FEDERAL UNIVERSITY OF TECHNOLOGY MINNA

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INAUGURAL LECTURE SERIES 17

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Design + Print: ***Global Links Communications*** ***✆: 08056074844, 07036446818, 08080255301***

1.0 INTRODUCTION

1.1 Groundwater

Water is life. Without water there can be no life. Every aspect of agriculture requires adequate and timely supply of water to succeed. Groundwater has sustained agriculture in some desert regions of the world and in Nigeria through tubewells and washbores. The pattern and level of life development depend to a great extent on the quality, quantity and rate of water supply to the species. Civilizations have flourished with the development of reliable water supplies and have collapsed as the water supplies failed (Fetters 1972, Troften, 1973). Groundwater offers the most abundant source of water to man. It is the cheapest and the most constant in quality and quantity. Because it is not visible on the surface and probably because of misinformation about groundwater, many people undervalue the importance of ground water in sustaining water supply needs.

Groundwater exists in three major rocks in Nigeria- Igneous rocks, sedimentary rocks and metamorphic rocks. Each of these rock types has many varieties which need careful studies by geologists. Experience has shown that most important organs of the human body are not seen outside. For example blood and the heart that pumps it are not visible yet they are very important. The existing situation whereby greater emphasis is placed on surface water than groundwater can be likened to a woman using costly soap and detergent to kill germs on her body without caring for the infections in the blood which have caused skin diseases.

The money, time and emphasis given to surface water development in Nigeria at the expense of groundwater development has not been justified in terms of meeting water needs. A study of water supply for irrigation, domestic purposes and hydro-electric power generation up to 1993 shows that 63 large dams and 99 small dams had been constructed (JICA, 1993; FAO, 2005). Out of these, 31 large dams and 45 small dams were used to irrigate 418,620 hectares and 45,880 hectares of land respectively. Twenty six (26 number) large dams and 53 small dams were used to supply water to 5,718,500 people and 2,298,300 people respectively. Six large dams were used to supply 4,978 MW of hydro-electricity and one small dam used to supply 16 MW. The huge amount spent without water reaching enough people could have been complemented with a conjunctive development of groundwater sources with better results (Olasehinde, 1983; 2003; Olasehinde and Awojobi, 2004).

1.2 Water Supply in Nigeria

The population of Nigeria has been increasing at a rate of about 3% yearly since 1991 (FOS/ Population Commissions, 2001) (Table1). Water supply has not followed the same trend, rather it has been stagnant. Water supply coverage of Nigeria has remained at 57% level for long. This percentage can be greatly improved upon by a conjunctive use of surface and groundwater sources. One of the limiting factors has been poor knowledge about the possibilities of groundwater sources and uses in Nigeria.

Table 1: Population of Nigeria (1952 – 2015)

Year	Population (millions)
1952	31
1963	56
1991	89
1993	94
1994	97
1995	99
1996	103
1997	105
1990	86 Projected
1995	99 Projected
2000	115 Projected
2005	134 Projected
2006	140 Projected
2010	155 Projected
2015	179 Projected

(Source: FOS/Population Commission 2001)

It has been observed that, poor health delivery, poor sanitation and low agricultural productivity are linkable to inadequate water supply or water "crises" (UN Water Report, 2003). This is true of Nigeria which ranks 151 out of 171 countries studied in 2004 (Offodile, 2009). The study shows that 70% of Nigerians are poor. Although there has been continuous decrease in infant mortality, the rate is still high. The government's water resources development program of 1999 has resulted in the rapid decline in reported cases of water related diseases such as cholera, hepatitis, diarrhea and guinea worm infestations. Also, the supply of electricity in Nigeria has depended more on hydro-electric sources than others. It is therefore pertinent to look into how water supply can be improved upon by complimentary use of groundwater and surface water sources in Nigeria. Water, must be seen as a social and economic resource as articulated in the African Vision for Water Resources Management at the Second World Water Forum held in the Hague (The Netherlands) in 2000. African governments under the New Partnership for African Development (NEPAD) also recognized the role of water in economic development of the continent. Among the ten point agenda of the African Vision, five deserve mention here that:

1. There is sustainable access to safe and adequate water supply and sanitation to meet the basic needs of all.
2. There is sufficient water for food and energy security.
3. There is an adequate number of motivated and highly skilled water professionals.
4. There is an effective and financially sustainable system for data collection, assessment and dissemination for national and trans-boundary water basins.
5. There are effective and sustainable strategies for addressing natural and man made water resources problems, including climate variability and change.

The other five points relate, mainly to institutional frame work for attaining the vision which will be considered later. Clean water is a *sine qua non* for enhancing people's health and wealth. Out of a sampled world population of 8 billions, over 1,100 billion people did not have access to safe and clean drinking water by (WHO, 2004). This led to the setting of 2015 as the United Nations year of reducing the number of people without clean water by half (United Nations, 2000, Millennium Development Goals). In Nigeria water resources, including rain harvesting, surface water and groundwater are obtainable in varying quantity from place to place. The least understood of these sources is the groundwater source, yet, it is the most abundant, most reliable and cheapest to harness. These undisputable realities motivated the Nigerian Association of Hydrogeologists (NAH) to organize a Mini Summit in Jos on 10th and 11th September 2009. Many of "my people are destroyed for lack of knowledge" of groundwater (Hosea 4:6, Bible King James Version). A look at the global water situation will convince all on the need to study, understand, and invest more in the more abundant groundwater resources for both the rural and urban areas of Nigeria. A passionate commitment to solving water supply problems and management in Nigeria is highly needed. Accurate information and appropriate expertise are essential to achieving this goal.

1.3 Hydrogeology as a Profession

Hydrogeology is all about understanding the occurrence and behaviour of groundwater. Hydrogeology is both a descriptive and an analytical science. It is a branch of hydrology which is the study of occurrence, distribution movement and chemistry of all waters of the earth. The term geohydrology is sometimes used to describe an engineering field dealing with subsurface fluid hydrology (Fetters, 1972). The practitioners are called Hydrogeologists. The Hydrogeologists borrow from other disciplines to enhance the effective supply and management of groundwater. The experience in Nigeria is such that most of these other professionals "take over" the primary functions of the hydrogeologists and hence misinform the end-users when they fail. Some practice "water witching" and carry many people along with them. The myth created about groundwater has been great and has penetrated communities so much that it becomes difficult for the laymen to appreciate the important roles of groundwater in sustaining water needs in Nigeria (MacDonald *et al*, 2005). Before progress can be made these myths must be removed. Groundwater can provide a good avenue to achieving the Millennium Development Goals of the United Nations to reduce by half the number of people without clean water by 2015.

2.0 WORLD WATERS

2.1 Water Transfers

The world waters are perpetually in motion while maintaining a dynamic equilibrium. The constant movement of water from the atmosphere in form of rainfall, dews hailstones and snowfalls to the land and overland as runoff, vertically and horizontally into the ground as groundwater, as base flow and infiltrate into the sea and back to the atmosphere through evaporation and transpiration is called the hydrologic cycle. (Fig. 1).

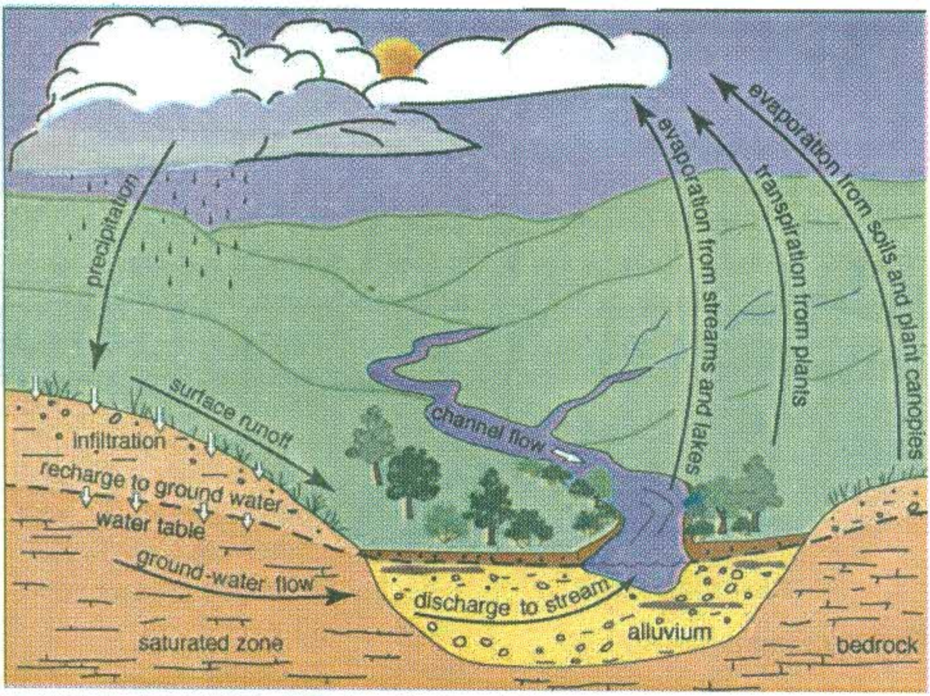

Fig. 1: Sketch of Hydrologic Cycle (http:/en.wikipedia.org/wiki/)

The sun seems to be source of energy that drives the cycle as evaporation from the sea and transpiration from the trees and plants take place to form clouds which condense to form rainfalls, dews, snowfalls and hailstones. The cycle is repeated over and over from time immemorial.

There is however a balance in the amount present in the following major areas of the world (Table 2).

Table 2: World Waters in Major Areas

1.	The Oceans	=	97.10% - 1,350, 400 x 10^3km^3
2.	Snow Field (ice caps and glaciers)	=	1.93% - 26,000 x 10^3km^3
3.	Groundwater	=	0.51% - 7,000 x 10^3km^3
4.	Lakes, Inland Seas	=	0.17% - 230 x 10^3km^3
5.	Rivers	=	0.0001% - 1.7 x 10^3km^3
6.	Atmospheric vapour	=	0.0001% - 13 x 10^3km^3
7.	Soil Moisture	=	Negligible

The amount of freshwater available to man includes:

i. Ice-caps and glaciers 1.9%

ii. Freshwater lakes.......................0.009%

iii. Rivers....................................0.0001%
iv. Groundwater...........................0.5000%

Total **2.5%**

Water from the ice-caps and glaciers are costly to extract, leaving 0.6% of world waters as extractable water source. Out of the extractable water sources, the groundwater is most abundant but less understood, despite its being the cheapest, fastest to harness and safest source compared with other sources. Water managers device means to increase the residence time of water as it moves in the hydrologic cycle (Offodile, 2002). Efforts to achieve these include surface impoundment of river water, well construction and rain harvesting.

The rates of water transfer in 4 major areas are:

i. Precipitation (Ocean + land) = $516 \times 10^3 km^3$/year
ii. Evapotranspiration = $516 \times 10^3 km^3$/year
iii. Surface runoff (Rivers) = $29.5 \times 10^3 km^3$/year
iv. Underground flow = $1.5 \times 10^3 km^3$/year

Residence time is given by

$$\text{Residence time} = \frac{\text{Volume of storage}}{\text{Rate of water transfer}}$$

The 4 different residence times are therefore:

i. Ocean = 3,035 years
ii. Rivers, lakes, inland seas = 231 years (all surface waters)
iii. Ice caps = 1,000years
iv. Groundwater outflow = 4,700years

The result shows that surface waters are the most dynamics source with very low residence time (Olugboye, 2008) while groundwater is the best with the highest residence time. This affords sufficient time for storage in the ground.

2.2 Water Balance Equation

The dynamic equilibrium in global water movements is expressed by the water balance equation. Simply put, it says **Output** of water in any water basin is equal to **Input**

That is, ***Input = Output***

Rainfall (P) is the major input. The output include infiltration (I) into the ground, run-off (R) on the surface through rivers and streams and evapotranspiration (E_T)

Precipitation/Rainfall = Infiltration + Runoff + Evapotranspiration.

That is $\mathbf{P = I + R + E_T}$

Where, **P** = Precipitation, rainfall, snowfall

I = Infiltration (Soil moisture, groundwater, baseflow)

R = Surface Runoff through rivers and streams

$\mathbf{E_T}$ = Evapotranspiration.

Hydrogeology therefore combines studies of climates, morphology, hydrology and geology of water basins of the world. Groundwater studies are therefore multidisciplinary in scope. The synthesis and integration of all disciplines is best done by a geologist and not by the associates.

Groundwater component of the hydrological cycle can be estimated from place to place before detailed exploration techniques are put in place. This is the stage to "Swim" inside the groundwater. If the soil moisture and base flow are assumed constant the major component of Infiltration (I) is the groundwater from the equation above.

$$I_{(GW)} = P - R - E_T$$

Where, $I_{(GW)}$ = Groundwater Component.

Once the precipitation, runoff and evapotranspiration are known the groundwater can be estimated. The potentials of groundwater cannot be appreciated unless accurate estimates are made. Case studies have shown that there is enormous groundwater potential in Nigeria more than expressed. One can "swim" inside them. In the light of the above the geology of Nigeria has been summarized next. This is the medium like Swimming pool that houses the groundwater. After the geology is known the groundwater characteristics can be studied.

To achieve the best in understanding groundwater rainfall, runoff and evapotranspiration must be systematically gathered for many years. There must be several years of continuous data gathering in order to make assumptions in water balance relevant (Todd, 1980, Adefila, 1977).

2.3 Meeting Water Needs in Nigeria

Water is present, but not restricted to, where there is life. Water is an essential element of life along with the air we breathe. Water is needed for drinking, washing, agriculture, food, hydro-electric power generation, transportation and industry. It is therefore correct to say that water is the most essential element for man's well being, social and economic progress.

The need for water is increasing all over the world and especially in Nigeria as a result of:

1. Increase in population. In Nigeria the growth rate is 3% per year. The population of 140million as at 2006 in Nigeria cannot cope with water facilities designed and constructed for 103million a decade ago.

2. Increase in Industrialization, commercial activities and public institutions. In earlier times, available water was sufficient for the type of activities of man but for example as the beverage industries increase the need for more water increases (Table 3).

3. Increase in standard of living. All over the world, with increase in knowledge, the standard of living is increasing. For example, the peasant farmer had no need for washing of cars, and watering the flower garden. With more learning, education, and civilization the hygiene level demands the use of more water.

Table 3: Comparative Water Uses in Selected Industries

Industry	M^3 Water/Ton of Product
Coal	1.5
Coca-cola	5.0
Steel	5 – 100
Brewing	10 – 20
Fermentation	20 – 100
Paper	30 – 300
Sulphuric acid	4 – 25
Caustic soda	90
Acetic acid	450
Amino sulphate	900

The target for water supplies to Urban and rural populace in Nigeria for 1970 – 80 was 114and 20 – 30 litres per head per day respectively (Olugboye, 2008). Only one state capital met the target as at 1972 while by 1980, nine state capitals out of twelve met the requirements. Towns like Ibadan, Calabar and Maiduguri did not meet the target probably due to high rate of population growth and lack of infrastructure to provide enough water for the growing population (Fig. 2).

