GEOELECTRICAL EXPLORATION FOR GROUNDWATER IN CRYSTALLINE BASEMENT ROCKS OF FOBUR AND ITS ENVIRONS, JOS-PLATEAU, NORTH-CENTRAL NIGERIA

[1]*BULUS, J. A., [3]ALUWONG, K. C.,[2]ODEWUMI, S. C., [1]ABALAKA, I. E. AND [1]KAZE, I. N.

[1]Department of Geology, Faculty of Natural Sciences, University of Jos, Jos, Nigeria.
[2]Department of Science Laboratory Technology, Faculty of Natural Sciences, University of Jos
[3]Department of Mining Engineering University of Jos

*Corresponding Author: bulusjosephazi@gmail.com

ABSTRACT

Fobur and its environs are underlain by crystalline rocks in the north-central sector of the Nigerian Basement Complex. A geophysical investigation involving electrical resistivity was carried out with the aim of evaluating the groundwater potential for alternative water supply due to inadequate surface water and low yield boreholes in the area. Thirty-three (33) Vertical Electrical Soundings (VES) were acquired from Fobur and its environs adopting Schlumberger electrode configuration with current electrode separation (AB) varying from 1.5 to 125 m. The acquired field data were interpreted and iterated using “RESIST” software. The total transverse resistance value (219.8 - 26721.50 Ωm^2) was adopted in the classification of the area into poor, weak, moderate and very good transmissivity zones. The groundwater potential of Fobur and its environs are classified into poor, low and good groundwater potential zones based on the integration of geo-electric and Dar-Zarrouk parameters. The VES data indicate two (2) to five (5) geo-electric layers namely: topsoil/lateritic, clayey soil, weathered layer, fractured unit and fresh basement. The Overburden comprises of the topsoil, laterite, and weathered basement with thickness ranging from 3.6 to 42 m. The zones with overburden thickness of 20m and above are viable for groundwater abstraction and constitute about 50 % of the area. The aquifer protective capacity of the area was classified into good (> 0.7 mhos), moderate (0.2 – 0.69 mhos), weak (0.1 – 0.19 mhos), and poor (< 0.1 mhos), based on the longitudinal conductance value (0.00192 - 1.587868 mhos). The basement resistivity ranges from 43.7 to 27717.3 Ωm and was used to classify the area into good, medium, low and negligible aquifer potential zones. Hence, the result of this research will form the tools for groundwater improvement, management and structural/infrastructural development planning of the study area.

Keywords: Aquifer, Transmissivity, Dar-Zarrouk, Electrical anisotropy and Fobur

INTRODUCTION

Groundwater is referred to as the waters found in the subsurface (Ariyo and Adeyemi, 2009).High percentage of water users in the world depend greatly on groundwater (Reilly *et al.,* 2008). Groundwater contributes substantially to meet the water needs for most domestic, municipal and industrial purposes worldwide, due to its availability in nearly all parts of the world. Nampak *et al.* (2014) stated that groundwater is being refilled by rain that infiltrated the soil naturally or through secondary pores of the subsurface rocks. The occurrence and distribution of groundwater in an area can be influenced by climatic condition, geology, the structural features of the subsurface rock, geomorphological features, land use type and their interplay with the hydrological features (Edet *et al*., 1998, Jaturon *et al*., 2014, Kumar *et al*., 2007). The urge to sustain groundwater need by people has strengthened the application of appropriate geophysical and hydrogeologic search to detect areas of high and dependable groundwater prospect or characterize seasonal variations in the near surface aquifer (Lashkaripour, 2003; Batayneh, 2010; Omosuyi, 2010; Anudu *et al*., 2011; Webb *et al*., 2011).

The geophysical method mostly used for groundwater exploration is the electrical resistivity method. Generally, materials either natural or artificial can resist the flow of electric current. Therefore, it is possible to recognize a good groundwater potential zone based on the resistance offered by subsurface layers. Factors such as mineral content, texture, moisture content, salinity, fissures and fractures of geological formation have a vital influence on the electrical resistivity of any formation. The variations in the resistivity value of rocks are produced by secondary porosity such as weathered zone, fractures and joints. For any community to grow and become an urban center there must be an unlimited supply of good water quality and the current study focuses on geoelectrical exploration for groundwater in the crystalline basement rocks of Fobur and its environs using vertical electrical sounding (VES).

Location of Study Area and General Geology

The study area occurs in Fobur and its environs located between latitudes 9.83^0 to 9.88^0 N and longitudes 9.00^0 to 9.08^0 E (Figure 1). The topography is characterized by rugged terrain, the elevation of the area varying from 1008 to 1229 m above sea level. According to the Koppen climate classification system, Jos has a tropical savanna climate with two prominent seasons: the wet and dry seasons. The wet season spans between April and October while the dry season commences from October to April. The highest rainfall is usually recorded in July while the dry season is at its peak in January. The annual rainfall across the area is 1400 mm with an average annual temperature of approximately 19.5 and a relative humidity of about 76 %. Evaporation is usually at a minimum rate due to heavy rainfall between June and September thereby encouraging infiltration to the water table.

Geologically, the main rock types within the study area were differentiated into the Jurassic Younger Granites and the Pan African Older Granites. The Precambrian crystalline basement rocks underlain these areas include: the undifferentiated migmatite, fine to medium grained biotite and biotite muscovite granite and gabbro. The Jurassic Younger Granite Complexes which intruded the crystalline basement rocks comprises of Neil's Valley granite porphyries, hornblende biotite granite and the Jos biotite granite rocks (Figure 2). Various structures observed on the rock surface include gneissosity, micro folds, joints and minor fractures. Generally, the rock is oriented approximately in NE – SW direction while the structures on the rock run parallel and perpendicular to the general strike direction of the rock.

