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Research Article

Assessment of Groundwater Potential and Vulnerability Using Electrical Resistivity Techniques: A Case Study of the FUPRE Campus and Agbarho Axis, Delta State, Nigeria

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Abstract

The quality and availability of groundwater are increasingly threatened by anthropogenic activities, including oil extraction and inadequate environmental management. This study focuses on the groundwater potential and vulnerability of the Federal University of Petroleum Resources (FUPRE) campus and Agbarho axis in Delta State. The research employs Vertical Electrical Sounding (VES) techniques to assess the subsurface structure and derive geoelectric parameters, such as transverse unit resistance (Tr), longitudinal resistance (ρL), and transverse resistivity (ρt), which inform the groundwater potential and vulnerability. The study also integrates second-order geoelectric indices, including Dar Zarrouk's parameters, to evaluate aquifer protective capacity using the GOD index and longitudinal conductance. Results indicate that while parts of the study area exhibit promising groundwater potential (high Tr values), the overall aquifer protective capacity is poor, with low longitudinal conductance values suggesting a high susceptibility to contamination. Geoelectric curve types, resistivity contrast, and coefficient of anisotropy further reveal a heterogeneous subsurface with varying permeability and porosity. The GOD index categorizes most of the area as moderately vulnerable to contamination, highlighting the need for enhanced groundwater management. This study underscores the importance of integrating hydrogeological and geophysical data for effective groundwater exploration, management, and protection in regions at risk of contamination.

Keywords

Groundwater Potential, Electrical Resistivity, Aquifer Vulnerability, Dar Zarouk Parameter, GOD Index, FUPRE

1. Introduction

Groundwater is essential for domestic, industrial, and agricultural purposes. It plays a critical role in ensuring access to potable water, which is fundamental for the health and productive life of people in any society [22]. In Sub-Saharan Africa, groundwater is a major source of water supply, particularly in rural, suburban, and urban areas [1]. Access to safe drinking water is not only a basic human right but also a necessary condition for both human and economic development. However, groundwater resources face increasing threats due to contamination, particularly in urban and industrial areas, where pollution sources such as leachate from landfills, oil spills, and septic tank leakage can degrade water quality [20]. Despite the importance of aquifers, aquifer protection has historically not been given adequate attention,

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particularly in regions with high pollution risks [12]. This issue is compounded by the growing population and the increasing demand for potable water. As a result, there is a critical need for an integrated assessment of groundwater resources, focusing not only on their availability but also on their vulnerability and protection.

The geophysical technique of Vertical Electrical Sounding (VES) is widely used to assess groundwater potential, as it provides valuable data on aquifer resistivity and thickness. This method helps estimate the hydraulic properties of aquifers and identify groundwater potential zones [1, 3]. For example, research by [29] on aquifer characterization using geoelectric survey data in IsseleUku, Delta State, Nigeria, found that the aquifer was not well-protected due to the absence of clay. Similarly, studies by [9] and [28] on groundwater quality and aquifer protection near dumpsites in Delta State revealed vulnerabilities in the aquifers due to poor protection from surface contaminants. Several methodologies have been proposed by [4] for evaluating groundwater vulnerability, including the DRASTIC model (depth to groundwater, recharge, aquifer type, soil properties, topography, impact of overburden zone, and hydraulic conductivity), which considers various hydrogeological parameters to assess contamination risks. Other models, such as the Aquifer Vulnerability Index (AVI) and the GOD method (groundwater occurrence, overlying lithology, and aquifer depth), are also used to evaluate groundwater susceptibility to pollution [14]. In Okeigbo, Nigeria, these models help in understanding how factors like aquifer permeability and the presence of low-permeability layers protect groundwater resources from contamination [13].

Despite the importance of aquifer protection, groundwater quality has deteriorated in regions such as the Niger Delta, due to increased oil and gas extraction, illegal refineries, and poor environmental management [8]. Similar concerns are evident in Ugbomro and surrounding areas, where the frequent failure of boreholes and contamination of water samples highlight the lack of detailed hydrogeological data for the region. This underscores the need for more comprehensive research on groundwater potential and protection.

The present study seeks to integrate hydrogeological and geoelectric indices to map groundwater potential and vulnerability within the premises of the Federal University of Petroleum Resources Effurun campus and the Agbarho axis. This research will focus on the following objectives:

1) Acquire Vertical Electrical Sounding (VES) data from the study area.
2) Process and interpret the VES data to determine geo-electric layer parameters (resistivity, thickness, and depth) using WinResist software.
3) Derive second-order geoelectric indices, such as Dar-Zarrouk parameters (e.g., transverse unit resistance, longitudinal resistivity, and transverse resistivity), for analyzing groundwater prospects.
4) Assess the aquifer protective capacity using the GOD and longitudinal conductance models.

This study was carried out within the premises of the premises of the Federal university of petroleum resources Effurun campus and Agbarho axis in Delta State, Nigeria. The Figure 1 showed the map of Delta state in Nigeria where the study area is located while the Figure 2 showed the both the google map of study areas in FUPRE and Agbarho location. The Figure 3 is the base map of all the points in both FUPRE and Agbarho location where all the VES data were acquired. The VES readings were taken at different locations within the premises of the premises of the Federal university of petroleum resources Effurun campus and Agbarho axis. The study area lies between latitude 5˚ 34'N and longitude 5˚ 24.'E.`

