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Assessment of Groundwater Potential and Aquifer Characteristics using Inverted Resistivity and Pumping Test Data within Lokoja Area, North-central Nigeria

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Abstract: *Aquifer potential were evaluated within Lokoja and environs with the aim of estimating their hydraulic parameters from resistivity and pumping test data. Twenty-six (26) vertical electrical sounding (VES) and eight (8) pumping test data were obtained and utilized for this purpose. The results of the analysis indicate that the area is underlain by five (5) geoelectric sections which have been interpreted as the topsoil, lateritic clay, sandy-clay/weathered/ fractured basement complex rocks (aquiferous units), and clay/fresh basement complex rocks for the sedimentary and basement portions respectively. The resistivity and thickness of these lithologic units are; the topsoil (10.8 – 407.7 Ωm; 0.7 –17.5 m), lateritic clay (1.1 – 1488.5 Ωm; 2.2 – 42.0 m), sandy-clay/weathered/ fractured basement (10.4 – 3,595.6 Ωm; 5.2 – 82.6 m), clay/fresh basement (3.2 – 3,844.2 Ωm; 4.5 – 23.4 m). The resistivity of the aquifer zone indicates that the southeastern to the northwestern portion of the study area has higher groundwater potential than the other portions. The aquifer thickness is higher in the southern portion compared to the rest of the study area. Depth to the aquifer is higher in the northern and parts of the southern portions. Transmissivity (7.605 – 721.648 m^2/day) and permeability (0.423 – 45.103 m/day) values support the view that the southeastern portion is most prolific for groundwater exploration in the study area. The Longitudinal conductance (0.013 – 1.600 mho-m), and the transverse resistance (119.0 – 29,710.7 Ωm^2) values suggest that the area has a poor – good vulnerability index. The fracture contrast (0.040-22.430) and reflection coefficient (-0.902-0.915) indicate that the water-filled fractures occur mostly in the southern part of the study area. The study highlighted the efficacy of the VES data in estimating aquifer hydraulic parameters and hence is recommended in areas with no available pumping test data.*

Keywords: *Groundwater potential, VES, Dar Zarrouk Parameters, Hydraulic Conductivity, Nigeria*

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1.0 Introduction

Given the ever-increasing demand for groundwater, significant emphasis is currently directed to measures that can encourage the availability of potable water at reduced cost (Anomohanran, 2014). The exploration of this very important resource requires the application of many geophysical and hydrogeological techniques which includes electrical resistivity, seismic, magnetic, electromagnetic, ground probing radar, pumping test, and down-hole logging (Anomohanran, 2013). Among the aforementioned techniques, the electrical resistivity method in the form of the vertical electrical sounding (VES) is commonly used by many researchers in groundwater investigation (Obasi *et al.,* 2021) due to its efficacy in delineating the thickness and resistivity of the different conducting layers at the subsurface (Egbai, 2011). In recent times, the VES has extended its application in groundwater studies to the estimation of some aquifer parameters using an indirect approach (Rubin and Hubbard 2005; Niwas *et al.*, 2006; Niwas and Singhal 1981; MacDonald *et al.*, 2012; Raji and Abdulkadir 2020; Ahmed II *et al.*, 2020).
The Pre-Cambrian Basement rocks and the poorly consolidated sediments of the post-Santonian age make up the hydrogeological unit of the study area (Sunmonu *et al.*, 2012), with the basement rocks being the dominant lithology. Groundwater occurrence in the basement part is a function of the availability of weathered, fractured, or faulted zone. The supply of potable water by government agencies is quite inadequate (Vantsawa *et al.*, 2020) partly due to a paucity of funds (Fashae *et al.*, 2014), and partly high population density (Alabi, 2009) arising from economic activities in the area. It is supposedly cheap to harness potable water from the aquifer system in the area due to the shallow nature of the weathered/fractured zones (Fashae *et al.*, 2014). However, the subsurface distribution of the aquifers and their characteristics need to be understood (Demirel *et al.*, 2018). The aquifer characteristics in the study area are yet to be understood. The absence of such information has discouraged public-private partnerships in the provision of potable water in the locality. Few geophysical investigations on groundwater studies in the area focused on the depth of groundwater (Musa and Schoeneich, 2011; Omali, 2014; Aku and Gani, 2015; Ige *et al.*, 2018). There is a need to characterize the regional aquifer system in the area to harness water from it. This research aims to estimate some of the aquifer parameters in the Lokoja metropolis from resistivity and pumping test data.

1.1 Location and geology of study area

The study area falls within Lokoja and its environs, part of sheet 247 North-West (NW) Lokoja, Kogi State, north-central Nigeria. It is bounded by latitude 07^{0}46’45.6’’ to 007^{0}53’21.0’’ and longitude 06^{0}40’0.0’’ to 06^{0}45’0.0’’ (Fig. 1) and accessible by major roads, minor roads, and footpaths which were utilized during the fieldwork.
The study area lies within the Crystalline Basement Complex and sedimentary area of the southern Bida Basin. Turner (1983)

divided the basement rocks into three groups of which the Igarra-Kabba-Lokoja belt was prominent when he studied rocks of western Nigeria. Odigi (2000) indicated that the migmatitic-gneisses in the Okene-Lokoja area are meta-igneous rocks that show mildly alkaline characteristics and are calc-alkaline, suggesting they were derived from an ensialic calc-alkaline magma. According to Obaje (2009), the pre-Cambrian basement rocks are mostly gneiss and migmatite with older granite intrusives. He also noted mineral foliations defined by alternating biotite-rich and quartz-feldspar rich which are common in the gneiss. Major foliation and fracture trends are in the N-S and NNE, SSW directions which correspond to the flow direction of the River Niger. Imasuen *et al.* (2013) discovered that the major rock types that occur within the study area are migmatites, augen gneiss, and biotite gneiss while there are minor occurrences of rock types like pegmatites and quartzo-feldspathic veins. Migmatites are the most widespread rock type in the area and form the country rock in which all other rocks occur. According to Omali (2014), Musa and Schoeneich (2011), the basement complex of Lokoja comprises Migmatite, undifferentiated older granite, mainly porphyroblastic granite, granite gneiss with porphyroblastic gneiss, and fine-grained biotite granite.

