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Evaluating Groundwater Resources in Basement Complex Areas Through Electrical Resistivity Techniques

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ABSTRACT

An approach engaging Vertical Electrical Sounding (VES) was carried out with a view to developing groundwater potential in Akure South local government area of Southwest Nigeria, thirteen (13) depth sounding data were acquired using Schlumberger array, with half maximum current electrode separation (AB/2) varies from 1 to 100 m. The VES data were quantitatively interpreted using partial curve matching and computer aided iteration to determine the geo-electrical parameters of each station. The result revealed a maximum of four (4) geoelectric layers which are topsoil (113–384 Ωm), laterite (248–1093 Ωm), weathered layer (72–155 Ωm) and fresh basement layer (955-9872 Ωm). Five (5) parameters namely, hydraulic conductivity, transmissivity, coefficient of anisotropy, aquifer thickness and aquifer resistivity which ranges from (0.0176–0.032) m/s, (0.128–0.3179) m/s^2, (1.016–1.7522), (4.0-16.3) m and (72–155) Ωm respectively were determined from the quantitatively interpreted geo-electrical parameters using the existing groundwater flow equations. The modeled aquifer hydraulic parameters are believed to have relevant contributions towards groundwater occurrence in the area of study. The produced aquifer hydraulic parameters were synthesized via Weighted Linear Combination (WLC)-multi criteria technique to determine the groundwater reservoir potential index (GRPI) values of the area. The GRPI results were processed to produce the groundwater potential map for the area and the direction of the ground water flow was also modeled using ground water modeling (GMS) software. The prediction map classified the area into very low, low and moderate potential zones as areas <95 Ω-m, 95–120 Ω-m, >120 Ω-m, respectively. About 85% of the area falls within low groundwater potential rating, the study area can be rated to be of low groundwater potential which can serve the proposed engineering building for domestic purpose.

1. Introduction

The majority of freshwater on Earth, around 98%, comes from groundwater, which is distributed pretty evenly over the planet. It offers a reasonable, continuous supply that, unlike surface water, is not entirely subject to drying up in the natural environment (Eyankware et al., 2023). Groundwater investigation is needed since statistics indicate that a portion of the earth's water is dangerous for human use, making drinkable and sanitary water a valuable resource. But water, which is present on Earth in such large quantities, is unevenly distributed in space, time, and circulation (Eyankware and Aleke, 2021). Because so much depends on groundwater, it's important to guarantee both the quantity and quality of the water.

According to Eyankware, et al. (2018), fresh water absorbed by the soil and held in the microscopic crevices between rocks and soil particles is known as groundwater. It is produced by rain or by melting ice and snow. Moreover, it denotes the percentage of water contained in geological formations like

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faults, fractures, and weathered rock regions that are the exclusive focus of geophysical research (i.e., the finding of subsurface features that are capable of storing groundwater in rechargeable quantity). Only approximately an eighth of the water on Earth is located on the surface. Not only is groundwater heavily relied upon as a primary drinking supply in many industrialized and developing nations, but it is also used as a secondary source of water for industrial and agricultural purposes (Eyankware, 2019). Groundwater is frequently found in a rock unit known as an aquifer. An aquifer is a rock or soil mass from which water can be extracted in substantial proportions (Eyankware and Akakuru, 2022).

An aquifer is said to be unconfined when it is exposed to the atmosphere, that is, when it is covered in permeable material, and confined when it is covered in impermeable rock. It takes an accurate grasp of the geo-hydrological properties of the aquifer units to successfully use groundwater in basement terrain. The discontinuous structure of basement aquifers makes this significant (Akinseye et al., 2023). The lithological structure known as an aquifer zone, which is characterized by fractures, shear, joints, fissures, and/or failed basement rocks, makes the location of boreholes crucial. It has been well demonstrated that geophysics may be applied to successfully identify aquifers in varied geologic terrains. But among other things, mapping prolific aquifer zones for the development of a productive well has proven possible and effective when using the electrical resistivity method. The depth sounding method (VES) is often used in surface geo-electrical methods. Because it is non-invasive, reasonably priced, and has other unique qualities, the geo-electric approach of groundwater research is unique (Opara et al., 2023; Opara et al., 2022).

Therefore, according to Zohdy et al. (1974), it is an efficient method of determining the subsurface geological frame of an area. In order to plan, develop, and manage groundwater resources in the area of investigation, this study aims to evaluate groundwater potential from geo-electrically derived aquifer hydraulic characteristics and the multi-criteria modeling of these parameters.

i. In order to evaluate groundwater potential, the research aims to understand the functional relationship between the geo-electric parameters and the features of the aquifer. The following are the goals of this work,
ii. ascertain the geo-electrical parameters from the interpreted geophysical data,
iii. identify the area's aquifer unit based on the outcome of (i),
iv. ascertain the geo-electrical parameter from the identified aquifer unit,
v. osing the groundwater flow equation that is currently in place, estimate the hydraulic properties of the aquifer, such as its hydraulic conductivity (K), transmissivity (T), coefficient of anisotropy (COA), thickness, and resistivity, from (iii) above; (v) create thematic maps of the aquifer hydraulic parameters and
vi. use a weight-linear combination multi-criteria synthesis technique to evolve the groundwater potential map of the region.

1.1. Climate, Location and Topography

The study area is in the Kure South local government area of Ondo State, Southwest Nigeria, along the Alagabaka Extension along Igbatoro Road. The study area is located inside the Universal Transverse Mercator (UTM) zones 31NWGS84datum, which is 749313–749341 m east and 799615–799664 m north (Fig. 1).

