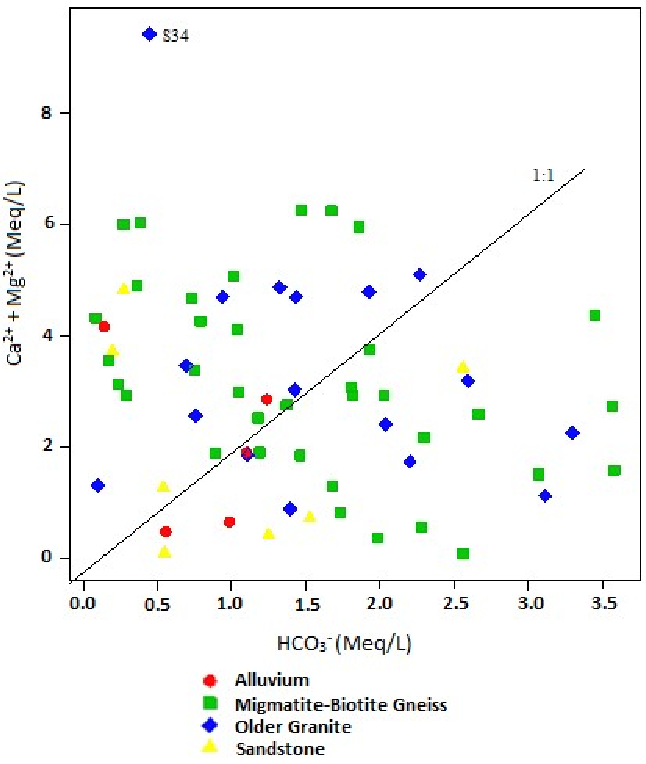

Fig. 4.20a. Plot of Ca^{2+} + Mg^{2+} vs. HCO_3^- of groundwater samples (dry Season)

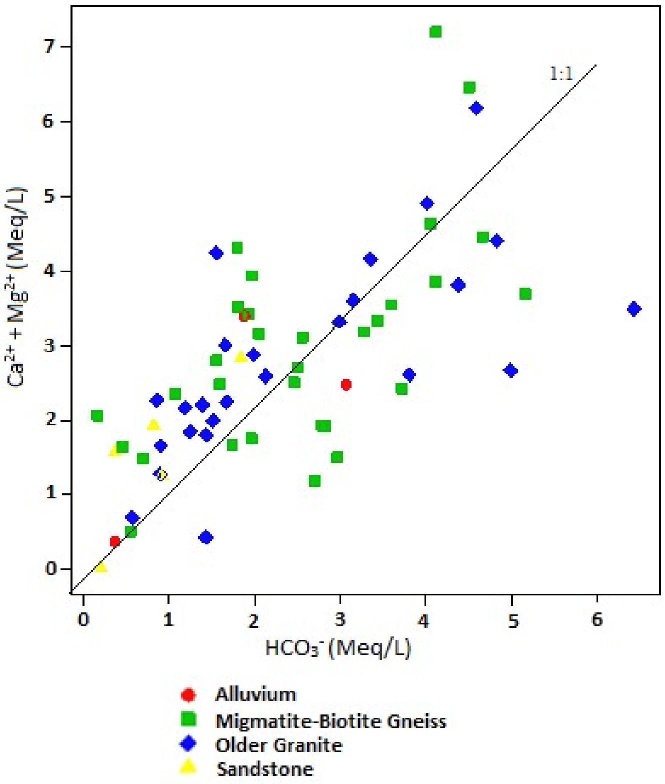

Fig. 4.20b. Plot of Ca^{2+} + Mg^{2+} vs. HCO_3^- of groundwater samples (wet Season)

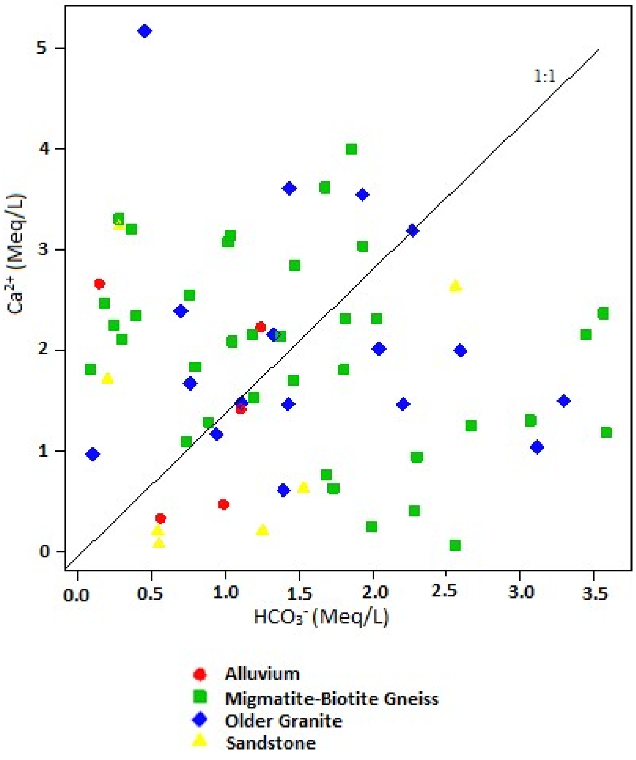

Fig. 4.21a. Plot of Ca^{2+} vs. HCO_3^- of groundwater samples (dry Season)

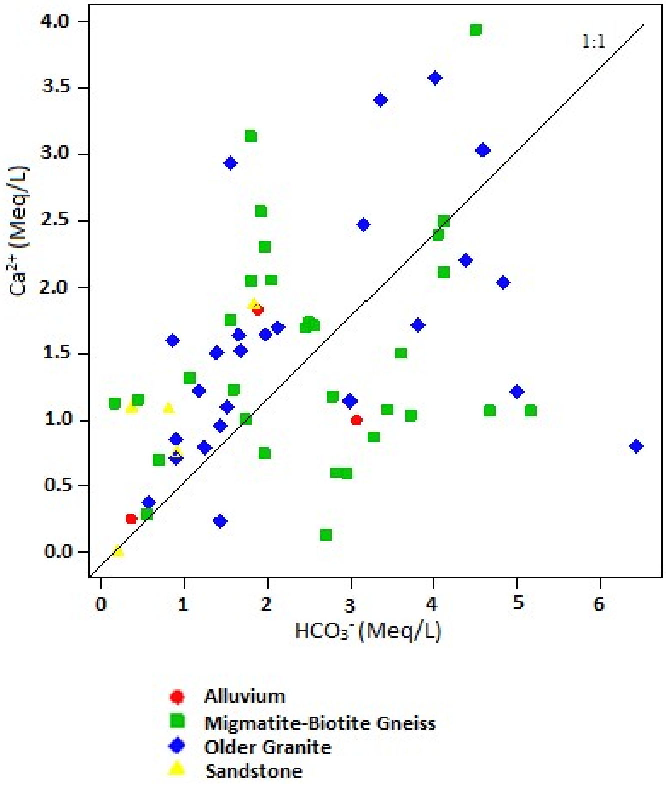

Fig. 4.21b. Plot of Ca^{2+} vs. HCO_3^- of groundwater samples (wet Season)

The linear correlation in wet season plot is attributed to higher dissolution of silicates minerals during the wet season than the dry season. Furthermore, geochemical processes control the groundwater chemistry especially in hard rock aquifers, and key of which is silicate weathering (Kumar *et al.,* 2006). The estimated ratio between $Na^+ + K^+$ and total cations (TZ) can be a guide to understanding silicate weathering. For dry and wet seasons, the majority of groundwater samples were plotted near the equiline (Fig. 4.22a and 4.22) and the Na+K:TZ ratio of > 0.5 for both seasons indicate the involvement of silicate weathering in geochemical processes, which mainly contributes sodium and potassium ions to groundwater (Stallard and Edmond, 1983).

4.9 Groundwater Quality Assessment

For groundwater of a particular quality to be considered suitable for a given use, it depends upon the requirements or standards of acceptable quality for such use (Todd, 2005). Quality limits of water supplies for drinking water, industrial purposes and irrigation apply to groundwater because of its extensive development for that purpose (Edmunds, 1992). The water quality as determined by its physical, chemical and biological components and its total dissolved solids is significant in determining the suitability for certain uses, i.e. domestic, agricultural and industrial uses.

5.9.1 Drinking Water Quality Assessment

Assessment of groundwater in Lokoja and its environs for drinking purposes was evaluated by comparing the groundwater physico-chemical parameters with the World Health Organization's proposed standard guideline values of 2011. From Table 4.21, it was noticed that the values of pH in the dry season for samples number S52 (5.9) from alluvium setting, S5 (8.6), S34 (5.5), S57 (5.7) from sandstone and S14 (5.9), S54 (10.6), S27 (8.7) from biotite-migmatite gneiss and S18 (10.1) from granite all representing 12.3 % were out of the range of recommended values of WHO, (2006). The groundwater was mostly neutral but few of the samples were slightly acidic and alkaline water. There are no health-based guidelines for electrical conductivity by WHO (2006) while the Total Dissolved Solid (TDS) measured in most samples were below 600 mg/L which is generally considered to be good in terms of palatability of the water.

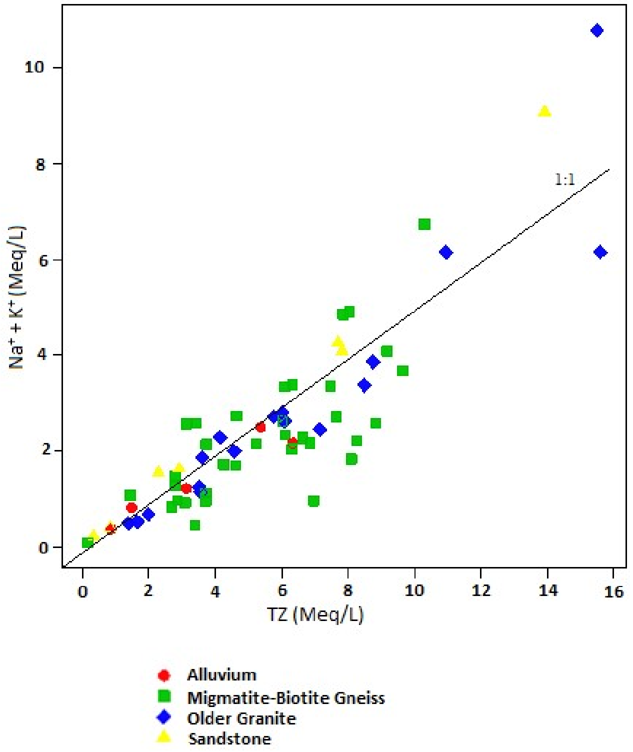

Fig. 4.22a. Plot of $Na^+ + K^+$ vs. TZ of groundwater samples (dry Season)

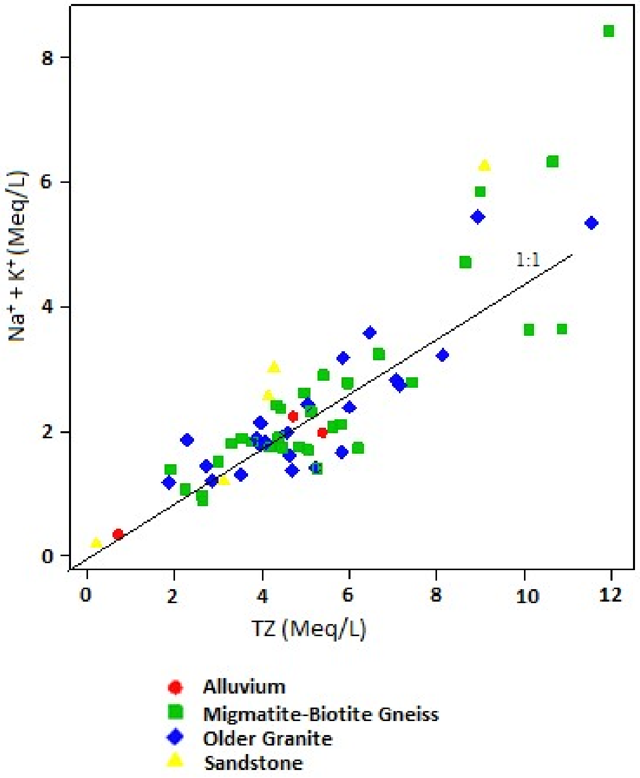

Fig. 4.22b. Plot of $Na^+ + K^+$ vs. TZ of groundwater samples (wet Season)

TDS values for sample locations S7 (909 mg/L), S9 (755 mg/L), S20 (620 mg/L), S24 (1040 mg/L), S32 (748 mg/L) and S33 (962 mg/L) representing 9.2 % of the samples were above 600 mg/L. However, water with TDS greater than 1,000 mg/L becomes significantly and increasingly unpalatable as it is the case of sample number S24 which is 1,040 mg/L. Twenty four percent or sixteen of the samples measured for total hardness were above the standard guideline value of 200 mg/L. Water with a hardness above 200 mg/L depending on the interaction with other factors, such as pH and alkalinity may cause a scale deposition in the treatment work, distribution system, piping and tanks (Ofoma *et al.,* 2005). The concentrations of Mg^{2+}, SO_4^{2-} and Cl^- were within the approved standard guideline values. Sample locations S20 (80.07 mg/L) and S24 (103.52 mg/L) for Ca, S7 (244.27 mg/L) for Na, S9 (72.50 mg/L), S20 (67.50 mg/L) and S24 (70.40 mg/L) for NO_3^- had values above the recommended WHO limit for drinking. There is no health-based guideline proposed for K^+ and HCO_3^-.

However, wet season data (Table 4.22) showed that samples from four (4) locations L2 (5.1), L28 (6.5), L48 (6.0) and L68 (5.4) were slightly acidic while a sample from location L1 (9.1) slightly alkaline was above the recommended limit. Total Dissolved Solids (TDS) of samples from 17 locations mostly from migmatite-biotite gneiss and from older granite and values of Total Hardness from eleven locations of the same rock units were above WHO, 2011 maximum permissible limits for drinking water. Sample locations L36 (55.43 mg/L) and L48 (59.40 mg/L) have nitrate above 50 mg/L recommended WHO for drinking water. All other parameters measured during the wet season were within the standards. The results of physico-chemical parameters in groundwater samples as compared with WHO (2011) standard suggested that groundwater of Lokoja area were generally with few exceptions within permissible limits and thus suitable for drinking purpose. The samples with concentrations above recommended limits could be attributed to the effects of leachate from waste dumps and pit latrine.

Table 4.21. Groundwater quality index parameters (dry season)

Water Quality Index	Range of values (mg/L)	Mean (mg/L)	WHO, 2006	No. of samples above guideline values
pH	5.5 – 10.6	7.39	6.5-8.5	8
EC	30 – 1390	527.28	-	-
TDS	31 – 1040	389.95	600	6
TH	4.11 – 472	151.47	200	16
Ca^{2+}	1.12 – 103.52	37.69	100	1
Mg^{2+}	0.32 – 52.02	14.12	100	0
Na^{+}	1.61 – 122.27	49.91	200	1
K^{+}	0.55 – 107.17	12.92	-	-
HCO_3^-	516– 128	87.03	-	-
NO_3^-	2 - 72.5	17.44	50	3
SO_4^{2-}	0.62 – 70.8	22.99	250	0
Cl^-	1.4 – 180	41.59	250	0

Table 4.22. Groundwater quality index parameters (wet season)

Water Quality Index	Range of values (mg/L)	Mean (mg/L)	WHO, 2006	No. of samples above guideline values
pH	0.7 – 9.1	7.15	6.5- 8.5	5
EC	70 – 1730	783.44	-	-
TDS	55 – 1273	558.45	600	17
TH	1.2 – 360	138.39	200	11
Ca^{2+}	0.1 – 79	29.74	100	0
Mg^{2+}	0.2 – 57.1	15.62	100	0
Na^{+}	3.4 – 157.7	48.1	200	0
K^{+}	1.5 – 72.2	14.18	-	-
HCO_3^{-}	10.3 – 398.7	146.41	-	-
NO_3^{-}	0.03 – 59.4	18.26	50	2
SO_4^{2-}	0.7 – 85.2	36.72	250	0
Cl^{-}	1.1 – 191.7	53.75	250	0

Further assessment of groundwater for drinking purpose in Lokoja area was further carried out using water quality index (WQI). Water quality index is an important parameter for determining the quality of groundwater and its suitability for drinking purpose. WQI is a rating method, which gives the composite influence of the individual water quality parameters on the general quality of water (Mitra and ASEBE Member, 1998). The drinking water standard as proposed by SON (2007) was used to calculate WQI. According to Chartterji and Rajiuddin, 2002, based on the values of WQI, the quality can be classified into five grades; excellent water quality (0-25), good water quality (26-50), poor water quality (51-75), very poor water quality (76-100) and unsuitable water quality (>100). The results of WQI estimated for the samples are presented in Table 4.23. The results showed that the WQI ranged from 4.12 to 72.94 with 37 samples (56.9 % of the total samples) falling within the 'excellent water quality' category, 23 samples (35.4 %) fell in the 'good water quality class' and five samples (7.7 %) fell in 'poor water quality' class (Fig. 4.23). Majority of the water samples across all the bedrocks displayed excellent and good water quality (Olarewaju *et al.,* 1997) and this confirms the earlier assertion that the groundwater in Lokoja is of low to moderately mineralised type with limited migration history. It was also observed that poor water quality noted in locations S9, S20 S24, S32 and S33 in the eastern part of Lokoja is a reflection of poor hygienic practice in this populated area, hence the anthropogenic contamination.

4.9.2 Irrigation Quality Assessment

The suitability of groundwater for irrigation depends on the effects of the mineral constituents of the water on both plant and soil. The significant chemical components that influence water's suitability for irrigation are the total dissolved salt contents, the relative amount of sodium, magnesium, and the relative ratio of sodium to calcium (Ewusi, 2013). Salt may physically damage plant growth by restricting water uptake through modified osmotic processes or chemically through metabolic reactions such as those triggered by harmful components (Todd, 1980). Salt also affects the soils by causing modifications in soil structure, permeability, and aeration that indirectly impact plant growth.

Table 4.23. Estimated WQI for the analysed groundwater samples

Sample Location	Sample ID	WQI	Water Type	Bedrock Setting
Ganaja 1	S1	29.88	Good water quality	Older Granite
Ganaja 2	S2	32.54	Good water quality	Older Granite
Ganaja 3	S3	16.55	Excellent water quality	Older Granite
Ganaja 4	S4	18.69	Excellent water quality	Older Granite
Ganaja 5	S5	22.28	Excellent water quality	Sandstone
Ganaja 6	S6	16.88	Excellent water quality	Older Granite
Lokoja 1	S7	40.62	Good water quality	Older Granite
Lokoja 2	S8	28.31	Good water quality	Migmatite-Biotite Gneiss
Lokoja 3	S9	56.76	Poor water quality	Older Granite
Lokoja 4	S10	29.03	Good water quality	Migmatite-Biotite Gneiss
Lokoja 5	S11	42.27	Good water quality	Older Granite
Lokoja 6	S12	8.23	Excellent water quality	Older Granite
Lokoja 7	S13	26.41	Good water quality	Older Granite
Lokoja 8	S14	10.65	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja 9	S15	18.49	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja 10	S16	35.31	Good water quality	Migmatite-Biotite Gneiss
Lokoja 11	S17	24.87	Excellent water quality	Older Granite
Lokoja 12	S18	10.04	Excellent water quality	Older Granite
Lokoja 13	S19	20.51	Excellent water quality	Older Granite
Lokoja 14	S20	50.18	Poor water quality	Migmatite-Biotite Gneiss
Adankolo 1	S21	15.47	Excellent water quality	Older Granite
Adankolo 2	S22	29.72	Good water quality	Older Granite
Adankolo 3	S23	12.33	Excellent water quality	Older Granite
Adankolo 4	S24	72.94	Poor water quality	Older Granite
Adankolo 5	S25	29.78	Good water quality	Migmatite-Biotite Gneiss
Adankolo 6	S26	30.01	Good water quality	Migmatite-Biotite Gneiss
Lokoja 15	S27	32.74	Good water quality	Migmatite-Biotite Gneiss
Lokoja 16	S28	21.79	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja 17	S29	22.39	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja 18	S30	35.36	Good water quality	Migmatite-Biotite Gneiss
Lokoja 19	S31	39.94	Good water quality	Migmatite-Biotite Gneiss
Lokoja 20	S32	65.93	Poor water quality	Migmatite-Biotite Gneiss
Lokoja 21	S33	52.82	Poor water quality	Sandstone

Table 4.23. Con'd. Estimated WQI for the analysed groundwater samples

Sample Location	Sample ID	WQI	Water Type	Bedrock Setting
Lokoja 22	S34	4.12	Excellent water quality	Sandstone
Lokoja 23	S35	24.34	Excellent water quality	Sandstone
Lokoja 24	S36	31.59	Good water quality	Migmatite-Biotite Gneiss
Lokoja 25	S37	24.37	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja 26	S38	13.57	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja 27	S39	10.48	Excellent water quality	Migmatite-Biotite Gneiss
Lokongoma 1	S40	16.02	Excellent water quality	Migmatite-Biotite Gneiss
Lokongoma 2	S41	28.63	Good water quality	Migmatite-Biotite Gneiss
Lokongoma 3	S42	20.9	Excellent water quality	Migmatite-Biotite Gneiss
Lokongoma 4	S43	26.14	Good water quality	Migmatite-Biotite Gneiss
Lokongoma 5	S44	13.72	Excellent water quality	Migmatite-Biotite Gneiss
Lokongoma 6	S45	32.39	Good water quality	Migmatite-Biotite Gneiss
Lokongoma 7	S46	23.49	Excellent water quality	Migmatite-Biotite Gneiss
Lokongoma 8	S47	35.96	Good water quality	Migmatite-Biotite Gneiss
Lokongoma 9	S48	12.36	Excellent water quality	Migmatite-Biotite Gneiss
Otokiti 1	S49	30.16	Good water quality	Migmatite-Biotite Gneiss
Otokiti 2	S50	26.35	Good water quality	Migmatite-Biotite Gneiss
Otokiti 3	S51	22.3	Excellent water quality	Migmatite-Biotite Gneiss
Filele 1	S52	33.52	Good water quality	Aluvium
Filele 2	S53	24.52	Excellent water quality	Aluvium
Filele 3	S54	18.09	Excellent water quality	Migmatite-Biotite Gneiss
Filele 4	S55	37.04	Good water quality	Migmatite-Biotite Gneiss
Filele 5	S56	13.74	Excellent water quality	Aluvium
Filele 6	S57	19.58	Excellent water quality	Sandstone
Filele 7	S58	8.49	Excellent water quality	Sandstone
Lokoja28	S59	25.93	Excellent water quality	Aluvium
Lokoja29	S60	13.44	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja30	S61	14.84	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja31	S62	16.39	Excellent water quality	Sandstone
Lokoja32	S63	18.22	Excellent water quality	Sandstone
Lokoja33	S64	22.25	Excellent water quality	Migmatite-Biotite Gneiss
Lokoja34	S65	19.78	Excellent water quality	Migmatite-Biotite Gneiss

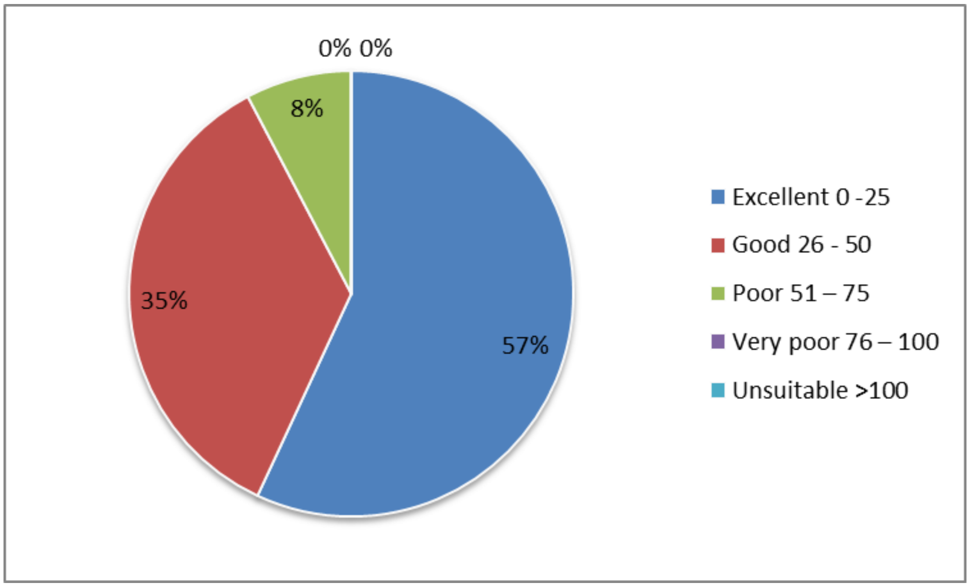

Fig. 4.23. Distribution of WQI in the study area

In this study, Wilcox diagram (1955) was used to characterise groundwater suitability for irrigation purposes. The diagram is based on the sodium adsorption ratio (SAR) and electrical conductivity (EC). According to Tijani (1994), these parameters are particularly important in the light of the fact that elevated levels of sodium can increase the salinity of the soil and decrease its permeability. The estimated water irrigation quality indices of the groundwater for dry and wet season are presented in Table 4.24 and 4.25.

a) Percentage Sodium: Percentage of sodium is very important in the classification of irrigation water as sodium reacts with soil to decrease permeability (Janardhana, 2007). Sodium saturated soils will favour little or no growth of plants because sodium concentration in water leads to decrease in the interconnectivity of the pore spaces within the soil, weakening of the soil mechanical characteristics, and reduced water infiltration (Richards 1954). Percentage sodium (Na %) in groundwater from Lokoja area during the dry season varied from 17.34 % to 85.90 % while that of wet season ranged from 34.15 % to 94.01 %. Percentage sodium in the wet season was slightly higher than that of the dry season and this could be attributed to the dissolution and increased chemical weathering of solute during the wet season. According to Sadashiviah *et al.,* (2008), groundwater for irrigation purpose is grouped as excellent if Na % <20 %; good if Na % is between 20-40 %; permissible if Na % is between 40-60 %; doubtful if Na % is between 60-80 %; and unsuitable if Na % >80 %. Based on this grouping and for dry season, 2 samples (3.13 %) have less than 20 Na % (excellent water), 27 representing 41.54 % of the total samples fell within 20-40 Na % (good category), 27 samples (41.54 %) samples fell within 40-60 Na % (permissible), 9 samples (13.85 %) were grouped between 60-80 Na % (doubtful) while a sample have >80 Na % (unsuitable). For wet season, four samples representing 6.25 % of the total samples, 34 (53.13 %) samples, 24 (37.5 %) samples and 2 (3.13 %) samples were within good, permissible, doubtful and unsuitable respectively (Table 4.26). However, no sample was categorised as excellent water (<20 %) during the wet season and this could be linked to increased weathering and dissolution of sodium solute from bedrock during the wet season. In summary, the groundwater samples from Lokoja and its environs are generally classified as good and suitable for irrigation.

