Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2024, Volume 15, Issue 5, Page 723-742

http://www.jmaterenvironsci.com

Identification of Groundwater Potential Zones for Boreholes Siting: A Case Study of Isale-Oyo, Oyo Town, Southwest, Nigeria

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***Received** 28 Mar 2024,*
***Revised** 21 May 2024,*
***Accepted** 22 Apr 2024*

Keywords:
- ✓ *Groundwater potential Zones;*
- ✓ *Indices of groundwater potential:*
- ✓ *Frequency of occurrence of zones:*
- ✓ *Groundwater potential zones rating.*

***Citation**: Fakunle M. A., Isiaka S. O., Oladejo O. F., Agbaje W.B., Popoola M. M., Ibrahim M. A., David A. K. (2024) Identification of Groundwater Potential Zones for Boreholes Siting: A Case Study of Isale-Oyo, Oyo Town, Southwest, Nigeria, J. Mater. Environ. Sci.,15(5), 723-742*

Abstract: This research study aimed to identify and predict sites with high groundwater potential for borehole development in Isale-Oyo, Oyo Town, Southwest Nigeria, with the goal of addressing the challenges arising from the poor and insufficient supply of groundwater in the study area. The study utilized ten Schlumberger Vertical Electrical Soundings (VES) within the geographic latitude 7° 51' 72" - 7° 52' 44.4"N and Longitude 3° 48' 54" - 3° 51' 18" E, and subsequently analyzed and interpreted the VES data using IP12WIN software to obtain the resistivity and thickness of each layer. The resistivity and thickness were then utilized to calculate seven (7) distinct groundwater potential indices (Transverse resistance, Transmissivity, Hydraulic conductivity, Coefficient of Anisotropy, Reflection Coefficient, Resistivity Contrast, and Resistivity of Formation). It had been reported by researchers that aquifer thickness and these indices have different values that they used for the identification, prediction and rating of groundwater potential. It was this information that were employed during the analysis of aquifer thickness and the calculated groundwater indices to identify, predict and rate groundwater potential of the study area. The frequencies of occurrence of rating of each zone in the various analyses were recorded. The results showed that the Oranyan zone had the highest groundwater potential, occurring seven (7) times out of the eight groundwater indices. Ajegunle, Alasela, Elere, Saabo, and Oroki zones had moderate groundwater potential, occurring four (4) times each. The Elegbo and Niresa zones had low productive potential, occurring three (3) times each in the analysis of various parameters of groundwater indices. The Sakutu and Akodudu zones were adjudged to have very low groundwater potential, occurring only twice (2) out of the eight groundwater potential parameters. Overall, the study demonstrated that the various parameters of groundwater potential indices can be used to identify and locate zones with high, moderate, low, and very low groundwater potential for siting boreholes. The results can serve as a baseline for groundwater resources management, facilitating water supply for domestic, industrial, and agricultural purposes.

1. Introduction

1.1. Background of the study

Water, a natural resource, is useful to plants, animals and human beings. It could be used for drinking, bathing, irrigation purposes, swimming, household chores (washing of plates and clothes), cooling of electricity generators in thermoelectric power industries, etc. Water dictates the pace of settlement.

The sources of water could be broadly classified as surface water and underground water and they amount to 1.37 x 10^8 million ha (Kumar *et al.*, 2005). Surface water is obtainable in lakes, rivers, streams, ponds, seas and oceans; while underground water, otherwise known as groundwater is the one that exists in spaces between loose particles of dirt, rocks, in cracks and crevices in rocks. The frequent contaminations of surface water by the activities of both animals and humans have made man to look for fresh water that will make them to live a disease freed life (Brahimi *et al.*, 2015). According to Singh *et al.* (2006) groundwater represents approximately 97% of the earth's freshwater. Abdulrahman *et al.* (2017) describe groundwater source as the part of precipitation which seeps down through the soil until it reaches rock materials that are saturated with water. The demand for water from this water source increases in manifold as a result of population growth and development of an area. UNESCO (2014) reported that 10%, 40% and 50% of groundwater were used for irrigation, industry use and drinking, respectively. Todd (1980) described the geological formation which can store and transmit groundwater in sufficient quantity for economic utilization as Aquifer. Freeze and Cherry (1979) identified aquifers to include sandstone, conglomerate, fracture lime, unconsolidated sand, and fractured volcanic rocks. For an aquifer to be good it must be permeable and water should be abstracted in sufficient volume. Therefore, the availability, quantity and exploitability of groundwater from the host rock depend on the porosity and permeability of the host rock. Porosity of a geological material is the ratio of volume spaces to the total volume of rock, sediment or soil (Obiora *et al.*, 2015). However, various geophysical techniques have been developed which are cost effective and save time, and can be deployed to acquire information about subsurface hydrogeology (Helaly, 2017). Among these is the electrical resistivity method. The different techniques of electrical resistivity survey for groundwater in an aquifer include: Vertical Electrical Sounding (VES), Horizontal Resistivity Profiling (HRP) and Azimuthal Electrical Resistivity Probing (AERP). In this study, VES was used because it gives detailed information on the vertical succession of different conducting zones (aquifers) or formation and their individual thickness as well as the true resistivity below a given point on the earth surface (Telford *et al.*, 1976). Knowing the thickness and resistivity of the aquifer, its transverse unit conductance (R) and Longitudinal unit conductance (C) can be calculated easily. Maillet (1947) introduced the concept of these parameters and named them as the Dar Zarrouk variable (R) and Dar zarrouk function (C). Also, Heigold *et al.*, (1979) established the association of aquifer hydraulic conductivity with resistivity measurements. So, this study aimed at identifying and predicting the aquifer potential zones of the study area by using groundwater indices parameters which were calculated from the field vertical electrical sounding data.

