

ELECTRICAL ASSESSMENT OF AQUIFERS IN THE BASEMENT COMPLEX OF UNILORIN: IMPLICATIONS FOR EXISTING BOREHOLES

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Abstract

Schlumberger 4-electrode array was employed to sound 21 stations. IPI2WIN and surfer12 softwares were used to infer lithological series, aquifer thickness and depth. The aquifer hydraulic conductivity K and transmissivity T were calculated from the VES data using the Dar Zarouk principles. The field curves show that the area has 3 and 4 geo-electric layers. The layers were interpreted as the topsoil (130- 1469 Ωm), clayey (wet to dry) (52.6- 8552 Ωm), weathered/fractured basement (46.2-249 Ωm) and fresh basement (454-5022 Ωm) respectively. The aquiferous zones lie within the second and third layers. The aquifer depth is between 6.17 m and 24.9 m while the thickness ranges from 1.89 to 22.7 m. The longitudinal conductance S ranges from 0.02 to 0.468 Ω^{-1} and transmissivity T varies from 246 to 2419.8 Ωm^2 . The results conformed with the functional boreholes, such as at VES 3, sited in areas with maximum aquifers and highest transmissivity T . The NE and NW parts were found most suitable for fresh water exploitations. Low longitudinal conductance which implies low protective cover, in the vicinity of the borehole near VES 6 suggests the contamination claim of its water.

Keywords: Aquifer, Borehole, Hydraulic Conductivity and Transmissivity

Introduction

Water is a key ingredient supporting food production, sanitation, human livelihoods as well as ensuring continuity and functioning of ecosystem. In fact, it could dictate the pace of human settlement, agricultural and industrial developments of any society. In the same vein, Humaira and Jose (2009) stated that establishment of any human settlement is usually centered on available source of water and that, in modern days, issue of water supply has taken prominences in global matters. A basement complex terrain, the major sources of good water in the studied area include surface water (river) and groundwater. These are exploited through an embankment dam and drilled boreholes. Groundwater is considered of high quality as it is naturally filtered while percolating through the subsurface layers of the earth. In addition, the distribution problem associated with surface water is of no consequence with respect to groundwater as it is available virtually anywhere in the subsurface, though with variable quantity in the rock pores (Olatunji & Osazuwa, 2012).

Litho logical unit that are adequately permeable to allow water to be abstracted in sufficient volume is called an aquifer. Aquifer water is usually contained within cracks, fractures and pore spaces of soil, sediment and rocks and as a result, they have a high degree of unpredictability. Efficiency and yield of aquifers are determined by the way in which groundwater flows through the strata and the way in which water is released from storage within the strata. This makes accurately describing the hydraulic characteristic of an aquifer difficult. Indirect measurements of aquifer water levels can be used to determine the direction of groundwater flow, to measure aquifer hydraulic characteristics and understand its interactions (Olatunji & Musa, 2013).

Electrical resistivity survey has been found useful in delineating the lateral and vertical limits of the diastrophic features like faults, fractures, joints and shears and delimit the extent and thickness of the weathered basement (Olorunfemi & Oloruniwo, 1985; Olorunfemi & Olayinka 1992). In spite of the associated problems with basement rock aquifers, Azeez (1972) emphasized that considerable water could be available in the area, though occurrence might be erratic, partly because of the discontinuous nature of the groundwater source and this could also be attributed to well sitting by intuition.

To avoid failures, Coker, Akujieze and Oteze 2003 reiterated the use of appropriate exploration techniques to delineate the subsurface water-bearing formations. Ward (1990) stated that VES is excellent for vertical resolution. Zohdy, Eaton, and Mabey (1974) emphasized that VES has easy field logistics and economical. Hence, the VES survey was employed to investigate the aquifer for predicting the sustainability of some existing boreholes (Table 1) and to establish the viability of any proposed boreholes in the area. To achieve this aim the following parameters were obtained: depth and thickness of the potential aquifers, their hydraulic characteristics, and the apparent resistivity of subsurface areas beside some existing boreholes in order to study the yield of the boreholes and identify the litho logical sequence around them.

Hydrology and Location of the Study Area

Permeability is the ability of a rock or unconsolidated sediment, to transmit or pass water through it (Garg, 2005). It is measured by the coefficient of permeability or as hydraulic conductivity. Transmissivity is another physical concept of describing groundwater flow. It has a mathematical relation (discussed later) with permeability.

The two main types of aquifer in this area are the weathered basement and fractured basement aquifers with the latter usually occurring below the former. The aquifers are usually localized and disconnected but occur essentially as unconfined to semi-confined under water table conditions. The crystalline nature of the basement rocks precludes development of porosity and permeability necessary for good groundwater occurrence. Diédhiou, Cissé Faye, Diouf, Faye and Wohnlich (2014) asserted that appreciable porosity and permeability may have been developed within these rocks through fracturing and weathering processes. Olorunfemi, Dan-Hassan and Ojo (1995) envisaged for granites and gneisses, higher storage capacities and higher groundwater potentials if they are well fractured and possess significant porosities because of their mineralogy. There is always very high degree of weathering of the primary rock forming minerals e.g. feldspars and the ferromagnetic minerals into secondary clay and iron oxides respectively (Durotoye, 1983). However boreholes, which penetrate the weathered basement aquifers, have lower yields than those which penetrate both the weathered and fractured basement aquifers (Olorunfemi & Fasuyi, 1993).

