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On the use of electrical resistivity method in mapping potential sources and extent of pollution of groundwater systems in Lapai Town, Niger State, Nigeria

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Abstract: Electrical resistivity method employing the Schlumberger array was used to occupy forty four (44) vertical electrical sounding points in Lapai town with the aim of determining the depth to aquifers, aquifer thicknesses and aquifer protective capacity. The G41 Geotron resistivity meter was used in obtaining the apparent resistivity data which was processed using Interpex 1XD resistivity interpretation software. The results revealed four lithologic sections which include top lateritic soil, sandy clay, fractured basement and fresh basement. Both confined and unconfined aquifers were identified within the area, with four classes of aquifer proactive capacities as high, moderate, weak and poor. While the aquifer at VES 20 was highly protected, twenty other aquifers were moderately protected, eight others had weak protection and fifteen aquifers were poorly protected. The aquifers were generally of good thicknesses and at varying reasonable depths, making them good reservoirs of water in appreciable quantity. The average aquifer thickness was estimated to be 48.36m while the average depth to aquifers was estimated to be 56.68m

Keyword : Aquifers, resistivity, protective capacity, Transmissivity and Conductance.

1. Introduction

Lapai town is the headquarters of Lapai Local Government Area of Niger State. It has an area of 3,051 km^2 and a population of 110,127 at the 2006 census (Lapai, 2020). The town houses the state University, Ibrahim Badamasi Babangida University that has students' population of over 10,000, more than 1,000 employees, over 50% of whom reside in Lapai with their families. As a result, there is an increased influx of people to the town for business opportunities.

The town has only one seasonal stream which goes round the township up to halfway of the town's circumference. Due to uncontrolled refuse dump, the stream is highly polluted making the water from the stream unsafe for domestic and Agricultural uses. The only source of potable drinking water is through borehole drilling into underground water bodies.

Water is an essential commodity that sustains all living things. There are many sources of water including rain, well, river, stream, groundwater, etc. A large portion of the world's fresh water resides underground, stored within cracks and pores in the rock that make up the Earth's crust. Groundwater is seen as liquid flowing through shallow aquifers, but it can also include soil moisture, permafrost, immobile water in very low permeability bedrock and deep geothermal or soil formation water. In recent times, attention has shifted to the use of groundwater to meet the need for water supply, since most surface and shallow water bodies have been polluted. Groundwater is often withdrawn for agricultural, domestic and industrial use; however, the heavy concentration on its usage has become a source of concern to hydrologists. The extreme use of groundwater resources can raise concerns such as uplifting and seismic activities, ecological environment deterioration, land subsidence, vegetation degradation of livelihoods for rural poor, and food security implications. In view of the shrinking groundwater resources, it is important to develop effective techniques and methods to study the trend of groundwater storage (increase/decrease) and its recharge-discharge relationship, which can support the mitigating measures of over pumping shallow groundwater to ensure the sustainable utilization of groundwater resources (Muhammad et al., 2020).

Due to increasing urbanization, surface water and groundwater resources are prone to over contamination and more stringent treatments would be required to make them potable. Studies of physico-chemical characteristics of underground water are often required to find out whether it is fit for drinking or some other beneficial. According to Environmental protection Agency (EPA, 2018), stressors that affect groundwater condition include application of pesticides and fertilizers to the land, waste from livestock and other animals, landfills, mining operations, and unintentional releases such as chemical spills or leaks from storage tanks. Some groundwater has high levels of naturally occurring dissolved solids (salinity), or metals such as arsenic found in natural rock formations.

There are a good number of water banks in close proximity to Lapai town. Prominent among them are the Agaie/Lapai Dam at Bakajeba over Ebba River and the Gurara River, which is a tributary of the Niger River. Another river is located in Badeggi, a town about 55km away from Lapai along Bida road. It is a tributary of River Kaduna. The Baro Sea Port is about 60km south of Lapai. The following surface water streams and Rivers are found within and around Lapai: River Dambugi, River Makara, River Etwanyagi, River Vudi, River Shekai and River Shikugi amongst others. Given this number of rivers around Lapai, one would conclude that there should be adequate supply of potable water to Lapai metropolis and its environs. But what we witness is that many water projects such as Agaie/Lapai Dam, Gurara and Baro water projects are abandoned. The only public water supply agency has in Lapai Town has remained moribund over the years and the open streams are continuously being contaminated by indiscriminate refuse disposal mechanisms.

The rapid growth in the population of Lapai town occasioned by the presence of the Ibrahim Badamasi Babangida University which attracts students, workers and business-minded people in thousands every year, has led to over dependence on borehole as the only dependable source of potable water. There is therefore, the need to explore for more sources of potable water and then study the likelihood of contamination of this natural resource in Lapai town and its environs. The rapidly growing population leading to high dependence on this essential commodity coupled with illegal disposal of effluents therefore portends a serious danger on the existing sources of groundwater.

As a matter of fact, groundwater contamination is a global problem that has a significant impact on human health and ecological services (Li et al., 2021). Organic pollutants, including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) are common contaminants of anthropogenic origin in groundwater that could cause serious health problems. The Ololade et al., (2021), investigated PAHs and PCBs in groundwater near selected waste dumpsites located in two southwestern states in Nigeria. They found that the more water-soluble, low molecular weight-PAHs accounted for more than 61% of the total PAHs detected across all locations, but surprisingly the more highly chlorinated hexa-PCBs dominated the congener profiles. In a related work, Ambade et al., (2021) investigated the occurrence, distribution, health risk, and composition of 16 priority PAHs in drinking water from southern Jharkhand in the eastern part of India. They found that lower and middle molecular weight PAHs were dominant in groundwater from the study area, but the levels were below concentrations that could constitute a carcinogenic risk.

In their research on A Comparative Investigation of Groundwater Contamination in Typical Dumpsites and Cemetery Using Electrical Resistivity Tomography and Physicochemical Analysis of Water in Benin Metropolis, Idehen (2020), observed the implications of land utilization for burial of dead human bodies in the form of cemeteries and location of refuse dumps as having a significant potential contaminant effect in the environment and especially the groundwater component.