1.2 Description of the study sites and its Climate

The study area comprises of ten (10) communities, namely Akodudu, Ajegunle, Alasela, Elegbo, Elere, Niresa, Oranyan, Oroki, Saabo and Sakutu. These communities constitute what is called Isale-Oyo, the largest parts of Atiba Local Government in Oyo State, southwest, Nigeria. These communities are located within the geographic latitude 7° 51' 7.2" - 7° 52' 44.4"N and longitude 3° 48' 54"- 3° 51' 18"E. These communities are well connected to one another and to other parts of the local government by good networks of tarred roads and footpaths. Since these communities are in the southwestern part of Nigeria, they also enjoy the warm climatic conditions with relatively high temperatures throughout the year. The two distinct seasons that characterize these communities are the rainy (wet) and dry seasons which are typical of the southwestern part of Nigeria. The rainy season usually takes off from March and ends with heavy downpour in the month of October. The two peaks of these seasons occur in the months of July and September. The dry season which is characterized by bright sunshine, hot and dry winds known as the Harmattan roughly starts between November and February. During this season, the humidity becoming extremely low, the grasses dried, and most of the rivers and streams in the area dried up. The changes in climatic conditions that occurred from rain to dry season affected the vegetation of the study area adversely which makes it to be thick in one season (rain) and light in the other (dry), typical of the vegetation of the southwestern Nigeria. Very light vegetation could also be attributable to human activities such as cultivation, mining, charcoal production and man's patterns of land use, as the practice in the study site. The topography of the study area is generally undulating, as it is lithology controlled, consisting of rugged terrains with series of highlands, lowlands with steep and gentle slopes. Thus, the landforms can simply be classified in to highlands, hills, plains and river valley systems. The drainage is perfectly dendritic and is such that most of the streams in these communities empty into the bigger river called Erelu, which flows southwards. This river is dammed to serve as the major source of water for these communities and its environ.

1.3 Geology of the study Area

The study site being an integral part of the southwestern part of Nigeria is underlain by Crystalline Basement Complex rock of Precambrian age. typical of the geology of the southwest Nigeria. The lithology of the crystalline basement complexes, comprises of (i) Migmatite-Gneiss Complex (quartzite, gneissic rocks), (ii) low to medium grade meta-sediments (Green schists facies, namely quartz schist and mica schist) and (iii) the pan African Granitoids (older granites) that are synthesis to late tectonic intrusion with this composite of rocks. Olayinka *et al.* (2004) identify the major lithological units to include the granite, gneiss, migmatite gneiss and charnockite. The grain size and mineral composition of the basement rocks varied significantly. The rocks of the study area are predominantly quartz gneiss and schists, consisting mainly of quartz with small amount of white micaceous minerals. The grain size varied from very coarse-grained pegmatite to medium grained gneiss. **Figure 1** is the map of Nigeria showing the geology of Oyo State and by extension the geology of the study area

1.4 Hydrogeology of the Study Area

The hydro geologic properties of a rock are determined by its porosity and permeability and these in turn depend on the size, shape and arrangements of the grains and mineralogy of the rocks. In the findings of Olorunfemi *et al.* (1991) and Fashae *et al.* (2014), rocks in basement complex terrain lack interconnected pore spaces (primary porosity) but the development of aquifer is limited to the overburden resulting from the in-situ chemical weathering of the bedrock and the fissure/fractured/weathered (secondary porosity) caused by tectonics activities. So, the major aquifer units are the saturated weathered or fractured zones (Olorunfemi *et al.* 1991). Although, situations may arise where clayey/sand may overlying the weathered zones which might have some significant amount of groundwater. Thus, the accumulation of groundwater in fractured or weathered zones depends on the effective porosity Φ_e, which is the combination of primary porosity (Φ_p) and secondary porosity (Φ_s), the nature and thickness of materials overlying the rocks are factors that determines the potential and storability of groundwater in rocks of basement complex. The mineralogy of a rock type also determines the degree of weathering to give clay minerals which are impermeable than that rocks rich in silica offers permeable water bearing sandy and gravely medium

(Offodile, 1983). In basement complex, the weathered and fractured basement determines whether groundwater is recoverable or not. The detection or delineation of hydro-geological structure helps to facilitate the location of groundwater prospective zones in a typical complex setting (Omosuyi *et al.*, 2007).