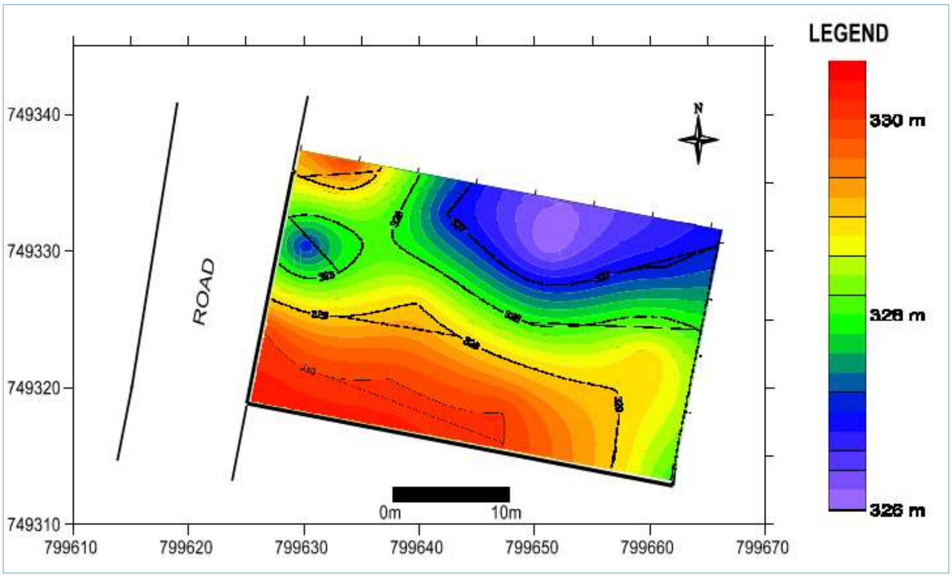

Fig. 1. Location map of the study area

The study area is approximately 629 m^2 in aerial extent. Alagabaka is one of the city's most developed regions, and both paved and unpaved roads make it simple to get to. The study area's elevation ranges from 326 to 330 meters (Fig. 1). Additionally, the location is in a tropical rainforest with a climate that features rainy and dry seasons. The region receives between 1500 and 2100 mm of rain on average each year (Agro-climatic and Ecological Project, 2006). The average temperature ranges from 18 to 33 ˚C. The vegetation is made up of many types of evergreen trees that produce tropical hardwood. Nevertheless, human activity has completely destroyed the study area's vegetation. Farmland makes up the majority of the area's vegetation at the time of data collection.

1.2. Local Geology of the Study Area

The research area is supported by the Basement Complex rocks of southwestern Nigeria (Fig. 2). Some of the petrological units discovered include the Migmatite-Gneiss-Quartzite Complex, charnockitic and dioritic rocks, older granites, and unmetamorphosed dolerite dykes (Rahaman, 1988). According to Kazeem (2010) and Olarewaju (1981), the older granite suite's granite rocks make up about 65% of Akure's total land area. The three primary petrographic variations are fine-grained biotite granite, medium- to coarse-grained non-porphyritic biotite-hornblende granite, and coarse-porphyritic biotite-hornblade granite. Categorization heavily relies on textural characteristics. Additionally distinct in Akure are the three primary textural types of charnockitic rocks. There are three different types of grains available: coarse, massive, and gneissic fine (Olarewaju, 2006). Unlike the majority of earlier granite, charnokite rocks are found as elongated, oval, or subcircular masses rather than as smooth, rounded boulders. Three separate occurrences of the charnockitic rocks are thought to exist nearby. The Akure body and a few other smaller bodies serve as examples of the first type of location, which is inside what seems to be the "core" of the granite rock. The second can be found near the edges of the granite bodies, as in the charnockitic bodies of Ijare and Uro Edemo-Idemo. The first two forms of occurrence are most prominent in the coarse-grained charnockitic type.

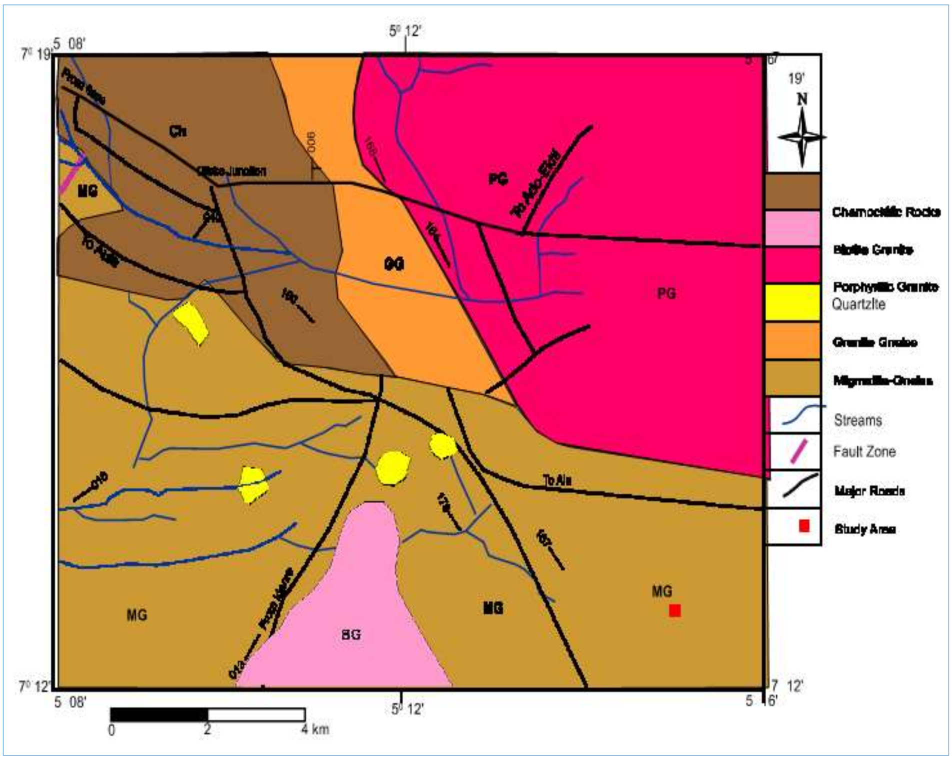

Fig. 2. Geological map of the study area (Modified after Owoyemi, 1996)

1.3. Hydrogeology of the Study Area

Groundwater in Nigeria is restricted by the fact that more than half of the country is underlain by crystalline basement. rock of the Precambrian era (Kazeem, 2007). The main rock types in this geological terrain include igneous and metamorphic rocks such as migmatites and granite gneisses (Fig. 2).

Dan-Hassan and Olorunfemi (1999) used the electrical resistivity method to delineate different subsurface geo-electrical layers, aquifer units and their characteristics, the subsurface structure, and its influence on the general hydrogeological condition in the north-central part of Kaduna State, Nigeria. According to previous authors, locating water-bearing units in an area underlain by basement complicated rocks is a difficult undertaking in general (Aboh and Osazuwa, 2000; Olurunfemi and Fasuyi, 1993). Exploration for groundwater is difficult due to the great variety in lithology and structure, as well as extremely localized water-producing zones (Abiola et al., 2009; Olurunfemi et al., 1999; Oladapo et al., 2004).

High topographical features that are associated with high bedrock relief are among the elements that are examined for a well site in basement complex locations (e.g., ridges). In some places, this is a crucial consideration for a good location. Because bedrock ridges' crests (when present) act as a radiating center for groundwater as water normally drains along steep slopes and hilltops to a point of discharge in adjacent lowlands, wells located on fat terrain and valleys tend to yield more water than wells located on hilltops and valley sides (Olorunfemi and Okhue, 1992). Fault breccias can be used to locate well locations in metamorphic terrains (Olorunfemi and Okhue, 1992). When features like a reef cut across a small piece of a valley with a high recharge area, hornblende gneiss and connected with basic dykes act as barriers to groundwater fow, and perfect conditions exist (Akakuru et al., 2023). However, both intergranular and fracture porosities can be seen in weathered rocks. The weathered portion's clay composition reduces permeability to some amount. Weathered and fractured aquifers in hard rock areas are capable of providing enough water to support the demands of a small hamlet or village (Patrick et al., 2021). Weathered, partially weathered, or fractured zones in crystalline rocks generate aquifers (Olorunfemi and Okhue, 1992). Weathering varies in nature and degree and is primarily determined by the presence of fractures at depth and favorable morphological features at the surface.

