Hydrogeophysical Investigation and Aquifer Evaluation of the Formations in Nsukka Area, Southeastern Nigeria

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Abstract

The study targeted the aquiferous Ajali Sandstone and Nsukka Formations that underlies the Nsukka metropolis and its environs (within Latitudes 6° 80^1N and 6° 89^1N; Longitudes 7° 21^1E and 7° 30^1E), covering an area of about 210 square kilometres. Thirty four (34) cross array Vertical Electrical Sounding (using the Schlumberger electrode configuration) and records from four (4) selected boreholes have been used to investigate the subsurface distribution of electrical resistivity and to delineate hydraulic properties of aquifers in Nsukka area, Southeastern, Nigeria.The electrical surveys of the area show high values of permeability, ranging from 0.0075 to $0.015cm^2$, hydraulic conductivity, ranging from 8.29 to 16.64m/s, transmissivity, between 455.87 and $1002.48m^2s^{-1}$, and specific yield, ranging from 2.35 to $4.76m^3$. A tie with the results of borehole logs analysis reveals the presence of at least four layers of contrasting hydraulic conductivity. Analyses, however, suggests that the Nsukka Formation (which overlies the Ajali Sandstone) is thick and poorly conductive while the Ajali Sandstone unit is homogenous and anisotropic and has higher conductivity (especially beyond the depth of 100 m), suggesting a prolific water-bearing formation at such depth and beyond. The Ajali Sandstone aquifer in the area is thick and prolific. The distribution of major geological units, well log data, static water level data were shown to have influence on the groundwater occurrence and flow pattern in the area.

Keywords: Ajali Sandstone Aquifer, Nsukka Metropolis, Resistivity measurements, Well data

DOI: 10.7176/JEES/11-7-04

Publication date: July 31st 2021

1. Introduction

The Nsukka area, southeastern Nigeria has little or no surface water, resulting to some water resources problem and to high dependent of groundwater. The area included the University of Nigeria community, Nsukka town and environs, in Enugu State, Southeastern Nigeria. The area lies within Latitude 6° 80^1 N and 6° 89^1 N, and Longitudes 7° 21^1 E and 7° 30^1 E and covers an area of about 210 km^2 (Figure 1). The geology is predominantly the Ajali Formation, overlain by thick Nsukka Formation that has high infiltration capability (Ezim *et al.,* 2016; Nwajide, and Reijers, 1996).

Mamah and Ekine (1989) had conducted a geo-electrical survey on the Nsukka Formation and distinguished two to three layers of the basal sandstone within the formation. Mamah (1997), suggested with the aid of the resistivity sounding survey data carried out at Orba for the UNDP, that the depth to water table in the area is about 95 m and that the aquifer is the Ajali Sandstone. The characteristics of this aquifer with respect to well yield remain uncertain, as most boreholes and hand dug wells in the area turn abortive. The need for adequate water supply in the Nsukka area necessitated the use of vertical electrical sounding to evaluate the hydrogeological potential of the Ajali Sandstone.

1.1 Geology of the Study Area

The Nsukka area, geologically, lies within the Anambra Basin. The Anambra Basin is an inland sedimentary basin sandwiched between the Southwestern part of the Benue Trough and the Petroliferous Niger Delta. The origin, sedimentology and stratigraphy of the basin have been well presented by several authors: Agagu *et al*. (1985), Benkhelil (1987), Kogbe, (1989b), Murat, (1972) and Nwajide, (2006a). The basin is bounded in the west by the Precambrian Basement Complex, of western Nigeria, and in the east by the Abakaliki Anticlinorium. The Southern boundary is at Onitsha which coincides with the northern boundary of the Niger Delta Basin, while the northern boundary is taken to correspond to the limit of the exposure of the Maastrichtian sediments Nwajide, (2006a and b). The basin is exposed over a roughly triangular territory estimated at some 95,000 km^2. It rests on the Awgu Formation of the southern Benue Trough (in an angular unconformity relationship), but underlies the Niger Delta for a considerable extent. The total area is possibly in excess of 140,000 km^2.
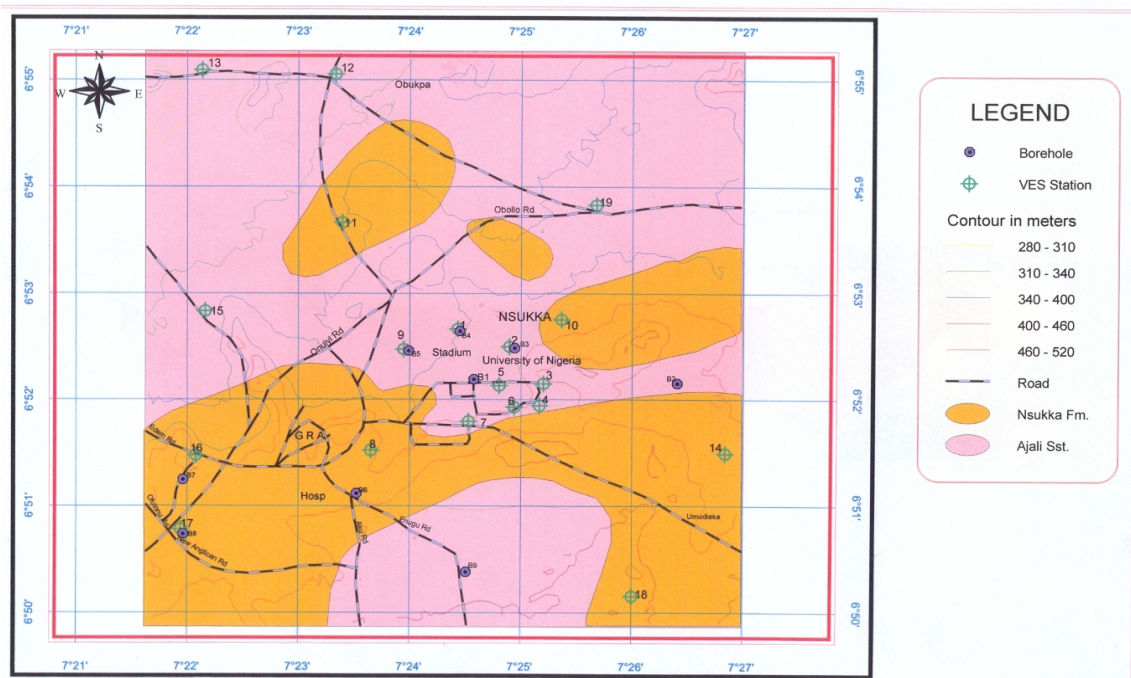
Figure 1. Geological map of the study area showing accessibility, sounding stations and borehole locations