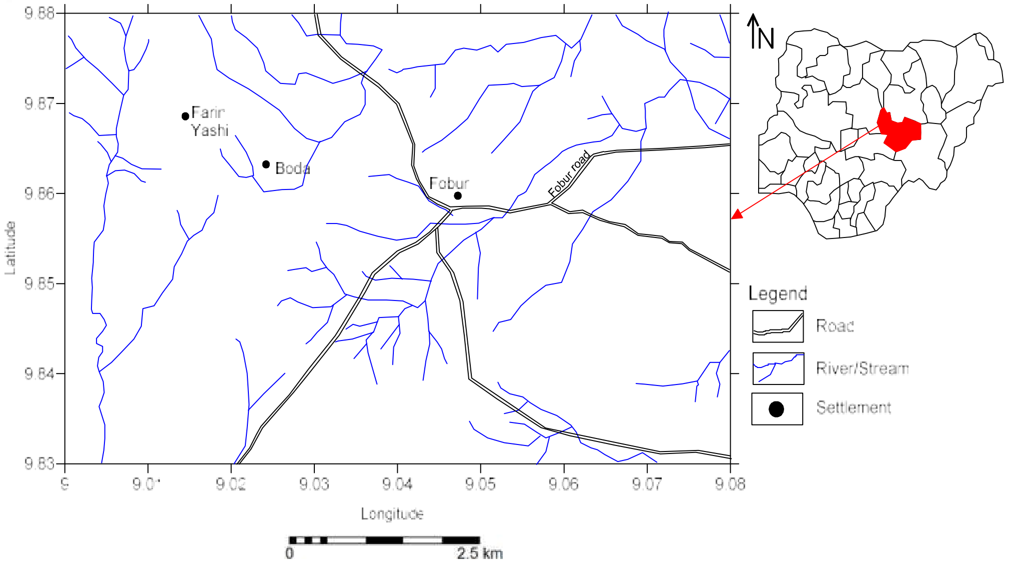


Figure 1: Location and drainage map of Fobur and its environs

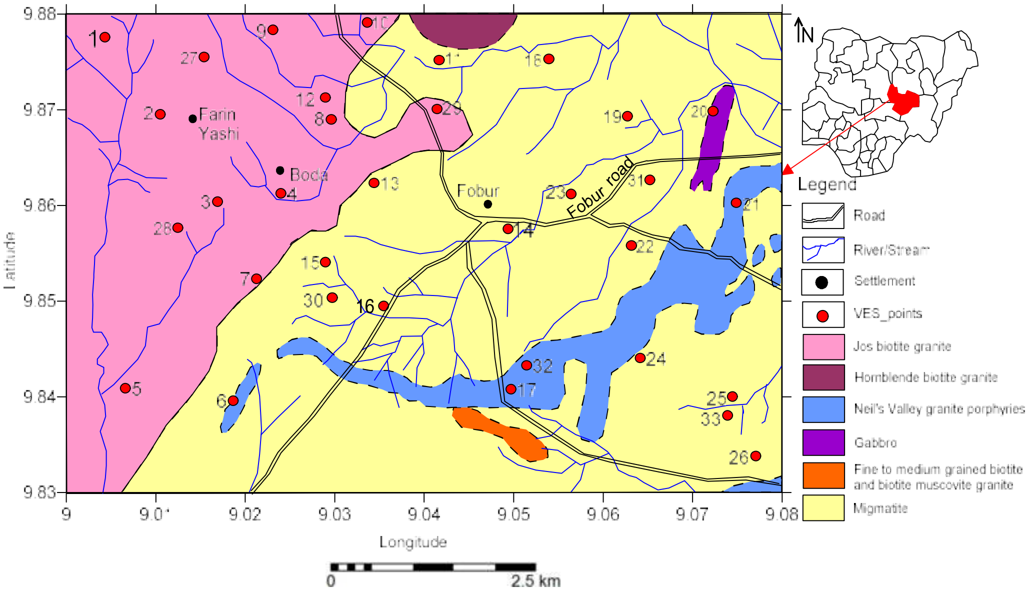


Figure 2: Geological map of Fobur and environs. (Source: NGSA, 2009)

MATERIALS AND METHOD

The electrical resistivity method is usually carried out with two pairs of electrodes; the current and potential electrodes. Electric current is applied between a pair of current electrodes and an apparent potential difference is passed across the pair of potential electrodes and the resultant electrical resistance is measured. In the homogenous ground, the depth of electric current penetration is proportional to the current electrode spacing. Information about the subsurface lithology can be realized by varying the electrode separation (Koefoed, 1979).

For this study, the Schlumberger electrode configuration was adopted and the vertical electrical sounding (VES) technique was employed for data acquisition. All the four electrodes were arranged collinearly, while the distance between the inner electrodes was kept constant, the distance between the outer electrodes was varied for each measurement. Omega resistivity meter was used to acquire the VES data with half electrode spacing [AB/2] ranging between 1 and 125 m.

Thirty-three (33) VES readings were spatially acquired (Figure 3) across Fobur and its environs and the interpretation were done with WINRESIST version 1.0 program's software. Geoelectric parameters derived from the model include: weathered basement resistivity, weathered basement thickness, overburden thickness, basement rock resistivity, basement rock topography, reflection coefficient, resistivity contrast and electrical anisotropy were acquired.

Thematic map for an individual geoelectric parameter was produced and then combined to give the groundwater potential map of the area. The basement rock topography was obtained by subtracting the overburden thickness of each VES point from the elevation of the same point. The reflection coefficients (r) of the study area were calculated using the method of Olayinka (1996); Bhattacharya and Patra (1968); and Loke (1999). The reflection coefficient shows the degree of freshness of the rock at the bedrock interface and can be defined as:

$$\mathbf{R_c}=\frac{\rho n-\rho(n-1)}{\rho n+\rho(n-1)}$$

and the fractured contrast (Fc) is defined as

$$\mathbf{Fc}=\frac{\rho n}{\rho(n-1)}$$

Where ρn is the resistivity of the n^{th} layer and $\rho(n-1)$ is the resistivity of the layer overlying the n^{th} layer. In interpreting and understanding the geoelectrical model for layered earth, certain parameters are fundamental and important. The combination of different thickness and resistivity for each layer in the model are related to these parameters (Singh, 2005). Dar-Zarrouk parameters introduce by Maillet, (1947) plays a vital role in geoelectrical resistivity soundings. In computing the distribution of surface potential for a set of n horizontal, homogenous and isotropic layers of resistivity (ρi) and thickness (hi), the longitudinal unit conductance S and the transverse unit resistance T are defined by

$$\mathbf{S}=\sum_{i=1}^{n} hi/\rho i \text{ and } \mathrm{T}=\sum_{i=1}^{n} hi\rho i$$

While the average longitudinal resistivity ρL, Average transverse resistivity ρt and electrical anisotropy **λ** are defined by

$$\rho L={}^{H}/_{S} \quad \text{Where } \mathrm{H}=\sum_{i=1}^{n} hi$$

$$\rho t={}^{T}/_{H}$$

$$\lambda=\frac{\sqrt{SXT}}{H}=\sqrt{\frac{\rho t}{\rho L}}$$

The parameters mentioned above were determined to the top of the basement rocks in this study area. A new image map method was used to produce colour maps for the geoelectric and Dar-Zarrouk parameters. The geoelectric and Dar-Zarrouk parameters were combined and used to rank the groundwater potential as a function of the aquifer resistivity (Wright, 1992), basement resistivity, weathered layer thickness, reflection coefficient (Olayinka *et al*., 1997; Oyedele and Olayinka, 2012) and longitudinal conductance (Oladapo *et al*., 2004; Abiola *et* al., 2009) to produce groundwater potential map of the study area.

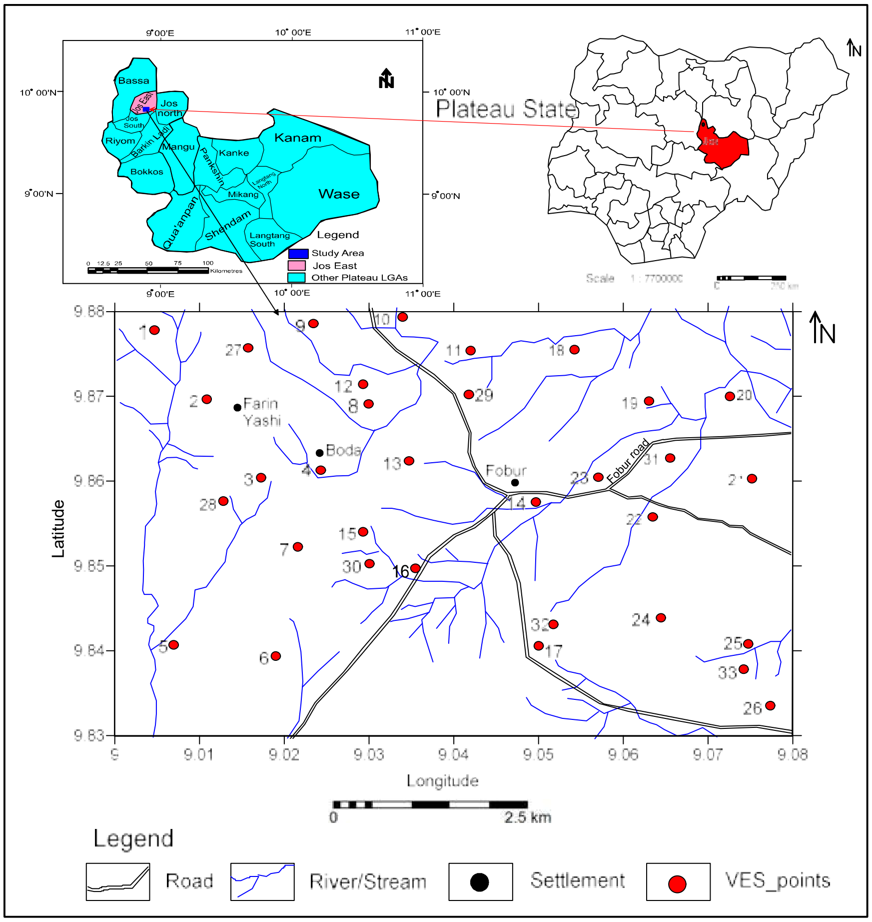
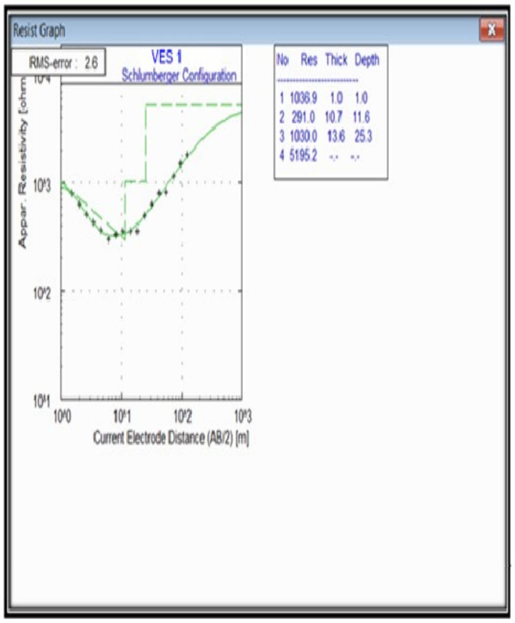