The study area lies between longitudes 04°37' 12'' E and 04°40' 47.52'' E and latitudes 08° 27' 1.44'' N and 08°29' 32.64'' N. (Figure 1). The 21 boreholes assessed are distributed over 17.8 km² area within the campus as shown in Figure 1 and their location details are in Table 1.

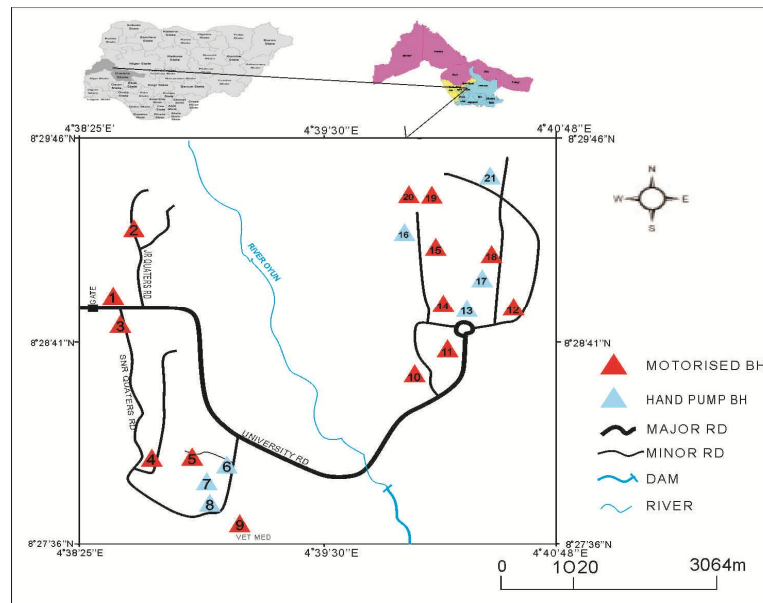


Figure 1: Locations of the Boreholes Surveyed

Table 1: Minutiae of the assessed boreholes

S/N	Location	Pumping Mode	Functionality	Remarks
1	Unilorin Garden		Not functional	Under Construction
2	Jalala Estate	Motorized	Functional	Good Yield
3	Unilorin Water Factory	Motorized	Functional	Very good yield
4	Pro-Chancellors Lodge	Motorized	Functional	Fair Yield
5	Primary School	Motorized	Not functional	In bad state
6	Adjacent Road to Primary School	Hand pump	Functional	Banned for consumption due to lead contaminant
7	Adjacent Road to Primary School	Hand pump	Functional	Good Yield
8	Adjacent Road to Primary School	Hand pump	Not functional	In bad state
9	Faculty of Vet Medicine	Motorized	Functional	Good Yield
10	Sports Field	Motorized	Not functional	In bad state
11	Central Mosque	Motorized	Functional	Good Yield
12	Beside Cooperative	Motorized	Functional	Good Yield
13	Between Senate Building & Block1	Hand Pump	Functional	Very good Yield
14	Behind Village I	Motorized	Not functional	Under Construction
15	Behind Village II	Motorized	Not functional	In bad state
16	Adjacent SUB	Hand pump	Not functional	In bad state
17	Adjacent Block 8	Hand pump	Not functional	In bad state

18	Adjacent Block 10	Motorized	Functional	Good Yield
19	Behind Abuja Hostel	Motorized	Functional	Good Yield
20	Behind Abuja Hostel	Motorized	Not functional	Under Construction
21	Trunil Hostel	Hand pump	Functional	Good Yield

Climate, Drainage and Localised Geology of the Area

The area is noted for two main seasons: rainy season that usually starts around April and last for the next 6 months, and dry season which spans for the next 6 months at the end of the rainy season. In between this period is the harmattan which is characterized by high temperature and dusty atmosphere (McCurry, 1976). The annual rainfall in the region is about 1252 ± 239 mm (Ejieji, 2004). The humidity ranges between 60 to 89% and the mean annual temperature is about 27.7°C with the maximum mean at 32.2° occurring from February to April (Iloeje, 1980); (Omotoso, Ojo, Morakinyo & Alao, 2012).

The drainage pattern in the study area is generally dendritic. The area is drained by both surface water and groundwater. The surface water is river Oyun. Discharging throughout the year, river Oyun flows in the southeast-northwestern direction (Olasunkanmi, Olatunji, Akoshile & Nwankwo, 2012) and out of the study area.

Nigeria is made up of three major litho-petrological components, namely, the Basement Complex [Pan-African and older (Precambrian) > 600 Ma], Younger Granites [(Jurassic) 200 – 145 Ma] and Sedimentary Basins [(Cretaceous to Recent) < 145 Ma]. The study area is mainly underlain by crystalline rocks, collectively referred to as the southwestern Nigeria Basement Complex (Fig. 2). The Basement complex is a polycyclic terrain which suffered its most pronounced deformation and mobilization during the Pan-African age (600 ma). Different ages have been ascribed to the Nigerian Basement Complex, but Grant (1969) and (1970) observed that the majority of the radiometric ages obtained fall in the range of 600 ma, which corresponds to the Pan-African thermo-tectonic event.

