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Geoelectric Investigation for Aquifer Characterization in Boi and Environs, Bauchi State, Northeast, Nigeria

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Abstract

A total of thirty eight (38) Vertical Electrical resistivity Sounding (VES) were used to characterize aquifers in Boi and its environs, Bogoro Area of Bauchi State, Northeastern, Nigeria. The purpose of the study is to characterize the aquifer system in the area using Schlumberger configuration. Because there are multiple failed wells and boreholes in the vicinity, the research is justified. A total of 38 vertical electrical sounding (VES) were carried out, with a maximum electrode spacing of 100 m. The sounding curves acquired were three layer earth models, and the curve types were H, Q, A, and K respectively. The following lithologies were discovered in the area: topsoil with a resistivity of 81Ωm to 264.21Ωm and a thickness of 0.56m to 3.77m, laterite with a resistivity of 526.43Ωm to 999.71Ωm and a thickness of 1.93m to 3.47m, weathered/fracture basement with a resistivity of 10.62Ωm to 238Ωm and a thickness of 2m to infinite depth, and the fresh basement with a resistivity of 1000.33Ωm to 1821Ωm. The longitudinal conductance (S), transverse resistance (T), reflection coefficient (RC), and resistivity contrast (FC) were used to assess the area's groundwater potentials. The area's aquifer protection capacity found to be moderate, weak, and poor, while the groundwater potentials categorized as high, medium, low and very low. According to the results of the evaluated parameters, the area has a predominantly good to moderate groundwater potential. The numerous occurrences of failed/aborted boreholes in the area could be linked to a variety of factors, including poor data quality, lack of technical know-how, incorrect point selection, and poor drilled hole development, all of which are common in Basement Complex terrains. The VES 5 and 10 results showed a dramatic decline in resistivity, indicating that the water likely heavily polluted, particularly by anthropogenic chemicals, or that it was an ancient dumpsite.

Keywords: Bauchi; Geoelectric; Hydraulic head; Iso-resistivity; Vertical electrical sounding

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INTRODUCTION

Safe drinking water is a basic human need, and its absence or contamination can have major public health consequences, ranging from illnesses to epidemic outbreaks. Humans get their water mostly from rain, streams, and lakes. However, due to pollution and contamination caused by human activity, there are unsuitable drinking water sources. Among other things, the foregoing has prompted the necessity for groundwater exploration in Boi, and the surrounding areas. There are numerous inactive boreholes in the area. Groundwater advancement in the study site is hampered by the failure of (abortive) hand-drilled wells and boreholes due to a lack of understanding of the hydro-geophysical features of the basement aquifers. This could be due to a variety of factors, including incorrect point selection, poor data quality/incomplete knowledge from the subsurface, a lack of technical expertise, and inadequate development of drilled holes, all of which are prevalent in the Basement Complex locations (Abiola *et al.,* 2013). Groundwater exploitation in basement-complicated terrain necessitates a thorough grasp of its hydrological properties. Groundwater is mostly trapped in permeable and leaky weathered areas in the Basement Complex terrain. The accumulated groundwater in the fractured and jointed column of the basement complex rocks often supplements the groundwater output from the weathered horizon. (Satpathy& Kanungo, 1976; Olorunniwo and Olorunfemi, 1987).

The electrical resistivity technique has been one of the geophysical methods used in groundwater studies in basement complex and rugged terrain (Limaye, 1989). The appropriateness of the technique is derived from the basic significant resistivity comparison between worn and/or fissured columns and highly resistive fresh bedrock. The weathered/fractured zones of the basement are where groundwater is most likely to be found. Researchers have used the resistivity approach to explore groundwater in Basement Complex (Acworth, 1987; Olurunfemi and Fasuyi, 1993; Edet and Okereke, 1997; Nur and Ayuni, 2004; Nur and Kujir, 2006; Zohdy *et al.*, 1974; and Olasehinde, 2010). Failure rates of the borehole are highest in the basement terrain, according to experience from around the world. This is primarily due to lack of understanding of the basement aquifers, resulting in weathering and/or depletion of the in-situ rocks of the basement. Many communities, private individuals and the Nigerian government have carried out various borehole projects to find reliable and safe drinking water. As a result, there is an increase in the application of surface geological and geophysical techniques for locating potential water-bearing formations in many parts of Nigeria (Nur, 2012). The resistivity technique is much more extensively employed in groundwater exploration when especially in comparison to other geophysical techniques (Nur and Afa, 2002; Nur and Ayuni, 2011). The research is aimed at conducting geoelectric investigations (VES) in Boi and its environs, Bogoro Area, of Bauchi, Northeastern, Nigeria in order to determine the electrical resistivity parameters of the area in preparation for groundwater exploitation. The study's goals are to evaluate the lithology of the study area, its aquifer protective capacity, and some aquifer parameters of the subsurface rocks in the area in order to delineate the subsurface layers for groundwater potential zones in the area. This was prepared to figure out what was responsible for rampant cases of failed/abortive boreholes in the area.

Description of Study Area, Location, Geology and Hydrogeology

The study area Boi and its environs, Bogoro Local Government, Bauchi State, Northeast, Nigeria is located between latitudes 9° 31′ N to 9° 37′ N, and longitudes 9° 30′ E to 9° 36′ E on scale of 1:50,000 Tafawa Balewa sheet 170SW Federal Survey of Nigeria (Fig.1). It is accessible via the Bauchi-Kabwir major route, as well as tarred and untarred roads that connect the numerous villages, settlements, and towns together. The area approximately about 121 kilometres squared. The area is located on a gently undulating landscape with topographic elevations ranging from 2250 to 2550 feet. The area's drainage pattern is mostly dendritic (tree-like branching), indicates a South and South East flow direction within the study area (Fig. 2). The People of the area get their water from surface water sources including streams, ponds, and lakes, while groundwater comes through hand-dug wells.

Nigerian Basement Complex rocks, which are made-up of crystalline rocks, underlay the area. The Basement Complex consists essentially of rock with granitic composition and in different stages of metamorphism occurs as gneisses, migmatite, quartzite, phyllite, Schist and pegmatite. The Biotite-Granite, Granite-Gneiss, and Migmatitic-Gneiss in the area are all estimated to be Birimian in age (McCurry, 1976). The area also underlain by the older granites of the Precambrian to lower Paleozoic epochs. Some of these rocks, such as Biotite Granite, Migmatite Gneiss, and Granite Gneiss (Fig. 3), found in boulders, outcrops. Bauchi State Agricultural Development Project (BSADP), Conred Nigeria Limited (1978), and Edok-Eter Mandilas Nigeria Limited (1976-1979) conducted hydrogeological field reconnaissance to determine the hydrogeology of the research region (Shemang and Jiba, 2005).They were able to determine and study area's stratigraphic succession. The sequence includes the weathered and fractured Basement Complex rocks. The weathered Basement Complex rock consists mainly of in-situ decomposed rocks. At shallow depths, the decomposed rocks are characteristically clayey, concretionary brown to reddish-brown, ferruginous and lateritic. A thin blanket of alluvium consisting of boulders, gravels, sand, clay, silt lenses and an intermixed of materials mainly as observed often products weathering, and are mainly derived from weathering of adjacent hills and reworked alluvium lies above the fresh basement. Flowing water carried them to lower elevations and stream valleys, where deposited. The groundwater occurs under water table conditions. Borehole yield depends mainly on the amount of recharge, depth and areal extent of the aquifer (Carter *et al.,* 1963). Fractured crystalline rocks underlie all parts of the area, the greater part is buried beneath overburdened materials and are sometimes encountered in boreholes or hand-dug well at variable depths. Outcrops and crystalline rocks may occur as flattish masses on the surface, in some stream channels or as hills. Jointing, faulting, and shearing linked with early tectonic cycles that influenced the Basement Complex, as well as the tectonic connected to subsequent intrusions, cause fracturing in crystalline rocks. These processes can result in the formation of a superficial, shallow and deep fracture. Most of the fractured zones buried beneath the overburdened materials through which it receives their recharge and it requires more details of the geological investigation to delineate them. In crystalline rocks, weathering, fracture, and erosion are often limited. As a result, groundwater only found in limited pockets or basins. Generally, rocks dominated by unstable ferromagnesian minerals weather into clayey, sometimes micaceous impervious non-water bearing formations, whereas rocks characterized by quartz and other steady minerals weather into porous water carrying gravelly or sandy medium (Carter *et al.*, 1963).