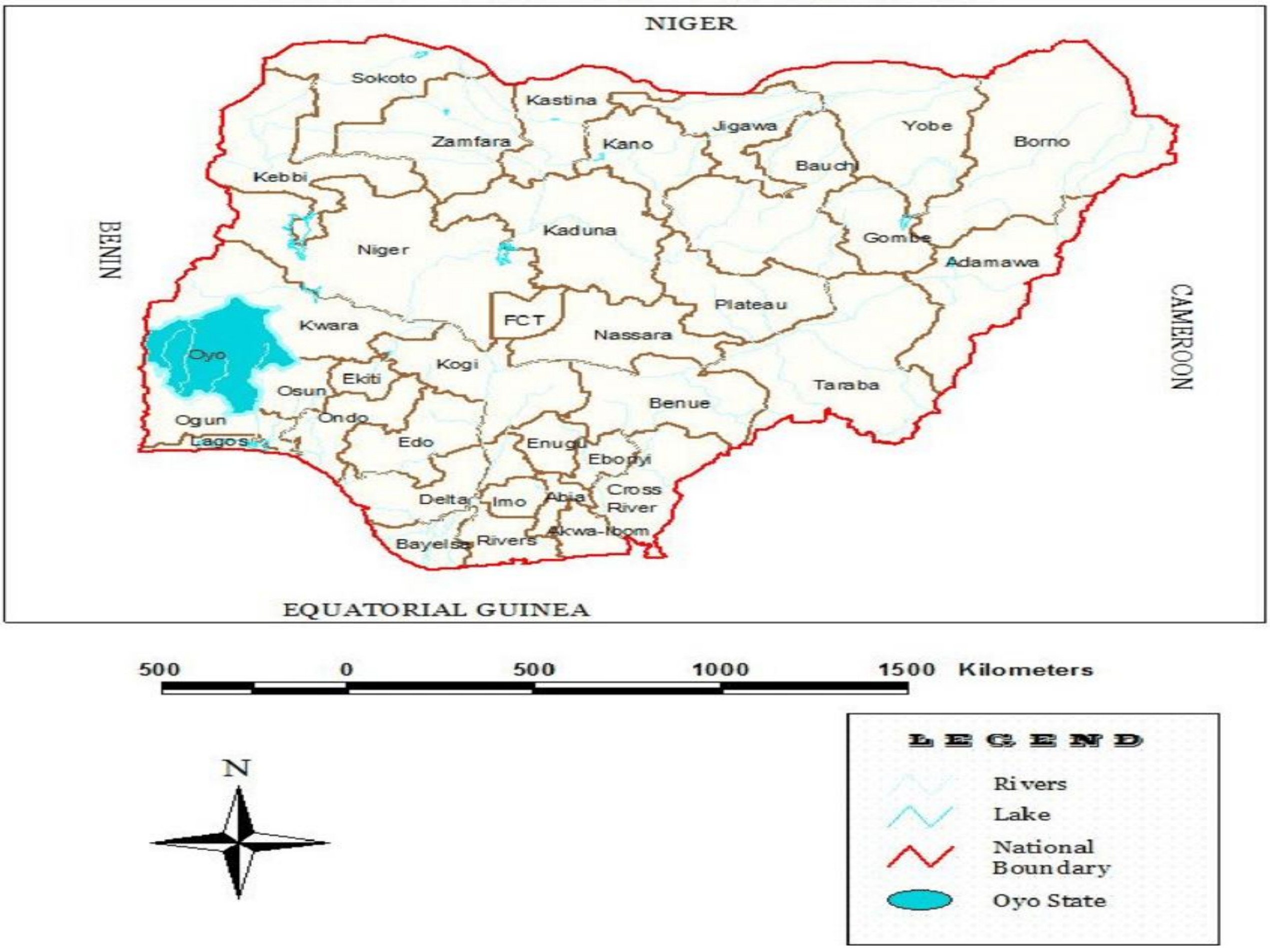

Figure 1, Map of Nigeria showing geology of Oyo state (http://www.researchgate.net)