Based on the structural, lithostratigraphy and geochemical data the Precambrian rocks of Nigerian are classified into the following age groups, corresponding to the major Orogenies that have punctuated the Precambrian history of Africa. It has been suggested that the major plutonic events; viz: Liberian (2,600 – 3,000 ma), Eburnean (2,000 - 2,400ma) and pan-African (450 – 750 ma) did take place, resulting in what is now known as the Basement Complex of Nigeria. According to Elueze (1992), the three principal recognizable subdivisions within the basement complex are: the migmatite gneiss complex which is 60% of the surface area of the Nigerian basement complex (Rahman, 1988), Schist belts, and the Pan African plutonic series, which make up 20% of the basement complex in the southwestern part of Nigeria (Harper, Sherrer, McCurry & Wright, 1973).

The crystalline basement complex of the study area consists of gneisses and migmatities, schists, quartzites, Pan-African granite, late-stage minor pegmatitic and aplitic intrusives. Ilorin is situated within the Basement Complex rocks of granitic and metamorphic origin (Olasehinde, Virbka and Esan, 1998). These rocks represent the deeper, fractured aquifer which partly lies on top of a shallow, porous aquifer within the lateritic soil cover (Annor and Olasehinde, 1996). The rock units form part of the regional South Western highlands of Nigeria running NW-SE parallel to the River Niger (Offodile, 1987; Olasehinde *et al.*, 1998).

The superficial deposit in the study area terrain varies in thickness from 4 to 8 m is made up of dark sandy and clayey-loamy topsoil, usually less than 2 m thick, followed by laterite red soils, in most cases. The subsurface comprises the weathered, slightly weathered and fractured or fresh crystalline basement rocks. The oldest rocks in the area comprise gneiss complex whose principal member is biotite-hornblende gneiss with intercalated amphibolites. This underlies,

over half of the area. Other rock types are the migmatite, granite, granite-gneiss and schist. Outcrops are rare except for a few laterite capping the bedrock. The laterite consists of different horizons with distinct petrographic characteristics which may have significant influence on the shape of the VES curves. The surface terrain is fairly uniform permitting easy stretch of the Schlumberger array.

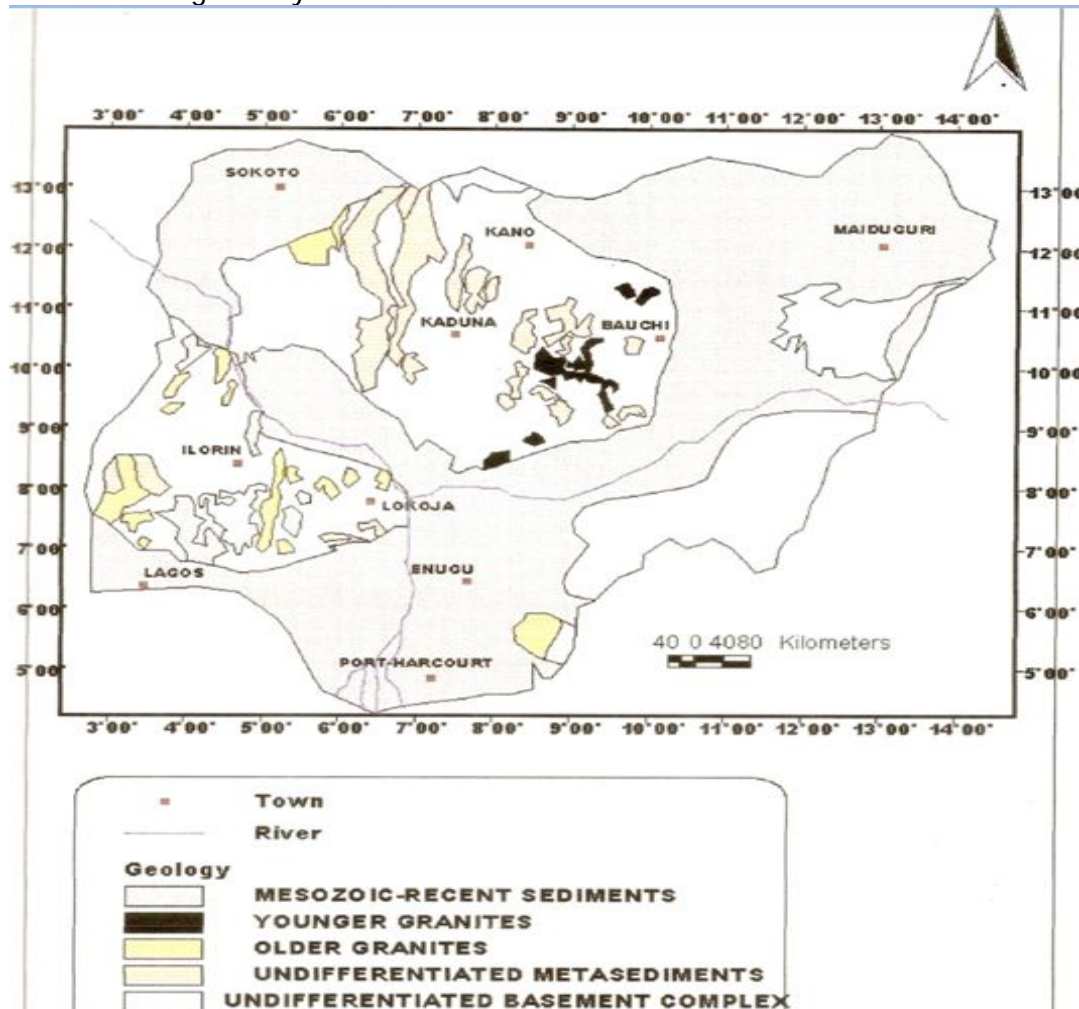


Figure 2: Geology of Nigeria

Source: Oyawoye, 1972

Material and Methods

Terrameter was used to monitor vertical variation of resistivity following Schlumberger 4-electrode Vertical Electrical Sounding (VES) technique. A VES point was located near each of the existing boreholes in the area (Fig. 1). The fieldwork was accomplished in April, around the driest period of the year in the area. The resistivity data was used to estimate the aquifer hydraulic characteristics such as hydraulic conductivity, K and transmissivity, T via the Dar Zarrouk concept.