Amongst the sediments of the basin are the Mamu, Nsukka and Ajali Sandstone Formations. Slow subsidence followed by a major regression led to the deposition of the Mamu (coal-bearing) and Ajali Formations which accumulated during the Maastrichtian Epoch. The Mamu Formation most probably documents a delta strand plain which resulted in coal seams in addition to delta sand bars and Chenier ridges. The overlying Ajali Sandstone has been attributed to fluvial deposition, and the development of shallow marine sub tidal sand bars [16]. The Danian Epoch of the Palaeocene period saw the deposition of the Nsukka Formation. Sedimentation was mainly of fluvial origin (Table 1) (Nwajide 2006a; Nwajide, and Reijers, 1996). The borehole data in the southern parts of the Anambra Basin used in the reconstruction of the stratigraphic unit reveals that the formations (i.e. Nsukka, Ajali and Mamu Formations) all appear to be steeply inclined and dipping towards the western flank of Onitsha High, and flattening out below the Imo Formation, (see Figure 2).
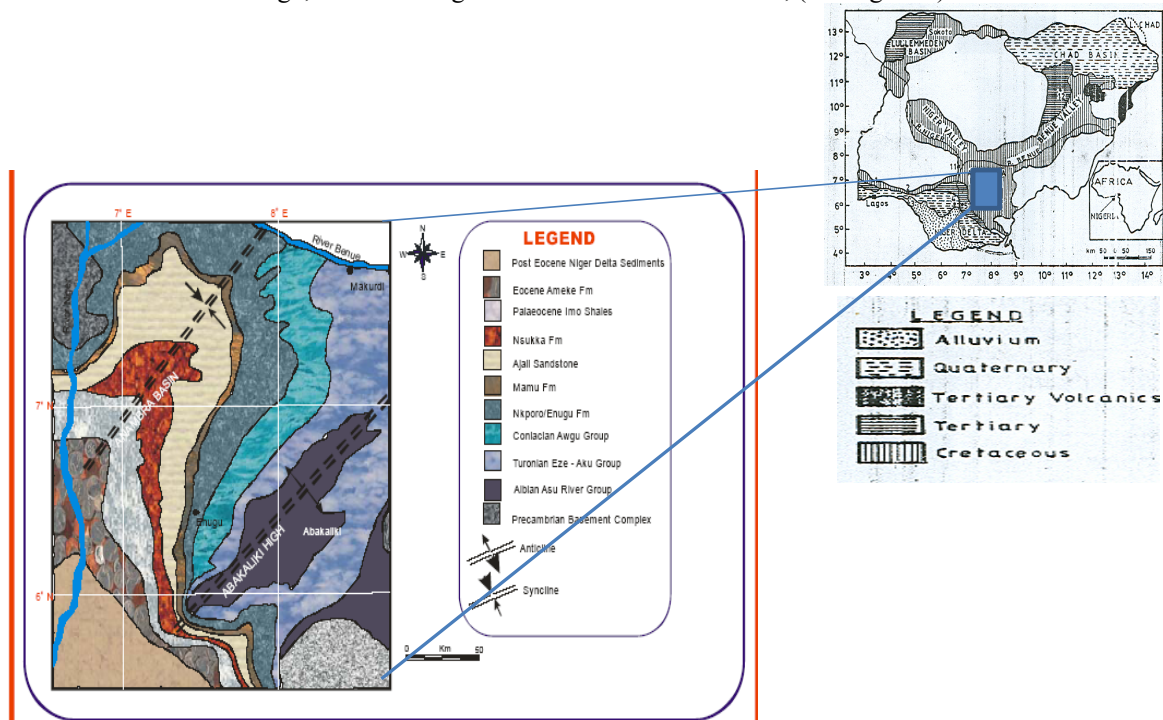