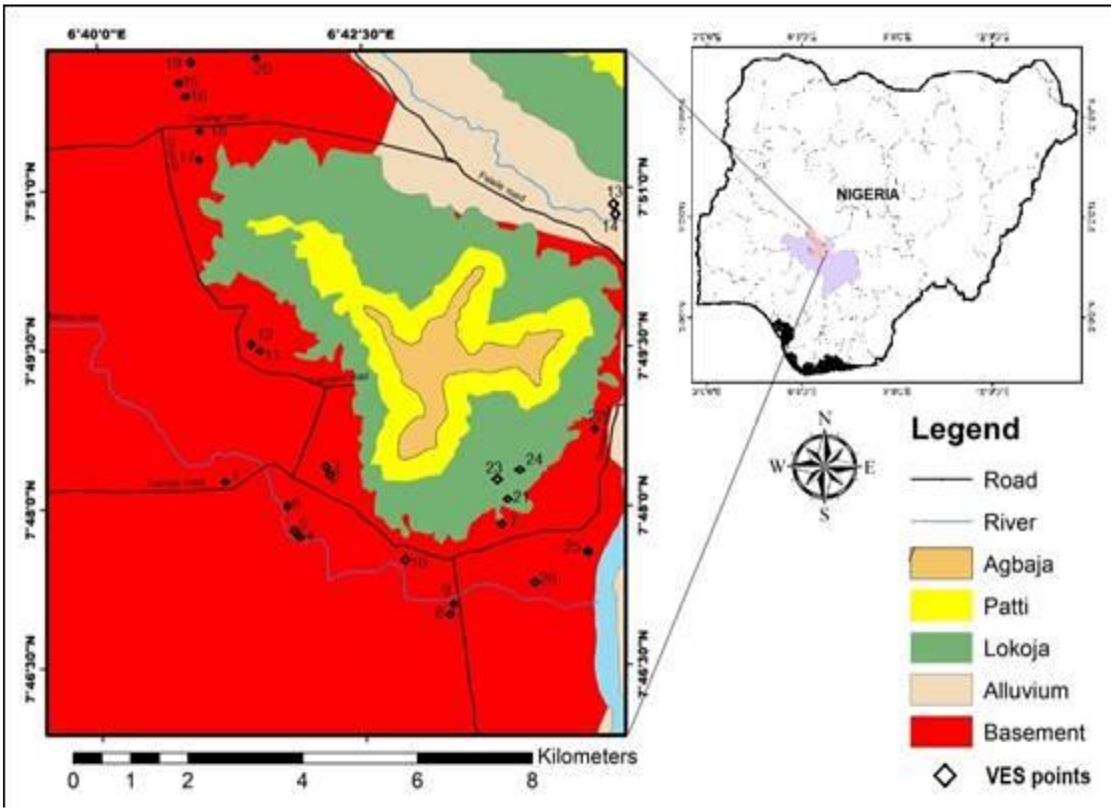

Fig. 1: Geological map of the study area indicating the VES points

The sedimentary basin of the study area lies within the Southern Bida Basin or Lokoja Sub-basin (Adeleye, 1973). However, King (1950), Kogbe *et al.* (1981), Ojo and Ajakaiye (1989) view the basin as a rift-bounded tensional structure produced by faulting associated with the Benue Trough system and the drifting apart of the African and Brazilian (South American) plates consequent to the breakup of these plates in the late Jurassic to Cretaceous times. The sub-basins developed as a result of wrench movements associated with the tectonic framework of the Nigerian sedimentary basins (Braide, 1992). According to Adeleye (1973), the lithostratigraphy of the Southern Bida Basin is broadly divided into three; these include the Campanian-Maastrichtian Lokoja Formation that non-conformably overlies the Pre-Cambrian to Lower Paleozoic Basement gneisses and schists, the Maastrichtian Patti Formation which overlies the Lokoja formation and succeeded by the Maastrichtian Agbaja Ironstone Formation. The Lokoja Formation consists of conglomerates, coarse to fine-grained sandstones, siltstones, and claystones in the Lokoja area, and a few thin oolitic iron stones (Obaje, 2009). The rocks are generally poorly sorted and comprise quartz and feldspar, and are texturally and mineralogically immature (Braide, 1992). The Patti Formation is a sequence of fine to medium-grained, grey and white sandstones, carbonaceous siltstone, claystone, shale and interbedded with oolitic ironstone (Obaje, 2009). The Agbaja Ironstone directly overlies the Patti Formation. It is the youngest oolitic ironstone unit in the southern Bida Basin. It is well exposed at Agbaja, where three subfacies i.e. oolitic, concretional, and massive ironstones with a thickness of 20 m have been recognized (Obaje, 2009).