Table 4.24. Irrigation water quality indices of groundwater for dry season

Sample Location	Sample ID	SAR	Na %	MH	RSC	PI
Ganaja 1	S1	2.1	55.1	13.7	-0.75	67.9
Ganaja 2	S2	1.8	42.9	21.7	-2.78	53.4
Ganaja 3	S3	1.9	51.7	10.4	0.46	71.1
Ganaja 4	S4	2.1	47.1	39.5	-1.61	63.6
Ganaja 5	S5	2.9	52.0	41.8	-3.54	63.2
Ganaja 6	S6	1.0	35.5	23.7	1.04	60.2
Lokoja 1	S7	6.9	69.4	64.9	-3.76	81.1
Lokoja 2	S8	1.2	26.7	49.0	-5.66	38.7
Lokoja 3	S9	3.7	56.1	17.7	-2.86	65.5
Lokoja 4	S10	1.9	43.7	16.7	-2.62	54.4
Lokoja 5	S11	2.0	39.6	26.8	-2.84	53.5
Lokoja 6	S12	0.6	35.3	22.1	0.50	74.0
Lokoja 7	S13	2.1	46.6	26.9	-0.61	63.3
Lokoja 8	S14	2.3	74.9	20.8	1.63	116.3
Lokoja 9	S15	1.7	53.2	30.0	0.39	78.3
Lokoja 10	S16	1.4	29.0	30.7	-4.58	41.9
Lokoja 11	S17	2.3	44.0	43.5	-3.55	58.2
Lokoja 12	S18	0.4	31.3	5.3	1.98	71.6
Lokoja 13	S19	1.6	43.6	24.7	-1.81	56.5
Lokoja 14	S20	1.9	38.0	23.1	-4.11	47.6
Adankolo 1	S21	0.8	32.0	10.8	-0.37	47.3
Adankolo 2	S22	1.4	34.1	15.6	-3.27	44.1
Adankolo 3	S23	0.7	33.9	17.9	-1.21	42.6
Adankolo 4	S24	2.7	39.3	33.4	-8.99	48.0
Adankolo 5	S25	1.5	38.3	12.7	-1.83	49.8
Adankolo 6	S26	2.0	53.4	19.3	-2.65	56.0
Lokoja 15	S27	3.4	60.9	19.3	-2.89	66.1
Lokoja 16	S28	1.4	34.6	45.9	-4.24	43.1
Lokoja 17	S29	1.2	32.2	44.7	-3.48	44.0
Lokoja 18	S30	1.5	35.5	24.7	-4.56	42.1
Lokoja 19	S31	2.7	61.7	21.1	-1.95	65.1
Lokoja 20	S32	4.0	65.3	21.1	-3.38	67.9
Lokoja 21	S33	4.1	65.2	23.2	-4.55	65.2

Table 4.24. Cont'd. Irrigation water quality indices of groundwater for dry season

Sample Location	Sample ID	SAR	Na %	MH	RSC	PI
Lokoja 22	S34	0.8	69.5	20.9	0.45	167.0
Lokoja 23	S35	2.2	59.0	22.3	-1.00	68.4
Lokoja 24	S36	2.0	54.7	15.0	-1.39	60.5
Lokoja 25	S37	0.9	29.9	39.9	0.07	56.5
Lokoja 26	S38	2.0	57.3	17.4	2.00	80.1
Lokoja 27	S39	3.9	75.7	16.0	0.91	93.5
Lokongoma 1	S40	1.4	40.4	9.8	-1.35	53.8
Lokongoma 2	S41	0.5	13.6	33.3	-5.73	19.6
Lokongoma 3	S42	1.7	40.9	30.2	-1.28	58.5
Lokongoma 4	S43	1.2	36.5	14.0	-1.11	50.2
Lokongoma 5	S44	0.9	33.5	13.0	-0.71	52.7
Lokongoma 6	S45	2.2	44.7	16.0	-3.08	54.8
Lokongoma 7	S46	1.3	31.3	66.7	-3.95	47.0
Lokongoma 8	S47	2.4	44.5	28.3	-4.05	55.5
Lokongoma 9	S48	0.7	29.6	44.4	0.13	56.7
Otokiti 1	S49	0.9	22.5	42.2	-4.79	33.6
Otokiti 2	S50	1.4	33.8	38.5	-0.93	52.3
Otokiti 3	S51	0.3	50.4	22.2	2.48	462.6
Filele 1	S52	1.2	55.2	19.9	0.33	85.6
Filele 2	S53	1.4	34.1	25.6	-4.03	42.1
Filele 3	S54	0.9	45.5	8.9	1.56	68.4
Filele 4	S55	0.6	43.3	22.2	0.07	82.0
Filele 5	S56	0.9	38.8	17.5	-0.81	52.9
Filele 6	S57	2.2	55.3	15.6	-0.87	61.0
Filele 7	S58	2.4	67.8	9.4	0.80	91.2
Lokoja28	S59	1.7	46.5	15.0	-1.63	56.1
Lokoja29	S60	4.6	82.0	18.6	1.72	102.7
Lokoja30	S61	0.5	25.8	9.0	0.82	42.3
Lokoja31	S62	0.8	48.8	39.5	0.83	113.2
Lokoja32	S63	1.3	55.8	76.8	-0.74	71.9
Lokoja33	S64	0.3	13.3	14.0	-0.90	32.2
Lokoja34	S65	0.8	31.0	5.0	-0.39	50.5

Table 4.25. Irrigation water quality indices of groundwater for wet season

Sample Location	Sample ID	Na %	SAR	MH	RSC	PI
Ganaja 1	L1	87.9	15.7	32.8	1.02	106.2
Ganaja 2	L2	74.0	7.9	34.1	-0.12	81.8
Ganaja 3	L4	52.9	8.3	20.4	-1.40	57.4
Ganaja 4	L5	64.4	11.9	44.6	-0.58	73.1
Ganaja 5	L6	65.1	14.8	31.2	-0.86	69.3
Ganaja 6	L8	48.3	9.5	21.2	-2.66	51.1
Ganaja 7	L10	45.6	6.1	22.0	-0.79	55.1
Ganaja 8	L11	57.2	15.5	38.6	-1.53	60.5
Ganaja 9	L12	47.1	10.3	18.4	-0.83	53.7
Ganaja 10	L14	36.0	4.9	11.8	-0.76	41.7
Ganaja 11	L15	54.7	8.8	32.0	-0.96	62.7
Ganaja 12	L16	66.2	13.0	42.2	2.40	76.0
Ganaja 13	L17	62.4	9.4	32.5	-0.36	73.6
Lokoja 1	L18	64.2	11.6	34.9	-0.35	72.9
Lokoja 2	L19	54.2	8.0	22.4	-0.54	61.2
Lokoja 3	L20	52.2	8.9	45.0	1.35	70.5
Lokoja 4	L21	48.4	10.2	41.4	0.50	59.7
Lokoja 5	L22	47.2	4.1	44.9	0.24	61.7
Lokoja 6	L23	58.5	9.7	33.4	-0.46	67.8
Lokoja 7	L24	52.1	7.0	36.4	-0.74	63.1
Lokoja 8	L25	44.5	6.7	33.5	-1.32	52.4
Lokoja 9	L26	39.6	6.2	53.5	-0.28	55.3
Lokoja 10	L27	34.3	5.6	30.8	0.63	50.4
Lokoja 11	L28	79.7	14.2	32.5	0.04	92.8
Lokoja 12	L29	57.9	9.4	27.9	0.90	72.3
Lokoja 13	L30	34.2	5.6	33.3	0.32	49.9
Lokoja 14	L31	56.3	11.0	24.1	1.26	69.4
Adankolo 1	L32	72.1	25.1	67.0	3.04	83.3
Adankolo 2	L33	48.4	8.6	21.7	-0.41	55.9
Adankolo 3	L34	51.4	9.0	24.3	-0.43	61.8
Adankolo 4	L36	64.5	15.9	29.9	-1.94	65.1
Adankolo 5	L37	49.4	6.7	25.4	-0.17	56.7

Table 4.25. Cont'd. Irrigation water quality indices of groundwater for wet season

Sample Location	Sample ID	Na %	SAR	MH	RSC	PI
Adankolo 6	L38	46.3	9.2	27.9	-1.89	47.7
Lokoja 15	L39	55.5	9.0	26.5	-1.22	58.5
Lokoja 16	L40	49.8	8.2	59.9	1.54	63.0
Lokoja 17	L41	48.9	7.7	45.2	0.11	57.9
Lokoja 18	L42	63.9	10.8	32.3	-1.27	64.3
Lokoja 19	L43	48.1	9.0	36.1	-0.52	54.5
Lokoja 20	L44	74.5	18.8	24.7	-1.09	71.6
Lokoja 21	L45	78.7	29.0	30.3	-1.69	77.7
Lokoja 22	L46	77.3	22.2	23.7	-0.96	75.9
Lokoja 23	L47	69.4	16.6	18.6	-2.49	63.0
Lokoja 24	L48	63.1	9.0	20.8	-1.19	62.4
Lokongoma 1	L49	94.0	8.2	70.1	0.18	187.6
Lokongoma 2	L50	52.8	9.5	38.2	-0.86	63.7
Lokongoma 3	L51	63.0	11.8	22.5	-0.01	68.2
Lokongoma 4	L52	45.7	7.3	55.9	0.15	59.6
Lokongoma 5	L53	66.8	14.4	57.3	0.94	81.8
Lokongoma 6	L54	44.5	7.6	33.0	-0.51	57.0
Lokongoma 7	L55	57.0	11.4	16.7	-1.47	59.3
Lokongoma 8	L56	45.9	5.3	28.4	0.10	62.8
Lokongoma 9	L57	66.4	9.9	40.8	-0.79	70.4
Lokongoma 10	L58	66.7	5.1	61.7	0.14	55.2
Lokongoma 11	L59	64.1	7.3	82.9	1.56	92.9
Otokiti 1	L60	41.5	6.0	65.8	0.28	52.5
Otokiti 2	L61	45.6	10.2	53.2	-3.02	49.9
Otokiti 3	L62	62.7	12.2	33.5	-1.90	63.6
Otokiti 4	L63	61.5	9.4	47.9	1.50	82.8
Filele 1	L64	47.7	7.2	34.1	-1.49	52.1
Filele 2	L65	58.9	3.3	22.3	0.00	85.8
Filele 3	L66	58.8	10.9	47.2	0.64	71.8
Filele 4	L67	49.6	5.5	32.2	-1.09	54.1
Filele 5	L68	69.2	14.6	21.2	-1.20	72.0
Lokoja 25	L69	78.4	17.9	28.9	-0.33	82.8

Table 4.26. Sodium percentage classification of groundwater

Range (%)	Class	Sample number		Percentage (%)	
		Dry	Wet	Dry	Wet
<20	Excellent	2	0	3.10	6.25
20-40	Good	27	34	41.54	53.13
40-60	Permissible	27	24	41.54	37.50
60-80	Doubtful	9	2	13.85	3.13
>80	Unsuitable	1	4	1.54	0

b) Sodium Adsorption Ratio (SAR): According to Jafar *et al.,* (2013), the sodium adsorption ratio expresses the extent to which irrigation water tends to affect cation-exchange reaction in the soil. There a risk as sodium, which replaced adsorbed calcium and magnesium in the soil, tend to damage the soil structure and cause it to become compact and impermeable. The estimated Sodium Adsorption Ratio (SAR) for the dry season samples ranged from 0.33 to 6.89 meq/L with an average of 1.77 meq/L while those of wet season varied from 3.29 to 29.05 meq/L with an average of 10.38 meq/L (Table 4.24 and 4.25). SAR value less than 10 indicates that the groundwater is suitable for irrigation while values greater than 10 meq/L are regarded as unsuitable for irrigation purpose (Mandel and Shiftan, 1991; Vasanthaviger *et al.,* 2010). SAR values for all the sixty-five samples collected during the dry season were less than 10 meq/L while twenty-three (23) samples during wet season representing 35.94 % were unsuitable for irrigation purpose as their values were greater 10 meq/L. As noted earlier, the increased weathering and dissolution processes during the wet season could be responsible for the higher SAR for wet season samples as expressed in equation 4.2.

A graphical classification based on Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) by the U.S. Salinity Laboratory (1954) is presented in Fig. 4.24 and Fig. 4.25. From the diagrams, the groundwater samples from the study area in both seasons fell in C1-S1 (low), C2-S1 (medium), C3-S1 (high) categories. The diagrams showed that eight samples fell within low salinity class, 46 samples were within medium salinity class and 11 samples fell within high salinity class during the dry season while 8 samples, 45 samples and 11 samples during the wet season fell within low, medium and high salinity categories respectively (Table 4.27).

c) Magnesium hazard (MH): Magnesium content of water is considered as one of the most important qualitative criteria in determining quality of water for irrigation. MH indicates the degree of damage to the soil structure caused by magnesium in irrigation water. A high level of magnesium is usually due to the presence of exchangeable sodium in irrigated soil. The high level of Mg^{2+} in groundwater leads to soil alkalinity and a large amount of water is adsorbed between magnesium and clay particles, which decrease the

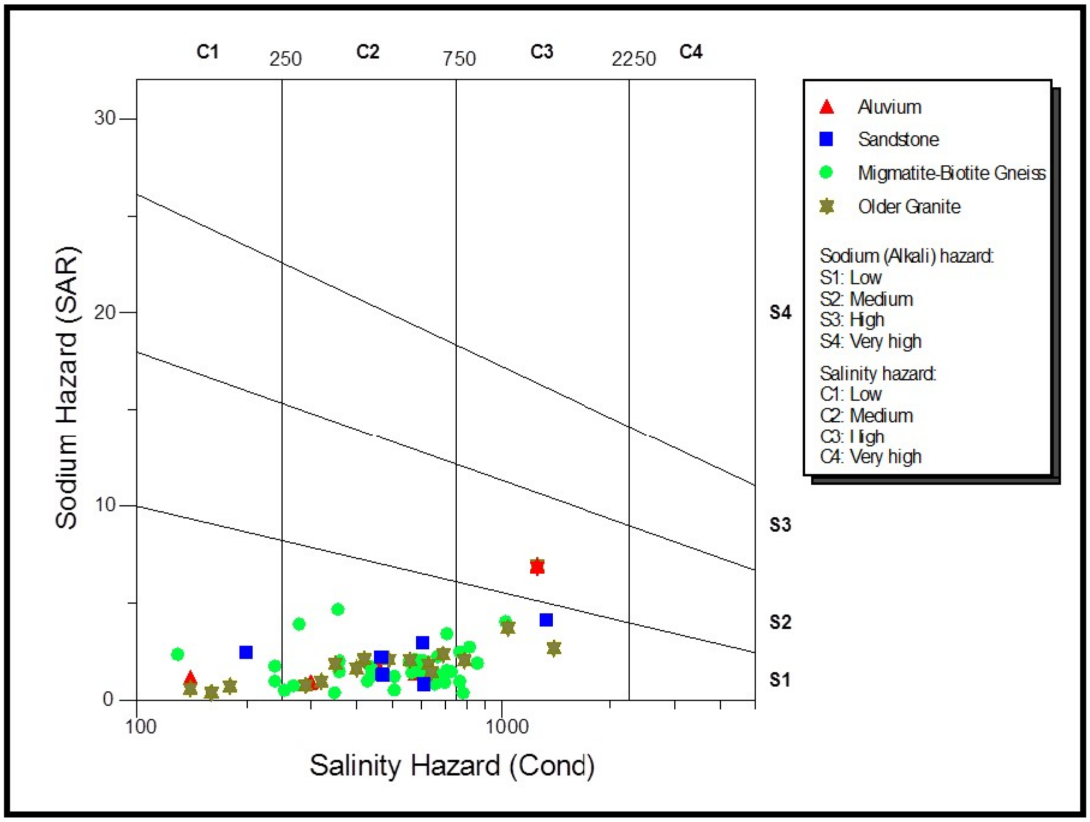

Fig. 4.24. Wilcox plot of groundwater samples (dry season)

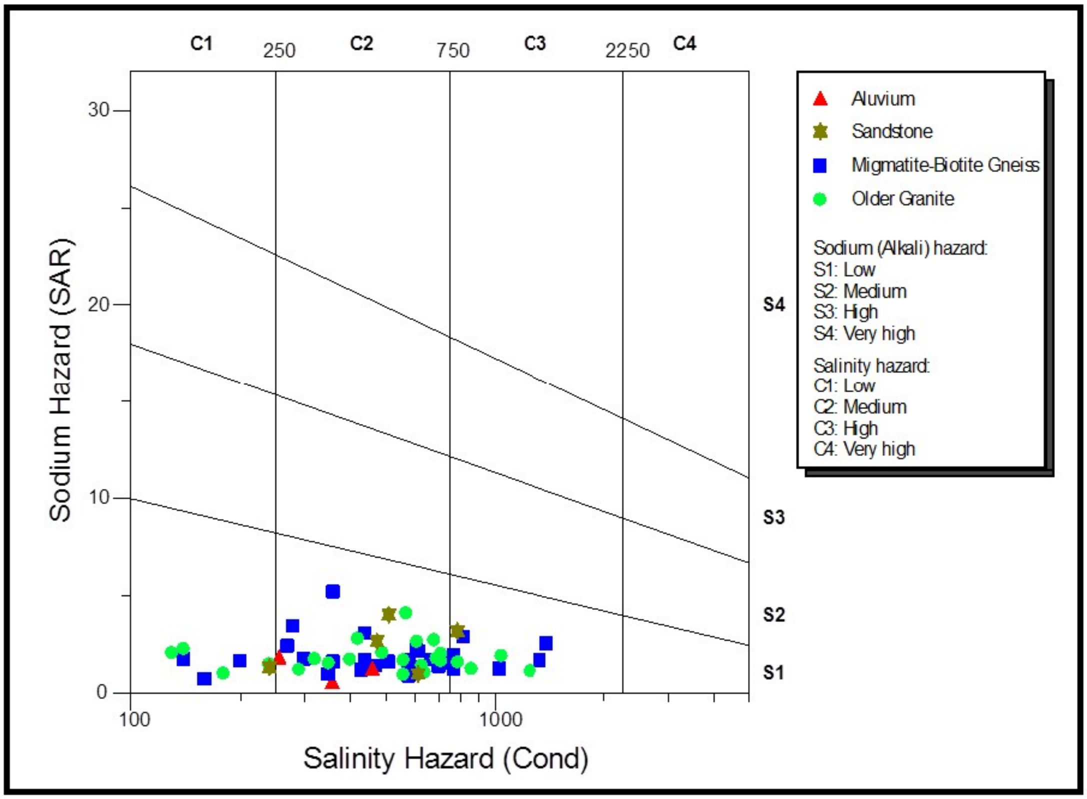

Fig. 4.25. Wilcox plot of groundwater samples (wet season)

Table 4.27. Sodium absorption ratio classification of groundwater

Category	Sample number		Percentage (%)	
	Dry	Wet	Dry	Wet
CI-S1	8	8	12.31	12.5
C2-S1	46	45	70.77	69.23
C3-S1	11	11	16.92	17.19

permeability of the soil, which has adverse effects on crops (Khalid, 2019). MH < 50 is suitable for irrigation while MH values > 50 are unsuitable for irrigation purposes (Kacmaz and Nakoman, 2010). The estimated magnesium hazard for groundwater in Lokoja area over the dry season ranged from 5.0 to 76.8 % with a mean of 25.4 % and 11.8 to 82.6 % with an average of 35.7 % during the wet season. The estimated magnesium hazard for dry season samples revealed that sixty-two samples representing 93.4 % of the total samples were suitable for irrigation and three samples (4.6 % of the total samples) from locations S67, S47 and S7 with MH > 50 % and were unsuitable for irrigation purposes because high magnesium in water reduce the soil permeability. In the wet season, 55 out 64 samples have MH <50 % and were suitable for irrigation while samples from locations L26, L32, L40, L49, L52, L58, L59, L60 and L61 with MH > 50 % and were unsuitable for irrigation purpose.

d) Residual Sodium Carbonate (RSC): RSC is an index used to determine the suitability of water for irrigation in soil with high capacity for cation exchange especially in clay soils. The prolong application of a certain water for irrigation will lead to an accumulation of sodium in the soil especially where the RSC of such water is high. A negative RSC indicates that sodium build-up is unlikely as sufficient calcium and magnesium exceed what can be precipitated as carbonates. A positive RSC indicates that sodium can build up in the soil. However, according to Richards (1954), RSC value < 1.24 meq/L is regarded as safe for irrigation, RSC between 1.25 and 2.5 meq/L is moderate, while RSC > 25 meq/L indicates water that is unsuitable for irrigation. Based on this criterion, sixty (60) samples of groundwater from the study area were regarded as safe for irrigation, five (5) as moderate and no sample as unsuitable for irrigation purposes during the dry season; for wet season, 58 samples were safe, five samples were moderate and one sample was unsuitable for irrigation (Table 4.28).