Figure 2. Geological map of Southeastern Nigeria showing the Southern Benue Trough and Anambra Basin, (Modified after Burke et al., 1972, Kogbe, 1989b, and Nwajide, 2006a)

Table 1. Lithostratigraphic Units of the Anambra Basin (Modified from Nwajide 2006a)

Age	Basin	Stratigraphic Units						
Thanetian	Niger Delta	Imo Formation						
Danian								
Maastrichtian	Anambra Basin	Coal Measures	Nsukka FormatIon					
			AjalI FormatIon					
			Mamu FormatIon					
Campanian								
		Nkporo Fm.	Nkporo Shale	Enugu Fm.	Owelli S St.	Afikpo S St.	Otobo S St.	Lafia S St.
Santonian	Southern Benue Trough	Awgu FormatIon						

The Ajali Formation consists of thick friable, poorly sorted sandstone typically white in colour but sometimes Iron-stained. Marked bandings of coarse and fine layers are displayed. The sand grains and large fragments are sub-angular, with a sparse cement of white clay. Large-scale, cross bedding is also one of its characteristic features (Banerjee, 1979; Kogbe, 1989b). Erosion surfaces within successions of the Ajali Sandstone are poorly defined but can be identified either by the presence of a laterally persistent granular bed usually a few centimetres thick or the abrupt truncation of burrowed horizons. The Ajali Formation is well displayed along the lowland and dry valley zones of the study area including: Obukpa, Onuiyi Road, Ibagwa Road, Obollo Road, Base of the Physics observatory, Odim area, Franco and beyond Zik's flat (Figure 1). The thickness of the Ajali Formation has been measured by several workers. According to Nwajide (2006a), maximum recorded thickness was from the Igbariam borehole where the formation is up to 534m thick. This thickness decreases gradually towards the west and east to only a few tens of metres around Okigwe.

The depositional environment of the Ajali Sandstone as described by some authors include; a fluvio-deltaic depositional environment (Agagu et al., 1985; Burke et al., 1972), an inert tidal bar and channel system (Banerjee, 1979), an inter-tidal flat, based strictly on its sedimentary facies characteristics (Amajor, 1984). The lateritic Nsukka Formation consists of an alternating succession of sandstone, dark shale, sandy shale, thin coal-seams at various horizons and thin beds of limestone towards the top (Kogbe, 1989b; Murat, 1972; and Nwajide, 2006b). The beds are generally gently dipping (amount of dip ranging from 1º to 6º). The lithology of the Nsukka Formation is similar to that of the Mamu Formation.

1.2 Hydrogeology of the Study Area

According to Onwuemesi (1990), the Ajali Sandstone aquifer is essentially unconfined and results of geo-electric resistivity surveys and static water level measurements in the relatively shallow boreholes near the crest of the escarpment indicate that the water table lies at a depth of about 55 m. The saturated thickness of the aquifer is about 85 m. Although the Ajali Sandstone Formation shows a wide textural variation across its thickness, borehole data show that below the water table the texture is relatively more homogenous and ranges only from fine to medium grain. Thus, within its saturated thickness, the hydraulic conductivity could range from 10^{-5} to 10^{-4} m/s. Values ranging from $7x\ 10^{-5}$ to $2\ x\ 10^{-3}$ m/s were obtained by Onwuemesi (1990), and Uma, et al. (1989), using grain size data. It would appear however, that the upper limits of this range reflects the gravely and coarse sand units which predominate in the region above water table.

2. Materials and Methods

2.1 Field work and Vertical Electrical Sounding (VES)

Different stages of field investigations were carried out and maps produced on a scale of 1:250,000. This was followed up by fourteen (14) sets of Vertical Electrical Sounding (VES) using the Schlumberger electrode configuration. One of the advantages of this configuration lies in the fact that only two electrodes are moved at once, hence it is less inconvenient, and requires lesser crew unlike the Wenner spread (Habberjam and Watkins, 1967; Telford et al., 1990). The positions and the elevations of the sampling points and VES locations were determined with the base map and Global Positioning System (GPS) device. The resistivity Surveys (VES) were

carried out with ABEM Terrameter (SAS 300B and SAS 1000). The ABEM Terrameter Signal Averaging System basically consists of a transmitter and receiver. The system automatically calculates the ratio of the potential difference across the layer and the current passing through the layer (V/I) and then displays it in digital form in kilo ohms, ohms or in milli-ohms.

Some precautions were taken during the field surveys in order to generate an accurate or near accurate data. For example; the electrodes were hammered firmly into the ground to at least a depth of 35 cm in order to avoid error reading and achieve good electrical contacts with the ground, water was poured at the point of electrode contact with the ground to possibly enhance ionic flow of current and measurements were avoided during rain and thunder-storms since they are capable of inducing hundreds of volts in long cable layout and this can cause damage to the equipment and can as well constitute risk to the crew.