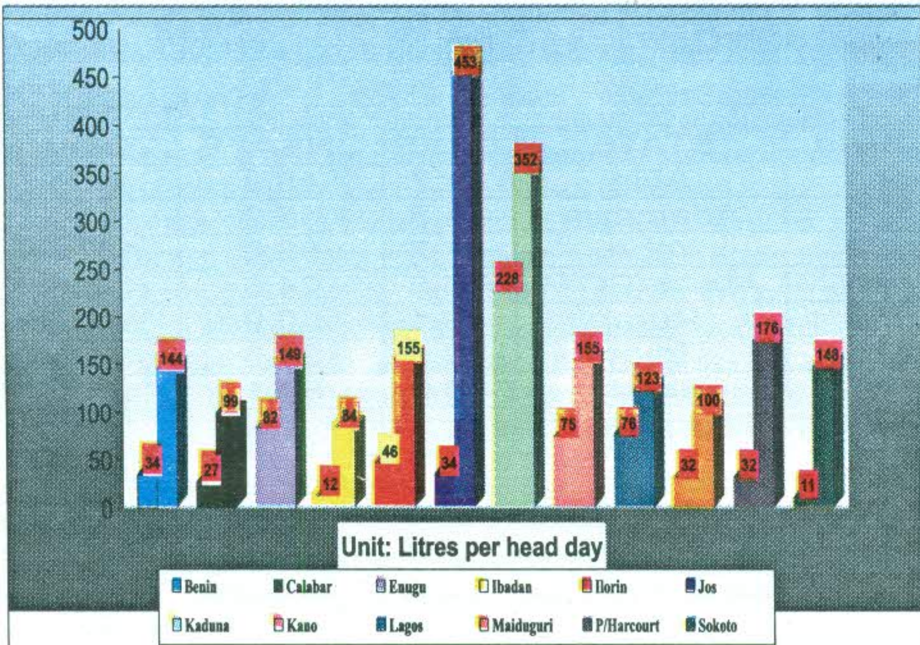

Fig. 2: Progress in Water Supply per Head per Day in Decade in 12 Selected State Capitals of Nigeria
Source: (WHO, 2004)

2.3.1 Water Supply Sources

By 1995 the United Nations Children and Education Fund (UNICEF) had identified eight major sources of water supply in Nigeria. These are ponds, protected and unprotected dugwells, hand pumped wells, public taps, piped borne water, water vendor and others (Table 4).

Table 4: Water Sources and Percentage Supplied

	Water Source	Percentage Supplied
i.	Piped borne water	9.4% of population supplied
ii.	Public tap water	11.4% of population supplied
iii.	Hand pumped	11.6% of population supplied
iv.	Protected dugwell	18.6% of population supplied
v.	Unprotected dugwell	17.4% of population supplied
vi.	Pond water sources	29.2% of population supplied
vii.	Water vendor	1.8% of population supplied
viii.	Others	0.6% of population supplied
	Total	**100% of population supplied**

These water supply sources are grouped into two-safe and unsafe (UNICEF 1995 Multiple Indicator Cluster Survey) (Table 5).

Table 5: Percentage Distribution of Households with Access to Safe Drinking Water in Nigeria

S/No.	STATE	SAFE	UNSAFE	TOTAL
1	Abia	51.7	48.3	100
2	Adamawa	44.8	55.2	100
3	Yobe	47.2	52.8	100
4	Abuja (FCT)	75.5	24.5	100
5	Rural	39.1	60.9	100
6	Urban	79.5	21.5	100
7	Total	49.9	50.1	100

Source: UNICEF, 1995 (Unpublished)

In Africa, the World Health Organisation computed in the Seventies that on average only 73% of urban population had access to potable water supply while for the rural area it is 19%. However, in Nigeria only 58% of Urban and 8% of rural populace have access to potable water supply (Olugboye, 2008).

2.3.2 Success of Groundwater Development

It is observed that government and private individuals have spent a lot of money and energy on groundwater development. However, these efforts have not yielded the right results. For example within a period of fourteen years (1989–2002) the number of bore holes drilled in the Northern Nigeria according to data from UNICEF (Nigeria) was 16,827 while only 13,903 were actually completed and a success rate of 93% (Table 6). The success rate had been found to be lower because many unsuccessful and failed boreholes were not recorded (Adelana *et al*, 2008). For example out of 53 boreholes in Asa Local Government Area of Kwara State Nigeria only 37 (70%) were successful while for Ilorin West LGA only 77(74%) out of 104 boreholes were successful (UNICEF, Kwara State, Nigeria Files). The percentages were lower for the PTF (Petroleum Training Fund) projects in Oyo state. (Sanusi Partnership, Oyo State).

Table 6: Summary of Borehole Information in Northern Nigeria

Period	No. of Boreholes Drilled	No. of Boreholes Completed	Success Rate %	Borehole Depth (m) mean rage	Static Water Level (m) mean Range
1989 – 2002	16,827	13,903	93	38.6: 2 – 240	7.8 : 0.1 – 120

Source: UNICEF Unpublished

However, contrary to all these, experiences have shown huge success (Olasehinde, 2010) with a good understanding of groundwater which cannot be had without a good understanding of geology. Geology is a multidisciplinary profession. Geology is the study of the earth in its entirety. All science subjects are needed in the study of geology. Chemistry is needed in studying the chemical components of rocks, minerals, and water. Physics is essential in studying the physical properties of the earth's fields such as electrical, magnetism, gravity, seismic and others. Mathematics and statistics are needed in data computation and modeling. Biology is essential in understanding past life. Economic geology makes use of knowledge of economics. None of these subject areas should be regarded as geosciences on its own, because a limb cannot stand as the whole body. A statistician cannot become a Geoscientist because he teaches geostatistics. The geology of areas must be studied in details before further measurement are made in groundwater explorations.

3.0 GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The study of groundwater resources of any country or area involves the study of geology, geophysics, hydrology, geography, and climate of such land area. These are needed in understanding the hydrogeology of the area and hence the hydrogeologist is a person trained in all aspects of several disciplines. (Offodile, 2002). A geologist is not qualified as hydrogeologist unless he is trained in all the aspects above, neither is a statistician, who helps in geostatistics, an hydrogeologist unless he is trained in the four areas above. However, a very good knowledge of hydrology and geology of an area is essential for a good knowledge of the groundwater. An engineer who is a specialist in hydrology should not boast as hydrogeologist and neither should a physicist who specializes in geophysics an hydrogeologist. Mathematics is necessary in the interpretation of geological data just as calculus is useful in phonetics. Many statements on groundwater sources in Nigeria are made by non-hydrogeologists leading to misinformation and failures.

Before giving a summary of the geology of Nigeria some information on the hydrology and climate are necessary. There is an interaction between surface water and groundwater of an area. This interaction needs careful study of large data which are still poorly collected and co-ordinated in Nigeria (The Nation, August 29, 2010). The surface-groundwater interaction study is still in its infancy and is on-going in Nigeria. It is therefore sufficient to give some information on hydrology and climate.

1.1 Geographical Information

Nigeria lies south of the Sahara within West Africa, with the Atlantic Ocean bordering the southern coastal region (Fig. 3). The country lies within longitudes 2°50′E and 14°20′E and latitudes 4°10′N and 13°48′N, an area of 923,786km². Four major physiographic regions are observed in Nigeria (figure 3). The drainages are derived mainly from the highland areas (mainly basement complex rocks). The climate is typically tropical with semi-arid north and humid in the south. The tropical climate is characterized by the dry and raining seasons which are linked with the movement of the Inter-Tropical Convergence Zone (ITCZ) north and south of the equator.

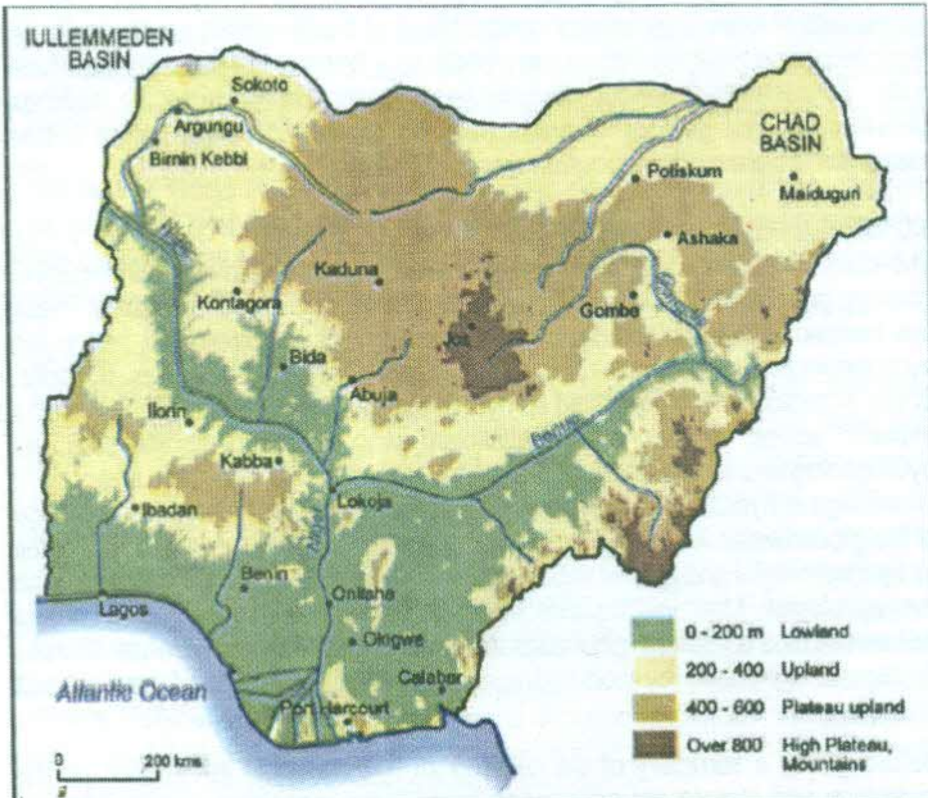

Fig. 3: Physiographic Regions of Nigeria (After Adelana *et al*, 2008)

The temperature varies spatially but on the average the day temperature exceeds 36°C while the night temperature is about 22°C. The variations in temperature are slight between the two seasons hence only the rainfall can be used to differentiate the two seasons into wet and dry in Nigeria except in the costal zones where it rains all year round. The mean annual rainfall along the coast in the southern region is 4,800mm while it is less than 500mm in the northeast (Goni, 2002; Adelana *et al*, 2003).

3.2 Hydrology

Surface water flowing from Nigeria to the sea is estimated at 263km^3/annum (FAO, 2005). There are four main rivers (Fig. 4):

i. The Niger - Benue River
ii. The Chad Basin
iii. The Southwestern lithoral
iv. The Southeastern lithoral with transborder flow from Cameroon.

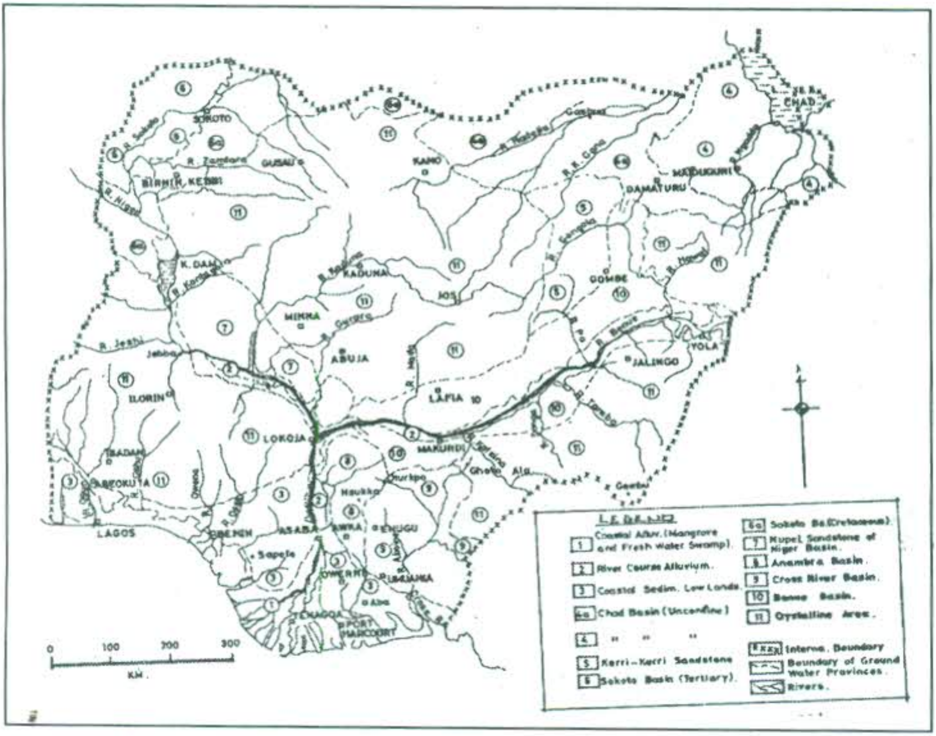

Fig. 4: Major Drainage of Nigeria (After Offodile, 2002)

Nigeria receives an estimated 30km^3 from River Niger (this dropped to about 18km^3 in the eighties) and 29km^3 from Cameroon – Benue tributaries.

Groundwater recharge from precipitation is estimated at 87km^3/annum of which about 80km^3 discharges as base flow to major rivers. A total of 63 large dams and 99 small dams have been built so far with a reservoir capacity of 30.3km^3 as at

1993. This is less than 50% of $87km^3$ for groundwater. The waters from the reservoirs are distributed as follows (FAO, 2005) (Table 7):

i. $10.9km^3$ (36%) for irrigation
ii. $0.8 km^3$ (3%) for water supply
iii. $18.6 km^3$ (61%) for hydro power.

Table 7: Surface Water Uses in Nigeria as at 1993

Total	Irrigation Dams	Water supply	Hydro power	Type
63	31	26	6	Large Dams
Uses	418,620 Hectares	5718,500 people	4,978 MW	
99	45	53	1	Small Dams
Uses	45,880 Hectares	2,298,300 people	16MW	

Source: (JICA, 1993; FAO, 2005)

Comparing these figures with boreholes within the same period we observe that out of 23,229 boreholes drilled for a population of 88.417million people in an area of 915,800Km2 only 17,640 were successful. Majority of the boreholes (14,330) were fitted with hand pumps while 3,310 were fitted with motorized pumps. The success rate was 76%

Eight Sub Hydrological Areas (SHA) are known in Nigeria. The land uses include – Forest land, Grass land, Agricultural land, Water area, Bare land and Urban areas (Table 8).

Table 8: Land Use in Sub Hydrological Areas (SHA) in Nigeria (km^2)

	I	II	III	IV	V	VI	VII	VIII	TOTAL
Land area	131,600	158,100	158,100	73,000	53,900	100,500	59,800	188,000	923,800
Forest land	2,755	27,380	13,365	14,700	14,760	44,250	13,705	5,920	136,835
Grass land	46,615	59,745	75,850	13,945	3,775	4,675	835	75,640	281,080
Agricultural land	69,520	67,020	46,275	39,290	14,265	41,015	38,650	76,300	392,335
Water area	1,400	1,040	630	370	1,745	1,850	420	340	7,795
Bare land	10,330	2,065	21,615	3,230	7,955	900	5,405	27,700	79,200
Urban	10	35	0	5	220	1,080	20	140	1,510
Sub total	12,710	3,955	23,410	5,065	21,100	10,560	6,610	30,140	113,550

Source: JICA, 1993

3.3. Summary of Geology of Nigeria

Various authors have described the geology of Nigeria (Kogbe, 1989). The three main rock groups include Precambrian and Mesozoic to Tertiary basement complex and volcanic rocks (crystalline metamorphic-igneous-volcanic rocks); Mesozoic to Tertiary sedimentary, younger granites and volcanic; and Quaternary to Recent alluvial deposits (Fig. 5). These groups of rocks can be divided into twelve sub-groups based on rock types and regions.

These are:

(1) The North Central Basement Complex Rocks
(2) The Western Basement Complex Rocks
(3) The Eastern Basement Complex Rocks of Obudu Plateau
(4) The Upper Benue Volcanic Rocks of Biu Hills
(5) The North Western Sedimentary Rocks of Sokoto Area
(6) The North Eastern Sedimentary Rocks of Chad Basin
(7) The Middle Niger Sedimentary Rocks: Nupe Sandstone Basin.
(8) The Upper Benue Sedimentary Rocks
(9) The Eastern States Sedimentary Rocks
(10) The Coastal Lowland Sedimentary Rocks of Benin Basin
(11) The Coastal Alluvium Mangrove and Freshwater Swamps
(12) The River Course Alluvium.