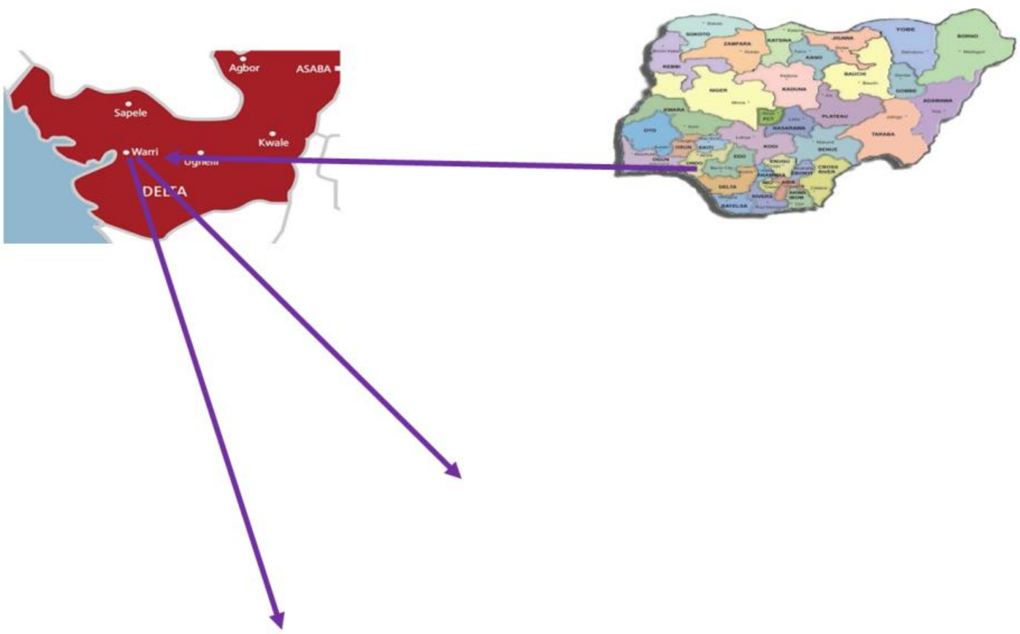

Figure 1. *Showing the maps of the delta state in Nigeria with the study area.*

Figure 2. Showing the google map of the study areas (Agbarho and FUPRE).

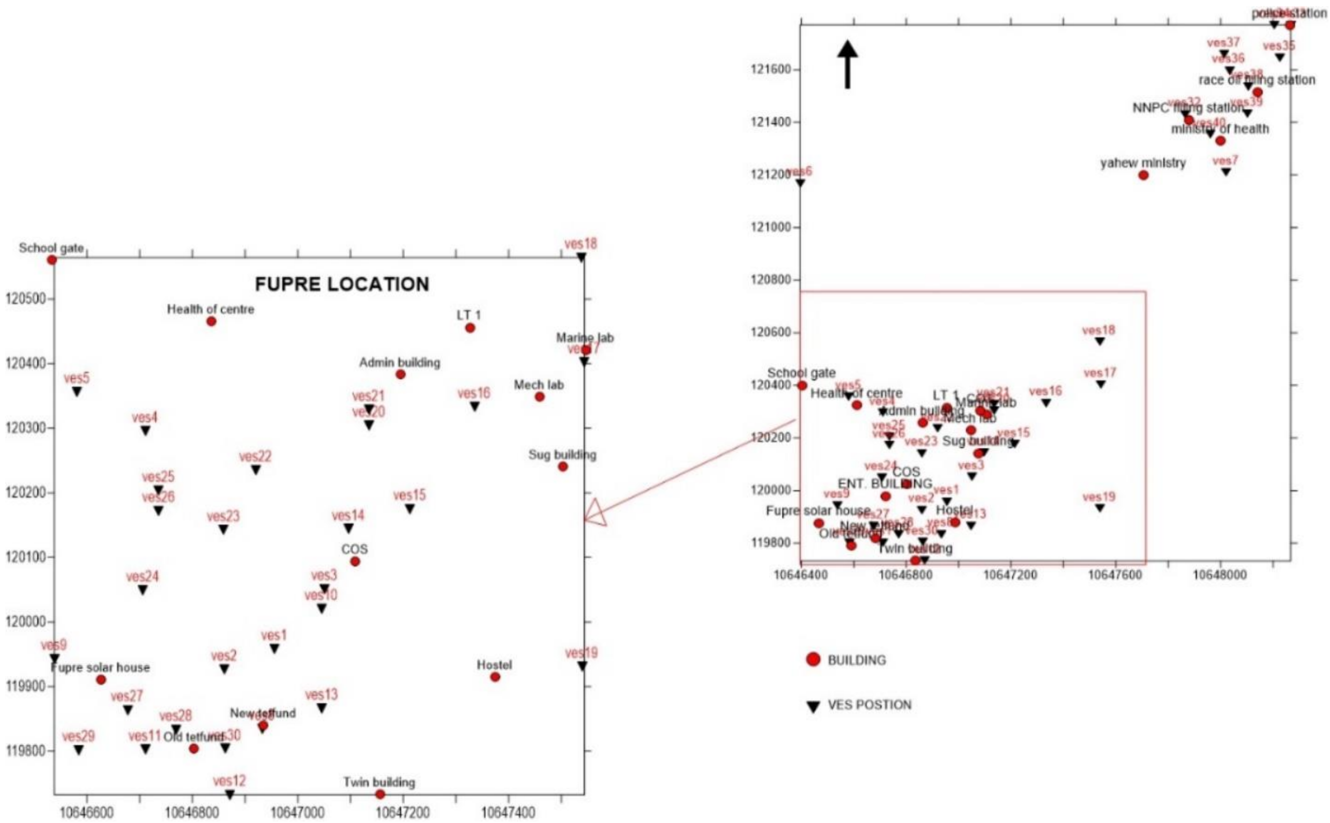

Figure 3. Base Map of study area showing the acquired VES points.

2. Methodology

This study involved the integration of field-based geophysical data consisting of 1-D geoelectrical resistivity data (also known as Vertical Electrical Sounding) set of groundwater within the study area using the Schlumberger array configuration. A total of 40 vertical Electrical Sounding (VES) was used. The materials used to acquire data in the study area were: Terrameter, pairs of electrode, Wire reels, Hammers, batteries, Meter tapes and Geographical positioning system (GPS). Vertical Electrical Sounding (VES) is one of the electrical resistivity geophysical methods used to investigate the subsurface properties of the Earth. It involves measuring the electrical resistivity of the ground at various depths in order to identify different geological formations and structures. It was used in this research to detect the depth of aquifer and to delineate the type of geological formation that housing the aquifer.

2.1. Theoretical Background of Research

The theoretical background of this research is based on Ohm's law which states that the voltage across a conductor is directly proportional to the current provided all physical conditions and temperature remain constant.