Also, positions of the electrodes were kept far away from power-lines and other lateral near surface inhomogeneities, to avoid altering the value of the potential difference.

2.2 Borehole Data acquisition
The Rotary method was employed in the drilling all the boreholes used this study. 15 inches bit was used in the entire drilling programme. The borehole loggings carried out were limited to SP and resistivity. While the SP probed the voltage developed as a response to electrochemical effects of differences in borehole fluid and oxygen reduction of minerals, the resistivity logging measured the electrical resistivity of soil, rock, and pore fluids [21]. Both were run in uncased condition. The static water level, hydraulic conductivity (K), transmissivity (T) and discharge (Q) were calculated following methods described by Ezim et al. (2017), Harleman, et al. (1963), Hazen (1983), Henriet (1976), Uma, et al. (1989).

3. Results and Discussions
3.1Borehole depths and static water levels
The summary of the results of the aquifer characterisation is presented in Tables 2, 3 and 4, while the selected borehole logs are presented in Figures 3, 4, 5 and 6. The results indicate that the borehole at the Abuja Building (A02), Franco Refactory (F03) and the Energy Centre (E04) [University of Nigeria, Nsukka (UNN)] all penetrated the Ajali Sandstone aquifer; with respective depths up to 720 ft (220m), 670fts (210m) and 682fts (208m). Also, static water levels were determined and they fall within the range of 500-550 ft, 350-400ft, and 485ft respectively (Figures 3 to 5).

Similarly, the Bore hole (Z05) at ZENITH BANK (along Enugu Road, Nsukka), was drilled to a depth of 656 ft (approximately 200 m), penetrated the Ajali Sandstone aquifer as well and having a static water level determined to be in the range of 580 to 600 ft (Figure 6).

Table 2. Average Hydraulic Conductivity (K) of earth Materials from the selected boreholes

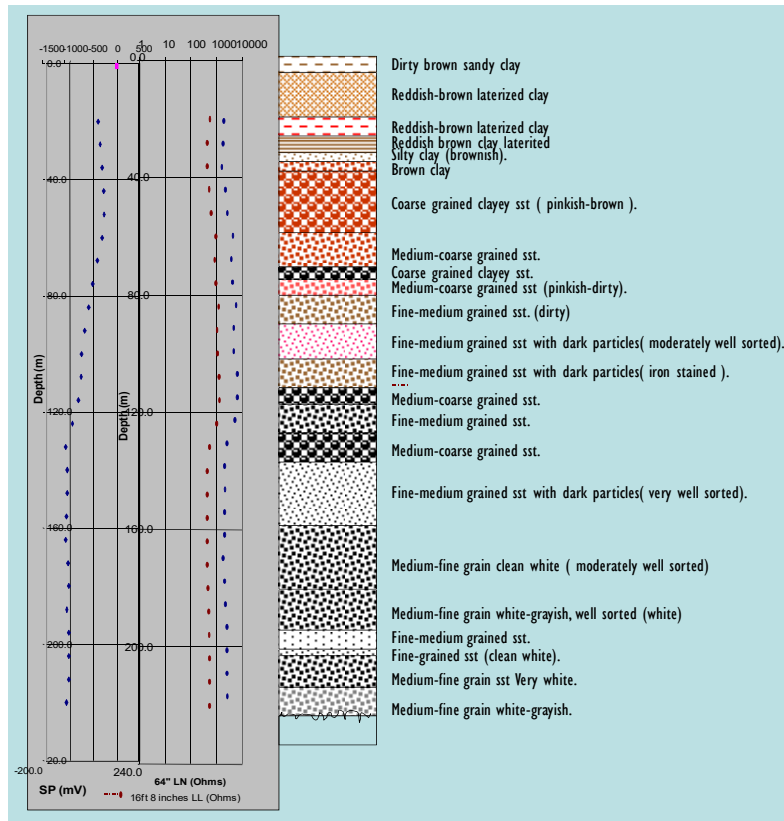| S/No.	Borehole Location	Average d_{10}^2	Cd_{10}^2 (cm^2)			
			Harleman et al. (1963) C= 6.54x10^{-4}	Hazen (1893) C = 100	Kozeny Carman in Bear (1972) C = 64.1	Uma et al., (1988) C = 6.1
1	Abuja 2 well	0.002332	1.62x10^{-6}	0.2332	0.1494812	0.0142252
2	Franco 3 well	0.001234	1.525x10^{-6}	0.1234	0.0790994	0.0075274
3	Zenith 5 well	0.002478	8.07x10^{-7}	0.2478	0.1588398	0.0151158