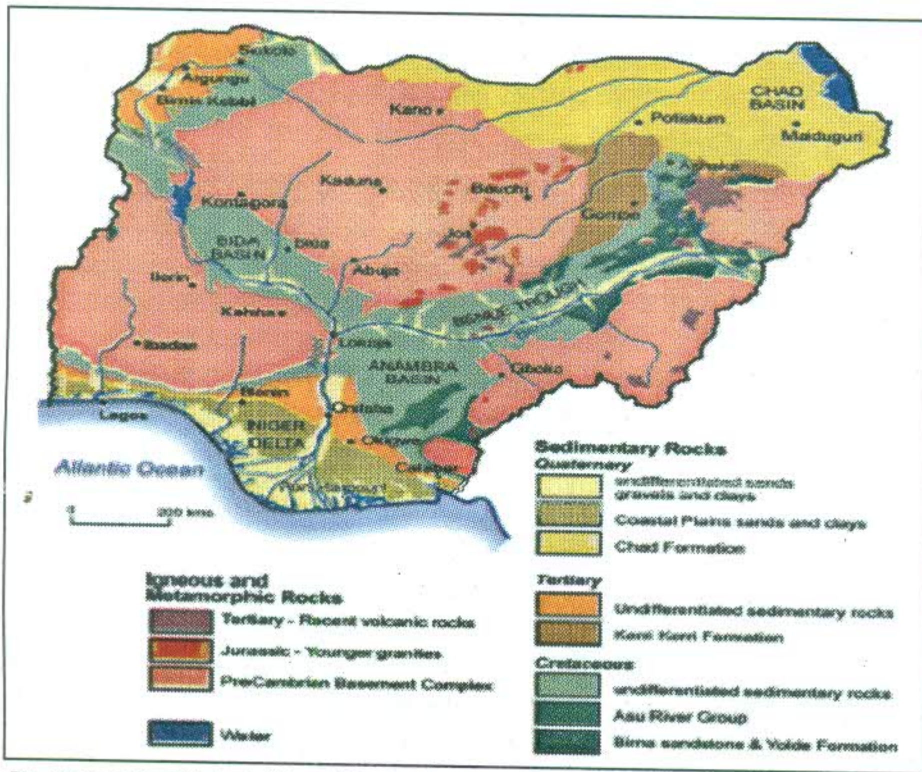

Fig. 5: Generalised Geological Map of Nigeria and Groundwater Provinces (After Adelana *et al*, 2008)

(A) BASEMENT COMPLEX ROCKS

The Precambrian Basement Complex and Mesozoic to Tertiary rocks can be described in four areas of the country. These are North-Central Area including the Jos Plateau and Kaduna–Abuja Areas, the Western Basement Complex, the Eastern Basement Complex and the Upper Benue Volcanic Rocks.

3.3.1 North-Central Basement Complex Rocks of Jos Plateau and Kaduna – Abuja Areas

These areas are generally 400-600metres above the sea level with Jos Plateau reaching above 800m above sea level. River Sokoto flows North West from this highland before turning at Argungu to flow to River Niger southwards (Fig. 4). Rivers Kaduna, Chanchanga and Gurara flow southernly to discharge into River Niger while, River Gongola flows to River Benue and Rivers Hadejia, Jamare flow northeasterly into Niger Republic and Chad Republic. The rocks are mainly composed of gneisses, migmatites, granites, schist, phyllites and quartzite. The North-Central Basement complex rocks can be divided into two - the western part with narrow, tightly folded north-south trending schists and the eastern with Jurassic age younger granites forming ring complex structures. (Jacobson and Macleod, 1977).

3.3.2 The Western Basement Complex

These consist of migmatites, banded gneisses and granite gneisses with low grade metasedimentary and metavolcanic schist intruded by Pan-African age granites and charnokites (Oyawoye, 1972). The migmatites and gneiss metasediments are often intruded by mineralized pegmatite veins and dykes (Oluyide *et al*, 1998). Older granites, granodiorites and syenites, with dolerite dykes, are also found here. The crystalline rocks are similar to the north-central rocks described earlier on but the quartzite-granite-schist complex are more prominent here than earlier ones. This is typically found around Ibadan area-Ibadan Quartzite schist complex.

Unlike the radial flow of surface rivers from the north-central basement rocks prominent rivers flow southernly to the Atlantic Ocean here. Most of the land area is 200-400 metres above sea level with a small portion south of Kabba and north of Ibadan being between 400–600 metres above sea level (Plateau upland). These rivers include Rivers Ogun, Oshun, Owena and Osse starting from the west to east. Rivers Moshi and Awon flow from the highland to the north to discharge into River Niger (Fig. 4).

3.3.3 The Eastern Basement Complex Rocks

The rocks here are found in the Oban massif and Obudu plateau. The rocks are distinct from the rest of the Basement Complex rocks in that they occupy a rugged, high altitude area of over 800 metres above sea level (Fig. 2). They form deep gorges between the plateaus. However, they are similar mineralogically to the other rocks. The combination of mineralogy and morphology gives distinct hydrogeological characteristics different from other areas. The rivers here especially River Katsina Ala and River Taraba flow westerly to River Benue.

The Oban massif consists of three rock types:

a. Migmatite and sheared gneiss
b. Older granite
c. Unmetamorphosed dolerite and microdioritic intrusive.

The Obudu Plateau has rocks mainly of gneisses and migmatites. Outside the hilly terrain rocks are not exposed due to thick weathered rocks (red soils) with broken quartz pebbles and laterite. The rocks are highly folded. However, north of the Obudu plateau in the Gongola area, older granite rocks and isolated tertiary to recent volcanic rocks are found and fractures are more than in the southern part.

3.3.4 The Upper Benue Volcanic Rocks (BIU Plateau)

This area is separated from the Gongola Plateau by the rift arm of the Upper Benue Trough (Fig. 5). It has its northern boundary with the Chad Basin. Volcanic rocks mainly basalts, are the dominating morphology in the Biu area (Biu Basalts). Theses rocks also occur dotted in the Jos Plateau (North-Central Basement Complex area) and Eastern part of Nigeria. The dominant rocks here comprise of granites, gneisses, schists and migmatites. The hydrogeological characteristics of Upper Benue volcanic terrain can be divided into two-the high yielding volcanic area and the low yielding basement complex rocks which occupy about two-third of this area. Rivers Ngadda, Yedecram and Gema spring from this terrain and flow northeasterly to Lake Chad, while River Hawal flow south to River Benue.

(B) SEDIMENTARY ROCKS

The Mesozoic to Tertiary sedimentary rocks are six in number:

3.3.5. The North Western Sedimentary Rocks of Sokoto Area.

The northwestern sedimentary rocks constitute the Sokoto Basins. They consist of the sedimentary rocks formation of Cretaceous age (Rima, Gundumi and Illo Formations) and sedimentary rocks formation of Tertiary age (Gwandu and Sokoto Group Formation) (Offodile, 2002; Olugboye, 2008; Adelana *et al*, 2008). These basins form part of the larger Lullemmeden Basin that extends to Niger, Chad and Benin Republic (Olugboye, 2008).

Five major aquifers are recognized within these two basins (Fig. 6):

(i) The Gundumi Formation (Lower Cretaceous) which includes river and lacustrine deposits, which contains comparatively coarser materials than any of the younger overlying formations of the Sokoto Basins.

(ii) The Illo Group (Cretaceous) includes non-marine cross-bedded pebbly sand and clay that underlie an area of about 6400km^2 in the southwestern part of Sokoto Basins.

(iii) The Rima Group (Upper Cretaceous) comprises from base to top of Taloka, Dukamaje and Wurno Formations of marine origin (Oteze, 1989). These include sandstone and shale interbedded by limestone and mudstone in places.

(iv) The Sokoto Group (Paleocene) consists of a lower unit (the Dange Formation of marine clay shale) and an upper unit of light-grey and white-clayey limestone with nodular crystalline limestone, known as the Kalambiana Formation.

(v) The Gwandu Formation (Paleocene) lies unconformably on the Sokoto Group. It consists of semi-consolidated fine to coarse-grained sand with clay-shale.

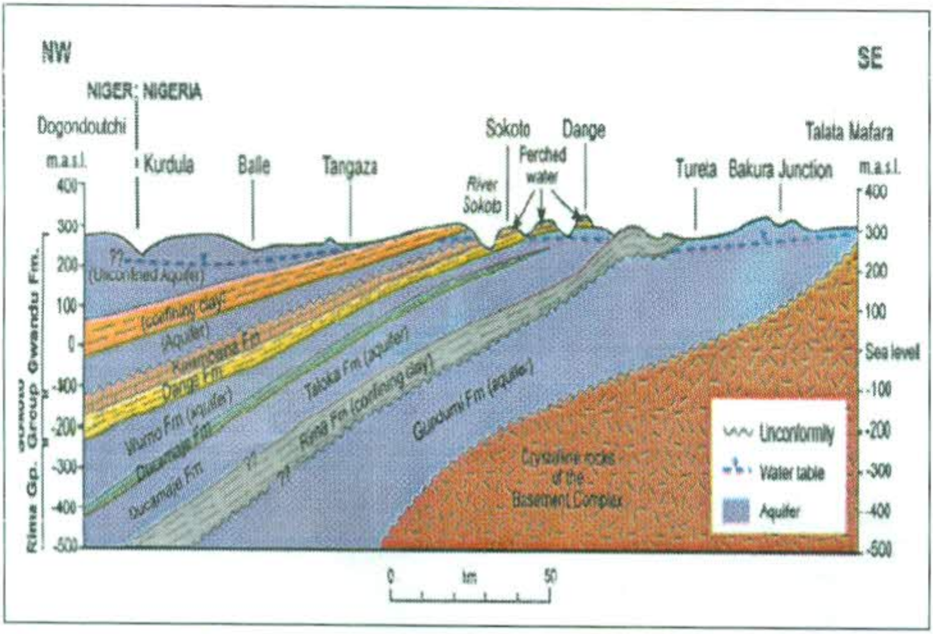

Fig. 6: Hydrogeological Cross-section through Sokoto Basin (after Anderson & Ogilbee, 1973; Adelana et al, 2008)

3.3.6. The Northeastern Sedimentary Rocks of Chad Basin

The Chad Basin is a vast area of inland drainage in the southern Sahara stretching from Northeastern Nigeria to Western Sudan and from Central African Republic to Niger Republic. The total area is about 1,536,000km^2 and only one tenth of the area lies within Nigeria. The deposits are of tertiary age. Three well-defined aranaceous horizons lie within the argillaceous Chad Formation and make up what are referred to as the upper, middle and lower aquifers (Fig. 7). The zones are aquiferous sands separated by thick clay sections. The Chad Formation therefore generally consists of sandstones and clays. The superficial deposits are composed of alluvium and aeolian sands and gravel of recent times.

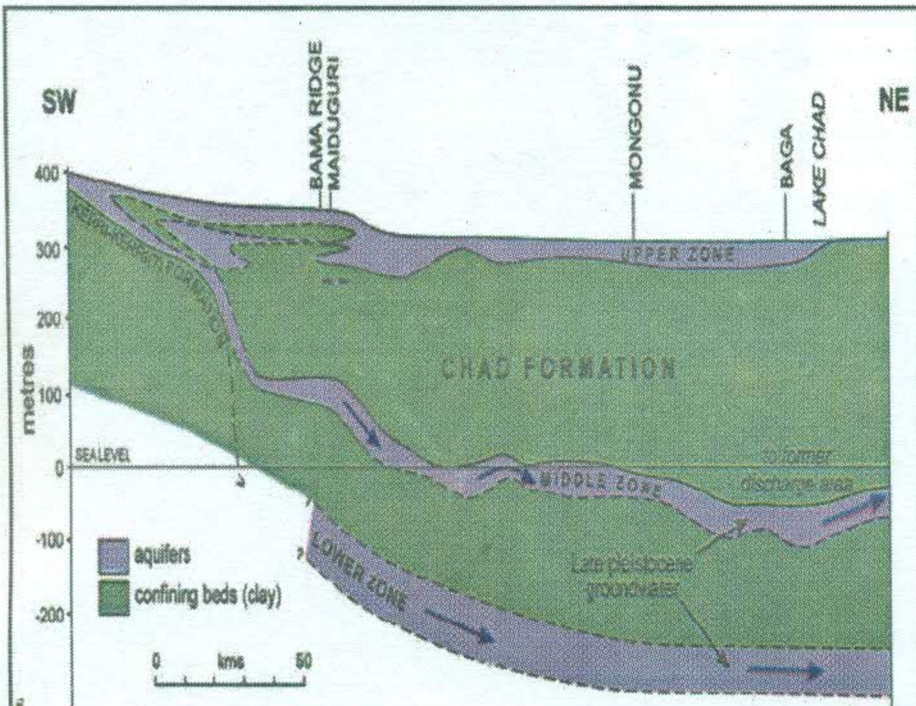

Fig. 7: Geological Cross-Section Showing the Aquifers of the Chad Basin (After Adelana *et al*, 2008)

3.3.7. The Middle Niger Sedimentary Rocks: Nupe Sandstone Basin

The Middle Niger Sedimentary rocks called Nupe Sandstone lie NW-SE parallel to River Niger almost entirely in Niger State, Nigeria and partly in Kwara State and Federal Capital Territory. It is encircled by rocks of the Basement complex. The sediments are composed of weakly cemented fine to coarse grained feldspathic sandstones and siltones with thin beds of carbonaceous shale that are locally interbedded. The carbonaceous shales are prominent around Kudu area – possibly a type locality of a new formation-"Kudu Formation" yet to be fully established (Idris-Nda, 2010). Lenses of conglomerate, clays and breccias also occur particularly near the contact with the underlying Basement rock (Fig. 8). The sediments are all of Cretaceous age. The formation is capped in many places by laterite and form mesas in places. The thickness of the sediments from the contact in the south to the north and from the north to a central portion of the basin around Kudu area (Fig. 8).

South North

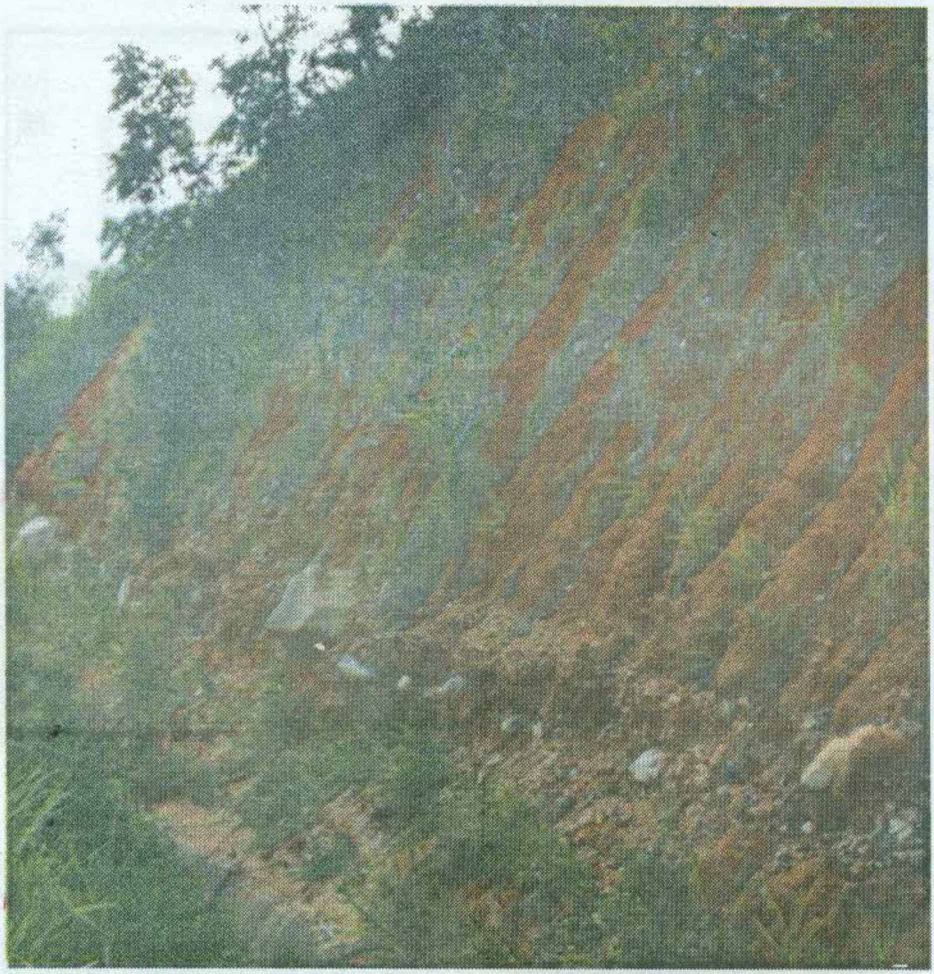

Fig 8: Contact between Nupe Sandstone and the Underlying Basement Rock
Source: Author, August, 2010

3.3.8 The Benue Trough Sedimentary Rocks

The Benue Trough is subdivided into three basins as Upper, Middle and Lower Benue basins. However, the Middle and Upper Benue sedimentary rocks are discussed in this section seeing that the hydrogeological characteristics of the Upper and Middle basins are similar. (Offodille, 2002, Olugboye, 2008, Adelana *et al*, 2008). It includes the sediments of the basal cretaceous sandstones of the Bima and Yolde Formation, the shales of Fika group, the estuarine sandstones of the Gombe Formations and the marine facies of Lafia, Keana and Awe areas.