Figure 3: Location map of Fobur and environs, showing the spatial distribution of the VES points

RESULTS AND DISCUSSION

Thirty-three (33) Vertical Electrical Sounding (VES) were acquired within the study area and the obtained resistivities, layer thicknesses and curve types for the thirty-three (33) VES stations are presented in Table 1. The sounding curve types obtained from Fobur and its environs are A, H, Q, HA, QH, AK and QHA (Table 1). The sounding curve type ranges from 2 to 5 layers with H curve type dominating the four (4) representative curve types found within the study area are shown in Figure 4. The geoelectric layers deduced from the resistivity data are topsoil, clay soil, laterite, weathered layer, fractured unit and fresh basement. The estimated geoelectric parameters such as overburden thickness, resistivity contrast, reflection coefficient, longitudinal conductance, transverse resistance and electrical anisotropy are also presented in Table 1.



```
No   Res    Thick  Depth
.........................
1  1036.9   1.0    1.0
2   291.0  10.7   11.6
3  1030.0  13.6   25.3
4  5195.2   -.-    -.-
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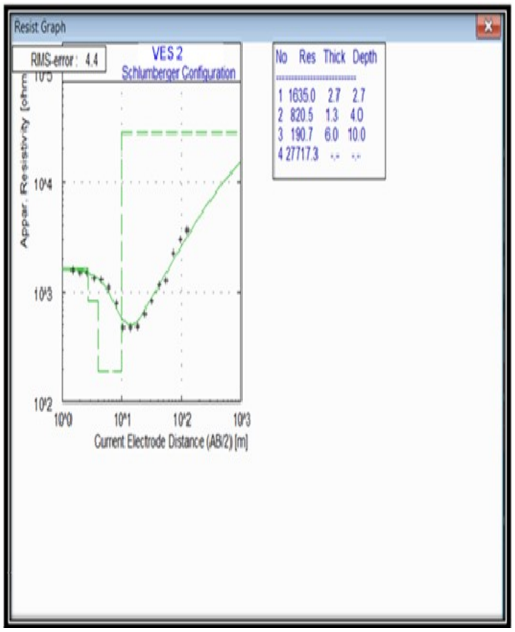

```
No   Res    Thick  Depth
.........................
1  1635.0   2.7    2.7
2   820.5   1.3    4.0
3   190.7   6.0   10.0
4 27717.3   -.-    -.-
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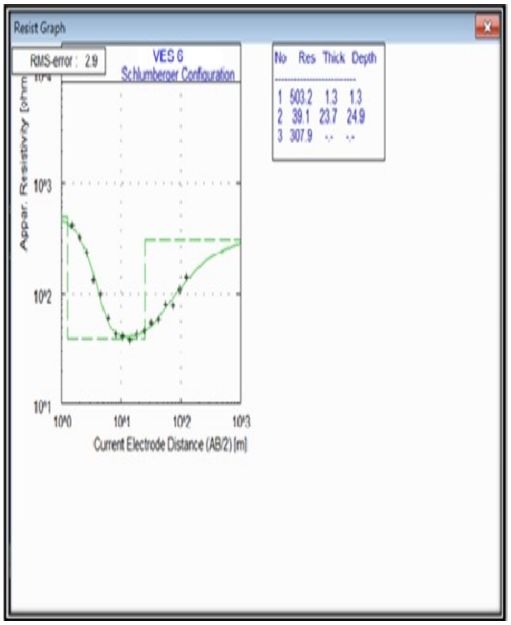
Figures 4a: Typical type HA curves for 4 layered earth. **Figures 4b:** Typical type QH curves for 4 layered earth.



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No   Res    Thick  Depth
.........................
1   503.2   1.3    1.3
2    39.1  23.7   24.9
3   307.9   -.-    -.-
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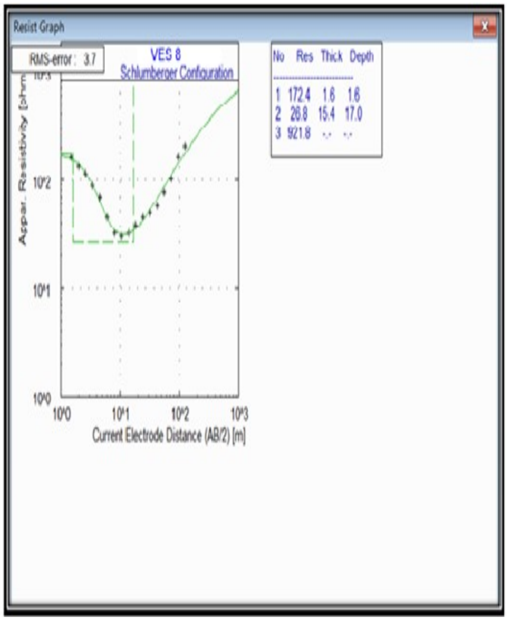