2.0 Materials and methods

2.1 Geophysical data

The geophysical survey was carried out in twenty-six (26) locations based on the availability of space for spreading using DDR-3 Geo-sensor Terrameter. Out of the 26 data points, 20 were obtained within the Basement Complex area and the remaining 6 (i.e., VES 13, 14, 21, 22, 23, and 24) are either within the sedimentary basin or at the contact between the two. Global Positioning System (GPS) was used to take the coordinate of each sounding point and this helped to locate the sounding points on the geological map. Vertical electrical sounding (VES) using the Schlumberger electrode configuration was adopted with current electrode spacing (AB/2) ranging from 1m to 100 m while potential electrode spacing (MN/2) ranged from 0.5 m to 15 m. The values of resistance (R) were obtained and the product of geometric factor (K) and resistance (R) was then computed to obtain the apparent resistivity (ρ_a). Both manual and computer modelling techniques were employed based on Zohdy *et al.* (1974) and Akpan *et al.* (2009). The manual modelling techniques were done by plotting a graph of apparent resistivity (ρ_a) against half-electrode spacing (AB/2) on a logarithmic graph, using master curves and auxiliary charts (Orellana and Mooney, 1966). These parameters obtained were then input into the computer software WinResist as input data for the computer iterative modelling. From the computer iterative modelling, graphs showing the layer resistivity, layer thickness, and depth to water for each sounding point were obtained (Fig. 2).

2.2 Dar Zarouk parameters

From the result of the analyses of the VES data, the Dar-Zarrouk parameters (i.e. the longitudinal conductance and Transverse resistance) were calculated using equations 1 and 2 below (Maillet, 1947; Obiora *et al.*, 2016).

Transverse unit resistance:

$$(T_R) = h\rho_{aq}\ (\Omega m^2) \qquad (1)$$

Longitudinal unit conductance :

$$(S) = \frac{h}{\rho_{aq}} (\text{mho-m}) \qquad (2)$$

where; h and ρ_{aq} are the thickness and the resistivity of aquifer layers respectively.

2.3 Estimation of the Aquifer Parameters from the VES data

The hydraulic conductivity (K) and Transmissivity (T) were estimated using equations 3 and 4 (Obiora *et al.*, 2016; Raji and Abdulkadir, 2020).

Hydraulic conductivity:

$$K = 386.40\ \rho_{aq}^{-0.93283}\ (\text{m/d}) \qquad (3)$$

Transmissivity:

$$T = \sigma T_R = \frac{KS}{\sigma} = Kh \quad (\text{m}^2/\text{d}) \quad (4)$$

where; ρ_{aq} is the aquifer resistivity, σ is the electrical conductivity (inverse of resistivity), K is hydraulic conductivity, h is the aquifer thickness, S is longitudinal unit conductance (S) and T_R is the total transverse unit resistance.

$$\text{Reflection coefficient, } R_C = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \qquad (5)$$

Fractured contrast:

$$F_C = \frac{\rho_n}{\rho_{n-1}} \qquad (6)$$

where ρ_n is the apparent resistivity of a geo-electric layer, and ρ_{n-1} is the apparent resistivity of the geo-electric layer overlying the nth layer.

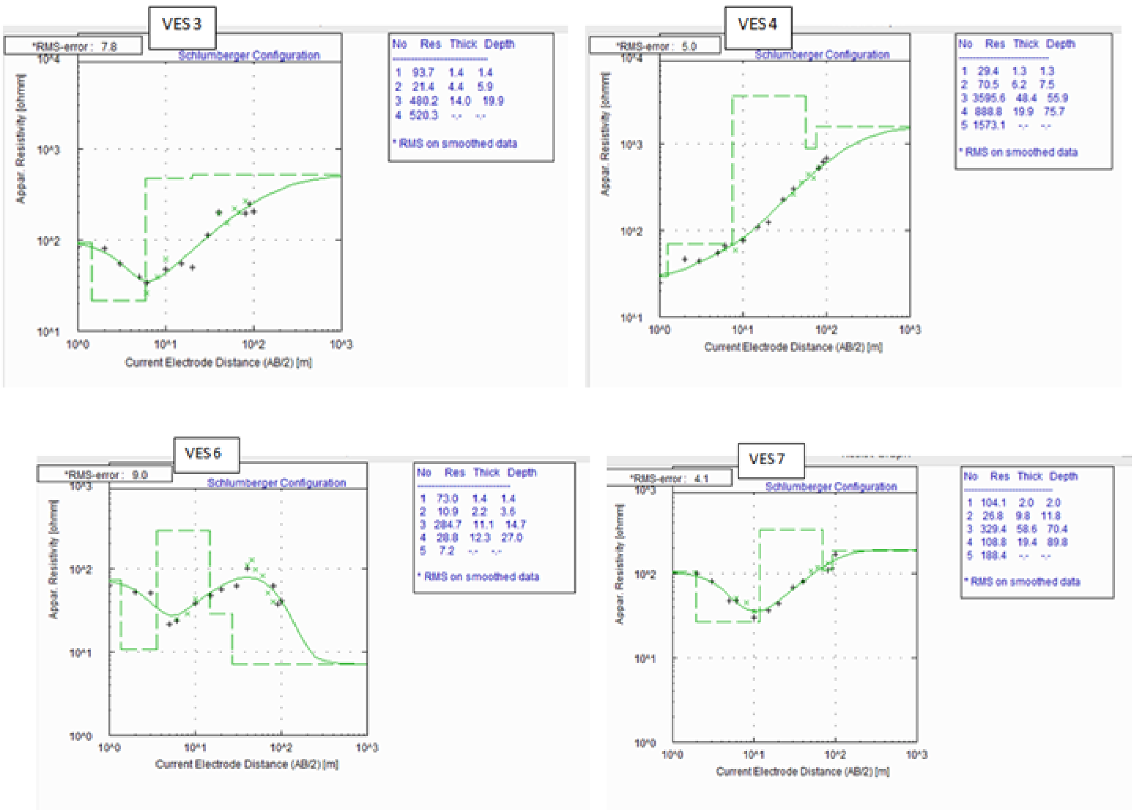

Fig. 2. Some VES graphs and their geoelectric sections

2.4 Estimation of the Aquifer Parameters from the pumping test data

The constant rate pumping method was employed in the pumping test that was carried out on eight (8) boreholes around some of the VES points within the study area to correlate the value of transmissivity and hydraulic conductivity obtained from the VES data. The average pumping rate (Q) in m^3/day for the duration of the test and the slope (which is the change in drawdown over one logarithmic cycle (Δs) determined from the graph of drawdown against time) (Fig. 3) were determined and then incorporated into Cooper and Jacob (1946) flow equation (for single well) as stated below for the computation of the transmissivity (T_P) and hydraulic conductivity (K_P).