The electrical resistivity method is an active geophysical method, employing an artificial energy source which is introduced into the ground through a pair of electrodes (Fig. 3). The procedure involves measurement of potential difference created in the vicinity of current flow. Based on

the first Ohm's law the total potential at the first current electrode due to the two current electrodes is determined and the same is done for the second potential electrode. Then, potential difference between the two potential electrodes is determined. Hence, based on the second Ohm's law apparent resistivity is calculated for each location of the current electrodes. The same calculations are done for each current position as the current electrode positions are expanded in steps.

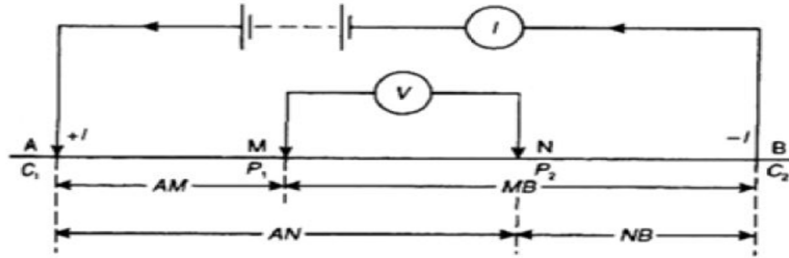


Figure 3: VES Electrode Configuration

The fundamental equation to get apparent resistivity is derived from Ohm's law; that is

$$V = IR \quad \text{Eq. 1.}$$

and

$$R = \frac{\rho L}{A} \quad \text{Eq. 2.}$$

where R is the electrical resistance, ρ is electrical resistivity, A is cross sectional area, and L is the length of the conductor.

The equipotential surface set up by the current flowing into the subsurface rocks is semispherical. So the area A in Eq. 2 could be that of a semi-sphere. Thus, the electric potential V at any point at a distance r from a surface point electrode emitting an electric current I in an infinite homogenous and isotropic semispherical medium of resistivity ρ could be written as

$$V = \frac{\rho I}{2\pi r} \quad \text{Eq. 3.}$$

The resistivity is considered constant in a homogenous and isotropic ground. However, it varies with the relative positions of electrodes in the presence of subsurface in-homogeneities and any computed value is known as the apparent resistivity ρ_a , given by

$$\rho_a = \frac{\Delta V}{I} (2\pi r) \quad \text{Eq. 4.}$$

So, for the Schlumberger technique used here (Fig. 3) the geometric factor G is thus given as:

$$G = \pi \frac{[(\frac{AB}{2})^2 - (\frac{MN}{2})^2]}{2(\frac{MN}{2})^2} \quad \text{Eq. 5.}$$

That is

$$\rho_a = \pi \frac{\Delta V}{I} \times G = R \times G \quad \text{Eq. 6.}$$

The resistance obtained from current and potential difference data at a given electrode spacing is applied in Eq. 6 to compute the apparent resistivity at that point. In this way, VES data at each sounding stations were computed and recorded.

Dar - Zarrouk procedure was followed to derive a formula in determining layer parameters. In doing this a unit square cross sectional area in a vertical direction is assumed, So, for horizontal aquifer layer, Dar-Zarrouk parameter, 'longitudinal conductance' (S) is equal to layer thickness over the layer resistivity (Maillet, 1947).

$$S = \frac{h}{\rho} = h\sigma \quad \text{Eq.7.}$$

To obtain a layer parameter, a unit square cross sectional area is cut out of the aquifer layers of infinite lateral extent. The transverse resistance, R, is given by:

$$R = h\rho \quad \text{Eq.8.}$$

where σ is the electrical conductivity, which is analogous to the hydraulic conductivity K of the layer, S is the longitudinal conductance which is analogous to layer transmissivity T and h is the thickness of the layer. R and S are called Dar Zarrouk parameter, which have been shown to be powerful interpretational aids in groundwater surveys (Zohdy *et al*, 1974).

When the variations in effective porosity controls the groundwater flow as in an unconsolidated, sandy, clay-free aquifer, a direct relationship would be expected between hydraulic conductivity and porosity (i.e. K proportional to Φ), while an inverse relationship would be expected between porosity and resistivity (i.e. Φ proportional to $1/\rho$). The factor controlling the relationship between hydraulic conductivity and resistivity changes with clay content as in a clay –rich aquifer. A direct relationship could be observed. Thus

$K \propto 1/\text{clay content}$

$$\frac{K}{\rho} = C \quad \text{Eq.9.}$$

where, K and ρ are hydrologic conductivity and formation resistivity, respectively.

Therefore, in clay-rich environments K/ρ should remain constant.