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No   Res    Thick  Depth
.........................
1   172.4   1.6    1.6
2    26.8  15.4   17.0
3   921.8   -.-    -.-
```

Figures 4c: Typical type H curves for 3 layered earth. **Figures 4d:** Typical type H curves for 3 layered earth.

Table 1: Summary of Geo-electrical parameter and Dar-Zarrouk parameters of the VES curves

VES NO	Resistivity (Ωm)					Layer Thickness m)				Curve Type	Overburden thickness (m)	Resistivity Contrast	Reflection Coefficient	Longitudinal Conductance S(mhos)	Transverse Resistance T (Ωm^2)	Electrical Anisotropy (λ)
	ρi	*ρii*	*ρiii*	*ρiv*	*ρv*	hi	hii	hiii	hiv							
1	1036.9	291	1030	5195.2		1	10.7	13.6		HA	25.3	5.05	0.67	0.050938	18158.6	1.2
2	1635	820.5	190.7	27717.3		2.7	1.3	6		QH	10	145.35	0.99	0.034699	6625.4	1.5
3	5450.0	534.2	9080.7			1.1	24.5			H	25.6	17	0.89	0.046065	19082.9	1.2
4	4789.6	1528.7	688.3			0.6	15.6			Q	16.2	0.45	-0.38	0.01033	26721.5	1.0
5	2135.7	515.4				4.1				Q	4.1	0.24	-0.61	0.00192	8756.4	1.0
6	503.2	39.1	307.9			1.3	23.7			H	24.9	7.87	0.77	0.608722	1580.8	1.2
7	233.5	617.3				3.6				A	3.6	2.64	0.45	0.015418	840.6	1.0
8	172.4	26.8	921.8			1.6	15.4			H	17	34.40	0.94	0.583908	688.6	1.2
9	76.3	16	877.4			1.9	11.9			H	13.8	54.84	0.96	0.768652	335.4	1.2
10	36.7	19.4	17.5	43.7	1340.1	0.7	3.6	7.1	8.8	QHA	20.2	30.67	0.94	0.811728	219.8	0.7
11	296.2	9.2	11.2	295.0		0.5	2.6	14.6		HA	17.6	26.34	0.93	1.587868	335.5	1.3
12	61.8	21.1	60.3	495.4		2.2	12.4	14.5		HA	29.1	8.22	0.78	0.863741	1271.9	1.1
13	244.1	104.5	512.6			1	13			H	14.1	4.91	0.66	0.128499	1602.6	1.0
14	122.7	96.2	415.1			2.2	10.1			H	12.3	4.315	0.62	0.12292	1241.6	1.0
15	158.3	59.7	158.1	962.4		0.8	2.5	11.5		HA	14.8	6.09	0.72	0.119669	2094.0	1.1
16	63.3	42.7	79.8	991.2		0.7	3.9	8.3		HA	12.9	12.42	0.85	0.206403	873.2	1.0
17	85.3	33.3	124.2	1788.6		0.9	4.9	5		HA	10.7	14.40	0.87	0.197956	860.9	1.2
18	1447.6	633	220			2.4	4.6			Q	7	0.353	-0.48	0.008925	6386.0	1.1
19	1089.9	828.0	173.7			1.7	5.5			Q	7.2	0.21	-0.65	0.008202	6406.8	1.0
20	239.2	115.6	559.4	747.7		1.1	3.5	13.7		HA	18.3	1.34	0.14	0.059366	8331.5	1.2
21	590.2	144.8	745.6	1764.3		1	5.5	14.5		HA	21	2.37	0.41	0.059125	12197.8	1.3
22	362.2	426.7	1413.3	969.7		1.1	2.1	8.5		AK	11.8	0.69	-0.19	0.013973	13307.5	1.2
23	51.4	1597.6	2011.8			4.1	3.7			A	4.1	1.26	0.11	0.082083	6121.9	2.9
24	249	105.3	26.1	597.5		0.8	2	14.8		QH	17.6	22.89	0.92	0.589256	796.1	1.2
25	777.2	168.5	46.9	591.1		0.7	3	24.9		QH	28.6	12.60	0.85	0.549622	2217.4	1.2
26	145.3	31.8	194.1			2.1	39.9			H	42	6.10	0.72	1.26917	1573.9	1.1
27	265.1	969.2	2097.9			5.1	11.3			A	16.4	2.16	0.37	0.030897	12303.9	1.2
28	233.9	1137.7	3257.7			9.0	16.6			A	25.6	2.86	0.48	0.053069	20990.9	1.3
29	84.3	824.8	20284.6			8.0	3.7			A	11.7	24.59	0.92	0.099385	3726.2	1.6
30	622.6	252.5	1605.2			1.3	5.2			H	6.6	6.36	0.73	0.022682	2122.4	1.1
31	1075.4	190.7	512.7			0.7	6.2			H	6.8	2.69	0.46	0.033163	1935.1	1.2
32	464.4	162.0	347.1			1.2	22.1			H	23.4	2.14	0.36	0.139004	4137.5	1.0
33	464.3	161.9	347.2			1.2	22.2			H	23.4	2.14	0.36	0.139706	4151.4	1.0

Aquifer Unit (Weathered Layer) Resistivity

The weathered Basement resistivity values obtained from the study area range from 9.2 to 291 Ωm (Figure 5) with average resistivity of 99.62 Ωm and the variations in the aquifer unit (weathered layer) resistivity across Fobur and its environs are shown in Figure 5. The material composition of the weathered basement comprises of the clayey soil, sandy clay and clayey sand. The aquifer resistivity map (Figure 5) indicates that VES points that fall between the layer resistivity values of 9.2 to 100 Ωm have higher groundwater potential because the basements have been weathered into sandy clay or clay layer which allows percolation and storage. The rock type, clayey contents and climatic conditions continuously influence the resistivity of the aquifer unit.