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

$$R = \frac{V}{I} \tag{2}$$

The electrical resistivity approach takes advantage of the resistance differential between various ground materials. The level of resistance a material exhibits to the passage of electrical current through, it is measured as resistivity.

In general, resistivity is the opposite of conductivity and is measured in ohm meters. Resistance of a medium (R) is proportional to its length (L) and inversely proportional to its cross sectional area (A).

$$R = \frac{\rho L}{A} \tag{3}$$

$$\rho = \frac{RA}{L} \tag{4}$$

$$\rho = \frac{VA}{IL} \tag{5}$$

where, R = Resistance of the medium, I = Current, V = Voltage, ρ = Resistivity

2.2. Hydraulic Conductivity

Hydraulic Conductivity could be referred as the relative ease with which fluids (groundwater) flows through a medium, in this research, a geological formation or rock found in the subsurface is quite different from intrinsic permeability. This describes the water-transmitting property of the medium and it is not influenced by the temperature, pressure or the fluid passing through the geological formation. Hydraulic conductivity of a geological formation depends on a variety of physical factors among which includes porosity, particle size and distribution, arrangement of particles and other factors. This is also known as permeability [6]

Mathematically, hydraulic conductivity (K) could be expressed by the formula below:

$$K= 0.0538E^{0.0072p} \tag{6}$$

Where is the aquifer layer resistivity.

2.3. Aquifer Transmissivity

Aquifer Transmissivity (T) more simply could be defined as the property of aquifer to transmit water. It could also be defined as the amount of water that can be transmitted horizontally through an aquifer unit by full saturated thickness of the aquifer under a hydraulic gradient of 1 or as the rate at which water of prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit gradient. Transmissivity (T) is the product of the hydraulic conductivity (k) and the aquifer layer thickness.

$$T=K \text{ x } h \tag{7}$$

2.4. Aquifer Protective Capacity

Aquifer protective capacity (APC) is the ability of the overburden unit to retard and filter percolating ground surface polluting fluid into the aquiferous unit. The combination of thickness and resistivity into single variables, other words known as the Dar-Zarrouk parameters [19] are often used as a basis for the evaluation of aquifer properties such as aquifer transmissivity and protection of ground-water resources [17].

Ageo-electrical layer is described by two fundamental parameters i.e. resistivity *(pa)* and thickness (h). For the analysis and comprehension of the geologic model, some factors linked to the different combinations of thickness and resistivity of the geoelectric layer are crucial [38, 19]. Dar Zarrouk's longitudinal (S) and transverse (T) parameters were derived via

$$S = \frac{h}{p} \tag{8}$$

$$T = hp \tag{9}$$

where h is the aquifer thickness and p is the aquifer resistivity.

Longitudinal Unit Conductance (*S*) was calculated using equation 10.

The longitudinal conductance is equal to the number of layers (n).

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_i}{\rho_i} + \frac{h_2}{\rho_2} + \cdots + \frac{h_n}{\rho_n} \tag{10}$$

as proposed by [5]

Transverse Unit Resistance (*Tr*) was calculated using equation 5.

The total resistance of the transverse unit is

$$Tr = \sum_{i=1}^{n} h_i\rho_i = h_i\rho_i + h_2\rho_2 + \cdots + h_n\rho_n \tag{11}$$

2.4.1. Longitudinal Resistance Was Calculated Using Equation 8

$$\rho_L = \frac{H}{S} = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{\rho_i}} \quad (12)$$

2.4.2. Transverse Resistance Was Determined from Equation 13

$$\rho_t = \frac{T}{H} = \frac{\sum_{i=1}^{n} h_i \rho_i}{\sum_{i=1}^{n} h_I} \quad (13)$$

The coefficient of anisotropy is a useful parameter of an anisotropic medium which indicates the degree of fracturing. It was determined using Equation 14

$$\lambda = \sqrt{\frac{\rho_t}{\rho_L}} = \frac{\sqrt{ST}}{H} \quad (14)$$

The Reflection Coefficient (R_C) and Resistivity Contrast (F_C) were calculated using equation 15, and 16 respectively.

As proposed by [25]

$$R_c = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \quad (15)$$

$$F_c = \frac{\rho_n}{\rho_{n-1}} \quad (16)$$

Where ρn is the layer resistivity of the nth layer, and ρ_{n-1} is the layer resistivity overlying the nth layer. [17]) described the protective capacity of an over burden over lying an aquifer as being proportional to its hydraulic conductivity. On a purely empirical basis, the hydraulic conductivity of clayey sediment could be linked to electrical resistivity through the concept of clay content. High clay content generally corresponds with low resistivity and low hydraulic conductivities, and vice versa. Hence, the protective capacity of the overburden could be considered as being proportional to the ratio of thickness to resistivity, or in other words to the longitudinal conductance. Thus, Equation (4) was used to evaluate the aquifer vulnerability or protective capacity of the aquifer overburden.

The second order geo-electric parameter, longitudinal conductance (DarZarrouk parameter) is generated from the primary/first order parameters (thickness and resistivity) of the geo-electric. Subsurface layers which were used in the classification of the Aquifer Protective Capacity. Highly impervious materials such as clay and shale usually have high longitudinal conductance values (resulting from their low resistivity values) while pervious materials such as sand and gravels have low longitudinal conductance values (resulting from their high resistivity values). While high longitudinal conductance value corresponds to excellent and good APC, low longitudinal conductance values are associated with poor and weak APC.

Table 1. *Longitudinal conductance/ protectivecapacity rating [23].*

Total longitudinal unit conductance (mhos)	Overburden protective capacity classification
<0.10	Poor
0.1-0.19	Weak
0.2-0.69	Moderate
0.7-4.9	Good
5-10	Very good
>10	Excellent

3. Results and Discussion

Longitudinal unit conductance (S), transverse unit resistance (Tr), average longitudinal resistance (ρL), transverse resistivity (ρt), coefficient of anisotropy (λ), refection coefficient Rc), and resistivity contrast (Fc) were calculated. The results were obtained from the primary resistivity parameters such as resistivity thickness and depth by performing system iteration using Winresist geophysical software for smooth curve with low root mean square value (Table 2).

