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Geoelectric Delineation of Aquifer Pattern in Crystalline Bedrock

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Abstract:
Groundwater is ubiquitous and immensely important for human uses but there is inadequate supply especially in the basement complex terrain as most boreholes are either abortive or can't yield sustainable water to wells. This research tends to delineate into the subsurface in order to understand the aquifer pattern in Ogbagba area. A geophysical survey involving twelve vertical electrical sounding (VES) was carried out at some selected locations in Ogbagba. Resistivity meter was used to acquire the geophysical field data. Conventional partial curve matching and WinResist software was used for the data processing. 75% of the aquifers in the study area are confined aquifers while the remaining 25% are unconfined aquifers. Also, three probable aquifer units were delineated where clayey sand has 75%, sandy clay constitutes 16.7% and fractured bedrock shares the remaining 8.3%. The study revealed that insufficiency of groundwater exploitation in the study area is due to the geologic formation of the aquifers and the depth to which groundwater is been abstracted. If these mistakes are corrected, Ogbagba will henceforth start to enjoy groundwater exploitation adequately.

Keywords:
Confined Aquifer, Crystalline Bedrock, Fractured Basement, Unconfined Aquifer, Weathered Layer

1. INTRODUCTION

Aquifer is defined as a rock formation that contains sufficient groundwater to be useful for water supply. Aquifers must be both permeable and porous and include such rock types as sandstone, conglomerate, fractured limestone and unconsolidated sand and gravel. In order for a well to be productive, it must be drilled into an aquifer. Rocks such as granite and schist are generally poor aquifers because they have a very low porosity. However, if these rocks are highly fractured, they make good aquifers. A well is a hole drilled into the ground to penetrate an aquifer. Aquifers come in two types: unconfined and confined aquifers. Unconfined aquifers are those into which water seeps from the ground surface directly above the aquifer while confined aquifers are those in which an impermeable dirt/rock layer exists that prevents water from seeping into the aquifer from the ground surface located directly above. Instead, water seeps into confined aquifers from farther away where the impermeable layer doesn't exist.

Every aquifer is unique, although some are more generic than others. The boundaries of an aquifer are usually gradational into other aquifers, so that an aquifer can be part of an aquifer system. The top of an unconfined aquifer is the water table. A confined aquifer has at least one aquitard at its top and, if it is stacked with others, an aquitard at its base. Aquitard is a bed of low permeability along an aquifer (*e.g.* clay). Also, aquiclude (or aquifuge) is an impermeable body of rock or stratum of sediment that acts as a barrier to the flow of groundwater. If aquitard becomes totally impermeable, it becomes aquiclude.

Fractured crystalline bedrock aquifers are good sources of potable water in many parts of the world. However, sitting of highly productive wells in these rock units remains a challenging and expensive task because fracture development at the regional scale is both heterogeneous and anisotropic [1]. Using low cost electrical resistivity data to determine units of rock that have similar lithologic and fracture characteristics can greatly reduce time, cost and energy spent on determining areas with better than average aquifer productivity. Basement aquifers are developed within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin which are mainly of Precambrian age [2]. Groundwater development may be primarily restricted to the aquifer in the weathered overburden or completed in the fractured bedrock in locations where the overburden is relatively thin. Viable aquifers wholly within the fractured bedrock are of rare occurrence because of the typically low storativity of fracture systems [3]. An intrinsically low porosity limits the quantity of water stored in fractured crystalline rock. Sustainable well yields for bedrock, therefore, may strongly depend on the quantity of water stored in surficial materials that can leak downward into bedrock and on periodic replenishment by recharge [4].

This research applied electrical resistivity method in the delineation of aquifer pattern in Ogbagba, a basement complex terrain. Electrical resistivity was chosen because it gives detail information about strata variations in the subsurface. Application of electrical resistivity to groundwater exploration has been elucidated by Patra and Nath [5] and Sunmonu *et al.* [6]. Although seismic refraction technique could also be employed in order to determine subsurface variations, one of the problems of seismic refraction technique is the hidden layer whereby all overburden strata are assumed to be a layer especially in a crystalline basement terrain shallow depths exist. Ogbagba one of the towns in Osun State, Nigeria, has received increase in number of residential buildings, siting of industrial estate and increase in commercial activities, which has resulted in population growth. The study area is envisaged to be facing problems like adequate water supply, for domestic and industrial uses. In view of this, a geophysical investigation of the study area was conducted, so as to unravel the aquifer pattern that could be favourable to the aforementioned problems. Hence in this study, Schlumberger electrode configuration was employed in order to identify the promising aquifers within the weathered layers and the aquifers in the bedrocks. This method has been used by Badmus and Olatinsu [7] and Aweto [8].