I. The Middle Benue basin consists of the sedimentary rocks of Lafia, Keana and Awe Formation (Nassarawa State). The rocks consist of thick marine transgressional shales superimposed by continental sandstones. Evidences of folding of the strata following emplacement of minor intermediate and basic intrusions are formed (Basil Assoc. 1979). The Awe Formation consists of calcareous sandstones – interbedded with carbonaceous shales and clays from which brine is sometimes found. The Keana Formation is massive, strongly current bedded fine to coarse-grained sandstones sometimes conglomeratic and often arkosic. This formation lies unconformably on the Awe Formation, dipping at a smaller angle, away to the north, south and east of the anticline. The Lafia Formation occupies the northwest limb of the Keana anticlinorium. The rocks consist of ferruginous sandstones, flaggy mudstones and clays.

The stratigraphic correlation of the Benue valley is shown in figure 9. The Middle Benue basin is shown consisting of Awe, Keana and Lafia formations. The Upper Benue basins are shown also.

ii. Upper Benue basin consists of Gongola and Benue basins. The sediments of Bima and Yolde Formations – sandstones (cretaceous and the sandstones (estuarine) of Gombe Formations are lateral equivalents of Awe, Keana and Lafia formation, respectively (Fig. 9).

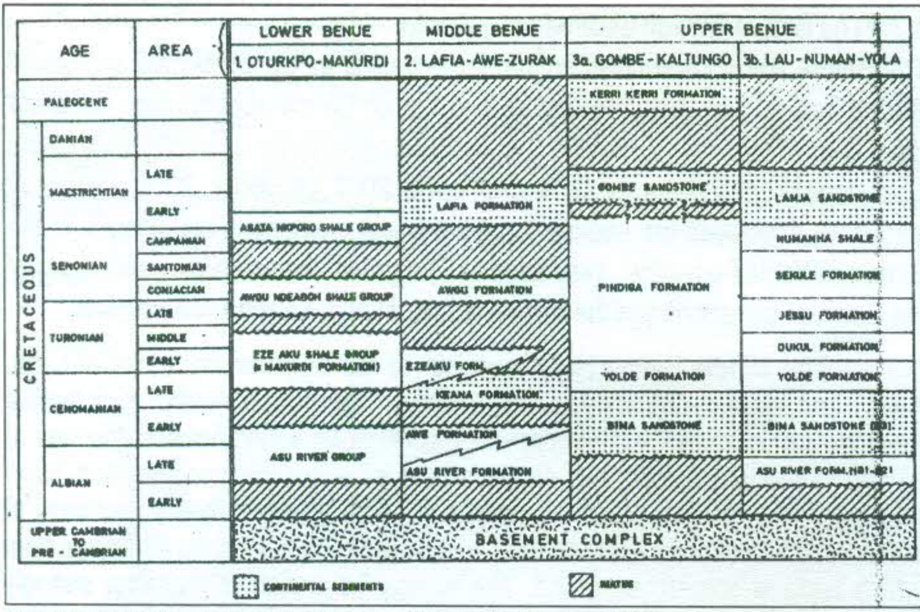

Fig. 9: Stratigraphic Correlation in the Benue Valley (After Olugboye, 2008)

3.3.9. The Eastern States Sedimentary Rocks

The Eastern States Sedimentary rocks are described in Anambra, Imo, Cross-River and Lower Benue basins of Nigeria (Fig. 5). They are of Cretaceous-Tertiary age and have common boundary. Three basins are described in Anambra, Cross-River and Lower Benue basins.

I. **The Anambra Basin:** The Anambra basin has boundary with Lower Benue basin to the north and with River Niger to the west and with the Cross River basin to the east. It is underlain by the false bedded sandstone (Lower and Upper coal measures) of Cretaceous age and Imo shale of Tertiary age.

ii. **The Cross River Basin:** The Cross River basin is found east of Anambra basin and south of Lower Benue basin. On the east is the Basement complex of the Obudu Plateau. The basin is underlain by cretaceous shale which has been intensely folded and faulted. Spring water from false-bedded sandstones of the Anambra basin feed the perennial rivers commonly found in this basin. Intrusive rocks that have been jointed and weathered contribute to the aquiferous potentials of this basin. High salinity is reported due to groundwater mineralization.

iii. **The Lower Benue Basin:** Is found in the south of River Benue and north of both Anambra and Cross River basins. The western boundary is the River Niger and the eastern boundary is Obudu and Gongola Plateau. Shale is more abundant in the basin making it poor in groundwater potential and the rocks are folded.

3.3.10. The Coastal Lowland Sedimentary Rocks of Benin Basin

The coastal lowland sedimentary rocks of western Nigeria have aquifers in sands and overburden deposits while shales and clays form the impermeable horizons (Longe *et al*, 1987). The basin can be divided into the west and east.

i. The western coastal swamps and alluvium. The northern boundary is the southwestern basement complex. (Fig. 10).

ii. The eastern coastal alluvium mangrove and fresh water swamps. The northern boundary is the Anambra and the cross River basins. (Fig. 5).

The whole terrain is underlain by the Tertiary sediments of the Deltaic plain and clay-shale group. The Benin Formation is underlain by the sandstones and shales of the upper Ilaro Formation which is predominantly continental sands and some lenses of shales and clays proved to be up to 107.7m thick (Jones *et al,* 1964) in the second horizons while the first and third horizons are up to 200m and 250m thick respectively (Longe *et al,* 1987).

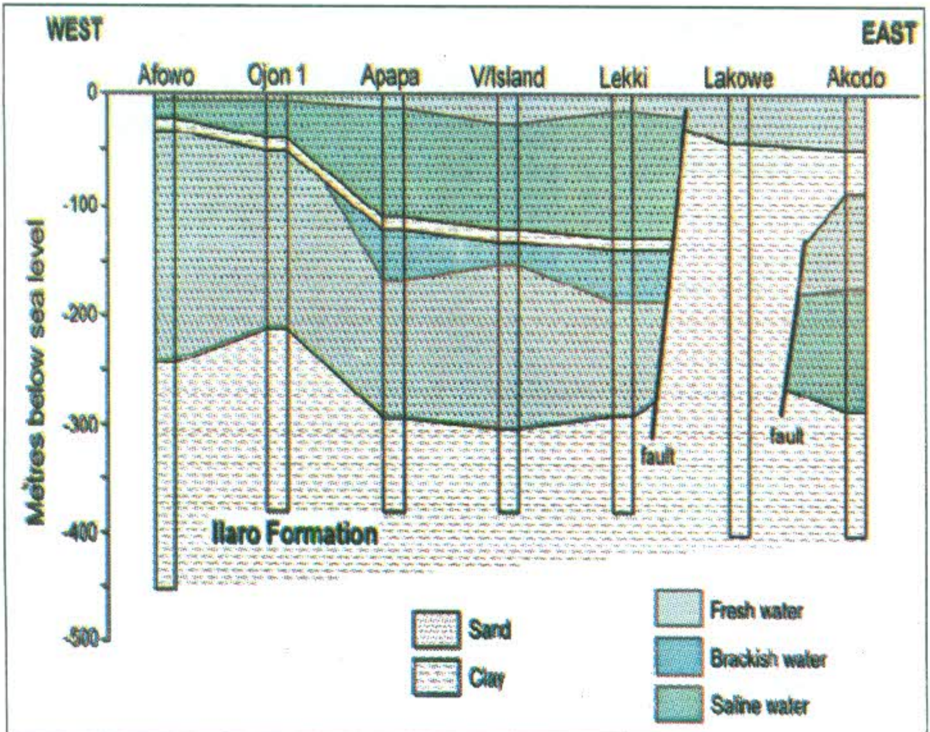

Fig. 10: Schematic Hydrogeological Cross-section along the Coastal Area of Lagos State, Southwestern Nigeria. (After Adelana *et al,* 2008)

(C) ALLUVIUM

The alluvium materials are two in number:

3.3.11. The Coastal Alluvium Mangrove and Fresh Water Swamps

The Quaternary to recent deposits of alluvium are predominantly sandy with intercalations of silts, pebbles. In the northern Niger Delta area unconfined aquifers of sandy formations predominate. However, some confining layers of silt and shale produce confined conditions. Coarse sand and gravel mark the transitional zone between coastal Alluvium and the coastal plain sand of the freshwater swamps. A lithostratigraphic and hydrostratigraphic correlation between Niger Delta, Calabar Plank, Abakaliki Trough and Anambra basin in southern Nigeria is shown in Table 9.

3.2.12. The River Course Alluvium

The River course Alluvium constitutes marshy lands and valleys along the channels of major rivers in Nigeria. The sediments include sands, gravel, silt and clays which have high groundwater potential. These sediments are regarded as regressive Tertiary Deltaic sediments. Some towns like Plategi and Songa as well as Asa River valley in Kwara State get their water supply from the aquifer of River course Alluvium.

Table 9: Lithostratigraphic and Hydrostratigraphic Correlation Between Niger Delta, Calabar Flank, Abakaliki Trough and Anambra Basin in Southern Nigeria

Age/Basin	Niger Delta	Calabar Flank	Abakaliki Trough		Anambra Basin	Hydrostratigraphic Units	Hydrogeological Groups
Pliocene	Benin formation				Benin formation	Benin Formation aquifer	Upper
Miocene Oligocene Eocene	Agbada shale Formation				Ogwashi-Asaba formation	Ogwashi-Asaba aquifer	
					Bende-Ameki formation	Bende-Amebi aquifer	
Paleocene	Akata shale				Imo shale group	Imo shale Aquifer	
Maestrichtian	Nkporo shale	Nkporo shale			Nsukka formation	Nsukka aquifer	Middle
					Ajali sandstone	Ajali sandstone aquifer	
Campanian					Mamu formation	Mamu Aquiclude	
					Enugu shale	Enugu shales aquitard	
					Nkporo Shale	Nkporo shales aquitard	
Santonian							
Coniacian		Now Natim Mari	Nkalagu formation		Agwu shale	Agwu aquitard	Lower
Turonian	Nkalagu Formation	Ekenipo shale Formation	Eze aku Group	Agu-ojo sandstones			
				Nara shale	Eze aku group	Eze aku aquitard	
Cenomanian			Asu-river Group	Ezilo	Asu- river group	Asu river aquitard	
				Ibiri/Aglla sandstone			
Albian Aptian ?		Nfamosing limestone formation		Ngbo Ekebeligwe			
		Awi formation					
Order	Basement Complex					Basement Aquifer	

4.0 SWIMMING INSIDE THE GROUNDWATERS OF NIGERIA

Swimming inside open surface water is not difficult to fathom. However, swimming inside groundwater needs special skills. It takes being like a monkey to catch a monkey. Many years ago it was difficult to believe that wireless telephones could become a common place. In the world of "waves" nothing is impossible. Force fields are thus being used as swimming gadgets. Data collected have been transformed from space domain to wave equivalents. Fourier methods have been used especially on magnetic data. After operations in the frequency domain, the same transformed ware data were inversely transformed to space domain (Bath 1974; Nettleton, 1976; Agarwal and Singh, 1977).

4.1 Spectral Transformation

Spectral transformation (Bath 1974) has emerged as an elegant tool for inverting magnetic and gravity data (Bhatacharyya, 1966; Spector and Grant 1970; Pal et al 1976; Hahn et al 1978Olasehinde at al 1990). This may partly be due to its ability to handle large body of data and partly owing to its efficiency for enhancing signal-to-noise ratio in the data. In the spectral method, any given spatial data are first decomposed into their component harmonics of sine and cosine wave forms whose frequency and amplitude features then enable the evaluation of spatial data in the frequency or wave- number domain.

Figure 10 shows the aeromagnetic map of central part of Nigeria (Fig. 10B), while Fig. 11 shows the amplitude spectrum of the aeromagnetic map of a smaller area (Fig. 10C). The spectrum is dominated mainly by two axes of symmetry trending N 15^{0}W and N30^{0}E and designated by XX' and YY' respectively (Fig. 11). These two axes correspond to lineaments directed across them, while the former is the trend sympathetic to the Benue trough (N 75^0 E- S75^{0}W) and the Atlantic fracture zones; the latter is oblique to it and parallel to the Niger basin (N60^0 W - S60^0 E). The XX' axis in Fig. 11 supports the inference drawn by Ajakaiye *et al,* 1986 that the NE-SW to ENE-WSW trending lineament dominates the structural framework of the basement complex. Being sympathetic to the Benue trough and the Atlantic fracture zones, this could well signify an ancient zone of weakness in the Basement that got reactivated during the late Phanerozoic plate tectonism in this region. It has also been observed by Ajakaiye *et al* 1986, the POGO and MAGSAT maps (Langel *et al* 1982) that lineated anomalies stretched along the magnetic equator and may represent the mid-Atlantic fracture zone (Olasehinde *et al,* 1990, Olasehinde and Annor, 1992). On this analogy, the somewhat weaker but significant YY' axis in figure 11 suggests that a NW-SE to WNW-ESE lineament is also present which is sympathetic to that of the Niger Basin.