Table 2. *Summary of VES 1-40- Interpretation showing the model layer parameters (layer resistivity, depth and thickness).*

VES	latitude longitude	Resistivity (Ωm)				Layer thickness (m)				Layer depth (m)				Curve type	No of layer
		ρ1	ρ2	ρ3	ρ4	h1	h2	h3	h4	d1	d2	d3	d4		
1		1456.9	727.5	17117.8	186878	3.2	6.4	28.9	∞	3.2	9.6	38.5	∞	HA	4
2		642	2320.8	732.2	213.5	0.6	3.5	38	∞	0.6	4.1	42.1	∞	KQ	4
3		1317.8	694.9	2293.5	149.2	2.4	7.9	16.4	∞	2.4	10.3	26.7	∞	AK	4
4		1025.3	2922.8	876.9	542.9	0.6	3.2	31.9	∞	0.6	3.8	35.7	∞	KQ	4
5		1852.7	2730.3	1151.5	575	0.8	2.7	43.6	∞	0.8	3.5	47.1	∞	KQ	4

VES	latitude longitude	Resistivity (Ωm)				Layer thickness (m)				Layer depth (m)				Curve type	No of layer
6		131.8	22.8	483.8	2072.7	2.9	6.6	12	∞	2.9	9.6	21.5	∞	HA	4
7		280.2	1589.4	312.9	389.2	1.4	8.6	33.6	∞	1.4	10	43.7	∞	KH	4
8		1640.3	2232	766.4	798	1.4	3.7	41.2	∞	1.4	5.2	46.3	∞	KH	4
9		215.3	729.5	2047.5	1543	0.7	5	20.9	∞	0.7	5.7	26.6	∞	AK	4
10		954	1302.9	1194	987	1	8	31	∞	1	9	40	∞	KQ	4
11		608.3	303.7	624.8	1016.5	1.6	4.6	38.5	∞	1.6	6.2	44.7	∞	HA	4
12		718.8	1653.3	1623.8	27.7	1	8.1	27.7	∞	1	9.1	36.8	∞	KQ	4
13		592.1	768.5	1510.1	466.3	1	8.5	28.7	∞	1	9.5	38.2	∞	AK	4
14		639.3	997.4	855.8	750.3	0.9	12	28.7	∞	0.9	12.9	41.6	∞	KQ	4
15		376	1145.3	501	1125.5	0.8	6.7	33.8	∞	0.8	7.5	41.3	∞	KH	4
16		591	1540.7	707.1	1155.7	0.7	8.6	19.6	∞	0.7	9.3	28.9	∞	KH	4
17		1856.9	1229.6	504.3		1.3	42		∞	1.3	43.3	∞	∞	Q	3
18		1411.7	1079.8	878.1	848.4	1	12.8	32.6	∞	1	13.8	46.4	∞	QH	4
19		1422.7	1166.8	651.7		1	40.5		∞	1	41.5	∞	∞	Q	3
20		1310	1080	2355.1	223.7	0.9	9.8	19.1	∞	0.9	10.7	29.8	∞	HK	4
21		817.7	1837.6	1704.1	460.3	1.2	12	17.5	∞	1.2	13.2	30.7	∞	KQ	4
22		466.6	2863.3	486.2	366.4	0.7	2.6	40	∞	0.7	3.3	43.3	∞	KQ	4
23		531.9	797.4	1252.8	294.8	1	7.3	20.8	∞	1	8.3	29.1	∞	AK	4
24		1004.2	2510.8	645.2	439.3	0.7	3.5	18.9	∞	0.7	4.2	23.1	∞	KQ	4
25		1840.6	1117.3	849	484	2.6	7.9	20.9	∞	2.6	10.5	31.4	∞	QQ	4
26		427.2	258.7	251.8	1312.2	1.4	7.5	15.2	∞	1.4	8.9	24.1	∞	QH	4
27		529.6	1376.9	701.6	439.9	1.1	8.1	20.9	∞	1.1	9.2	30.1	∞	KQ	4
28		1361.6	1947.9	493.8	391.5	0.9	4.6	20.1	∞	0.9	5.5	25.6	∞	KQ	4
29		483.7	1163.7	1611	1111.3	1	7.2	29.9	∞	1	8.2	38.1	∞	AK	4
30		560.6	1695	1539.9	1483.4	0.8	14.1	19.9	∞	0.8	14.9	34.8	∞	KQ	4
31		767.4	477.6	1131.1	737.1	1.9	12.6	29.1	∞	1.9	14.5	43.6	∞	HK	4
32		555.1	1597.4	1344.3	905.8	0.9	8	30.2	∞	0.9	8.9	39.1	∞	KQ	4
33		472.8	736.5	2095.3	401.9	0.7	13.2	18.9	∞	0.7	13.9	32.8	∞	AK	4
34		541.4	977.6	489	1241.5	1.3	11.9	19.4	∞	1.3	13.2	32.6	∞	KH	4
35		235.4	1243.4	603	879.4	0.7	7.3	41.3	∞	0.7	8	49.3	∞	KH	4
36		406.9	1861.4	721.7	862.3	0.7	4.9	29	∞	0.7	5.6	34.6	∞	KH	4
37		946.6	1099.1	773.3	816.4	1	10.8	38	∞	1	11.8	49.8	∞	KH	4
38		798.6	1065.8	684.2	448.7	0.7	6.6	34.4	∞	0.7	7.3	41.7	∞	KH	4
39		663.9	965.4	1000.3	333.7	0.5	8.8	33.7	∞	0.5	9.3	43	∞	AK	4
40		457.6	784.7	2729.3	103.3	0.5	6.8	15.1	∞	0.5	7.3	22.4	∞	AK	4

Longitudinal unit conductance (S), Transverse unit resistance (Tr), Average longitudinal resistance (ρL), Transverse resistivity (ρt), Coefficient of anisotropy (λ), Reflection Coefficient (Rc), and resistivity contrast (Fc) are calculated results obtained from primary resistivity parameters such as resistivity thickness, and depth using equation 10-16. The calculated results are presented in table 3 below.

Table 3. The results of Dar Zarrouk Parameter Of The Study Area.