2. GEOLOGY, HYDROGEOLOGY, AND CLIMATE OF THE STUDY AREA

Ogbagba is underlain by Precambrian basement rocks of Southwestern Nigeria (**Figure 1**) which comprise of crystalline and metamorphic rocks over 550 million years old [6]. precambrian basement rocks comprise predominantly of migmatized and undifferentiated gneisses, schist and quartzite. Locally, the rock sequence in the study area consists of fine grained biotite gneiss, quartzite's schist complex of Precambrian age [9]. The gneiss complex underlain the northern and southern part of the study area and constitute a considerable larger area with rock exposures. The rocks appear to be readily weathered and give rise to an undulating topography dipping in a north-south direction and cross cutting by numerous bands and lenses of pegmatites at several locations. The topsoil association of the site is the Fasola and Ajawa groups with great fertilities, which support good agricultural practice. They have fine texture and are of variety of colour ranging from brown to brownish red, fairly brownish yellow and white clay, and are of average thickness of 50mm [10]. Generally Iwo is located in southwest Precambrian basement complex of Nigeria, predominantly composed of; oldergranite, migmatite gneiss complex, dolorite dykes and charnockitic rocks. The occurrence of groundwater in crystalline rocks depends on the extent and depth of weathering and fracturing. Basement aquifers are developed within either the regolith (relatively high storativity but low permeability) or the fractured bedrock (low storage capacity with a relatively high permeability). The groundwater is contained in the weathered/ fractured formations and is primarily recharged through surface precipitation and secondarily through lateral flow from rivers and tributaries.

The study was conducted in some selected locations (**Figure 2**) within Ogbagba, a very close town to Iwo, Southwestern Nigeria. Ogbagba is located between latitude $7°50'$ to $8°00'$ N and longitude $4°00'$ to $5°00'$ E. The study area is located within tropical climate marked by the alternating wet and dry seasons. Temperature is moderately high during the day and also varies from season to season. Due to the passage of the sun on its way to and from the tropic of cancer, this resulted to two periods of high temperatures as recorded annually. The first period occur in March - April and the second period in November - December. The average daily temperature varies between about 20°C (for a very cold day) and about 35°C (for a very hot day). The coolest period is in the middle of the raining season (July – August) [10].

Figure 1. Geological map of Nigeria showing the study area [11].

3. MATERIALS AND METHODS

For electrical resistivity survey, Ohm's law is the basis for this technique which states that the current flowing through a metallic conductor is directly proportional to the potential difference between its terminal ends provided that temperature and the other physical conditions are kept constant.

Mathematically,

$$V = IR \tag{1}$$

Generally, four-electrode array is used at the surface, one pair for introducing current into the earth and the potential difference established in the earth by the current is measured in the vicinity of current flow with the second pair (**Figure 3**). Different types of arrays are used. It depends on the purpose of a particular survey. The electrode

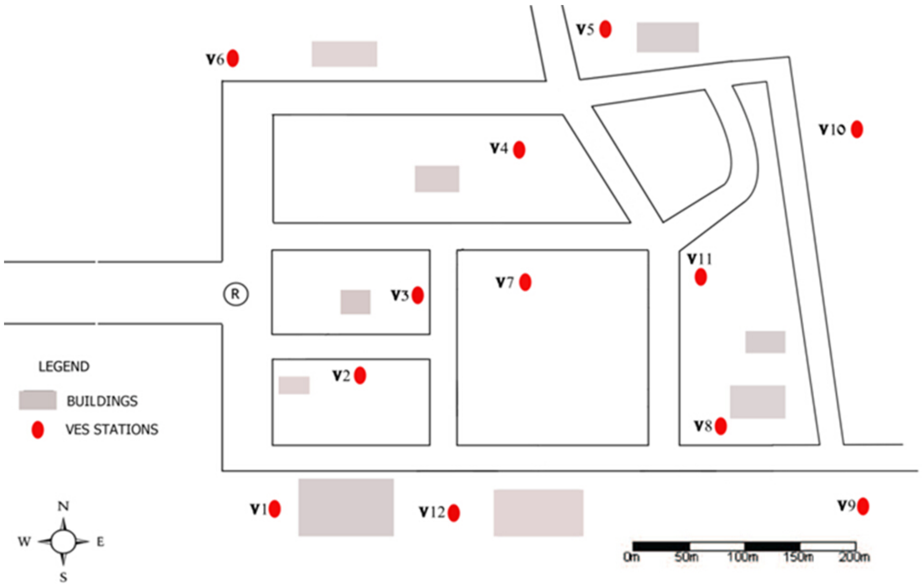

Figure 2. Showing the base map of the study area.

spread in use include: Wenner spread, Schlumberger spread, Three-point spread or Gradient array, Dipole–dipole spread and Lee- partition spread [12]. The electrode most commonly used especially in groundwater exploartion is the Schlumberger configuration, adopted by Conrad Schlumberger in his pioneer work. In this configuration, the four electrodes are positioned symmetrically along a straight line, the current electrodes on the outside and the potential electrodes on the insides. To change the depth range of the measurements, the current electrodes are displaced outward while the potential electrodes, in general, are left at the same position (**Figure 4**). However, when the ratio of the distance between the current electrodes to that between potential electrodes becomes too large, the potential electrodes must also be displaced outward, otherwise the potential difference becomes too small to be measured with sufficient accuracy. At the beginning of a series of measurements, the ratio of the potential electrode spacing to the current electrode spacing may be taken as ${}^{1}/_{3}$. Outward displacement of the potential electrodes is usually necessary when the above ratio has decreased to ${}^{1}/_{20} - {}^{1}/_{50}$. When the potential electrodes are displaced outward, it is necessary to carry out measurements at the two values of the potential electrode spacing, combined with the same value of the current electrode spacing. Preferably, these repeat measurements with a single value of the current electrode spacing and the two values of the potential electrode spacing should be carried out at two or three consecutive values of the current electrode spacing. This procedure will provide a reasonable amount of information on the effect of the displacement of the potential electrodes upon the measurements. Further study about Schlumberger configuration could be found in Adagunodo and Sunmonu [12] and Koefoed [13].