Figure 3. Log and lithological results of the borehole (A02) at Abuja Building, University of Nigeria, Nsukka
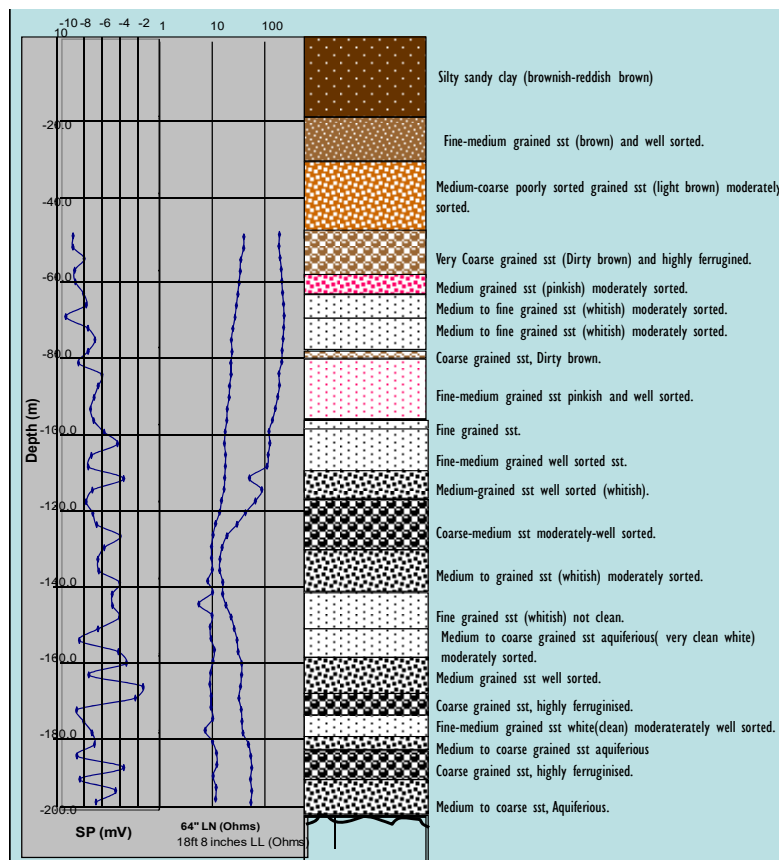

Figure 4. Log and lithological results of the borehole (F03) opposite Franco, University of Nigeria, Nsukka
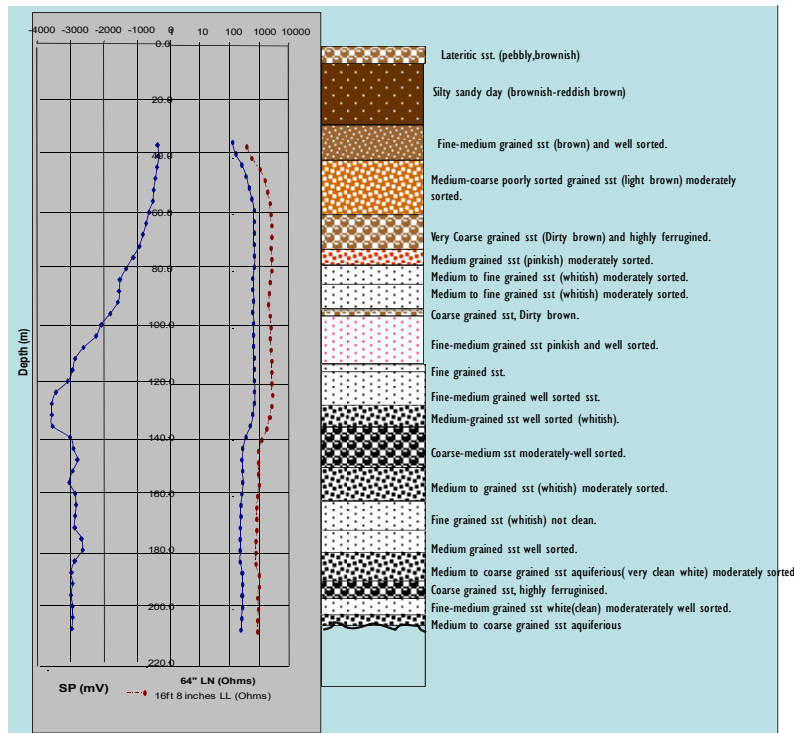
Figure 5. Log and lithological results of the borehole (E04), at the Energy Centre, University of Nigeria, Nsukka
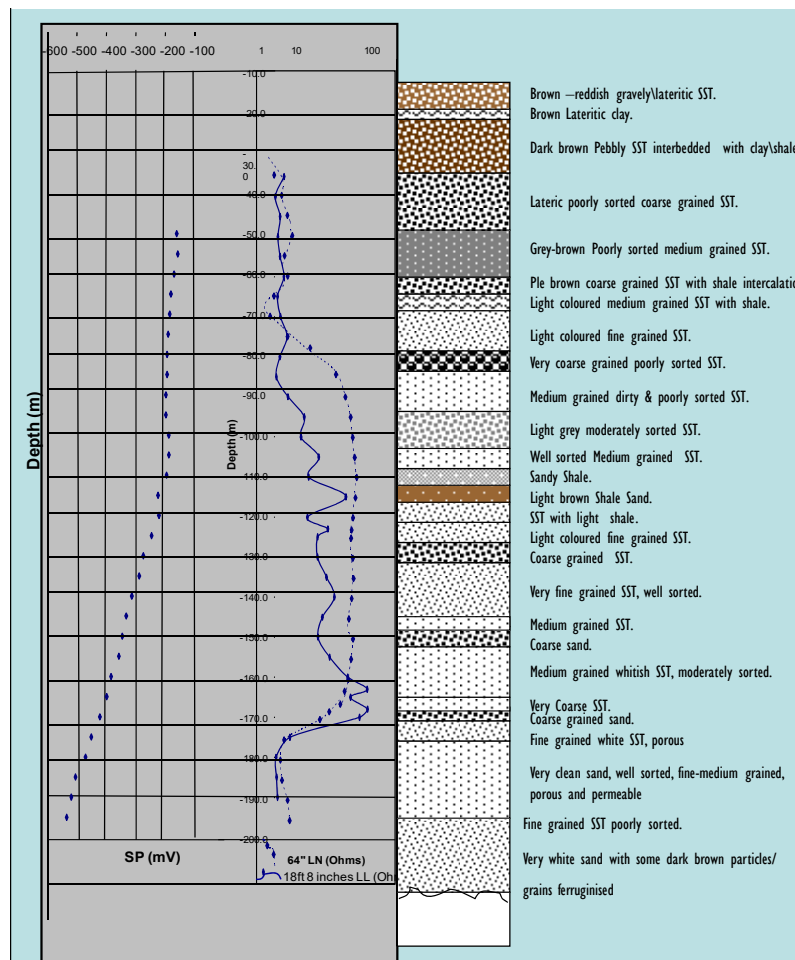