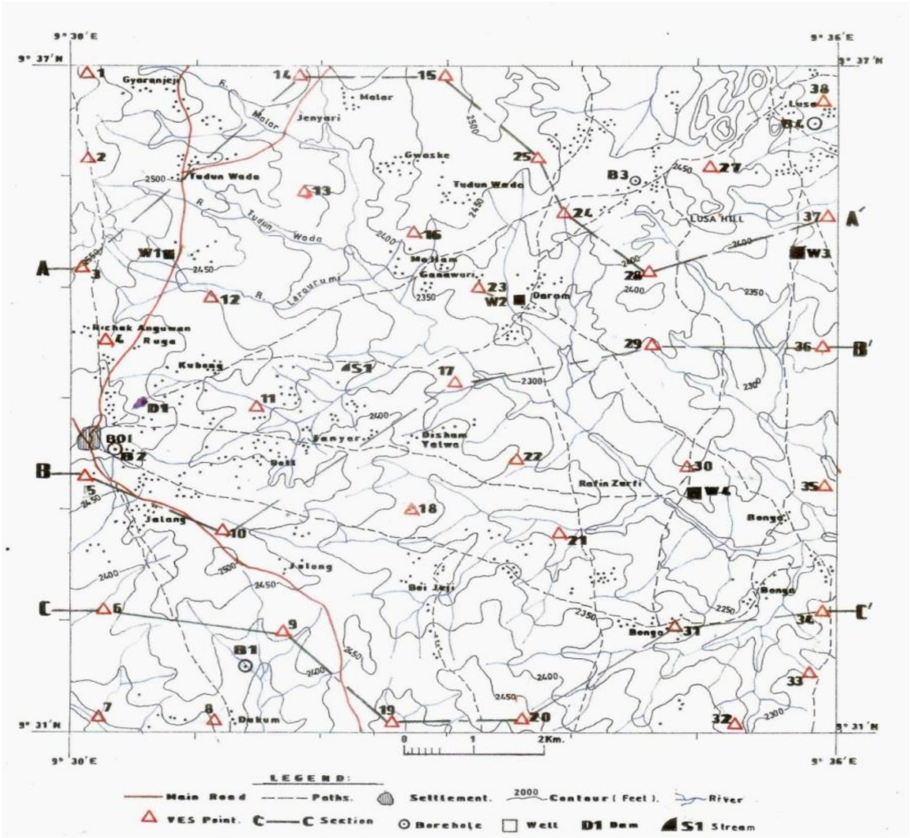


Figure 1: Topographical Map of the Study Area (Federal Survey of Nigeria, 1976)

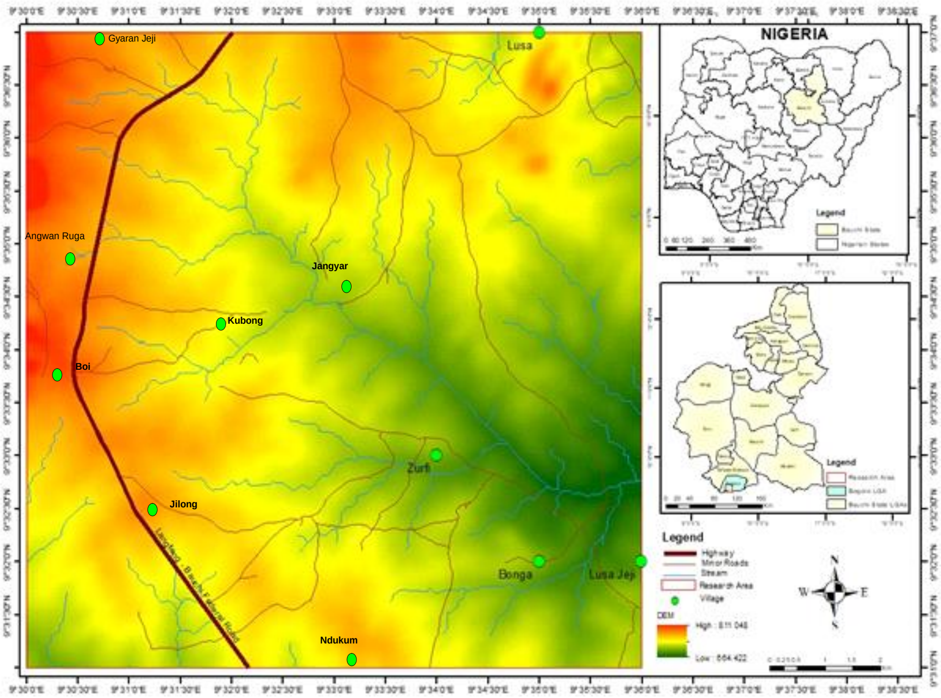


Figure 2: Map showing Digital Elevation Model of the Study Area

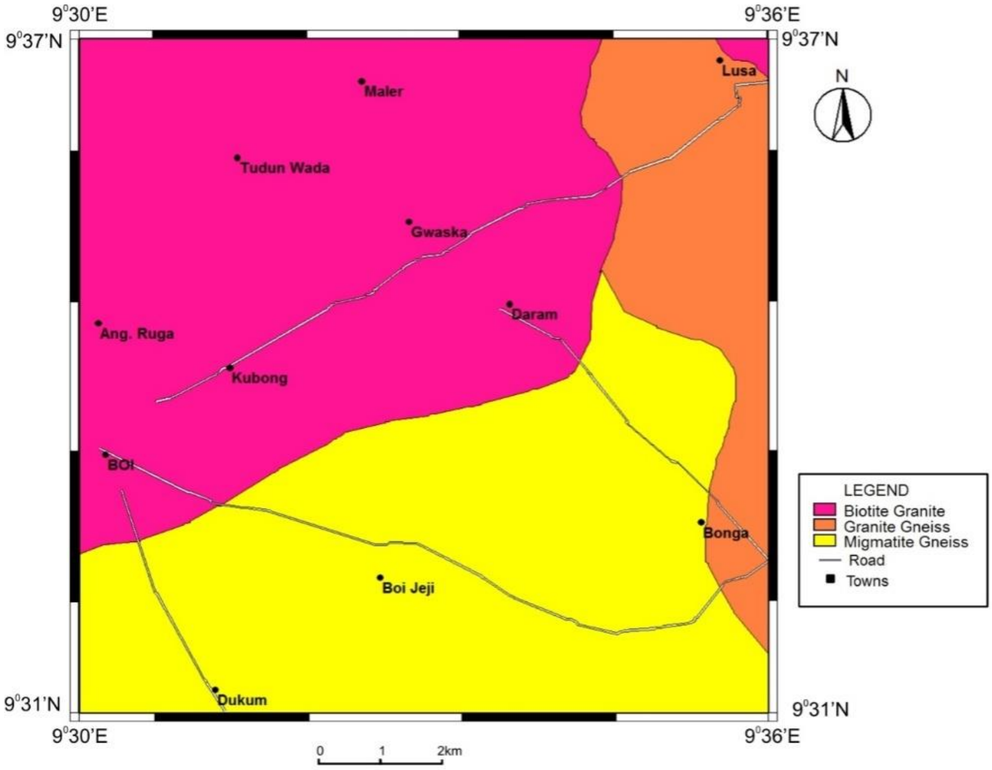


Figure 3: Geologic Map of the Study Area (After Geological Survey of Nigeria 2014)

MATERIALS AND METHOD

The topographical, geologic map and other materials relevant to this research study acquired from Nigerian Geological Survey Agency. The reconnaissance survey of the area carried out intending to determine the lithology and trends of the primary rock types and their structures in the area of study, which led to the selection of the best locations for a geophysical survey using the resistivity method. ABEM SAS - 200C Terrameter was used to collect the resistivity data. Schlumberger electrode configuration used to acquire the 38 VES points throughout the area. The distance between current electrodes, (AB/2) was varied from 1 to 100 meters, while the distance between potential electrodes was varied from 0.2 to 1.5 meters. The apparent resistivity calculated using the formula in equation (1) below. For each electrode spacing, the apparent resistivity values calculated as the product of the resistance measured from the resistivity meter and its corresponding geometric factor (K). The apparent resistivity values then shown as sounding curves against AB/2 on a bi-logarithm graph. The plotted sounding curves manually interpreted using several master curves and partial curve matching (Zohdy, 1965). The partial curve matching geoelectric characteristics used as the input model for computer-assisted iteration with IX1D software.

$$\rho a = \pi.\left\lfloor\frac{(AB/2)-(MN/2)}{MN}\right\rfloor.Ra \qquad \ldots\ldots (1)$$

Where,

ρa is the apparent resistivity,
AB is the distance between the two current electrodes,
MN is the distance between the potential electrodes, and
Ra is the apparent electrical resistance measured.