Table 4.28. RSC classification of groundwater

Range (meq/l)	Water class	Sample number		Percentage %	
		Dry	Wet	Dry	Wet
<1.25	Safe	60	58	92.3	90.6
1.25-2.5	Moderate	5	5	7.7	7.8
>2.5	Unsuitable	0	1	0.0	1.6

e) Permeability Index (PI): High concentrations of sodium as well as carbonate and bicarbonate in water affect the permeability of the soil (Ayuba *et al.,* 2013). Usually, a part of CO_3^- and HCO_3^- is precipitated from irrigation water as $CaCO_3$ or $MgCO_3$ removing Ca^{2+} and Mg^{2+} and results in increased proportion of salinity of the solution. The estimated PI for the groundwater from Lokoja and its environs ranged from 19.6 to 462.6 % with an average of 68.3 % during the dry season and 41.7 to 187.5 % with a mean of 67.3 % during the wet season. According to Doneen (1961), groundwater for irrigation purpose is excellent if PI > 75 %, good if PI is between 25 and 75 % and unsuitable if PI < 25 %. In this study, twelve (12) samples representing 18.5 % of the total samples were classified as excellent (PI >75 %), fifty-two (52) samples (80.0 %) as good (PI > 25 but < 75 %) and sample location S41 (1.5 %) as unsuitable (< 25 %) during the dry season. In the wet season, thirteen (13) samples representing (20.3 %) were classified as excellent (PI >75 %), fifty-one (51) samples (79.7 %) as good (PI >25 % but <75 %) while no sample was classified as unsuitable (PI <25 %) (Table 4.29).

4.10 Stable Isotope Analyses

Isotope hydrological methods have been employed over the year in various hydrogeological investigations especially in respect of groundwater age dating and characterisation of groundwater system in terms of source of recharge (Fritz and Fontes, 1980). Isotopes are atoms of the same element that have the same atomic number but different mass number. Hydrogen with an atomic number of 1 for instance has three isotopes, ${}_{1}^{1}H$, ${}_{1}^{2}H$ and ${}_{1}^{3}H$ respectively with a superscript mass of 1, 2, and 3. The first of these isotopes is stable, while the last ${}_{1}^{3}H$ generally written as ${}^{3}H$ radioactively decays to ${}_{2}^{3}He$. Radioactive decay is the process by which an unstable atomic nucleus loses energy by radiation. A material containing unstable nuclei is considered radioactive. Three of the most common types of decay are alpha decay, beta decay, and gamma decay, all of which involve emitting one or more particles. Radioactive decay is therefore one of the major processes involving isotope. Atoms of a particular isotope spontaneously change into a new, more stable isotope in radioactive decay and processes such as evaporation, condensation, or water/rock relationships alter isotope concentrations (Furi, 2011).

Table 4.29. Groundwater quality based on Permeability Index

Range %	Class	Sample number		Percentage %	
		Dry	Wet	Dry	Wet
>75	I (>75% permeability)	12	13	18.5	20.3
25-75	II (>25% but <75% permeability)	52	51	80.0	79.7
<25	III (<25% permeability)	1	0	1.5	0

These processes typically favour one of the isotopes of particular element over another, resulting in fractionation. Isotopes can be divided broadly into stable and radiogenic varieties. The stable isotopes are used mainly for tracing groundwater and climate reconstruction while the radiogenic isotopes are used to date groundwater. In the assessment of chemical processes, hydrogen, oxygen, carbon and sulfur isotopes are useful. Commonly, groundwater studies involve ^{2}H or D, ^{18}O ^{13}C and ^{34}S. Usually one isotope of an element typically dominates the others based on thee relative abundance depending on their respective atomic or mass number. Changes due to fractionation are therefore too low to be correctly measured, requiring isotope abundances to be reported as a positive or negative deviation away from a standard isotope ratio. This assertion is depicted in Fritz and Fontes (1980) general equations.

$$\delta = \frac{R_{sample} - R_{s\tan dard}}{R_{s\tan dard}} \times 100$$

Where δ, reported as permil (‰) represent the deviation from the standard and *R* is the particular isotope ratio (e.g ^{18}O/^{16}O) for the sample and the standard. For example, sulphur –isotope ratio is express as

$$\delta^{34}{}_{sample} = \frac{(^{34}S/^{32}S)_{sample} - (^{34}S/^{32}S)_{s\tan dard}}{(^{34}S/^{32}S)_{s\tan dard}}$$

A δ^{34}S value of – 20‰ means that the sample is depleted in ^{34}S by 20%.

Deuterium and oxygen–18 composition of water are usually measured with respect to the V-SMOW (Vienna Standard Mean Ocean Water) standard (Fritz and Fontes, 1980). This choice of standard is particularly appropriate because precipitation that recharge groundwater originated from the evaporation of ocean water. However, the isotope composition of rain or snow in most areas is not the same as ocean water. Evaporation and subsequent cycle of condensation significantly charge the isotopic composition of water vapour in the atmosphere. Variation in stable isotope of ^{18}O and D along the meteoric water line in groundwater examines situations where the isotopic composition of groundwater falls along the meteoric water line. However, shallow groundwater has an isotopic composition that is similar to the precipitation assuming that no processes are operating to change the isotopic composition of the precipitation once it recharges the groundwater. A groundwater system is more complicated than atmospheric system. The reason is that the flow system can contain meteoric water that recharged groundwater thousands even tens of thousands years ago. In effect, the groundwater system can be an archive for information on the isotopic composition of precipitation through time. Also, low permeability unit could contain the original water of formation when the unit was deposited, with a climate much different than the present one (Bradbury, 1984, Desaulnier*,* 1981, Hendry and Wassenaar, 1999, Remenda*,* 1994).

Fractionation processes normally result in lighter isotope molecules favoring the less dense phase and the heavier molecules favoring the denser phase. Lighter isotopic molecules of water have a higher zero-point energy, therefore requiring less energy input for phase change from liquid to vapor than that of heavier water. In addition, during evaporation the water molecule with the least significant energy barrier for phase change will preferentially evaporate, resulting in residual water that becomes progressively heavier or enriched in $\delta^{18}O$ and $\delta^{2}H$. Similarly, the heavy isotopes of water are the first to fall as rain, resulting in water vapor masses that become progressively lighter as one moves inland (continental effect) from a water source or to a higher elevation (Orographic rainout effect). Other factors that can influence the fractionation of $\delta^{18}O$/ $\delta^{16}O$ and $\delta^{2}H$/ $\delta^{1}H$ generally include temperature, diffusion, and the kinetic effects of humidity (Clark and Fritz, 1997). However, deviation in ^{18}O and D away from the meteoric water line from plotting $\delta^{18}O$ and δD data for water samples with reference to the meteoric water line provides the framework for identifying the isotope processes that are at work. When water resides in a lake or pond, or even river for a long time under evaporative conditions, the isotopic composition of the water can change. Overall, there is enrichment in the heavier isotopes because the lake or pond is a finite reserviour. The dynamics of the evaporation process causes the isotopic composition of the lake or pond to follow an evaporation line, with a slope ranging from one to five depending on the local rates of evaporation (Fritz and Fontes, 1980).

Usually the point of intersection between the evaporation line and the meteoric water line is taken as the unaltered precipitation isotopic composition. Generally, the farther along the evaporation line the data points lie, the greater the evaporation. In deep, basinal flow systems and in geothermal systems, the isotope exchange between minerals and groundwater is essential. The comparatively high temperature allows for the exchange of oxygen and hydrogen among phases as well as achieving equilibrium distribution. The fractionation factor for the mineral describes this equilibrium. Savin (1980) summarised fractionation variables for various minerals and explained how they alter as a function of temperature and the exchange of meteoric water with oxygen-containing minerals results in the type of deviation. The sample typically falls along a horizontal line, reflecting an oxygen shift away from the meteoric water line, because only ^{18}O is involved in exchange. The size of the oxygen shift is in proportion to the original $^{18}\delta O$ difference between water and rock, temperature and contact time and, in reverse, the water/rock ratio (Truesedell and Hulston, 1980).

4.10.1 Results of $\delta^{18}O$ and δD Isotopes

In this present study, a total number of thirty-nine (39) groundwater samples for stable isotope analyses were collected. The results of the analyses (Table 4.32) showed variations ranging between -3.9 and -1.2 ‰ with an average of -2.7 ‰ for $\delta^{18}O$ and -23.9 and -11.7 ‰ with a mean of -16.9 ‰ for δ^2H. The plot of δD against $\delta^{18}O$ data for water samples provided the framework for identifying the isotope processes that were at work in the study area. Diversity of processes such as evaporation from open surfaces or shallow groundwater system, exchange with rock mineral, H_2S exchange, silicate hydration, CO_2 and condensation leads to deviations in the isotopic compositions away from meteor water line either by enriching or depleting isotopic compostion of the groundwater. Consequently, negative values of $\delta\ ^{18}O$ and δD indicate depletion of the samples relative to $\delta\ ^{18}O$ and δD as compared to SMOW (Standard Mean Ocean Water) standard while positive values imply enrichment of the samples relative to the standard (Craig, 1961). However, all groundwater samples plotted deviated from Global GMWL except a sample (L69) from sandstone bedrock that was plotted along the line (Fig. 4.26) applying this equation: $\delta D = 8\delta^{18}O + 10$. The plot of δD versus $\delta^{18}O$ shows that most of the groundwater samples were plotted on the right side of the meteoric water line and with the slope of 5.3, it is an indication of groundwater that have undergone evaporation.

Table 4.30. Results of stable isotopes of groundwater from Lokoja area

ID	18O	D	d-excess
2B	-3.9	-22.4	8.8
4B	-3.4	-21.2	5.8
6B	-2.3	-19.3	-1.1
8B	-1.9	-21.6	-6.3
11B	-2.1	-15.4	1.1
14B	-2.1	-12.5	4.7
16B	-3.6	-12.9	16.2
18B	-2.3	-16.2	2.3
19B	-2.2	-14.0	3.4
20B	-3.8	-17.1	13.3
22B	-1.4	-11.8	-0.4
23B	-2.8	-17.3	4.7
25B	-2.1	-16.0	0.4
27B	-1.5	-16.5	-4.1
28B	-3.2	-18.3	7.5
30B	-3.5	-14.7	13.0
31B	-1.7	-16.0	-2.4
33B	-2.1	-15.2	1.6
36B	-1.2	-15.6	-6.1
37B	-2.9	-18.5	4.3
39B	-2.2	-16.6	1.4
40B	-3.7	-23.9	6.1
42B	-2.7	-17.9	3.8
43B	-3.1	-21.2	3.7
45B	-2.2	-16.4	1.3
46B	-2.6	-18.5	2.7
48B	-2.4	-18.1	1.1
49B	-3.5	-23.0	5.1
50B	-1.8	-16.9	-2.4
52B	-2.9	-17.5	5.6
53B	-2.9	-18.4	5.1
55B	-3.0	-17.5	6.7
57B	-3.1	-20.0	4.6
59B	-3.5	-14.8	13.5
61B	-2.6	-14.5	6.3
62B	-2.2	-11.7	6.3
63B	-3.2	-12.5	13.0
66B	-3.5	-14.8	13.1
69B	-3.0	-13.2	10.6
MIN	-3.9	-23.9	-6.3
MAX	-1.2	-11.7	16.2
MEAN	-2.7	-16.9	4.5

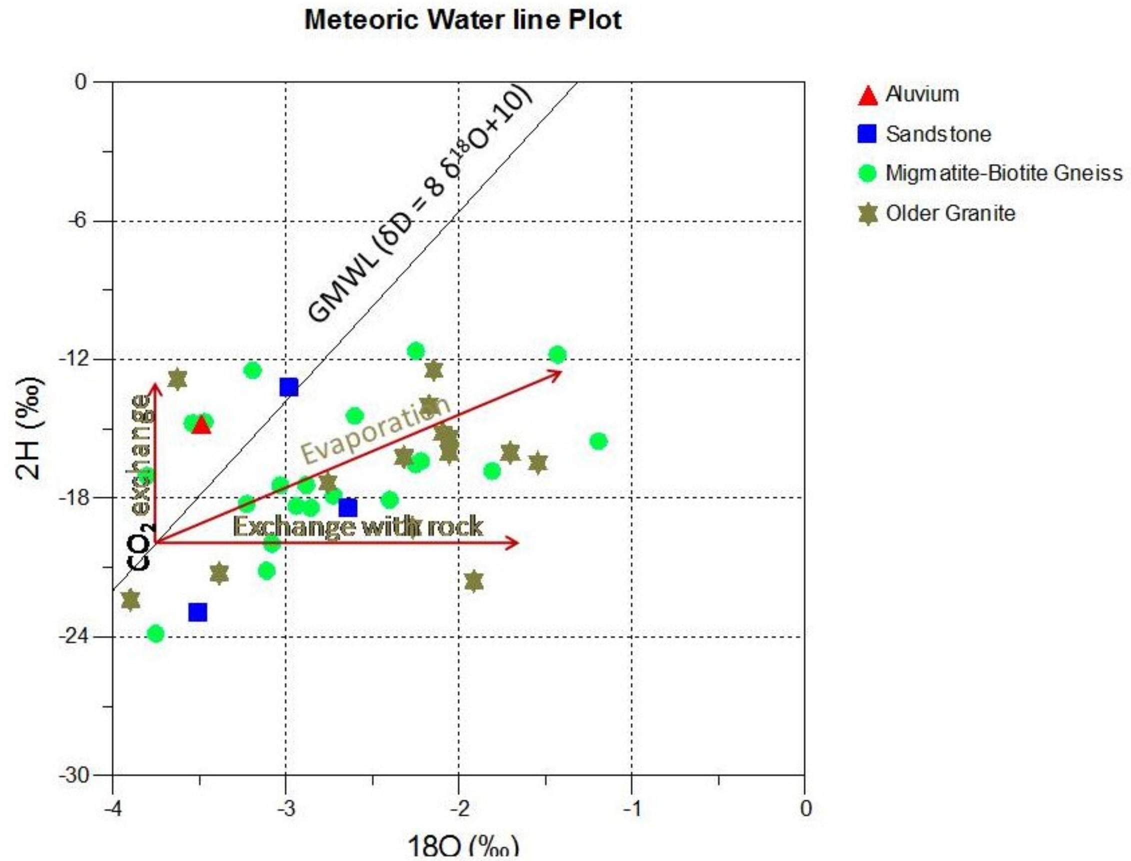

Fig. 4.26. Plot of δ ^{2}H vs. δ ^{18}O of groundwater samples

The groundwater that have undergone evaporation usually display systematic enrichment in stable isotopes, resulting in divergence from the GMWL along evaporation lines that have slopes of between 4 and 6 (Clarke and Fritz, 1997; IAEA, 2007a and b). The plot also indicated a predominantly recent precipitation source of recharge (Tijani and Abimbola, 2003) with isotope enrichment possibly because of intense kinetic evaporative effect as well as rock-water interaction and carbondioxide exchange effects. The high ambient temperature in the study area was though to favour evaporation thereby considerably modifying isotopic composition of groundwater from that of local precipitation due to the strong isotopic enrichment in water. The point of intersection of the evaporation line with the meteoric water line usually is taken as the isotopic composition of unaltered precipitation. In general, the farther along the evaporation line the data point lie, the greater the evaporation (Shwartz and Zhang, 2003).

Furthermore, the positive correlation between Electrical Conductivity (EC) and $\delta^{18}O$ indicated groundwater undergoing evaporation (Gibrilla *et al.,* 2010). The plot of EC versus $\delta^{18}O$ (Fig. 4.27) of data of groundwater samples from the study area showed positive correlation coefficient (r = 0.45) which corroborate the earlier assertion that the majority of the samples plotted on the right hand side of GMWL, an indication of evaporation prior to recharge or kinetic interaction with the subsurface medium (Giggenbach, 1990). In sample group I, EC range of between 400 and 1,000 µS/cm and $\delta^{18}O$ of -3.9 and -1.2 ‰ indicated moderate mineralisation accompanied with minimal variation of $\delta^{18}O$. Samples with EC > 1,000 indicate effects evaporation with mineralization accompany enrichment of $\delta^{18}O$ (‰) as shown by sample group II. The infiltration of precipitation water through the unsaturated zone and the lateral flow from surrounding areas influence the nitrate concentration of groundwater (Akiti, 1986). The recharge to aquifer system in the study area has been established to come from precipitation and therefore, some forms of correlation should exist between $\delta^{18}O$ and NO_3^- contents of groundwater depending on the infiltration/recharge characteristics and the rate of evaporation of water on land surface.

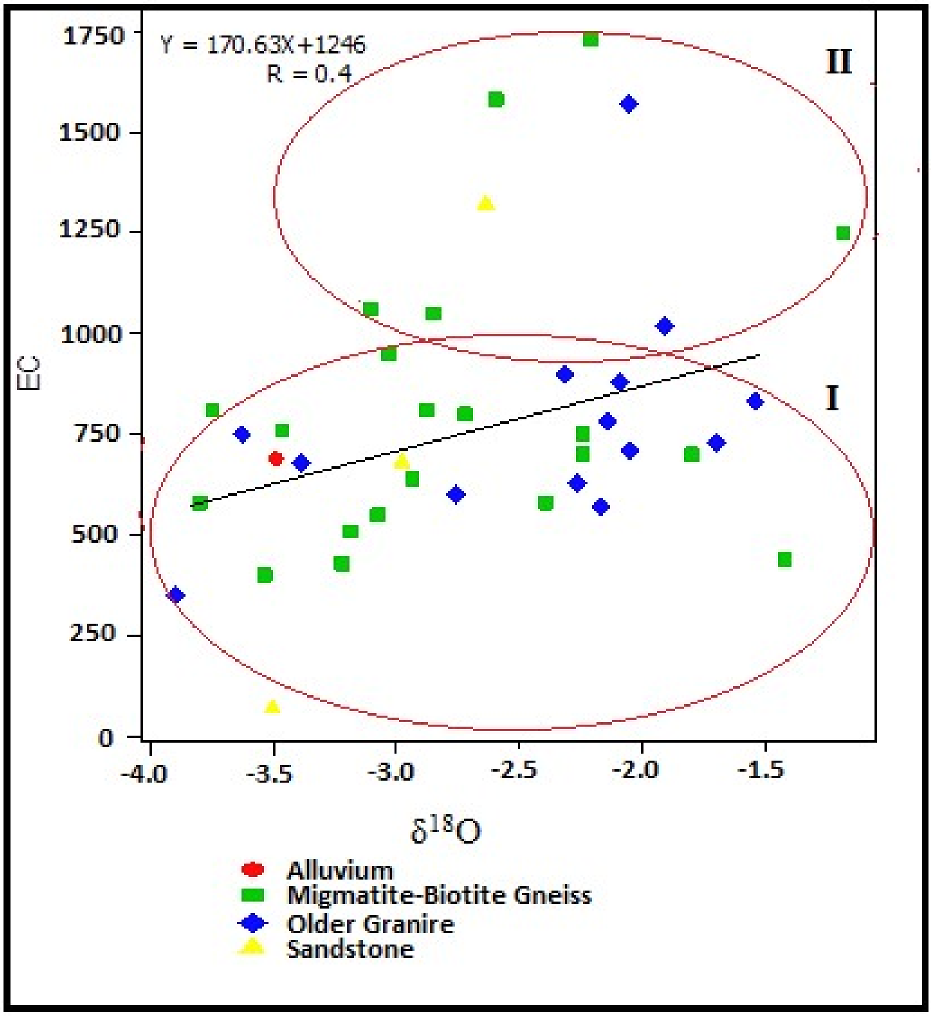

Fig. 4.27. Plot of EC vs $\delta^{18}O$ of groundwater samples

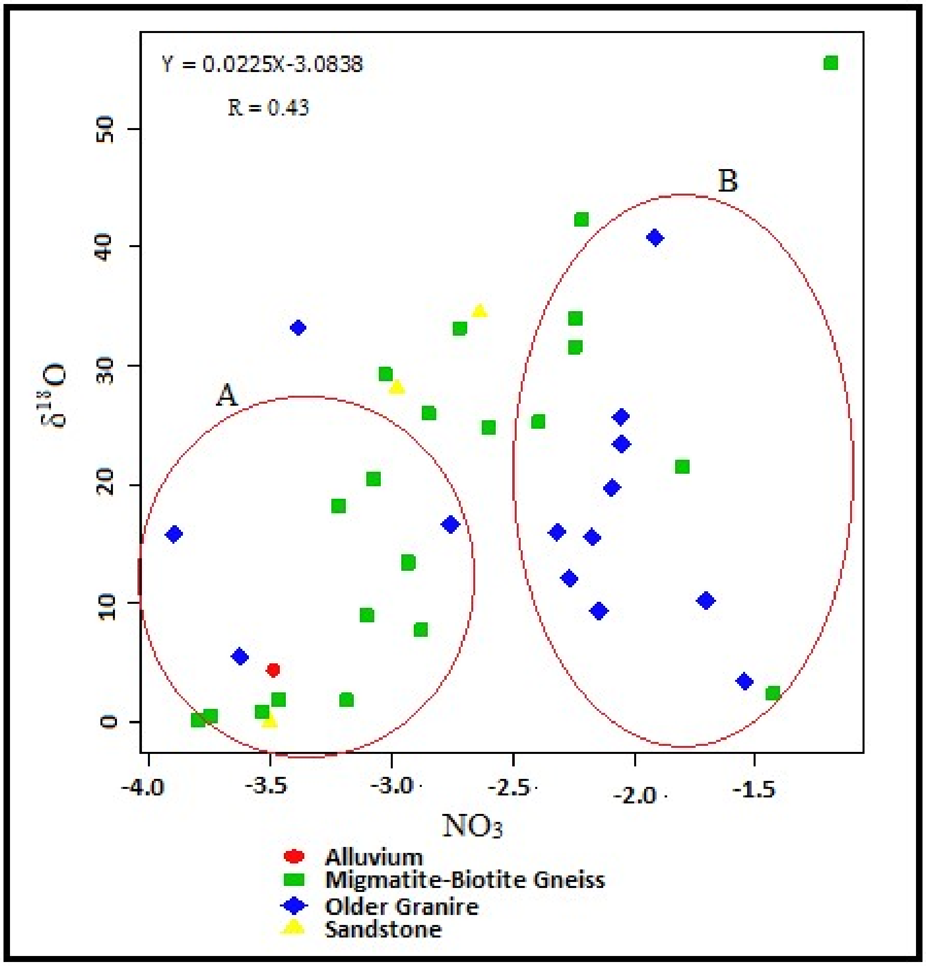

Fig. 4.28. Plot of $\delta^{18}O$ vs. NO_3 of groundwater samples

The plot of $\delta^{18}O$ and NO_3^- (Fig. 4.28) of shallow groundwater samples from the study area shows a week positive correlation coefficient of 0.43. The samples in circle A indicate low nitrate groundwater associated with depleted $\delta^{18}O$ signifying anaerobic conditions at deeper relatively deeper level in the aquifer. Whereas, in circle B, relatively high concentration of nitrate accompanied enriched $\delta^{18}O$, indicating that some wells were recharged by appreciable amount of evaporated rainwater infiltrating through contaminated soil and picking along nitrate salts to the groundwater system (Datta et al., 1997).

According to Gibrilla et al., 2010, stable isotopes can give an independent variable which can help in identification of mechanism of salinisation. There are two types of mechanism of salinisation; a salinisation arising from leaching of salts which is not accompanied by changes in stable isotope composition of the leaching water and, salinisation as a result of evaporation is accompanied by increase in stable isotope composition i.e. isotope enrichment enrichment. A plot of Cl and $\delta^{18}O$ (Fig. 4.29) of groundwater samples from Lokoja area shows two types of water; the first tytpe is groundwater in which dissolution of soluble salts leads to salinisation and increase in chloride concentration does not correspond with enrichment of $\delta^{18}O$. The second type is groundwater affected by evaporation and increase in chloride concentration corresponds with a gradual increase in $\delta^{18}O$ composition. In addition, a plot of Cl and $\delta^{18}O$ showed two water types, the first groundwater type are samples plotted at $Cl^- > 140$ mg/L in which mild leaching of salts lead to increase salinisation of groundwater. The second water type are samples with chloride content < 100 mg/L showed a linear correlation between Cl and $\delta^{18}O$ values which suggested little leaching of salts hence low salinisation.

4.10.2 Deuterium-Excess

Deuterium-excess (d-excess) a measure of the relative proportions of D or ^2H and ^{18}O in the water, which according to Dansgaard (1964) is described using $d = \delta^2H - 8\delta^{18}O$ equation. An excess of deuterium relative to ^{18}O in vapor (d-excess) occurs when water molecules diffuse across a density gradient during evaporation.