Electrical resistivity methods have been applied for studying variations of resistivity with depth or for lateral variations. These variations arise due to the difference in electrical properties of rocks in the lithologic units of the subsurface and fluid content. The aim of VES survey is usually to obtain true resistivity logs similar to the induction log of a well in the vicinity without actually drilling a hole. The method has remained the most inexpensive of subsurface exploration methods with a very good propensity for noble results thereby making the method very suitable for groundwater exploration.

Geophysical investigations have been carried out in different parts of the world for groundwater investigation. Oni et al., (2020) used magnetic method as a tool in groundwater investigation in a basement complex terrain. Olorunfemi et al., (1999) used the electrical resistivity method in investigation of geo-electric and hydro-geologic characteristics of areas in Southwest Nigeria. Ayolabi, et al., (2009) carried out groundwater investigation at Igbogbo, Lagos, using seismic refraction and electrical resistivity techniques. Osuagwu, (2009), used very low frequency electromagnetic and vertical electrical sounding techniques in delineating aquifer zones in Modeme area, Ife, Osun State. Tsepav et al., (2015) used electrical resistivity method to characterise aquifer precincts in parts of Lapai, North Central Nigeria. Oladipo et al., (2011) in their work titled “Contaminant evaluation of major drinking water sources (boreholes water) in Lapai metropolis,” observed that Lapai and its environs depend solely on spring water, running stream water, private and general boreholes water for drinking and other household usages.

Tsepav and Israel (2011), conducted an investigation on some areas of Ibrahim Badamasi Babangida University, Lapai, using D. C. resistivity method. The survey was aimed at providing information on the groundwater potentials of the areas. It was discovered after analysis, that areas under study have very good groundwater potential. In another related work, Olabode et al., (2015) evaluated groundwater resources of the Middle Niger (Bida) basin. They evaluated the hydrogeological potential of the terrain. A total of about 50 boreholes located in the area were selected for study. In the final analysis, it was discovered that groundwater occurred both in confined and semi-confined conditions and that depth to water rarely exceeds 50m, though in some few cases the depth might be over 70m. On the average, they estimated well yield to vary between 1.08m^3/hr and 19m^3/hr. Obiora et al., (2015) carried out electrical resistivity survey in Makurdi, Benue state capital, north–central Nigeria to evaluate aquifer protective capacity and soil corrosivity of overburden units. Using Winresist software, 3–4 geoelectric layers were obtained and the protective capacities of the study area were classified as 36.67% weak, 10% poor, 40% moderate, and 13.33% as good. The corrosivity ratings of the study area show that 10% is strongly corrosive, 23% moderately corrosive, 37% slightly corrosive, and 30% noncorrosive.

In a related study, Olajide et al., (2020) evaluated the groundwater potential and aquifer protective capacity of the overburden unit in part of Iju, Akure North, Ondo State using integrated geophysical methods involving Very Low Frequency Electromagnetic (VLF-EM) profiling and Vertical Electrical Sounding (VES). Four major traverses were established of varying length extents while forty two Vertical Electrical Soundings were also conducted with half electrode spacing varying between 1 and 100 m and interpretation was done using the partial curve matching techniques and computer aided iteration. Five subsurface geological units were identified consisting of the top soil, lateritic, weathered, partly weathered and fresh basement layers consecutively. The aquifer protective capacity of the study area shows that close to 70 % of the study area fell within the zones of low groundwater potential, 25 % falls within medium potential zones while only 5 % made up the high potential zones while 75 % of the study area constituted the weak to poor protective capacity zones.

The data used in this study was obtained from Lapai town within 5km radius. Thus the result of this work may not be applicable to locations other than this, except where similar conditions prevail. The scope of the study will cover geophysical mapping of good aquifers, depth to aquifer measurements and determination of aquifer protective capacity.

2. Geology of the study area

About ninety per cent (90%) of Lapai is underlain by rocks of the basement complex and about ten per cent (10%) by sedimentary rocks (Obaje et al., 2020). The basement complex rocks occur to the north, south and east of Lapai while sedimentary rocks cover the areas to the West with contact to the basement at the stream valley by the Water Board on the road to Agaie (Fig. 1). These different rock types determine the water table levels, the aquifer systems and the water budget. These variables become more diversified depending on the component of the basement complex and the sedimentary formation that make up the bedrock under study. The bedrock geology of Lapai can further be discussed within the context of the regional geology of Nigeria made up of the Basement Complex, Younger Granites and Sedimentary Basins (Fig. 2).

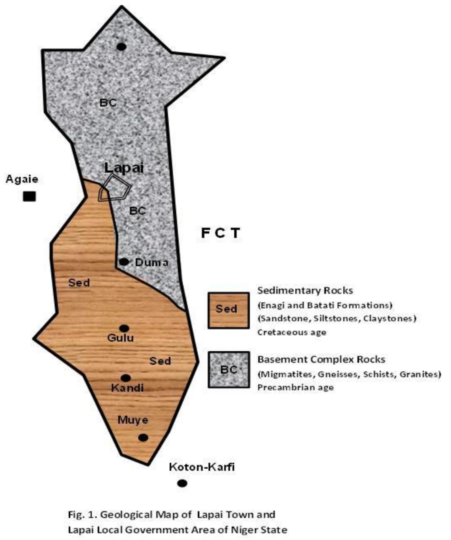


Figure 1. Geological Map of Town and Lapai Local Government area

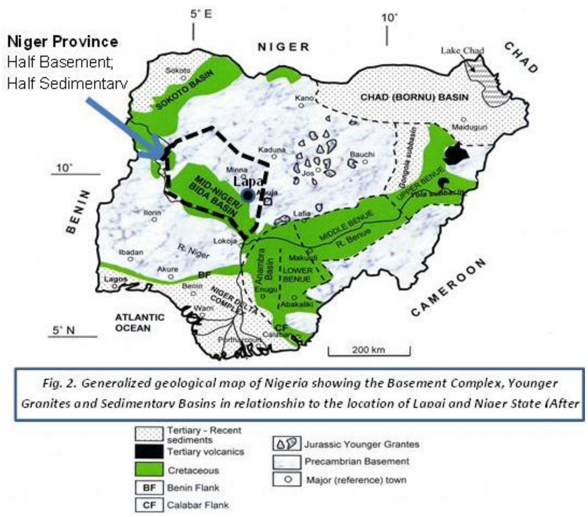


Figure 2. Generalized geological map of Nigeria

2.1. The Basement Complex Rocks

Within the basement complex of Nigeria three major petro-lithological units are distinguishable, namely: Migmatite – Gneisses, Schists, and Older Granites (differentiating them from the Younger Granites concentrated around Jos).