$$T_P = \frac{2.3Q}{4\pi\Delta S} \quad (7)$$

$$K_P = \frac{T_P}{h} \quad (8)$$

In the above equations, Q represent the discharge rate, ΔS the change in drawdown while h is the aquifer thickness. Surfer 10 version was then used to produce spatial distribution maps for all the calculated parameters.

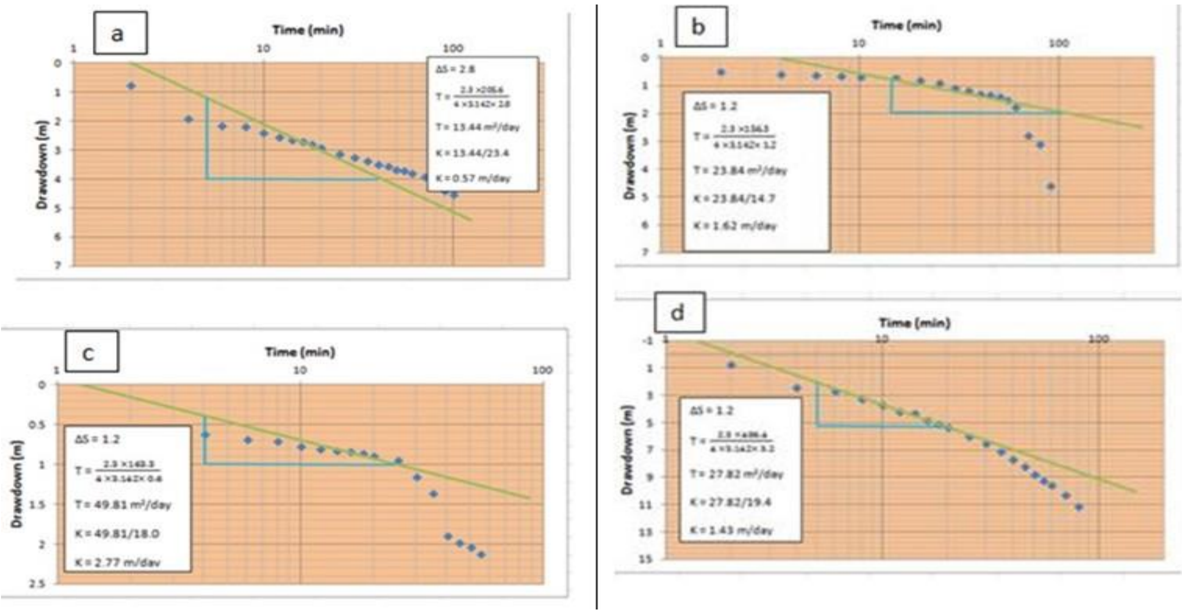

Fig. 3: Variation of drawdown with time for pumping data at (a) Army Signal I (b) Old Poly Quarters I (c) Phase I (d) GRA I

4.0 Results and Discussion

The results of the VES data shown in Table 1 reveal that the study location has a range of 4 – 5 geoelectric layers underlying it, with three prevalent curve types namely HK, HA, and H. The geoelectric layers have been interpreted from layers 1 – 5 as the topsoil, lateritic clay, sandy-clay/weathered /confining weathered basement (i.e., the aquiferous unit), and clay/fresh basement for the sedimentary and basement portions respectively. The topsoil has a resistivity and thickness range of 10.8 – 407.7 Ωm and 0.7 –17.5 m. The resistivity, thickness, and depth of the second layer range from 1.1 – 1488.5 Ωm, 2.2 – 42.0 m, and 3.4 – 59.6 m, while that of the third layer range from 10.4 – 3,595.6 Ωm, 5.2 – 82.6 m, and 14.7 – 86.7 m respectively. The fourth layer has a resistivity, thickness, and depth ranging from 11.7 – 3,844.2 Ωm, 4.5 – 23.4 m, and 24.8 – 93.3 m. The resistivity of the fifth layer ranges from 3.2 – 3299.2 Ωm with an undefined thickness.

The resistivity of the aquifer zone (Table 2, Fig. 4a) within the study area ranges from 10-1493 Ωm. The resistivity range for both the prolific weathered regolith and fractured basement aquifer in the study area is ≤ 600 Ωm (Aku and Gani, 2015). Consequently, the eastern to the central portion of the study area has a higher potential for groundwater (Fig. 4a) occurrence than the extreme south and western portions. This is geologically related. While the sedimentary rocks outcrop at the eastern and central portion, the basement rocks underlie the rest of the map area. The high aquifer conductivity observed in the sedimentary portion of the study area is due to the impact of clay as part of the lithologic unit. Clay has been identified as a major conductor of current within a geologic profile. The resistivity range of > 600 Ωm signifies either areas with low yield or an aquiclude within the basement rocks.

The aquifer thickness, *h*, (Table 2, Fig. 4b) ranges from 4.5 – 33.7 m with a mean value of 15.1 m.

The central – middle – southern portion of the study area has a higher aquifer thickness (≥ 14 m) compared with the rest of the map area. Low aquifer thickness can imply low water volume and by extension, low water yield to a well bore. Consequently, industrial boreholes for regional water supply should be sited towards the area with high aquifer thickness.