2. Methodology

2.1 Electrical Resistivity Field Procedure and Data Acquisition

Electrical resistivity method was employed in the determination of the subsurface layer parameters (thickness, depth and resistivity) that are necessary and used in the derivation of four other parameters for groundwater potential. Vertical Electrical Sounding (VES) which is one of the modes of deployment of electrodes array was based majorly on the assumption that the subsurface consists of horizontal, discrete, isotropic and homogeneous layers. This deployment measures the vertical variation of resistivity with depth. In this study, a total of ten (10) vertical electrical soundings were carried out across the study area using DDR 2 resistivity meter which was powered by DC source. Germin Global Positioning System (GPS) was used to record the geographic coordinates of each VES station. The Schlumberger method of electrodes arrangement was adopted because it is convenient, more economical, faster, and the software to process the collected data is readily available. The four electrodes in Schlumberger array include two stainless steel current electrodes and two stainless steel potential electrodes. These electrodes were linearly arranged with different inter-electrode spacing as shown in **Figure 2**. The distance between the two current electrodes spacing is such that it was greater or equal to five times that of the spacing between the two potential electrodes. The spacing between current electrodes in this research study ranged from 2.0 m to 180.0 m (i.e. AB/2 = 1.0 m to 90.0 m) while that of the potential electrodes ranged from 1.0 m to 10.0 m (MN/2 = 0.5 m to 5.0 m). To measure the spacing between the electrodes, non-conducting measuring tapes were laid alongside of them. During field measurements, four electric cables were used, two of which were connected to the resistivity meter and to the pair of current electrodes while the remaining two were connected to both the resistivity meter and the pair of potential electrodes. The two current electrodes (AB) with electric cables on them were spread at a measured distance and driven with hammers into the ground to send current from the current sender on the resistivity meter located at the centre of the array. Also, the potential electrodes (MN) were spread out from the centre and when the measured distance was reached, they were driven down with hammer into the ground and the resulting potentials that was built up as a result of the sent current was passed through the electric cables on them and was received by the voltage receiver on the resistivity meter. The magnitude of the potential difference developed was a measure of the electrical resistance between the probes. According to Dobrin (1976), this resistance is a function of the geometrical configuration of the electrodes and the electrical parameters of the ground. At each position of the two current electrodes, the value of the current sent, built up voltage, and the distances between the current electrode and potential electrodes were recorded.

2.1.1 The Theory of electrical resistivity

Let I be the value of the current sent to a homogeneous medium of resistivity ρ, this current flows away radially. Then, the voltage drop between any two points on the surface can be described by the potential gradient (-δV/δx). For hemispherical shell of incremental thickness δr, the potential difference is

$$\frac{\delta V}{\delta r} = -\rho J = -\rho \frac{I}{2\pi r}$$ **Eqn. (1)**

At a point r, from the current source, the voltage V_r is

$$V_r = \int \delta V = -\int \rho \frac{I\delta r}{2\pi r^2} = \frac{\rho I}{2\pi}\frac{1}{r}$$

If we add a current sink, a new potential is built up **Eqn. (2)**

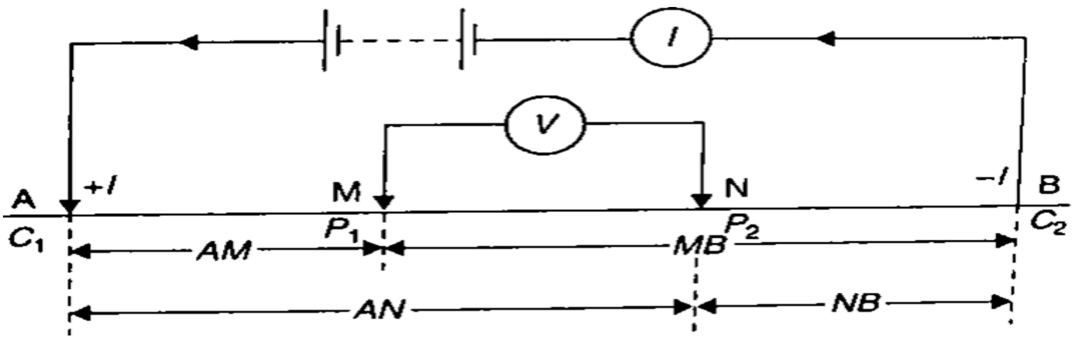

Figure 2. The Arrangement of electrode configuration in Schlumberger array

From **Figure 2** the potential at point P in the ground is the sum of the voltages from the two electrodes. That is

$$V_p = V_A + V_B$$ **Eqn. (3)**

where V_A and V_B are the potential contributions from the two electrodes A (+I) and B (-I). The respective potentials at electrodes M and N are

$$V_M = \frac{\rho I}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB}\right], \text{ and } V_N = \frac{\rho I}{2\pi}\left[\frac{1}{AN} - \frac{1}{NB}\right] \quad \textbf{Eqn. (4)}$$

It was the potential difference (δV_{MN}) that was measured and given as

$$\delta V_{MN} = V_M - V_N = \frac{\rho I}{2\pi}\left\{\left[\frac{1}{AM} - \frac{1}{MB}\right] - \left[\frac{1}{AN} - \frac{1}{NB}\right]\right\} \quad \textbf{Eqn. (5)}$$

After rearrangement and making ρ the subject we have

$$\rho = \frac{2\pi\delta V_{MN}}{I}\left\{\left[\frac{1}{AM} - \frac{1}{MB}\right] - \left[\frac{1}{AN} - \frac{1}{NB}\right]\right\}^{-1} \quad \textbf{Eqn. (6)}$$

Where:

$$K = 2\pi\left[\frac{1}{AM} - \frac{1}{MB}\right] - \left[\frac{1}{AN} - \frac{1}{NB}\right]^{-1} \quad \textbf{Eqn. (7)}$$

K is called the geometric factor.