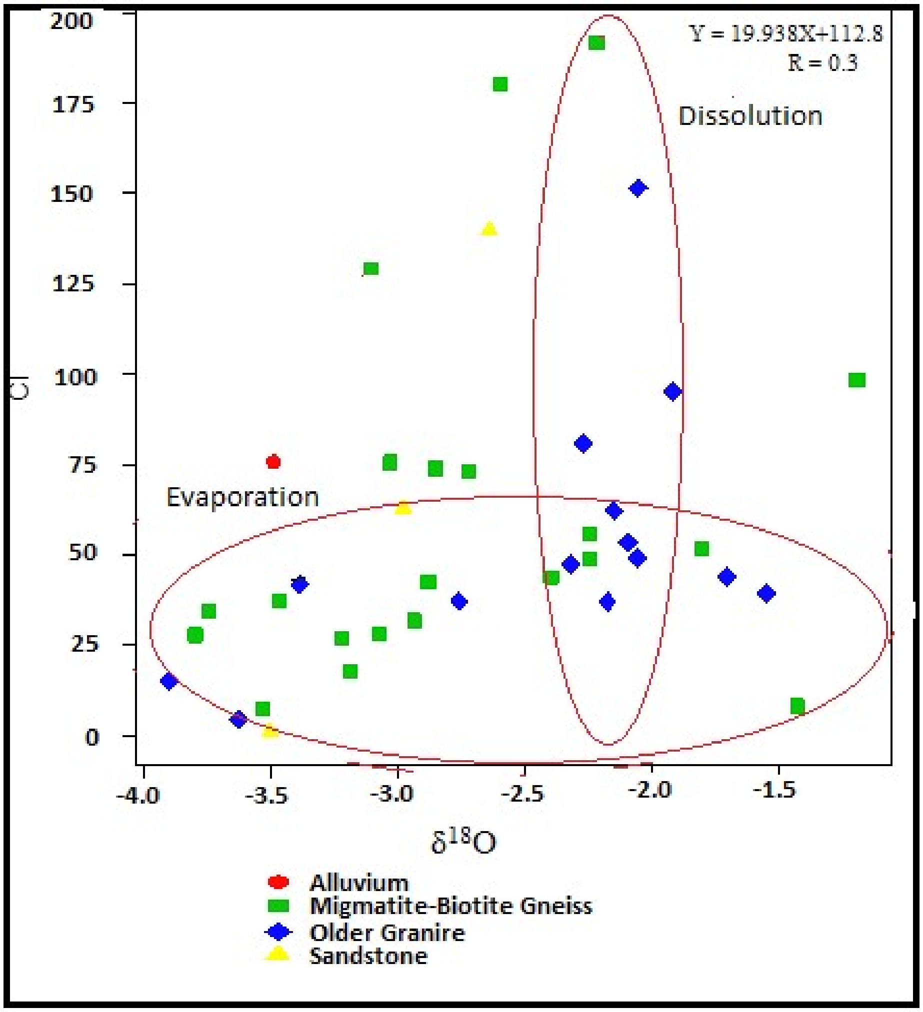

Fig. 4.29. Plot of Cl vs. δ^{18}O of groundwater samples

A difference in the weight of a water molecule that contains deuterium compared to heavy oxygen results in more diffusive fractionation of heavy oxygen during evaporation (Bershaw, 2018). The more diffusion (kinetic fractionation) that occurs, the higher the deuterium excess observed in vapor (evaporated moisture). Deuterium-excess has shown to be a useful parameter to trace the effect of evaporation in modifying the isotopic characteristics of rainwater prior to groundwater recharge. It is an index of deviation from global meteoric water line, in which the value is usually close 10 ‰ for meteoric waters on a global scale. In this study, the estimated d-excess of groundwater samples ranged between -6.3 and 16.2 ‰ with an average of 4.5 ‰. It was observed from Fig. 4.20 that the enrichment of $\delta^{18}O$ resulted in gradual increase of d-excess hence an indication of evaporative effects on the groundwater system. The negative d-excess values recorded in sample 6B (-1.1), 8B 9-6.3), 22B (-0.4), 27B (-4.1), 31B (-2.4) and 26b (-6.1) were as a result of partial evaporation of the samples, either as the precipitation falls from the cloud or during storage (Allison and Hughes, 1983). However, the significant variation occurred in the d-excess values in this study and this can be attributed to evaporation from unsaturated zone during recharge.

4.11 Synthesis

Lokoja area is the Basement complex–sedimentary transition zone where both crystalline and sedimentary rocks are represented. The sedimentary portion consists of Quaternary-Recent River Alluvium and Cretaceous false-bedded sandstone. The false-bedded sandstone formation consists of medium to fine grained poorly sorted invariably pebbly, white to yellow-brown conspicuously planner tubular cross bedded sandstone (Hockey and Sachi, 1986). The basement complex comprises mainly granite and gneisses. The coarsely porphyritic granite with biotite and hornblende generally form the major ferromagnesian minerals. The gneisses have relatively regular banding as a result of the mineral segregation in which light bands alternate mainly with dark bands. The thickness of individual banding in gneiss varies from a few mm to several centimeters.

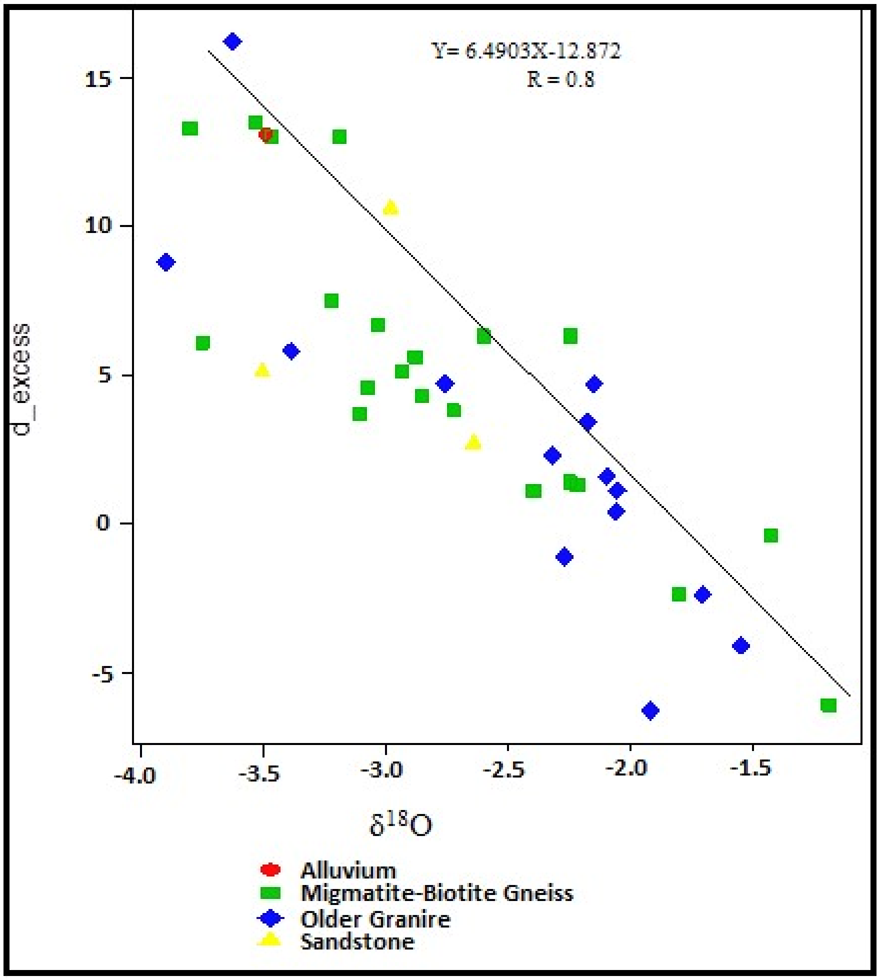

Fig. 4.30. Plot of d-excess vs. δ^{18}O of groundwater samples

Factors such as the geology and climate control the groundwater occurrence in the basement part of the study area. This is because geological formations underlying a particular area and the structures contained in them determine the kinds of aquifer to be found and how the aquifers are recharged while the climate determines the quantity and rate of recharge of the aquifer. In sedimentary rocks, factors controlling aquifer porosity, permeability, and specific yield include particle size, particle distribution, particle shape, and particle cementation state. Highly angular and rounded particles generally produce high values, while subangular particles tend to be compacted and offer very poor values of porosity and permeability. In addition, several variables control groundwater chemistry and quality. These variables include the geological environment through which water flows, groundwater flow rate, groundwater source, and anthropogenic activities. Lithology, nature of geochemical interactions and solubility of interacting rocks usually govern the concentration of dissolved ions in groundwater (Nosrat and Asghar 2010). Processes like cation-anion exchange and mixing can also affect groundwater chemistry considerably (Tijani and Abimbola, 2003).

The results of petrographical, physico-chemical and stable isotopes analyses were linked to generate a model in order to determine the physico-chemical (temperature, pH, EC and TDS, Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}, and anions: HCO_3^{-}, $NO3^{-}$ Cl^{-} and SO_4^{2-}); trace elements (As, Fe, Mn, Pb, Zn, Cr and Cd) and stable isotope (Deuterium or ^{2}H and ^{18}O) characteristics of groundwater in the study area. This model is discussed in the perspectives of occurrence and chemistry of groundwater in Lokoja area based on the parameters outlined above. Groundwater forms one part of a hydrological cycle known as the earth's circulatory water system. This starts with water evaporation from the ocean's surface. When the humid air is raised, it cools and condenses water vapor into clouds. Moisture is carried around the world as a rainfall (meteoric water) until its return to the ground. Once the water hits the ground, a portion evaporates into the atmosphere, some may be intercepted by vegetation and then evaporated from the surface of the leave, some infiltrate into the ground to form groundwater and the remainder flows directly as surface runoff to streams/rivers which in turn reaches the ocean. Groundwater originates from other sources which include connate, juvenile, geothermal and magmatic origins. In the study area, the groundwater originates mainly from precipitation (meteorite water) which recharges the aquifer. This CO_2 charged precipitation produces weak acid that will eventually dissociated into hydrogen ion and bicarbonate ion as expressed in the following equations:

$$CO_2(g) + H_2O \longrightarrow H_2CO_3(aq)$$

$$H_2CO_3(aq) \longrightarrow H^+(aq) + HCO_3^-(aq)$$

The CO_2 precipitation permeate into the ground which strongly react with rock minerals (especially plagioclase and microcline in older granite and migmatite-biotite gneiss) as determined from petrographical analysis to give rise to groundwater that contains the major ions and many other trace ions in groundwater. Some examples are expressed in the following equations:

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3$$

$$2NaAlSi_3O_8 + 2CO_2 + 3H_2O \leftrightarrow 4SiO_2(OH)_4 + 2Na^+ + 2HCO_3^-$$

Mechanisms and processes such as rock-water interaction, ion exchange and reverse ion exchange were also responsible for groundwater hydrochemistry in the study area. An examination of the relationships between the cations and anions suggests that these mechanisms or processes were responsible for groundwater hydrochemical profile.

Furthermore, the hydrochemical facies such as $Ca^{2+}(Mg^{2+}) - HCO_3^-$, $Na^+(K^+) - Cl^- - SO_4^{2-}$, $Ca^{2+}(Mg^{2+}) - Cl^- - SO_4^{2-}$ and $Na^+(K^+) - HCO_3^-$ were delineated in Lokoja area and were the products of all the mechanisms and processes mentioned above. In addition, human activities such as lack of proper domestic, municipal and industrial waste disposal system, poor hygiene practice such as building of septic tanks and pit latrines close to water wells and application of chemical fertilizer and manure in agriculture are some of the factors responsible for the alteration of groundwater chemistry in Lokoja area. Stable isotope finger print indicated recent precipitation as source of recharge with isotope enrichment possibly because of intense kinetic evaporative effect. The recent precipitation as source of recharge from isotope fingerprint suggested groundwater system with limited migratory histoy. The overall mechanisms and processes affecting groundwater quality is presented in Fig. 4.31.

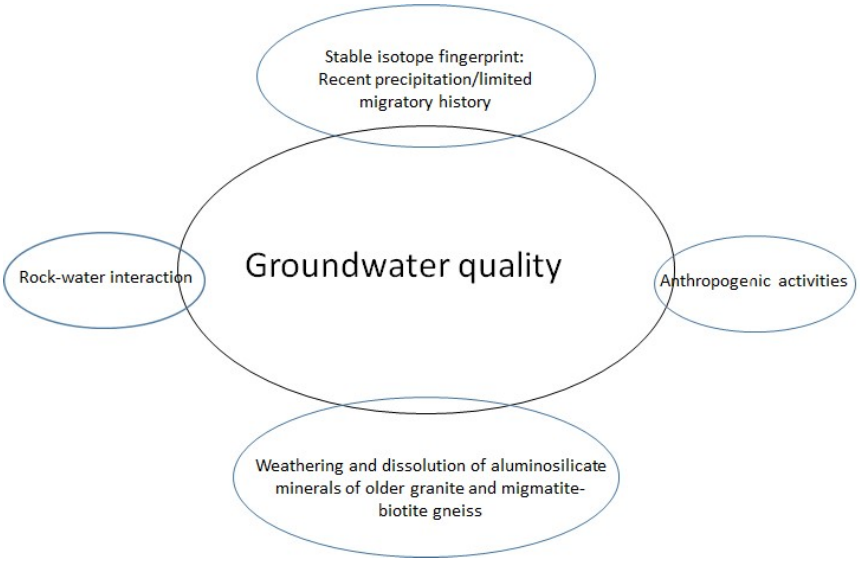

Fig. 4.31. Processes affecting groundwater chemistry in the study area

CHAPTER FIVE

5.0 SUMMARY AND CONCLUSION

5.1 Summary

This research work, hydrochemical evaluation and stable isotopes studies of groundwater in Lokoja area were undertaken to investigate the shallow groundwater system as relate to its chemistry and source of recharge. Several approaches were employed to achieve the objectives of this work. They are; geological mapping with emphasis on rock types, boundaries between rock types and the composition of the rocks; hydrochemical studies involving well inventory, in situ measurements and laboratory analyses of shallow groundwater samples for physico-chemical parameters and trace elements. In addition, stable isotopes studies involving laboratory determination of deuterium and oxygen-18 to establish source of recharge and the processes that act to alter the isotopic composition of recharge water. From the field geological mapping, four major rock types including alluvium, sandstone, migmatite-biotite gneiss and older granite were mapped with migmatite-biotite gneiss the most dominant rock. Well inventory showed that the depth to water level (DWL) varied from 0.5 to 10.1 m with an average of 3.21 m, total depth of well (TDW) varied from 3.0 to 10.5 m and saturated water column (SWC) ranged between 0.5 to 4.2 m.

Physico-chemical investigations indicated that the groundwater samples from the study area were mostly neutral with few samples slightly acidic and slightly alkaline. The hardness classification of groundwater revealed that the samples was mostly classified 'moderately hard' and 'hard' with few samples classified as 'soft' and 'very hard'. The Total Dissolved Solids (TDS) classification revealed 'soft water' except very few samples that were determined to be 'slightly saline water'. The TDS values were generally low (<1000 mg/L) and this is an indication of low to moderate mineralised groundwater system accompanied by limited migratory history and moderate rock-water interaction. Hydrochemical studies of groundwater samples showed that the composition of groundwater in Lokoja area was considerably influenced by weathering and dissolution of underlying igneous and metamorphic rocks. However, weathering and dissolution in sedimentary portions of the area were found to have little or no influence on groundwater chemistry because the compositions of the rocks are predominantly quartz and sandy materials which can not easily weathered. The results of hydrochemical analyses of sixty-five (65) samples in dry and sixty-four (64) samples in wet season using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Emission Optical Spectrometry (ICP-ES) showed that the order of concentration of major cations were $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ for both seasons. Na^{2+} accounted for 49.91 % of the major cations, Ca^{2+} for 37.69 % and Mg^{2+} and K^+ accounts for 14.12% and 12.92% respectively. The order of major anions concentration was $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$, representing 87.03 %, 41.59 %, 22.99 % and 17.44 % respectively.

Hydrochemistry based on rock types showed that the concentrations of Ca^{2+} Mg^{2+} and Na^+ were relatively higher in migmatite-biotite gneiss and older granite rock units than those in alluvium and sandstone. This is because of dissolution and leaching of aluminosilicate minerals in the basement rock by CO_2 charged precipitation infilttrating these rock units. However, the order of abundance of cations were $Ca^{2+} > Na^+ > K^+ > Mg^{2+}$ in samples from alluvium, $Na^+ > Ca^{2+} > > K^+ > Mg^{2+}$ in samples from sandstone, $Na^{2+} > Ca^{2+} > Mg^{2+}$ K^+ in samples from migmatite-biotite gneiss and $Na^{2+} > Ca^{2+} > Mg^{2+}$ K^+ in samples from older granite for dry season and $Na^{2+} > Ca^{2+} > Mg^{2+}$ K^+ in samples from alluvium, $Na^{2+} > Ca^{2+} > K^+ > Mg^{2+}$ in samples from sandstone, $Na^{2+} > Ca^{2+} > Mg^{2+}$ K^+ in samples from migmatite-biotite gneiss and $Na^{2+} > Ca^{2+} > Mg^{2+}$ K^+ in samples from older granite during the wet season. HCO_3^- was the dominant among the major anions in all the rock units and this dominance could be as result of CO_2 charged precipitation water that is recharging the aquifer in the area while NO_3^- values were generally low across all the rock units indicating little or no effects of agricultural and anthropogenic wastes on groundwater system.

Statistical evaluation of the physiochemical data showed that Ca^{2+}, Cl^-, Electrical Conductivity (EC), Mg^{2+} and Na^+ appeared as the major contributor of the groundwater dissolved constituents because they positively correlated with Total Dissolved Solids (TDS). Calcium and magnesium were positively correlated with each other and this suggested that the hardness of the groundwater was mainly as a result of calcium and magnesium. For the Principal Component Analysis (PCA), 12 variables (parameter) in 65 and 64 groundwater samples for dry and wet season respectively were used and extracted were 4 principal component (PCs) which tested 70.54% (dry season) and 88.29% (wet season) of the total variance. PC1 for dry season which explained 41.06% of the total sample variances had a loading for $Ca^{2+,}$ Cl^-, EC, K^+, Na^+ and TDS while PC1 for wet season explained 54.17% and had loading for all the parameters. Groundwater quality assessment in Lokoja area revealed that the water quality for drinking purpose is suitable as compared with World Health Organisation (WHO, 2016) standards though few samples exceeded the minimum permissible limits. Majority of the samples based on the water quality index (WQI) had excellent and good water quality categories respectively and poor water quality category especially in the eastern part of Lokoja which is a reflection of poor hygienic practice in this populated area, hence the anthropogenic contamination.

Water quality assessment for irrigation purposes indicated that most samples fall in the "good and permissible" category for irrigation quality on the basis of sodium percentage (% Na^+) and Sodium Adsorption Ratio (SAR), the salinity of water is primarily medium but few fall in low and high fields in Wilcox diagram. Magnesium hazard evaluation indicated the water were mostly suitable for irrigation while the groundwater samples were mostly unsuitable based on Residual sodium carbonate, whereas, majority of the samples had permeability index of <75 % indicating suitability for irrigation. The major hydrochemical facies delineated using Piper diagrams are Ca^{2+} (Mg^{2+}) - HCO_3^-, Na^+ (K^+) – HCO_3^-, Ca^{2+} (Mg^{2+}) – Cl^- – SO_4^{2-} and Na^+ (K^+) – Cl^- – SO_4^{2-} water types. Bivariate plots of Ca^{2+} + Mg^{2+} versus HCO_3^- + SO_4^{2-} showed that 45 (69.2 %) and 34 (53.1 %) for dry and wet season respectively of the samples were clustered below the 1:1 equiline representing reverse exchange while 20 (30.8 %) and 30 (46.9 %) for dry and wet seasons respectively of the samples clustered above the line towards ion exchange process. The plot of Ca^{2+} versus HCO_3^- indicated that in the case of carbonate, the common weathering reaction is simple dissolution, giving the ratio of 1.3 and 1.6 in dry and wet season respectively of Ca:HCO_3^-. The Ca:HCO_3^- high molar ratio (> 0.5) measured in groundwater suggested reverse ion exchange source for Ca^{2+} and Mg^{2+}, which is observed with an increase in salinity in hard rock formations. The ratio between $Na^+ + K^+$ and total cations (TZ) was used to estimate silicate weathering. For dry and wet seasons, the majority of the samples were plotted close to the equiline and Na^++K^+:TZ ratio of 0.5 indicates the involvement of silicate weathering in geochemical processes, which mainly contributes sodium and potassium ions to groundwater. Durov diagrams indicated that three processes influence the chemistry of groundwater in Lokoja area and these include, ion exchange processes, reverse ion exchange and simple dissolution or mixing.

The results of the stable isotope analyses showed variations ranging between -3.9 and -1.2 ‰ with an average of -2.7 ‰ for $\delta^{18}O$ and -23.9 and 11.7 ‰ with a mean of 16.9 ‰ for δ^2H. The plot of deuterium versus oxygen-18 of groundwater system of Lokoja area showed that the samples were mostly to the right hand side of Global Meteoritic Water Line (GMWL) indicating recent meteoritic recharge with effects of kinetic evaporation.

5.3 Conclusion

Petrographical analysis of samples from major rock units i.e. migmatite-biotite gneiss, granite, sandstone revealed dominance of quartz, microcline, plagioclase and biotite as major minerals in the rocks. Physico-chemical data from this study revealed that the groundwater was generally neutral but a few samples were slightly acidic and some alkaline. The TDS concenrations of groundwater samples were mostly low (<1,000 mg/L), and this is an evidence of water with restricted migration history and water/rocks interactions, with low to moderate mineralisation. Water classification based on hardness indicated that the water in Lokoja area was 'moderately hard' and 'hard'. Based on rock types, Ca^{2+}, Mg^{2+} and Na^+ show relatively higher concentrations in migmatite-biotite gneiss and older granite rock units than those in alluvium and sandstone. HCO_3^- is the dominant among the major anions in all the rock units and this dominance could be as result of CO_2 charged precipitation that recharges the aquifer in Lokoja area while NO_3^- values were generally low in the samples across all the rock units indicating little effects of agricultural and anthropogenic waste on groundwater system. Though, few samples with NO_3^- concentrations > 50 mg/L were consequence of anthropogenic pollution. Generally, hydrochemical studies from all the methods of data evaluation indicated that groundwater in Lokoja area was generally 'good' (barring few samples) in terms of potability of the water. The generally good quality of the water is an indication of low to moderate mineralised with limited migration history and water-rock interaction, and little influence of anthropogenic contamination. The plot of Deuterium versus oxygen-18 of groundwater showed that the data were mostly plotted on the right hand side of the global meteoric water line indicating a trend with a slope of 5.3, and this is consistent with evaporative slope. Stable isotope fingerprint showed recent precipitation as source of recharge, and hence a groundwater system with limited migratory history. The plot of plot Deuterium versus oxygen-18 also shows isotope enrichment as a result of high ambient temperature which favours evaporation. The evaporative effect was thought to be the consequence of intense temperature and heat usually experience in Lokoja area.

5.4 Recommendations

Based on the hydrochemical evaluation and stable isotopes studies of groundwater in Lokaja area, the following recommendations have been made.

1. Borehole and hand dug wells be located properly away from flow direction, waste dumps, septic tanks and pit latrines to avoid leachates contaminating the groundwater.
2. Further studies on microbial parameters such as E. coli, Coliforms, Faecal coliforms and Salmonella should be carried to determine groundwater quality in term microbial characteristics.
3. Modeling of groundwater in the study area be carried out to simulate and predict aquifer condictions such as recharge, discharge, flow rate and water level in order for proper management of groundwater resources.