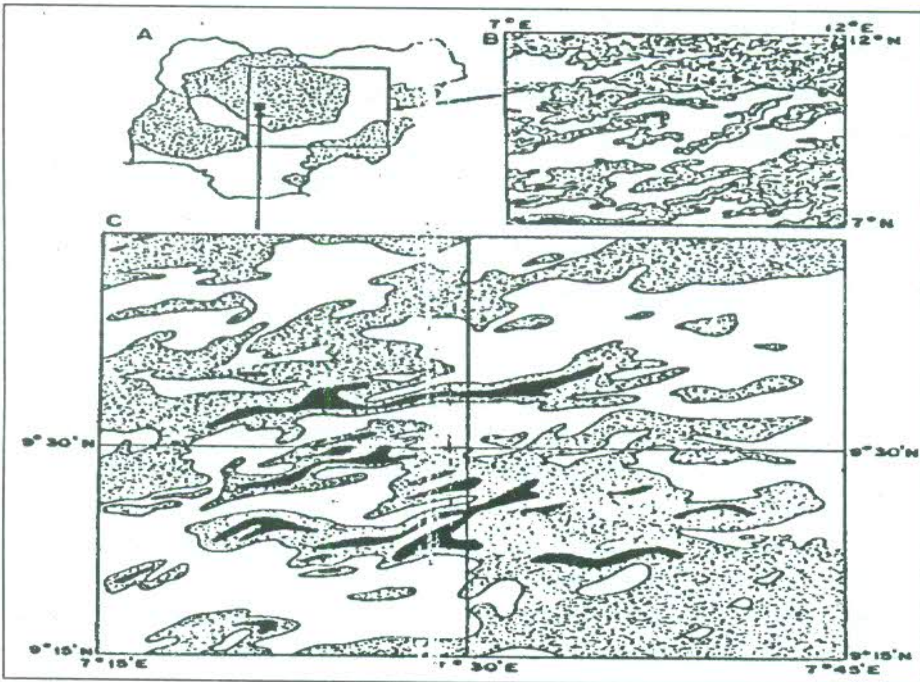

Fig. 10: Aeromagnetic Map of Central Nigeria

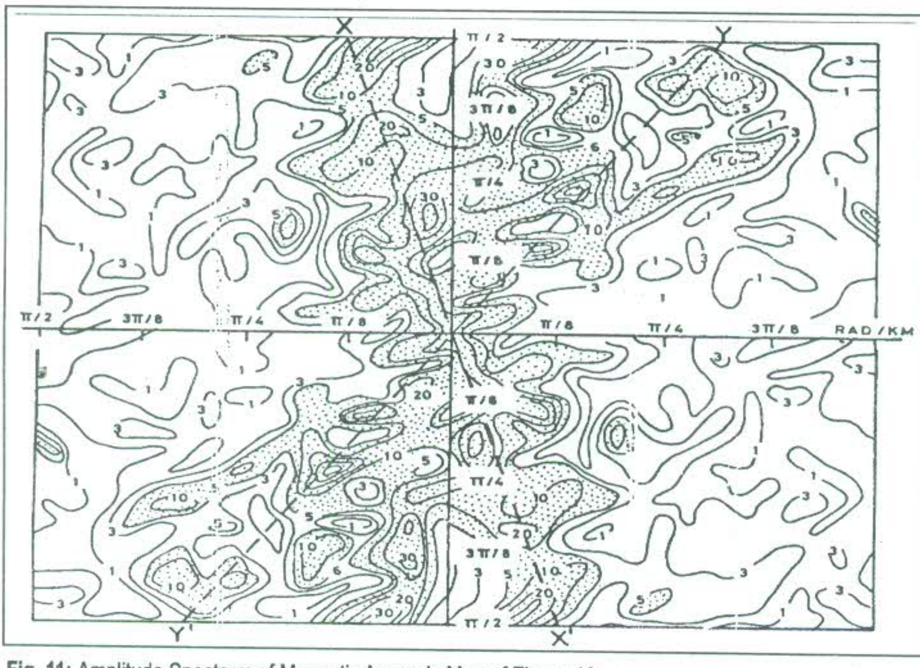

Fig. 11: Amplitude Spectrum of Magnetic Anomaly Map of Figure 10

4.2 Significance of the Lineaments

Two important notes must be significantly drawn from these lineaments. One is the tectonism along these lineaments and two is ground water enhancement.

4.2.1 Tectonism

Intermittent tectonism has been prevalent along these lineaments ever since the late Mesozoic times as seen in the Younger Granites of Jos Plateau. These are localized along an N-S line at the intersections of these lineaments and could be progressively younger southward (Bowden and Van Breeman, 1972). It is interesting to note that both topographic, photogeological data and other remote sensing pictures suggest that recent tectonisms in West African region are localized along the intersection of these lineaments. Recent earthquakes (Accra, Ghana, 1906, 1939; Ibadan, Nigeria, 1984) as well as volcanism along the Romanche fracture zone's possible inland continuations are suspected to be located along these lineaments intersections. The available West African seismicity evidence (Ambruseys and Adams, 1986) strongly suggests that major pre-existing zones of weakness control the transform faults.

The result of the spectral transformation and evaluation of the aeromagnetic data in this region is therefore relevant in the study of the tectonic history of the Nigerian Basement Complex.

4.2.2 Ground Water Exploration

The use of spectral analysis in evaluating aeromagnetic data in Nigeria has been demonstrated in many basement complex areas (Annor *et al*, 1990; Olasehinde, 1992; Annor and Olasehinde 1996; Olasehinde, 2010). The intersection of the lineaments call for caution in engineering geology studies but it is a welcome development in groundwater exploration. (Olasehinde and Awojobi, 2004). Ground follow-up done in many places confirm the presence of giant pools of ground water within the fractured basement rocks in Nigeria (Olasehinde, 1999; Olasehinde and Awojobi, 2004). Ball (1980) had indicated that thick weathered rocks have been enhanced by criss-crossing fractures in Nigeria. The two factors of fracturing and weathering are very important for groundwater accumulations especially in the hard basement complex rocks in Nigeria. Thick vegetation cover of tall trees has been used as remote sensor of sub-surface aquifer in Jere area, central Nigeria (Annor and Olasehinde, 1996). The zig-zag water channel of Gurara River and Chanchaga River in central Nigeria has been described as caused by intersection of these fractures (Annor *et al,* 1990).

Whenever a combination of remote sensing pictures and aeromagnetic or ground magnetic studies are made preceding groundwater exploration, the success rate has been very high (Olasehinde and Amadi, 2009). Following these two swimming gadgets into the groundwater a ground follow-up programme of electrical resistivity studies and geological/hydrogeological exploration have been made and recommendations made from such never fail. (Olaselinde, 2010).

4.3 Case Studies of Swimming inside Groundwaters

An upward continued spectral map of the central Nigeria has been produced using statistical techniques (Olasehinde, 1992) (Fig. 12). This was found to be cost-effective considering similar results obtained by other workers who used robust computer software and hardware (Langel *et al,* 1982; Ajakaiye *et al,* 1986). The fracture map of central Nigeria has been interpreted from these spectral evaluations has been produced (Fig. 13).

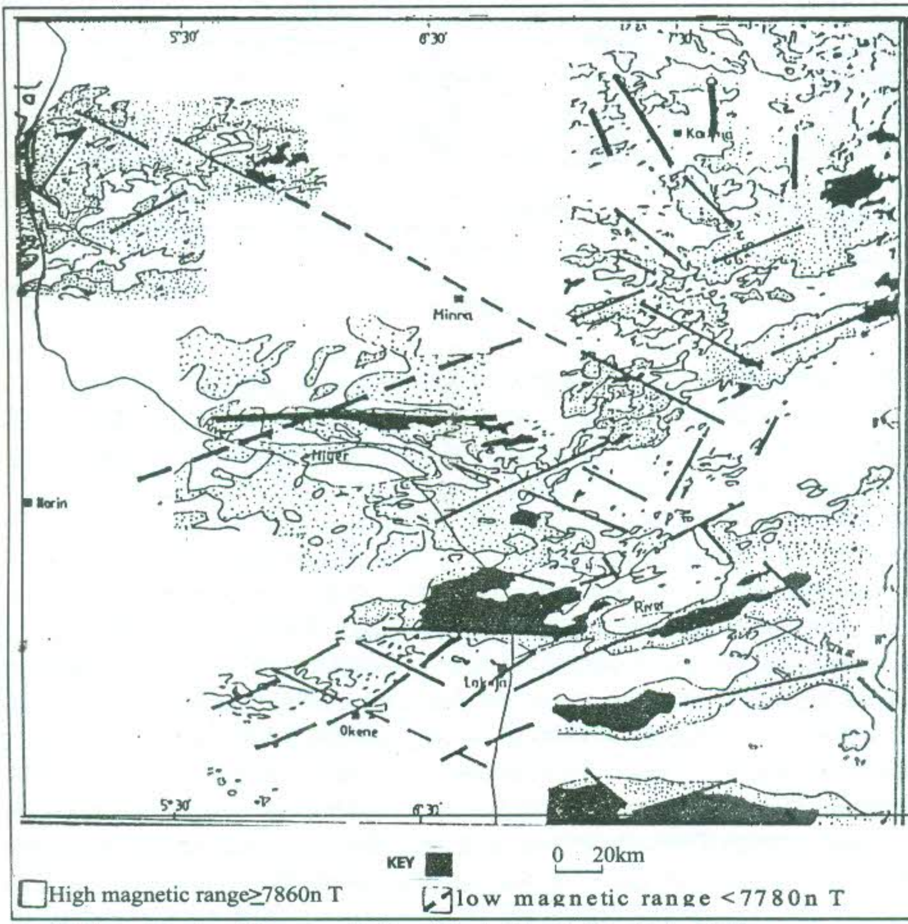

Fig. 12: Upward Continued Aeromagnetic Map of Central Nigeria (Olasehinde, 1992)

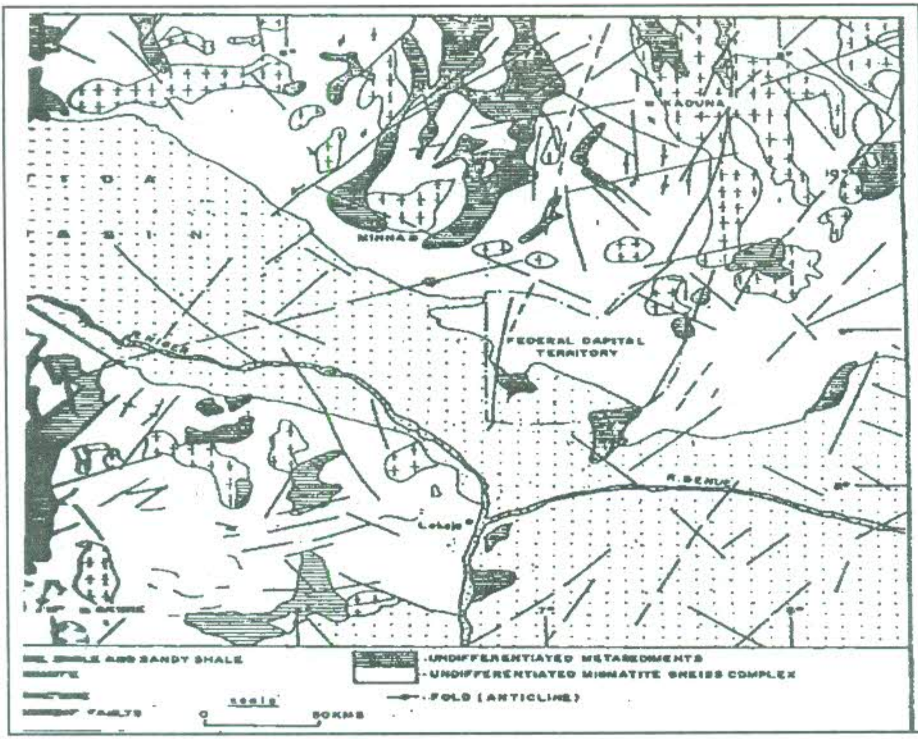

Figure 13: Fracture Map of Central Nigeria (Olasehinde, 1992).

Three places of interest where ground follow-up have been done in Nigeria are Ilorin, (Kwara State), Gurara River (stradling Kaduna and Niger States) and Ogbomosho (Oyo State). These three places have been selected out of many others because of the target of clients. The Ilorin example was picked because the Department of Agricultural Engineering, University of Ilorin wanted a borehole for irrigation. The mandate was picked up and the results justified the means. The Gurara River project initially started as a search for places where a battery of boreholes can be drilled to augment water supply to the Nigerian Federal Capital Territory. Later, the idea of borehole was dropped for a dam across River Gurara in central Nigeria. The search continued from Jere town along Abuja-Kaduna road and ended up eastwards. The River Gurara was discovered to be sustained by groundwater and this made the river perennial even close to its source (Fig. 19). The Dam, 79 kilometers north of Abuja now serves both as source of water supply to Lower Usman Dam as well as source of hydro-electric power generation (Adewumi and Gundiri, 2003). There has been a plan to also use the water from the dam for irrigation and possibly to divert water to Shiroro Dam through either

River Rubu or River Wachi (Olasehinde, 1990-2010 studies). The Ogbomosho case study demonstrated that smaller communities can benefit from the "Swimming Technique" introduced. The University community had tried in vain to get adequate water supply to the students' population. Only the present effort has recommended the western side of the Institution for productive borehole drilling.

4.3.1 Ground Follow-up at Ilorin

The 'fact .that numerous unsuccessful boreholes have been drilled in the hard rock terrains of Nigeria unabated is 'common knowledge. A multi-sensor exploration approach within the poorly exposed basement complex terrain of a part of West Central Nigeria has been employed in the present study to proffer solution to this problem.

An area of 50sq. kilometer was surveyed to locate suitable points for drilling groundwater boreholes for the University of Ilorin community. The methods include electrical studies processed as vertical and radial geo-electric soundings, and pseudosections. The magnetic anomaly map of the area was qualitatively interpreted. The results showed negative magnetic values at the eastern end where the electrical anisotropy polygon indicated an east-west fracturing. This eastern end of the area is underlain by sheared gneisses. The geo-electric section can almost be drawn from the pseudosection. The interpreted VES data also agreed with the borehole log very accurately.

A log of the drilled hole revealed an overburden of 2m, a weathered rock of 3.5m thickness and fractures encountered at 13.5m, 20.5m and 48m depths respectively. These agree very well with the predictions from the geophysical studies. The pumping test gave a water yield of $9.8m^3$/hour, and transmissivity of $2.41m^2$ /day. These results obviously justify the adoption of a multisensor approach in groundwater explorations for successful results.

There has been an over dependence on the use of electrical methods in groundwater explorations in Nigeria. This is in spite of the known limitations and non-uniqueness of the interpretation of the electrical resistivity data (Koefoed, 1970; 1976). For this reason not only 'have data from the Vertical Electrical Soundings (VES) been handled in three different modes (depth interpretations, analysis of anisotropy polygons and pseudosections) they have been matched with the magnetic data interpretation and geological mapping. The electrical resistivity and the magnetic methods have been used after a careful geological mapping of the few exposed rocks of the area. The study area is found north east of Ilorin city in the West Central Nigeria. The area mapped covers fifty square kilometers and falls within longitudes 4°39'and 4°42'E and latitude 8°28'and 8°30'N (Fig. 14). The University of Ilorin Permanent Site falls within the area and surface water supply had not been perennial here. The ongoing development of surface and ground water resources of **this** community has benefited immensely from **this** integrated study as well.

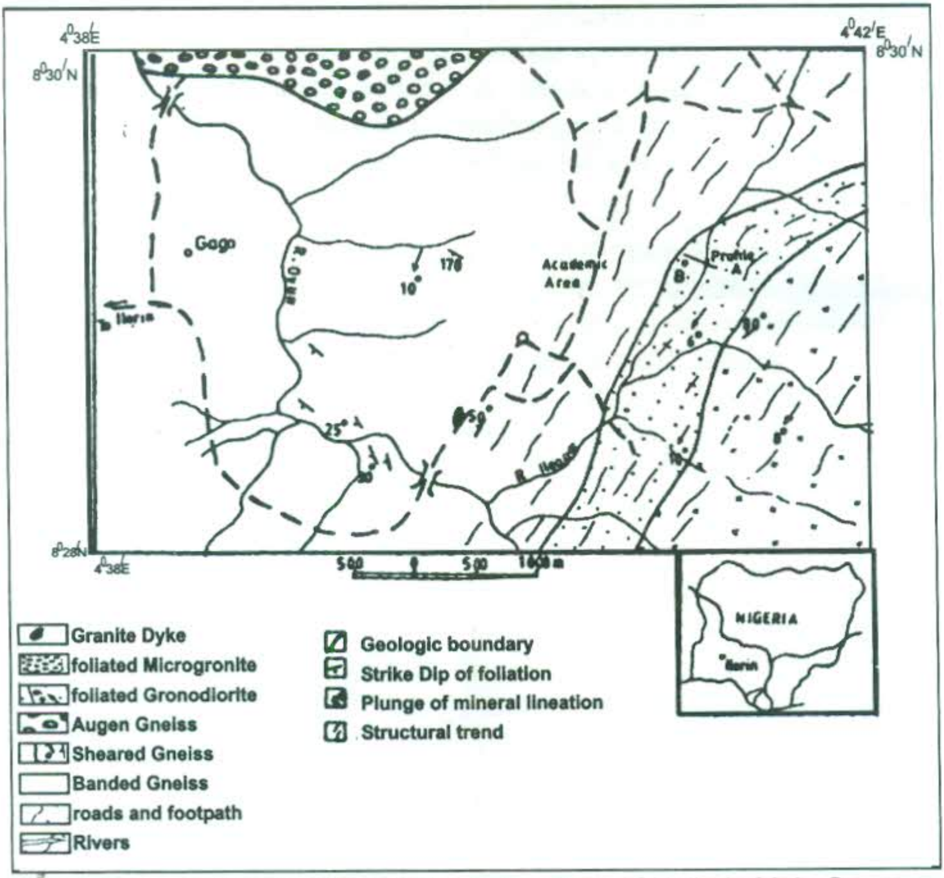

Figure 14: Location (inset) and Geological Map of Unilorin Main Campus

Several joints have been found but the pattern which may be said to be irregular trend generally NW-SE. The values of the joints range between 120° and 160°. No faulting was interpreted but few micro faults strike 10° and dip 50° easterly.