In addition to determining apparent resistivity and thickness of various formations in the study area, the electrical resistivity parameters of longitudinal conductance (S), transverse resistance (T), reflection coefficient (RC), and resistivity contrast (FC) reflecting the characteristics of layered earth were determined in this work. The longitudinal conductance (S) is important when the current flows parallel to the geoelectric borders, while the transverse resistance (T) is important when the current flows normal to the bed boundaries (Telford *et al.* 1978).The longitudinal unit conductance values of the overburden rock units in the research area used to characterize the aquifer protection capacity of the area. The longitudinal unit conductance is a measure of the confining clay layer's impermeability, which has low resistivity and hydraulic conductivity. The longitudinal unit conductance is proportional to the protective capacity of the overburden layers in a given area (Tsepav *et al.*, 2015). Equation (2) used to calculate the longitudinal layer conductance (S) of the overburden at each VES station (Henriet, 1976).

$$S= \sum_{i=1}^{n}(\mathrm{hi/pi})\ldots\ldots\ldots\ldots \text{ (2)}$$

Where hi is the layer thickness, ρi is the layer resistivity, while the number of layers from the surface to the top of the aquifer varies in the range i = 1… n. The results of the longitudinal unit conductance used to classify the areas into good, moderate, weak and poor aquifer protective capacity (Table 3). This was done using the classification given by Oladapo and Akintorinwa (2007).

$$T = \sum_{i=1}^{n}(hipi)\ldots\ldots\ldots\ldots.. \text{ (3)}$$

Where T is the transverse resistances, ρi is the layer resistivity and h_i layers with thicknesses. According to Olayinka (1996), the resistivity of the basement can't be depended on only in finding areas of suitable aquifers within a basement terrain; thus, the basement's reflection coefficient must be included in efficiently evaluating groundwater potential in the research area. The reflection coefficient (Bayewu, *et al.,* 2018) indicates the degree of fracturing of the underlying basement. Equation (3), as described by Bhattacharya and Patra (1968) and Loke (1999), used to calculate the study area's reflection coefficients(r).

$$r = \frac{(\rho\mathrm{n} - \rho(\mathrm{n}-1))}{(\rho\mathrm{n}+ \rho(\mathrm{n}-1))}\ldots\ldots\ldots.. \text{ (4)}$$

Where ρn is the layer resistivity of the nth layer and $\rho\ (n-1)$ is the layer resistivity overlying the nth layer.

According to Bayewu *et al.*(2018), groundwater yield in a basement terrain can be classified as high, medium, or low based on the overburden thickness and/or reflection coefficient (Table 3). Where thick overburden overlies the fractured zone, the largest groundwater output found, the resistivity contrast (FC) calculated as follows:

$$F_{\mathrm{C}} = \frac{pn}{\rho\mathrm{n}-1}\text{................ (5)}$$

Where p_n is the layer resistivity of the nth layer and p_{n-1} is the layer resistivity overlying the nth layer.

Static water level (SWL) measurements

The static water levels (SWLs) and well depths of boreholes and hand-dug wells calculated using Dipper (the dipper-T model). The topography and coordinates (latitude and longitude) of each location were determined using Global Positioning System (GPS) (e-Trex 20 Garmin model). Residents began water abstraction early in the morning, therefore sampling was done first.To ensure that samples were evenly distributed; the study area was divided into ten quadrants. The SWL and topographic elevation above mean sea level values used to estimate the hydraulic head of each well. These measurements used to make a hydraulic head map of the area.

RESULTS AND DISCUSSION

Plotting the apparent resistivity against AB/2 or halving the spread length on log-log paper, the sounding data presented as sounding curves. Smoothened data inputted into a computer system using IX1D software to generate sounding curves. The curves were smoothened until smooth layer curves obtained. The general features of the sounding curves observed were three layers types. The H, Q, A, and K were discovered in the study area's geological formations (Fig 4a-d). Thirty of these curves were class H types (Fig.4a) with a resistivity relationship of $\rho_1 > \rho_1 < \rho_1$ (Lowrie, 2007). They made up 78.95% (Fig 5) of the total curve of the study. They area at VES 1, VES 2, VES 3, VES 4, VES 5, VES 6, VES 7, VES 8, VES 9 VES 10, VES 11, VES 14, VES 15, VES 16, VES 17, VES 18, VES 19, VES 20, VES 21, VES 22, VES 23, VES 26, VES 27, VES 28, VES30, VES 32, VES 33, VES 36, VES 37, and VES 38. The resistivity connection for Type Q curves is $\rho_1 > \rho_1 > \rho_1$. They were found in VES 12, VES 24, VES 29, VES 31, and VES 34, and account for 13.16% (Fig 5) of the total curves in the study area . The resistivity relationship of Type A curves is $\rho_1 < \rho_1 < \rho_1$. They made up 5.26% of all curves in the research area found in VES 25 and VES 35, respectively. The resistivity relationship of Type K curves is $P_1<P_2>P_3$ (Table 1). They made up 2.63% (Fig 5) of all curves in the research area found at VES 13 (Fig.4d). First-order geometric parameters (resistivities, thicknesses, fitting errors and their corresponding curve types) of all sounding points presented in (Table2). This contains details of layer thicknesses, resistivities, longitudinal conductance, transverse resistivities and their fitting errors for all the points sounded in the study area. The general features of the sounding curves observed have fitting errors ranging from 0.215 percent to 0.98 percent respectively. Because each of the type curves indicates a specific geometry of the geoelectric layers in the subsurface, these curves evaluated in terms of their hydrogeological relevance to serve as a foundation for the description of aquifer architecture within the study area. The major aquiferous zone is thus at the base, where selective mineral weathering has produced gravel-like materials containing a large number of medium to coarse-grained quartz particles, resulting in improved permeability and yield. Fresh bedrock lies immediately beneath the aquiferous zone (Abiola *et al.,* 2013)

Table 1: Showing different curve types and their layer relationships

S/N	Curve type	Layers
1.	H	$\rho_1 > \rho_1 < \rho_1$
2.	Q	$\rho_1 > \rho_1 > \rho_1$
3.	A	$\rho_1 < \rho_1 < \rho_1$
4.	K	$P_1<P_2>P_3$

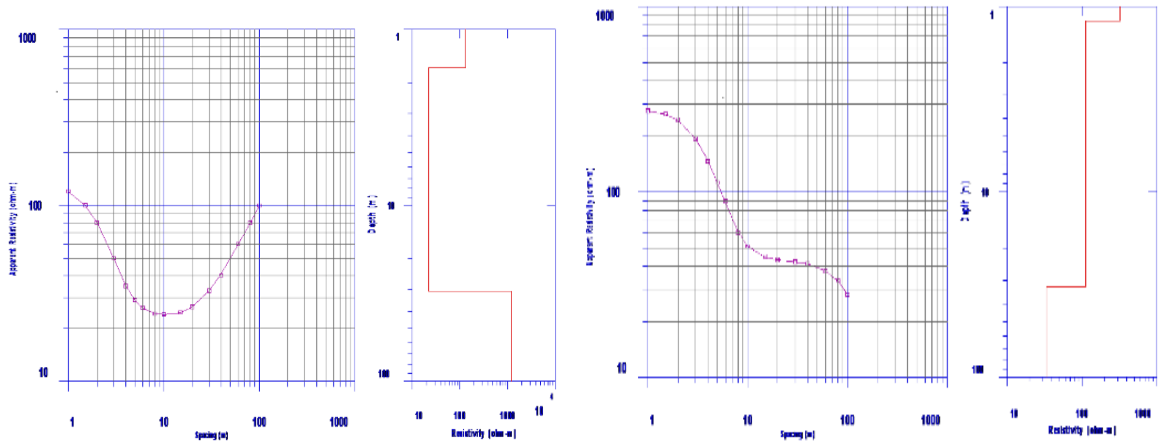
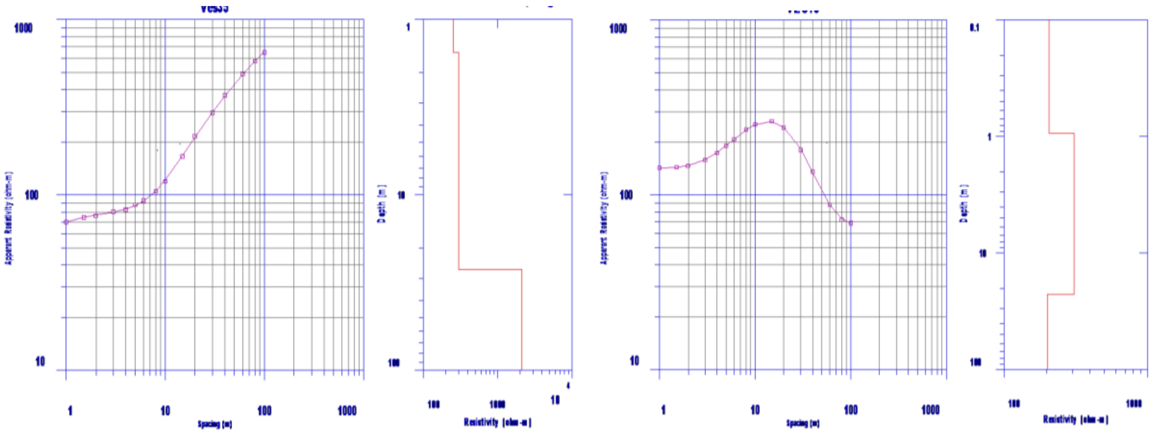