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APPENDIX I: WELL INVENTORY (Dry season)

L/NAME	S/1D.	LONGITUDE	LATITUDE	ELEV. (m)	SOURCE	DWL (m)	TDW (m)	SWC (m)	REMARK
GANAJA 1	S1	N07^{0}44’40.2’’	E006^{0}44’32.6’’	67	HDW	1.2	4.8	3.6	Poorly cased with concrete, open and the water is cloudy.
GANAJA 2	S2	N07^{0}44’44.4’’	E006^{0}44’31.9’’	41	HDW	1.1	4.3	3.2	Well is cased and covered with iron sheet. The water is colourless.
GANAJA 3	S3	N07^{0}44’43.4’’	E006^{0}44’23.1’’	56	HDW	1.4	5.2	4.2	Well is properly completed. The water is colourless
GANAJA 4	S4	N07^{0}44’49.2’’	E006^{0}44’10.0’’	58	HDW	1.6	3.6	2.0	Well is cased and covered with iron sheet. The water is colourless.
GANAJA 5	S5	N07^{0}44’55.2’’	E006^{0}44’08.6’’	59	HDW	2.1	3.2	1.1	Poorly completed well covered with planks. The water is cloudy in colour.
GANAJA 6	S6	N07^{0}44’59.3’’	E006^{0}44’23.6’’	63	HDW	2.4	5.1	3.3	Cased well, not covered. The water is colourless.
LOKOJA 1	S7	N07^{0}45’23.8’’	E006^{0}44’25.2’’	57	HDW	3.4	4.1	1.3	Properly completed well. Water is colourless.
LOKOJA 2	S8	N07^{0}46’25.2’’	E006^{0}44’14.0’’	69	HDW	4.3	4.9	0.5	Properly completed well. Water is colourless.
LOKOJA 3	S9	N07^{0}46’24.3’’	E006^{0}44’04.0’’	70	HDW	5.3	5.7	0.4	Properly completed and abandoned well. Water is colourless.
LOKOJA 4	S10	N07^{0}46’20.6’’	E006^{0}44’10.2’’	80	HDW	3.7	4.6	0.9	Properly completed and abandoned well. The water is cloudy in color
LOKOJA 5	S11	N07^{0}46’40.5’’	E006^{0}44’01.0’’	74	HDW	1.0	3.2	2.2	Well is cased and covered with iron sheet. The water is colourless.
LOKOJA 6	S12	N07^{0}46’46.7’’	E006^{0}43’59.8’’	64	HDW	0.8	4.3	3.5	Well cased with concrete and covered with planks. The well is within 8m of pit latrine.
LOKOJA 7	S13	N07^{0}46’42.0’’	E006^{0}43’45.6’’	55	HDW	4.7	4.9	0.2	Well is cased and covered with iron sheet. The water is colourless.
LOKOJA 8	S14	N07^{0}46’30.4’’	E066^{0}43’37.2’’	75	HDW	3.4	4.1	0.7	Well is cased and covered with iron sheet. The water is colourless.
LOKOJA 9	S15	N07^{0}46’42.1’’	E006^{0}43’39.6’’	70	HDW	3.3	4.0	0.7	Open well with concrete casing. The water is cloudy in colour
LOKOJA 10	S16	N07^{0}46’00.2’’	E006^{0}44’16.7’’	59	HDW	4.8	4.9	0.1	Poorly completed well covered with roofing sheet. The water is cloudy with some suspended particles
LOKOJA 11	S17	N07^{0}45’46.6’’	E006^{0}44’06.0’’	30	HDW	7.2	7.3	0.1	Well is cased and covered with iron sheet. The water is colourless.
LOKOJA 12	S18	N07^{0}45’51.6’’	E006^{0}44’13.8’’	68	HDW	2.9	4.2	1.3	Well is cased and covered with iron sheet. The water is colourless.
LOKOJA 13	S19	N07^{0}45’30.1’’	E006^{0}44.22.4’’	66	HDW	1.1	3.8	2.7	Well is cased and covered with iron sheet. The water is colourless.
LOKOJA 14	S20	N07^{0}46’40.3’’	E006^{0}44’35.8’’	53	HDW	3.5	4.1	0.6	Well is cased with bricks and covered with roofing sheet. The water is colourless.
ADANKOLO 1	S21	N07^{0}47’14.5	E006^{0}43’55.5’’	54	HDW	0.5	3.3	2.2	Well is cased with concrete and covered with roofing sheet. The is well abandoned and water is greenish in colour
ADANKOLO 2	S22	N07^{0}47’16.1’’	E006^{0}44’03.4’’	59	HDW	0.5	3.8	2.5	Properly completed well. Water is colourless.
ADANKOLO 3	S23	N07^{0}47’12.9’’	E006^{0}44’13.7’’	68	HDW	2.7	5.0	2.3	Well is cased and covered with iron sheet. The water is colourless.
ADANKOLO 4	S24	N07^{0}47’22.2’’	E006^{0}44’32.0’’	65	HDW	1.9	3.6	1.7	Well is cased with concrete and covered with

iron sheet.

L/NAME	S/1D.	LONGITUDE	LATITUDE	ELEV. (m)	SOURCE	DWL (m)	TDW (m)	SWC (m)	REMARK
ADANKOLO 6	S26	N07^{0}47’48.4’’	E006^{0}44’45.3’’	54	HDW	2.8	3.8	1.0	Well is cased with concrete and covered with iron sheet.
LOKOJA 15	S27	N07^{0}48’00.6’’	E006^{0}44’44.8’’	53	HDW	1.9	4.4	3.5	Well is cased with concrete and covered with iron sheet. Poor sanitation around the well.
LOKOJA 16	S28	N07^{0}48’05.9’’	E006^{0}44’47.9’’	48	BH	-	-	-	Properly completed borehole. The water is colorless
LOKOJA 17	S29	N07^{0}48’26.6’’	E006^{0}44’48.3’’	65	BH	-	-	-	Properly completed borehole. The water is colorless
LOKOJA 18	S30	N07^{0}48’41.6’’	E006^{0}44’51.8’’	60	BH	-	-	-	Properly completed borehole. The water is colorless. Poor sanitation around the well
LOKOJA 19	S31	N07^{0}48’50.4’’	E006^{0}44’49.6’’	53	HDW	1.1	3.2	2.1	Well is cased with concrete and covered with roofing sheet. Poor sanitation around the well.
LOKOJA 20	S32	N07^{0}49’02.3’’	E006^{0}44’51.3’’	58	HDW	4.6	4.7	0.1	Well is cased with concrete and covered with iron sheet. Poor sanitation around the well.
LOKOJA 21	S33	N07^{0}49’06.0’’	E006^{0}44’43.6’’	73	HDW	5.7	6.3	1.4	Well is cased with concrete and covered with iron sheet. Poor sanitation around the well.
LOKOJA 22	S34	N07^{0}49’10.3’’	E006^{0}44’31.4’’	115	SPRING	-	-	-	Undeveloped low pressure spring.
LOKOJA 23	S35	N07^{0}48’56.7’’	E006^{0}44’39.2’’	86	HDW	4.9	5.8	1.1	Poorly completed well covered with planks. The water is cloudy in colour.
LOKOJA 24	S36	N07^{0}48’40.4’’	E006^{0}44.40.4’’	49	HDW	3.7	5.5	2.2	Properly completed borehole. The water is colorless
LOKOJA 25	S37	N07^{0}4’.30.7’’	E006^{0}44’18.8’’	87	HDW	1.2	3.7	2.5	Well is cased with concrete and covered with iron sheet. The water is colourless.
LOKOJA 26	S38	N07^{0}48’30.6’’	E006^{0}44’11.3’’	96	HDW	5.1	5.8	0.3	Well is cased with concrete and covered with iron sheet. The water is colourless.
LOKOJA 27	S39	N07^{0}48’36.5’’	E006^{0}44’00.1’’	112	BH	-	-	-	Properly completed borehole. The water is colorless
LOKONGOMA 1	S40	N07^{0}47’38.5’’	E006^{0}43’26.0’’	80	HDW	2.2	4.5	2.3	Well is cased with concrete and covered with iron sheet. The water is colourless.
LOKONGOMA 2	S41	N07^{0}47’19.6’’	E006^{0}43’04.8’’	68	BH	-	-	-	Properly completed borehole. The water is colorless
LOKONGOMA 3	S42	N07^{0}47’43.7’’	E006^{0}43’05.5’’	86	HDW	2.4	3.1	1.3	Well is cased with concrete and covered with iron sheet. The water is colourless.
LOKONGOMA 4	S43	N07^{0}47’23.5’’	E006^{0}42’51.6’’	72	HDW	1.1	4.8	3.7	Well is cased with concrete and covered with iron sheet. The water is colourless. The well is close to septic tank
LOKONGOMA 5	S44	N07^{0}47’38.0’’	E006^{0}42’29.0’’	72	HDW	5.4	8.3	3.1	The well is cased with concrete but uncovered. The water is cloudy/brownish in colour
LOKONGOMA 6	S45	N07^{0}47’37.0’’	E006^{0}42’19.7’’	91	HDW	2.6	5.0	2.4	Well is cased with concrete and covered with iron sheet. The water is cloudy. Well is directly next chicken shelter.
LOKONGOMA 7	S46	N07^{0}47’45.6’’	E006^{0}41’59.9’’	70	HDW	5.3	6.2	0.9	Well is cased and covered with iron sheet. The water is colourless.
LOKONGOMA 8	S47	N07^{0}48’14.4’’	E006^{0}42’02.3’’	99	HDW	3.8	4.7	0.9	Well is cased with concrete and covered with roofing sheet. Water is colourless.
LOKONGOMA 9	S48	N07^{0}48’25.5’’	E006^{0}41’51.5’’	104	BH	-	-	-	Properly completed borehole.

L/NAME	S/1D.	LONGITUDE	LATITUDE	ELEV. (m)	SOURCE	DWL (m)	TDW (m)	SWC (m)	REMARK
OTOKITI 2	S50	N07^{0}48’09.6’’	E006^{0}40’38.0’’	88	HDW	2.6	3.0	0.4	Well is cased and covered with iron sheet. The water is colourless.
OTOKITI 3	S51	N07^{0}48’10.4’’	E006^{0}40’19.3’’	92	HDW	2.9	4.6	2.2	Well is cased with concrete and covered with iron sheet. The water is colorless.
FILELE 1	S52	N07^{0}51’07.5’’	E006^{0}43’09.9’’	106	HDW	1.8	3.8	2.0	Well is cased with concrete and covered with iron sheet. The water is brownish.
FILELE 2	S53	N07^{0}51’14.6’’	E006^{0}43’21.3’’	84	BH	-	-	-	Properly completed borehole. The water is colorless
FILELE 3	S54	N07^{0}51’26.6’’	E006^{0}43’13.2’’	98	HDW	4.3	4.8	0.5	Well is cased with concrete and covered with iron sheet. The water is colorless.
FILELE 4	S55	N07^{0}51’39.7’’	E006^{0}42’57.2’’	105	HDW	4.2	5.1	0.9	Well is cased with concrete and covered with iron sheet. The water is colorless.
FILELE 5	S56	N07^{0}51’05.3’’	E006^{0}43’20.6’’	84	HDW	1.9	3.7	1.2	Well is cased with concrete and covered with iron sheet. The water is colorless.
FILELE 6	S57	N07^{0}50’33.0’’	E006^{0}43’14.6’’	100	HDW	1.0	3.3	2.3	Well is cased with concrete and covered. The water is colorless. The water is cloudy.
FILELE 7	S58	N07^{0}50’52.9’’	E006^{0}43’49.8’’	81	HDW	10.1	10.5	0.4	Well is cased with concrete and covered with iron sheet. The water is colorless.
LOKOJA 28	S59	N07^{0}49’47.9’’	E006^{0}44’59.6’’	59	HDW	3.3	3.8	0.5	Well is cased with concrete and covered with iron sheet. The water is colorless. Poor sanitation around the well.
LOKOJA29	S60	N07^{0}48’29.9’’	E006^{0}39’35.5’’	78	HDW	4.9	6.3	1.4	Well is cased with concrete and covered halfway with roofing sheet. The water is cloudy. Poor sanitation around the well.
LOKOJA30	S61	N07^{0}50’31.5’’	E006^{0}44’30.5’’	66	HDW	5.1	5.7	0.6	Well is cased with concrete and covered with iron sheet. The water is colorless.
LOKOJA31	S62	N07^{0}45’18.7’’	E006^{0}43’28.5’’	71	HDW	3.8	4.9	1.1	Well is cased with concrete and covered with iron sheet. The water is colorless.
LOKOJA32	S63	N07^{0}46’07.4’’	E006^{0}43’19.6’’	88	HDW	4.6	5.3	0.7	Well is cased with concrete and covered with iron sheet. The water is brownish in colour.
LOKOJA33	S64	N07^{0}46’47.9’’	E006^{0}42’46.3’’	83	HDW	5.0	5.5	0.5	Well is cased with concrete and covered with iron sheet. The water is colorless.
LOKOJA34	S65	N07^{0}49’25.9’’	E006^{0}42’06.9’’	93	HDW	3.4	4.5	1.1	Well is cased with concrete and covered with iron sheet. The water is colorless.

***NOTE**: SWL= Static Water Level, TDW= Total Depth of Well, SWC= Saturated Water Colum.*

APPENDIX II: WELL INVENTORY (Wet season)

Location Name	Sample ID	Latitude	Longitude	Elev. (m)	SOURCE	DWL (m)	TDW (m)	SWC (m)	REMARK
Ganaja 1	L1	N7044'32.5"	E6043'42.8"	82	HDW	8.55	9.6	1.05	Properly completed well. Water is cloudy.
Ganaja 2	L2	N7044'32.1	E6043'36.6"	75	HDW	0.75	5.2	4.45	Properly completed well. Water is colourless.
Ganaja 3	L4	N7044'42.6"	E6044'02.1"	71	HDW	0.1	3.6	3.5	Well is cased and covered with wooden planks. The water is colourless.
Ganaja 4	L5	N7044'41.2"	E6044'07.6"	78	HDW	0.3	3.2	2.9	Well is cased and covered with iron sheet. The water is colourless.
Ganaja 5	L6	N7044'25.4"	E6044'07.6"	79	HDW	0.4	5.1	4.7	Well is cased with concrete and covered with iron sheet. The water is colorless.
Ganaja 6	L8	N7044'35.3"	E6044'14.2"	77	HDW	3.1	4.1	1	Well is cased with concrete and covered with iron sheet. The water is colorless.
Ganaja 7	L10	N7044'35.2"	E6044'20.8"	66	HDW	1.8	4.9	3.1	Well is cased and covered with wooden planks. The water is colourless.
Ganaja 8	L11	N7044'19.6"	E6044'28.2"	56	HDW	0.15	5.7	5.55	Well is cased with concrete and covered with iron sheet. The water is colorless.
Ganaja 9	L12	N7044'35.8"	E6044'33.4"	56	HDW	0.6	4.6	4	Well is cased with concrete and covered with iron sheet. The water is colorless.
Ganaja 10	L14	N7044'09.2"	E6044'46.4"	57	HDW	0.06	3.2	3.14	Well is cased with concrete and covered with roofing sheet. The is well abandoned and water is greenish in colour
Ganaja 11	L15	N7043'59.3"	E6044'23.4"	71	HDW	0.7	4.3	3.6	Well is cased with concrete and covered with iron sheet. The water is colorless.
Ganaja 12	L16	N7043'31.2"	E6044'24.0"	55	HDW	4.8	4.9	0.1	Well is cased and covered with iron sheet. The water is brownish in colour
Ganaja 13	L17	N7042'56.7"	E6044'24.8"	58	HDW	0.1	4.1	4	Well is covered with roofing sheet. Water is colourless.
Lokoja 1	L18	N7044'52.2"	E6044'15.7"	54	HDW	1.8	4	2.2	Well is half covered by roofing sheets. Water is cloudy.
Lokoja 2	L19	N7045'29.6"	E6044'20.6"	63	HDW	0.2	4.9	4.7	Poorly completed well. Water is cloudy.
Lokoja 3	L20	N7046'00.1"	E6044'21.6"	53	HDW	3	7.3	4.3	Well is cased with concrete and covered with roofing sheet. The is well abandoned and water colourless
Lokoja 4	L21	N7046'02.4"	E6044'02.6"	69	HDW	2.6	4.2	1.6	Well is cased with concrete and covered with roofing sheet. The is well abandoned and water colourless
Lokoja 5	L22	N7046'26.0"	E6044'14.1"	66	HDW	1	3.8	2.8	Well is cased with concrete and covered with iron sheet. The water is colorless.
Lokoja 6	L23	N7046'34.0"	E6043'58.8"	74	HDW	0.3	4.1	3.8	Well is cased and covered with wooden planks. The water is colourless. Poor sanitation.
Lokoja 7	L24	N7046'44.2"	E6044'02.0"	66	HDW	1.3	3.3	2	Well is cased and covered with wooden planks. The water is colourless.
Lokoja 8	L25	N7046'48.1"	E6044'27.7"	73	HDW	0.8	3.8	3	Well is cased with concrete and covered with iron sheet. The water is colorless.
Lokoja 9	L26	N7046'54.8"	E6044'15.8"	50	HDW	0.8	4.8	4	Well is cased and covered with iron sheet. The water is colourless.
Lokoja 10	L27	N7046'42.0"	E6043'51.6"	70	HDW	3	4.3	1.3	Well is cased with concrete and covered with iron sheet. The water is colourless. The well is close to septic tank
Lokoja 11	L28	N7046'30.4"	E6043'37.3"	64	HDW	3	3.8	0.8	Well is cased with concrete and covered with iron sheet. The water is brownish.

Location Name	Sample ID	Latitude	Longitude	Elev. (m)	SOURCE	DWL (m)	TDW (m)	SWC (m)	REMARK
Lokoja 13	L30	N7046'52.7"	E6043'21.6"	60	HDW	2.1	3.3	1.2	Well is cased with concrete and covered with iron sheet. Poor sanitation around the well.
Lokoja 14	L31	N7047'16.5"	E6043.54.7"	52	HDW	0.2	3.8	3.6	Well is cased and covered with wooden planks. The water is colourless. Poor sanitation.
Adankolo 1	L32	N7047'11.1"	E6043'58.5"	52	HDW	0.1	5	4.9	Well is cased and covered with iron sheet. The water is colourless.
Adankolo 2	L33	N7047'17.9"	E6044'03.9"	56	HDW	0.1	3.6	3.5	Well is cased and covered with iron sheet. The water is colourless.
Adankolo 3	L34	N7047'13.0"	E6044'10.8"	56	HDW	2.5	3.4	0.9	Well is cased with concrete and covered with roofing sheet.
Adankolo 4	L36	N7047'24.6"	E6044'37.6"	48	HDW	2.8	3.8	1	Well is cased and covered with wooden planks. The water is colourless. Poor sanitation.
Adankolo 5	L37	N7047'38.1"	E6044'28.7"	76	HDW	3.6	4.4	0.8	Well is cased and covered with iron sheet. The water is colourless.
Adankolo 6	L38	N7047'40.3"	E6044'39.4"	54	HDW	2	3.8	1.8	Well is cased with concrete and covered with roofing sheet.
Lokoja 15	L39	N7047'48.7"	E6044'38.9"	57	HDW	3.1	3.5	0.4	Well is cased and covered with iron sheet. The water is colourless
Lokoja 16	L40	N7048'05.9"	E6044'47.9"	56	BH			0	Properly completed borehole. The water is colorless
Lokoja 17	L41	N7048'13.4"	E6044'51.0"	51	HDW	1.1	4.3	3.2	Properly completed well. Covered with roofing sheets
Lokoja 18	L42	N7048'28.4"	E6044'54.1"	67	HDW	0.2	5.6	5.4	Well is cased and covered with iron sheet. The water is colourless.
Lokoja 19	L43	N7048'41.9"	E6044'51.8"	55	BH			0	Properly completed borehole. The water is colorless
Lokoja 20	L44	N7048'50.6"	E6044'49.6"	59	HDW	0.15	6.7	6.55	Well is cased with concrete and covered with iron sheet. Poor sanitation around the well.
Lokoja 21	L45	N7049'02.4"	E6044'51.2"	59	HDW	3.2	8.4	5.2	Well is cased with concrete and covered with iron sheet. Poor sanitation around the well.
Lokoja 22	L46	N7048'55.7"	E6044'39.7"	80	HDW	5	6	1	Well is cased with concrete and covered halfway with roofing sheet. The water is cloudy. Poor sanitation around the well.
Lokoja 23	L47	N7048'29.7"	E6044'32.1"	71	HDW	2.6	5.2	2.6	Well is cased and covered with iron sheet. The water is colourless
Lokoja 24	L48	N7048'30.3"	E6044'10.0"	98	HDW	2.8	5.9	3.1	Well is cased with concrete and covered with roofing sheet
Lokongo 1	L49	N7048'57.3"	E6043'30.0"	201	SPRING			0	Undeveloped low pressure spring.
Lokongoma 2	L50	N7047'41.1"	E6043'38.4"	77	HDW	1.8	5.1	3.3	Well is cased with concrete and covered with wooden planks
Lokongoma 3	L51	N7047'24.2"	E6043'20.7"	72	HDW	1.8	4.9	3.1	Well is cased and covered with iron sheet. Abandoned and water is greenish in colour
Lokongoma 4	L52	N7047'12.3"	E6043'17.6"	53	HDW	2	6	4	Well is cased and covered with iron sheet. The water is colourless
Lokongoma 5	L53	E7047'43.6"	E6043'05.6"	85	HDW	2.1	8.9	6.8	Well is cased with concrete and covered with roofing sheet
Lokongoma 6	L54	E7047'20.0"	E6042'54.1"	60	HDW	1.8	6.2	4.4	Well is cased with concrete and covered with roofing sheet
Lokongoma 7	L55	E7047'35.3"	E6042'13.1"	70	HDW	1.6	5.9	4.3	Well is cased and covered with iron sheet. The water is colourless
Lokongoma 8	L56	N7047'47.5	E6041'55.1"	66	HDW	2	7.2	5.2	Well is cased and covered with iron sheet. The water is colourless

Location Name	Sample ID	Latitude	Longitude	Elev. (m)	SOURCE	DWL (m)	TDW (m)	SWC (m)	REMARK
Lokongoma 10	L58	N7048'10.4"	E6041'51.6"	77	HDW	1.6	4.6	3	Well is cased and covered with iron sheet. The water is colourless
Lokongoma 11	L59	N7048'25.4"	E6041'51.6"	98	BH			0	Properly completed borehole. The water is colorless
Otokiti 1	L60	N7048'08.7"	E6040'49.4"	82	BH			0	Properly completed borehole. The water is colorless
Otokiti 2	L61	N7048'13.8"	E6040'30.4"	90	BH			0	Properly completed borehole. The water is colorless
Otokiti 3	L62	N7048'43.7"	E6038'27.1"	153	HDW	2.8	5.6	2.8	Poorly completed well and covered with wooden planks. Water is cloudy
Otokiti 4	L63	N7050'29.7"	E6040'22.3"	119	BH			0	Properly completed borehole. The water is colorless
Filele 1	L64	N7051'08.5"	E6043'00.6"	108	HDW	1.8	5.3	3.5	Well is cased and covered with iron sheet. The water is colourless
Filele 2	L65	N7050'45.9"	E6043'00.4"	101	HDW	3	5.6	2.6	Well is cased and covered with iron sheet. The water is colourless
Filele 3	L66	N7051'14.6"	E6043'21.2"	75	BH			0	Properly completed borehole. The water is colorless
Filele 4	L67	N7051'35.0"	E6043'03.5"	89	HDW	3	6	3	Well is cased with concrete and covered with iron sheet. Poor sanitation around the well
Filele 5	L68	N7050'29.2"	E6044'17.5"	73	BH			0	Properly completed borehole. The water is colorless
Lokoja 25	L69	N7050'11.5"	E6044'56.2"	50	HDW	3.4	5.7	2.3	Well is covered by metal sheet. Poor sanitation around the well

***NOTE**: SWL= Static Water Level, TDW= Total Depth of Well, SWC= Saturated Water Colum.*

APPENDIX III: PHYSICAL PARAMETERS OF GROUNDWATER FROM THE STUDY AREA BASED ON ROCK TYPES (Dry season)