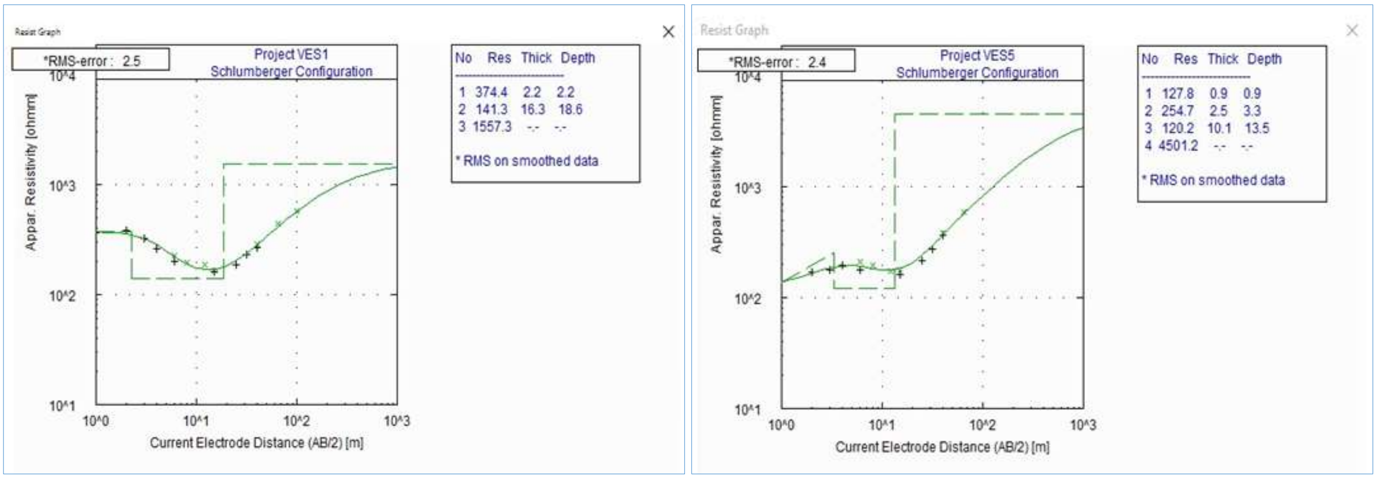

Fig. 3. Showing VES 1 (a) and VES 5 (b), respectively

Table 1. Scoring rate of the hydraulic parameter thematic maps (modified after Omo-Irabor et al., 2011)

Hydraulic Parameters	Category/Class	Aquifer expected productivity potential	Scores X_i	Weight age %	Normalized weight
Aquifer Thickness	0–9.79	Very low	1	25	0.25
	9.80–10.6	Low	2		
	10.7–11.3	Medium	3		
	11.4–16.3	High	4		
Aquifer resistivity	72–107.2	Very low	1	30	0.30
	107.3–118.2	Low	2		
	118.3–128.3	Medium	3		
	128.4–155	High	4		
Hydraulic conductivity	0.0176–0.0265	Very low	1	15	0.15
	0.0266–0.0287	Low	2		
	0.0288–0.0342	Medium	3		
	0.0243–0.0360	High	4		
Transmissivity	0.128–0.217	Very low	1	15	0.15
	0.218–0.238	Low	2		
	0.239–0.261	Medium	3		
	0.262–0.318	High	4		
Coefficient of anisotropy	1.75–1.25	Very low	1	15	0.15
	1.24–1.20	Low	2		
	1.19–1.16	Medium	3		
	1.15–1.01	High	4		

1.4. Hydrogeology of the Basement Complex Area

The crystalline rocks of the basement complex have flow porosity and permeability. Groundwater accumulation in this geologic setting is dependent on a number of factors, including the aquifer's degree of transmissivity and storage capacity, the nature and degree of rock fracturing, the rate at which water seeps into it, and the degree of weathering and overburden thickness. Groundwater is typically found in the subsurface's worn layer, joints, and severely cracked bedrock (Olorunfemi, 2000). The underlying rock of the basement may include broken and faulty systems that resulted from past tectonic activity, and they may encourage the buildup of groundwater. Thus, in typical basement settings, the identification of groundwater prospective zones may be made easier by the discovery of these hydrogeology formations (Omosuyi et al., 2003).

2. Methodology

2.1. Geo-electrical Measurements

Sixteen (16) VES were conducted within the study area, as shown in Fig. 1, with the help of an OHMEGA Terrameter and its accessories. For each VES profile, a Schlumberger electrode array was used with a maximum half current (AB/2) electrode separation of 100 m and a half potential (MN/2) electrode separation of 5 m. Surfer software was used to map the spatial distribution of S, Tr, L, and ρt. The following *Equation 1* was used to convert the observed field data to apparent resistivity (a) values:

$$\pi\left[\frac{(AB/2)^2}{(MN)}\right]\Delta V/I \tag{1}$$

The geo-electrical curves were generated by plotting the apparent resistivity data against the current electrode spacing (AB/2). The data processing was aided by the use of WINRESIST software, which allowed for the creation of sound curves (Figs. 3a and 3b). The thickness of the aquifer was calculated using the geo-electrical sections, which were produced using the information from the sounding curves. The charts supplied by Loke (1999) and Eyankware et al. (2022) were used to deduce lithologies that corresponded to the geoelectric section (2002). 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 (Zohdy et al., 1974; Maillet, 1947). Dar Zarrouk's longitudinal (S) and transverse (T) parameters were derived via *Equation 2* and *3*, respectively.

$$S = \frac{h}{p} \tag{2}$$

$$T = hp \tag{3}$$

where; h is the aquifer thickness and p is the aquifer resistivity as proposed by Akinseye et al., (2023).

The coefficient of anisotropy is a useful parameter of an anisotropic medium which indicates the degree of fracturing. It was determined using *Equation 4*.

$$\lambda = \sqrt{\frac{\rho_t}{\rho_L}} = \frac{\sqrt{ST}}{H} \tag{4}$$

The Reflection Coefficient (R_C) and Resistivity Contrast (F_C) were calculated using *Equations 5* and *6*.

As proposed by Umayah and Eyankware (2022) and Oladunjoye and Jekayinfa (2015).

$$R_c = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \tag{5}$$

$$F_c = \frac{\rho_n}{\rho_{n-1}} \tag{6}$$

where, ρn is the layer resistivity of the nth layer, and ρ_{n-1} is the layer resistivity overlying the nth layer as proposed by Akinseye et al., (2023).