The observed depth to the aquifer (Fig. 4c) varied from 19.9 – 93.3 m with a mean value of 54.6 m. A higher depth of the aquifer was observed at the extreme northern and southern parts of the study area. Therefore, when sitting boreholes within these locations' deeper aquifer, approximately 70 – 90 m depth, should be targeted for groundwater development while in other areas, ≤ 50 m depth should be the target for groundwater development.

The transmissivity (*T*) values (Fig. 5a) range from 7.605 – 721.648 m^2/day with a mean value of 113.404 m^2/day. Aquifer transmissivity has been used as an indirect indicator of borehole yield and it describes the lateral movement of groundwater in the aquifer (Acheampong and Hess, 1998; Graham *et al.*, 2009; MacDonald *et al.*, 2012). The highest transmissivity values were recorded within the sedimentary areas and decrease far into the basement part. This suggests that there is a higher degree of weathering/fracturing near the basement sediment boundary than in the interior part of the Basement Complex. The high transmissivity in the sedimentary part is correlatable to the low aquifer resistivity recorded by the VES in the area. In the case of the basement area, lower transmissivity values were observed at the extreme of the northern and southern parts of the area. Based on Krasny's (1993) classification of transmissivity (Table 3), low – high transmissivity occurs in the study area.

The value of hydraulic conductivity (*k*) estimated from the VES data (5b) ranges from 0.423 – 45.103 m/day with a mean value of 8.990 m/day. The *k* values followed the same trend as the *T* values. The Lower *k* values were observed at the extreme of the northern and southern parts of the area and the highest values at the eastern part. Both *k* and *T* plots show the same spatial distribution indicating that the eastern part of the study area has the highest groundwater potential. The value of transmissivity and hydraulic conductivity obtained from pumping test data fall within the range of that obtained from inverted resistivity data (Table 2, Fig. 6). This, therefore, attests to the reliability of resistivity data in estimating the aquifer parameters such as transmissivity and hydraulic conductivity.

Longitudinal conductance in the study area (Fig. 5c) ranges from 0.013 – 1.600 mho-m with a mean value of 0.237 mho-m. Longitudinal conductance is used to describe the aquifer's protective capacity. According to Oladapo *et al.* (2004) (Table 4), the aquifer protective capacity of the study area ranges from poor to good. Areas that have poor and weak longitudinal conductance are more prone to contamination, moderate areas are less vulnerable and areas with good protective capacity are not vulnerable to contamination from leachate and infiltration. Consequently, the vulnerability of the aquifers increases towards the basement rocks and is very low in the sedimentary basin. This is due to the absence of clay in the area to prevent the infiltration of pollutants from the upper layer (Oseji *et al.*, 2018).

Table 1: Interpreted Geo-electrical Layer results obtained from the plotted graphs

VES NO.	Location name	Coordinates	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	h_1	h_2	h_3	h_4	d_1	d_2	d_3	d_4	Curve Type
1	Otokiti village	N7° 48’ 14.3’’ E6° 41’ 9.6’’	140.5	19.8	106.7	174.1	1868.7	1.2	2.2	16.7	16.1	1.2	3.4	20.1	36.2	HA
2	Army Signal I	N7° 48’ 20.3’E6° 42’12.2’’	10.8	215.8	878.6	766.7	1175.3	2	4.4	22.2	23.4	2	6.4	28.6	51.9	HA
3	Army Signal II	N7° 48’ 23.8’E6° 42’14.1’’	93.7	21.4	480.2	520.3	-	1.4	4.4	14	-	1.4	5.9	19.9	-	H
4	Phase II A	N7° 47’ 46.3’E6° 41’49.4’’	29.4	70.5	3595.6	888.8	1573.1	1.3	6.2	48.4	19.9	1.3	7.5	55.9	75.7	HA
5	Phase II B	N7° 47’ 48.9’E6° 41’49.5’’	77.9	585.3	1110.3	447.6	824	6	10.4	41.6	9.5	6	16.4	58	67.5	HA
6	Phase II C	N7° 47’ 59.7’E6° 41’47.9’’	73	10.9	284.7	28.8	7.2	1.4	2.2	11.1	12.3	1.4	3.6	14.7	27	HK
7	GRA I	N7° 47’50.3’E6° 43’47.8’’	104.1	26.8	329.4	108.8	188.4	2	9.8	58.6	19.4	2	11.8	70.4	89.8	H
8	Old Poly Quarters I	N7° 47’ 3.3’’E6° 43’19.3’’	21	1488.5	1347.4	319	551.9	3.3	11.6	42.3	14.1	3.3	15	57.3	71.4	HA
9	Old Poly Quarters II	N7° 46’ 59.4’ E6° 43’15.6’’	90.7	1075.7	340.6	217.1	322.6	6.6	17.3	27.4	21.2	6.6	24	51.4	72.5	HK
10	Phase I	N7° 47’ 30.3’ E6° 42’53.5’’	407.7	59.5	565.2	142.4	366.7	1.1	10.6	47.3	18	1.1	11.7	59.1	77.1	H
11	CBN I	N7° 49’ 32.6’ E6° 41’35.6’’	64.9	251	363.1	403	-	3.4	27.4	33.7	-	3.4	30.8	64.5	-	HA
12	CBN II	N7° 49’ 33.8’ E6° 41’30.9’’	14.2	254.1	467.7	337.8	3299.2	7.6	5.5	7.1	4.5	7.6	13.2	20.3	24.8	HA
13	Sarkin Noma I	N7° 50’ 46.5’E6° 44’49.8’’	72.9	8.5	13.6	147.9	-	3.5	23.4	8.5	-	3.5	26.9	35.5	-	H
14	Sarkin Noma II	N7° 50’ 44.6’E6° 44’49.2’’	17.2	7	10.4	42.1	-	1.8	23.6	16	-	1.8	25.4	41.4	-	H
15	FUL Felele I	N7° 51’ 58.2’E6° 40’58.4’’	181.2	2106.9	1947.2	1493	1648.9	4.2	29.2	20.4	19.9	4.2	33.4	53.8	73.6	HA
16	FUL Felele II	N7° 51’ 50.5’E6° 41’1.1’’	42.2	964.5	260.3	323.7	-	17.5	42	26.4	-	17.5	59.6	86	-	HA
17	FUL Felele III	N7° 51’ 20.4’E6° 41’2.1’’	74.5	16.2	65.7	110.9	1180.1	7	12.1	7.5	7.6	7	19.2	26.7	34.1	H
18	Crusher	N7° 51’ 34.7’E6° 41’7.3’’	257.9	35.6	590.2	148.2	454.5	1.2	12.9	48.2	14.2	1.2	14.1	62.3	76.5	H
19	FUL Felele IV	N7° 52’ 20.6’E6° 41’4.3’’	163.8	46.3	348.2	3844.2	-	1.3	13.7	10.5	-	1.3	15.1	25.5	-	H
20	FUL Felele V	N7° 52’ 45.6’E6° 41’8.1’’	198.6	25.2	466	656.4	2512.5	1.4	8	9.6	9.9	1.4	9.4	19	28.9	H
21	GRA II	N7° 48’ 4.8’ E6° 43’50.9’’	70.2	1.1	1065.5	54.6	302.6	1.3	2.7	82.6	9.6	1.3	4	86.7	93.3	H
22	GRA III	N7° 48’ 42.5’E6° 44’44’’	36.5	4.2	15.1	25.7	488.4	1.4	14.2	5.2	5.8	1.4	15.6	20.9	26.7	H
23	GRA IV	N7° 48’ 16.5’E6° 43’45.5’’	29.9	12.3	25.9	11.7	3.2	1.6	12.2	19.8	13	1.6	13.7	33.5	46.5	HK
24	GRA V	N7° 48’ 23.7’E6° 43’59.6’’	102.7	3.9	14.1	69.3	-	3.5	15.5	12.2	-	3.5	19	31.2	-	H
25	BRCM	N7° 47’ 28.2’E6° 44’51.8’’	299	107.8	752.5	327.1	753.5	0.7	29.4	36	19.9	0.7	30.1	66.1	86	H
26	Adankolo NL	N7° 47’19.5’E6° 44’8.3’’	17	1234.4	393.4	366.1	1162.1	9.6	24.6	10.4	11.8	9.6	34.1	44.6	56.3	HA