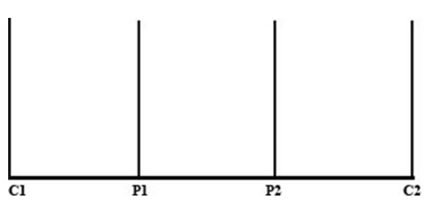

Figure 3. Current-Potential Electrode Configuration [12].

3.1 Schlumberger Configuration

The distances between potential electrodes are too small compared to the current electrodes. **Figure 4** shows the distance between electrodes for Schlumberger spread.

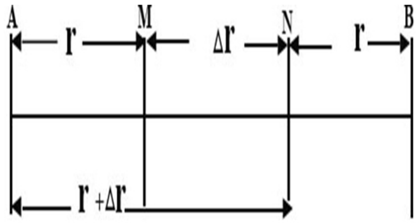

Figure 4. Schlumberger electrodes array [14].

$$r_1 = r_4 = r \tag{2}$$

$$r_2 = r_3 = r + \Delta r \tag{3}$$

$$\rho_a = 2\pi \frac{v}{I} \left\{ \frac{1}{\frac{1}{r} - \frac{1}{r+\Delta r} - \frac{1}{r+\Delta r} + \frac{1}{r}} \right\} \tag{4}$$

$$\rho_a = 2\pi \cdot \frac{v}{I} \left\{ \frac{1}{\frac{2}{r} - \frac{2}{r+\Delta r}} \right\} \tag{5}$$

$$\rho_a = 2\pi \cdot \frac{v}{I} \left\{ \frac{\frac{1}{r+\Delta r - r}}{2r(r+\Delta r)} \right\} \tag{6}$$

$$\rho_a = \pi \cdot \frac{v}{I} \left\{ \frac{1}{\frac{\Delta r}{r^2}} \right\} \tag{7}$$

$$\rho_a = \pi \cdot \frac{v}{I} \left\{ \frac{r^2}{\Delta r} \right\} \tag{8}$$

$$\rho_a = \pi \cdot R \frac{AM^2}{MN} \tag{9}$$

3.2 Schlumberger Configuration Sensitivity

The Schlumberger array is one of the most commonly used arrays for resistivity sounding surveys. A modified form of this array that can be used on a system with the electrodes arranged with a constant spacing ”a”. Note that the ”n” for this array is the ratio between the Cl -PI (or P2 - C2) electrodes to the spacing between the PI -P2 potential pair. The Schlumberger array is moderately sensitive to both horizontal and vertical structures. In areas where both types of geological structures are expected, this array might be a good compromise between the Wenner and the dipole-dipole array The effective depth of investigation for this array is about 10% larger than the Wenner array, for the same distance between the outer (Cl and C2) electrodes [12].

3.3 Field Procedure

In this study Schlumberger electrode array is chosen because thickness and apparent resistivity of each layer is needed. The resistivity meter also known as terrameter called R 50 Resistivity meter was used for resistance measurements employing Schlumberger electrode configuration. The terrameter used is a fully automated resistivity meter that gives initial and final potential as well as current value for every measurement [15]. The transmitter and receiver units are combined in the box (**Figure 5**). A total of twelve (12) depths sounding were conducted, with maximum electrode spacing of 200 m. The resistance was later calculated using equation 1. The product of the measured ground resistance (R) value and the geometric factor (K) of the electrode array gave the ground apparent resistivity value which is giving as:

$$\rho_a = KR \tag{10}$$

Figure 5. The resistivity meter during geophysical field work.

3.4 Data Interpretation

The initial interpretation of the VES data was accomplished using conventional partial curve matching technique utilizing master curves [13] and the corresponding auxiliary curves [16] from which resistivity values and thicknesses of the layers were obtained. The Sounding Curve for each survey point was obtained by plotting the apparent resistivity on the ordinate against half current-electrode spacing on a bi-logarithmic paper. The well-known partial curve matching technique using available album of master curves for interpretation of layer parameters is always used at least as the initial guess for the direct interpretation methods for inversion of Vertical Electrical Sounding (VES) data [5]. The field data plotted on the double-logarithm paper will be traced out on a tracing paper, and the theoretical master curves (**Figure 6**) which are plotted on a double-logarithm graph sheet with a modulus of 62.5 mm [5] will be used for construction and interpretation of multi-layer curves. This was done as a quick way to know the layer parameters of each curve before using automated technique to finally interpret the data. One of the advantages of log-log plot is that at two different points where the resistivity of the underlying layers (or their thicknesses) increases or diminishes by the same constant multiple, the two resistivity curves would look alike, although they may be shifted horizontally or vertically with respect to one another [15].