The Migmatite – Gneiss Complex is generally considered as the basement complex sensu stricto and it is the most widespread of the component units in the Nigerian basement It has a heterogeneous assemblage comprising migmatites, gneises, and a series of basic and ultra-basic metamorphosed rocks (Rahaman et al., 2019) and it is the most widespread of the component units in the Nigerian basement Obaje et al., (2019). It has a heterogeneous assemblage comprising migmatites, gneises, and a series of basic and ultra-basic metamorphosed rocks. They generally occur intricately associated with the Older Granites intruding into them and in some places along with schist belts, but chronologically the Migmatite-Gneiss complexes are oldest (older than Schist Belts older than Older Granites). In Lapai area, Migmatite-Gneisses occur to the east and are readily mappable on the road that passes through Gulu Junction (Mararaba) though Kudna to Lambata. Schistose rocks are also very abundant on the same axis. Older Granites dominate the bedrock cover from Lapai central to the north on Lapai – Paiko road.

2.2. Sedimentary Rocks

In Lapai, sedimentary rocks comprising the Bida Sandstone and the Enagi Formation (made up mainly of sandstones, siltstones and claystones) form the bedrock to the west beginning from the stream channel at the Lapai Water Board office. As stated earlier, these rock types (sedimentary) make up only about 10% of the total areal rock cover of Lapai. The sedimentary rocks belong to the larger sedimentary sequences that form the Bida Basin. The Bida Basin itself is a NW-SE trending intracratonic structure extending from slightly south of Kontagora in Niger State in the north to the area slightly beyond Lokoja (Kogi State) in the south. The formations deposited in the Bida Basin comprise the Bida Sandstone at the base, followed successively upward by the Sakpe, Enagi and Batati Formations in the Northern/Central Bida Basin while the Lokoja, Patti and Agbaja Formations constitute lateral equivalents in the Southern Bida Basin (Obaje et al., 2020).

3. Materials and Methods

3.1. Materials

The materials used for the work were G41 Resistivity Meter, non-polarizable electrodes, current and potential cable reels, hammers, measuring tapes, GPS device, recording materials and Interpex 1XD Resistivity interpretation software.

3.2. Theory of Electrical Resistivity

These are based on Ohm's law which holds for simple circuits as well as earth materials through which current flows. When measurements are made over a heterogeneous earth, it is apparent resistivity ρa that is measured. These apparent resistivity values from field observations at various locations, and with various electrode configurations, are used to estimate the true resistivities of the several earth materials present at a site and to locate their boundaries spatially below the surface of the site. The apparent resistivity is expressed as:

$$\rho_a = \frac{K\Delta V}{I} \quad (1)$$

where ΔV and I are voltage drop and current respectively and

$$K = 2\pi\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} - \frac{1}{r_4}\right)^{-1} \quad (2)$$

is the geometric factor which depends on the electrode spacing.

An electrode array with constant spacing is used to investigate lateral changes in apparent resistivity reflecting lateral geologic variability or localized anomalous features while the electrode spacing is varied if the changes in resistivity with depth are to be investigated (Tsepav et al., 2015). The types of electrode arrays that are most commonly used are Schlumberger and Wenner. In each case, direct current is passed into the earth at A and received at B. The potential generated in the earth as a result of this current is measured between the potential electrodes $M$and N as shown in Figure 3.

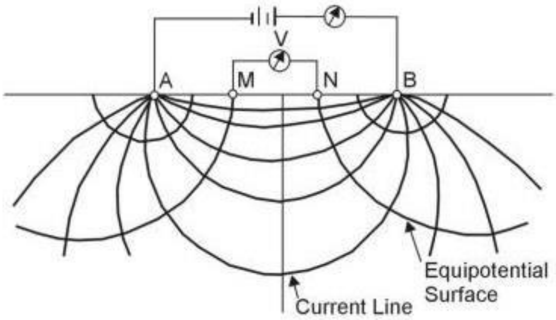


Figure 3. Electrode configuration

3.3. Aquifer Protective Capacity Evaluation

The ability of an earth medium to retard and filter percolating fluid is the measure of its protective capacity (Olorunfemi et al., 1999). The protective capacity of an overburden exerted by retardation and filtration of percolating pollutants is directly proportional to its thickness and inversely proportional to its hydraulic conductivity. As such, clayey material content is generally characterized by low permeability, low resistivity, low hydraulic conductivity and longitudinal unit conductance values. Hence the protective capacity can be considered as being proportional to the longitudinal conductance (S). Therefore, the higher the overburden longitudinal conductance of an area, the higher its protective capacity.

If we have $n-1$ layers overlying a semi-infinite substratum of resistivity ρ_n, the Longitudinal Conductance S is obtained according to Bello et al., (2019) as:

$$S_i = \sum_{i=0}^{n} \frac{h_i}{\rho_i} \text{(Siemens)} \quad (3)$$

where ρ_i and h_i are the layer resistivity and thickness of the i^{th} layer respectively.

The protective capacity (P_c) of an overburden layer is proportional to its longitudinal conductance S, so that:

$$P_c = S$$

According to Bello et al., (2019) when the longitudinal conductance value is greater than 0.7 mhos, the layers are adjudged zones of good protective capacity. The portion where the conductance value ranges between 0.2 and 0.69 mhos is classified as zones of moderate protective capacity. The zones which have conductance value ranging from 0.1 and 0.19 mhos are classified as zones of weak protective capacity and where it is less than 0.1 mhos the areas are considered as having poor protective capacity.

The Dar Zarouk parameter for transverse resistance (R) is expressed by Bello et al., (2019) as:

$$R_i = \sum_{i=1}^{n} h_i \,.\, \rho_i (ohm.m^2) \quad (4)$$

where p_i is the layer resistivity and h_i is the thickness of the ith layer.