The subsurface layers are not homogeneous and so, the calculated resistivity is an apparent one. **Eqn. 6** now;

$$\rho_a = R\,K \quad \textbf{Eqn. (8)}$$

Eqn. 8 was used to calculate the apparent resistivity.

2.2 VES Surveying Data Processing and Interpretation

A resistivity sounding interpretation computer software called IPI2WIN (Moscow, 2001) was used to process the data generated from the field. The software plotted the logarithmic values of the apparent resistivity (ρ_a) and that of the current electrode half – separation (AB/2) on the vertical and horizontal axes respectively, of log-log graph. After inversion and iteration, the software displayed the curve signature or type, the number of layers, thickness, depth and apparent resistivity of each layer.

2.3 Indices for Identification of Groundwater Potential Zones

Apart from aquifer resistivity and overburden thickness that were obtained from the VES interpretation and analysis that could be used for groundwater potential indices, other indices that could be used to identify groundwater potential zones of the study area include the following transverse resistance, transmissivity, hydraulic conductivity, coefficient of anisotropy, reflection coefficient, resistivity contrast and resistivity of formation (Adeniji *et al;* 2017. Usman *et al;* 2015). These parameters were evaluated and calculated using the appropriate equations as shown in section 2.3.1

2.3.1 Dar-Zarrouk (DZ) Parameters Calculation

Two basic parameters were used to characterize the geoelectric unit: the layer thickness (h_i) and the layer resistivity (ρ_i) for the i^{th} layer (i = 1 for the surface layer). These parameters are related to different combination of the thickness and resistivity of each geoelectric layer (Antonio *et al.*, 2006). The division and multiplication of these parameters as seen in **Eqns. (9) and (10)** are called Longitudinal Conductance (S_L) and Transverse resistance (T), respectively.

$$S_L = \frac{h}{\rho}$$ **Eqn. (9)**

and Transverse resistance

T= h. ρ **Eqn. (10)**

Mailet (1947) called the sum of the entire longitudinal conductances and transverse resistances for a layered ground "the Dar Zarrouk function and Dar Zarrouk variables" respectively.

Supposing we have n horizontal, homogeneous and isotropic layers of thickness (h_i) and resistivity (ρ_i), then the Dar Zarrouk (DZ) parameters were calculated using the following equations

$$S_L = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots + \frac{h_n}{\rho_n}$$ **Eqn. (11)**

$$T = \sum_{i=1}^{n} (h_i \rho_i) = h_1\rho_1 + h_2\rho_2 + h_3\rho_3 + \ldots + h_n\rho_n$$ **Eqn. (12)**

While the longitudinal resistivity ($(\rho_L) = H/S_L$ **Eqn. (13)**

and the Transverse resistivity $(\rho_T) = T/H$ **Eqn.(14)**

Where H = $\sum_{i=1}^{n} h_i$ **Eqn. (15)**

From **Eqns. (12) and (13)** another parameter can be deduced called Coefficient of Electrical Anisotropy (λ) which is defined and calculated as;

$$\lambda = \sqrt{\frac{\rho_T}{\rho_L}}$$ **Eqn. (16)**

If **Eqn. (9)** is written as

$$S = \sigma_i h_i$$ **Eqn.(17**

where σ_i is the conductivity. But in groundwater hydro-geology, Transmissivity T_r which is the ability of an aquifer to transmit water over the entire saturated thickness is given as

$$T_r = Kh$$ **Eqn. (18)**

Todd (1980) used equation (18) to relate longitudinal conductivity and transverse resistance as

$$T_r = K\sigma R = Kh$$ **Eqn. (19)**

T_r = Transmissivity, K = hydraulic conductivity, σ = Electrical conductivity (reciprocal of resistivity and R = Transverse resistance.

Transmissivity can assist to understand the groundwater potential, secondary porosity, and hydrogeological conditions of an area for groundwater development. Transmissivity provides a general idea of the water producing capabilities of aquifer. According to Todd (1980), Transmissivity is defined as the rate at which water of a certain prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

The hydraulic conductivity K which is a measure of aquifer's ability to transmit the groundwater was determined using **Eqn. 20** (Heigold *et al;* 1979)

$$K = 386.40R_{rw}^{-0.93283}$$ **Eqn. (20)**

K = hydraulic conductivity and R_{rw} = aquifer resistivity (resistivity of the inferred aquiferous layer from the interpreted curves).

Other groundwater indices that were calculated and used in this study include

Mean value resistivity, which was calculated using **Eqn. 21**

$$\rho_m = \sqrt{\rho_L \rho_T}$$ **Eqn. (21)**

The reflection coefficient (R_c) which was calculated using **Eqn. 22**

$$R_C = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \qquad \textbf{Eqn. (22)}$$

Resistivity contrast was calculated using **Eqn. 23**

$$F_c = \frac{\rho_n}{\rho_{n-1}} \qquad \textbf{Eqn. (23)}$$

Where ρ_n and ρ_{n-1} are the layer's resistivity of the n^{th} layer and layer's resistivity overlying the n^{th} layer, respectively.