2.2. Aquifer unit Hydraulic Properties Estimation

This method entails adding the resistivity and thickness value of the delineated aquifer for each VES station to the groundwater flow equation (aquifer hydraulic characteristics equation) for existing groundwater.

The standard equation was utilized to get the hydraulic parameters of the aquifer, and the resulting values were utilized to create a thematic map of the hydraulic properties within the study area.

The Modeling Groundwater Flow Equations see *Equation 7*. Hydraulic Conductivity (K) is given by *Equation 7*.

$$K=0.0538e^{0.0072p} \tag{7}$$

where, p is the aquifer layer resistivity.

Transmissivity (T) is the product of hydraulic conductivity (k) and the aquifer layer thickness, as shown in *Equation 8*.

$$T = K x h \tag{8}$$

where, h is the aquifer thickness.

2.3. Synthesis and Analysis Modelling

This involves analyzing the thematically generated hydrologic maps and allocating a weighted value to the identified aquifer hydraulic parameters based on their relevance and reference to the occurrence of groundwater in the designated study area.

Table 2. The computed GPI result for the study area

VES	AT (x)	AR (x)	K (x)	T (x)	λ (x)	AT (nw)	AR (nw)	K (nw)	T (nw)	λ (nw)	AT (w)	AR (w)	K (w)	T (w)	λ (w)	GPI
1	4	4	1	4	4	0.25	0.30	0.15	0.15	0.15	1	1.2	0.15	0.60	0.60	3.55
2	4	3	1	2	4	0.25	0.30	0.15	0.15	0.15	1	0.9	0.15	0.30	0.60	2.95
3	1	1	3	1	1	0.25	0.30	0.15	0.15	0.15	0.25	0.3	0.45	0.15	0.15	1.30
4	2	1	2	3	1	0.25	0.30	0.15	0.15	0.15	0.5	0.3	0.30	0.45	0.15	1.70
5	3	3	1	2	4	0.25	0.30	0.15	0.15	0.15	0.75	0.9	0.15	0.30	0.60	2.70
6	1	1	3	3	1	0.25	0.30	0.15	0.15	0.15	0.25	0.3	0.45	0.45	0.15	1.60
7	1	1	3	3	1	0.25	0.30	0.15	0.15	0.15	0.25	0.3	0.45	0.45	0.15	1.60
8	3	1	1	4	3	0.25	0.30	0.15	0.15	0.15	0.75	0.3	0.15	0.60	0.45	2.25
9	4	4	1	4	4	0.25	0.30	0.15	0.15	0.15	1	1.2	0.15	0.60	0.6	3.55
10	4	4	1	1	3	0.25	0.30	0.15	0.15	0.15	1	1.2	0.15	0.15	0.45	2.95
11	1	3	1	1	2	0.25	0.30	0.15	0.15	0.15	0.25	0.9	0.15	0.15	0.3	1.75
12	3	4	1	1	4	0.25	0.30	0.15	0.15	0.15	0.75	1.2	0.15	0.15	0.60	2.85
13	1	1	3	1	1	0.25	0.30	0.15	0.15	0.15	0.25	0.3	0.45	0.15	0.15	1.30

AT(X): Scoring value for the Aquifer Thickness ,AR(x): Scoring value for the Aquifer resistivity, K(x): Scoring value for the hydraulic conductivity, T(x): Scoring value for the transmissivity, λ(x): Scoring value for the Coefficient of Anisotropy, NW: the normalized weight for each of the parameters, GPI: groundwater potential index

Table 3. Summary of VES interpreted results

VES point	Curve type	Layer	Thickness (m)	Depth (m)	Apparent resistivity	Inferred lithology
1	H	3	2.2	2.2	374	Topsoil
			16.3	18.6	141	Weathered layer
			----	----	1557	Fresh basement
2	KH	4	0.3	0.3	115	Topsoil
			1.3	1.7	711	Laterite
			12.8	14.5	127	Weathered layer
			----	----	1120	Fresh basement
3	KH	4	0.6	0.6	146	Topsoil
			3.2	3.8	392	Laterite
			4.0	7.9	72	Weathered layer
			----	----	955	Fresh basement
4	KH	4	0.5	0.5	193	Topsoil
			2.4	2.9	509	Laterite
			9.5	12.5	91	layer
			----	----	4912	Fresh basement
5	KH	4	0.9	0.9	128	Topsoil
			2.5	3.3	255	Laterite
			10.1	13.5	120	Weathered layer
			----	----	4501	Fresh basement
6	KH	4	0.6	0.6	113	Topsoil
			2.6	3.1	676	Laterite
			8.6	11.7	91	Weathered layer
			----	----	5049	Fresh basement
7	KH	4	1.1	1.1	259	Topsoil
			2.3	3.4	671	Laterite
			8.5	11.9	90	Weathered layer
			----	----	9872	Fresh basement
8	KH	4	0.5	0.5	263	Topsoil
			2.4	0.9	411	Laterite
			10.7	13.5	100	Weathered layer
			----	----	5340	Fresh basement
9	KH	4	0.6	0.6	146	Topsoil
			2.2	2.9	248	Laterite
			14.8	17.7	145	Weathered layer
			----	----	3164	Fresh basement
10	KH	4	0.7	0.7	383	Topsoil
			3.4	4.1	570	Laterite
			11.6	15.7	150	Weathered layer
			----	----	2544	Fresh basement
11	KH	4	0.4	0.4	206	Topsoil
			2.5	2.9	627	Laterite
			9.4	12.3	120	Weathered layer
			----	----	2338	Fresh basement
12	KH	4	0.8	0.8	278	Topsoil
			4.6	5.4	434	Laterite
			10.7	16.2	155	Weathered layer
			----	----	8562	Fresh basement
13	KH	4	0.4	0.4	118	Topsoil
			1.8	2.3	1093	Laterite
			5.4	7.6	80	Weathered layer
			----	----	4566	Fresh basement

2.3.1. Weighting Assignment and Normalized Weight Determination

The weighting assignment is a qualitative method, as demonstrated by the research by Omoribor et al. (2011). Nonetheless, *Equation 8* was used to standardize the weighted values provided. This requires giving each criterion a weighted percentage value based on how much of a contribution they make to the productivity of groundwater potential. The normalized weights for these aquifer hydraulic parameter requirements were calculated using *Equation 9*. The weight age% and normalized weights are displayed in Table 1.

$$NW = \frac{Wi}{\sum_{i}^{n} = 1\, Wi} \qquad (9)$$

where; *NW* is the normalized weight, *W1* is the assigned weight for each criterion and *Σw* is the summation of all the assigned weight.