Transverse resistance is numerically equal to the transmissivity, T. If the transverse resistance values are >400 Ωm^2 and correspond to zones where the thicknesses and resistivities of the aquifer are large, the aquifer materials are highly permeable to fluid movement within the aquifer, which may possibly enhance the migration and circulation of contaminants in the groundwater aquifer (Bello et al., 2019).

3.4. Field Procedure

The preliminary field techniques involved clearing of profiles, measurements and pegging at prospective electrode points. The G41 Geotron Resistivity Meter was used for data collection, while a global positioning system (GPS) device model 60Cx was used to obtain the coordinates of each VES point. Direct current was introduced into the ground through a pair of steel, non-polarizable electrodes driven into the ground. Two potential electrodes closely spaced and symmetrical about the sounding point were sandwiched by two current electrodes.

Measurements of the apparent resistivity values were then read off from the equipment at each potential and current electrode spacing, at the lowest standard deviation. To increase the depth of investigation, the current electrode separation was increased while the potential separation remained constant. The potential electrodes were however changed whenever a loss in sensitivity was noticed and measurements repeated for the same current spacing.

With the use of Schlumberger electrode spacing, forty four (44) VES stations were occupied and the apparent resistivity data so obtained were plotted against half electrode separation on a logarithmic scale and interpreted quantitatively using the interpex 1xD sounding interpretation software which provides an automatic means of analyzing and determining models.

4. Results and Discussion

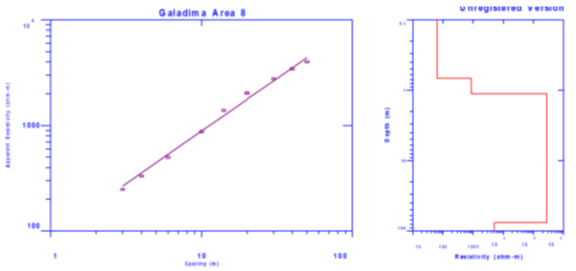
The quantitative treatment of the vertical electrical soundings provided geoelectric information characterized by the values of resistivity and thickness. These geoelectric parameters defined the geoelectric model.

VES 1 – 4 were obtained in Magaji area of Lapai while VES 5 – 8 and 9 – 12 were respectively obtained from Galadima and Kure areas. VES 13 – 16 were situated in Mararaba area with VES points 17 – 20 located in Lapai Market while IBB University contributed VES points 21 – 44.

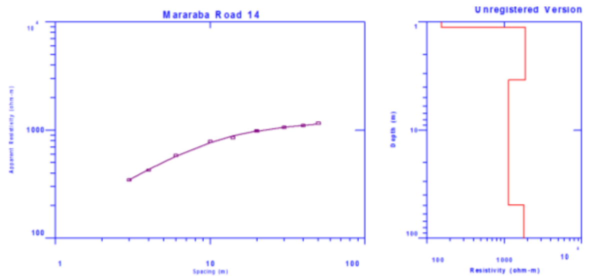
The raw resistivity values measured at various VES points within the study area using Schlumberger array were plotted against half electrode spacing (AB/2) using Interpex 1XD software to obtain the resistivities of the various subsurface layers together with their thicknesses. This information was then used to compute the longitudinal conductance and transmissivity values for each layer using equations (8) and (9) respectively, from where aquifer protectivity was inferred.

Figures 4 (a – f) show the results of the plot along with depth logs while Table 1 shows the number of layers, resistivity of each layer, layer thickness, depth to top of each layer, longitudinal conductance, transverse resistance and lithology of the layers. Four basic lithologic units comprising the top lateritic soil; sandy clay; fractured basement and the basement rock were delineated. Table 2 shows the protective capacity of aquifers at each

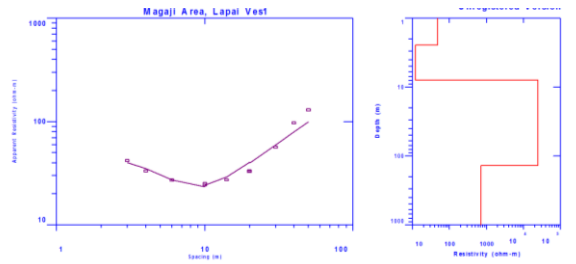
VES point, based on the total longitudinal conductance of the overburden, and using the rating by Bello *et al*., (2019).



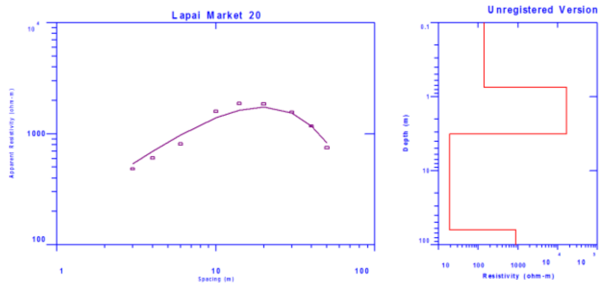
(a) Apparent Resistivity vs AB/2 with depth log for VES 1



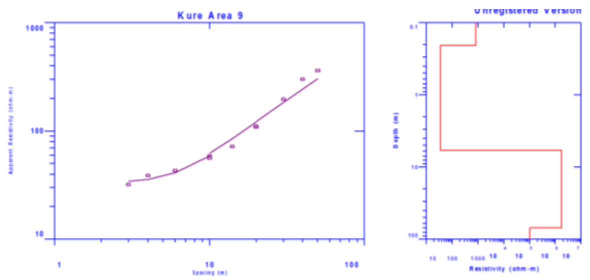
(d) Apparent Resistivity vs AB/2 with depth log for VES 14



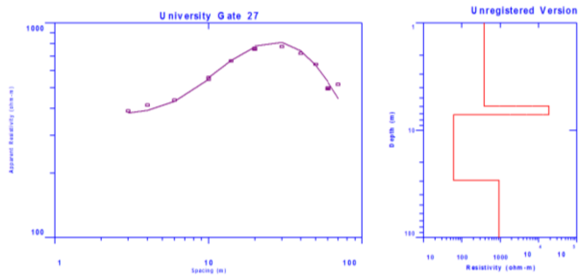
(b) Apparent Resistivity vs AB/2 with depth log for VES 9