Weathered layer resistivity only cannot be used to infer groundwater potential; other factors such as Overburden thickness, bedrock relief, basement resistivity and reflection coefficient are also considered (Table 1). The magenta and orange colour areas are characterized by low resistivity weathered basement (Figure 5) and this with other geoelectric parameters could be a pointer to good groundwater yield. The presence of clay within the regolith will reduce the resistivity of the weathered layer to less than 100 Ωm and thus, decreases the permeability and likewise lower the aquifer potential (Carruthers and Smith, 1992; Olayinka *et al.*, 1997).

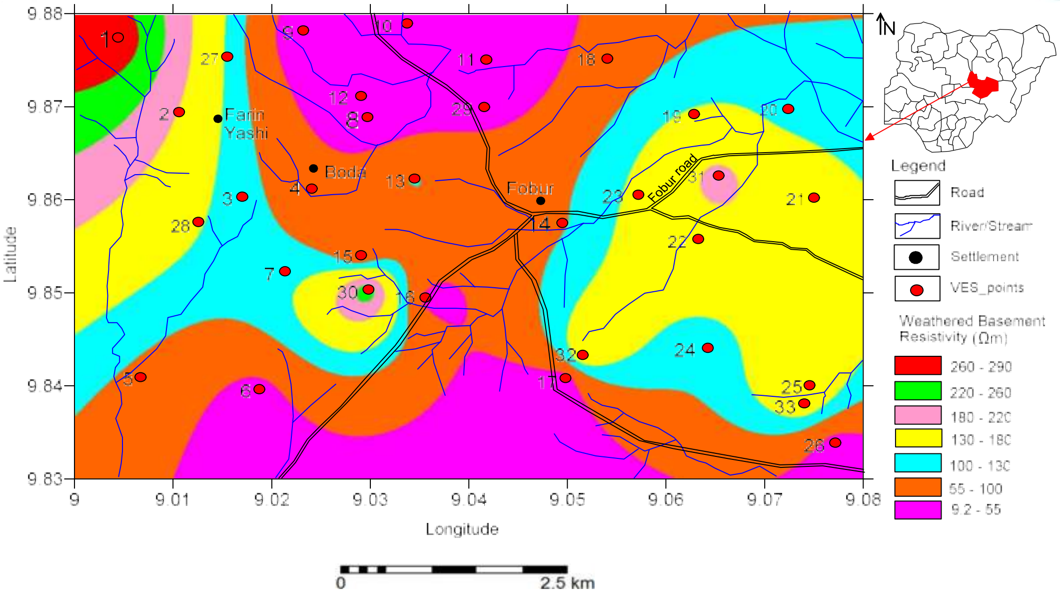

Figure 5: Aquifer unit (Weathered basement) resistivity map of Fobur and environs

Aquifer Unit (Weathered Layer) Thickness

The aquifer unit/weathered layer underlay the topsoil/laterite unit and as well overlay the basement rock. The thickness of the aquifer unit/weathered layer ranges from 2.0 to 39.9 m (Figure 6) with an average thickness of 10.69 m. The variations in aquifer unit/weathered basement thicknesses across the Fobur and its environs are shown in Figure 6. The study area is underlying by areas showing thickness values less than the average aquifer unit thickness (10.69 m) and is dominated by aquifer unit thickness of less than 9 m which constitutes more than 45 % of the study area (Figure 6). Thick aquifer unit which is 23 m and above is found in the red, green and pink colour zones of the study area while the intermediate thickness which is between 16 to 23 m is found at the yellow colour part of the area and the orange colour area is dominated by the lowest aquifer unit thickness (Figure 6). The aquifer unit shows the degree of weathering that has affected the basement around the study area. The basement around the study area has not been affected by the weathering agent using the weathered basement thickness as a benchmark.

Overburden Thickness

Overburden thickness comprises of the topsoil, laterite, and weathered basement. The overburden thickness across the study area varies from 3.6 to 42 m (Figure 7) with an average thickness of about 16.48 m. Olayinka *et al.* (1997) recommended overburden thickness of 20 - 30 m for good groundwater yield in a well, while Oladapo *et al.*, (2004) and Olorunfemi and Okhue (1992) suggested 25 m as the thickness of overburden that is feasible for groundwater abstraction. The area showing overburden thickness of 20m and above (Figure 7) is comparable with the overburden thickness suggested by Olayinka *et al.* (1997); Oladapo *et al.*, (2004); Olorunfemi and Okhue (1992). The red, cyan and yellow colour parts of the study area (Figure 7) are viable for groundwater abstraction and constitute about 50 % of the area. This indicates that groundwater prospect around Fobur and environs is moderate.

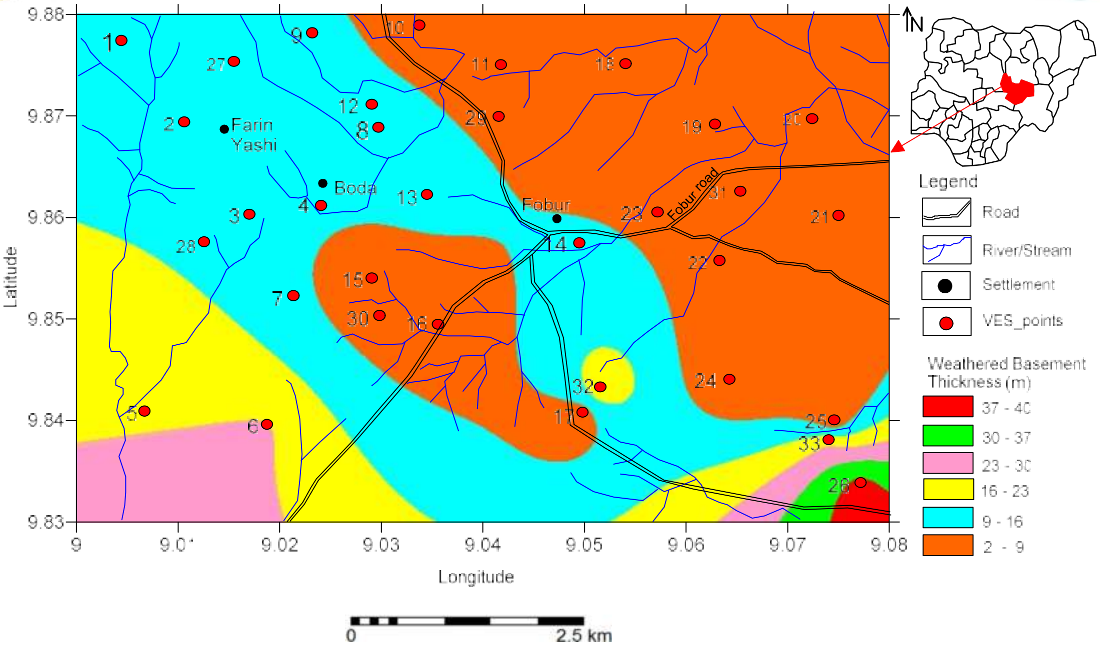

Figure 6: Aquifer unit (Weathered layer) thickness map of Fobur and environs

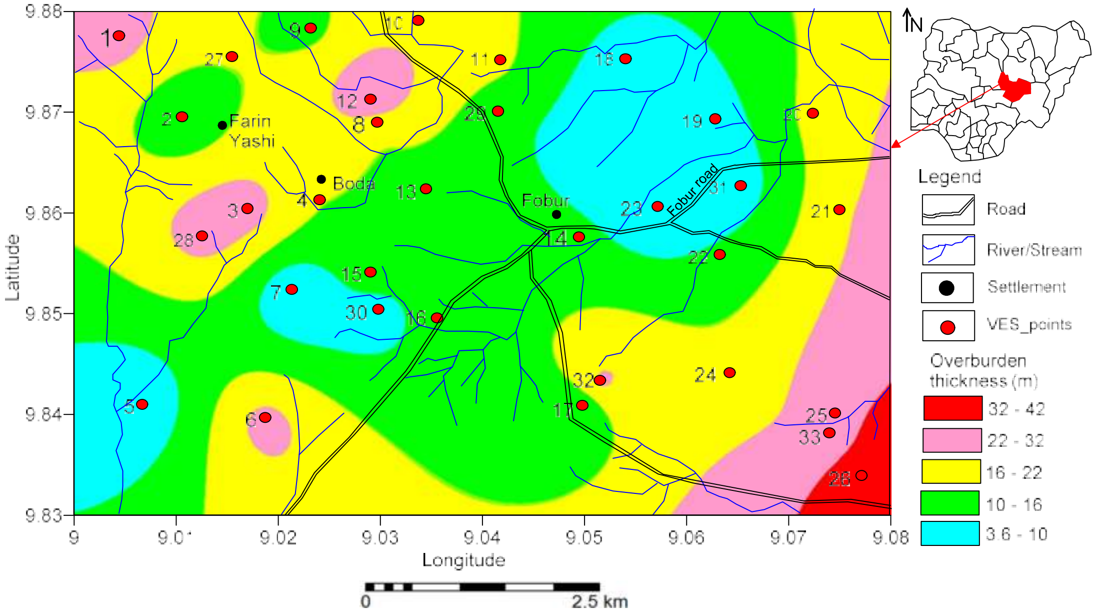

Figure 7: Overburden thickness map of Fobur and environs

Basement Resistivity

The basement resistivity ranges from 43.7 to 27717.3 Ωm (Figure 8) with an average resistivity of about 2640.84 Ωm. Geologically, the unevenness in the weathering of the basement rocks will result in varying basement aquifer resistivities. Oladapo *et al.* (2004) stated that the difference in mineralogy and the occurrence of different bedrock structures could be ascribed to variation in bedrock resistivity in an area. Groundwater yield is enhanced by the presence of fractures within the basement rock which could be due to relatively high permeability