Figure 6. Log and lithological results of the borehole (Z05) at Zenith Bank, Nsukka Town

Table 3. Calculated permeability (k), hydraulic conductivity (K) and Transmissivity (T) values for Ajali Sandstone Aquifer from the selected boreholes locations

Aquifer Units	Method for obtaining the Hydraulic conductivity values	Aquifer parameters			
		Permeability (k)		Hydraulic conductivity (K)	Transmissivity
		(cm^2)	(m^2)	(ms^{-1})	(T) (m^{2}s^{-1})
Abuja 2 well	Kozeny	0.1494812	1.4948x10^{-5}	164.5973	10534.2300
Franco 3 well	Carman in Bear	0.0790994	7.9099x10^{-6}	87.0982	4790.4000
Zenith 5 well	(1972) C = 64.1	0.1588398	1.5884x10^{-5}	174.9023	7870.6000
Abuja 2 well	Uma et al.	0.0142252	1.4225 x10^{-6}	15.6640	1002.4770
Franco 3 well	(1989)	0.0075274	7.5274x10^{-7}	8.2886	455.8730
Zenith 5 well	C = 6.1	0.0151158	1.5116x10^{-6}	16.6444	748.9964

Note 1. Hydraulic conductivity (K) = kδg/μ

Where k = permeability; δ = Density of water = {1000kg/m3}; g = Earth's gravitational acceleration = {9.8m/s2};

μ = Viscosity of water = {0.00089Newton.Sec/m2 Bolz and Tuve (1973)}

Note 2. Transmissivity (T) = Kb, Where K = Hydraulic conductivity; b = Aquifer thickness

The borehole results were utilized to produce water level in different locations as presented in Tables 4 and 5; Figure 7).
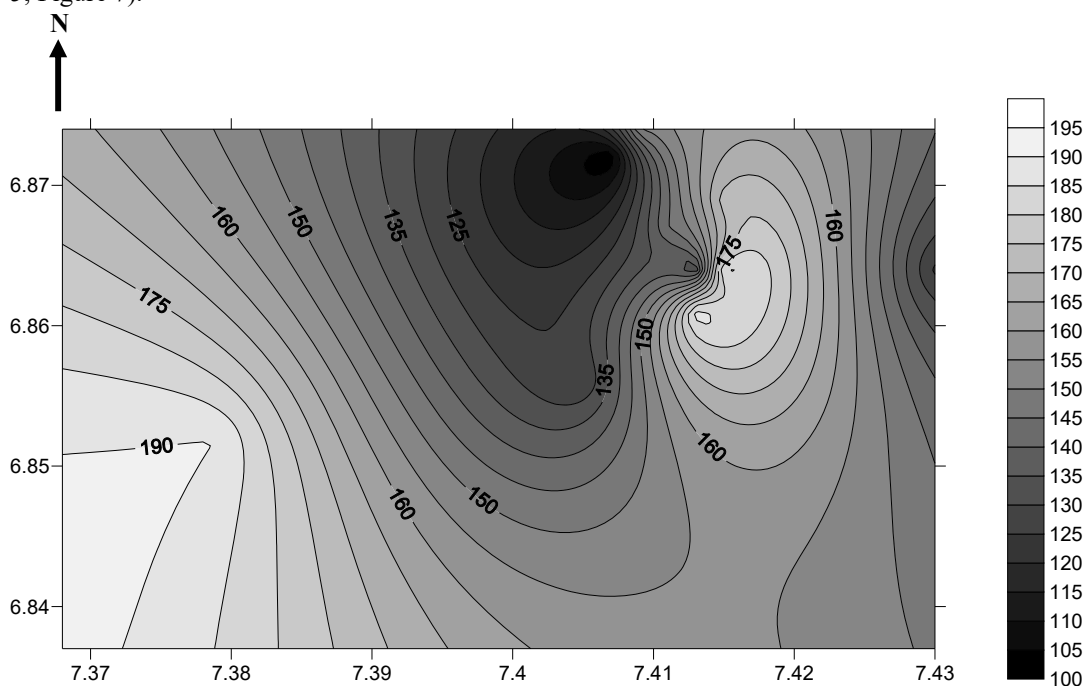