In a three-layer medium such as overburden above groundwater level, overburden below water level and solid rock below overburden the longitudinal conductance is the dominant parameter for the middle layer, which has low resistivity. Therefore, the electrical current tends to flow parallel to the bedding controlling the shape of sounding curve (Keller & Frischnechck, 1979). Horizontal ground water flow through an aquifer is not governed by hydraulic conductivity alone, but also depends on the transmissivity (T), the parameter characterizes the ability of the aquifer to transmit water (Ekwe, Nnodu, Ugwumbah & Onwuka, 2010). Transmissivity is defined as the product of the saturated thickness of the aquifer (h) and the average value of the hydraulic conductivity (K);

$$T = Kh \quad \text{Eq.10.}$$

K is the hydraulic conductivity of the aquifer layer with thickness h.

The hydraulic conductivity is proportional to the resistivity of the aquifer. This implies that in the absence of a pumping test data, the aquifer hydraulic conductivity K can be approximated to be the true resistivity of the aquifer derived from geoelectric investigation (Hubbard & Robin, 2002). Therefore,

$$T = Kh = \rho h \quad \text{Eq.11.}$$

But the product of the a layer's resistivity and its thickness is the transverse resistance R (Eq. 8), which is numerically equal to the transmissivity (T), that is

$$T = R \quad \text{Eq.12.}$$

Hence, an analytical relationship between transmissivity and longitudinal conductance has been suggested by Niwas and Singhal (1981) by combining Equations 7, 8 and 9we get

$$T = S(K\sigma); T = SC \quad \text{Eq.13.}$$

Therefore, Eq. (13) offers a possibility of estimating transmissivites and hydraulic conductivities from the values of longitudinal conductance, once the nature of variation of products $K\sigma$ is known (Niwas & Singhal, 1981). It is also emphasized that in areas of similar geologic setting and water quality the product $K\sigma$ remains fairly constant. Thus, knowledge of K from some existing boreholes and of σ from VES sounding can be used to estimate $K\sigma$ for the same

geologic zone. This relationship forms the basis for the determination of aquifer hydraulic parameters used in this study.

Results and Discussions

The sounding data were analyzed with the IPI2WIN software to delineate the sub-surface layering as well as their depths, thickness and the resistivity values (Table.4.1). Sample field curves are shown in Figures 4 and 5; and others are summarized in Table 2. The area is mostly underlain by four and three geoelectric layers of various lithologies

Characteristics of the aquifers in the areas of the boreholes are summarized in the Table 3. The aquifer thickness ranges between 1.89 to 22.7 m. The aquifers in the area are categorized as thickest, thick and fairly thick as shown in Figure 6, the horizontal contour of the thicknesses, with VES 3, having the highest thickness of about 22.7 m. This is the location of the University sachet water factory. VES 10 coincides with the lowest aquifer thickness of 1.89 m. The aquifer unit in the area is the second or third geoelectric layer.

The depth to the aquifer ranges between 6.17 m and 24.9 m. The depth to the aquifer is shallow around VES 12, 13, 20 and 11 with an average depth of around 12.88 m. The deepest aquifers at about 24.9 m depth lie coincidentally around the location of the thickest aquifer. The thickest aquifer in the area appears suitable for the groundwater exploitation due to its greater depth (high volume of water) and is presumably free from sewage and surface contaminations. However, chemical analysis of the groundwater is still required to determine its suitability for consumption.

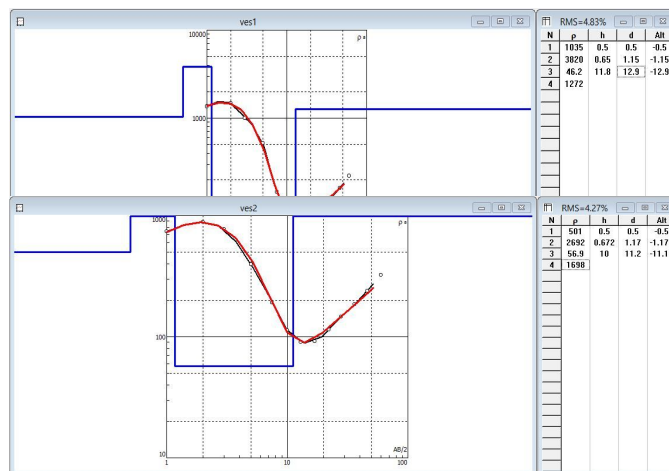


Fig. 5: Resistivity Curve for VES2

The litho logical series in the area are identified as shown in Table 2, based on the typical resistivity ranges for various rock suggested by Olatunji and Osazuwa (2012); Goodman (1989).

Table 2: Summary of the Geoelectric parameters obtained

VES	Layers	ρ_a (Ωm)	Thickness h(m)	Inferred Litho logical Series
1	4	1035, 820, 46.2, 1272	0.5, 0.7, 11.8	Lateritic top soil, Dry clayey sand, weathered or fractured basement, Fresh basement
2	4	501, 2692, 56.9, 1698	0.5, 0.672, 10	Top soil, Dry clayey sand, weathered or fractured basement, fresh basement
3	4	1563, 1921,	1.02, 1.18,	Lateritic top soil, dry clayey sand, weathered or fractured