(e) Apparent Resistivity vs AB/2 with depth log for VES 20



(c) Apparent Resistivity vs AB/2 with depth log for VES 8



(e) Apparent Resistivity vs AB/2 with depth log for VES 27

Figure 4 (a – f). Graphs of Apparent Resistivity vs AB/2 with depth logs for selected VES points

Table 1. layered earth models for the ves stations

VES Point	Coordinates	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Long. Cond. (Siemens)	Trans. (ohm.m^2)	Lithology
1	09˚02.794N	1	47.93	2.46	2.46	0.0513	117.9	Top lateritic soil
	006˚34.137E	2	12.19	5.46	7.92	0.448	66.69	Sandy clay
		3	24148.4	128.5	136.4	0.00532	3.105E+06	Fractured basement
		4	713.0	∞	∞			Fresh basement
2	09˚02.798N	1	18.36	0.761	0.761	0.0414	13.97	Top lateritic soil
	006˚34.140E	2	459.5	0.213	0.974	4.654E-04	98.10	Sandy clay
		3	73289.4	86.95	87.92	0.00119	6.373E+06	Fractured basement
		4	1285.9	∞	∞			Fresh basement

VES Point	Coordinates	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Long. Cond. (Siemens)	Trans. (ohm.m^2)	Lithology
3	09˚02.780N	1	13.17	0.455	0.455	0.0345	6.00	Top lateritic soil
	006˚34.150E	2	469.3	0.158	0.614	3.378E-04	74.41	Sandy clay
		3	1112.8	107.2	107.8	0.0963	119319.5	Fractured basement
		4	1126.6	∞	∞			Fresh basement
4	09˚02.782N	1	969.8	0.812	0.812	8.381E-04	788.3	Top lateritic soil
	006˚34.108E	2	94.21	1.05	1.86	0.0112	99.50	Sandy clay
		3	1.716E+06	66.98	68.85	3.905E-05	1.149E+08	Fractured basement
		4	95036.2	∞	∞			Fresh basement
5	09˚02.536N	1	590.3	0.212	0.212	3.592E-04	125.1	Top lateritic soil
	006˚33.887E	2	17.80	1.00	1.21	0.0562	17.82	Sandy clay
		3	1.280E+06	58.29	59.50	4.554E-05	7.463E+07	Fractured basement
		4	96231.1	∞	∞			Fresh basement
6	09˚02.533N	1	846.9	0.185	0.185	2.189E-04	157.0	Top lateritic soil
	006˚33.878E	2	11.29	0.742	0.927	0.0657	8.38	Sandy clay
		3	3.637E+06	29.65	30.58	8.155E-06	1.079E+08	Fractured basement
		4	55676.3	∞	∞			Fresh basement
7	09˚02.780N	1	827.8	0.219	0.219	2.648E-04	181.4	Top lateritic soil
	006˚34.150E	2	13.86	0.537	0.756	0.0387	7.44	Sandy clay
		3	2.322E+06	65.91	66.66	2.839E-05	1.530E+08	Fractured basement
		4	95597.4	∞	∞			Fresh basement
8	09˚02.529N	1	63.58	0.671	0.671	0.0105	42.68	Top lateritic soil
	006˚33.863E	2	871.3	0.457	1.12	5.249E-04	398.5	Sandy clay
		3	275633.7	75.21	76.33	2.729E-04	2.073E+07	Fractured basement
		4	4983.0	∞	∞			Fresh basement
9	09˚02.168N	1	816.4	0.206	0.206	2.527E-04	168.4	Top lateritic soil
	006˚34.225E	2	34.72	5.64	5.85	0.162	196.0	Sandy clay
		3	1.709E+06	63.89	69.74	3.739E-05	1.092E+08	Fractured basement
		4	100246.1	∞	∞			Fresh basement
10	09˚02.140N	1	14.94	0.843	0.843	0.0564	12.61	Top lateritic soil
	006˚34.241E	2	4.05	0.00439	0.848	0.00108	0.0177	Sandy clay
		3	81149.2	47.44	48.29	5.847E-04	3.850E+06	Fractured basement
		4	637351.1	∞	∞			Fresh basement
11	09˚02.159N	1	841.9	0.278	0.278	3.304E-04	234.2	Top lateritic soil
	006˚34.213E	2	25.65	1.95	2.23	0.0762	50.21	Sandy clay
		3	1.600E+06	93.00	95.24	5.813E-05	1.488E+08	Fractured basement
		4	94459.0	∞	∞			

VES Point	Coordinates	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Long. Cond. (Siemens)	Trans. (ohm.m²)	Lithology
								Fresh basement
12	09˚02.168N	1	61.72	1.16	1.16	0.0188	71.72	Top lateritic soil
	006˚34.225E	2	873.2	1.06	2.22	0.00122	929.6	Sandy clay
		3	161044.4	106.2	108.4	6.597E-04	1.711E+07	Fractured basement
		4	3931.3	∞	∞			Fresh basement
13	09˚02.442N	1	809.2	0.196	0.196	2.432E-04	159.2	Top lateritic soil
	006˚34.479E	2	8.94	0.938	1.13	0.104	8.39	Sandy clay
		3	1.735E+06	86.36	87.49	4.979E-05	1.498E+08	Fractured basement
		4	11512.7	∞	∞			Fresh basement
14	09˚02.456N	1	154.3	1.11	1.11	0.00723	172.2	Top lateritic soil
	006˚34.476E	2	1865.8	2.31	3.43	0.00124	4322.6	Sandy clay
		3	1136.6	45.39	49.39	0.0404	52240.4	Fractured basement
		4	1804.5	∞	∞			Fresh basement
15	09˚02.455N	1	30.62	1.19	1.19	0.0390	36.58	Top lateritic soil
	006˚34.459E	2	48.33	0.690	1.88	0.0142	33.39	Sandy clay
		3	52227.8	89.42	91.31	0.00171	4.671E+06	Fractured basement
		4	1213.4	∞	∞			Fresh basement
16	09˚02.424N	1	75.30	0.461	0.461	0.00613	34.75	Top lateritic soil
	006˚34.425E	2	1180.1	77.86	78.32	0.0659	91894.9	Sandy clay
		3	1.655E+06	5.32	83.65	3.219E-06	8.820E+06	Fractured basement
		4	77044.8	∞	∞			Fresh basement
17	09˚02.719N	1	10.24	0.679	0.679	0.0663	6.96	Top lateritic soil
	006˚34.426E	2	361.3	0.647	1.32	0.00179	234.0	Sandy clay
		3	987414.9	73.07	74.39	7.400E-05	7.215E+07	Fractured basement
		4	15757.9	∞	∞			Fresh basement
18	09˚02.714N	1	12.43	1.36	1.36	0.109	16.93	Top lateritic soil
	006˚34.456E	2	10.22	5.486E-04	1.36	5.363E-05	0.00561	Sandy clay
		3	20737.5	39.74	41.11	0.00192	824290.5	Fractured basement
		4	5595.5	∞	∞			Fresh basement
19	09˚02.724N	1	161.1	0.942	0.942	0.00585	151.8	Top lateritic soil
	006˚34.462E	2	19.59	1.60	2.54	0.0817	31.38	Sandy clay
		3	38510.6	90.47	93.01	0.00235	3.484E+06	Fractured basement
		4	1841.2	∞	∞			Fresh basement
20	09˚02.728N	1	142.1	0.751	0.751	0.00529	106.7	Top lateritic soil
	006˚34.471E	2	16621.6	2.44	3.19	1.470E-04	40623.3	Sandy clay
		3	19.02	59.27	62.47	3.11	1127.9	
		4	891.4	∞	∞			