Fobur and its environs are classified into good, medium, low and negligible aquifer potential zones based on the classification of basement rock aquifer potential zones of Olayinka *et al.* (1997) and Oyedele and Olayinka, (2012). The basement rock of high fractured permeability due to weathering with resistivity of less than 750 Ωm as observed in the cyan and orange colour portion of the study area (Figure 8) indicates a good aquifer potential zone. The basement with resistivity value ranges from 750 to 1500 Ωm which has reduced influence of weathering and observed in the yellow colour portion of the study area (Figure 8) is classified as medium aquifer potential zone while basement resistivity with values ranging from 1500 to 3000 Ωm which resulted from low effect of weathering is classified as low aquifer potential zone as depicted by pink colour. Resistivity value above 3000 Ωm is classified as a negligible aquifer potential zone with little or no weathering of the basement rock and is observed as green and red colours in the study area (Figure 8).

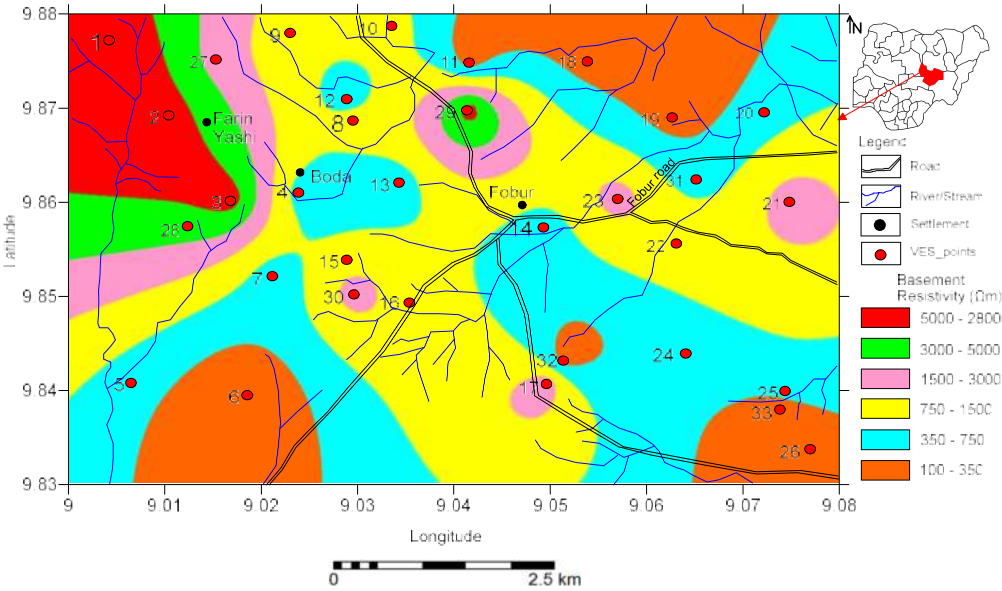

Figure 8: Basement resistivity map of Fobur and environs

Basement Topography

The basement topography map of the study area (Figure 9) shows the bedrock elevation morphology at each VES point which helps to predict the area suspected to have good groundwater prospects. The importance of basement topography for hydro-geological studies have been identified by Dan-Hassan and Olorunfemi (1999); Bala and Ike (2001). The best zones of groundwater prospect can be projected from the basement relief map, this is possible because the area with basement topographic depression (basement trough) corresponds with thick overburden and low basement resistivity can be observed to have good groundwater prospect likewise, an area with basement topographic ridges corresponds with thin overburden and high basement resistivity and is said to have poor groundwater prospect.

The magenta, orange, cyan, yellow and pink colour parts of the study area (Figure 9) suggest the basement depression zones with thick overburden, while the red (1190-1196m) and green (1184-1190m) coloured areas represent the basement ridges (Figure 9). This indicates that the overburden is shallow and any infiltration from the run off to the basement will flow to the location where basement depression is present and it will serve as a groundwater storage zone.

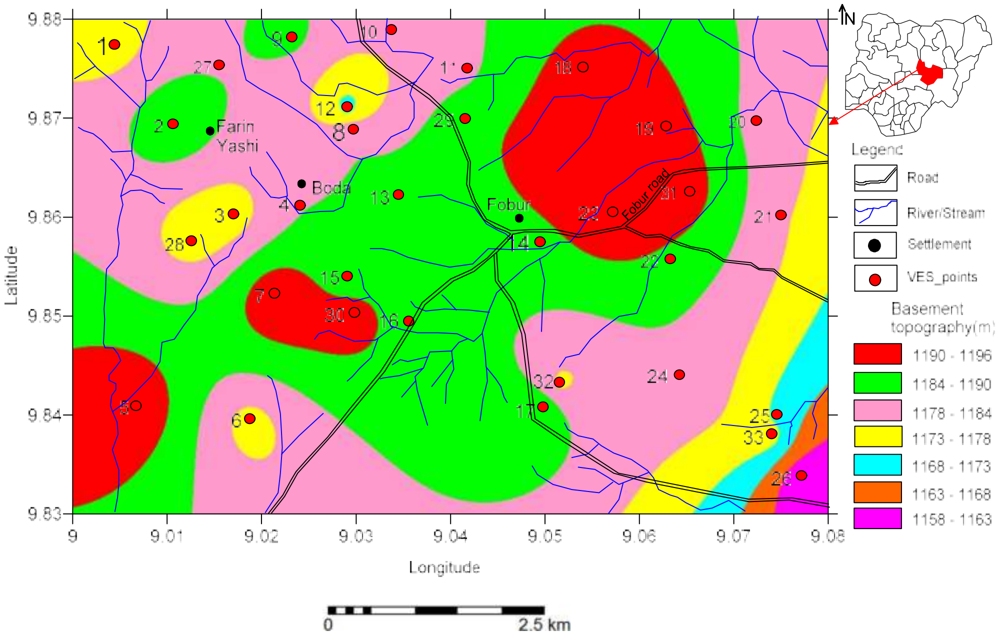

Figure 9: Basement topography map of Fobur and environs

Reflection Coefficient and Resistivity Contrast of the Basement Rock

The reflection coefficient and resistivity contrast at the interface of fresh bedrock provide information about the degree of freshness or fracturing of basement rock. Olayinka, (1996) proposed that when the reflection coefficient value of VES point is increasing towards maximum value 1, and the resistivity contrast is greater than 19, the basement is becoming fresh. When using basement resistivity, the reflection coefficient and the resistivity contrast is a prerequisite to be considered in delineating aquiferous zone.

The area where the reflection coefficient is less than 0.75 and the resistivity contrast is less than 19 and also, the overburden thickness is greater than 25 m, such location can be considered as a good aquiferous zone. The reflection coefficient map (Figure 10) shows the distribution of the reflection coefficient across the study area, it was observed from the map that the red colour parts have a reflection coefficient greater than 0.75 and could not be good for groundwater prospecting. Similarly, Figure 11 shows the resistivity contrast map and it was observed that the orange and magenta colour parts of the study area have resistivity contrast less than 19 while the other colours have value of resistivity contrast above 19 (Figure 11).

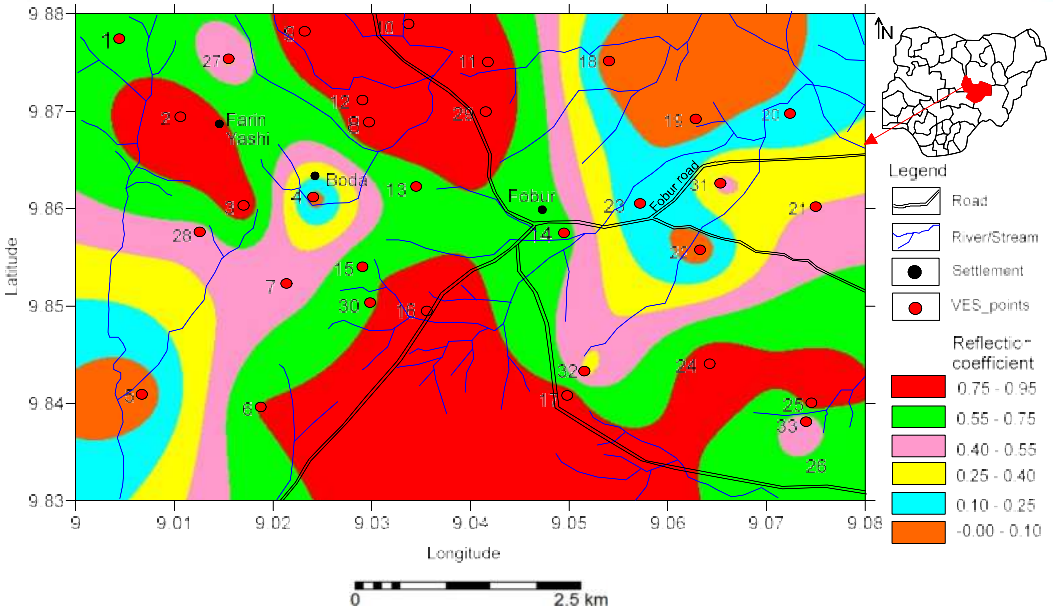

Figure 10: Reflection coefficient map of Fobur and environs