BEDROCK	S/1D.	T0C	pH	EC	TDS	TH
ALLUVIUM				(µS/cm)	(ppm)	
	S52	32.7	5.9	140	110	32.9
	S53	33.7	7.2	580	415	208
	S55	32.5	7	80	62	24.3
	S56	30.4	6.6	300	220	95.4
	S59	31.4	6.3	460	367	143
SANDSTONE	S5	29.6	8.6	610	436	185
	S33	29.8	8.4	1330	962	242
	S34	30.1	5.5	30	31	5.02
	S57	30	5.7	50	42	172
	S58	32.2	7	200	148	36.7
	S62	29.4	7.6	614	436	21.1
	S63	29.6	7.4	473	367	63.9
BIOTITE AND MIGMATITE GNEISS	S8	25.3	7.5	680	486	302
	S10	29.5	6.8	560	400	169
	S14	30.5	5.9	130	178	17.9
	S15	29.3	6.6	240	530	64.8
	S16	31.3	7.3	730	530	313
	S20	29.1	7.4	860	620	299
	S25	32.3	7.2	580	4I9	188
	S26	28.7	7	580	416	147
	S27	30.4	8.7	710	511	156
	S28	29.1	7.3	570	406	216
	S29	28.9	7.1	510	365	213
	S30	30.9	6.8	710	509	246
	S31	29	7.3	820	589	150
	S32	30.2	7.4	1030	748	178
	S35	31.4	7.1	470	341	94.5
	S36	32.2	6.5	610	442	94.5
	S37	27	7.2	770	555	130
	S38	32.1	6.7	360	265	79.4
	S39	32.1	7.2	280	208	41.2
	S40	29.7	8	360	257	127
	S41	30.2	7.4	510	371	300
	S42	30.3	7.2	440	316	154
	S43	33.3	7.4	440	320	146

	S/1D.	T0C	pH	EC	TDS	TH
	S45	30.2	7.5	670	479	206
	S46	27.6	7.3	610	439	234
	S47	31.8	8	770	555	254
	S48	31.6	6.8	270	194	109
	S49	30.2	6.9	700	505	313
	S50	28.4	7.3	620	444	219
	S51	30.4	7.2	350	256	4.11
	S54	31.9	10.6	430	309	75.6
	S60	28.9	6.7	357	272	28.1
	S61	28.9	6.8	255	187	137.4
	S64	29.8	7.5	786	563	146.5
	S65	29.8	7.3	658	490	92.6
OLDER GRANITE	S1	29.7	8.3	420	303	92.8
	S2	28.9	6.7	630	451	174
	S3	28.2	8.1	350	255	87
	S4	28.8	8.2	490	351	152
	S6	29.4	7.2	320	235	113
	S7	26.2	7.5	1250	909	235
	S9	27.9	8.4	1040	755	240
	S11	29.8	7.8	790	570	255
	S12	30	7.1	140	108	44.5
	S13	31.9	7.8	560	403	160
	S17	29.6	7.3	690	499	244
	S18	30.8	10.1	160	124	56.6
	S19	30.8	7.1	400	292	128
	S21	31.9	7.8	290	213	121
	S22	30.3	7.5	640	458	235
	S23	31.9	9.1	180	133	65.6
	S24	31.7	7.6	1390	1040	472

APPENDIX IV: PHYSICAL PARAMETERS OF GROUNDWATER FROM THE STUDY AREA BASED ON ROCK TYPES (Wet season)

BEDROCK	Sample ID	Temp.	pH	EC	TDS
ALLUVIUM	L64	29.1	7.3	730	525
	L65	30.6	7.1	150	112
	L66	30.8	6.7	690	500
SANDSTONE	L46	29.8	7.8	1320	960
	L49	30	7.6	70	55
	L67	26.6	6.6	480	342
	L68	28.2	5.4	570	405
	L69	28.8	6.3	680	455
BIOTITE AND MIGMATITE GNEISS	L20	28.7	8	580	422
	L22	29.4	7.6	440	274
	L28	30.1	6.3	430	306
	L29	29.2	6.8	730	481
	L30	28.5	7.4	760	549
	L36	30.6	7.8	1250	905
	L37	28.2	8.4	1050	753
	L38	29.2	7.2	1350	984
	L39	29.8	7	750	542
	L40	29.9	7.3	810	568
	L41	31.6	7.5	790	526
	L42	30.1	6.9	800	569
	L43	30.5	7.2	1060	767
	L44	29.6	8	1210	876
	L45	26.5	6.7	1730	1273
	L47	31.3	8	1540	1122
	L48	30.7	6	580	417
	L50	24.7	6.6	700	505
	L51	29.6	7	910	605
	L52	29.7	6.8	810	503
	L53	28.7	6.8	640	464
	L54	29.2	7.5	730	524
	L55	28.9	7	950	687
	L56	28.8	8.1	480	347
	L57	30.2	7.2	550	396
	L58	28.4	7.2	590	426
	L59	28.9	6.9	400	293
	L60	29.1	6.7	950	659
	L61	29.8	0.71	1580	1150

	Sample ID	Temp.	pH	EC	TDS
	L63	29.4	6.8	510	362
OLDER GRANITE	L1	27.7	9.1	390	290
	L2	27.7	5.9	350	254
	L4	27	8.3	680	470
	L5	26.4	7.5	630	447
	L6	29.6	6.9	870	629
	L8	29.5	7.6	1020	721
	L10	26.6	7.3	560	400
	L11	29	6.7	1570	1148
	L12	27	7.5	980	710
	L14	29.3	7.1	780	586
	L15	29	6.7	640	452
	L16	31	8.1	750	541
	L17	25.2	7.2	570	378
	L18	27.9	7.1	900	572
	L19	30.4	7.1	570	410
	L21	29.2	7.1	1030	748
	L23	30.2	7.4	600	428
	L24	29.8	7.2	560	400
	L25	28.2	7	710	508
	L26	28.9	7.3	730	522
	L27	28	7.7	830	594
	L31	28.4	7.8	730	528
	L32	28.5	8.1	1090	786
	L33	28	7.3	880	637
	L34	29	8.3	670	486

APPENDIX V: RESULTS OF CATIONS OF GROUNDWATER FROM THE STUDY AREA BASED ON ROCK TYPES (Dry season)

BEDROCK	Sample ID	Ca	Mg	Na	K
ALLUVIUM	S52	9.35	2.32	15.49	5.5
	S53	53.25	18.36	46.99	4.86
	S55	6.61	1.89	6.31	3.85
	S56	28.3	6.01	21.13	11.54
	S59	44.54	7.84	47.06	17.66
SANDSTONE	S5	34.26	24.6	91.71	3.58
	S33	64.61	19.51	145.9	107.17
	S34	1.4	0.37	4.21	1.84
	S57	52.72	9.73	65.65	55.06
	S58	12.54	1.3	33.57	3.33
	S62	4.08	2.66	8.34	1.67
	S63	3.97	13.11	23.23	24.21
BIOTITE AND BIOTITE GNEISS	S8	46.93	45.04	50.03	1.7
	S10	50.9	10.2	58.03	4.33
	S14	5	1.31	22.61	3.53
	S15	15.22	6.52	31.65	4.26
	S16	72.39	32.13	58.11	1.98
	S20	80.07	24	74.06	17.93
	S25	60.76	8.86	47.5	10.79
	S26	42.23	10.12	57.05	35.17
	S27	44.96	10.74	97.2	26.35
	S28	36.19	30.66	46.62	11.08
	S29	36.69	29.64	39.78	12.17
	S30	63.96	20.99	53.6	15.23
	S31	41.65	11.13	75.7	60.89
	S32	49.48	13.24	122.77	54.72
	S35	25.71	7.37	48.39	24.77
	S36	42.79	7.54	53.99	38.66
	S37	24.85	16.48	24.3	2.26
	S38	23.58	4.98	40.56	14.6
	S39	12.58	2.39	57.26	3.74
	S40	42.99	4.65	37.02	4.36
	S41	66.1	32.93	19.06	4.94
	S42	36.1	15.63	47.65	2.94
	S43	46.24	7.52	33.02	9.89
	S44	30.57	4.58	21.11	1.65
	S45	62.74	11.91	72.8	6.99

	Sample ID	Ca	Mg	Na	K
	S47	61.54	24.32	89.3	8.05
	S48	18.79	15.01	16.94	7.17
	S49	56.89	41.6	35.49	11.28
	S50	43.18	27.03	46.49	8.99
	S51	1.12	0.32	1.61	0.55
	S54	26.08	2.54	18.67	17.78
	S60	8.16	1.87	56.34	4.74
	S61	47.34	4.67	12.56	16.05
	S64	46.23	7.54	9.12	2.16
	S65	34.12	1.8	17.51	2.86
OLDER GRANITE	S1	29.47	4.66	46.51	10.24
	S2	47.77	13.22	55.89	7.45
	S3	29.24	3.39	40.14	4.8
	S4	29.27	19.11	59.04	5.81
	S6	29.95	9.3	23.71	8.49
	S7	23.32	43.04	244.27	6.61
	S9	70.92	15.21	131.88	16.51
	S11	63.8	23.4	75.12	4.12
	S12	12.14	3.44	8.9	3.94
	S13	39.91	14.67	59.87	8.05
	S17	43.07	33.16	84.51	7.38
	S18	20.74	1.15	6.69	8.83
	S19	33.4	10.96	42.09	6.51
	S21	40.25	4.87	19.3	11.63
	S22	72.2	13.36	50.82	9.29
	S23	19.33	4.21	13.25	3.9
	S24	103.52	52.02	133.26	14.15

APPENDIX VI: RESULTS OF CATIONS OF GROUNDWATER FROM THE STUDY AREA BASED ON ROCK TYPES (Wet season)

BEDROCK	Sample ID	Ca	Mg	Na	K
ALLUVIUM	L64	36.722	19.04	38.19	12.59
	L65	5.103	1.467	5.98	3.431
	L66	20.049	17.92	47.66	6.499
SANDSTONE	L46	37.487	11.66	110.2	57.157
	L49	0.1	0.234	3.35	1.893
	L67	21.626	10.29	22.14	9.313
	L68	21.87	5.894	54.26	8.12
	L69	15.086	6.144	58.26	18.982
BIOTITE AND MIGMATITE GNEISS	L20	20.729	16.99	38.64	2.606
	L22	14.984	12.22	15	9.357
	L28	5.788	2.79	29.4	4.345
	L29	23.595	9.152	38.07	7.032
	L30	42.355	21.17	31.45	1.495
	L36	46.307	19.79	91.69	28.376
	L37	34.816	11.83	32.32	13.222
	L38	79.042	30.56	67.98	26.536
	L39	35.176	12.7	43.85	15.957
	L40	21.402	31.95	42.42	10.582
	L41	30.144	24.88	40.2	12.512
	L42	26.419	12.59	47.6	21.429
	L43	48.065	27.18	55.41	14.379
	L44	41.177	13.48	98.1	61.316
	L45	41.087	17.86	157.7	60.665
	L47	62.886	14.36	102.9	72.225
	L48	23.105	6.072	34.28	15.578
	L50	24.633	15.23	42.56	2.09
	L51	33.956	9.867	55.23	19.441
	L52	21.631	27.47	36.39	4.968
	L53	12.05	16.16	54	2.652
	L54	34.362	16.96	38.7	2.48
	L55	51.616	10.33	63.46	18.751
	L56	20.178	8.008	19.71	4.213
	L57	14.022	9.672	34.18	12.669
	L58	17.467	28.12	24.42	67.007
	L59	2.654	12.83	20.33	7.328
	L60	21.408	41.25	33.44	10.935
	L61	50.171	57.13	74.91	15.146

	Sample ID	Ca	Mg	Na	K
	L63	11.975	11.01	31.93	4.811
OLDER GRANITE	L1	4.803	2.34	29.63	22.161
	L2	7.564	3.917	18.92	13.792
	L4	32.008	8.196	37.13	8.034
	L5	15.897	12.79	45.24	6.596
	L6	32.981	14.97	72.26	17.088
	L8	58.899	15.85	57.94	11.799
	L10	30.196	8.524	26.85	5.548
	L11	60.836	38.28	109.2	23.021
	L12	71.683	16.17	67.96	10.366
	L14	68.376	9.138	30.72	12.788
	L15	24.462	11.53	37.49	5.965
	L16	24.28	17.73	59.73	22.596
	L17	14.304	6.873	30.74	4.367
	L18	19.181	10.27	44.5	8.342
	L19	30.479	8.784	35.65	10.838
	L21	40.759	28.83	60.03	5.145
	L23	21.92	11.01	39.17	7.287
	L24	17.117	9.789	25.71	3.61
	L25	32.926	16.58	33.2	6.549
	L26	22.94	26.43	30.63	1.794
	L27	44.089	19.63	31.44	1.849
	L31	34.35	10.89	52.53	5.814
	L32	16.071	32.7	124	1.922
	L33	49.627	13.74	48.59	10.808
	L34	34.001	10.9	42.63	4.817

APPENDIX VII: RESULTS OF ANIONS OF GROUNDWATER FROM THE STUDY AREA BASED ON ROCK TYPES (Dry season)

BEDROCK	Sample ID	HNO3	NO3	SO4	Cl
ALLUVIUM	S52	60.1	3.5	6.1	22
	S53	8.56	2	17.4	78
	S55	34	7.6	0.62	4.7
	S56	67.2	2	4.59	19
SANDSTONE	S5	12	<2.0	14	14
	S33	16.7	28.9	52.8	180
	S34	33.4	<2.0	7.36	3
	S57	156.3	7	45.2	68
	S58	93.3	<2.0	3.28	4.6
	S62	76.3	8	17.5	57
BIOTITE AND BIOTITE GNIESS	S8	23.7	10.6	11.9	21
	S10	46.2	18	14	78
	S14	121.4	7.1	1.76	19
	S15	102.6	<2.0	16.1	25
	S16	102.2	16.4	30.4	59
	S20	113.4	67.5	34.8	110
	S25	118	22.3	39	54
	S26	17.8	22	44.8	53
	S27	14.6	14.5	68	60
	S28	5.16	<2.0	8	27
	S29	48.2	<2.0	13.7	38
	S30	21.9	3.4	31.1	88
	S31	63.9	42.6	43.7	84
	S32	10.6	34.8	55.7	140
	S35	54	22.6	10.8	74
	S36	83.6	28.9	42.1	63
	S37	162.7	19.8	20.5	25
	S38	218.6	<2.0	10.6	17
	S39	105.6	<2.0	5.43	6.7
	S40	72	4.9	9.39	11
	S41	16.7	5.2	16.5	17

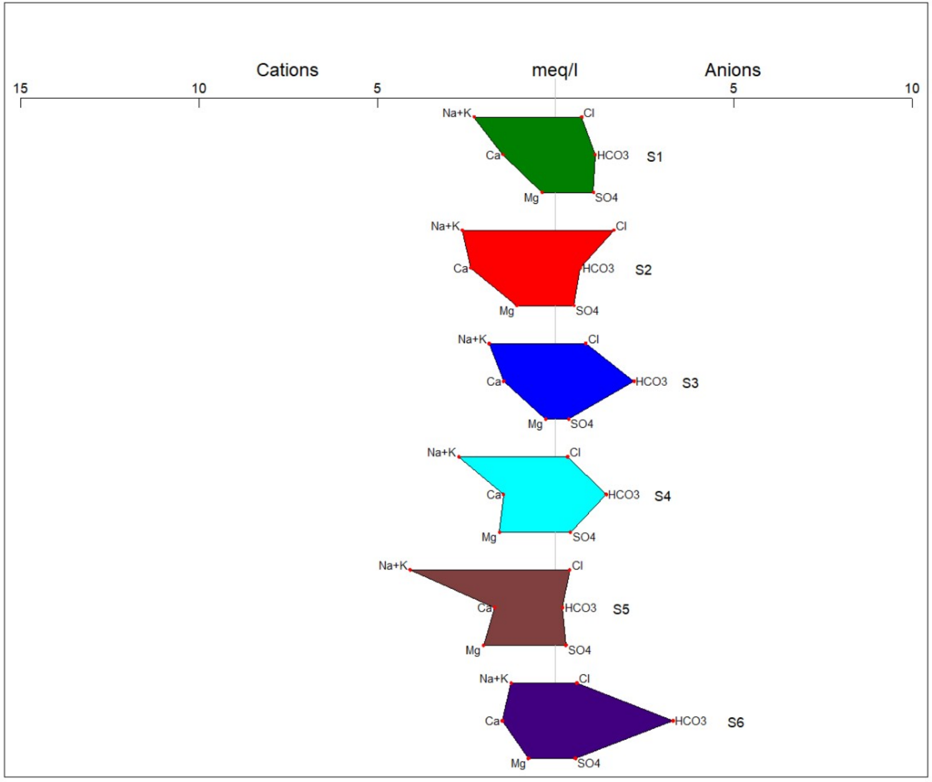
	Sample ID	HNO3	NO3	SO4	Cl
	S43	110.7	20.2	34.8	28
	S44	72.6	2.1	21.2	8.2
	S45	63.1	22.9	40	40
	S46	44.9	8.2	6.38	52
	S47	62	8.3	43	86
	S48	140.2	<2.0	3.06	4
	S49	89.6	<2.0	9.35	57
	S50	210.4	7.4	18.4	49
	S51	156.2	<2.0	1.22	1.4
	S54	187.2	23	9.05	23
	S60	139	13.5	5.7	8
	S61	217.5	4.8	8.9	5
	S64	123.8	3.9	5.7	7
OLDER GRANITE	S1	67.6	6	50.9	26
	S2	42.3	39	24.7	58
	S3	134.4	9.7	17.7	30
	S4	86.9	2.8	`20.0	12
	S6	201.1	6.8	26.9	21
	S7	57.3	9.7	19.8	33
	S9	117.6	72.5	55.5	97
	S11	138.5	35.6	50.6	98
	S12	85	2.9	17.6	3.6
	S13	158.2	20.4	29.4	40
	S17	80.8	2	7.84	13
	S18	190	<2.0	20.5	3.1
	S19	46.2	6.7	31.8	21
	S21	124.4	<2.0	26	6.1
	S22	87.5	4.5	38.6	47
	S23	5.86	17.9	1.21	19
	S24	27.4	70.4	70.8	170

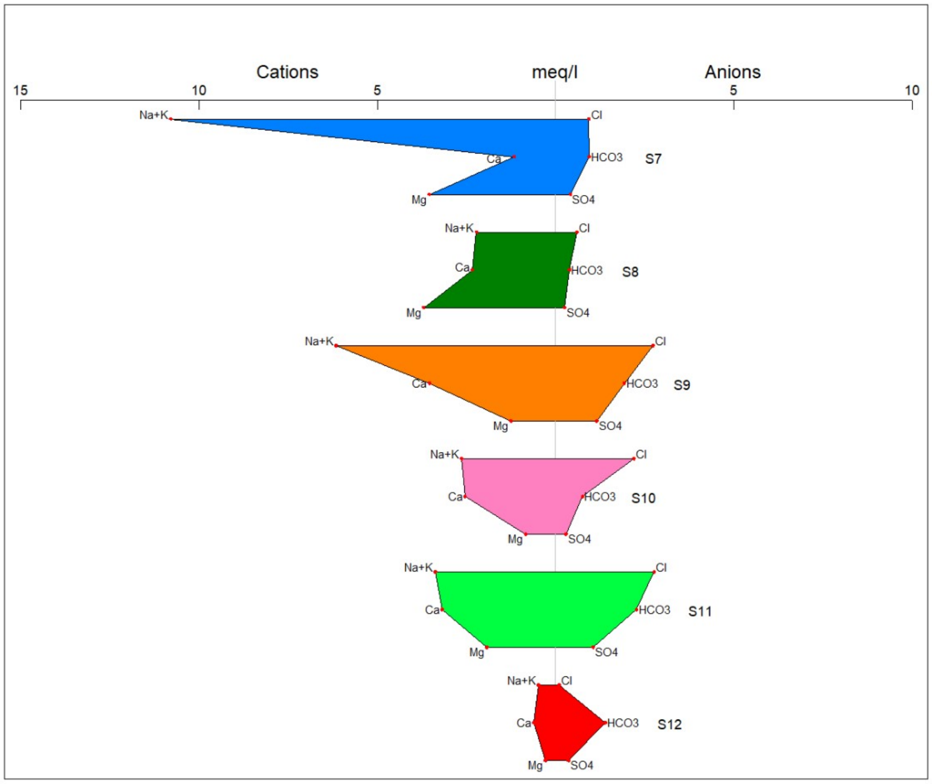
APPENDIX VIII: RESULTS OF ANIONS OF GROUNDWATER FROM THE STUDY AREA BASED ON ROCK TYPES (Wet season)

BEDROCK	Sample ID	HNO3	NO3	SO4	Cl
ALLUVIUM	L64	116.7	19.435	12.076	51.926
	L65	22.9	6.73	0.733	3.328
	L66	190.3	4.343	16.525	75.7
SANDSTONE	L46	114.2	34.486	37.942	139.765
	L49	12.7	0.025	1.984	1.134
	L67	50.7	20.386	8.352	32.819
	L68	23	29.047	4.958	62.293
	L69	56.8	28.105	22.327	62.869
BIOTITE AND MIGMATITE GNEISS	L20	230.8	0.169	25.554	27.837
	L22	121.7	2.329	31.516	8.159
	L28	34.2	18.262	5.983	26.881
	L29	172.6	2.049	35.162	35.546
	L30	254.9	1.847	55.884	37.477
	L36	121.9	55.431	74.531	98.393
	L37	154.7	25.911	62.827	73.934
	L38	279	39.451	75.574	108.378
	L39	96.5	31.631	48.95	48.943
	L40	319.7	0.451	7.815	34.514
	L41	223.3	14.53	44.012	38.911
	L42	66.1	33.179	42.996	73.009
	L43	251.1	8.946	36.614	128.739
	L44	126.8	48.347	54.196	11.692
	L45	111.7	42.248	70.519	191.715
	L47	111.6	59.4	77.918	43.761
	L48	28	25.209	15.109	43.761
	L50	98.9	21.433	40.341	51.452
	L51	152.2	15.768	58.451	50.843
	L52	213.1	7.72	41.349	42.429
	L53	175.1	13.397	27.086	31.727
	L54	158.5	13.628	32.464	49.542
	L55	119.2	29.221	51.457	75.568
	L56	107.8	8.958	28.352	16.408
	L57	43.2	20.417	24.791	28.18
	L58	202.9	7.532	22.708	29.354
	L59	167.5	0.772	5.324	7.396
	L60	289.2	3.354	10.368	70.079
	L61	254.9	24.777	52.411	180.128

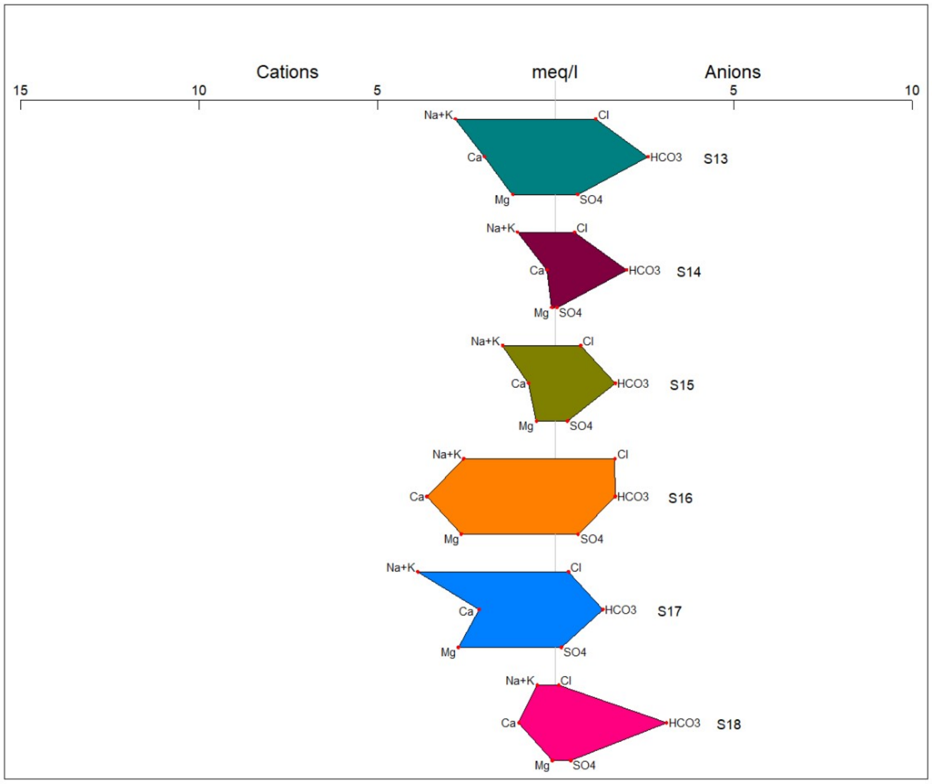
	Sample ID	HNO3	NO3	SO4	Cl
	L63	183.5	1.773	5.502	17.756
OLDER GRANITE	L1	88.8	13.749	12.471	8.563
	L2	35.5	15.791	20.578	15.141
	L4	53.3	33.209	33.42	41.853
	L5	77.3	12.045	14.022	80.75
	L6	123	32.431	30.989	80.306
	L8	96.4	40.795	40.594	95.248
	L10	86.2	11.681	36.208	45.006
	L11	284.2	23.389	62.726	151.463
	L12	248.7	15.249	85.235	59.874
	L14	207.9	9.326	38.26	62.117
	L15	73.5	19.02	34.63	54.577
	L16	309.5	5.464	26.787	4.58
	L17	55.9	11.153	42.293	37.524
	L18	88.8	15.95	45.185	47.276
	L19	104	15.551	40.205	37.005
	L21	299.2	16.611	42.335	66.276
	L23	94	16.625	50.016	37.086
	L24	55.8	17.382	56.846	31.366
	L25	102.7	25.693	42.059	49.062
	L26	185.3	10.728	51.165	37.642
	L27	271.3	3.408	49.628	39.282
	L31	235.8	10.178	43.764	43.946
	L32	398.3	4.424	39.912	52.73
	L33	195.3	19.685	54.485	53.488
	L34	131.9	14.726	55.387	39.381