A ground magnetic anomaly map of the area has been prepared on scale 1:10,000 (Fig. 15). The proton magnetometer was used and the data were reduced to a base station at the eastern part of the study area. Roads and foot paths were used as traverses and readings were taken every five meters. The reduced and smoothened data (In Nanotesla) have been contoured (Fig. 15). The area is characterised by negative anomalies, especially the eastern areas. The magnetic anomalies of the rocks are broad, having long wavelength and low gradients. A NE-SW fracture can be inferred at the eastern part of the study area (Fig. 15). These fractures are favourable for groundwater locations (Olasehinde, 1989; 1991).

The River Ile Apa and River Oyun are seen to be fracture controlled as depicted by (F-F) fracture in the area (Fig.15).

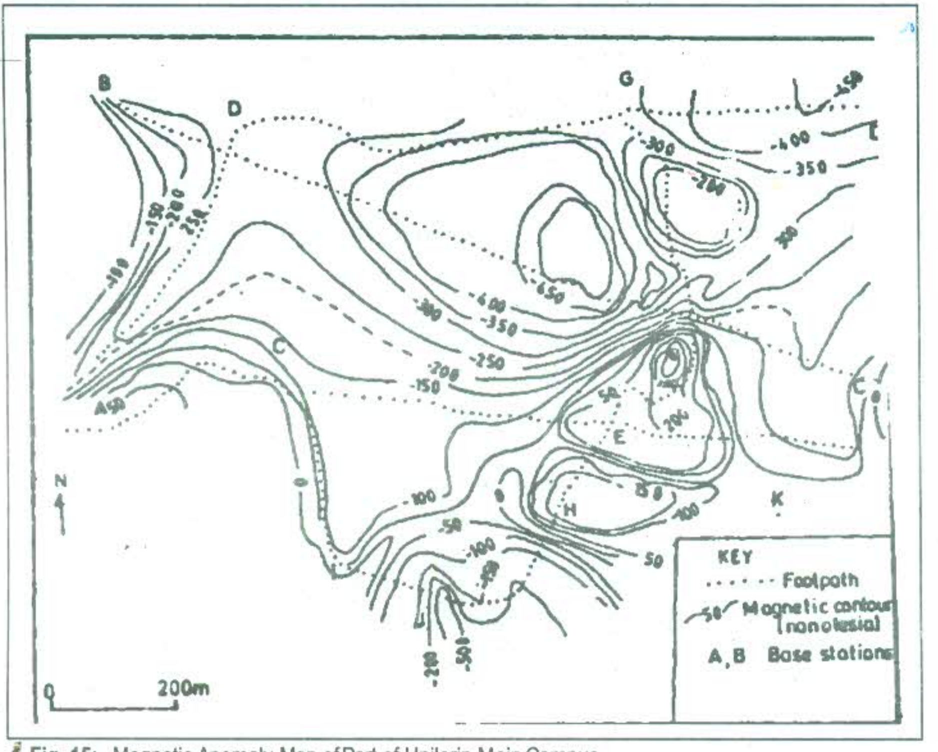

Fig. 15: Magnetic Anomaly Map of Part of Unilorin Main Campus

The eastern side of the study area was considered suitable for groundwater exploration following the interpreted fractures from geological and magnetic studies carried out earlier on. An east–west profile was selected that runs across the suspected fracture on the sheared gneisses (Fig. 14).

The resistivity pseudosection is shown in Fig. 16a. Furthermore the VES curve for each station has been interpreted to get the layer parameters (Fig. 16b). The geo-electric section shows low resistivity values for the top 3 meters moving from west to east around station A2W and between stations A5E and A6E. These places coincide with areas with thinner top layer which is lateritic as shown in the depth section. At A1 which is close to the river channel the resistivity value is very high and also the top layer is thickest here. There is a high probability of a fracture zone in area of low resistivities flanked by areas of high resistivity values here. These locations are marked as F1, F2, and F3, respectively (Fig. 16a).

For an isotropic medium the resistivity has the same value in all directions. On the other hand resistivity plots around a point in an anisotropic medium will give an ellipse whose long - axis coincides with the direction of the bedding plane or lineaments (Sumner, 1976). In the present study radial VES measurements in three directions around a point (Fig. 14) have been made following the method of Mallik *et al*, 1983. The anisotropy polygon is shown in Fig. 17a.

The anisotropy polygon shows a clearly anisotropic medium and a change in the major axis of the ellipse from approximately E-W direction at shallow depths to approximately NW-SE at deeper subsurface levels. This implies a change in the direction of fractures with depth (Olasehinde, 1984). This direction agrees with the Pan African Orogeny fractures mentioned earlier on. Also, the coefficient of anisotropy, λa, (Fig. 17b) shows a decrease with depth, corroborating the generally expected diminution of fractures with depth.

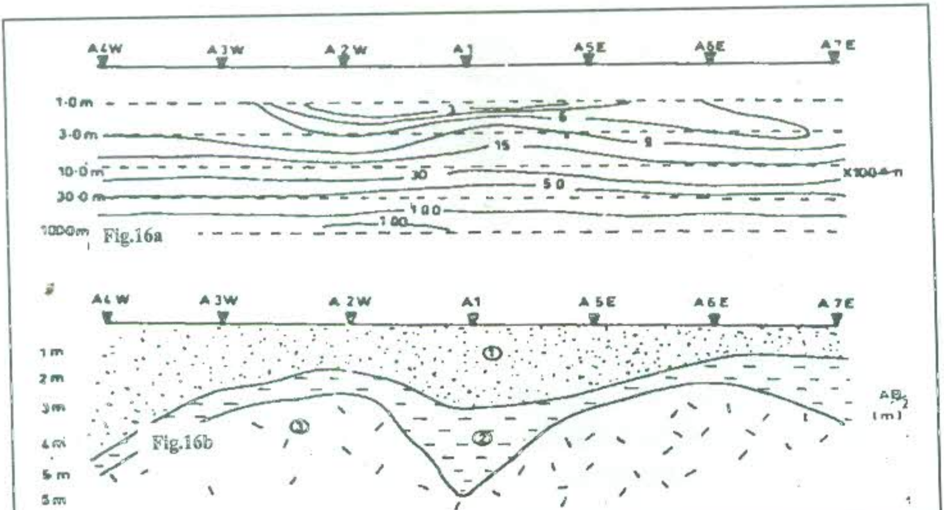

Figure 16: (a) Resisitivity of Pseudosection and (b) Depth Section Accross Profile A

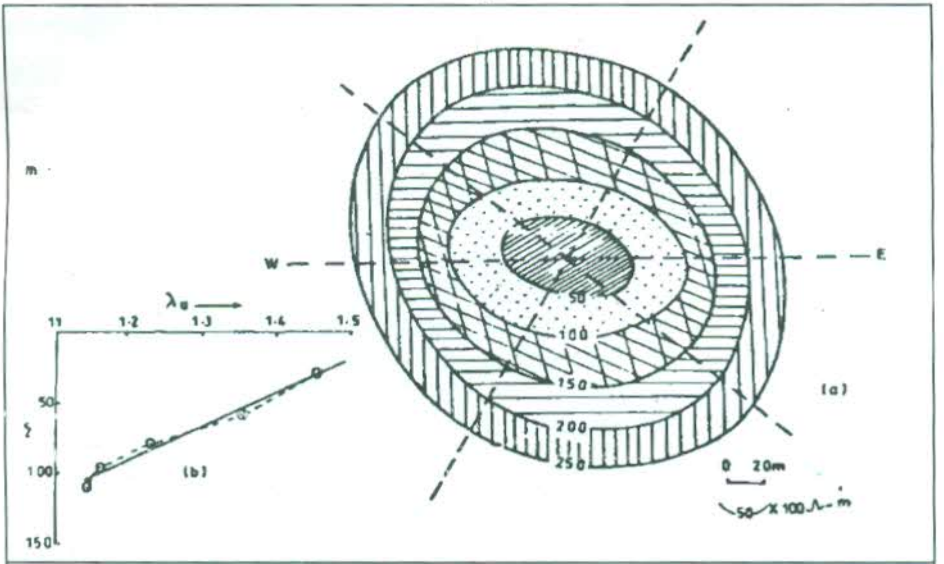

Figure 17: Anisotropy Polygon for Location B on Profile A

The borehole log at the place which coincides with the radial VES location (B) is shown below:

Table 10: Borehole Log at Unilorin Agric. Engineering Department

Depth (m)	Description
0.0 – 2.0	Dark brown friable clay with lateritic pebbly sands
2.0 – 4.5	Dark grey micaceous friable clay with fine to medium quartz sands grading into highly weathered gneiss
4.5 – 13.5	Gneiss (probably banded)
13.5 – 15.0	Fractured gneiss plus water
15.0 – 20.5	Banded gneiss
20.5 – 26.0	Weathered gneiss
26.0 – 48.0	Fresh gneiss plus pyrite
48.9 – 50.5	Highly fractured gneiss plus water
50.5 – 53.0	Fresh banded gneiss

The overburden was only 4.5m thick but the fractures at 13m, 20m and 48m depth are responsible for the success of the borehole. The overburden corresponds to the 3 metres of the geo-electric section. The fractures were inferred from magnetic studies while the depths were interpreted from the electrical anisotropy polygon. These fractures could not have been detected with only VES studies without corroborating evidences from other geophysical methods.

The static water level was 0.42 meters and the dynamic water level: at 16.15m throughout a 24 hours pumping test. The yield was 9.8 cubic meters per hour with a draw dawn of 15.73 meters. The transmissivity is *2.41m²/day.* This is regarded as a successful borehole in a basement complex terrain. The success can be attributed to the interception of fractures located by the magnetic and electrical studies. Previous efforts based on VES studies alone in the same area had been unsuccessful. The borehole that was intended for irrigation was fitted with a 10 Horse Power (HP) pump and pumped for days non stop.

4.3.2 Ground Follow-up at Ogbomosho

Ogbomosho is a town close to Ilorin. The Ladoke Akintola University of Technology site was surveyed because many borehole projects had been abortive here before (Adeleke and Olasehinde, 2010). The area surveyed was about 0.8 square kilometers. A combination of geological, hydrogeological and geophysical methods was used. Such parameters as thickness of weathering, extent of fracturing, transmissivity and resistivity of bedrock and saprolites were used to prepare a groundwater potential map of the area. Table 11 shows the five parameters used while Fig. 18 shows the groundwater potential map. The western part was found to be the best for groundwater development whereas efforts had been concentrated on the eastern area without success.

WEATHERED LAYER RESISTIVITY (Ωm)	RANGE	AQUIFER CHARACTERISTICS	WEIGHTING	(Modified after Wright, 1992)
	< 20	Clay with limited potential	7.5	
	21 - 100	Optimum weathering and good ground water potential	10	
	101 - 150	Medium conditions and potential	7.5	
	151 - 300	Little weathering and poor potential	5	
	> 300	Negligible potential	2.5	

WEATHERED LAYER THICKNESS (m)	RANGE	WEIGHTING
	< 5	2.5
	5 - 10	5
	10 - 15	7.5
	> 15	10

TRANSVERSE RESISTANCE (Ωm²)	RANGE	WEIGHTING
	< 400	2.5
	400 - 1000	5
	1000 - 2000	7.5
	> 2000	10

BEDROCK RESISTIVITY (Ωm)	RANGE	AQUIFER CHARACTERISTICS	WEIGHTING
	< 750	High fracture permeability as a result of weathering; high aquifer potential	10
	750 - 1500	Reduced influence of weathering; medium aquifer potential	7.5
	1500 - 3000	Fairly low effect of weathering; low aquifer potential	5
	> 3000	Little or no weathering of the bedrock; negligible potential	2.5

ANISOTROPIC COEFFICIENT (λ)	RANGE	WEIGHTING
	< 1	2.5
	1 - 1.5	5
	1.5 - 2	7.5
	> 2	10

CONVERSION WEIGHTING FACTORS

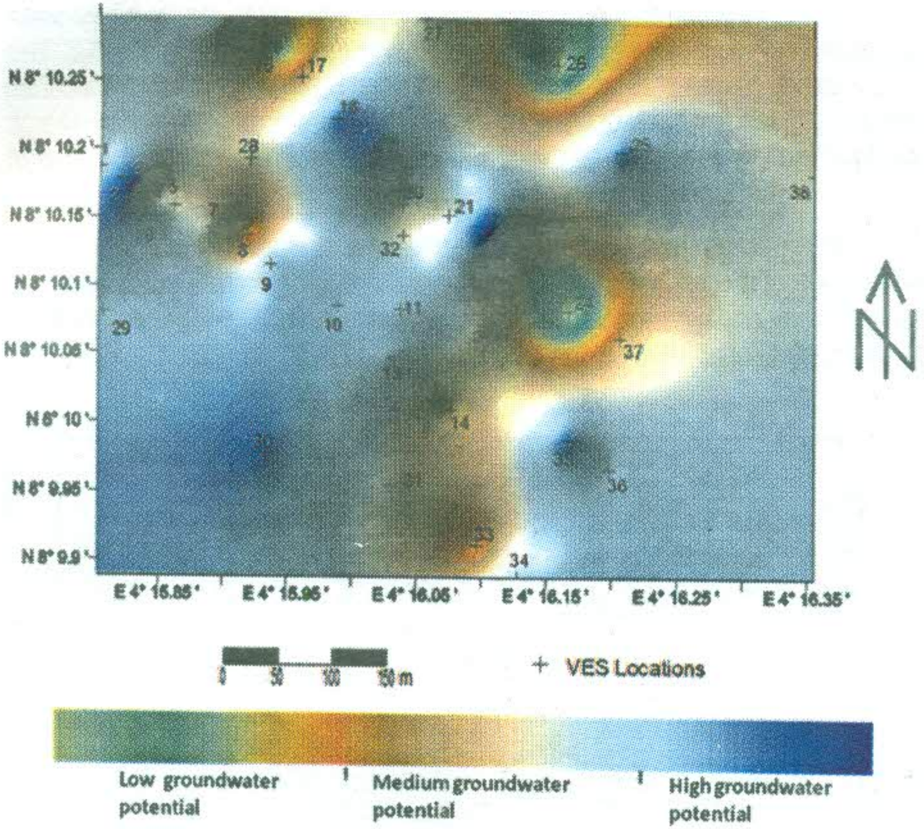

Fig. 18: Groundwater Potential Map of LAUTECH Ogbomosho

It can be concluded that the low resistivity and significantly thick weathered rock/clay and the fractured basement constitute the aquifer systems in this area and that the most promising site for drilling of a water-supply borehole may not necessarily coincide with the thickest development of the saprolite. This becomes evident after considering other geo-electric parameters which may impact on the aquifer characteristics, especially the resistivity of the saprolite as well as that of the bedrock. The presence of thick weathered materials essentially of sands/gravels underlain by fractured bedrock is desirable for groundwater development of this area.