**** BRCM= Beside Redeem Church Maternity, Adankolo New Layout**

Table 2: Summary of the interpreted aquifer parameters and Dar-Zarrouk parameters

VES NO.	ρ_{aq} (Ωm)	h (m)	d (m)	ρ_{n-1} (Ωm)	S (mhom)	T_R (Ωm^2)	K (m/day)	T (m^2/day)	T_P (m^2/day)	K_P (m/day)	Fc	Rc
1	174	16.1	36.2	106.7	0.093	2801.4	3.14	50.554	-	-	1.631	0.24
2	767	23.4	51.9	878.6	0.031	17947.8	0.787	18.416	13.44	0.57	0.873	-0.088
3	480	14	19.9	21.4	0.029	6720	1.219	17.066	-	-	22.43	0.915
4	889	19.9	75.7	3595.6	0.022	17691.1	0.686	13.651	9.87	0.5	0.247	-0.604
5	448	9.5	67.5	1110.3	0.021	4256	1.3	12.35	-	-	0.404	-0.425
6	29	12.3	27	284.7	0.424	356.7	16.706	205.484	-	-	0.102	-0.815
7	109	19.4	89.8	329.4	0.178	2114.6	4.858	94.245	27.82	1.43	0.331	-0.503
8	319	14.7	71.4	1347.4	0.046	4689.3	1.784	26.225	-	-	0.237	-0.617
9	217	21.2	72.5	340.6	0.098	4600.4	2.556	54.187	23.84	1.62	0.637	-0.222
10	142	18	77.1	565.2	0.127	2556	3.796	68.328	49.81	2.77	0.251	-0.598
11	363	33.7	64.5	251	0.093	12233.1	1.582	53.313	-	-	1.446	0.182
12	338	4.5	24.8	467.7	0.013	1521	1.69	7.605	-	-	0.723	-0.161
13	14	8.5	35.5	8.5	0.607	119	32.953	280.101	-	-	1.647	0.244
14	10	16	41.4	7	1.6	160	45.103	721.648	-	-	1.429	0.177
15	1493	19.9	73.6	1947.2	0.013	29710.7	0.423	8.418	9.04	0.45	0.613	-0.132
16	260	26.4	86	964.5	0.102	6864	2.159	56.998	-	-	0.27	-0.575
17	111	7.6	34.1	65.7	0.069	843.6	4.776	36.298	-	-	1.689	0.256
18	148	14.2	76.5	590.2	0.096	2101.6	3.652	51.858	-	-	0.251	-0.559
19	348	10.5	25.5	46.3	0.03	3654	1.645	17.273	-	-	7.565	0.765
20	656	9.9	28.9	466	0.015	6494.4	0.911	9.019	-	-	1.408	-0.134
21	55	9.6	93.3	1065.5	0.175	528	9.196	88.282	-	-	0.052	-0.902
22	26	5.8	26.7	15.1	0.223	150.8	18.497	107.283	69.84	12.04	0.04	0.265
23	12	13	46.5	25.9	1.083	156	38.049	494.637	-	-	0.463	-0.367
24	14	12.2	31.2	3.9	0.871	170.8	32.953	402.027	-	-	3.59	0.564
25	327	19.9	86	752.5	0.061	6507.3	1.743	34.686	-	-	0.435	-0.394
26	366	11.8	56.3	393.4	0.032	4318.8	1.569	18.514	11.64	0.99	0.93	-0.036