Figure 4(a and b): Typical Examples of H and Q types curves of the Study area



c d

Figure 4 (c and d): Typical Examples of A and K curve types of the Study

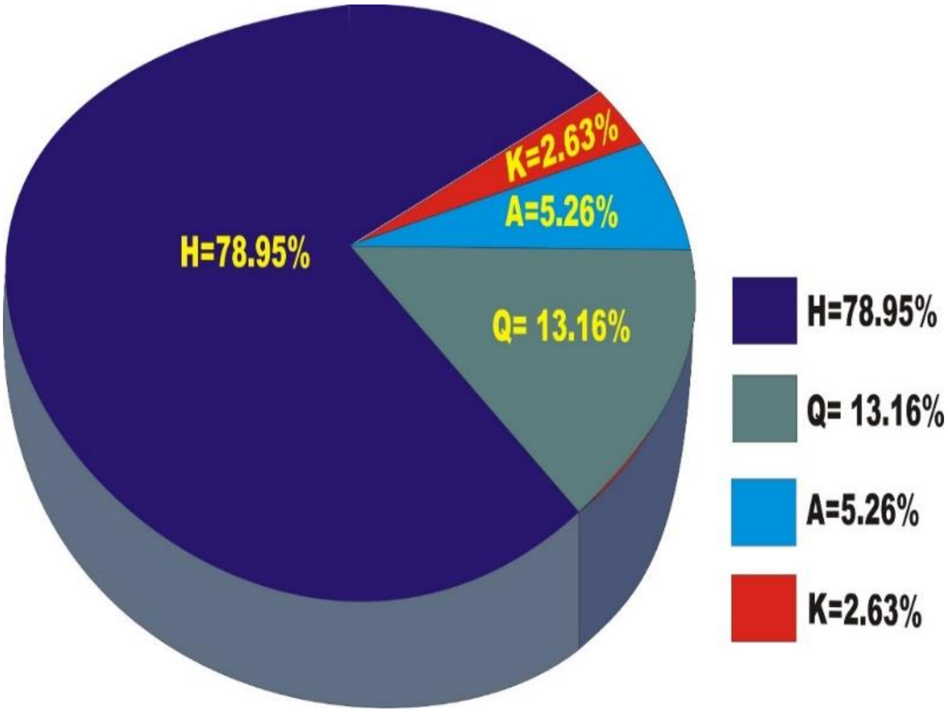


Figure 5: Piechart Showing the Distribution of Various curve Types in the Study Area

Table 2: Result obtained From Computed Output of the Thirty Eight (38) VES showing resistivities, thicknesses, fitting errors and their corresponding curve types In Boi and Environs

VES	**Coordinates**		**Thickness of Layers(meters)**		**Resistivity of Layers(Ohms-meter)**			**Fitting Error (%)**	**Curve Type**
	Northing	**Easting**	**H1**	**H2**	**ρ_1**	**ρ_2**	**ρ_3**		
1	9.61557	9.50278	0.70	23.70	128.96	40.10	1214.70	0.77	H
2	9.60222	9.50278	1.53	24.45	284.07	37.61	1211.21	0.28	H
3	9.58640	9.50116	2.28	30.42	601.26	138.16	1000.33	0.88	H
4	9.57502	9.50556	0.98	8.05	775.84	92.99	1384	0.29	H
5	9.55613	9.50029	1.70	25.67	999.71	35.52	238.85	0.83	H
6	9.53556	9.50500	1.31	27.31	592.23	130.65	1546	0.27	H
7	9.51722	9.50419	0.94	21.12	394.92	144.82	1043.75	0.93	H
8	9.51945	9.51891	0.86	22.53	119.80	42.51	1151	0.36	H
9	9.53278	9.52780	1.43	29.26	111.58	23.75	1100	0.37	H
10	9.54722	9.52001	2.86	26.60	556	51	1331	0.63	H
11	9.56419	9.52500	0.98	23.55	342.67	106.82	1096	0.39	H
12	9.58194	9.51889	0.99	21.31	263.40	139.35	59.79	0.34	Q
13	9.59778	9. 53057	0.93	21.65	206	308.42	201	0.73	K
14	9.61613	9.53001	1.55	6.35	758.72	83.87	1000.50	0.36	H
15	9.61641	9.54835	1.64	29.23	576.20	14.43	1231	0.80	H
16	9.59169	9.54445	0.91	23.00	227.60	77.97	1327	0.90	H
17	9.56947	9.55001	1.80	26.99	81	26.60	1821	0.81	H
18	9.55056	9.54445	1.84	16.64	100	15	1220.80	0.39	H
19	9.51778	9.54168	0.57	17.95	1679	126.60	1039.01	0.44	H
20	9.51969	9.55835	1.55	15.57	563.43	77.26	200	0.39	H
21	9.54723	9.56336	0.71	26.30	413.38	106.93	1060	0.35	H
22	9.55836	9.55807	0.70	8.29	265.34	93.60	208	0.98	H
23	9.58362	9.55280	2.64	26.65	371.81	169.47	280	0.84	H
24	9.59446	9.56389	1.52	25.87	126.77	22.13	10.80	0.61	Q
25	9.60280	9.56058	0.56	9.08	243.95	200	1118	0.90	A
26	9.61667	9.57502	1.14	27.51	507.87	25.59	1254	0.47	H
27	9.60135	9 58278	0.57	28..60	323.43	55.24	1380	0.77	H
28	9.58611	9.57502	1.77	29.30	264.21	18.45	1080	0.70	H
29	9.57502	9.57529	0.85	10.00	211.13	129.66	55.32	0.89	Q
30	9.55694	9.58002	0.93	18.94	100	34.23	1393	0.37	H
31	9.53362	9.57808	1.19	31.08	526.97	112.04	33.91	0.95	Q
32	9.51806	9.58612	1.34	4.30	590.86	13.43	1618	0.97	H
33	9.53308	9.59751	1.25	5.36	326.86	17.64	1100	0.37	H
34	9.53558	9.59722	1.03	8.44	281.97	217.68	12.38	0.21	Q
35	9.55417	9.59752	1.54	25.08	557	300	1019.2	0.90	A
36	9.57503	9.59723	3.60	13.59	364.88	113.49	1094.	0.65	H
37	9.59444	9.59919	1.03	30.34	113.35	10.62	1250	0.70	H
38	9.61113	9.59946	2.47	17.37	455.20	147.11	1500	0.90	H
Mean			1.37	20.85	363.35	96.07	12488.58	0.67	

Iso-resistivity Maps

An Iso-resistivity map is a map that links points of equal electrical apparent resistivity. This was prepared for AB/2 = 60 m and AB/2 = 100 m. Iso-resistivity contour maps were displaying the resistivity values acquired from sounding curves at a consistent electrode spacing for all sounding places$\frac{AB}{2}$ = 60 m, and $\frac{AB}{2}$ = 100 m and the contours of spots with similar resistivity values were created. Thus, indeed a qualitative interpretation that shows the change in resistivity at a specific electrode spacing but only shows the overall lateral variation in electrical characteristics in the area.

Iso-resistivity for AB/2 = 60m

The resistivity values shown here range from 150 Ωm to 850 Ωm (Figure 6). At AB/2 = 60 m the probable depth of investigation could be from the depth of 15m- 30m. The map reveals the heterogeneity in the composition of the subsurface. High resistivity values discovered along with the Northwestern and Northeastern parts of the study area, while the low resistivity values found along the Southeastern, area's southwestern and central part of the area. The anomaly zones may be discovered in the northern section of Boi, Ndukum, Jolong, Lusa Jeji and Lusa.