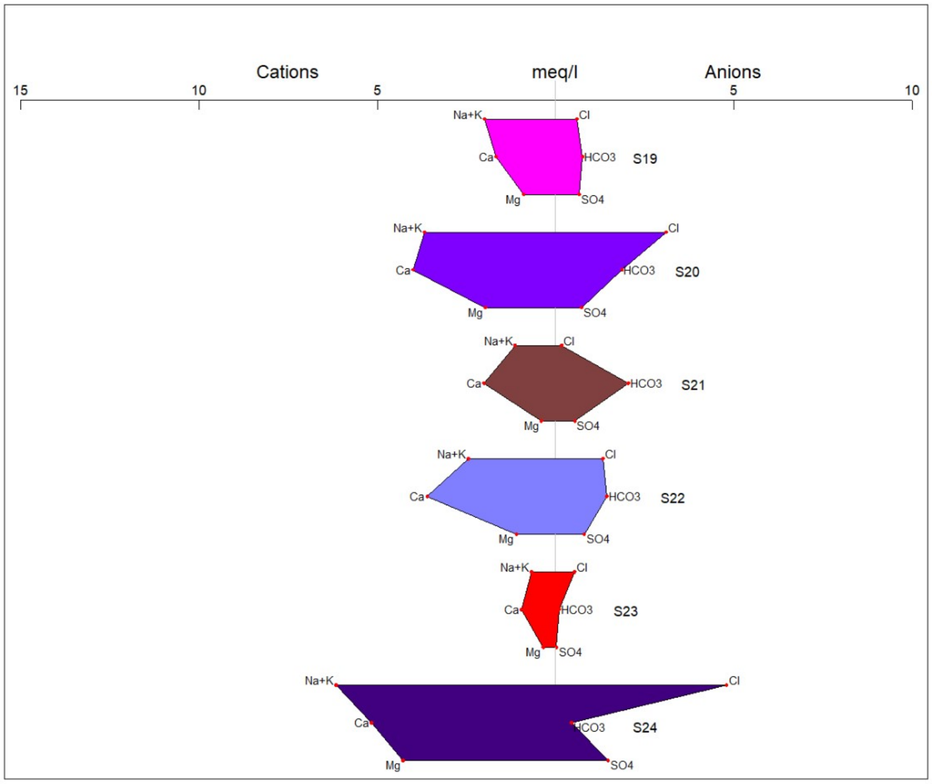
APPENDIX IX: Stiff diagrams for groundwater samples during the dry season



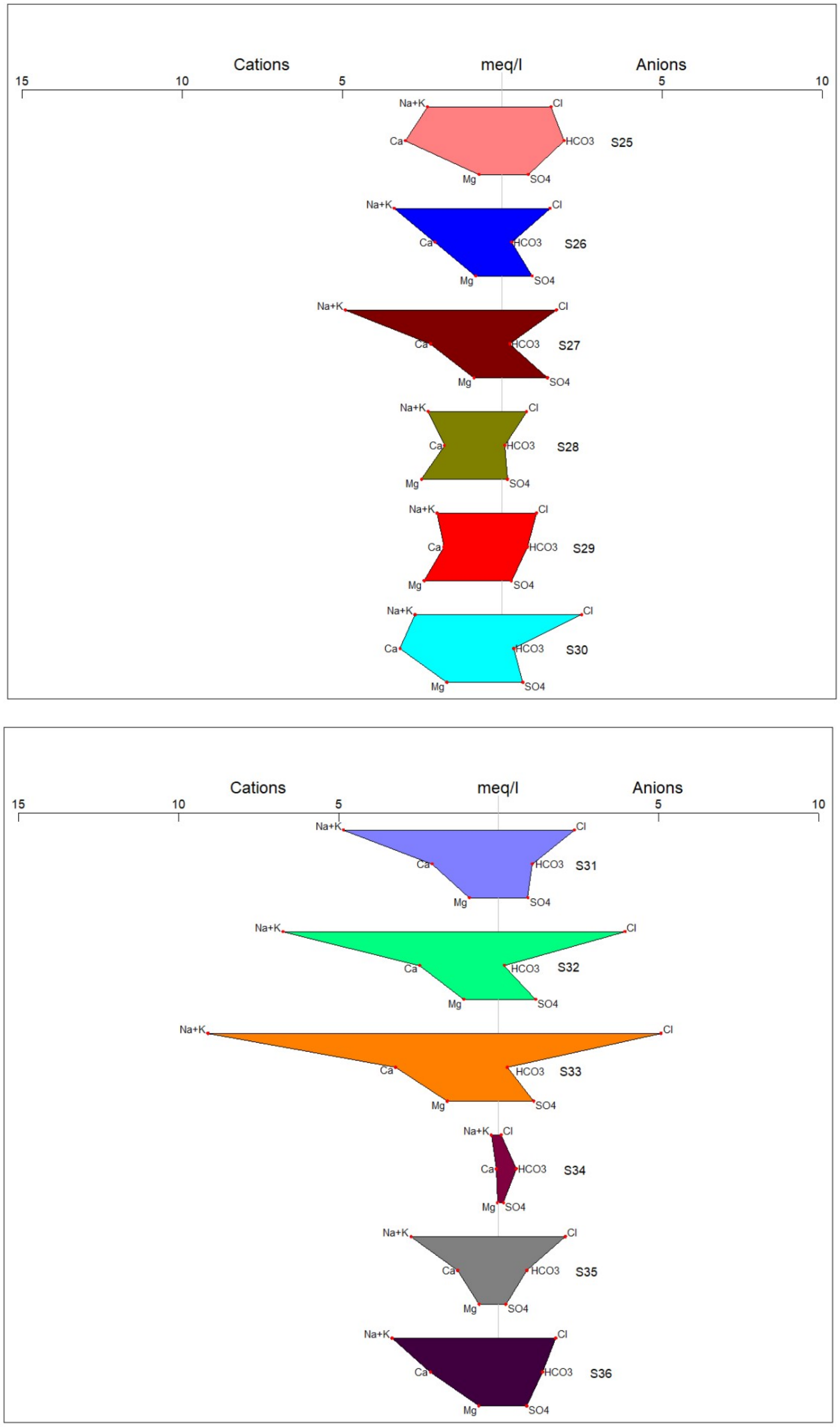


Stiff diagram for groundwater samples during the dry season (S1-S12)

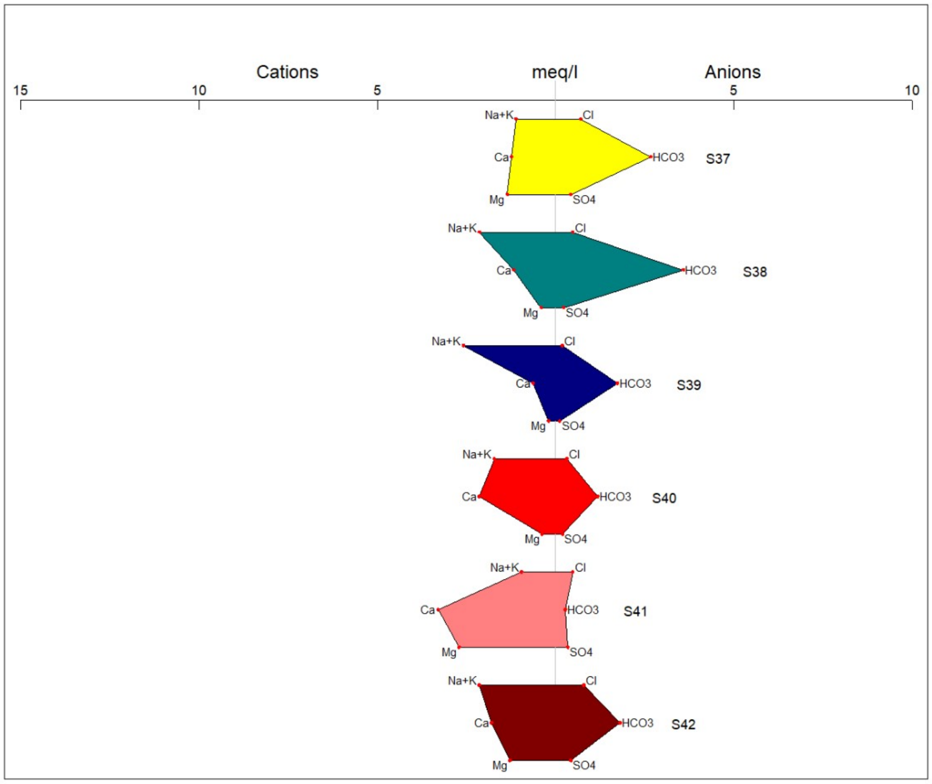


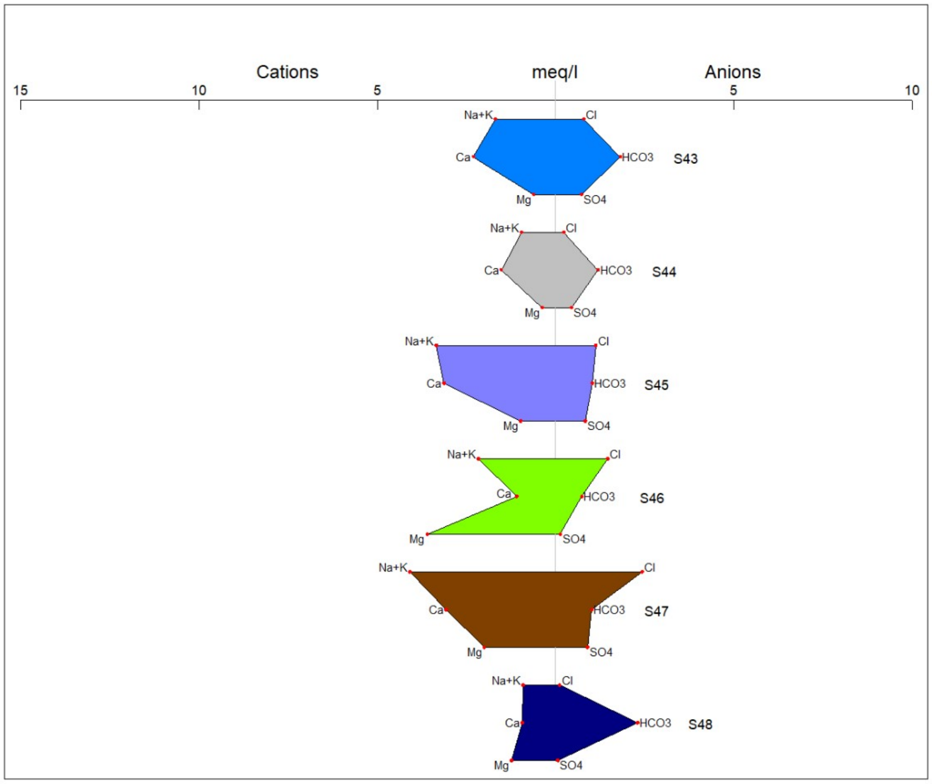


Stiff diagram for groundwater samples during the dry season (S12-S14)

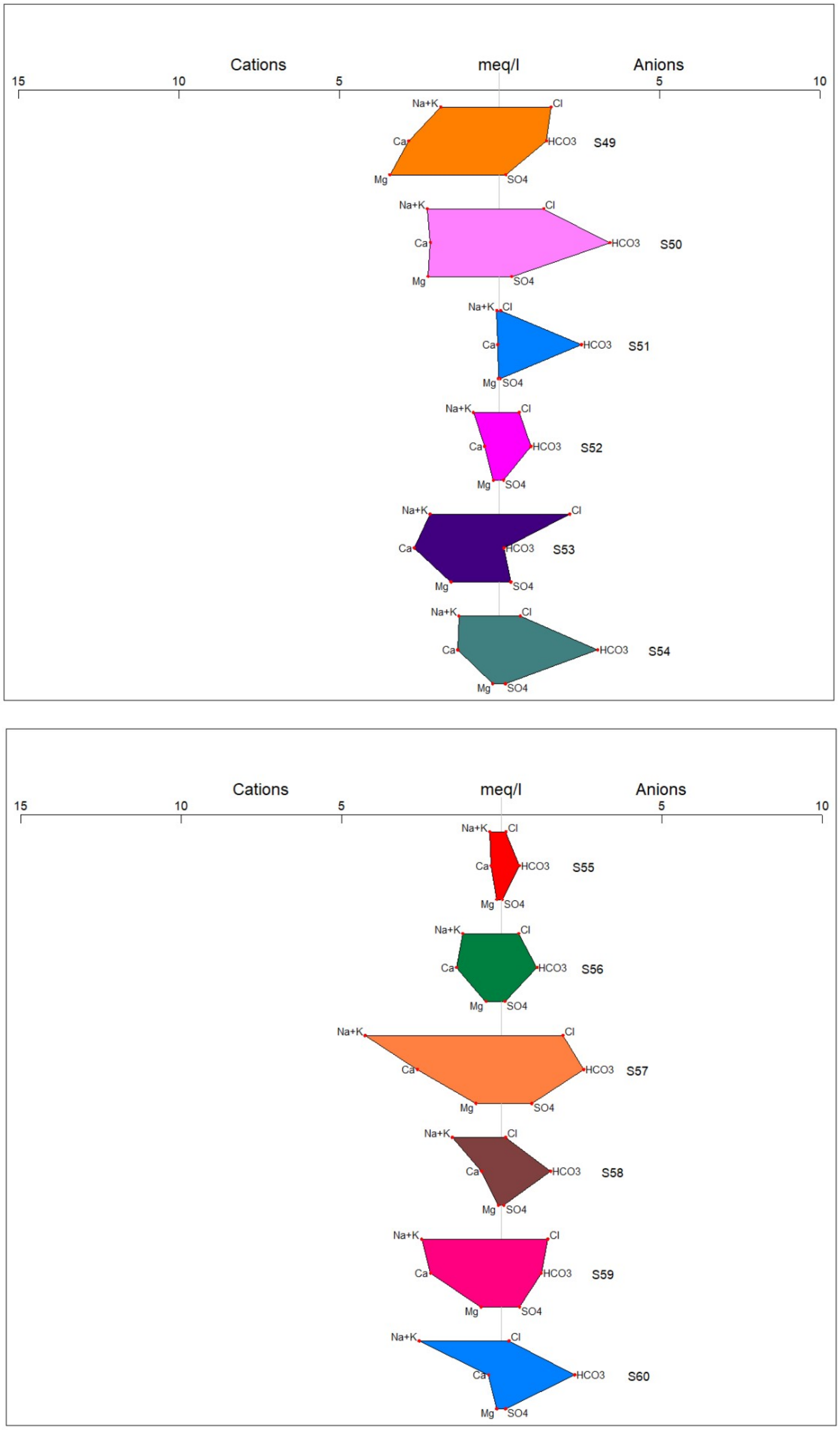


Stiff diagram for groundwater samples during the dry season (S24-S36)

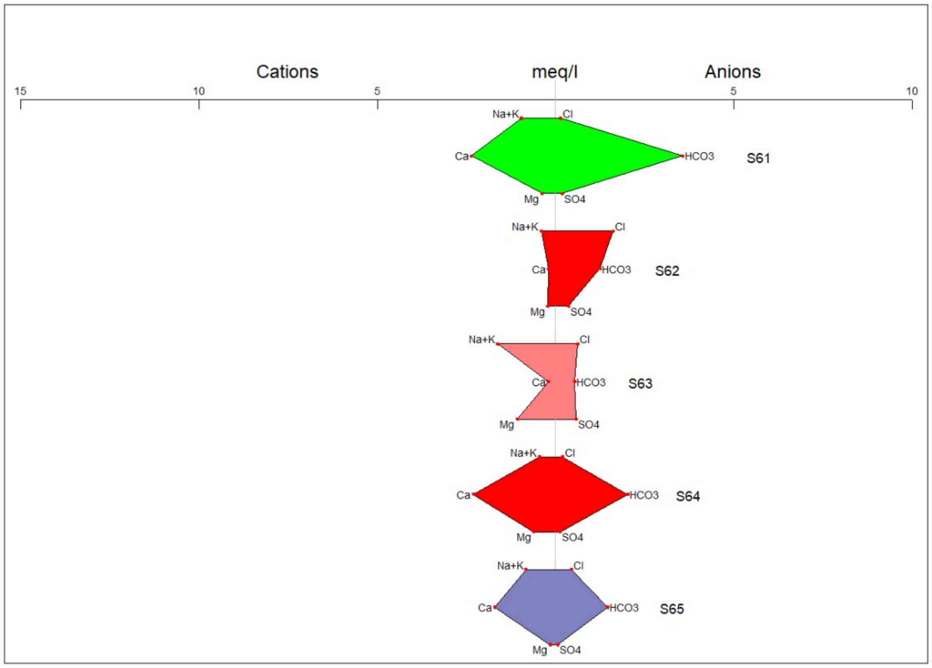




Stiff diagram for groundwater samples during the dry season (S36-S48)

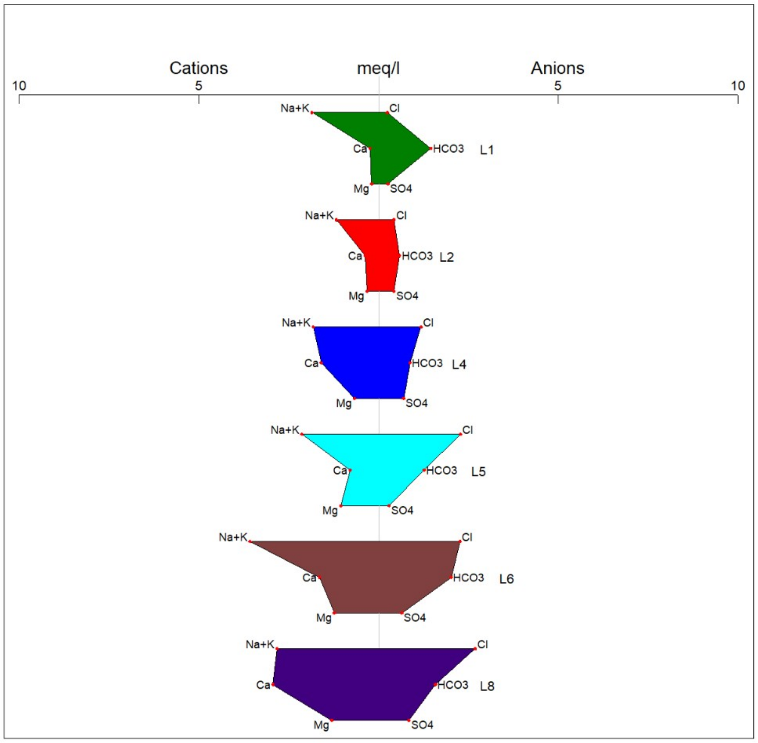


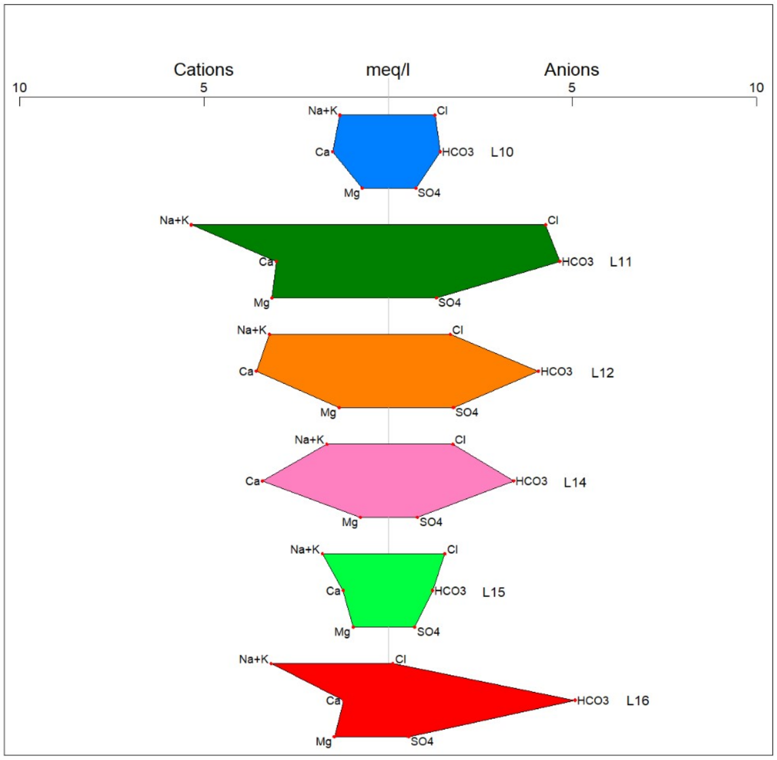
Stiff diagram for groundwater samples during the dry season (S48-S60)