An automated iterative program that was based on inversion, WinResist version 1.0 software [17] was used to refine the partial curve matching interpretative results which successfully reduced the interpretation errors to acceptable levels [18]. In iterative interpretation methods, the field data are compared with the data derived from a layer model obtained by approximate method. If the agreement between the two sets of data is unsatisfactory, then the parameters of the layer model are adjusted. This procedure is repeated until a sufficient agreement between the model data and the field data is obtained. A version of this method, in which the adjustment of the layer parameters is done by human judgment, has been common practice in resistivity sounding interpretation for many years but today, an automated iterative interpretation is done, in which the decisions regarding the adjustment of the layer parameters are made by computer. This method is at present probably the most widely applied tool in the exact interpretation of resistivity sounding measurement [15]. The summary of the processed field data, lithology, and its probable aquifer conditions are presented in **Table 1** and **Table 2**.

4. RESULT AND DISCUSSION

4.1 VES Analysis

The VES analysis shows series of lithologies in the study area which are: topsoil, shale/clay, sandy clay, clayey sand, compacted sandstone, fractured bedrock, and fresh bedrock (**Table 1**). The aquifers are also grouped into confined and unconfined aquifers base on their resistivity values (**Table 2**). An aquifer is a body of saturated rock through which water can easily move. Aquifers must be both permeable and porous and include such rock types as sandstone, conglomerate, fractured limestone and unconsolidated sand and gravel. Fractured volcanic rocks such as columnar basalts also make good aquifers. The rubble zones between volcanic flows are generally both porous and permeable and make excellent aquifers. In order for a well to be productive, it must be drilled into an aquifer. Rocks such as granite and schist are generally poor aquifers because they have a very low porosity. However, if these rocks are highly fractured, they make good aquifers. An aquifer is filled with moving water and the amount of water in storage in the aquifer can vary from season to season and year to year. Ground water may flow through an aquifer at a rate of 50 feet per year or 50 inches per century, depending on the permeability. But no matter how fast or slow, water will eventually discharge or leave an aquifer and must be replaced by new water to replenish or recharge the aquifer. Thus, every aquifer has a recharge zone or zones and a discharge zone or zones [20].

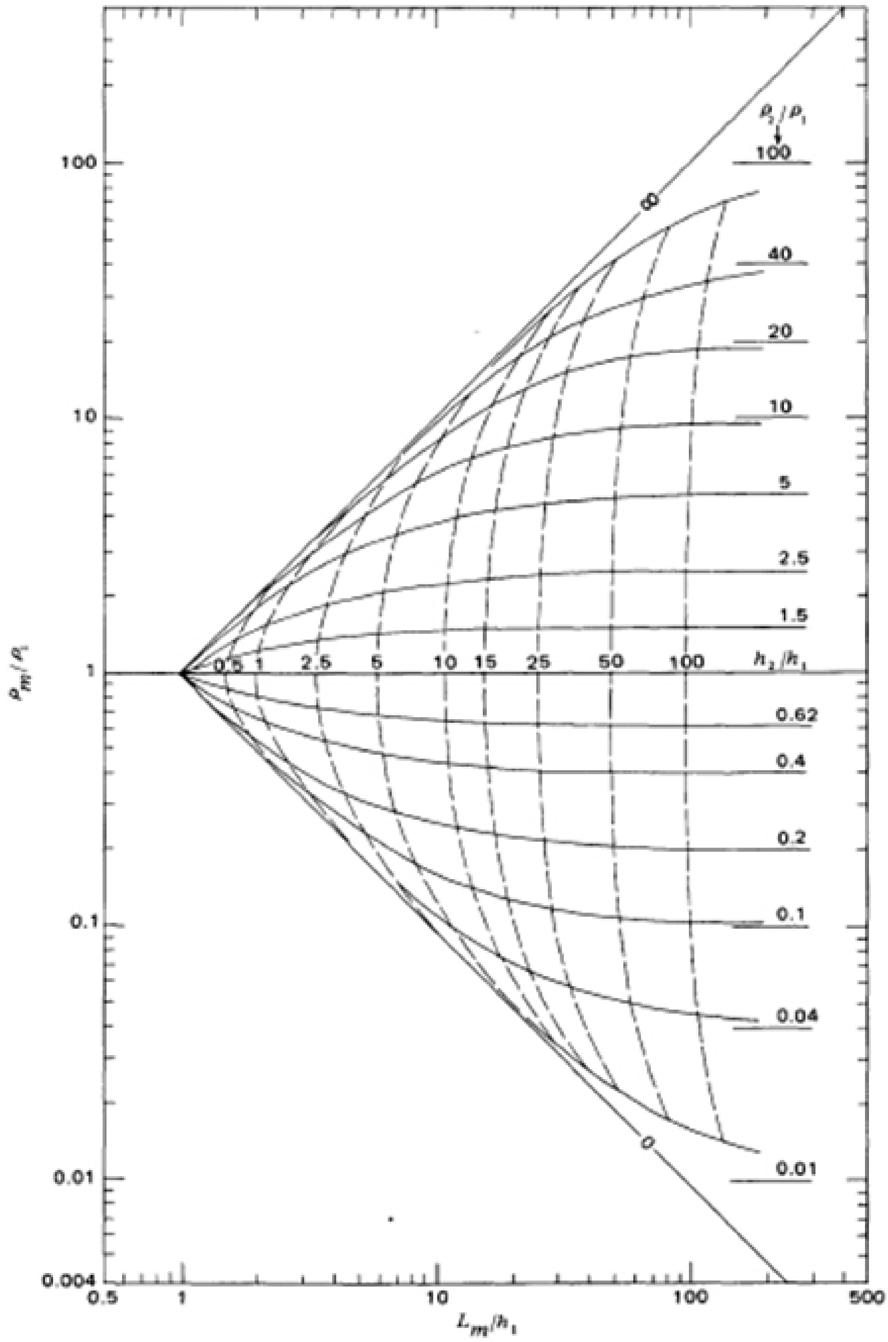

Figure 6. The theoretical master curves [19].