3. Results and Discussion

3.1 VES Interpretation Results

The samples of the log-log plot of the field data (apparent resistivity against the half current electrode spacing) for ten soundings are as shown in **Figures 3a-e.** The curves of the ten soundings revealed that the study area is characterized by 3 to 5 subsurface layers with the topsoil having resistivity value which ranged from 41.3 to 231.0 Ω m and thickness value of this layer was in the range 0.277 to 1.630 m. The resistivity and thickness of the second layer varied from 9.7 to 3963.0 Ωm and 0.346 to 18.6 m, respectively. This layer was majorly dominated by weathered or fractured basement. The third layer was dominated by fractured or weathered basement whose resistivity values were in the range 9.01 to 30661 Ω m. The thickness of this layer varied from 1.79 to 12.7 m. The resistivity of the fourth layer ranged from 15.3 to 59783.0 Ω m. This layer and the fifth layers were purely basement. The results of the VES data analysis are shown in **Table 1**

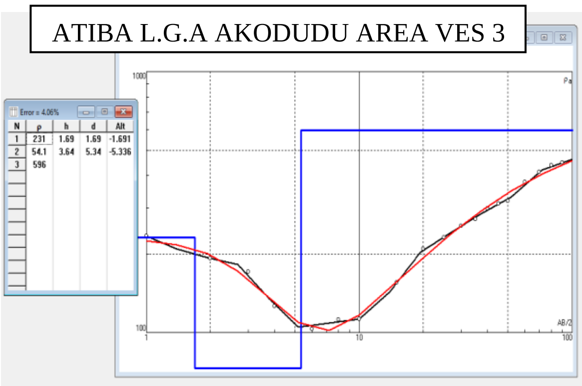

Figure 3a. Log-Log Plot sample of Akodudu

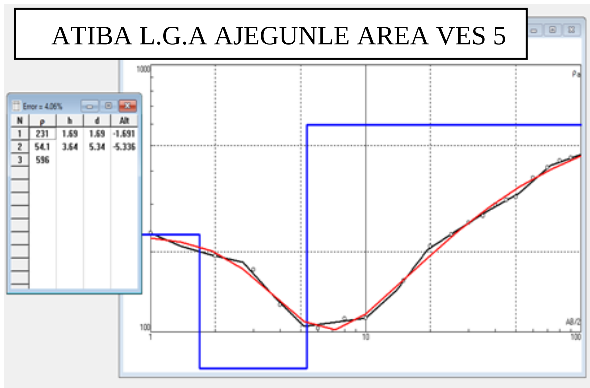

Figure 3b. Log-Log Plot sample of Ajegunle

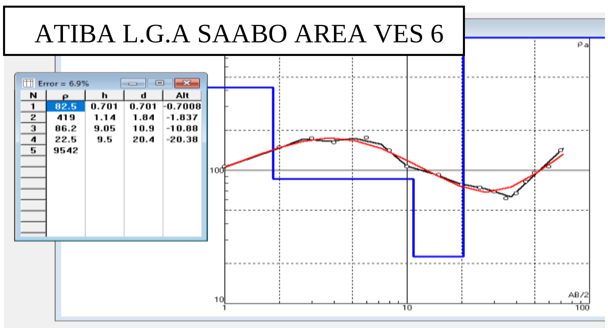

Figure 3c. Log-Log Plot sample of Saabo

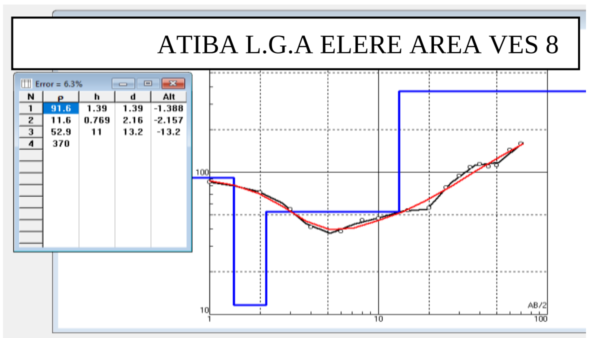

Figure 3d. Log-Log Plot sample of Elere

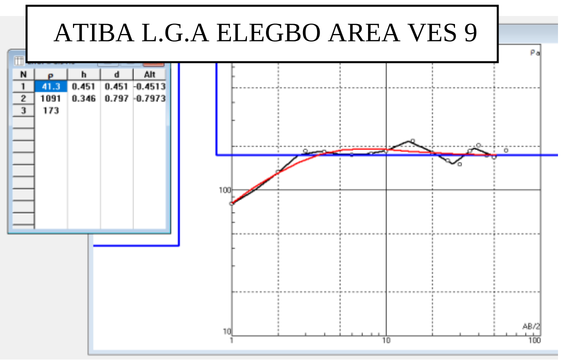

Figure 3e. Log-Log Plot sample of Elegbo

Table 1. The Results of VES Data Analysis and the Location of Study Area

S/N	VES Location	No of Layer	Layer's Resistivity (Ω m)	Layer's Thickness (m)	Layer's Depth (m)	Lithology Formation
1	Sakutu	5	86.6, 9.7, 258, 15.3, 20575	0.815, 0.705, 1.92, 7.11	0.815, 1.6, 3.52, 10.6	Clayey topsoil, clay, weathered, fractured basement, fresh basement
2	Niresa	3	81.1, 39.4, 30661	1.63, 18.6	1.63, 20.2	Clayey topsoil, weathered/fractured basement, fresh basement
3	Akodudu	4	106, 924, 11.9, 59783	0.414, 0.726, 1.79,	0.414, 1.14, 2.93	Lateritic topsoil, dry clayey sand, weathered/ fractured basement, Fresh basement
4	Oranyan	4	65.6, 194, 9.01, 112	0.756, 0.601, 12.7	0.756, 1,44, 14.2	Clayey topsoil, dry clayey sand, weathered basement, fractured basement
5	Ajegunle	3	231, 54.1, 596	1.69, 3.64	1.69, 5.34	Lateritic topsoil, weathered basement, fractured basement