VES Point	Coordinates	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Long. Cond. (Siemens)	Trans. (ohm.m^2)	Lithology
								Fractured basement
								Fresh basement
21	9.07216^{0}N 6.57080^{0}E	1	182.4	4.0	4.0	0.02193	729.6	Top lateritic soil
		2	3254.1	5.4	9.4	0.00166	17572.14	Sandy clay
		3	237.6	36.8	46.3	0.15488	8743.68	Fractured basement
		4	715.2	∞	∞			Fresh basement
22	9.06780^{0}N 6.56831^{0}E	1	390.7	5.7	5.7	0.01459	2226.99	Top lateritic soil
		2	2971.4	6.1	11.8	0.00205	18125.54	Sandy clay
		3	122.1	22.6	34.4	0.18509	2759.46	Fractured basement
		4	1297.9	∞	∞			Fresh basement
23	9.06760^{0}N 6.57211^{0}E	1	358.2	3.5	3.5	0.00977	1253.7	Top lateritic soil
		2	843.9	1.7	5.2	0.00201	1434.63	Sandy clay
		3	90.4	17.8	23.0	0.1969	1609.12	Fractured basement
		4	534.3	∞	∞			Fresh basement
24	9.06700^{0}N 6.57249^{0}E	1	278.7	3.8	3.8	0.01363	1059.06	Top lateritic soil
		2	418.4	3.9	7.7	0.00932	1631.76	Sandy clay
		3	47.1	12.7	20.4	0.26964	598.17	Fractured basement
		4	1299.2	∞	∞			Fresh basement
25	9.06374^{0}N 6.57409^{0}E	1	246.3	2.9	2.9	0.01177	714.27	Top lateritic soil
		2	162.6	16.0	18.8	0.0984	2601.6	Sandy clay
		3	136.3	36.1	55.0	0.26486	4920.43	Fractured basement
		4	529.2	∞	∞			Fresh basement
26	9.06467^{0}N 6.57025^{0}E	1	318.3	5.1	5.1	0.01602	1623.33	Top lateritic soil
		2	1644.5	11.2	16.3	0.00681	18418.4	Sandy clay
		3	78.0	25.1	41.4	0.32179	1957.8	Fractured basement
		4	1481.4	∞	∞	∞	∞	Fresh basement
27	09.0719N 006.5344E	1	378.8	5.90	5.90	0.01558	2234.98	Top lateritic soil
		2	18516.0	1.19	7.10	0.0000643	22034.04	Sandy clay
		3	61.34	22.20	29.30	0.36192	1361.748	Fractured basement
		4	936.3	∞	∞			Fresh basement
28	09.7619N 006.554E	1	217.4	5.49	5.49	0.0252	1194.0	Top lateritic soil
		2	18254.9	1.31	6.80	7.213E-05	24038.3	Sandy clay
		3	61.82	22.30	29.10	0.360	1378.9	Fractured basement
		4	938.7	∞	∞			Fresh basement

VES Point	Coordinates	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Long. Cond. (Siemens)	Trans. (ohm.m^2)	Lithology
29	09.7535N 006.5532E	1	475.2	1.43	1.43	0.00301	680.8	Top lateritic soil
		2	301.8	7.76	9.19	0.0257	2343.8	Sandy clay
		3	124.3	41.45	50.65	0.333	5155.7	Fractured basement
		4	298.8	∞	∞			Fresh basement
30	09˚02'57.3N 006˚35'59.9E	1	83.119	17.4	17.4	0.209338	1446.271	Top lateritic soil
		2	24932.1	34.7	52.1	0.001392	865143.9	Sandy clay
		3	765.80	40.0	92.1	0.052233	30632	Fractured basement
		4	1060.8	∞	∞			Fresh basement
31	09˚02'55.6N 006˚35'56.3E	1	25.126	2.00	2.00	0.079599	50.252	Top lateritic soil
		2	79.901	4.40	6.40	0.055068	351.564	Sandy clay
		3	137.68	10.0	16.4	0.072632	1376.8	Fractured basement
		4	998.06	∞	∞			Fresh basement
32	09˚02'53.6N 006˚35'52.9E	1	28.112	6.03	6.03	0.213432	168.672	Top lateritic soil
		2	711.09	1.55	7.59	0.010688	5404.284	Sandy clay
		3	1579.7	30.0	37.59	0.023796	59380.92	Fractured basement
		4	0.11779	∞	∞			Fresh basement
33	09˚02'54.4N 006˚36'01.2E	1	96.765	2.47	2.47	0.025834	241.925	Top lateritic soil
		2	13.244	2.45	4.92	0.188822	33.1	Sandy clay
		3	102.34	0.14	4.92	0.001368	14.3276	Fractured basement
		4	0.23839	∞	∞			Fresh basement
34	09˚02'43.7N 006˚36'01.6E	1	195.95	3.38	3.38	0.017249	662.311	Top lateritic soil
		2	216.59	5.87	9.25	0.027102	1271.383	Sandy clay
		3	483.88	60.0	69.3	0.123998	29032.8	Fractured basement
		4	1221.4	∞	∞			Fresh basement
35	09˚02'50.5N 006˚35'53.6E	1	13.780	0.77	0.77	0.058055	11.024	Top lateritic soil
		2	214.96	0.67	0.84	0.003256	150.472	Sandy clay
		3	1033.7	10.0	10.8	0.009674	10337	Fractured basement
		4	129.83	∞	∞			Fresh basement
36	09˚02'59.8N 006˚36'04.6E	1	44.045	2.27	2.27	0.051538	99.98215	Top lateritic soil
		2	107.93	3.05	5.32	0.028267	329.095	Sandy clay
		3	275.85	46.0	51.3	0.166757	12689.1	Fractured basement
		4	525.00	∞	∞			Fresh basement
37	09˚02'47.3N 006˚35'59.1E	1	175.33	0.82	0.82	0.004677	143.7706	Top lateritic soil
		2	22.272	0.74	1.57	0.033229	16.4798	Sandy clay
		3	307.80	54.0	55.6	0.175439	16621.2	Fractured basement
		4	0.1255					