2.4. Multi-criteria Weight Linear Combination Application

The Weighed Linear Combination (WLC) multi-criteria sizing technique is used to evaluate the groundwater potential index, as reported in the study by Omo-Irabor et al. (2011). In *Equation 10*, the WLC simple mathematical modeling expression is shown.

$$Y = \sum_{i=1}^{n} NWiXi \qquad (10)$$

where; *Y* is the groundwater reservoir potential index, *NW* is the normalized weighted value for each team that varies from 1-4 (aquifer hydraulic conductivity, transmissivity, thickness and coefficient of anisotropy) and *Xi* is the assign score for the classes in each team (criterion) that is derived from the theoretical map produced.

2.5. Estimation of Groundwater Potential Index (GPI)

The above *Equation 10* has been modified and changed to produce *Equation 11*.

$$GPI=AT_{NW}AT_X+AR_{NW}AR_x+K_{NW}K_X+T_{NW}\,T_X+COA_{NW}COA_X \quad (11)$$

where; ATx is the s core value for aquifer thickness, AR_{NW} is the normalized weight for aquifer resistivity, ARx is the s core value for aquifer resistivity, K_{NW} is the normalized weight for aquifer hydraulic conductivity, Kx is the s core value for hydraulic conductivity, T_{NW} is the normalized weight for aquifer a transmissivity, Tx is the s core value for aquifer transmissivity, COA_{NW} is the normalized weight for coefficient of anisotropy and $COAx$ is the score value for coefficient of anisotropy.

The GPI of a sounding station is determined by adding together the contributions made by each team at a given site. Table 2 shows the estimated GPI values for each VES station using *Equation 11*.

2.6. The GPI Modeling

The groundwater potential modeling approach is based on the synthesizing index results obtained from multi-criteria modeling, such as the GPI. The partial attributes that indicate the variance of the area's aquifer properties index are displayed by the predicted model potential map soft end. The calculated GPI values (Table 2) were put on the base map utilizing the geophysical software (Surfer 13) platform to spatially distribute the index attribute based on the coordinates of each VES station. These index attributes were subsequently divided using the equal class intervals scheme into four (4) categories. The resulting map is the region's GPI model map.

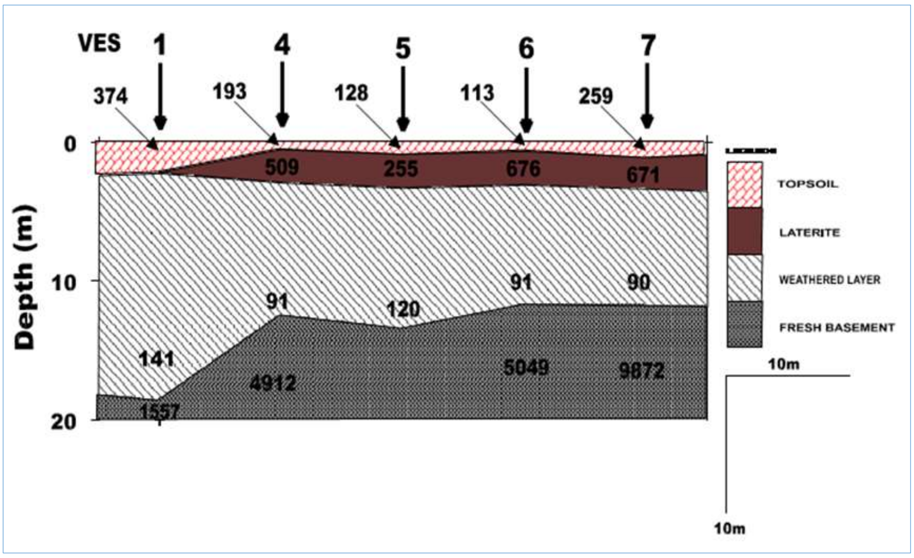

Fig. 4. Geoelectric section along Transverse1

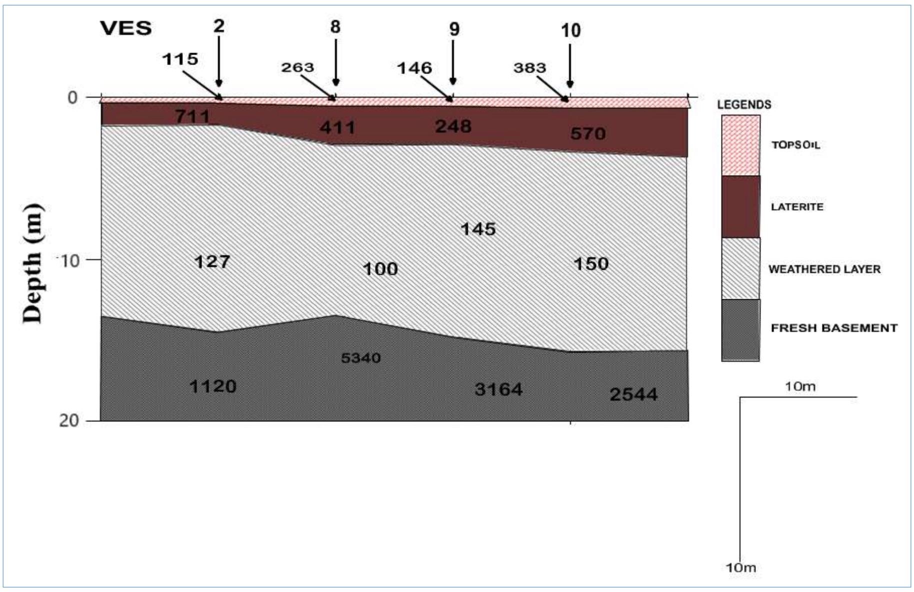

Fig 5. Geo-electric section along Transverse2

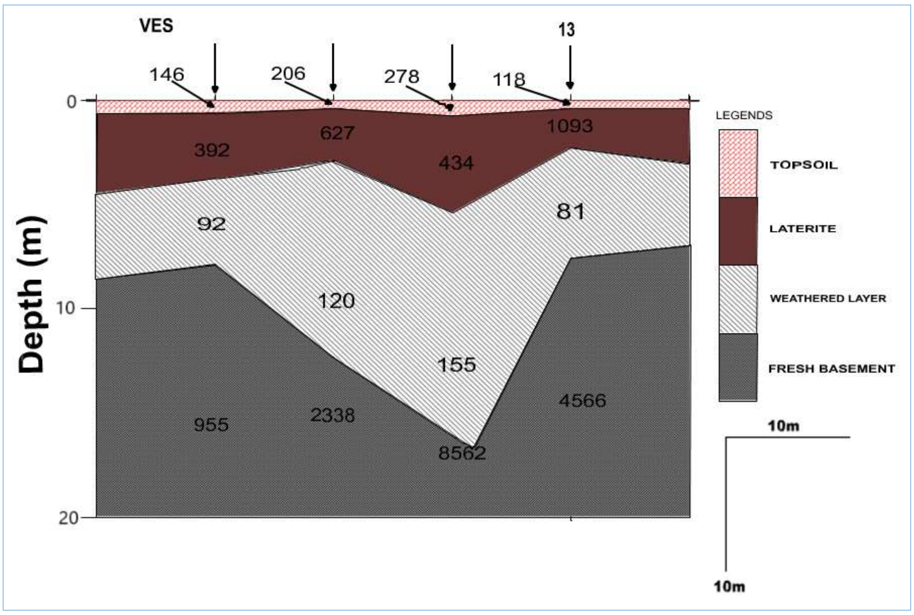

Fig. 6. Geoelectric section along Transverse3

3. Results and Discussion

3.1. Discussion of the Vertical Electrical Sounding Result

Table 3 presents an overview of the interpreted VES data. The study area's curve types are H and KH. Three to four layers make up the distinctive geo-electric layers shown by these curves.