6	Saabo	5	82.5, 419, 86.2, 22.5, 9542	0.701, 1.14, 9.05, 9.5	0.701, 1.84, 10.9, 20.4	Topsoil, lateritic soil, clayey sand, weathered basement, Fresh basement
7	Alasela	4	139, 1567, 117, 1285	0.277, 0.51, 5.82	0.277, 0.788, 6.61	Lateritic topsoil, weathered basement, fractured/basement, fresh basement
8	Elere	4	91.6, 11.6, 52.9, 370	1.39, 0.769, 11	1.39, 2.16, 13.2	Clayey topsoil, dry clayey sand, weathered/fractured basement, fresh basement
9	Elegbo	3	41.3, 1091, 173	0.451, 0.346	0.451, 0.797	Clayey topsoil, Fractured/weathered basement, Weathered basement
10	Oroki	4	69.6, 3963, 9.85, 33823	0.343, 0.377, 2.46	0.343, 0.72, 3.18	Clayey sand, weathered or fractured basement, clayey sand, fresh basement

3.2. Identification of Groundwater Potential in terms of Aquifer Resistivity and Overburden Thickness

In basement rocks, the weathered or weathered fractured layer formed the water saturation zone or aquiferous units. The aquifer resistivity values of the study area varied from 9.81 Ω m to 1091.0 Ω m with an average value of 142.376 Ω m. The least value of 9.81 Ω m was observed at Oranyan site while the highest value of 1091.0 Ω m occurred at Elegbo. This implies that the area with lowest resistivity will have the highest conductive material of the study site and that the groundwater quality of this zone will be a poor one. According to Olayinka *et al*., (2019), the presence of fractures and hence water contained within the fissures are responsible for the fairly low bedrock resistivity. Olayinka *et al*., (2019) were of the opinion that the occurrence of low resistivity values were indication of high degree of weathering and that at such points, the weathered basement layer was saturated with water. **Figure 4** shows the 2-dimensional (2D) contour map of the spatial distribution of the aquifer resistivity. **Table 2** shows the variation of the aquifer thickness of the study site. This variation of aquifer thickness may be attributed to the lithologic composition. The highest aquifer thickness of 18.6 m occurred at Niresa while the lowest value of this parameter was found to be 0.346 m at Elegbo. The average value of this parameter was 7.2966 m. The spatial distribution of the aquifer thickness is shown on the contour map of **Figure 5**.

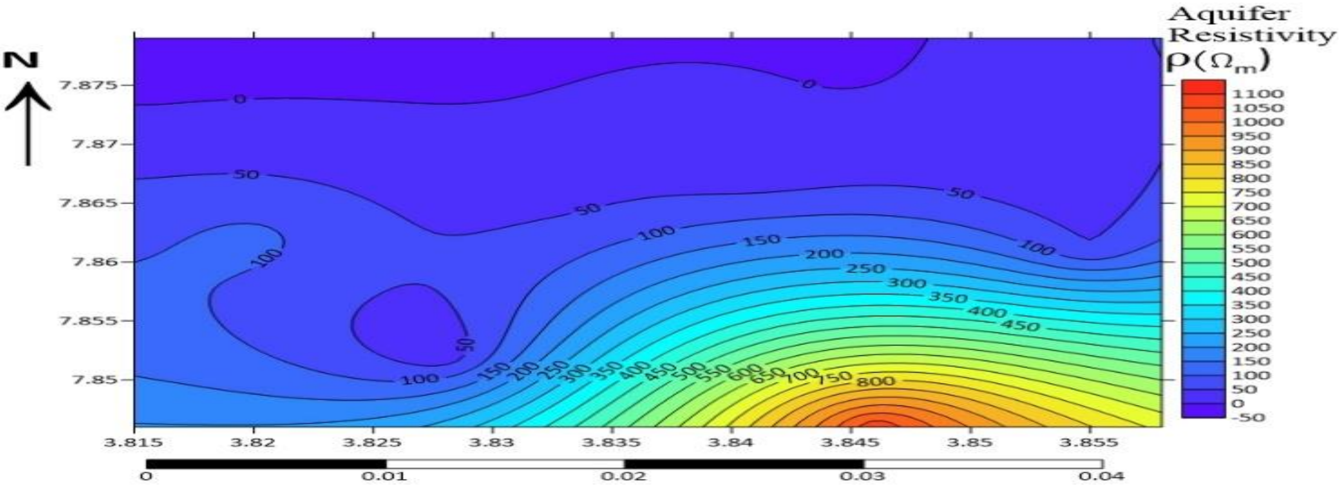

Figure 4: The Spatial distribution of Aquifer Resistivity of the study site.