VES Point	Coordinates	Layer	Resistivity (Ωm)	Thickness (m)	Depth (m)	Long. Cond. (Siemens)	Trans. (ohm.m^2)	Lithology
								Fresh basement
38	09°02’45.4N 006°35’54.2E	1	46.959	2.70	2.70	0.057501	126.7812	Top lateritic soil
		2	27.438	1.90	4.60	0.069242	52.136	Sandy clay
		3	307.80	54.0	58.6	0.175439	16621.2	Fractured basement
		4	0.1751	∞	∞			Fresh basement
39	09°02’48.3N 006°36’3.8E	1	2.3084	0.14	0.14	0.060648	0.323176	Top lateritic soil
		2	101.00	0.41	0.56	0.004059	41.41	Sandy clay
		3	527.66	54.0	54.6	0.102339	28493.64	Fractured basement
		4	2593.0	∞	∞			Fresh basement
40	09°02’47.3N 006°35’59.1E	1	80.319	1.69	1.69	0.021041	135.7391	Top lateritic soil
		2	21.565	0.51	2.20	0.023649	10.99815	Sandy clay
		3	307.80	26.0	28.2	0.08447	8002.8	Fractured basement
		4	1680.6	∞	∞			Fresh basement
41	09°02’45.4N 006°35’54.2E	1	48.945	1.83	1.83	0.037389	89.56935	Top lateritic soil
		2	22.460	0.35	2.18	0.015583	7.861	Sandy clay
		3	124.50	20.0	22.2	0.160643	2490.00	Fractured basement
		4	0.1363	∞	∞			Fresh basement
42	09°02’45.4N 006°36’05.3E	1	2.4820	0.16	0.16	0.064464	0.39712	Top lateritic soil
		2	449. 60	71.0	71.2	0.157918	31921.60	Sandy clay
		3	588.60	20.0	91.2	0.033979	11772.00	Fractured basement
		4	7982.8	∞	∞			Fresh basement
43	09°02’43.7N 006°36’01.6E	1	142.11	2.03	2.03	0.014285	288.4833	Top lateritic soil
		2	16.517	0.37	2.39	0.022401	6.11129	Sandy clay
		3	97.260	6.00	8.39	0.06169	583.56	Fractured basement
		4	102.84	∞	∞			Fresh basement
44	09°02’42.2N 006°35’57.8E	1	43.314	2.87	2.87	0.06626	124.3112	Top lateritic soil
		2	6.6037	1.67	4.54	0.252889	11.02818	Sandy clay
		3	676.52	40.0	44.5	0.05913	27060.80	Fractured basement
		4	365.91	∞	∞			Fresh basement

An examination of the interpreted data has revealed both confined and unconfined aquifers within the study area. Three VES points displayed some irregular patterns by having very low resistivity values for the basement rock compared to the fractured basement. These irregularities were observed at VES points 33, 38 and 41 (Table 1 refers). These low resistivities could be attributed to the presence of high conductive material in the basement which could be rich in ironstones.

Whereas the aquifer formations at VES points 20, 21, 22, 23, 24, 25, 26, 27, 29, 30, 31, 34, 36, 39, 40, 42 and 43 were identified as unconfined aquifers on account of the low resistivity values of the fractured basement compared to the basement rock, all other aquifer formations at the other VES points (except for the irregular ones mentioned earlier) were identified as confined. This is because of the higher resistivity values of those formations compared to the basement rock.

Table 2 shows four classes of aquifer proactive capacity as delineated, to be high, moderate, weak and poor. While the aquifer at VES 20 was highly protected, twenty other aquifers were moderately protected. These were the aquifers at VES 1, 2, 22 – 33, 36, 37, 38, 41, 42 and 44. Eight other aquifers had weak protection; these include the aquifers at VES points 3, 9, 13, 18, 21, 34, 40 and 41. The remaining fifteen aquifers were poorly protected. They include the aquifers at VES points 4 – 8, 10 – 12, 14 – 17, 19, 35 and 43.

Generally, the aquifers are of good thicknesses and at reasonable depths, making them good reservoirs of water in appreciable quantity. However, most areas have high values of Transverse resistance which are associated with the zones of high transmissivity; hence, these zones are suggested for the installation of monitoring wells for the unconfined aquifer.