3.1.1. Geoelectric Section

The geoelectric section, which is generated along the established transverses, revealed variations in the resistivity and thickness values of the layers delineated beneath the study area and are summarized in Table 4. The sections revealed three to four geoelectric layers, namely topsoil, laterite, weathered layer, and fresh bedrock. The thickness ranges for topsoil are from 0.3 to 2.2 m, while the resistivity ranges from 113 to 383 Ωm, typical of sandy clay/clay sand. The laterite, which is the main aquifer unit in the area, has a thickness range of 4.0 to 16.3 m, and the resistivity ranges from 72 to 155 Ωm, typical of clay/sandyclay. The bedrock ranges in resistivity from 955 to 9872 Ωm, and the depth of the bedrock varies from 7.6 to 18.6 m, as shown in Figs. 4–6, respectively.

Table 4. Results of the estimated aquifer hydraulic parameters of the study area

VES No	Aquifer interpreted Parameters		Aquifer Hydraulic parameters		
	AT (m)	AR (Ωm)	K (m/s)	T (m/s^2)	COA
1	16.3	141	0.0195	0.3179	1.0524
2	12.8	127	0.0216	0.2765	1.1457
3	4.0	72	0.032	0.128	1.3483
4	9.5	91	0.0279	0.2651	1.2613
5	10.1	120	0.0227	0.2293	1.0431
6	8.6	91	0.0279	0.2399	1.3946
7	8.5	90	0.0281	0.2389	1.3697
8	10.7	100	0.0262	0.2803	1.1663
9	14.8	145	0.0189	0.2797	1.016
10	11.6	150	0.0183	0.2123	1.1668
11	9.4	120	0.0227	0.2134	1.2447
12	10.7	155	0.0176	0.1883	1.1116
13	5.4	80	0.030	0.162	1.7522

3.2. Aquifer Hydraulic Parameters of the Study Area

A summary of the hydraulic parameters of the aquifer assessed in the research region is presented in Table 4.

3.2.1. Aquifer Unit Thickness Map of the Study Area

Fig. 7 displays the study area's aquifer thickness map. The aquifer unit's thickness varies from 4 to 16.3 m. The areas designated K1 to K2 have a comparatively thicker aquifer unit than 10 m, while the areas labeled J1 and J2 have a relatively thin one. A major water-bearing layer is thought to be the thick aquifer unit (Bala and Ike, 2001; Olonfemi and Fasuyi, 1993). Therefore, the study area's J1–J3 areas are prospective zones for groundwater development due to their comparatively moderate groundwater potential.

3.2.2. Aquifer Unit Resistivity Map of the Study Area

The aquifer's resistivity measurements underneath each VES station were contoured to create Fig. 8. The area labeled

"Mislow Resistive Aquifer Unit" has resistivity ranging from 95 Ω-m to 120 Ω-m, while the area underlain by comparably very low resistive aquifer units (Q1 and Q2) has resistivity less than 95 Ω-m. These areas are exposed by Thema. Given that the areas designated M and Q are thought to contain a substantial amount of water, they are promising zones for the development of groundwater in the research area.