VES	Longitudinal unit conductance (S), mhos	Transverse unit resistance (Tr), Ωm^2	Average longitudinal resistance (Pl) Ω^{-m}	Transverse resistivity (pt)	Co-efficient of anisotropy (λ)	Refection co-efficient (Rc)	Resistivity contrast (Fc)	G.O.D
1	0.004	9318.08	2184.4	12849.5	0.333	0.918	0.042	0.38
2	0.001	385.2	642	660.9	0.383	0.567	3.170	0.48
3	0.005	8652.43	2012.7	1408.7	0.401	0.535	0.303	0.34
4	0.001	615.18	1025.3	783.6	0.397	0.481	3.333	0.48
5	0.001	8853.97	4583	1065.9	0.203	0.191	2.371	0.43
6	0.034	6338.3	638.4	270.0	0.680	0.622	0.047	0.19
7	0.005	392.28	280.2	240.6	0.374	0.700	5.080	0.56
8	0.001	2296.42	1640.3	682.0	0.519	0.153	2.912	0.48
9	0.006	3798.21	944.8	1608.8	0.389	0.475	0.356	0.38
10	0.004	11377.2	2256.9	925.4	0.355	-0.095	1.091	0.38
11	0.029	26425.1	1536.8	538.1	0.620	0.239	0.486	0.29
12	0.004	14110.53	2372.1	1222.3	0.402	-0.009	1.018	0.38
13	0.007	7124.35	1360.6	1134.6	0.370	0.325	0.509	0.38
14	0.008	12544.17	1636.7	590.4	0.429	0.219	1.165	0.34
15	0.020	24908.11	2022.3	410.0	0.546	0.384	2.286	0.51
16	0.010	27522.88	2838.8	479.6	0.579	0.241	2.179	0.48
17	0.001	2413.97	1856.9	1192.7	0.173	-0.203	2.438	0.34
18	0.006	15233.14	2491.5	616.9	0.363	-0.103	1.230	0.48
19	0.001	1422.7	1422.7	1138.7	0.155	-0.099	1.790	0.34
20	0.004	11763	2390	1509.5	0.406	0.371	0.459	0.34
21	0.001	23032.44	817.7	971.4	1.461	0.384	1.078	0.48
22	0.002	7771.2	466.6	449.1	2.247	0.720	5.889	0.48
23	0.006	6352.92	1329.3	895.5	0.405	0.222	0.636	0.38
24	0.001	702.94	585.8	527.9	0.228	0.429	3.892	0.48
25	0.004	4785.56	732.4	565.1	0.456	-0.245	1.316	0.43
26	0.026	2538.33	346.3	158.8	0.552	-0.014	1.027	0.45
27	0.005	582.56	228.0	487.2	0.527	0.444	1.963	0.56
28	0.002	1225.44	541.6	387.7	0.641	0.177	3.945	0.56
29	0.005	8862.34	1647.4	1264.3	0.376	0.161	0.722	0.38
30	0.007	24347.98	2255.6	880.6	0.557	-0.048	1.101	0.34
31	0.012	7475.82	1245	754.9	0.371	0.406	0.422	0.45
32	0.004	13278.79	2152.5	1038.3	0.397	-0.086	1.188	0.38
33	0.011	10052.76	1209.3	1207.4	0.503	0.480	0.352	0.34

VES	Longitudinal unit conductance (S), mhos	Transverse unit resistance (Tr), Ωm^2	Average longitudinal resistance (Pl) Ω^{-m}	Transverse resistivity (pt)	Co-efficient of anisotropy (λ)	Refection co-efficient (Rc)	Resistivity contrast (Fc)	G.O.D
34	0.016	21823.86	2008	291.0	0.577	0.435	1.999	0.45
35	0.003	164.78	235.4	505.2	0.296	0.682	2.062	0.64
36	0.012	30334.99	2990	604.9	0.541	0.089	2.579	0.29
37	0.018	42202.28	2819	590.1	0.548	0.027	1.421	0.29
38	0.001	559.02	798.6	564.4	0.310	0.143	1.558	0.48
39	0.006	8827.47	1629.3	784.0	0.355	0.018	0.965	0.38
40	0.006	5564.76	1242.3	1839.8	0.447	0.553	0.288	0.38
MAXIMUM	0.034	42202.3	4583.0	12849.5	0.717	0.9	5.889	0.6
MINIMUM	0.001	164.8	228.0	158.8	0.301	-0.2	0.042	0.2
AVERAGE	0.007	10399.5	1535.4	1102.4	0.504	0.3	1.667	0.4