Table 2. Aquifer Parameters

VES Point	Coordinates	Aquifer Thickness (m)	Depth.to Aquifer (m)	Long. Conductance.of Overburden	Aquifer Protective Capacity
1	09˚02.794N; 006˚34.137E	128.5	136.4	0.50462	Moderate
2	09˚02.798N; 006˚34.140E	86.95	87.92	0.0430554	Moderate
3	09˚02.780N; 006˚34.150E	107.2	107.8	0.1311378	Weak
4	09˚02.782N; 006˚34.108E	66.98	68.85	0.0120772	Poor
5	09˚02.536N; 006˚33.887E	58.29	59.50	0.0566047	Poor
6	09˚02.533N; 006˚33.878E	29.65	30.58	0.0659271	Poor
7	09˚02.780N; 006˚34.150E	65.91	66.66	0.0389932	Poor
8	09˚02.529N; 006˚33.863E	75.21	76.33	0.0112978	Poor
9	09˚02.168N; 006˚34.225E	63.89	69.74	0.1622901	Weak
10	09˚02.140N; 006˚34.241E	47.44	48.29	0.0580647	Poor
11	09˚02.159N; 006˚34.213E	93.00	95.24	0.0765885	Poor
12	09˚02.168N; 006˚34.225E	106.2	108.4	0.0206797	Poor
13	09˚02.442N; 006˚34.479E	86.36	87.49	0.104293	Weak
14	09˚02.456N; 006˚34.476E	45.39	49.39	0.04887	Poor
15	09˚02.455N; 006˚34.459E	89.42	91.31	0.05491	Poor
16	09˚02.424N; 006˚34.425E	5.32	83.65	0.0720332	Poor
17	09˚02.719N; 006˚34.426E	73.07	74.39	0.068164	Poor
18	09˚02.714N; 006˚34.456E	39.74	41.11	0.1109736	Weak

VES Point	Coordinates	Aquifer Thickness (m)	Depth.to Aquifer (m)	Long. Conductance.of Overburden	Aquifer Protective Capacity
19	09˚02.724N; 006˚34.462E	90.47	93.01	0.0899	Poor
20	09˚02.728N; 006˚34.471E	59.27	62.47	3.115.437	High
21	9.07216^{0}N ; 6.57080^{0}E	36.8	46.3	0.17847	Weak
22	9.06780^{0}N; 6.56831^{0}E	22.6	34.4	0.20173	Moderate
23	9.06760^{0}N; 6.57211^{0}E	17.8	23.0	0.20868	Moderate
24	9.06700^{0}N ; 6.57249^{0}E	12.7	20.4	0.29259	Moderate
25	9.06374^{0}N; 6.57409^{0}E	36.1	55.0	0.37503	Moderate
26	9.06467^{0}N; 6.57025^{0}E	25.1	41.4	0.34462	Moderate
27	09.0719N; 006.5344E	22.20	29.30	0.3775643	Moderate
28	09.7619N; 006.554E	22.30	29.10	0.3852721	Moderate
29	09.7535N; 006.5532E	41.45	50.65	0.36171	Moderate
30	09˚02'57.3N; 006˚35'59.9E	40.0	92.1	0.262963	Moderate
31	09˚02'55.6N 006˚35'56.3E	10.0	16.4	0.207299	Moderate
32	09˚02'53.6N; 006˚35'52.9E	30.0	37.59	0.247916	Moderate
33	09˚02'54.4N; 006˚36'01.2E	2.45	4.92	0.216024	Moderate
34	09˚02'43.7N 006˚36'01.6E	60.0	69.3	0.168349	Weak
35	09˚02'50.5N 006˚35'53.6E	10.0	10.8	0.070985	Poor
36	09˚02'59.8N; 006˚36'04.6E	46.0	51.3	0.246562	Moderate
37	09˚02'47.3N; 006˚35'59.1E	54.0	55.6	0.213345	Moderate
38	09˚02'45.4N; 006˚35'54.2E	54.0	58.6	0.302182	Moderate
39	09˚02'48.3N; 006˚36'3.8E	54.0	54.6	0.167046	Weak
40	09˚02'47.3N; 006˚35'59.1E	26.0	28.2	0.12916	Weak
41	09˚02'45.4N; 006˚35'54.2E	20.0	22.2	0.213615	Moderate
42	09˚02'45.4N; 006˚36'05.3E	20.0	71.2	0.256361	Moderate
43	09˚02'43.7N; 006˚36'01.6E	6.00	8.39	0.098376	Poor
44	09˚02'42.2N; 006˚35'57.8E	40.0	44.5	0.378279	Moderate
	Minimum	**2.45**	**4.92**		
	Maximum	**128.5**	**136.4**		
	Average	**48.36**	**56.68**		

The highest and lowest aquifer thicknesses were observed at VES 1 and VES 33 with respective values of 128.5m and 2.45m. The depth to the top of each aquifer varied from 4.92m at VES 33 to 136.4m at VES point 1. The average aquifer thickness within the study area is estimated to be 48.36m while the average depth to aquifers is estimated to be 56.68m. Boreholes drilled within the vicinity of the study area have had very good yield at depths ranging from 40m to 60m. These results are consistent with those obtained by Tsepav et al., (2015) and Oladipo et al., (2011).

5. Conclusion

The geophysical survey has allowed us to obtain lithological identification and to characterize the conditions of the underground water of the studied area. Four geoelectric layers were identified; the top lateritic soil, sandy clay, fractured basement and the fresh basement. Aquifers thicknesses and depths to geoelectric layers were delineated within the study area. Areas with high values of Transverse resistance were associated with the zones of high transmissivity; hence, these zones are suggested for the installation of monitoring wells. The longitudinal conductance illustrates the non-permeability of the confining clay layer. Values of S > 1.0 siemens indicated zones in which the confined aquifer would be well protected; in comparison, values of S < 1.0 siemens would indicate zones of probable risks of contamination. Between these extreme values, moderately, weakly and poorly protected areas were also identified.

In order to fully harness the natural potentials of potable groundwater and its full utilisation, the following recommendations are evident:

i) Geophysical survey should be conducted anywhere there is need for potable groundwater to determine the best and most protected aquifers.
ii) Citing of indiscriminate dumpsites should be discouraged especially in the vicinity of residential houses so as to guide against the risk of exposure to contaminated groundwater.
iii) Geochemical analysis should also be conducted to ascertain the types of contaminant effluents present in the groundwater reservoirs, for the purpose of comparison to world standards.
iv) Where necessary, water from the suspected areas of contamination should be subjected to proper treatment before usage, especially for drinking.
v) Periodic geophysical and geochemical investigations should be undertaken to determine the rate of leachate migration in the areas so as serve as a guide for further groundwater developmental plans.

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Declaration of interests

The authors declare that no known competing interests, whatsoever, that could have appeared to influence the work reported in this paper exist.

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