		53.9, 454	22.7	basement, fresh basement
4	4	198, 75.9, 8552, 110	0.815, 1.91, 9.92	Top soil, clayey sand, dry clayey sand, weathered or fractured basement
5	3	1172, 127, 1461	1.08, 6.91	Lateritic top soil, weathered or fractured basement, fresh basement
6	4	398, 1387, 91.5, 542	0.5, 0.882, 7.27	Top soil, dry clayey sand, weathered or fractured basement, fresh basement
7	4	666, 414, 93.3, 842	0.5, 2.64, 13.3	Lateritic top soil, clay sand, weathered or fractured basement, fresh basement
8	4	880, 1992, 101, 528	0.699, 0.551, 7.8	Lateritic Top soil, dry clayey sand, weathered or fractured basement, fresh basement
9	3	872, 52.6, 197	1.11, 7.22	Lateritic top soil, clayey sand, weathered or fractured basement
10	4	604, 78.2, 1053, 629	1.46, 1.89, 17.8	Lateritic top soil, weathered or fractured basement, dry clayey sand, weathered or fractured basement
11	4	362, 1109, 38.5, 1216	0.5, 1.05, 6.39	Top soil, Lateritic soil, weathered or fractured basement, fresh basement
12	4	372, 881, 79, 768	0.5, 1.57, 4.1	Top soil, Lateritic soil, weathered or fractured basement, fresh basement
13	4	325, 71, 25.3, 249	0.646, 4.21, 4.96	Top soil, clayey sand, weathered basement, fractured basement
14	4	564, 1735, 98.7, 1893	1.22, 1.19, 18.7	Lateritic top soil, soil, dry clayey sand, weathered or fractured basement, fresh basement
15	4	290, 1047, 111, 832	0.923, 3.82, 21.8	Top soil, Lateritic soil, weathered or fractured basement, fresh basement
16	4	1469, 5974, 82.7, 2418	0.5, 0.822, 8.9	Lateritic Top soil, dry clayey sand, weathered or fractured basement, fresh basement
17	3	213, 36.5, 5022	1.55, 17.1	Top soil, weathered or fractured basement, fresh basement
18	4	235, 533, 46.2, 716	0.627, 1.45, 11.1	Top soil, Lateritic soil, weathered or fractured basement, fresh basement
19	3	447, 41.4, 1144	1.46, 6.72	Top soil, weathered or fractured basement, fresh basement
20	3	447, 24.9, 2276	1.87, 5.7	Top soil, weathered or fractured basement, fresh basement
21	4	130, 731, 46.8, 884	0.489, 0.734, 6.95	Top soil, Lateritic soil, weathered or fractured basement, fresh basement

Table 3: Aquifer Thickness and Depth as Inferred from Resistivity Data

VES	LONGITUDE	LATITUDE	ELEVATION	DEPTH (m)	THICKNESS (m)
1	004°38'21.4"	008°28'53.3"	326	12.9	11.8
2	004°38'28.9"	008°29'11.2"	329	11.2	10
3	004°38'27.3"	008°28'43.7"	336	24.9	22.7
4	004°38'43.6"	008°28'01.2"	365	12.6	9.92
5	004°38'58.2"	008°28'00.5"	331	7.99	6.91
6	004°39'03.4"	008°28'00.8"	318	8.65	7.27
7	004°39'00.4"	008°27'57.4"	333	16.4	13.3
8	004°39'00.5"	008°27'53.7"	325	9.05	7.8
9	004°39'04.5"	008°27'43.5"	351	8.33	7.22
10	004°40'06.9"	008°28'27.8"	349	21.1	1.89
11	004°40'19.0"	008°28'38.6"	363	7.94	6.39
12	004°40'38.3"	008°28'45.1"	351	6.17	4.1
13	004°40'25.0"	008°28'48.2"	362	9.81	5.64
14	004°40'18.3"	008°28'49"	353	21.1	18.7
15	004°40'14.3"	008°28'54.6"	349	26.5	21.8
16	004°40'07.5"	008°28'56.4"	344	10.2	8.9
17	004°40'26.5"	008°29'01.1"	383	18.6	17.1
18	004°40'28.8"	008°29'04.8"	371	13.2	11.1
19	004°40'10.3"	008°29'06.4"	336	8.18	6.72
20	004°40'10.5"	008°29'05.7"	336	7.57	5.7
21	004°40'30.7"	008°29'28"	382	8.17	6.95