Aquifers come in two types: unconfined and confined aquifers [20, 21].

Unconfined aquifers are those into which water seeps from the ground surface directly above the aquifer. This type of aquifers is prone to contamination [20]. Unconfined aquifers can also be defined as aquifers that doesn't have a confining layer (an aquitard or aquiclude) between it and the surface [21].

Confined aquifers are those in which clay or impermeable layer exists on top of the aquifer that prevents water from seeping into the aquifer from the ground surface located directly above it. Instead, water seeps into confined aquifers from farther away where the impermeable layer doesn't exist [22]. Clay has resistivity ranging from 10 to 100 Ωm [15].

The subsurface is underlain with maximum of four layers per VES station. The curve types gotten from the VES curves are: HA, KH, QH, AA and QQ respectively. Some of these VES curves are shown in **Figure 7**. In order to name the VES curves, it is imperative to know the difference between individual VES curves.

Two-layer Curves

Two sets of theoretical two-layer master curves are available for (ρ_2/ρ_1) greater than unity, ascending type (set I) and for (ρ_2/ρ_1) less than unity descending type (set II). The values of ρ_2/ρ_1 for which curves have been plotted are:

Set I: ρ_2/ρ_1 = 11/9, 3/2, 13/7, 2, 7/3, 3, 4, 5, 17/3, 7, 9, 19, 39, 99, ∞

Set II: ρ_2/ρ_1 = 9/11, 2/3, 7/13, 1/2, 3/7, 1/3, 1/4, 1/5 3/17, 1/7, 1/9, 1/19, 1/39, 1/99, 0

Three-layer Curves

The whole set of three-layer sounding curves can be divided into four groups, depending on the relative values of ρ_1, ρ_2, ρ_3.

i. Minimum type: When $\rho_1 > \rho_2 < \rho_3$. This is referred to as H-type (associated with the name of Hummel).

ii. Double-ascending type: When $\rho_1 < \rho_2 < \rho_3$. This is also known as A-type (corresponding to term anisotropy).

iii. Maximum type: When $\rho_1 < \rho_2 > \rho_3$. This is known as K-type or is sometimes referred to as DA-type (meaning displaced or modified anisotropy).

iv. Double descending type: When $\rho_1 > \rho_2 > \rho_3$. This is known as Q-type and is sometimes referred to as DH-type (meaning displaced Hummel or modified Hummel).

Four-layer Curves

From a combination of the curves of the three-layer type (*i.e.* H, A, K, and Q), Patra and Nath [5] reported that there can be only eight types of four-layer curves. These may be designated as HA, HK, AA, AK, KH, KQ, QH, and QQ. The values of the parameters on the theoretical master curves when using partial curve matching are:

ρ_2/ρ_1 = 1/39, 1/19, 1/9, 3/17, 1/4, 3/7, 2/3, 3/2, 7/3, 17/3, 3, 4, 9 and 39,

ρ_3/ρ_1 = 1/39, 1/19, 1/9, 3/17, 1/4, 3/7, 2/3, 3/2, 7/3, 17/3, 3, 4, 9 and 39,

$h_2/h_1 = 1/2, 1, 2, 3, 5, 24,$

h_3/h_1 = 1/2, 1, 2, 3, 10, 12 and 72.

However, five (5) out of the eight cases of four-layer curves were gotten in this study (*i.e.* HA, KH, QH, AA and QQ where 25% of the curves are HA-type, 16.7% are KH-type, 41.7% are QH-type, while AA-type and QQ-type takes 8.3% each (**Figure 8**). However, 75% of the aquifers in the study area are confined aquifers while unconfined aquifers are 25% (**Figure 9**).

Three probable aquifer units were delineated where clayey sand has 75%, sandy clay constitutes 16.7%, and fractured bedrock shares the remaining 8.3% (**Figure 10**). Most of the aquifers in the study area are confined aquifers which mean they might be free from municipal contaminant. VES 5 aquifer in the study area is categorized as confined aquifer based on Adagunodo and Sunmonu [23] claim that if topsoil resistivity falls below 100 Ωm, the topsoil will protect the aquifer beneath against any contaminant. This is indicative that the aquifer beneath a clayey zone is a confined aquifer (*i.e.* an impermeable layer that prevents water from seeping into the aquifer from the ground surface located directly above it). The fourth layer of VES 12 should not be misinterpreted as an aquifer but an aquitard. The sandy clay aquifers in the study area (beneath VES 5 and 9) are not recommended for borehole drilling due to high concentration of clay in the aquifers.