SAMPLES OF THE DERIVED GEOLECTRIC CURVES

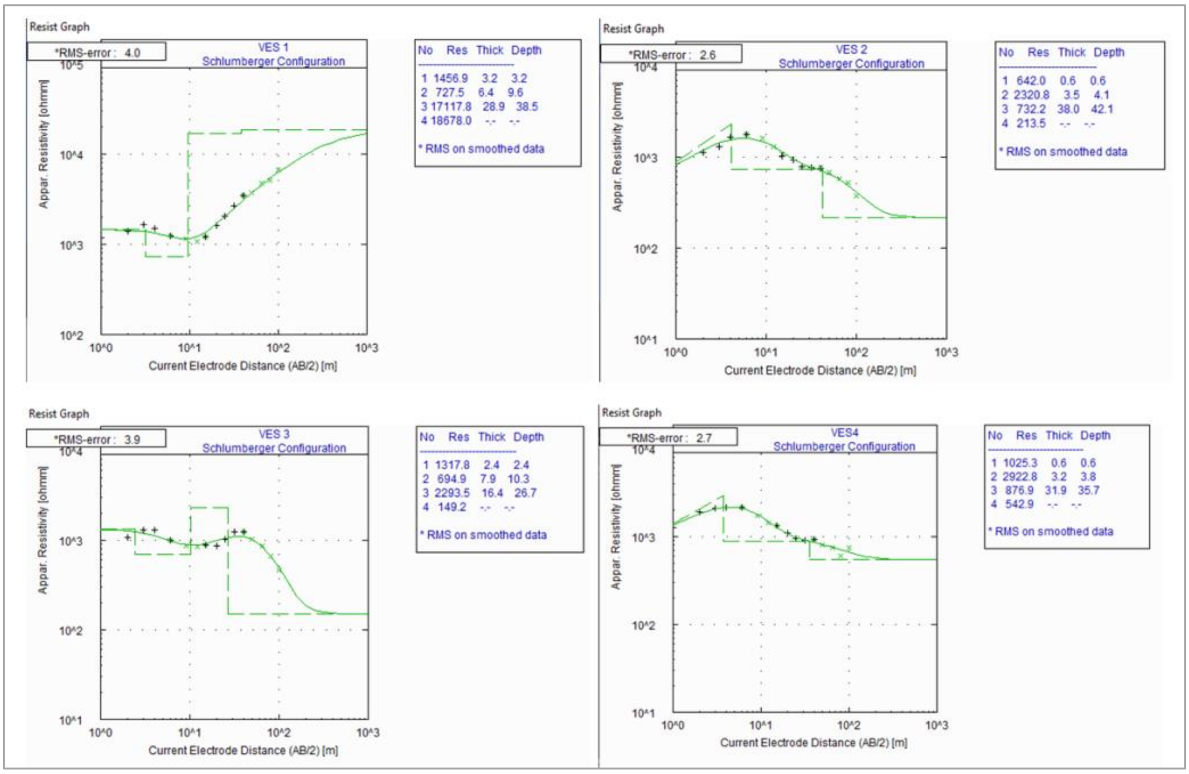

Figure 4. *Samples of Derived Geoelctric curves.*

3.1. Longitudinal Units Conductance (S)

It helps to define the degree of groundwater protection from vertical infiltration of pollutants [27]. According to [24] and [17], they stated that geologic formations with longitudinal conductance greater than 10 Ω-1 can be rated to have excellence aquifer protective capacity, while formations with (5-10) Ω-1 are rated very good, formations with (0.7-4.9) Ω-1 are rated good, formations with (0.2-0.69) Ω-1 are moderate, formations with (0.1-0.19) Ω-1 weak and formations with less than 0.1 Ω-1 are poor. It could be inferred that the entire study area has poor aquifer protection capacity since they all have S with less than 0.1 Ω-1.

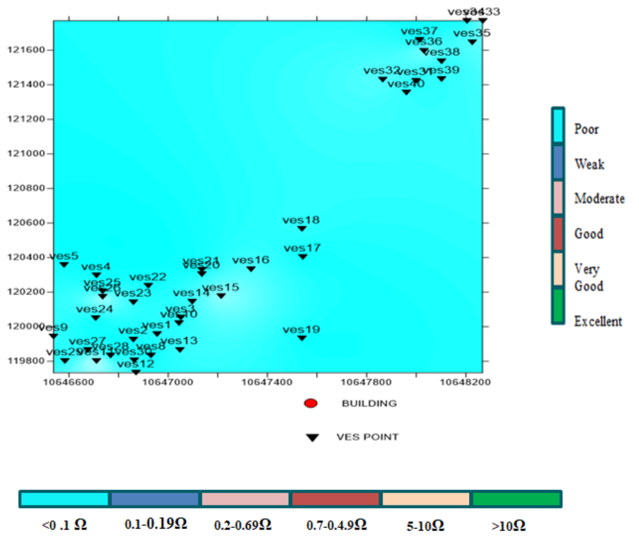

Figure 5. Spatial variation of longitudinal conductance (S) across the study area.

3.2. Transverse Unit Resistance (Tr)

It is used to delineate the most prolific area of groundwater potential for the purpose of hydrogeological investigation [21, 11]. The northeastern region from figure 2, (around VES 35 and 36) and southwestern region (around VES 12, 15, 16, 20) revealed relatively high Tr values, suggesting promising groundwater potential. In contrast, VES 2, 9, 19, 24, 25, 26, 27, 28, 34, and 37 have very low Tr values, indicating limited groundwater potential. VES 1, 4, 5, 13, 17, 18, 23 and 25 showed fair ground water potential.

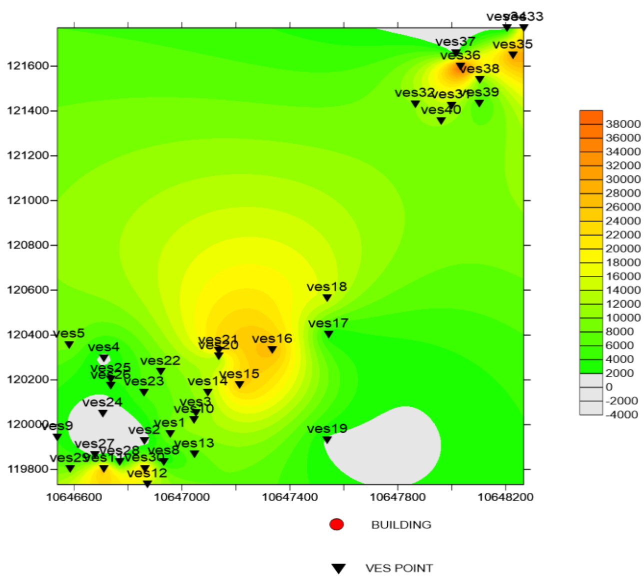

Figure 6. Spatial variation of Transverse unit resistance.

This infer that the major part of the study area are characterized with moderate to high groundwater potential.

3.3. Average Longitudinal Resistance (ρ_L)

The study notes that ρL can help assess the susceptibility of aquiferous units to infiltration and determines the direction of conductivity with depth. [15, 16] In addition, it was observed that an increase in thickness with depth results in a decrease in longitudinal resistivity with depth, and ρL reveals the rate of uniformity with the layer around it. Indicates high ρL values in the southwest, northwest, and few part of northeast compared to other areas, suggesting low conductivity with depth. This may be due to the geological units present in these regions.