Figure 7. Isopach map of the aquiferous layer(s)

Table 4. Water level in different locations of the study area

S/No.	Location	Lat (X) ^{o}N	Long (Y) ^{o}E	Elevation (m)	Depth to Water Table (m)	Depth to groundwater from well log data (m)	Range of Depth to groundwater from Sounding results (m)	Depth to groundwater from Sounding results (Mid/Average value) In meters	In feet
1.	UNN-BH	6.869	7.415	402.9	14		145-200	172.5	565.94
2.	ABUJA-BH	6.867	7.411	421.5	10	132 (SWL=145)	135-155	145	475.72
3.	ENERGY CTR.	6.868	7.413	424.2	18	145 (SWL=148)	145-165	155	508.53
4.	AWOLOWO HALL	6.864	7.413	445.6	17		85-175	130	426.51
5.	UBA	6.864	7.415	455.3	18		180-190	185	606.96
6.	AKPABIO HALL	6.862	7.415	448.0	26		180-180	180	590.55
7.	MEDICAL CTR.	6.861	7.413	456.8	29		180-195	187.5	615.16
8.	ODENIGWE	6.856	7.405	460.3	33		120-130	125	410.10
9.	FRANCO-BH	6.867	7.407	412.1	6	125 (SWL=135)	80-120	100	328.08
10.	ORBA AREA	6.863	7.424	448.6	21		100-128	114	406.82
11.	ODIM AREA	6.874	7.409	410.2	28		140-160	150	492.13
12.	OBUKPA RD.	6.881	7.399	382.5	18		110-130	120	393.70
13.	OBUKPA L/OUT	6.879	7.397	385.2	13		80-120	100	328.08
14.	ZENITH BANK	6.852	7.395	454.1	35	165 (SWL=175)			
15.	NEW ANGLICANRD	6.837	7.368	456.5	45	175			
16.	OFULONU RD.	6.852	7.379	453.1	45	170			
17.	EDE-OBALLA	6.811	7.447	457.4	20		120-130	125	410.10

Table 5. Results of the thickness of the aquiferous layers and aquifer yield in selected locations of the study area

S/No.	Location	Sounding results				Information from Borehole log results					
		Average thickness b (m)	Resistivity ρ (ohm-m)	Average Long. Conductance S (Siemens)	Trans. Resistance T (Ohmm^2)	Layer depths Range h or z(m)/Aquifer Thickness (m)	True Formation Resistivity average (ρ$_T$ or ρ$_i$ - Ωm)	Average Long. Conductance S (Siemens)	Average Trans. Resistance T (Ohmm^2)	Ave. Water Resistivity (ρ$_w$ -Ωm)	Aquifer Storage/Unit Vol. OR Yield OR Vol. of H$_2$O (dW) m^3
1.	ABUJA-BH A02	90.34	1677.15	0.0011 0.045989 Average ΔS= 0.023545	12502.6 151432.8	132-196 Δh= 64	1346.31	0.123590	220726.52	134.634	4.755
2.	FRANCO-BH F03	71.22	1257.80	0.01852 0.00351 Average ΔS= 0.011015	5210.2 1133.0	125-180 Δh= 55	1850.05	0.084413	285055.20	185.01	3.057
3.	ENERGY CTR.- BH E04	113.1	2689.10	0.00641 0.00521 Average ΔS= 0.0581	60002.1 109074.4	148-204 Δh= 56	2692.28	0.065960	473719.41	269.23	2.346
4. *	ZENITH BANK- BH Z05					150-195 Δh= 45	2409.17	0.625668	3924324.50	240.92	

* No good sounding work done in built up location(s)

Note: ρw = ρT /F; dW = 1.5 x ΔS x ρw . Where F = Formation factor ~ 10

3.2 VES, Borehole and Aquifer parameters

The objective of a well planned borehole geophysical survey was to obtain more information from a well than can be obtained from drilling, sampling and testing. The interpretations of the VES were from analyses of curve matching and the Parameters and functions of Dar Zarrouk (Habberjam and Watkins, 1967; Henriet, 1976; Mamah, 1998; Mamah and Ekinne, 1989).

Most of the sounding curves including VES: UNN, ABUJA, ENERGY CENTRE, MEDICAL CENTRE, FRANCO BH-I, EDE-OBALLA-I are a four-layer HA type section while sounding curve VES: AWOLOWO II, and OBUKPA ROAD I, are a three-layer HA-type section. VES: ABUJA I, AWOLOWO I, UBA, AKPABIO,

ODENIGWE, FRANCO BH-II, ODIM, OBUKPA LAYOUT I, are a five-layer HA-type section while only OBUKPA ROAD II AND OBUKPA LAYOUT II are a 6 layer A-type section. The lithologic information from a producing borehole (A02) in conjunction with the geology of the area was utilized in constructing the various earth models.