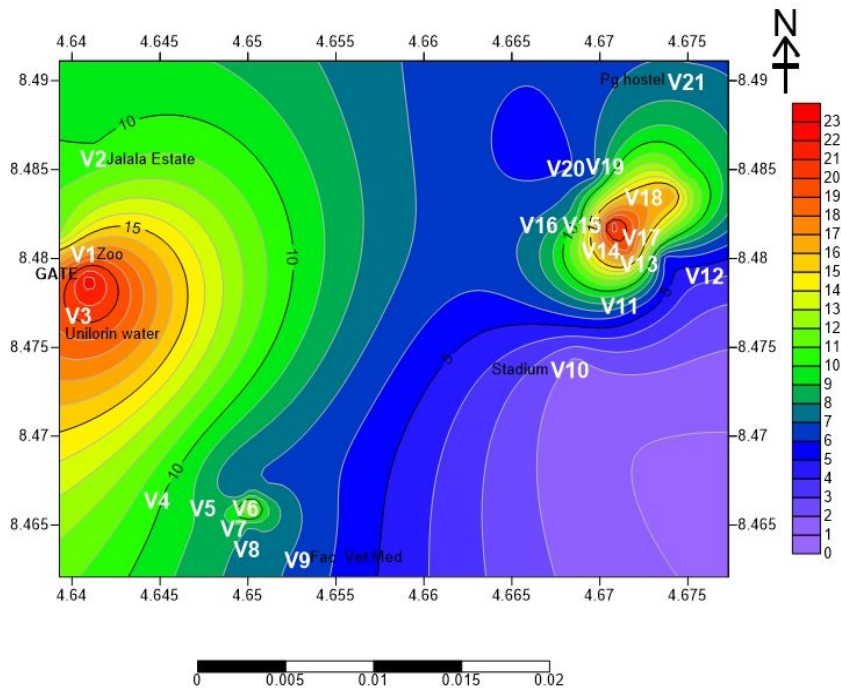


Fig. 6: Aquifer Thickness Map

The Dar-Zarrouk parameters obtained are shown in Table 4. Clayey overburden, which is characterized by relatively high longitudinal conductance, offers protection to the underlying aquifer. S values is used to classify areas into poor ($<0.01 \Omega^{-1}$), weak ($0.01 - 0.1\Omega^{-1}$), moderate ($0.1 - 0.2 \Omega^{-1}$), good ($0.2 - 0.4 \Omega^{-1}$) and very good ($>0.4 \Omega^{-1}$) protective capacity zones (Oladapo & Akintorinwa, 2007; Atakpo, 2013).

The longitudinal conductance (S) value varies from 0.02 to $0.468 \Omega^{-1}$ in the study area with contour intervals of $0.02 \Omega^{-1}$ (Fig. 6). The NW-SE trend is noted with low S values (0.02 to $0.1 \Omega^{-1}$), the highest values of $0.468 \Omega^{-1}$ and $0.412 \Omega^{-1}$ is oriented NE-SW, the locations of VES stations 3 and 17. High S values ($> 0.2 \Omega^{-1}$) are observed at VES stations 1, 18 and 21. Elsewhere, the S value is moderate

The S-map (Fig. 7) revealed that 10% of the area depict very good protective capacity rating, 52% constitutes the good/moderate and 38% exhibits weak protective capacity. Oteri (1981) reported that an increase in S value may correspond to an increase in the clay content and therefore, a decrease in the transmissivity of the aquifer. Thus, moderate to high longitudinal conductance in the area envisages good aquifer protective capacity rating. Clayey/silty overburden in this part, which is characterized by relatively high longitudinal conductance, offers protection to the underlying aquifers. The longitudinal conductance value at VES 17 and 3 falls under very good protective capacity rating.

Table 4: Dar-Zarrouk Characterization Parameters

VES No	Aquifer Thickness h(m)	App. Resist. of Aquifer ρ_a (Ω m)	Transverse Resistance $R=h\rho$ (Ω m ²)	Longitudinal Conductance $S =h/\rho$ (Ω^{-1})	Hydraulic Conductivity K (Ω m)	T = R (Ω m ²)
1	11.8	46.2	545.16	0.255	46.2	545.16
2	10	56.9	569	0.178	56.9	569
3	22.7	53.9	1223.53	0.421	53.9	1223.53
4	9.92	110	1091.2	0.09	110	1091.2
5	6.91	127	877.57	0.054	127	877.57
6	7.27	91.5	665.2	0.079	91.5	665.2
7	13.3	93.3	1240.9	0.143	93.3	1240.9
8	7.8	101	787.8	0.077	101	787.8
9	7.22	197	1422.3	0.037	197	1422.3
10	1.89	78.2	147.8	0.023	78.2	147.8
11	6.39	38.5	246	0.166	38.5	246
12	4.1	79	323.9	0.052	79	323.9
13	5.64	289	1629.9	0.02	289	1629.9
14	18.7	98.7	1845.7	0.189	98.7	1845.7
15	21.8	111	2419.8	0.196	111	2419.8
16	8.9	82.7	736	0.108	82.7	736
17	17.1	36.5	624.2	0.468	36.5	624.2
18	11.1	46.2	512.8	0.24	46.2	512.8
19	6.72	41.4	278.2	0.162	41.4	278.2
20	5.7	24.9	141.93	0.229	24.9	141.93
21	6.95	46.8	325.3	0.149	46.8	325.3