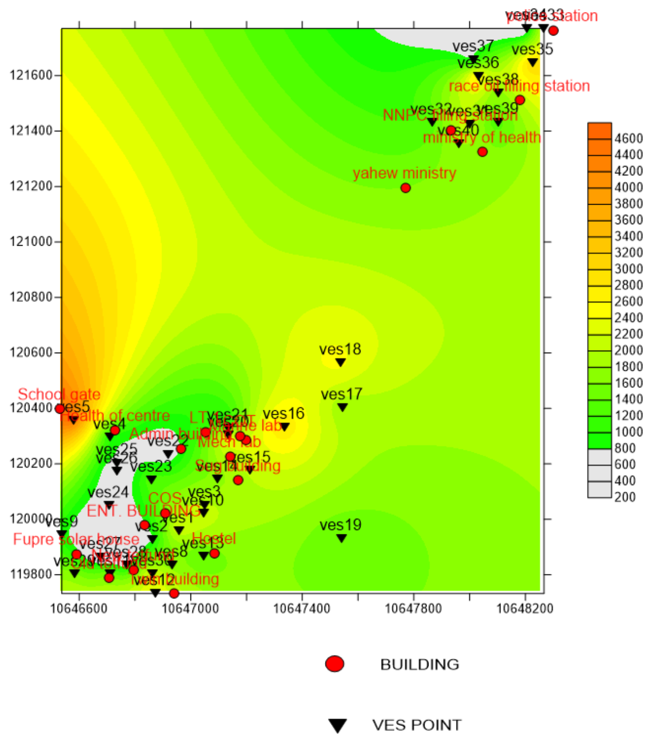

Figure 7. Spatial variation of Average longitudinal resistance (ρL) across the study area.

3.4. Transverse Resistivity (ρ_t)

Figure 5 reveals traverse resisitivity (ρ_t) is very low towards the southeast (VES 17 &19) and southwestern flanks of the study area. High ρ_t could be observed at VES 22, 23 and 24 while a fairly low ρ_t could be seen at the rest VES points locations. This can be attributed to the resistivity of subsurface rocks such as clayey sand and fine sand within the aforementioned area which tends to control the resistivity of rock within the area [7].

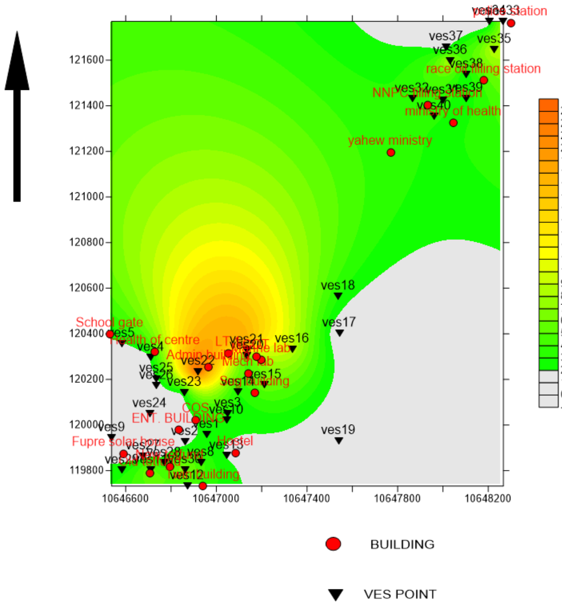

Figure 8. *Spatial variation of Transverse Resistivity (Pt) across the study area.*

3.5. Coeffcient of Anisotropy (λ)

It could be observed that a very low coefficient of anisotropy characterised the major part of southeastern (VES 17 and 19), northeastern (VES 35) and few part of south western flanks (VES 5 and 24) indicating significant variations in the anisotropic nature of the rock formations [10]. However, VES 22 and 23 are domiciled with high COA while all other VES points are characterrised with fairly low COA. According to [26, 18], high anisotropy values are an indication of low porosity and permeability which implies that such areas are of low hydrogeological viability or vice versa.

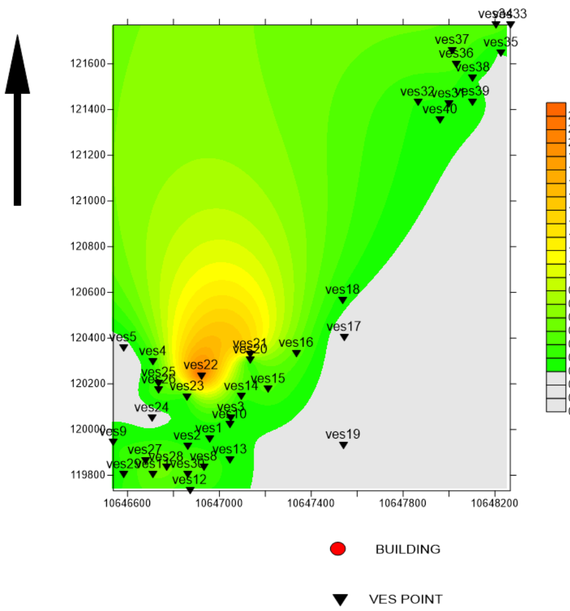

Figure 9. *Spatial variation of Coefcient of anisotropy (λ) across the study area.*

3.6. Resistivity Contrast (Fc)

Resistivity contrast (Fc) provides information on the area of water-bearing potential; low resistivity contrast values indicate high groundwater potential [2]. For this study, the estimated value of Fc ranges from 0 to 5.6. [2] believed that an area with a low value of Fc might indicate an aquiferous unit. From figure 7, over 67% of the study area are characterized with low resistivity contrast (0 to 2.0) which is VES 1, 3, 6, 9, 10. 11, 12, 13, 14, 18, 19, 20, 21, 23, 25, 26, 27, 29, 30, 31, 32, 33, 34, 37, 38, 39 and 40 while the rest 33% VES points have relatively high resistivity contrast. This implies that the study area is hydrogeological viable.