4.3.3 Ground Follow up of Gurara Area

In the search for alternative water supply to Federal Capital Territory (FCT), Abuja several methods were tried. The first was the Directorate for Foods, Roads and Rural Infrastructure (DIFRRI) project to drill several boreholes in the FCT. The

River Usman was damned and this was later found inadequate for future water supply. In the middle of the eighties the search was extended north of the FCT. This led to locating places around Jere town in Kaduna State. The search started from Jere and proceeded eastwards along the River Gurara. Progressively the search revealed increase in fracturing of the underground. This proved existence of increase in groundwater as one moves eastwards.

The existing aeromagnetic maps of the area were studied (Fig. 19). Spectral evaluations of the aeromagnetic maps were made. The better understanding of the hydrology and hydrogeology of the area was gained (Fig. 20) (Olasehinde *et al,* 1990; Annor *et al,* 1990).

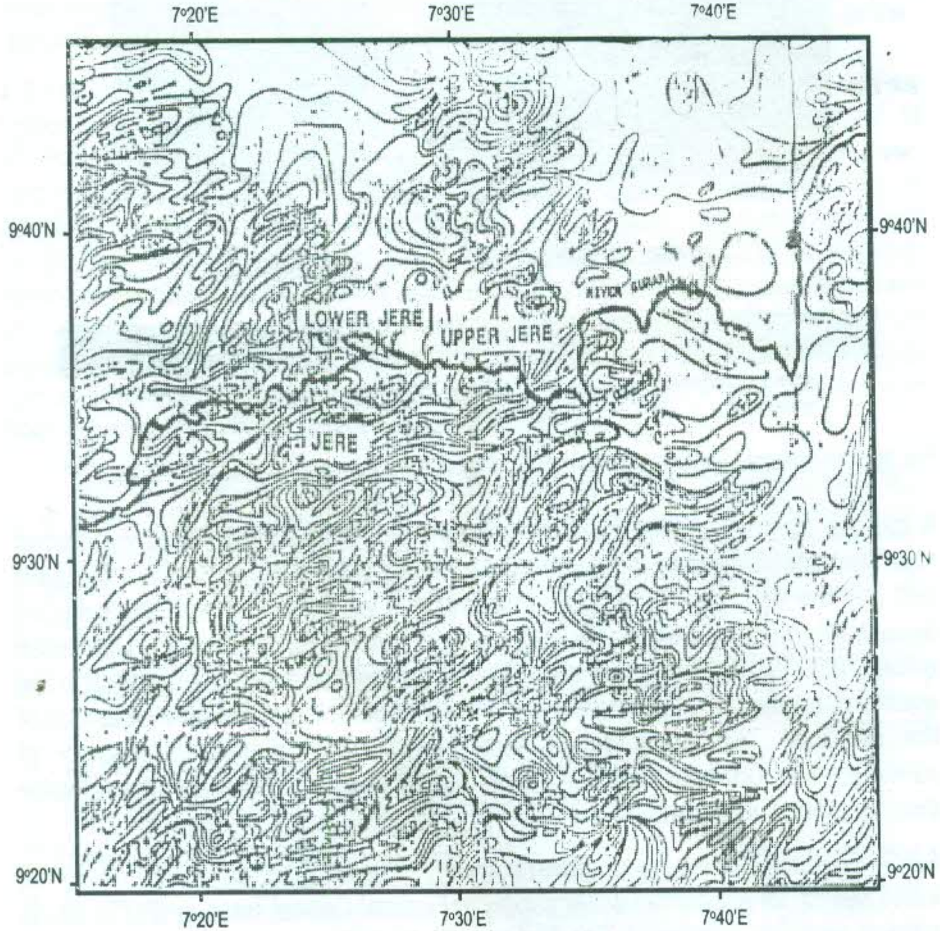

Fig. 19: Aeromagnetic Map of Gurara Area

The geological map of the area was produced (Fig. 21). Fifty three (53) boreholes were drilled close to the source of River Gurara (Fig. 22) and the hydrogeological parameters studied. By 2000 a dam costing forty six billion naira (N46billion) was designed. The perennial nature of River Gurara, especially close to the source of the river should be understood in terms of groundwater effects.

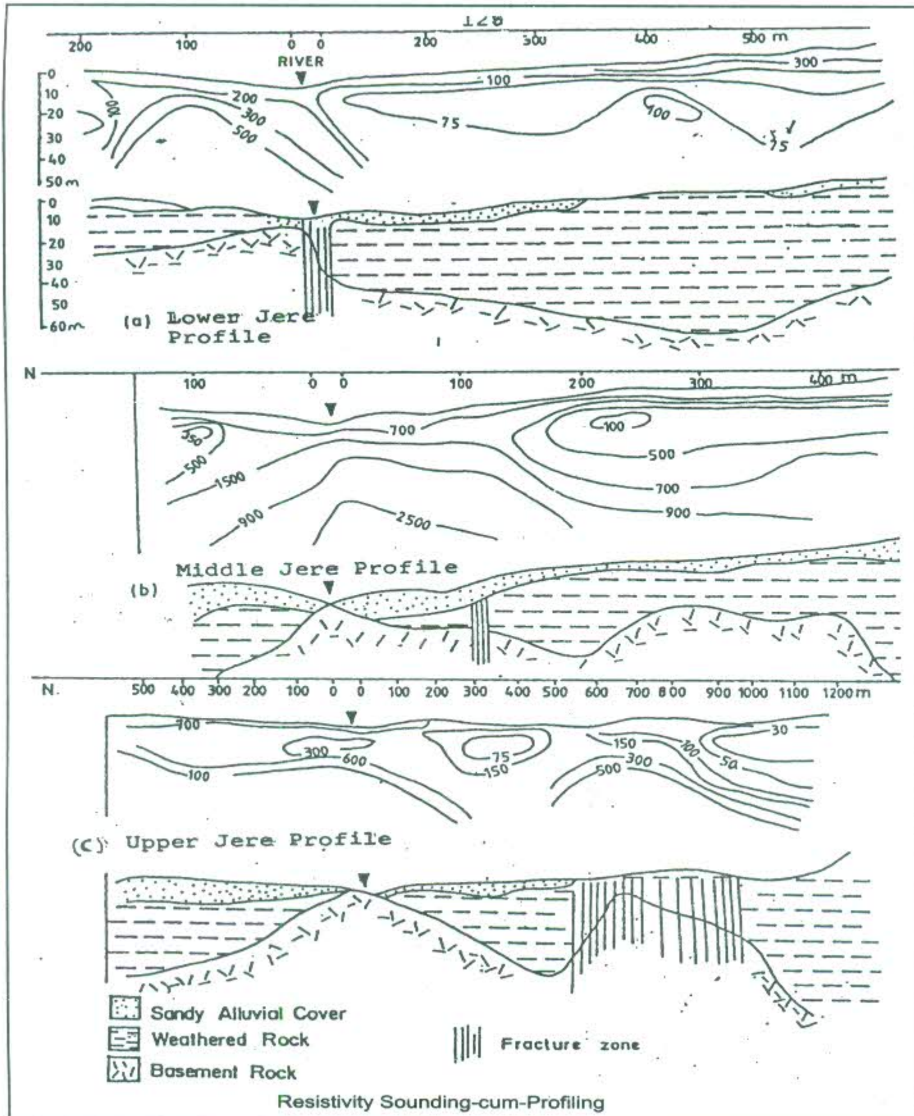

Figure 20: Geo-electric Sections Derived from Electrical Resistivity Pseudosection of Gurara Area

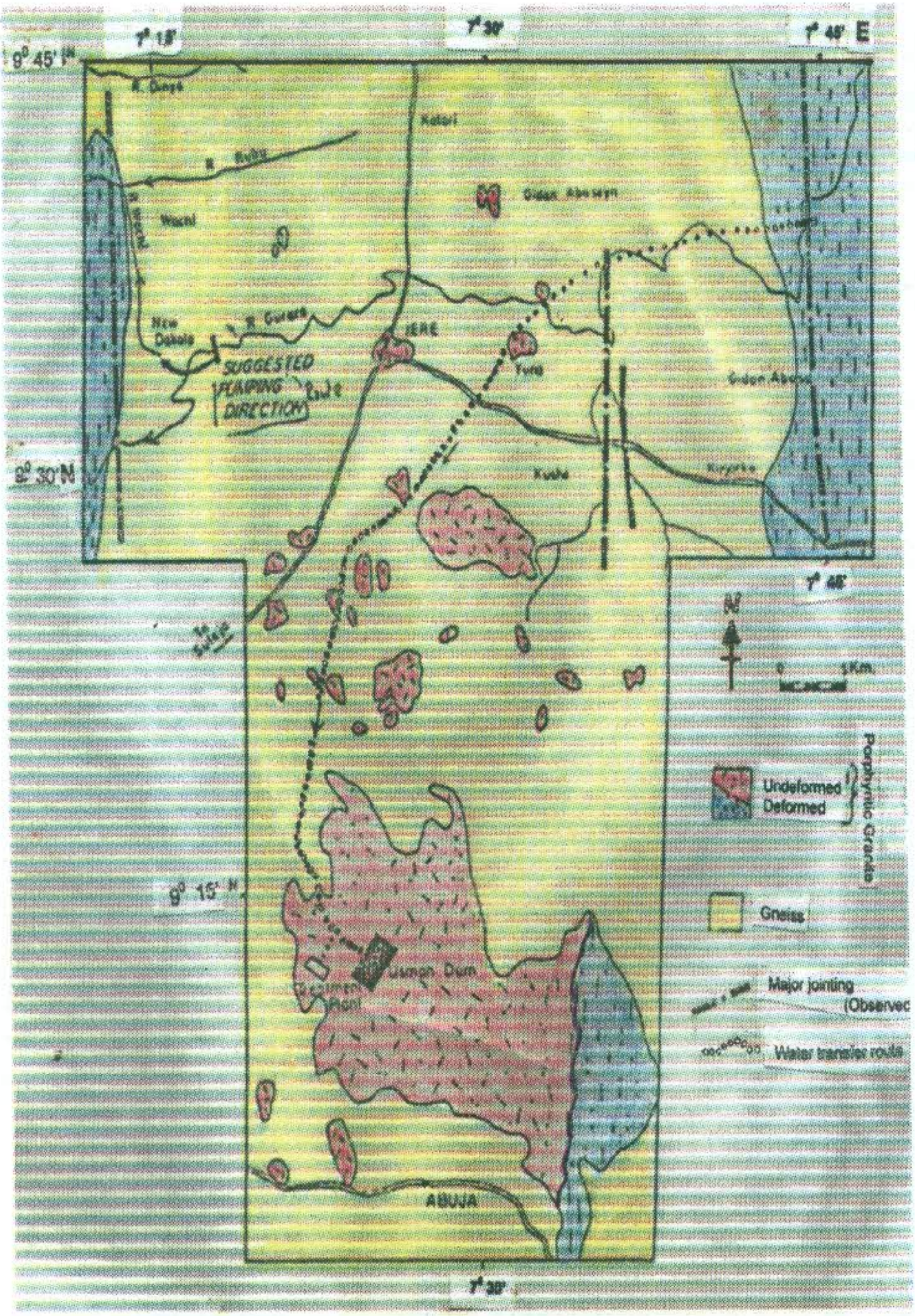

Fig. 21: Geological Maps of Gurara Area (Author, 2000)

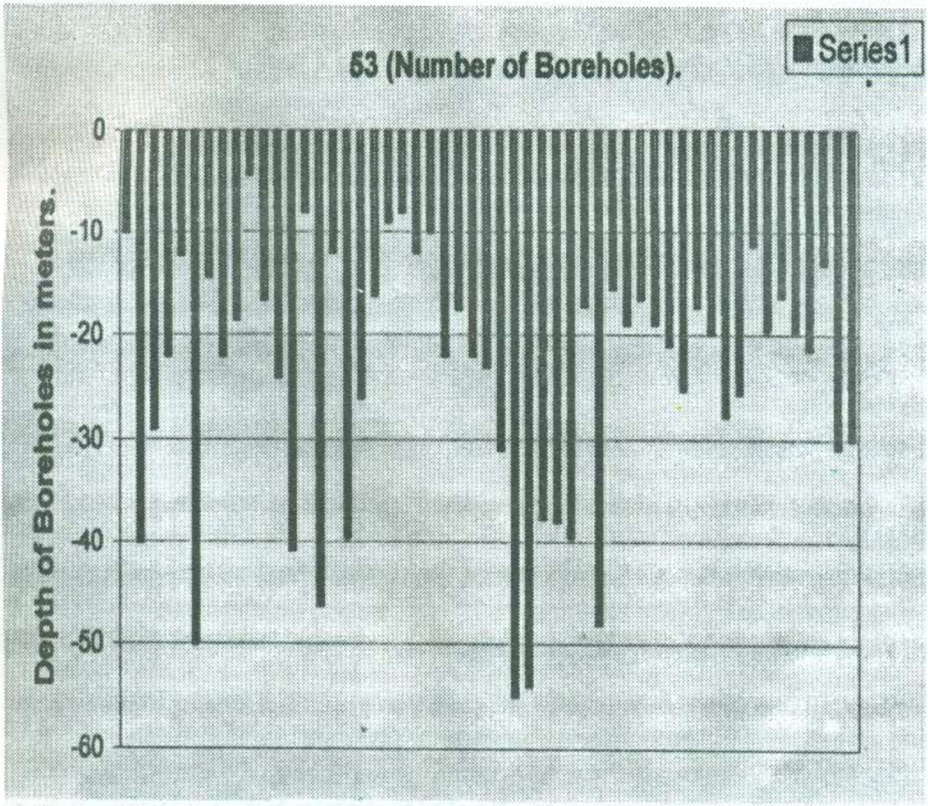

Fig. 22: Depth of Boreholes in Gurara Area

5.0 ISOTOPE TECHNIQUES AND SUSTAINABLE GROUNDWATER DEVELOPMENT AND MANAGEMENT

Water resources development management is crucial to the development of the economy of any nation. The steadily growing population in Nigeria in the last four decades has put tremendous pressure on the available water resources globally; subsequently pushing hydrogeologists and water practitioners to a greater task. In semi-arid regions water resources are being mined from recharge from former humid episodes (Edmunds, 2001) Unfortunately, the development of groundwater resources in semi-arid regions often proceed without a good understanding of the recharge rates and processes. Over-development of groundwater is evident from the falling water tables, especially when the rates of groundwater abstraction exceed the rates of natural replenishment from current rainfall or, that a transient condition is produced where water level decline is proportional to the hydraulic diffusivity (transmissivity/storage) of aquifer (Custodio, 1992).

Moreover, the valuable groundwater resource is unfortunately under continuous threat due to growing anthropogenic impacts, mostly in form of:

1. Increasing pumping
2. Sewage effluents and
3. Industrial and agricultural-induced pollutants.

Therefore, adequate knowledge of hydrogeology and hydrology as well as the quantification of residence time, recharge and precipitation/evaporation in assessment and management of groundwater resources. The application of Isotope technique to water resources management in Nigeria has become a necessity, especially, when data from records of rainfall, run-off and other climatic factors have not been consistent or unavailable. Where such records are available they should be given for research purposes free of charge.

5.1 Examples of Applications of Isotope Technique in Nigeria

Most of the isotope studies in Nigeria have been related to the evaluation of recharge mechanism especially in the semi-arid areas of Northern Nigeria (Adelana *et al*, 2002; Olasehinde *et al*, 2001; Goni and Edmunds 2001; Onigba *et al*, 1989; Oteze, 1989; Geyh and Wirth, 1980).

(I) In one of the earliest isotopic research in North-Western Nigeria (Geyh and Wirth, 1980) groundwater dating in Gwandu formation showed that radiocarbon is low close to the area of recharge and increases with the direction of flow (east to west). The study also revealed that groundwater velocity was from east to west at a rate of 3–4 m/year. The absence of ^{3}H (tritium) reveals that the samples do not contain recently recharged groundwater.