Iso-resistivity for AB/2 = 100m

This shows resistivity values between 150 Ωm to 1050 Ωm correspond to the depth of 25 m-33 m. The map revealed heterogeneity of the ground, whose composition varies. The Southeastern and Northeastern, north, northwest, and southwest parts of the study region have high resistivity values, while the north, northwest, and southwest parts have low resistivity values (Figure 7).The anomalous zones were seen at with a length of km and width of 8 km extend to Ndukum. In the northern part of Boi, measuring 3.5 kilometres in length and 2 kilometres in width, and in Lusa, measuring 3.2 kilometres in length and 1.1 kilometres in width, and in the western part of Ndukum, measuring 4 kilometres in length and 1.1 kilometres in width, respectively.

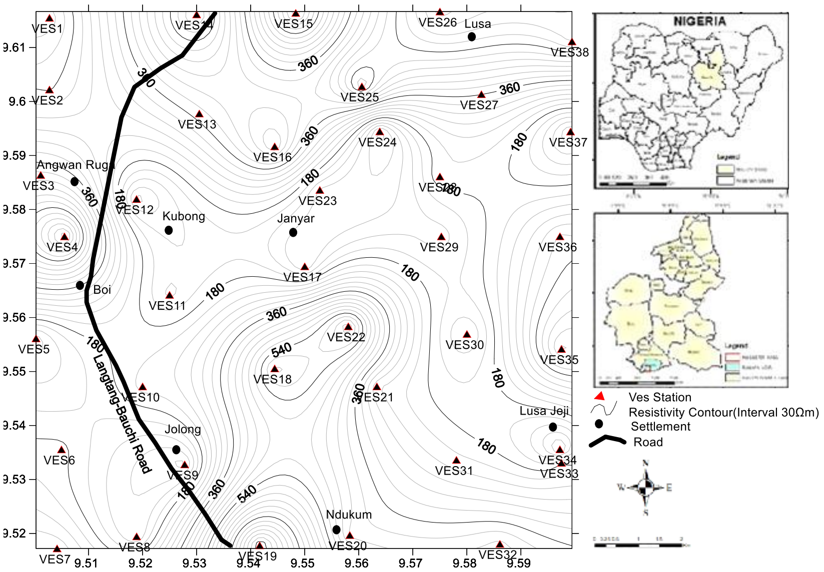


Figure 6: Iso Resistivity Map for AB/2= 60m of Boi and Environs

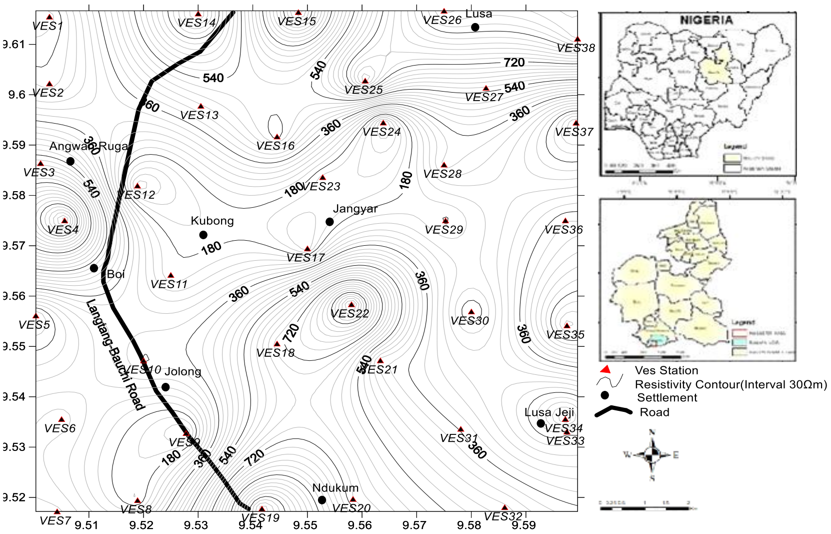


Figure 7: Iso-resistivity Map for AB/2 = 100 m of Boi and Environs (Contour Interval 30Ωm)

Geoelectrostratigraphic Sections

Geoelectric sections were prepared using the VES interpretation results. These sections developed through the interpretation of data from several VES stations located along the sections. To obtain each section first the maximum length of each profile taken and drawn to scale both vertical and horizontal scales as shown in each section, the position of each VES point was then marked out using station intervals, then resistivity boundaries beneath each VES station were located along with their thickness drawn. There are three sections in all. The topsoil, laterite, weathered layer/fractured basement, and fresh bedrock all identified as geoelectric subsurface layers in the geoelectric sections.

Geo-electric Section along with profile A-A¹

Three geoelectric layers discovered in this region: topsoil or laterite, weathered/fractured basement, and fresh basement (Figure 8). Topsoil has a resistivity of 113.35 Ωm to 264.21 Ωm and a thickness of 0.56 m to 3.77 m, while laterite has a resistivity of 576.20 Ωm to 758.72 Ωm and a thickness of 1.93 m to 3.47 m. The resistivity of the weathered/fractured basement ranges from 10.62 Ωm to 200 Ωm, while the thickness varies from 2m to infinite depth. The resistivity of the fresh bedrocks ranges from 1000.33 Ωm to 1250 Ωm, while the thickness varies from 6.35 m to infinite depth. There are three levels on each of the VES points in the section are VES 3, VES 14, VES 15, VES 25, VES 24, VES 28, and VES 37 are among them(Figure 1).

Profile B-B¹ Geo-electric Section

The topsoil or laterite, weathered/fractured basement, and fresh basement were all visible in this geo-electric segment (Figure 9). The resistivity of the topsoil varies from 81 Ωm to 211.12 Ωm and its thickness ranges from 1.56 to 2.84 metres. Laterite has a resistivity range of 564.88 Ωm to 999.71 Ωm and a thickness range of 2.54 to 3.86 metres. The resistivity of the weathered/fractured basement ranges from 26.60 Ωm to 238.85 Ωm, with a thickness of 2.22 m to infinite depth, whereas the resistivity of the fresh basement ranges from 1094.70 Ωm to 1821 Ωm, with a thickness of 4.64 m to infinite depth. VES 36 discovered to have the least depth to the fresh basement. The VES on the section are VES5, VES0, VES17, VES29 and VES36 (Figure 1).

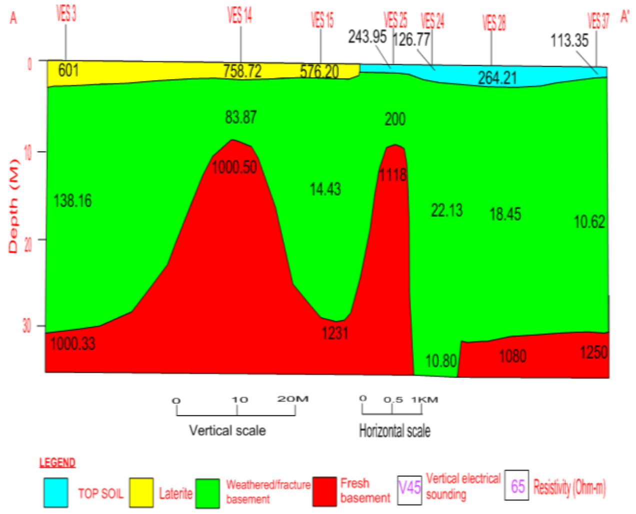


Figure 8: Geoelectro stratigraphic Section along profile A-A¹ of the Study Area

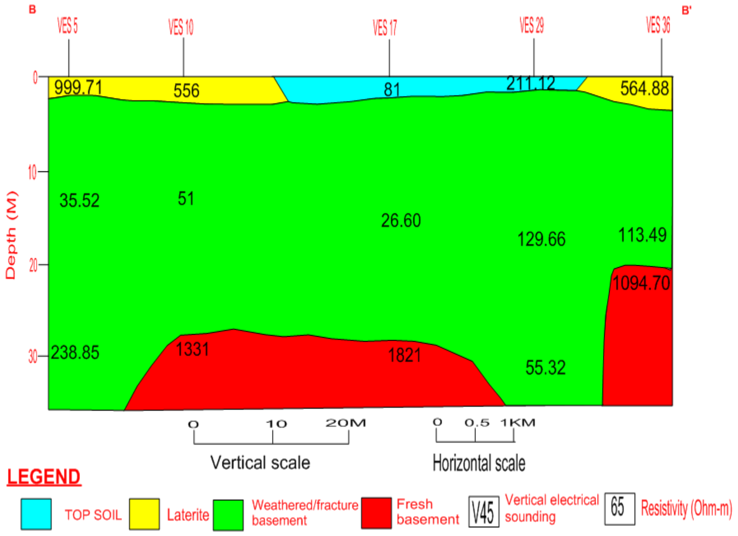


Figure 9: Geoelectro stratigraphic Section a long profile B-B¹ of the Study Area

Profile C-C¹**Geoelectric Section**

Three geoelectric layers discovered in this section: topsoil or laterite, weathered/fractured basement, and fresh basement (Figure 10). Topsoil with resistivity value of 111.58 Ωm and a thickness of 2 m - 2.34 m, laterite has a resistivity range of 526.86 Ωm to 1679 Ωm and a thickness of 1.57 m to 2.55 m, weathered/fractured basement has a resistivity range of 12.38 Ωm to 217.68 Ωm and a thickness of 2.30 m to infinite depth, and the fresh basement has a resistivity range of 1039 Ωm to 1500 Ωm. The VES points on this section are VES6, VES9, VES19, VES20, VES3 and VES34 (Figure 1).