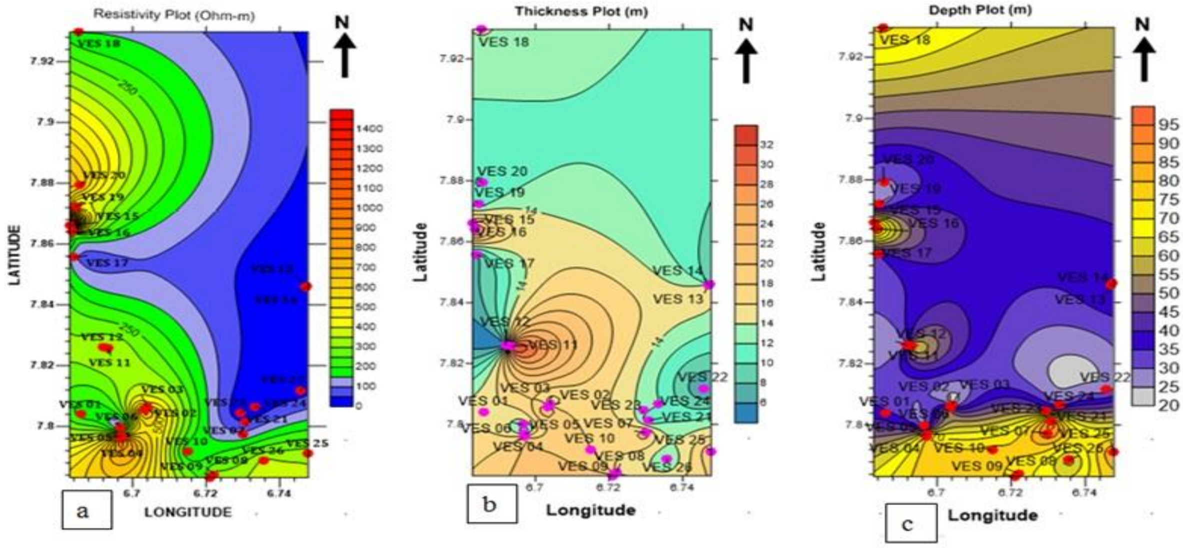

Fig. 4. Spatial distribution of (a) resistivity; (b) thickness; (c) depth of the study area

Table 3: Classification of Transmissivity Magnitude (Krasny, 1993)

S/N	Magnitude of Transmissivity (m^2/day)	Class	Designation
1.	>1000	I	Very high
2.	100 - 1000	II	High
3.	10 - 100	III	Intermediate
4.	1 - 10	IV	Low
5.	0.1 - 1	V	Very low
6.	<0.1	VI	Imperceptible

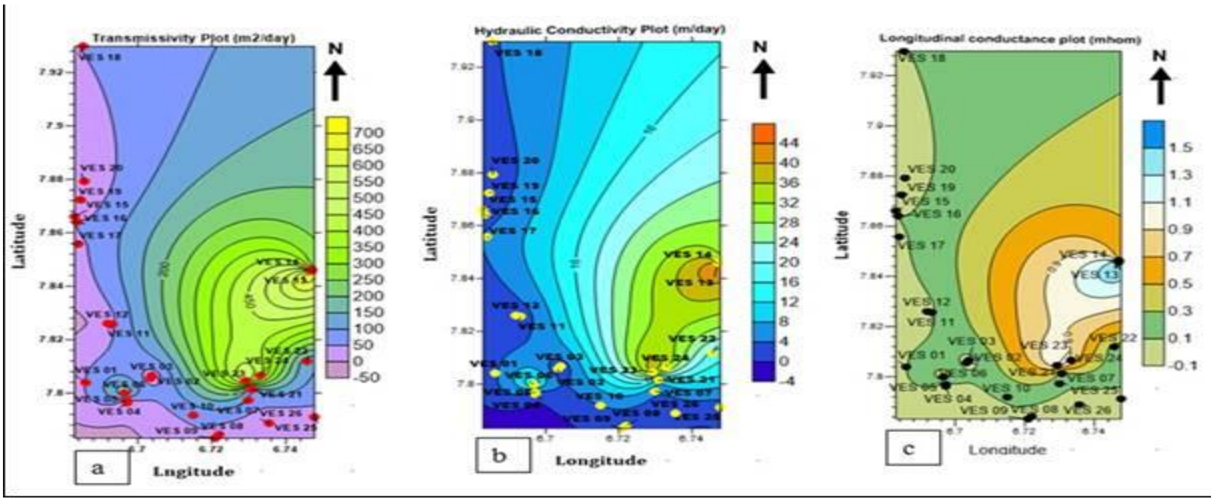

Fig. 5. Spatial distribution of (a) Transmissivity; (b) hydraulic conductivity; (c) longitudinal Conductance of the study area