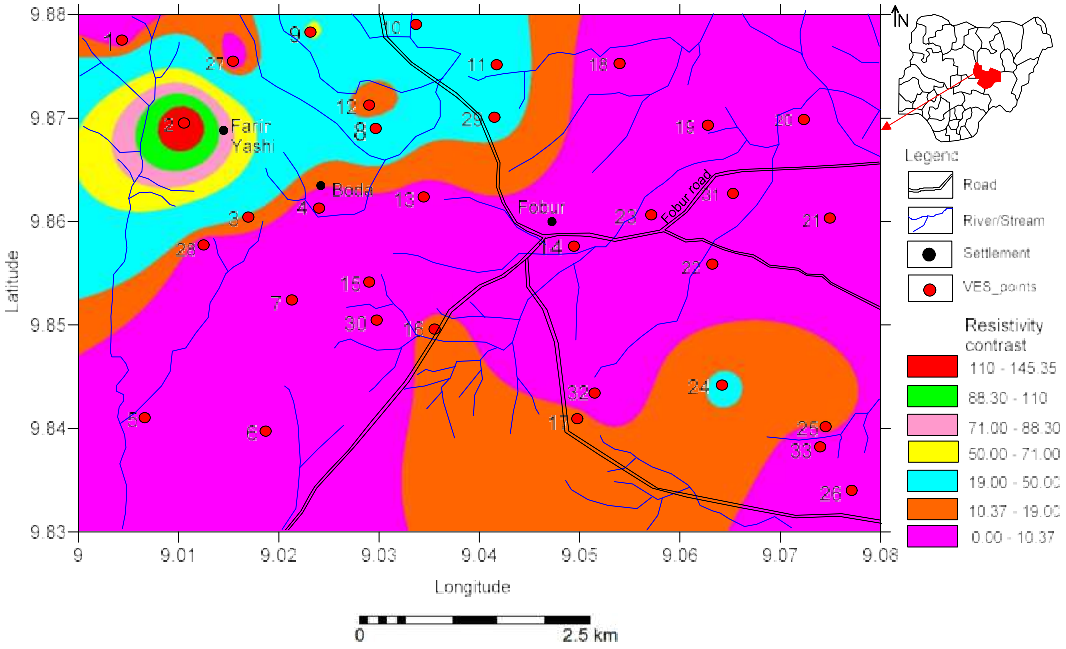

Figure 11: Resistivity contrast map of Fobur and environs

Total Longitudinal Conductance

The longitudinal conductance value of Fobur and its environs ranges from 0.00192 to 1.587868 mhos (Figure 12). Aquifer protective capacity of the area is classified into good, moderate, weak and poor based on the classification of Oladapo *et al.* (2004) and Abiola *et al.* (2009) using longitudinal conductance as a function of aquifer protection of overburden to groundwater zone. Poor aquifer protective capacity was observed in the study area (Figure 12) where the overburden longitudinal conductance was less than 0.1 mhos (yellow colour) The longitudinal conductance of 0.1 to 0.19

mhos (pink colour) is classified as weak protective capacity while the longitudinal conductance values of 0.2 to 0.69 mhos (green colour) is classified as moderate aquifer protective capacity while the longitudinal conductance value greater than 0.7 mhos (red colour) is classified as good protective capacity (Figure 12).

The inconsistency observed in the value of longitudinal conductance from one VES point to another is used qualitatively to note the variations in the total thickness of low resistivity materials found within the overburden unit. According to Khalil (2009) an increase in the value of longitudinal conductance may correspond to an increase in clay content and hence, a reduction in aquifer transmissivity. The clay overburden which gives relatively high longitudinal conductance protects the underlying aquifer.

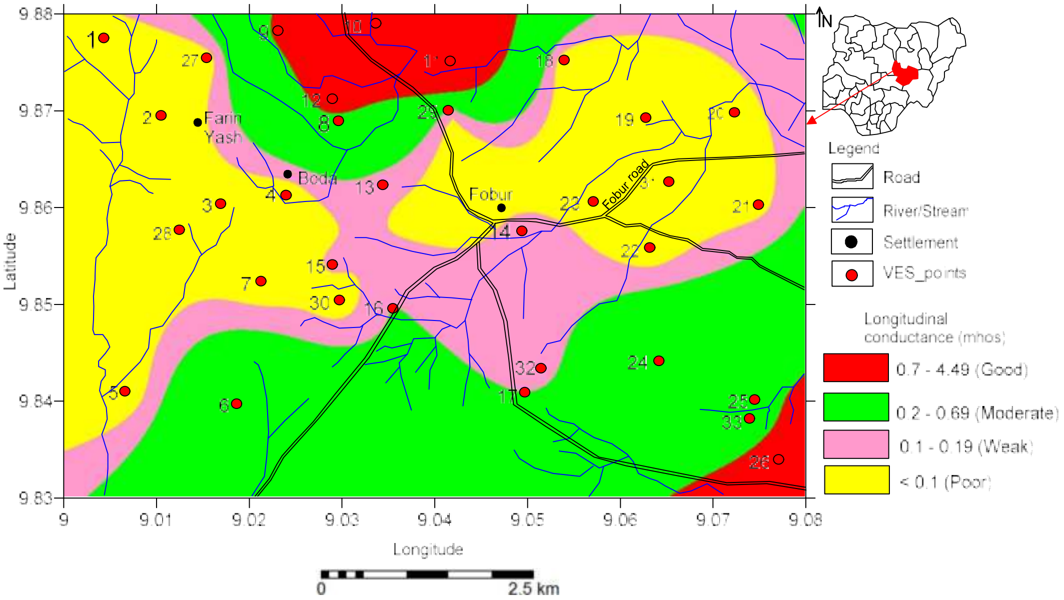

Figure 12: Total longitudinal conductance map of Fobur and environs

Total Transverse Resistance

The total transverse resistance to the top of the basement has a direct relationship with transmissivity and the highest transverse resistance value probably reflects the highest transmissivity values of the aquiferous zone (Braga *et al.*, 2006). The total transverse resistance ranges from 219.8 to 26721.50 Ωm^2 (Figure 13). The total transverse resistance value was adopted in the classification of Fobur and its environs into poor, weak, moderate and very good transmissivity zones. The area with poor negligible transmissivity has transverse resistance of less than 400 Ωm^2, weak transmissivity zone has transverse resistance of 400 to 1000 Ωm^2, moderate transmissivity zone has transverse resistance of 1000 to 2000 Ωm^2 and very good transmissivity zone has transverse resistance of greater than 2000 Ωm^2 with good aquifer transmissivity (Figure 13).

From the map generated for the total transverse resistance it was observed that more than 27 % of the area investigated has poor to weak transmissivity based on their total transverse resistance value and is represented by orange, cyan and yellow colour zones (Figure 13). The green and red colour parts of the area has good transmissivity because of the high value of total transverse resistance while the pink colour part has moderate transmissivity as observed from the value of the total transverse resistance (Figure 13).

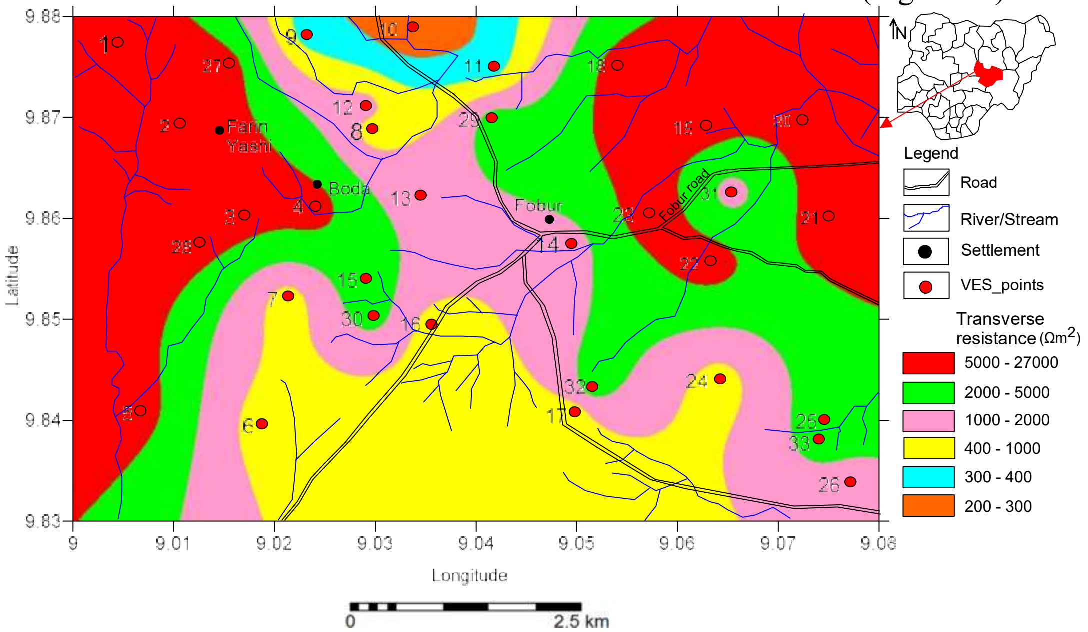

Figure 13: Total transverse resistance map of Fobur and environs

Electrical Anisotropy/Coefficient of Anisotropy

The coefficient of anisotropy to the top of the bedrock ranges from 0.7 to 2.9 (Figure 14). The mean coefficient of anisotropy for igneous rock (2.12) and metamorphic rock (1.56) in the Basement Complex of Southwestern Nigeria was given by Olorunfemi *et al.* (1991). The coefficient of anisotropy values (0.7 - 2.9) showed that the rock unit underlying the area comprises of Younger Granite Complex and metamorphic rocks as indicated by the geologic map (Figure 2). Coefficient of anisotropy of resistivity in rocks are either caused by orientation of elongated grains or by layering with different resistivity values and can also be a result of rock fracturing, metamorphism or disseminated ore grains in the rocks (Habberjam, 1972; Watson and Baker, 1999).