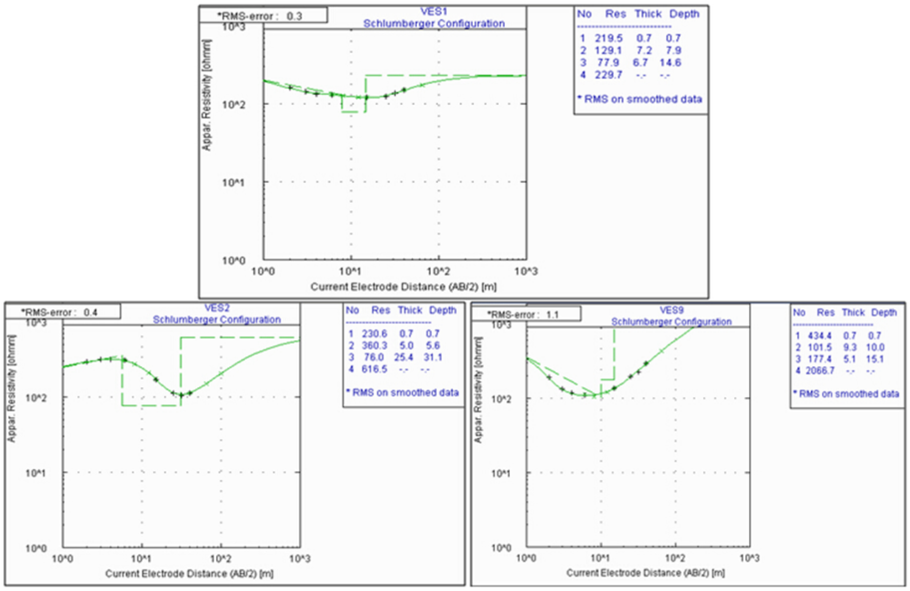

Figure 7. The modeled curve for VES 1 (QH-Type), VES 2 (KH-Type), and VES 9 (HA-Type).

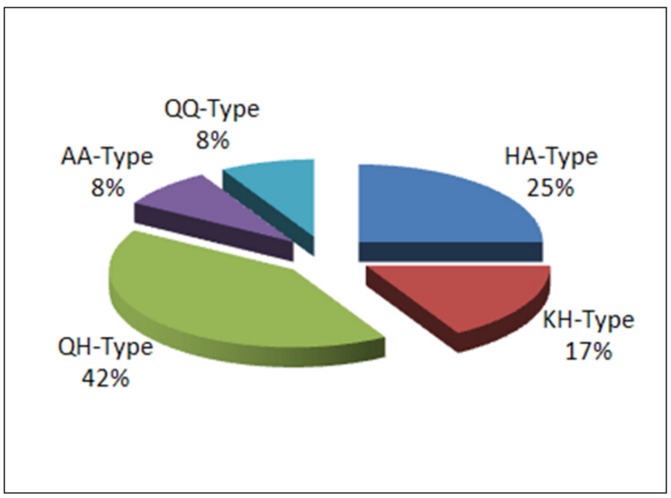

Figure 8. The modeled VES curve types.

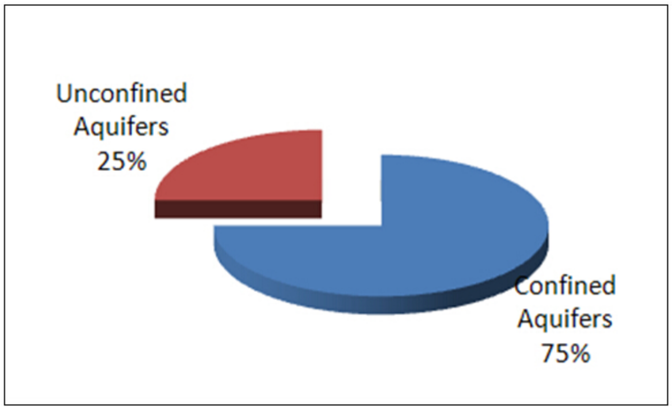

Figure 9. The aquifer types.

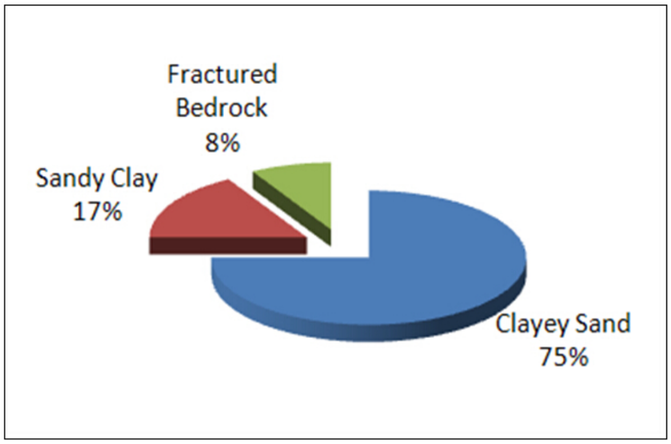

Figure 10. The probable aquifer units delineated.