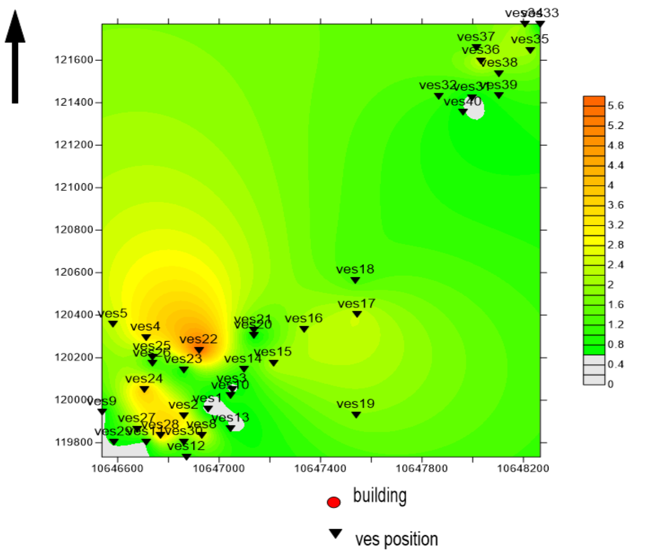

Figure 10. *Spatial variation of Resistivity contrast (Fc) across the study area.*

3.7. GOD Index

The result of the God index revealed that about 10% of the investigated VES points fall within low rating (VES 6, 11, 36, 37), 80% are moderate (VES 1-5, 7-10, 10-14, 16-26, 24-34, 38-40) while the rest 10% have high GOD index rating. The revealed that most part of the study area are moderately vulnerable to groundwater contamination. The GOD outline in Figure 8 identifies the divergence of the groundwater vulnerability to defilement within the study area.

A total of forty (40) electrical resistivity data were generated to a maximum current electrode spread of 100m wide at the study area using Schlumberger array The processed and interpreted result of the electrical sounding conducted at the study area revealed that it is majorly characterized with a maximum of four subsurface layers of eight (8) geoelectric curve type: HA (7.5%), KQ (32.5%), AK (20%), KH (22.5%), Q (5%), QH (5%), HK (5%) and QQ (2.5%). The second order geoelectric indices (Dar Zarrouk's parameter) which are the transverse unit resistance (Tr) revealed that the major part of the study area characterized with good to high groundwater potential.

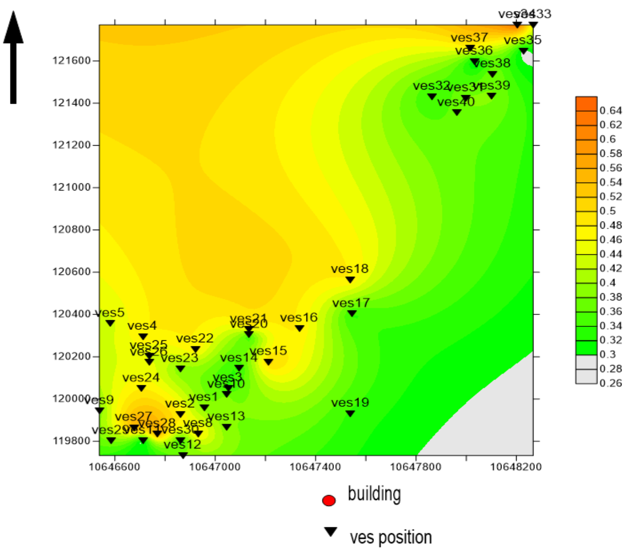

Figure 11. GOD-Index contour map.

The average longitudinal resistance (ρ_L) revealed that the study area is heterogeneous in nature. The transverse resistivity (ρ_t) of the study area connote that the study area are massively deposited with clayey sand and fine sand which tend to control the resistivity within the study area. The Coeffcient of anisotropy (λ) revealed that the major part of the study area are characterized with low Coeffcient of anisotropy which indicate high porosity and permeability thereby imply high hydrogeological viability of the study area. The resistivity contrast are revealed that the major part of the study area are characterized by low resistivty constract which implies high hydrogeological viability. The God index indicates that the most part of the study area moderately vulnerable to groundwater contamination while the Longitudinal unit conductance (S) revealed that the entire study area are characterized with low groundwater protective capacity.

4. Conclusion

This study offers crucial insights into the aquifer protective capacity and groundwater potential of the FUPRE campus and Agbarho axis in Southern Nigeria. The findings highlight a generally poor aquifer protective capacity, with values indicating significant vulnerability to contamination. Areas with high transverse unit resistance (Tr) values suggest promising groundwater potential, while low values point to limited availability. The resistivity and anisotropy analyses further reveal significant variations in subsurface properties, emphasizing the complex nature of the region's geology. The GOD Index assessment categorizes most of the study area under moderate vulnerability, with a considerable portion at high risk of contamination. These results underscore the need for effective groundwater management strategies, particularly in areas with high susceptibility to pollution. The study lays the foundation for future research that could integrate more detailed hydrogeological and geophysical data, which can help in ground water management and also to enhance the ground-water resources in sustaining the ability to protect the study area from any intrusion that can contaminate or pollute the subsurface water in the region.

5. Recommendations

1. *Enhanced Monitoring and Management:*

Regular Monitoring: Implement a regular monitoring program to continually assess groundwater quality and aquifer protective capacity. This will help in identifying changes in groundwater conditions and early detection of potential contamination risks.

Data Expansion: Extend the current dataset by increasing the number of Vertical Electrical Soundings (VES) and incorporating additional geophysical methods. This will provide a more comprehensive understanding of the subsurface conditions and improve the accuracy of groundwater potential and vulnerability assessments.

Strengthening Aquifer Protection: Use Planning: Develop and enforce land use policies that minimize activities which could compromise aquifer protection, especially in areas identified with poor longitudinal conductance. These activities include industrial operations, waste disposal, and intensive agriculture.

Protective Measures: Establish buffer zones around identified vulnerable areas to mitigate the risk of contamination. Implement pollution control measures and best practices in waste management to safeguard groundwater resources.

2. *Infrastructure Development:*

Recharge Enhancement: Consider artificial recharge techniques to enhance groundwater levels, particularly in areas with promising groundwater potential but low protective capacity. Techniques such as rainwater harvesting and recharge wells can be beneficial.

Well Construction Standards: Ensure that new wells are constructed with appropriate protective measures to prevent contamination, especially in regions with poor aquifer protective capacity.

Abbreviations

AVI	Aquifer Vulnerability Index
VES	Vertical Electrical Sounding
GOD	G-index O-index D-index
FUPRE	Federal University of Petroleum Resources Effurun

Conflicts of Interest

The authors declare no conflicts of interest.

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