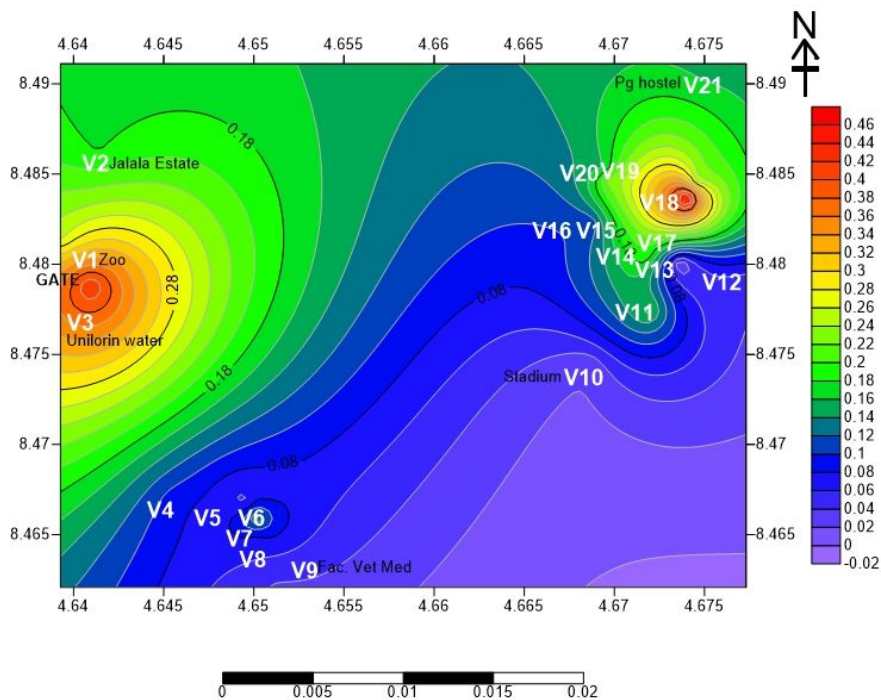


Fig. 7: Longitudinal Conductance Map

Further from Fig. 7, it can be surmised that the north-western and north-eastern part of the study area reflects very good to good protective capacity rating as can be envisaged from the high longitudinal conductance values. The low value of the protective capacity is a consequence of the absence of significant amount of clay as an overburden impermeable material in the south-eastern part thereby enhancing the percolation of contaminants into the aquifer. The

aquifers here may be prone to contaminations such as industrial and agricultural wastes, septic tanks and landfills, if located close to the sounding points. A prove of this is the contermination of borehole located at VES 6 whose S value is $0.08 \Omega^{-1}$.

The transmissivity (T) contour map with a contour interval of $100 \Omega m^2$ is shown in Fig. 7. The T value varies from a minimum of $246 \Omega m^2$ at VES 11 to a maximum of $2419.8 \Omega m^2$ at VES 15. It is evident from Fig. 8 that high T values ($> 700 \Omega m^2$) are encompassing VES stations 3, 4, 5, 7, 8, 9, 13, 14, 15 and 16 in the study area, indicating fresh water zone. Increasing T values indicates fast recharge of water into aquifer after water is pumped out. The south-eastern and southern part of the study area is characterized by low T values, $< 700 \Omega m^2$.

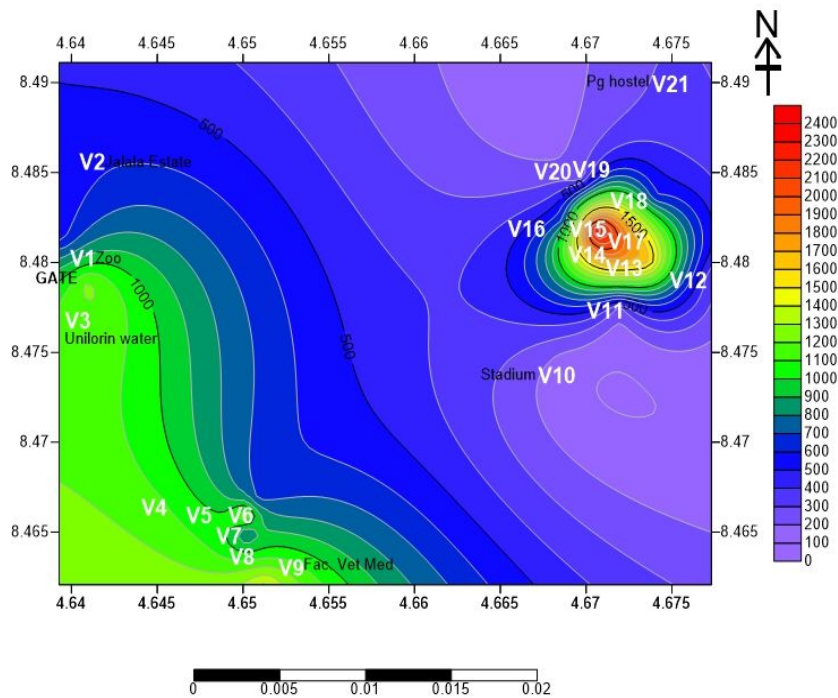


Fig. 8: Transmissivity Distribution

Conclusion

From the results, aquifers here are made of clay, weathered and fractured basement rocks. There exist three to four subsurface layers. The first layer, top-soil has apparent resistivity of 130 to 1469 Ωm . The second layer is clay with apparent resistivity of 52.6 to 8552 Ωm . The third layer is weathered or fractured basement having apparent resistivity of 46.2 to 249 Ωm while the fourth layer is fresh basement with apparent resistivity of 454 to 5022 Ωm . The aquifer thickness and depth range is 1.89 to 22.7 m and 6.17m to 26.5 m.

The NW, NE and part of SW (representing 62%) reflects good protective capacity rating as can be envisaged from the high longitudinal conductance range of $0.412 \Omega^{-1}$ - $0.468 \Omega^{-1}$. 38% of the area witness low S value, with a minimum of $0.02 \Omega^{-1}$ in the SE. The recharge ability, T, after pumping shows a range of $246 \Omega m^2$ to $2419.8 \Omega m^2$.

The most recommended location would be that which has high protective cover, thick and deep aquifer; and high transmissivity. VES 3 most satisfied this condition as the borehole there is

effective. VES 17, although has high S value, coincides with low T value ($624.2 \Omega\text{m}^2$) which could be among the reasons for the failure of the borehole there (Table 1). VES 6 coincides with low protective cover ($S = 0.08 \Omega^{-1}$). That could have been one of the reasons responsible for the contamination of the borehole in that location (Table 1). Among the reasons for the failure of other boreholes such as those located at VES's 5 and 8 could be due to the low transmissivity values around their vicinities (Fig. 8).

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