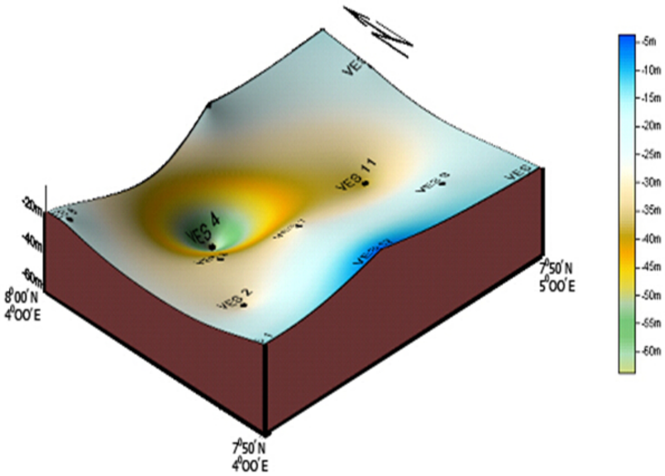

Figure 11. 3-D map of depth to crystalline bedrock.

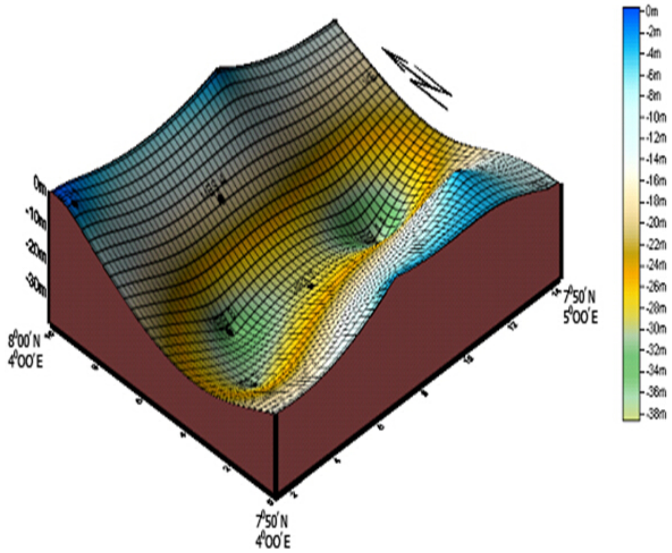

Figure 12. 3-D map of Depth to the aquifers.

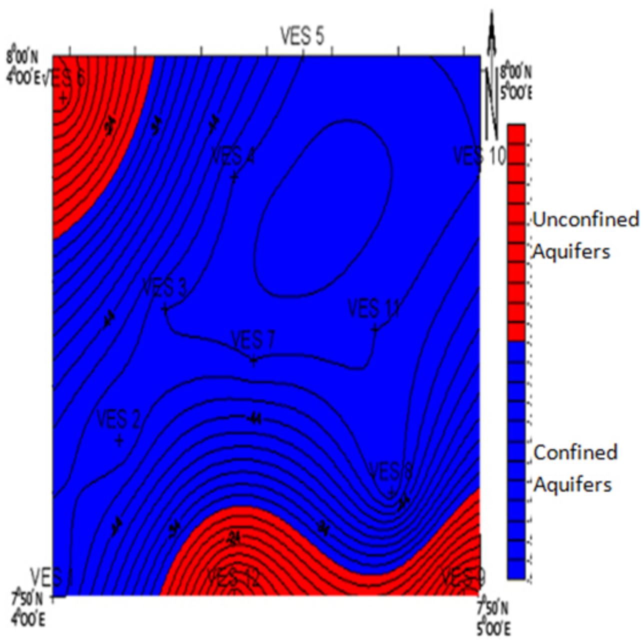

Figure 13. 2-D map of aquifer pattern in the study area.

Table 1. The summary of VES processing and interpretation.

VES STATIONS	LAYERS PARAMETERS				LITHOLOGY	AQUIFER TYPE
	Layer Number	Resistivity (Ωm)	Thickness (m)	Depth (m)		
1	1	219.5	0.7	0.7	Topsoil	Confined
	2	129.1	7.2	7.9	Sandy Clay	
	3	77.9	6.7	14.6	Shale/Clay	
	4	229.7	–	–	Clayey Sand	
2	1	230.6	0.7	0.7	Topsoil	Confined
	2	360.3	5.0	5.6	Clayey Sand	
	3	76.0	25.4	31.1	Shale/Clay	
	4	616.5	–	–	Fractured Bedrock	
3	1	309.2	1.1.	1.1	Topsoil	Confined
	2	223.0	1.1	2.2	Clayey Sand	
	3	75.8	32.5	34.7	Shale/Clay	
	4	230.5	–	–	Clayey Sand	
4	1	273.0	1.7	1.7	Topsoil	Confined
	2	85.3	16.1	17.8	Shale/Clay	
	3	219.8	46.9	64.7	Clayey Sand	
	4	4497.9	–	–	Fresh Basement	
5	1	88.5	0.6	0.6	Topsoil	Confined
	2	196.8	2.3	2.9	Sandy Clay	
	3	1058.8	13.3	16.2	Compacted Sandstone	
	4	2951.6	–	–	Fresh Bedrock	
6	1	108.8	0.6	0.6	Topsoil	Unconfined
	2	320.3	2.3	2.9	Clayey Sand	
	3	145.4	16.3	19.1	Sandy Clay	
	4	1727.2	–	–	Fresh Bedrock	
7	1	169.6	7.3	7.3	Topsoil	Confined
	2	101.1	13.4	20.7	Sandy Clay	
	3	71.8	8.4	29.1	Shale/Clay	
	4	268.1	–	–	Clayey Sand	
8	1	376.8	0.7	0.7	Topsoil	
	2	181.8	2.3	3.0	Sandy Clay	
	3	270.0	16.0	19.0	Clayey Sand	
	4	1146.3	–	–	Fresh Bedrock	
9	1	434.4	0.7	0.7	Topsoil	Unconfined
	2	101.5	9.3	10.0	Sandy Clay	
	3	177.4	5.1	15.1	Sandy Clay	
	4	2066.7	–	–	Fresh Bedrock	
10	1	1380.7	2.1	2.1	Topsoil	Confined
	2	478.2	0.9	3.1	Clayey Sand	
	3	93.6	16.5	19.6	Shale/Clay	
	4	264.0	–	–	Clayey Sand	
11	1	2169.9	1.1	1.1	Topsoil	Confined
	2	494.5	3.5	4.5	Clayey Sand	
	3	58.6	34.6	39.1	Shale/Clay	
	4	202.4	–	–	Clayey Sand	