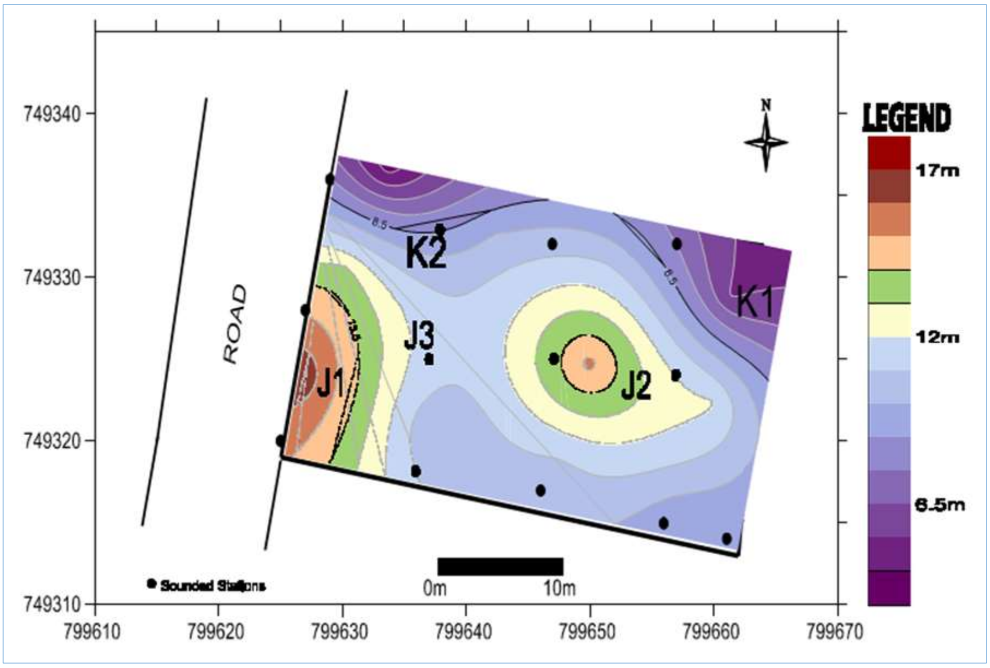

Fig. 7. Aquifer unit thickness map of the study area

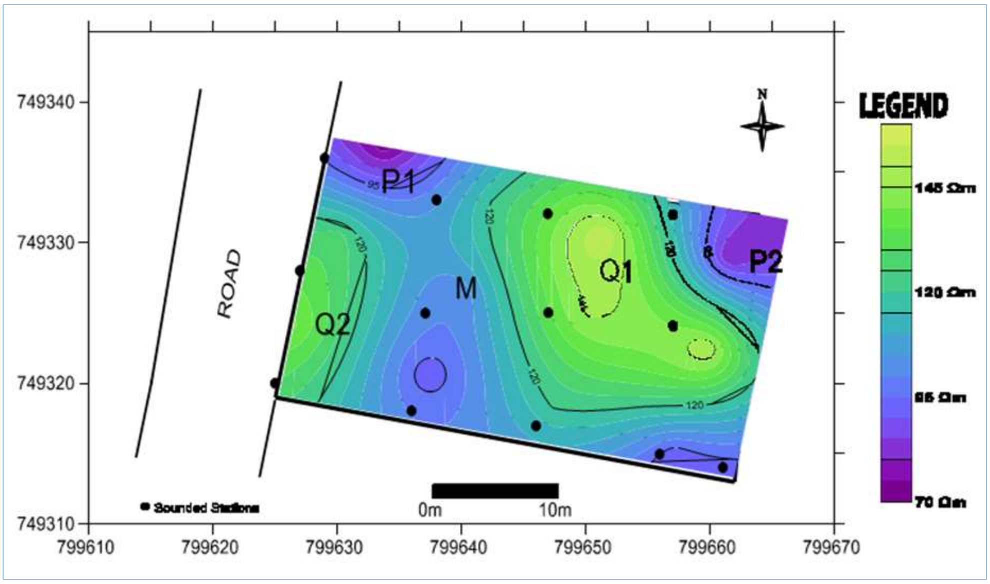

Fig. 8. Aquifer unit resistivity map of the study area.

3.3. Hydraulic Conductivity Map of the Study Area

Fig. 9 showed the aquifer hydraulic conductivity (K) map of the study area. It was observed from the map that the K values range between 0.0176 and 0.030 m/s. It is a measure of the volume of water the aquifer is able to transmit per unit area per hydraulic gradient. The regions labeled A1 and A2 are of low conductivity, which implies the region is of low transmitting rate; the regions labeled B1 and B2 are of medium-high conductivity, which implies moderate transmitting rate; and the regions labeled C1 and C2 are of high conductivity, which signifies high transmitting rate.

3.3.1. Hydraulic Transmissivity Map of the Study Area

The hydraulic transmissivity of an aquifer is a function of the aquifer layer thickness and the conductivity, with values ranging between 0.128 and 0.3179 m^2/s.

Fig. 10 shows the hydraulic transmissivity map of the study area. The zones with the highest transmissivity are labeled A1 and A2 with transmissivity values greater than 0.33 m^2/s; the area with moderate transmissivity is labeled B with transmissivity values ranging between 0.24 and 0.32 m^2/s; and the areas with low transmissivity are labeled C1 and C2 with transmissivity values below 0.24 m^2/s. The study areas show moderate-high transmitting rate.

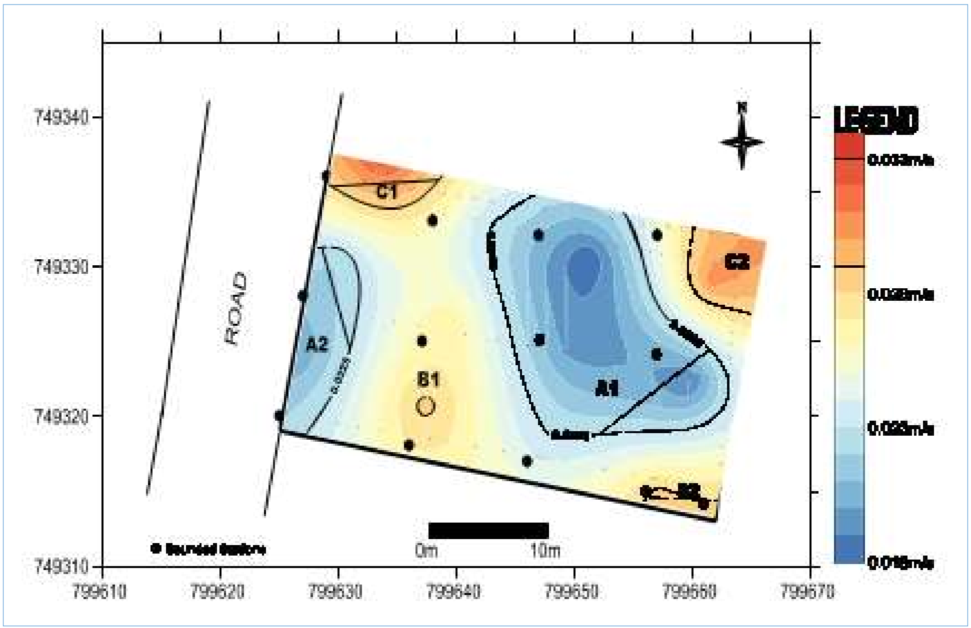

Fig. 9. Hydraulic conductivity map of the study area

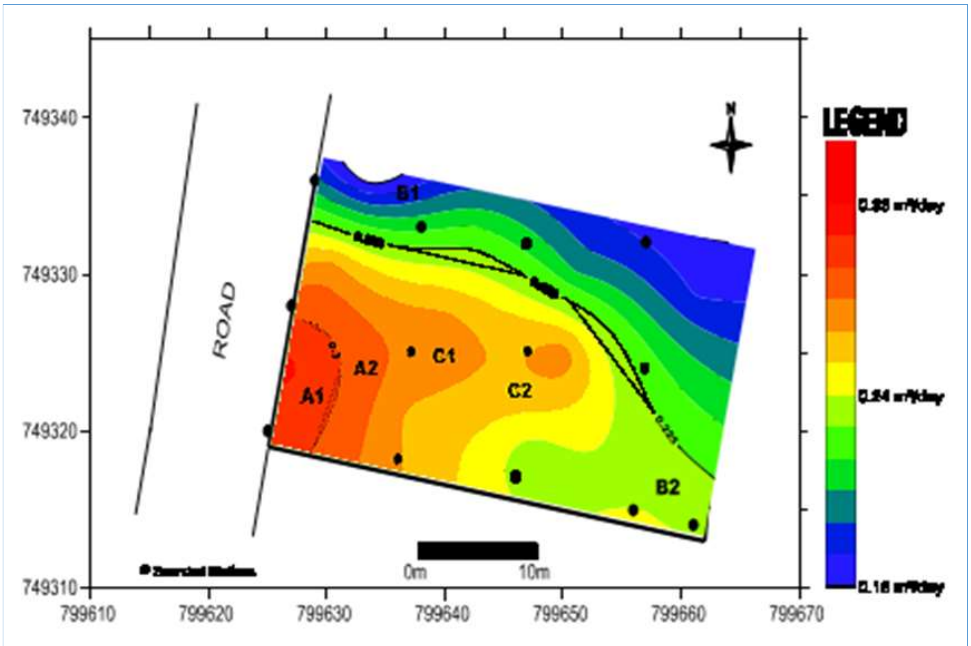

Fig. 10. Aquifer transmissivity map of the study area

3.4. Coefficient of Anisotropy of the Study Area (λ)

Olayinka and Oyedele (2019) and Keller and Frischnecht (1966) state that high anisotropy values are a sign of low porosity and permeability, indicating low hydrogeological viability in those places. Nevertheless, regions with low anisotropy values indicate considerable porosity and permeability, along with some degree of fractures, down to a specific depth. The spatial distribution map of the coefficient of anisotropy is presented in Fig. 11. The degree of nonuniformity resulting from cracking, faulting, weathering, and other processes is known as the coefficient of anisotropy. Consequently, the λ serves as a measure of the degree of fracture, with the lower the λ, the more the fracture (Adelusi et al., 2004). The research area's coefficient of anisotropy is in line with the study conducted by Akinseye et al. (2023). Deduction according to Akinseye et al. (2023) revealed that the value of λ within the Oba-Ile estate from the NTA road axis of Akure ranges from 1 to 1.5.