The electrical anisotropy has a linear relationship with groundwater yield and an increase in electrical anisotropy value will lead to an increase in groundwater yield (Olorunfemi and Olorunniwo, 1985; Olorunfemi *et al.*, 1991; Olorunfemi and Okhue, 1992). Based on linear relationship inference between the coefficient of anisotropy and groundwater yield, it was observed that the red, green and pink colour zones on the map (Figure 14) have a high value of electrical anisotropy which indicates that Fobur and its environs have good groundwater yield.

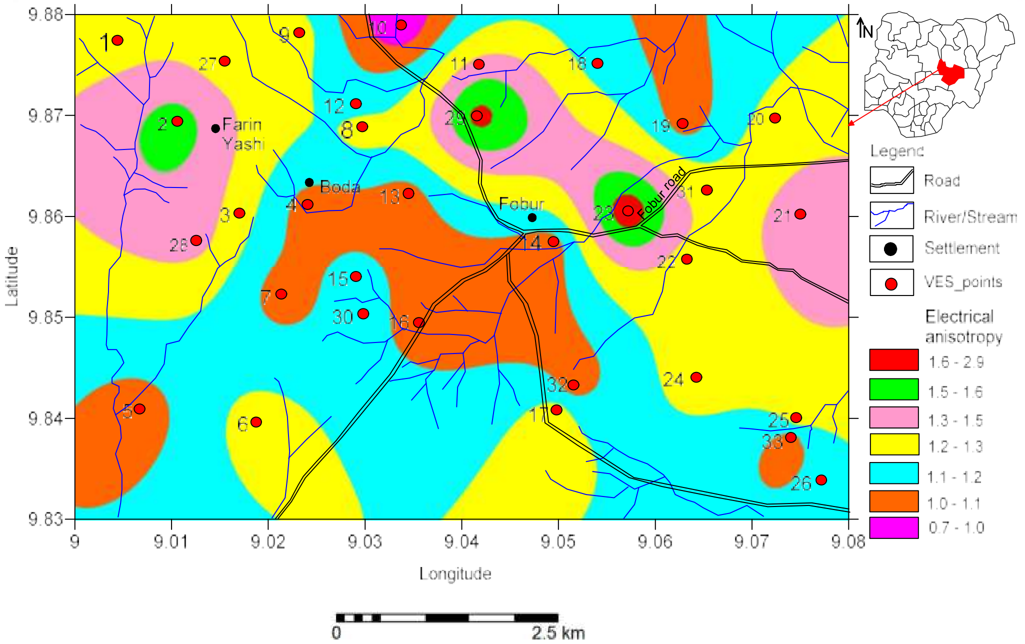

Figure 14: Electrical anisotropy/coefficient of anisotropy map of Fobur and environs

Groundwater Potential Assessment

The groundwater potential map of Fobur and environs (Figure 15) was obtained by a combination of the results of aquifer unit (weathered basement) resistivity, basement resistivity, overburden thickness, reflection coefficient, basement topography, longitudinal conductance, transverse resistance and electrical anisotropy. The groundwater potential map (Figure 15) was produced from the integration of geo-electric and Dar-Zarrouk parameters and was used to assess the groundwater potential of the study area. The groundwater potential zones of Fobur and its environs are classified into poor, low and good groundwater potential zones (Figure 15). The area with cyan colour zone is characterized by poor aquifer potential and constitutes about 21.21 % of the study area. The yellow colour zone is characterized by low groundwater potential which accounts for 51.52 % of the area and the pink colour part is characterized by good aquifer potential which accounts for 27.27 % of the mapped area (Figure 15).

The good groundwater potential zone must have an overburden greater than 10 m, the basement must show an indication of fracture from the basement resistivity value which should be less or equal to 800 Ωm and the aquifer unit (weathered basement) resistivity should be between 50 to 300 Ωm (Olayinka *et al.*, 2004 and Barker *et al.* 1992). In addition, the zone should be classified as basement depression on the basement topography map while the value of the reflection coefficient should be less than 0.75 and the coefficient of anisotropy value should be greater than 1.2 which indicate basement fracture and should have a low longitudinal conductance unit which shows an increase in transmissivity and high transverse resistance.

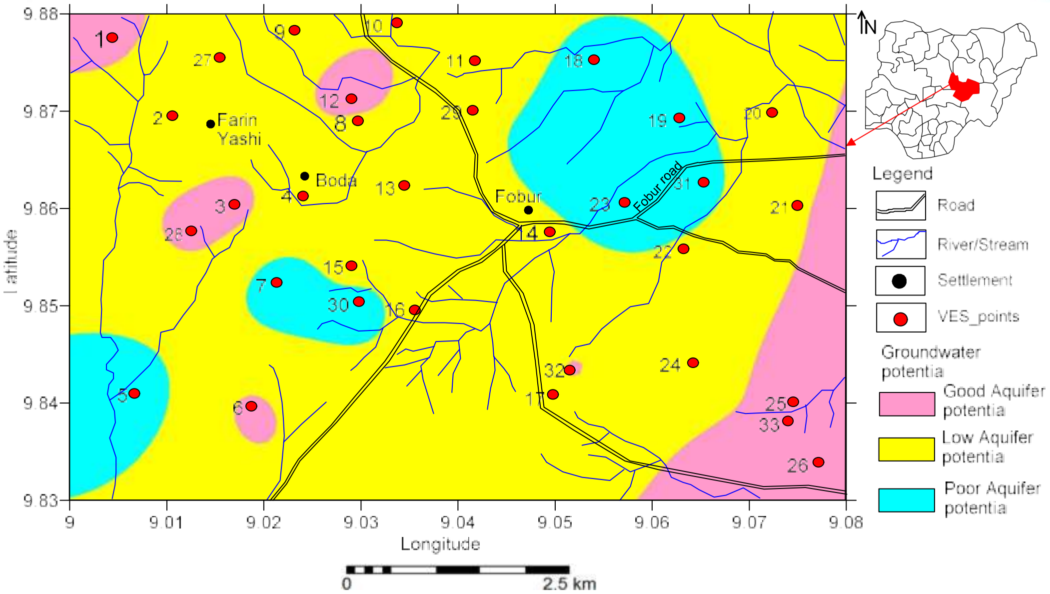

Figure 15: Groundwater potential map of Fobur and environs

CONCLUSION

The curve types obtained from VES data are: A, H, Q, HA, QH, AK and QHA with H curve type dominating and the two (2) to five (5) geo-electric layers deduced from the resistivity data are topsoil, clay soil, laterite, weathered layer, fractured unit and fresh basement. The basement resistivity value was used to classify the area into good, medium, low and negligible aquifer potential zones. The total transverse resistance value was also adopted in the classification of the area into poor, weak, moderate and very good transmissivity zones. The groundwater potential zones of Fobur and its environs are classified into poor, low and good groundwater potential zones based on aquifer thickness. The good aquifer potential zone accounts for 27.27 % of the mapped area. Consequently, areas for locating groundwater should be narrowed to regions of moderate/good groundwater protective capacity. The result of this study will serve as a reference point for groundwater development and management planning of the study area.

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