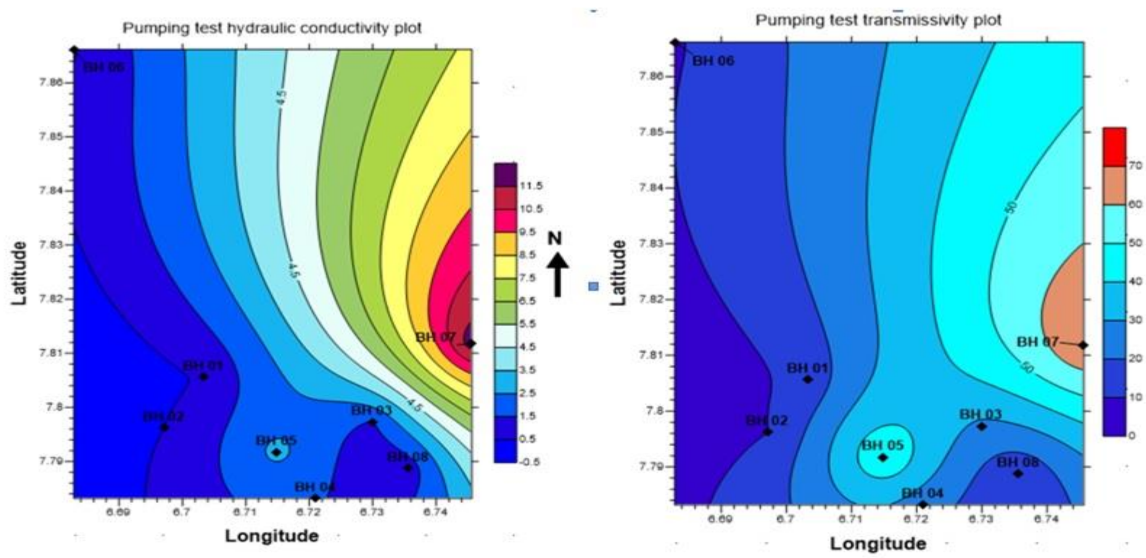

Fig. 6: Maps of the Pumping Test derived aquifer parameters; (a) Pumping Test derived Hydraulic conductivity map of the area (b) Pumping Test derived Hydraulic conductivity map of the area.

The transverse unit resistance (*TR*) (Fig. 7a) value ranges from 119.0 – 29,710.7 Ωm^2 with a mean value of 5356.0 Ωm^2. The highest values are found in the southwest and northwest of the study area. This is because the areas are underlain by fresh, less weathered/fractured but highly resistant basement rocks that occur without clay zone interference. The clay effect can reduce the values of *TR* (Oseji *et al.*, 2018).

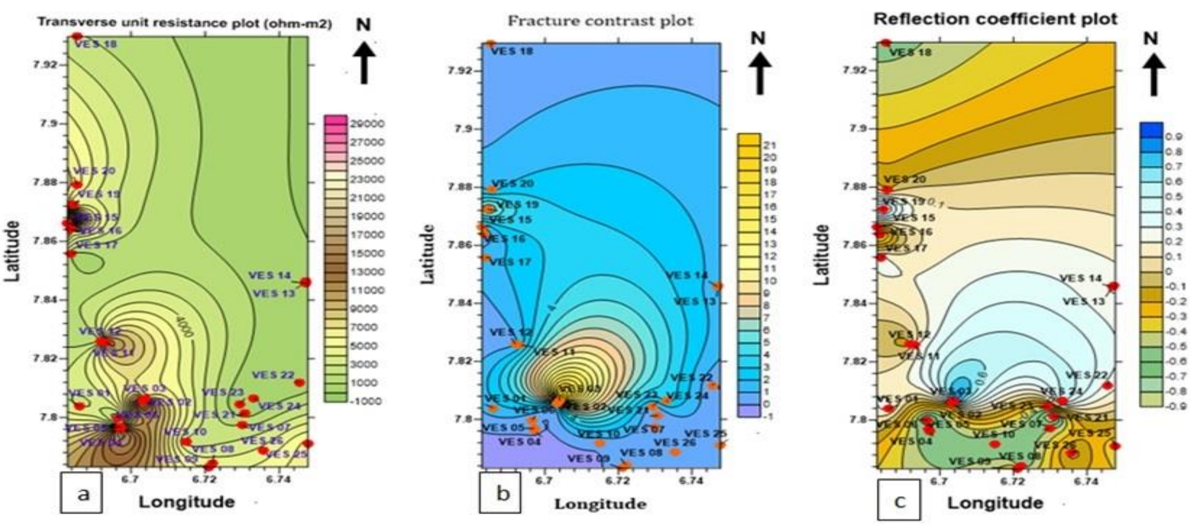

Fig. 7: Spatial distribution of (a) transverse unit resistance; (b) fracture contrast (c) reflection coefficient

The results of the fracture contrast (*Fc*) (Fig. 7b) and the Reflection coefficient (Fig. 7c) indicate their highest values occur in the central to the southern part of the study area while the remaining part has a low value. Both parameters are popular for their role in defining water-filled fractures. The areas with low values indicate high water-filled fractures (Olayinka *et al.*, 2000; Obiora *et al.*, 2016). From the result of this analysis, except for the central to the southern part of the study area, all other parts have high water-filled fractures

4.0 Conclusion

The assessment of groundwater potential and aquifer characteristics within the study area shows the southern portion which includes the contact zones between the sedimentary deposit and the basement complex rocks is more prolific for groundwater exploitation than the other areas. The depth to groundwater is as deep as 90 m in the southern and northern ends and reduces to as low ≤ 50 m. The aquifer parameters estimated from the VES data were quite correlatable with their counterparts from the pumping test data. This research has further emphasized the efficacy of the VES data in estimating aquifer hydraulic parameters.

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Declarations

The authors declare that they have no conflict of interest.

Data availability

All data used in this study will be readily available to the public.

Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data Public.

Competing interests

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Authors' contributions

All the authors took part in data collection, processing and analyses. Kizito O. Musa drafted the manuscript, Andrew C. Nanfa and Jacob B. Jimoh produced the maps and Jamilu B. Ahmed II proof read the manuscript.