3.5. Groundwater Evaluation of the Study Area

The GPI for the research area is 1.30 to 3.55, as shown on Fig. 12. The study area is divided into three classes based on the groundwater potential model: very low, low, and moderate (Fig. 12).

The groundwater potential of the studied region might be considered poor as most of it (about 85%) is situated in the zone of low groundwater potential.

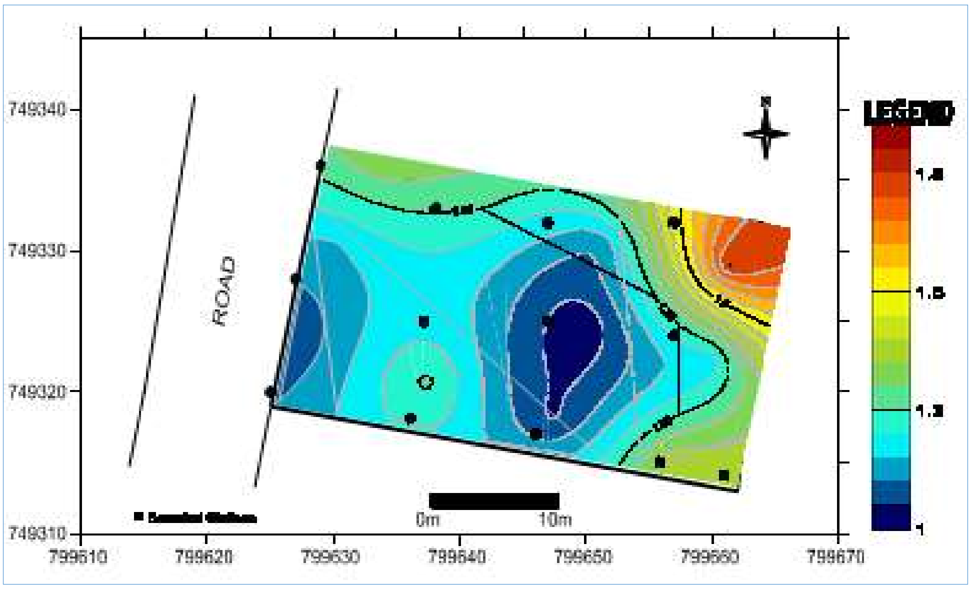

Fig. 11. Coefficient of anisotropy map of the study area

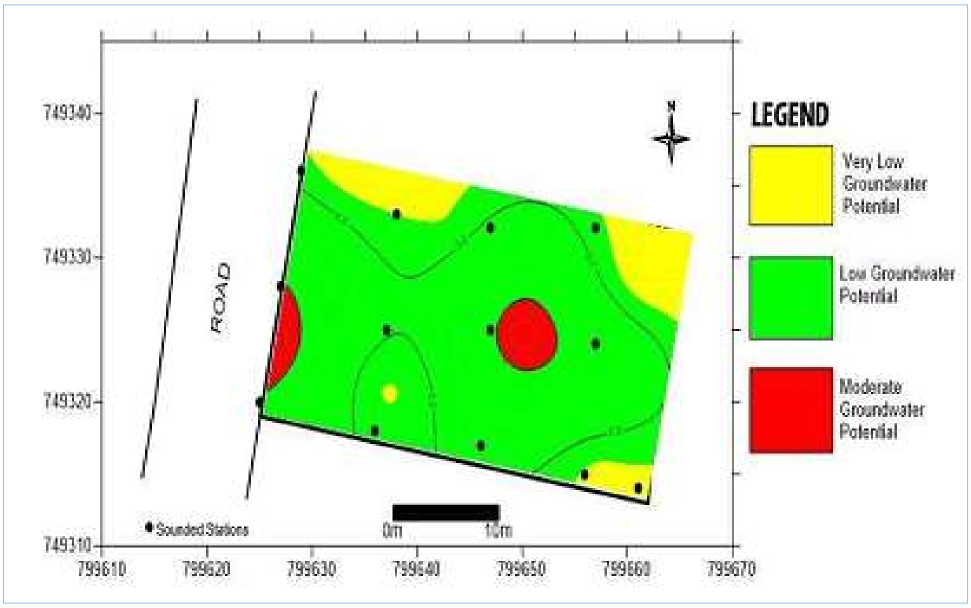

Fig. 12. Groundwater potential map of the study area

4. Conclusions

Geophysical investigation for assessment of groundwater potential was carried out in parts of the Ondo state, southern, Nigeria. The VES data obtained from the study was used to generate second geoelectric parameters such as aquifer thickness, aquifer resistivity, hydraulic conductivity, transmissivity and coefficient of anisotropy. This study used the electrical resistivity technique to evaluate the hydraulic properties of a typical basement complex. The results provided information on the aquifer's hydraulic characteristics, including thickness, anisotropy coefficient, transmissivity, hydraulic conductivity, and resistivity. The hydraulic properties of the aquifer were plotted out thematically. The hydrologic temperature gradient GPI model map inside the study region was created using the multi-criteria weight linear combination model. Using the specified scoring rate scale and the estimated productive potentiality of the aquifer, the generated GPI map was used to create the groundwater potential map of the research region. Three groundwater potential zones—very low, low, and moderate potential—were identified using the potential map. The area can be inferred to have low level groundwater potential rating based on the anticipated area coverage of the low potential zone. The produced groundwater potential map serves as a vital tool for stakeholders, guiding decisions regarding the use of groundwater for domestic purposes while emphasizing the need for sustainable management practices in areas characterized by low potential. This study underscores the importance of geophysical techniques in groundwater exploration and sets a foundation for further research aimed at improving water resource availability in the region.

5. Recommendations

It is advised that the hydraulic conductivity and other aquifer hydraulic parameters be determined in the laboratory or estimated from borehole data in the study area to validate this model because groundwater reservoir potential is directly correlated with aquifer hydraulic properties (transmissivity, hydraulic conductivity, coefficient of anisotropy, aquifer thickness, and aquifer resistivity). Ground-truthing by drilling is highly essential to validate the result in this research. The research area's best groundwater development and exploration can be achieved by utilizing the areas with defined moderate groundwater potential.

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