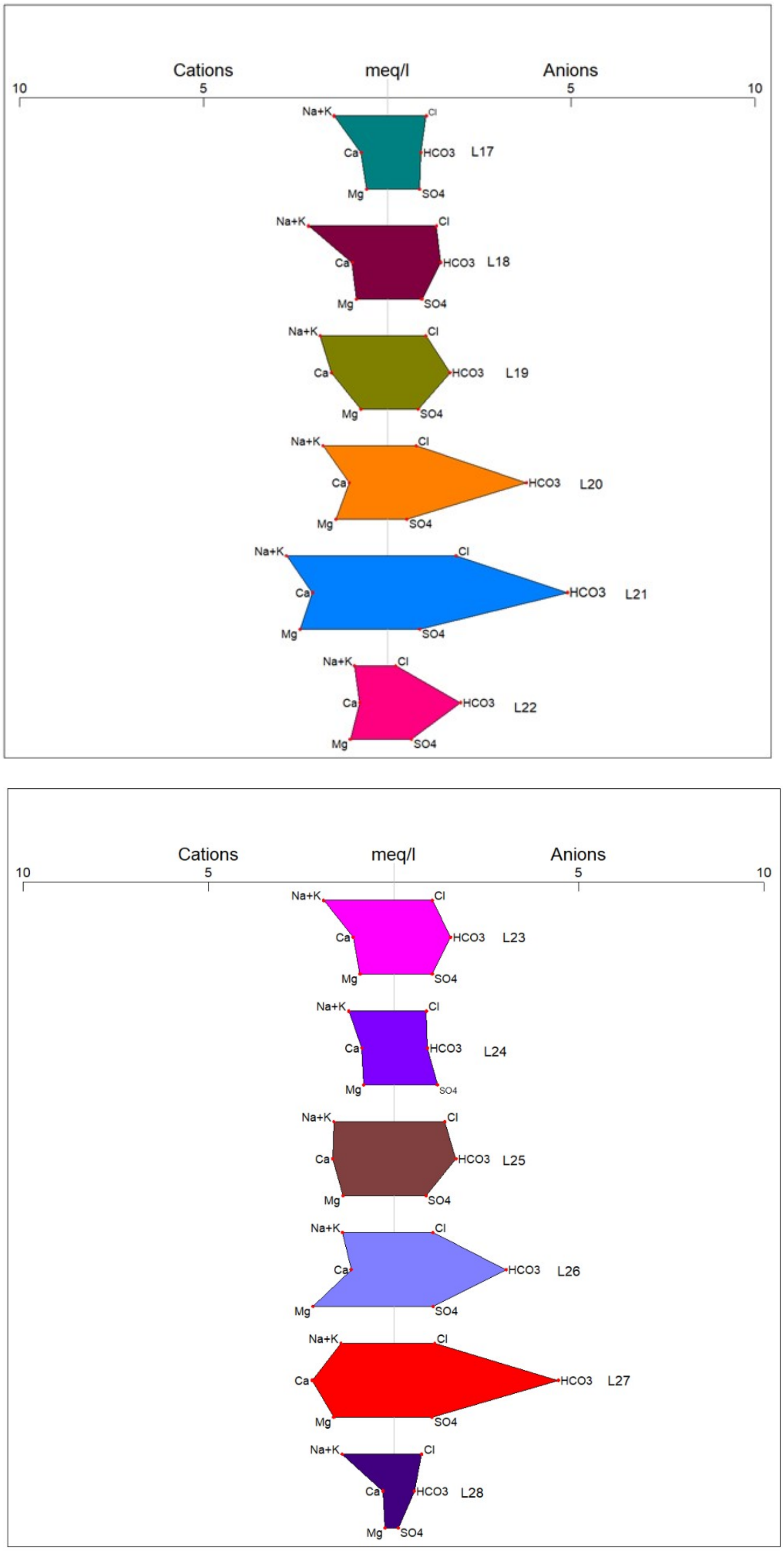
Stiff diagram for groundwater samples during the dry season (S60-S65)

APPENDIX X: Stiff diagrams for groundwater samples during the wet season

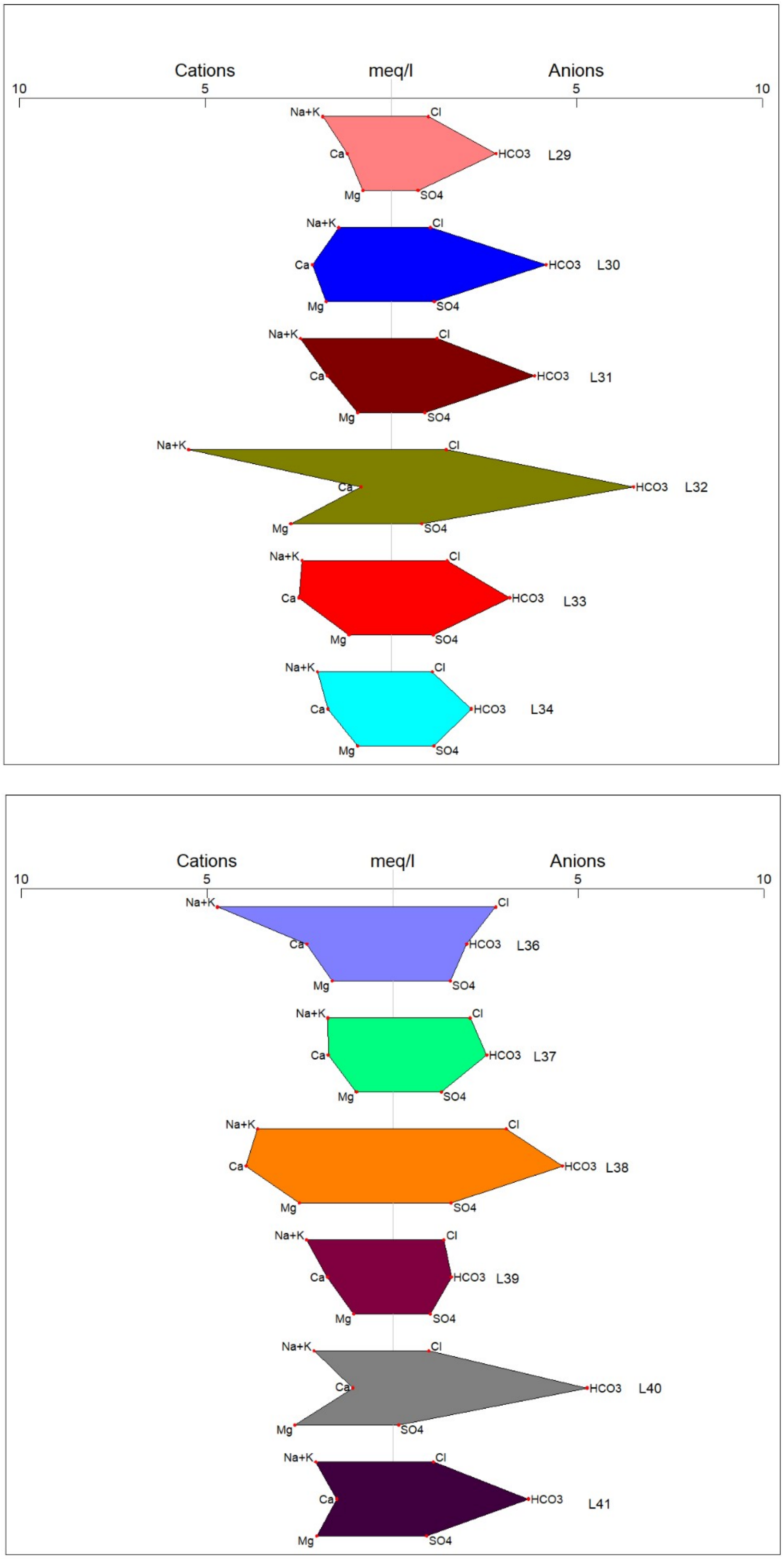




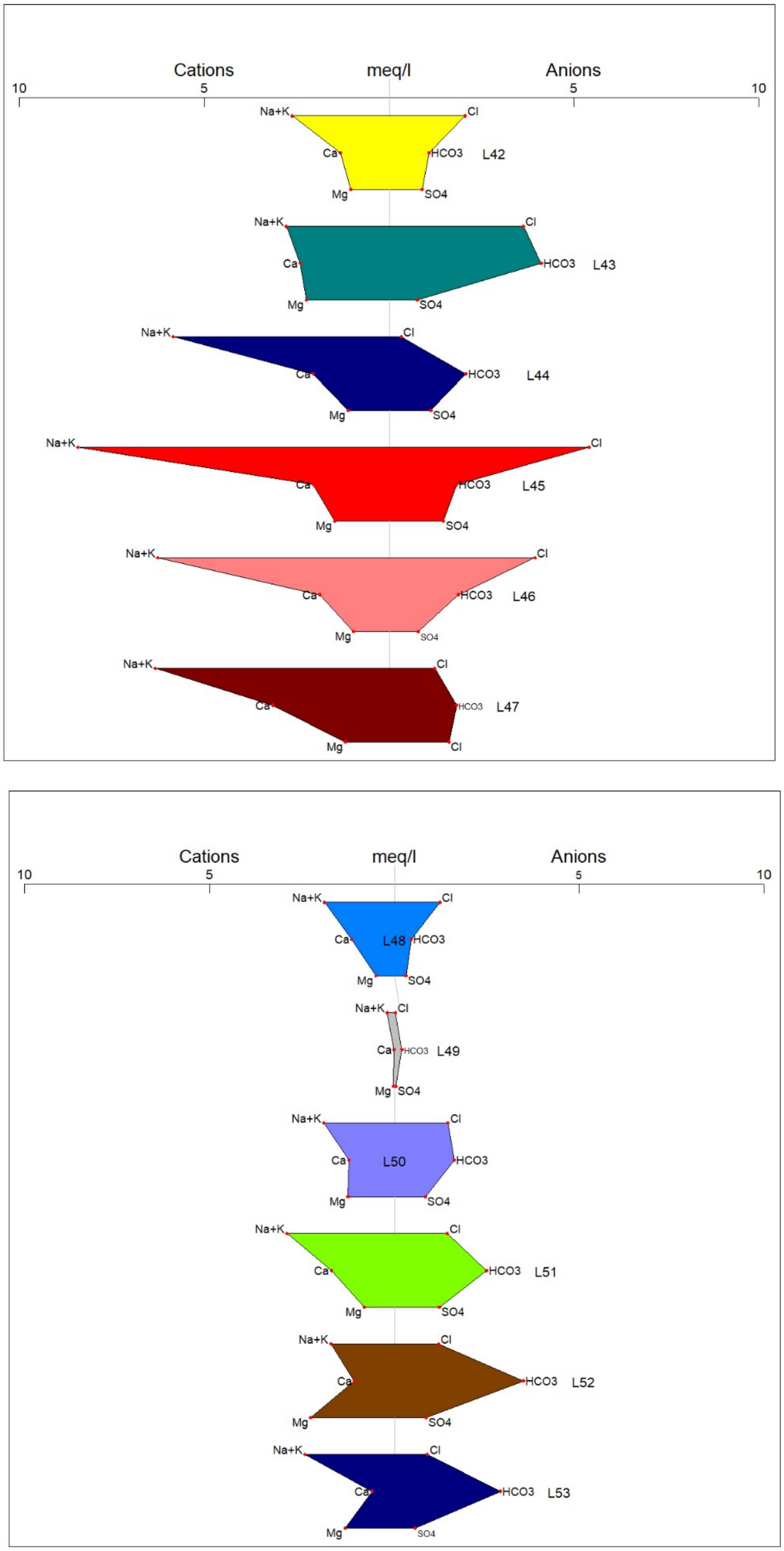
Stiff diagram for groundwater samples during the dry season (L1-L16)



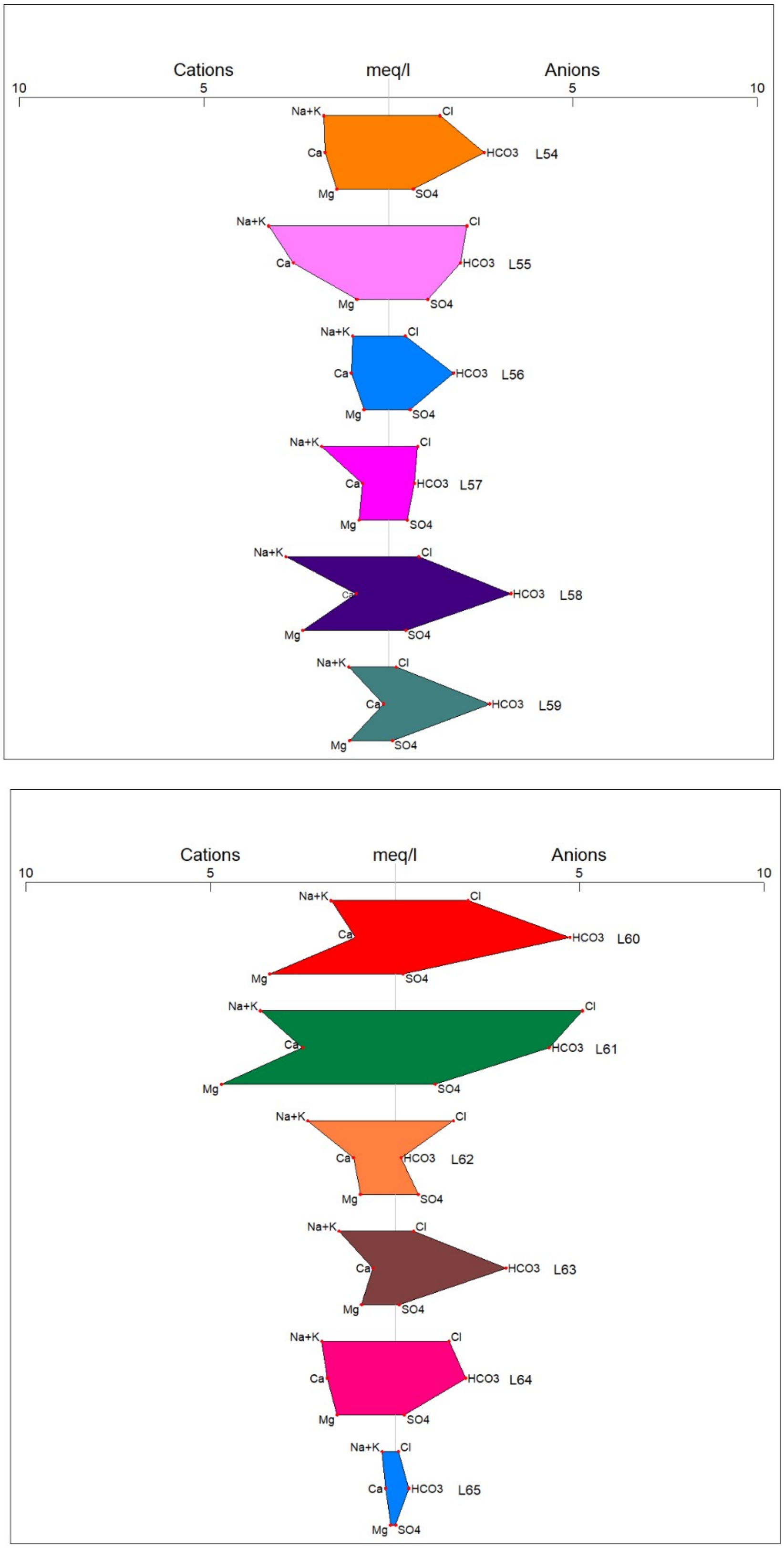
Stiff diagram for groundwater samples during the dry season (L17-L28)



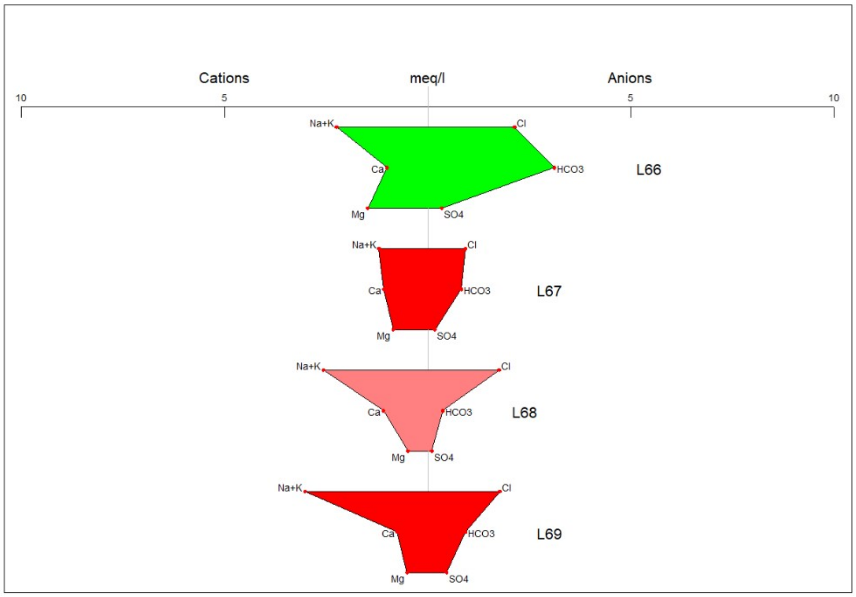
Stiff diagram for groundwater samples during the dry season (L29-L41)



Stiff diagram for groundwater samples during the dry season (L42-L53)



Stiff diagram for groundwater samples during the dry season (L54-L65)



Stiff diagram for groundwater samples during the dry season (L66-L69)

APPENDIX XI: FIELD PHOTOGRAPHS

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Conductivity meter used for pH, EC, TDS and Temperature readings

Packaged samples ready for shipping to Canada

Etrex GPS used for elevation and location readings

A typical motorized borehole sampled at Felele

Animal shelter built close to a hand dug well at phase II Lokoja

A typical hand dug well sampled at Filele

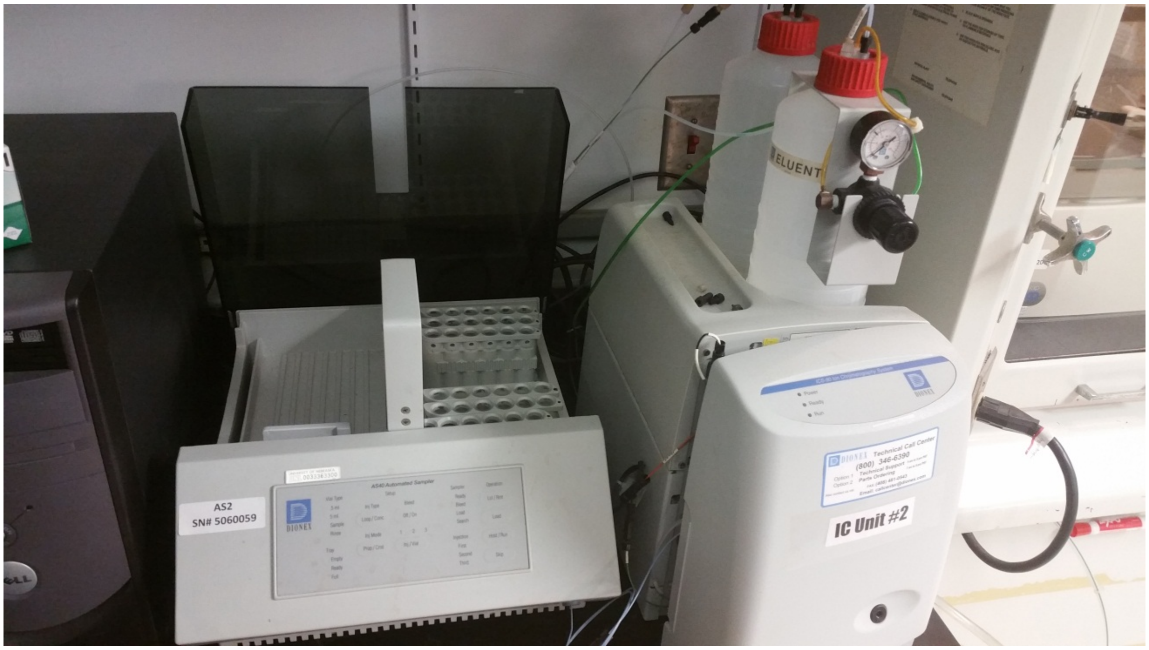
Labelled samples ready for packaging

A refuse dump and animal shelter close to a sampled well Rimi Wodi Lokoja

APPENDIX XII: Instruments used for analyses

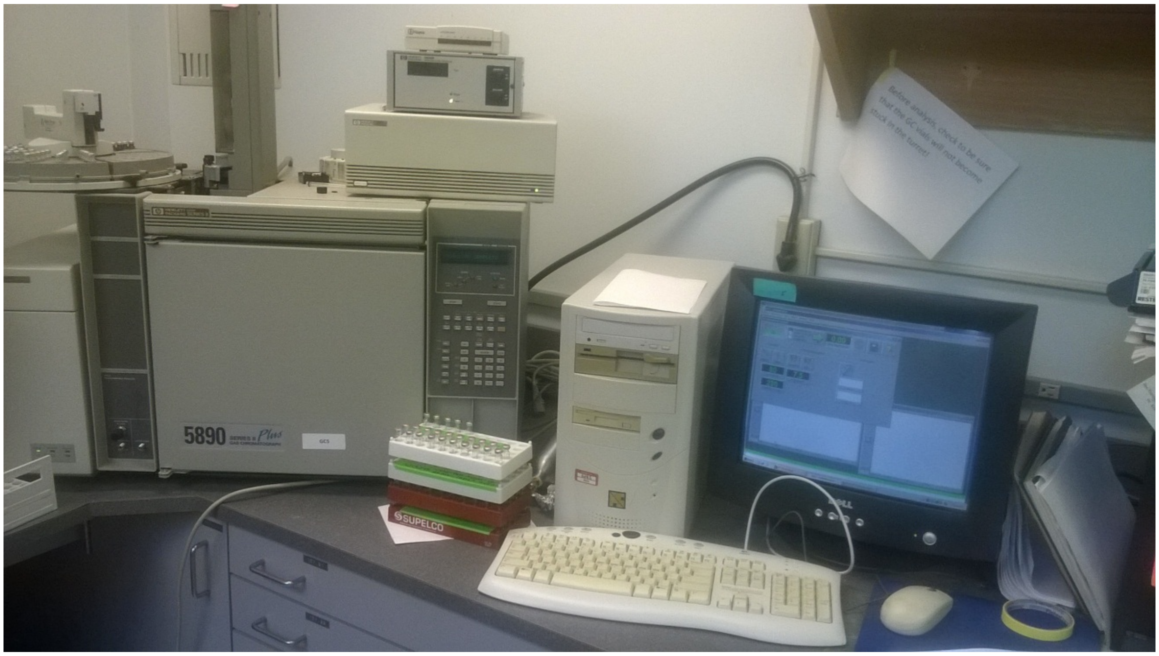
Hillquist Machine for thin section analysis

ICP-MS machine used for cations analyses



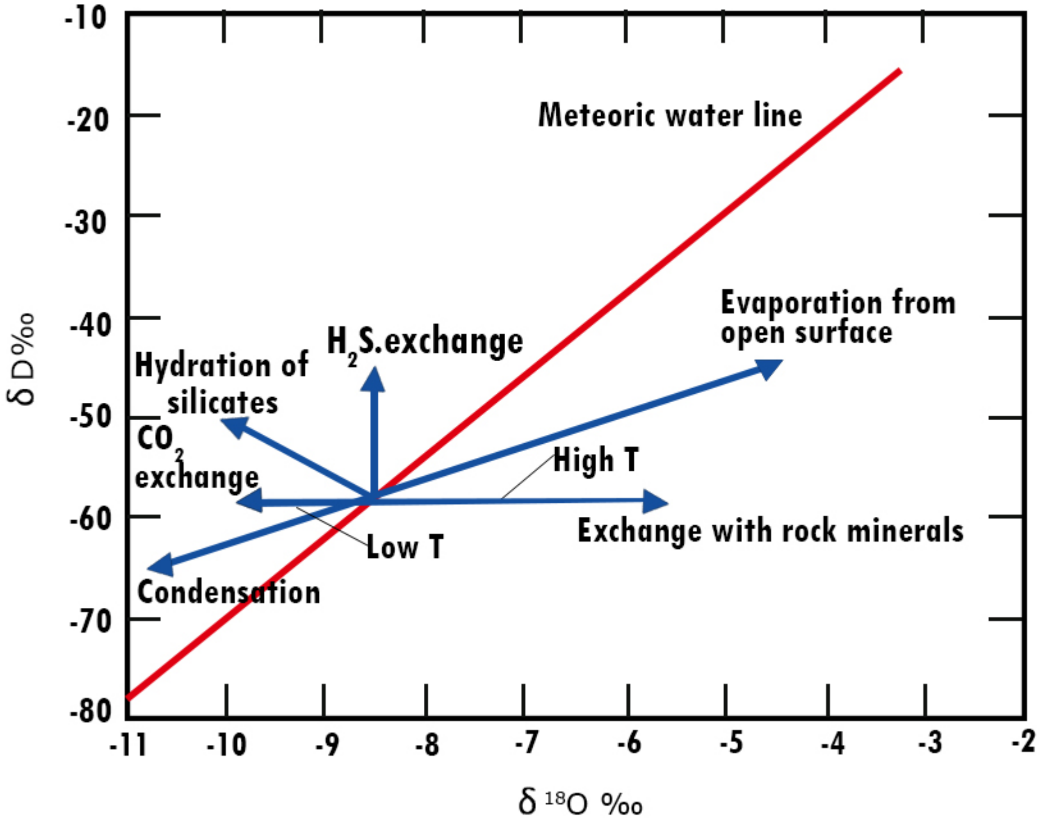
Ion chromatography machine used for anion analysis

Mass spectrometer used for δD anlysis



Mass spectrometer used for δ^{18}O analysis

APPENDIX XIII: Isotope compositions deviations away from the meteoric water line



Isotope compositions deviations away from the meteoric water line.

(Source: Shwartz and Zhang, 2003)