12	1	1699.8	0.9	0.9	Topsoil	Unconfined
	2	434.1	0.7	1.6	Clayey Sand	
	3	313.7	2.1	3.7	Clayey Sand	
	4	89.3	–	–	Shale/Clay	

Table 2. Aquifer pattern and its lithology.

VES STATIONS	**PROBABLE AQUIFER**			**LITHOLOGY**	**AQUIFER TYPE**
	Resistivity (Ωm)	**Thickness (m)**	**Depth to the Aquifer (m)**		
1	229.7	–	14.6	Clayey Sand	Confined
2	616.5	-	31.1	Fractured Bedrock	Confined
3	230.5	–	34.7	Clayey Sand	Confined
4	219.8	46.9	17.8	Clayey Sand	Confined
5	196.8	2.3	0.6	Sandy Clay	Confined
6	320.3	2.3	0.6	Clayey Sand	Unconfined
7	268.1	–	29.1	Clayey Sand	Confined
8	270.0	16.0	3.0	Clayey Sand	Confined
9	177.4	5.1	10.0	Sandy Clay	Unconfined
10	264.0	–	19.6	Clayey Sand	Confined
11	202.4	–	39.1	Clayey Sand	Confined
12	313.7	2.1	1.6	Clayey Sand	Unconfined

4.2 2-D and 3-D Maps of Ogbagba Subsurface

2-D and 3-D maps were further used to depict the pattern of the subsurface and that of the aquifers. Surfer 8 software [24] was used for the processing of the maps. Depth to bedrock, depth to the aquifer, and aquifer type were used to describe the aquifer pattern in the study area. The depth to bedrock or basement values ranges from 3.7 to 64.7 m with an average of 25.5 m. Depth to bedrock map (**Figure 11**) shows various total depths of the VES locations with depression towards the central portion of the study area. Sunmonu *et al.* [6] reported that areas with thick overburden corresponding to basement depression are known to have high groundwater potential particularly in the Precambrian basement complex terrain. Based on this, this region with depression will be productive for groundwater exploration, especially borehole drilling due to the depths to aquifers. The overburden thickness to the aquifer values ranges from 0.6 to 34.7 m with an average of 16.8 m. **Figure 12** shows a 3-D map of the depth to the aquifer. This map gives subsurface image about approximated depths to which the study area can be drilled or dug before the aquifer can be explored. **Figure 13** however, shows aquifer pattern of the study area. The edges of Southern, Southeastern, and Northwestern part of the study area constitute the unconfined aquifers which are prone to contaminations while the remaining part constitutes the confined aquifers type. However, groundwater flow pattern of the confined aquifer (*i.e.* the direction at which the recharge takes place in confined aquifers) in the study area trend at SW-NE direction.

5. CONCLUSIONS

The geophysical investigation carried out at Ogbagba has revealed the lithologies in the area to be: topsoil, shale/clay, sandy clay, clayey sand, compacted sandstone, fractured bedrock, and fresh bedrock. The weathered and fractured bedrock constitutes the main aquiferous units in the area. Scarcity of groundwater in this region during prolong dry season might be due to the depth at which the masses abstract the groundwater. Since the maximum depth to basement in this region is not even up to 70 m; a maximum recommended depth for borehole drilling in basement terrain, it is recommended that borehole drilling should be encouraged instead of hand-dug wells that will dry off when the water table is lowered during dry season. It is revealed that depth to the aquifer beneath VES 1 is 14.6 m, this depth is within hand-dug well limit. Depth to the aquifer beneath VES 6 is 0.6 m, the aquifer thickness is 2.9 m while it is underlain with fresh bedrock. Depth to aquifer of VES 8 is 3 m, the aquifer thickness is 16 m while it is underlain with fresh bedrock. VES 12 has depth to aquifer of 1.6 m and aquifer thickness of 2.1 m. VES 12 is underlain with aquitard which would not transmit water. From these deductions, area under the coverage of VES 1, 6, 8, and 12 are probable zones for hand-dug wells since depth to aquifers are within the limit of hand-dug well depth.

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