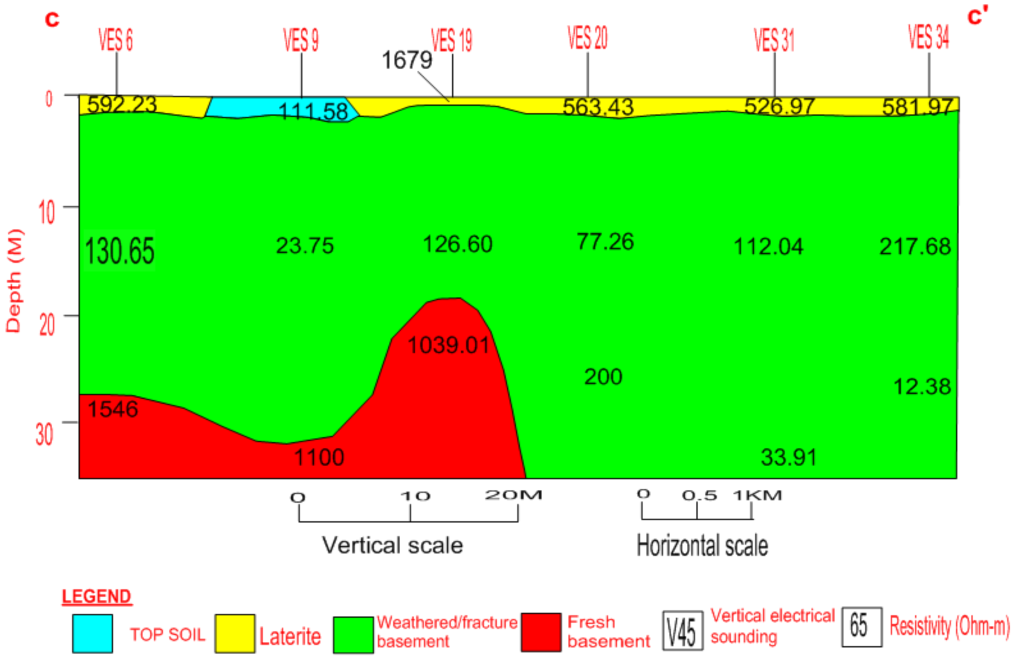


Figure 10: Geoelectro stratigraphic Section along profile C-C^1 of the Study Area

Assessment of Aquifer Protective Capacity

According to Olusegun *et al.* 2016 and Aina *et al.* 2019, the protective capacity in the study area has a poor, weak, and moderate capacity rating (Table 3). The research area's aquifer protective capacity calculated using the parameters such as, longitudinal conductance (S) and transverse resistance (T), as well as the aquifer protective capacity rating in Table 4. Changes in longitudinal conductance from one VES point to the next indicated that the total thickness of low-resistivity materials had changed (Worthington 1977; Glain 1979). Total longitudinal conductance is one of the geoelectrical properties used to determine target locations for groundwater potentials (S). Low T values indicate low-resistivity formations (such as clayed soil) and a shallow basement, whereas higher T values indicate high-resistivity formations and a deeper basement. Total longitudinal conductance is one of the geoelectrical properties used to determine target locations for groundwater potentials (S). Low T values indicate low-resistivity formations (such as clayed soil) and a shallow basement, whereas higher T values indicate high-resistivity formations and a deeper basement. Particularly high transverse resistance values correspond to very resistive subsurface deposits. The direction of groundwater flow in the aquifer can also be determined using transverse resistance values. One of the geoelectric characteristics used to define the biggest area of groundwater potential is total transverse resistance (T). It has a direct relationship with transmissivity, with the greatest (T) values most likely reflecting the highest transmissivity values of the aquifers or aquifer zones, and vice versa (Olusegun *et al.*, 2016). Overburden materials in the research area had longitudinal unit conductance values ranging from 0.089 to 2.86 Siemens (Table 4). Eight (8) VES stations have a low protective capacity rating, seven have a weak protective capacity rating, and twenty-three have a medium protective capacity rating. Around 60% have a moderate protection capacity rating, whereas 18% have a weak protective capacity rating and 22% have a bad protective capacity rating. The research region's longitudinal unit conductance and transverse resistance maps, shown in Figures 11 and 12, reveal that the northeastern and northwestern parts of the study area have moderate protective capacity, indicating that precipitation infiltration is minimal.

Table 3: Showing aquifer protective capacity rating (Olusegun *et al.* 2016)

Rating	Remarks
Greater than 10	Excellent
5–10	Very good
0.2–4.9	Moderate
0.1–0.19	Weak
Less than 0.1	Poor

Table4: Longitudinal unit Conductance, Transverse resistance and Aquifer protective capacity of the study area.

VES	**Coordinates**		**Longitudinal Conductance(Siemens)**	**Transverse Resistance (ohms-meter)**	**Overburden's aquifer protective capacity rating**
	Northing	**Easting**			
1	9.61557	9.50278	0.59	950.37	Moderate
2	9.60222	9.50278	0.65	919.56	Moderate
3	9.58640	9.50116	0.22	4202.83	Moderate
4	9.57502	9.50556	0.087	748.57	Poor
5	9.55613	9.50029	0.72	911.8	Moderate
6	9.53556	9.50500	0.21	3568.05	Moderate
7	9.51722	9.50419	0.15	2058.6	Weak
8	9.51945	9.51891	0.53	957.75	Moderate
9	9.53278	9.52780	1.23	694.93	Moderate
10	9.54722	9.52001	0.52	1326	Moderate
11	9.56419	9.52500	0.22	2526.29	Moderate
12	9.58194	9.51889	0.15	2968.48	Weak
13	9.59778	9. 53057	0.070	6677.29	Poor
14	9.61613	9.53001	0.076	532.57	Poor
15	9.61641	9.54835	2.03	421.79	Moderate
16	9.59169	9.54445	0.29	1793.31	Moderate
17	9.56947	9.55001	1.01	717.93	Moderate
18	9.55056	9.54445	1.12	249.6	Moderate
19	9.51778	9.54168	0.14	2272.47	Weak
20	9.51969	9.55835	0.20	1202.94	Moderate
21	9.54723	9.56336	0.25	2812.26	Moderate
22	9.55836	9.55807	0.089	775.94	Poor
23	9.58362	9.55280	0.16	4516.38	Weak
24	9.59446	9.56389	1.17	572.5	Moderate
25	9.60280	9.56058	0.12	4816	Weak
26	9.61667	9.57502	1.08	614.42	Moderate
27	9.60135	9 58278	0.51	703.98	Moderate
28	9.58611	9.57502	1.05	356.09	Moderate
29	9.57502	9.57529	0.077	1296.6	Poor
30	9.55694	9.58002	0.55	629.83	Moderate
31	9.53362	9.57808	0.028	3482.2	Poor
32	9.51806	9.58612	0.32	57.75	Moderate
33	9.53308	9.59751	0.30	94.55	Moderate
34	9.53558	9.59722	0.039	1837.22	Poor
35	9.55417	9.59752	0.084	7524	Poor
36	9.57503	9.59723	0.12	1542.33	Weak
37	9.59444	9.59919	2.86	322.21	Moderate
38	9.61113	9.59946	0.12	2630.33	Weak