(ii) Oteze (1989) used environmental isotopes in the Rima aquifer waters of the Sokoto Basin and showed that away from the recharge areas, there was no tritium, an indication that recharge is not from modern recharge. Carbon (^{14}C) dating confirmed that at Birni-Kebbi (90km from the recharge zone) the water is 19,000 years old while at Kaloye (190km away) the age is 26,000 years confirming the east to west flow direction. Further studies using ^{13}C, ^{18}O, and ^{2}H confirmed that recharge by direct infiltration from rainfall through the soil has not been changed since Pleistocene times when the climate in the area was much cooler than it is today.

(iii) Bassey *et al*, 1999 took 56 water samples from Rima River Basin and from shallow dug wells, tube wells, hand pumped wells and boreholes for isotopic analysis. The results revealed that most of the samples from the shallow aquifer, dugwells and tube wells have an isotopic composition close to the long-term weighted mean of precipitation in Kano reported in Onugba *et al*, (1990). The data for annual weighted mean values for δ^2H and $\delta^{18}O$ the corresponding annual precipitation and mean temperature for the period 1961-1973 at Kano is shown below (Onugba *et al*, 1990). The water samples from Wurno Irrigation Scheme gave positive delta values for stable isotopes in surface waters of Rima River, Wurno Lake and Carnal waters.

Table 12: Maximum and Minimum Weighted Mean Values of 8^2H and $8^{18}O$, Corresponding Precipitation P and Temperature for 1961-1973 at Kano, Nigeria (after Onugba *et al*, 1990).

	$\delta^{18}O$%	% of P	δ^2H%	% of P	P(mm)	T °C
Max	-0.79	100	-2.32	100	1140	27.0
Min.	-7.32	18.0	-41.17	18.0	416	25.5
Range	6.35	82.0	38.85	82.0	724	1.5
St. Dev.	2.25	16.7	14.20	31.1	207	0.4
Median	-3.40	98.9	-19.71	94.9	698	26.2

(iv) Recently, Adelana *et al*, (2003, 2002) and Olasehinde *et al*, (2001) used bomb tritium ^3H). Oxygen -18 (^{18}O) and carbon-14 (^{14}C) together with hydro-chemical parameters (chloride method) to identify recharge conditions/sources and mechanism of groundwater replenishment in the north-western Nigeria. It was found that the $\delta\ ^2H$ and $\delta\ ^{18}O$ compositions of groundwater span a considerable range when compared with that of surface water in the area. This was interpreted as resulting from natural rainfall infiltration. Shallow groundwater near the Sokoto/Rima River courses has $\delta\ ^{18}O$ and $\delta\ ^2H$ enriched when compared with those away from the river courses, indicating recharge from river channel during flooding. Generally, there is strong depletion in isotopic content (^{18}O and ^2H) and has deuterium excess in groundwaters of the area, reflecting the contribution of old meteoric water that recharged the Cretaceous aquifers in pluvial times (between 5,000 and 15,000 BP).

(v) In the Semi-arid N.E Nigeria Edmunds *et al*, (2002) and Goni and Edmunds (2001) used solutes, deuterium and tritium profiles to study groundwater recharge in the area. Two unsaturated zone profiles: Mallam Fatori (MF) and Magumeri (MG) have been samples for Cl, Br NO_3 and δH to investigate recharge rates and processes. The upper MF and MG profiles have sandy lithology, lower moisture content (<5%), low conservative solute concentrations and δH around -30%$_0$. All these indicate that present day recharge is taking place. The lower section of the MF profile shows a distinct contrast with high moisture content (up to 27%$_0$) very high chloride (average 2892 mg/l) and relatively enriched deuterium (-12%). (Goni and Edmunds, 2001) indicating the effect of evaporate enrichment. The chloride profile technique gives an estimated direct vertical recharge rates of 14mm/a and 22.5mm/a, and residence times of 9 years and 21years for the upper 3m MF and MG profiles respectively.

(vi) In the Ogoja-Ikpona area S.E Nigeria Isotope techniques have been used to evaluate the hydrogeological and hydrochemical controlling processes in groundwater system. Tijani *et al*, (1996) had used stable isotopes of ^{2}H, ^{18}O and ^{3}H to compliment hydrochemical evidence for the evolution of Na-Cl water type that dominate the area. They observed depletion of the saline groundwater with respect to tritium (< -1.5 TU) and stable isotopes of oxygen and hydrogen (<-3.5%$_0$, δ^{18}O and <-10.5%$_0$, δ^{18}O, δ^{2}H).

(vii) In the S. W. Nigeria (Adelana *et al*, 2003; Loehnert, 1988) isotope techniques have been applied in few localities. Loehnert (1988) observed evidence of chemical variations in water chemistry which was supported by environmental isotopes ^{2}H, ^{3}H, ^{18}O studies. Streams show homogeneous water composition similar to soil waters and are unaffected by seasonal variation but have varying proportion of base flow when sampled in headwater areas. The isotope evidence showed departure from SMOW and Global Metric Water Line (MWL).

(viii) In the Bida Basin the origin of the saline waters were studied by Uma and Loehnert, 1992. Both hydrochemical and isotope data were used on 16 water samples were taken. All the groundwater samples in the area contain ^{3}H and indicate active recharge suggesting little or no surface in-put (or near surface mixing) relative to those of the saline ponds. Kehinde and Loehnert (1989) had earlier made the same observations. The combination of these with hydrochemical and stratigraphic settings led to the conclusion that the brines are marine in origin and might be related to palaeo fossil seawater embedded within the transgressive marine sediments and/or precipitated salts formed within the regressive interbeds during the sedimentation cycle.

6.0 SUMMARY OF FINDINGS

An integrated approach-employing geological hydrogeological, hydrogeophysical, hydrogeochemical, isotopic and remote sensing techniques and a logical interpretation of data has enhanced groundwater explorations in Nigeria. Efforts made to locate giant groundwater pools like that of Gurara River area have led to locating places where groundwater can safely be used to meet domestic, agricultural and hydro-electric power needs of the nation (Olasehinde and Awojobi, 2004, Olasehinde, 1999; Annor and Olasehinde, 1996). A battery of productive boreholes like the Gurara Area can lead to perennial surface water system because of the interaction between surface and groundwater sources.

An integrated geologic and multisensor geophysical exploration technique is more suited for successful groundwater exploration in the basement complex terrain of Nigeria (Olasehinde, 2010). The complex nature of the terrain demands a confirmation of the inference from any geophysical method with another one. It is not enough to decide a borehole location on the thickness of weathering alone but fractures are very good sources of groundwater as well.

In an overview of the groundwater sustainability problems worldwide application of isotope techniques for water resources development and management have been discussed with reference to Nigeria. Studies in the quite unique Nigerian environments have proved that isotope techniques are becoming an integral part of many hydrogeological investigations and a complimentary tool to hydrochemical controlling processes in groundwater system for hydrological investigations.

Studies in the semi-arid northern Nigeria as well as in the southern/coastal areas show that environmental isotope techniques are often indispensable in understanding hydrogeological processes, in uniquely identifying and quantifying recharge and educating transport of pollutants. These have shown that environmental isotopes techniques are indispensable in understanding hydrogeological processes and thus useful for sustainable groundwater development and management.

The applications of isotope techniques in determining groundwater pollution vulnerability or in direct contaminant studies have not been fully utilized in Nigeria in spite of the locally elevated concentrations of NO_3, Cl and SO_4 (pollution indicators) in many places attributable to increasing population, rapid urbanization and industrialization as well as the indiscriminate disposal of wastes.

7.0 RECOMMENDATIONS

The following recommendations are made:

i. A conjunctive development of surface water and groundwater sources in Nigeria is recommended. The approach to groundwater exploration as done now in Nigeria cannot lead to sustainable water supply unless the right emphasis is placed on groundwater situations in Nigeria.

ii. Data gathering should be encouraged, especially basic weather data. The data collections in "geographical garden" in elementary and secondary schools should be resuscitated while relevant Departments in tertiary institutions should be mandated to collect hydrological data especially run-off data and simple data on climate-temperature, rainfall, evaporation, wind direction among others. The Water Boards, Basin Development Authorities, Ministries of Works, Agriculture and Aviation should be made to collect necessary data and log books kept.

iii. Data on evaluated groundwater characteristics should be kept in the Nigeria Geological Survey Agency (NGSA), National Institute of Hydrological Services (NIHS) and National Water Resources Institute (NWRI).

iv. Relevant professionals should be allowed to enhance groundwater resources development and give correct assessment of situations in the twelve hydrogeological provinces.

v. Presently the Basin Development Authorities are hydrologically biased to the negligence of hydrogeology. Efforts should be made to emphasise hydrogeology in the demarcation of Basins in Nigeria. Twelve hydrogeological provinces as demonstrated here should be adopted.

vi. Appropriate pricing for groundwater explorations and development should be worked out. At present the engineering aspects of groundwater development are grossly exaggerated. For example, the generator house in a borehole scheme is ten times higher than the exploration for the borehole. The price of water in for a borehole project is five times higher than the borehole itself. The goose that is laying the golden egg should not be killed.

8.0 CONCLUSION

The Chief Servant and Executive Governor of Niger State, Dr. Muazu Babaginda Aliyu, His Deputy, Alhaji Musa Ibeto, the Vice-Chancellor of our great University, Professor M.S. Audu, his crop of Principal Officers, Deans, Heads of Department, Professors and other fellow lecturers, spiritual leaders, traditional rulers (present or represented), invited quests, ladies and gentlemen, I thank you all. Members of the University Seminar Committee led by the Chairman, Dr. E. E. Udensi, have encouraged the realization of this lecture. I am grateful to you all.

9.0 APPRECIATION

The almighty God is Alpha and Omega, the Beginning and the End. I give Him all praises and adorations for letting me be what I am and will be. He has placed me, always, among people who understand me. From birth till date I have received His mercies and loving Kindness. How Great Thou Art, my God. That is why I have no choice than to be for Him alone.

My parents Pa Joseph Olasehinde, Head of Ibinise House, Ora compound, Omu-Aran, and mother Madam Deborah Olabimpe Olasehinde have been my mentors from cradle. The best gift of life and children had been given to them. They have gained heaven and waiting for us to come there. They laid good foundation for us for life and eternity. All the children were given opportunity to be educated and we in turn have taken a cue from them. My siblings are all here. I promise by God's grace I will not disgrace you as I am proud to be your leader today. You will be better than me in Jesus name.

My wife, Dr. (Mrs.) Martha Olufemi Olasehinde has taken over the role of my mother. She buys and put my dresses and shoes on me. Mummy is her name not just Darling. It is too cheap to say I love her but she knows I am her father. God will keep her for me. Our eight children are all here today and many adopted children. We have shown you examples of what our parents taught us. Do better to your own children. Mrs. Yetunde Abiodun, Mrs. Bukola Joshua, Mrs. Oluwaseyi Atolani, Femi, Gideon, Toyin, Ibukun and David and Mrs. Kike Olasehinde (daughter-in-law) are here. Thank you for doing me proud. I will not let you down. Keep the Ibinise House banner flying.

When I left my home base in 1962 I was in Government College, Zaria (now Barewa College). Barewa Old Boys (BOBA) are here today. You are too many to mention one by one. The Spirit of hardworking (He who works, succeeds) and Unity have been used greatly by BOBA to move Nigeria forward. Entrepreneurs, clergymen, lecturers, and military men among others are from this great school. Barewa Spirit will not die. The Spirit of our founding fathers will not rest until we have done Nigeria proud permanently. Alhaji Isa Ozi Salami and Dr. Maji Chado were my roommates in Dan Hausa House; they serve as representatives of BOBA here today.

Many friends are here today. Above all are my spiritual friends, father and mothers, brothers and sisters in the Deeper Life Bible Church. I went to read geology as an adventurer but studying the earth in its entirety has made me to love God deeply. I love you all. Thanks for your prayers and encouragement. I wish to point out, how the wife of one of our Pastors, Sister Adefila, gathered children to pray for me to conclude my PhD in the middle eighties when I least needed it. Today, God has answered the prayers of the woman and youths; hence I have stepped down from making boreholes to mentoring people in borehole drilling. The print out here has been facilitated by a personal assistant given to me by the Deeper Life Campus Fellowship, Federal University of Technology, Minna, Nigeria. He is Mr. Stephen Olude, a faithful, loyal and hardworking computer processing expert. God bless you all.

My secular and academic friends are many. They have contributed greatly to me academically and professionally. We had a team for tutorials at the University of Ibadan, Nigeria called comrade "Q". Meaning ***Comrade in Questions.*** Prof. Olarewaju, Prof. Malomo, Prof. Odeyemi, Dr. Ogunyomi, Mr. Ogedengbe, Dr. Offrey, I cannot forget you all. We have contributed our quota to earth Sciences. My students have made me feel fulfilled academically Prof. Olorunmaiye (Dean of Engineering, University of Ilorin, Nigeria), Dr. Adelana S.M.A., Dr. Levi Nwankwo (PhD, Physics), Dr. O. Bayewu (Olabisi Onabajo University), Dr. (Pastor) M.O. Awojobi, Dr. Idris Nda A. (Federal University of Technology, Minna), Mr. Dan Hassan (FCT Water Board), Mr. A.N. Amadi (Federal University of Technology, Minna) and a host of others, I am proud of you all.

My Lecturer and father, Prof M.O. Oyawoye has been my mentor. We of the 1972 Graduating set of University of Ibadan, Nigeria honoured him at Abuja when he was 72 years of age. Because of age, rough road and distance I did not bother to invite him. You have produced many great children who are producing grand children in geology. I set a target to be like you and I am still trying my best. You will see many more years in joy.

10.0 TRIBUTE

This is a tribute to Nigerian government for roles played to contribute to my education at various times. First is the former Northern Nigerian Government whose policy on education enabled a child like me from a poor family back ground to be trained in Government College Zaria (now Barewa College 1962 to 1968). Most of the science equipment in the school cannot be found in many Universities today. Next is the Federal Government of Nigeria. The consultancy services to carry out aeromagnetic survey of Nigeria in the seventies were supervised by the Geological Survey of Nigeria. Training in all aspects of airborne geophysics were afforded me at home and abroad. The higher we flew the surveying aircraft the deeper we saw into the ground. The idea of upward continued frequency domain operations (Swimming) were gained during the period of 1975 to 1980 by most of the geologists trained in airborne geophysics then. The third is the Federal Ministry of Agriculture and Water Resources, Abuja, Nigeria that offered consultancy services opportunity to University of Ilorin, Ilorin, Nigeria in the late eighties to survey for alternative water supply to Abuja. The production capacity of 8,000 M^3/hour of treated water from Lower Usuma Dam became inadequate as a result of population increase and industrialization. In order to meet the growing demand for water there was heavy dependence on ground water. The team of Geologists and Civil Engineers at the University of Ilorin had a stint in surveying for both groundwater and surface water resources. The multibillion naira Gurara Dam project came about as a result of the confidence reposed in a University to research into solving water problem for the country. The capacity built in terms of personnel training, infrastructures are great. We had Departmental motor cycles, land rovers and cars for easy movement on the field plus free accommodation. Where are the opportunities now?

Time and tide wait for nobody. Soon we will be gone. It is therefore suggested that Nigerian governments should tap resources in the Universities by endowing projects that solve problems of infrastructural needs of the nation. Private companies are also encouraged to invest in capacity building of Departments of Geology. Water supply problems and road failures will soon be a thing of the past. The Niger State Government of Nigeria has started good things by the emphasis on education at all levels and also the memorandum of understanding signed with the Federal University of Technology, Minna, Nigeria. The understanding will lead to great development for the state. Studies in Geothermal Energy resources evaluation and use of groundwater in hydro-electric power generation will soon be started in the Department of Geology to make the Power State improve power supply in Nigeria.

We are swimming in abundant groundwater now. Time will come when we will have a final swim and not come back to tell stories. It is a must.

Thank you all.

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