Generally the sounding curves indicate a high resistivity (> 1000 ohm-m) for the top weathered lateritic layer of varying thickness and dryness. Most of the VES including: ABUJA I and II, ENERGY CENTRE I and II, FRANCO I and II, and OBUKPA I and II, penetrated Ajali Sandstone at a depth of at least 30m (see Tables 4 and 5). Apart from VES FRANCO I and II, the maximum current electrode spacing used was 1000m, the rising part of the resistivity curves are not well developed to enable the resistivity of the basal rock unit to be determined.

In most of the VES results, the third layer have high resistivity (>5000 ohm-m) and are probably sandstone-bearing freshwater zone. In all the sounding curves, this layer/zone is overlain by a low resistivity layer (200-500 ohm-m) which was interpreted as clay. A freshwater aquifer thickness of about 100m is indicated in most of the sounding curves/results, while in others ones, the rising nature of the resistivity curves makes it difficult to determine the thickness of the freshwater zone. However, since at the same current electrode spacing the shale bed (Mamu Formation) is yet to be penetrated along all the sounding curves it follows that from the point of view of groundwater potential, the neighbourhood of this sounding point may be the most promising. Table 4 shows the results of water level in different locations of the study area.

It should be noted that, practically, there are often erratic variations in field sounding measurements of ρ_a due to local resistivity changes near surface and poor electrode contacts. In addition, anisotropic ground and terrain effects will lead to errors in estimating both h and ρ_1.

3.3 Hydrogeology and Hydrology

During rainy season, the water table rises, and as the frequency of the rainfall increases and the soil becomes increasingly saturated, the amount of infiltrations into the dynamic groundwater system increases. The run-off is significantly very low at most of the parts of the study area because of the high permeability of underlying formations. There is more or less no surface water in Nsukka area hence, little or no drainage network but there are several springs issuing from the flanks of the ridges of the several hills. Most parts are underlain by porous and permeable sandy units and so are devoid of any surface water bodies, due to the absence of intervening shale layers for infiltrating rainwater, and the

Conversely, few ephemeral springs arise from the interception of few sand lenses (perched aquifers) that exist in the areas dominated by shales and laterites of the Nsukka Formation. However, these springs do not produce enough water to meet the demand of the inhabitants.

The shortage of water, despite the high annual rainfall, about 167.5 cm/yr, therefore presents a problem in the area. Uma *et al.* (1989) noted that this water deficiency results from the combination of two factors as the prolonged dry season and the high permeability of the strata which allows the rainwater to infiltrate to great depth.

Limitations of the geophysical surveys

With respect to accessibility, the sounding stations were hampered by non-motorable/ winding roads that strongly threatened the straight course of the cross array sounding work. In conducting an electrical resistivity survey, the voltages are relayed to the receiver over long wires that are grounded at each end. These wires act as an antenna receiving the radiated electrical noise that in turn degrades the quality of the measured voltages. The major problem in resistivity sounding is caused by the spurious effects of near-surface lateral resistivity variations. This effect was ameliorated by measuring earth resistances at two electrode array positions such that in one position the lateral effect was a positive contribution to the total measured signal and in the other, the contribution was negative. The subsequent combination of the two measurements virtually eliminates the lateral effect. Also, Equipment errors such as: obstruction in the electrode and improper current flow, were among the factors that affected the sounding work in the study area.

4. Conclusions

This study has provided insight into the groundwater potentials of a portion of the Nsukka area, where hitherto, several sunk boreholes proved abortive. Geophysical surveys carried in this research indicated that the aquifer systems occur as perched and confined aquifers. Previous works on the geology of the Nsukka area, such as Akudinobi, and Egboka (1996), Nwankwor et al. (1988) and Onwuemesi, 1990) have shown that most of the lithological logs have lateritic caps varying in thickness form 10m to 95m. Hence, boreholes that penetrated only to this depth range would yield poorly (some of the boreholes records clearly indicated a multi-aquifer system separated by clayey or sandy-clayey aquitards) or out rightly yield not water to the boreholes. This layer's lithology conforms to the literature description of the Nsukka Formation.

Boreholes that were struck the Ajali Sanstone recorded depths of penetration of between 120m and 220m. Most of these were terminated in sandy layers. Deeper drilling would have encountered more aquiferous horizons, and reduce the present under utilization of the aquifers. All the wells drilled as at the time of the study were screened at a section of one aquifer. It would be more advisable to screen two or more aquifers and tap all of them in a coupled manner to provide a better well-yield from the aquifer system.

Electrical resistivity survey on the top of basal Nsukka Formation was found to be poorly conductive because of tortuous current flow in the weathered vesicular laterite. The variations in the resistivities of the top layers are dependent on the moisture content, with resistivity contrast being high on drier days; parameters like: permeability (k), hydraulic conductivity (K), transmissivity (T), and Specific yield have high values in most parts. This has inferred that the area has thick and prolific aquiferous zone of the Ajali Sandstone.

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