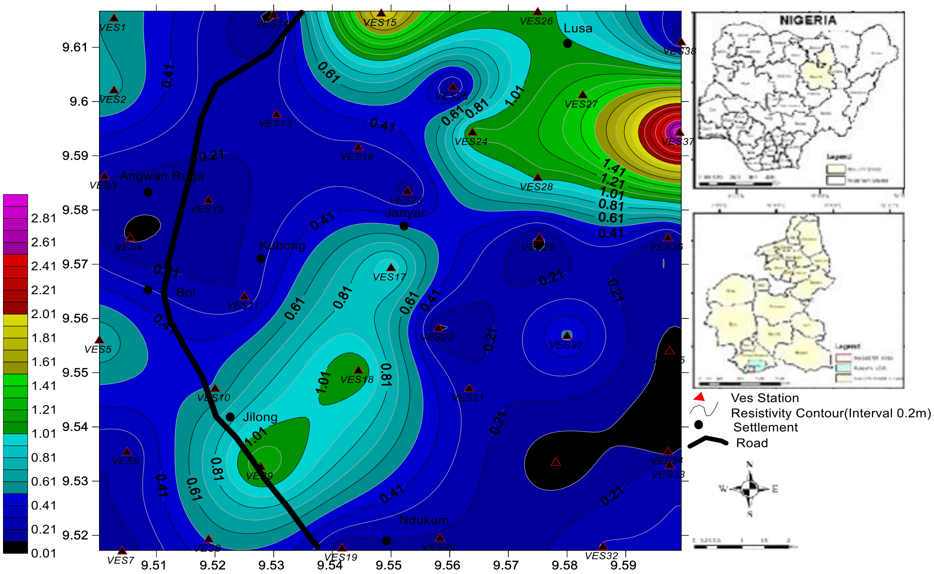


Figure 11: The Longitudinal conductance map of the Study Area

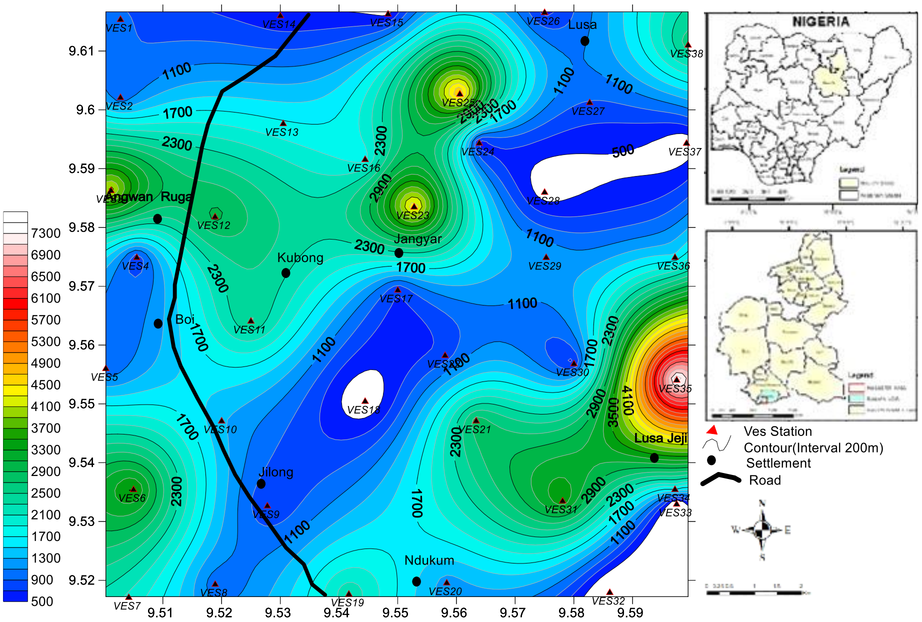


Figure 12: The Transverse resistance map of the Study Area

Assessment of Groundwater Potential

Figures 13 and 14 depict the study area's reflection coefficient and overburden thickness map. In the studied area, the reflection coefficient ranges from 0.894 to 0.958. (Table 5). The study area's groundwater possibilities divided into three categories: high, medium, and low. In this study, zones where the overburden thickness is >13 m and the reflection coefficient is <0.8 are considered as zones with high groundwater potential, while zones with overburden thickness <13 m and reflection coefficient <0.8 are considered as zones having very low groundwater potential (Aina *et al*, 2019). In general, about 18% of the study area has high groundwater potential, which is mostly restricted to areas underlain by biotite granite and granite gneiss, while 40% of the study area has medium groundwater potential; additionally, 24% of the area has low groundwater potential, and 18% has very low groundwater potential. This finding invariably highlights the importance of conducting a thorough groundwater survey and exploration in the research area in order to identify potential productive boreholes locations.

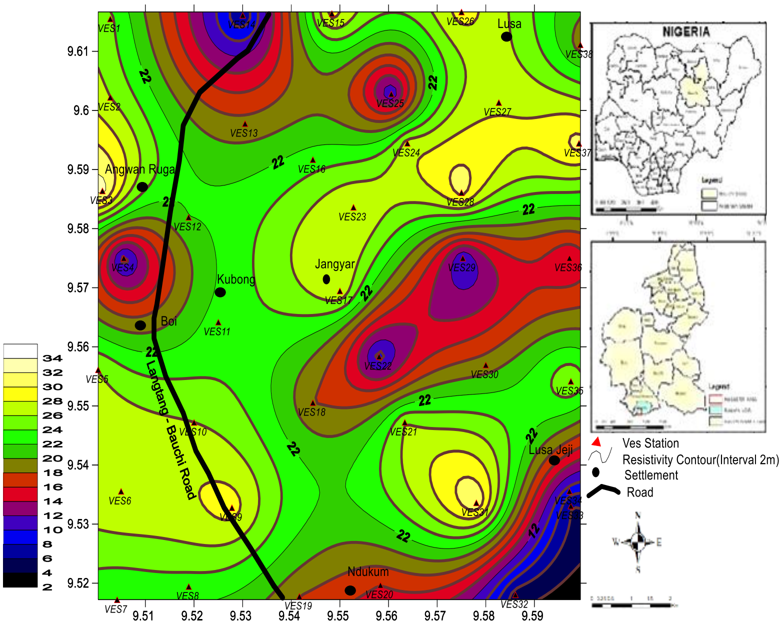


Figure 13: The Iso patch map showing overburden thickness of the Study Area

Reflection coefficient

Table 5 shows the values of the study area's reflection coefficient (RC). Water potential is strong in areas with low reflection coefficient values. It is a measurement of an area's degree. The bedrock interface coefficient is a critical metric for determining whether a bedrock fracture filled with water fractures (Olusegun *et al.,* 2016). For these parameters to be considered, they must have a direct association with the reflection coefficient value, except for VES 12, 13, 24, 29, and 34, which had values of 0.400, -0.211, -0.343, -0.402, and -0.894, the reflection coefficient values for this study range from 0.246 to 0.952 for all VES locations. The reflection coefficient and resistivity contrast values exhibited a linear connection for the majority of the locations investigated in this study. As a result, the parameter might be deemed a good factor for borehole development when combined with other parameters (Olusegun *et al*., 2016).

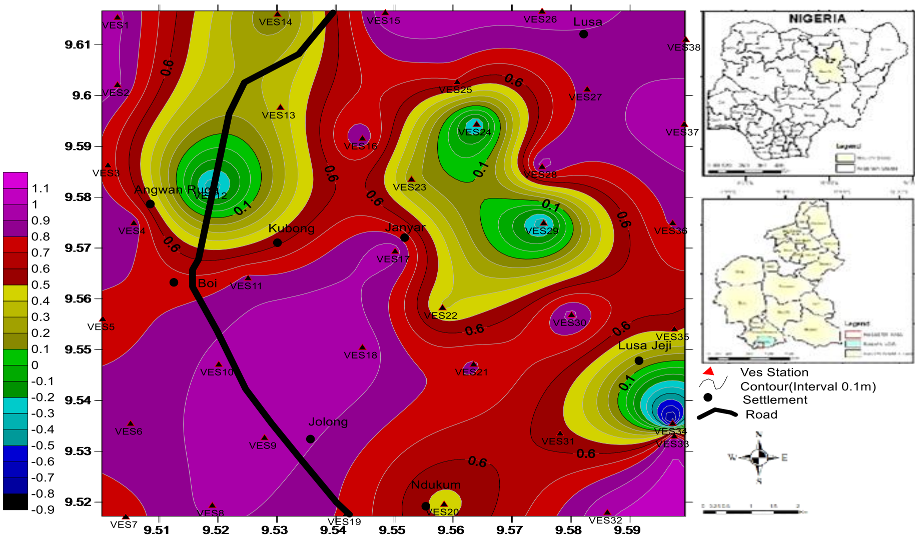


Figure 14: The Reflection coefficient map of the Study Area

Resistivity contrast

Measurements of resistivity contrast can reveal a location's groundwater potential (Olusegun et al. 2016). In this study, the resistivity contrast values range from 0.31 to 120.47. (Figure15). VES 32 and 37, according to the research, have the greatest potential for groundwater exploration (Table 5).

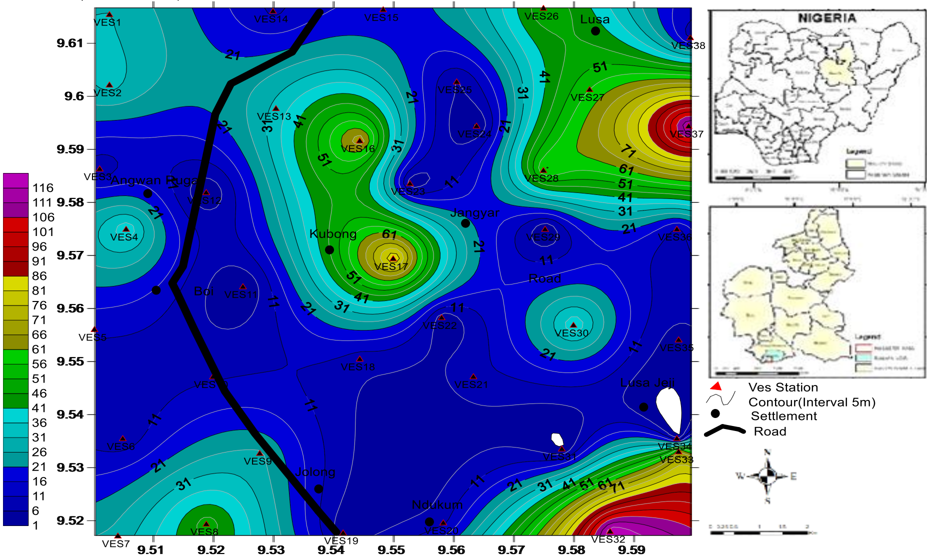


Figure 15: The Resistivity contrast map of the Study Area

Groundwater Flow Directions

The hydraulic head map for the area created by connecting sites with equal hydraulic heads and drawing right-angled Piezometric lines to depict the areas of groundwater flow direction. Regional groundwater from the recharge area around Angwan Ruga in the northwest flows towards Ndukum and Boi areas in the south and southwest, according to the hydraulic head map of the distribution of the study area (Fig. 16). Another recharging zone found in the northern part of the area, and it flows northeast to Lusa. The second discharge area is the Ndukum area in the south. The research area's highest hydraulic head discovered in the northern and northwest sections, with some locations in the middle and southern sections. While the research region's lowest hydraulic heads identified in the southwest, some discharge zones were also found in the northeastern, mid, and southern parts of the study area, respectively.

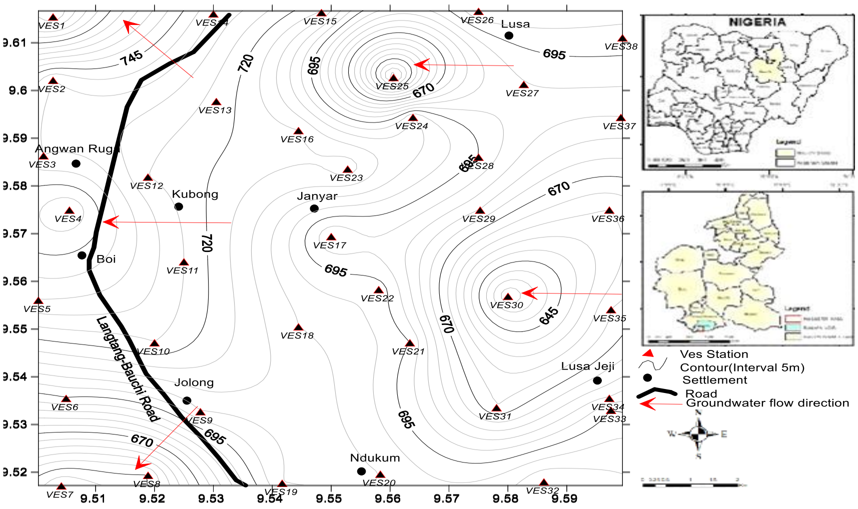


Figure 16: Hydraulic Head Distribution of the Study Area

Table 5: Groundwater potential across the VES locations in the study area

VES	**Coordinates**		**Overburden Thickness(m)**	**Reflection Coefficient**	**Resistivity Contrast**	**Groundwater yield**
	Northing	**Easting**				
1	9.61557	9.50278	24.4	0.936	31.07	High
2	9.60222	9.50278	26.0	0.931	33.08	High
3	9.58640	9.50116	33.0	0.758	7.29	High
4	9.57502	9.50556	9.0	0.874	40.09	Low
5	9.55613	9.50029	26.0	0.741	11.93	Medium
6	9.53556	9.50500	28.0	0.844	7.26	High
7	9.51722	9.50419	22.0	0.756	27.73	Low
8	9.51945	9.51891	23.0	0.929	48.94	Medium
9	9.53278	9.52780	29.0	0.958	26.62	High
10	9.54722	9.52001	26.0	0.926	10.36	Medium
11	9.56419	9.52500	23.0	0.822	0.43	Medium
12	9.58194	9.51889	22.0	-0.400	0.65	Very Low
13	9.59778	9. 53057	22.0	-0.211	11.92	Very Low
14	9.61613	9.53001	6.0	0.091	9.66	Very Low
15	9.61641	9.54835	29.0	0.977	17.24	Medium
16	9.59169	9.54445	23.0	0.892	70.04	Medium
17	9.56947	9.55001	28.0	0.971	87.20	Medium
18	9.55056	9.54445	18.0	0.976	8.27	Medium
19	9.51778	9.54168	18.0	0.783	2.59	Low
20	9.51969	9.55835	16.0	0.443	10.01	Low
21	9.54723	9.56336	26.0	0.817	10.09	Medium
22	9.55836	9.55807	9.0	0.379	2.26	Very Low
23	9.58362	9.55280	28.0	0.246	1.65	Low
24	9.59446	9.56389	27.0	-0.343	0.51	Very Low
25	9.60280	9.56058	10.0	0.697	5.59	Low
26	9.61667	9.57502	29.0	0.960	50.97	Medium
27	9.60135	9 58278	29.0	0.926	25.56	Medium
28	9.58611	9.57502	31.0	0.966	61.89	High
29	9.57502	9.57529	10.0	-0.402	0.43	Very Low
30	9.55694	9.58002	19.0	0.952	40.69	Medium
31	9.53362	9.57808	32.0	0.535	0.31	Low
32	9.51806	9.58612	5.0	0.984	120.47	Low
33	9.53308	9.59751	6.0	0.968	68.75	Low
34	9.53558	9.59722	9.0	-0.894	0.06	Very Low
35	9.55417	9.59752	26.0	0.545	3.41	Medium
36	9.57503	9.59723	14.0	0.817	9.77	Medium
37	9.59444	9.59919	31.0	0.983	117.70	High
38	9.61113	9.59946	19.0	0.820	8.22	Medium

CONCLUSION

The electrical resistivity sounding method with the Schlumberger array design used to explore the study area. The investigation analyze the area's groundwater potential in Boi and its environs, Bogoro Local Government Area, Bauchi State, Nigeria. The results provide details on the formation parameters. There were 38 vertical electrical soundings dispersed across the area during the investigation. Three geoelectric layers discovered from the findings. The curves obtained are mostly of the H, Q, A, and K types, which are common in the Basement Complex terrains. The following formation parameters investigated longitudinal conductance, transverse resistance, reflection coefficient, resistivity contrast, and formation resistivity. The layers' mean resistivity values are ρ_1 = 363.35 Ωm, ρ_2 = 96.07 Ωm, ρ_3 = 12488.58Ωm and their corresponding mean thickness are H_1 = 1.37 m and H_2 = 20.85 m. The mean values of each layer's longitudinal conductance $S_1 = 6.1x10^{-3}$ Siemen $S_2 = 4.6x10^{-1}$Siemen and their transverse resistance values to be $T_1 = 1171.73Ωm$, $T_2 = 1819.22$ Ωm. The most of the studied areas exhibited a shallow aquifer level. According to the results of these evaluated parameters, the area has a good to moderate groundwater potential. The numerous cases of failed/aborted boreholes in the area could be linked to a variety of reasons, including poor data quality, a lack of technical expertise, incorrect point selection, and poor drilled hole development, all of which are common in Basement Complex terrains. Particularly anthropogenic pollutants heavily polluted the data from VES 5 and 10 showed a dramatic decline in resistivity, which could indicate that the area,, or that it was an ancient dump site.

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