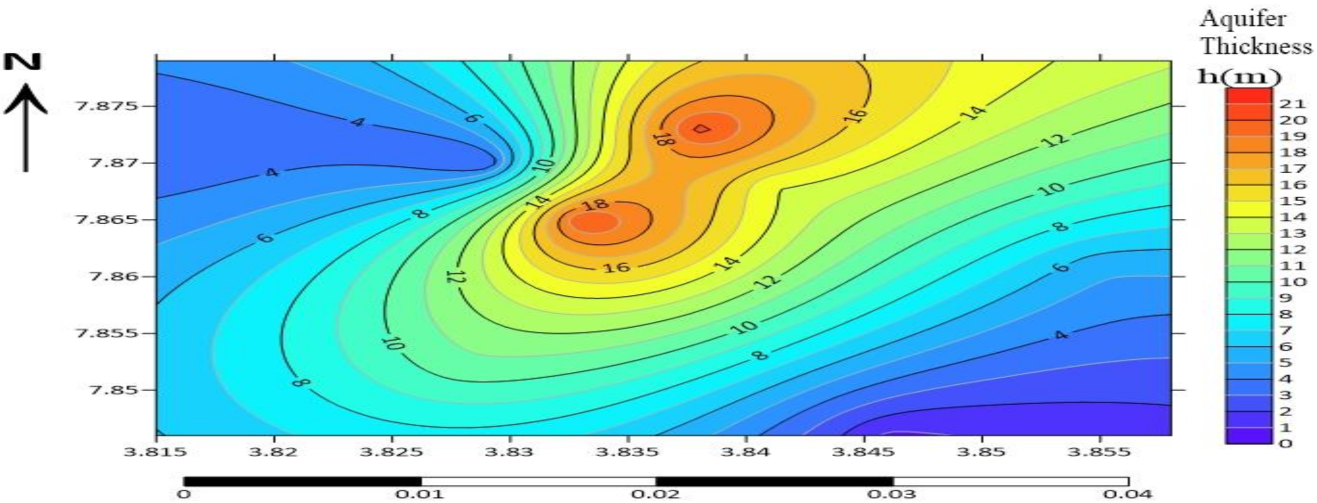

Figure 5: The Spatial distribution of Aquifer Thickness of the study site.

The spatial distribution indicated that the aquifer thickness of the study area decreases from the northern part to the southern part and also from the western part to the eastern part of the study area. 40% (Akodudu, Ajegunle, Elegbo and Oroki) of the study area had their overburden thickness (aquifer thickness) less than 5.00 m and so they were classified as poor groundwater potential zones, Zones such as Sakutu, Saabo and Alasela (30%) of the study area had their aquifer thickness less than 10.0 m so they could be a moderate groundwater potential while zones like Niresa, Oranyan and Elere (30%) whose aquifer thickness were less than 20.00 m were observed to be the best water bearing zones.

3.3 Identification of Groundwater Potential Zones in Terms of Transverse Resistance

The calculated data of Transverse resistance were used to prepare two-dimensional (2D) contour maps of the above mentioned parameters. 25.3290 Golden Surfer version (2023) computer software was used to prepare the 2D contour maps so in order to show the spatial distribution of these parameters in the study site and to identify and infer zones of good, moderate and poor groundwater aquifer potential zones. The 2D contour map of the spatial distribution of transverse resistance (T) for the assessment of groundwater potential in the study site is shown in **Figure 6.** From **Table 2,** transverse resistance values of the study area ranged from 132.2674 Ωm^2 to1541.949 Ωm^2 with the average value of 832.399 Ωm^2. The highest value of the transverse resistance is 1541.949 Ωm^2 while the lowest value is132.2674 Ωm^2. Opara *et al.*, (2012) opined that the highest borehole yields usually come from the zone with the highest transverse resistance value (Saabo, Alasela and Oroki) while the minimum yield occurred at Akodudu.

Table 2: Evaluation of Dar Zarrouk Parameters

VES No	Latitude (N)	Longitude (E)	Aquifer Resistivity (ρ) (Ωm)	Thickness h (m)	Transverse Resistance (Ωm^2)	Transmissivity (m^2/day)
1	007°51'7.2"	003°49'40.8"	15.3	7.11	666.04	317.44
2	007°51'54"	003°49'58.8"	39.4	18.60	865.03	249.98
3	007°52'12"	003°49'44.4"	11.9	1.79	132.27	110.61
4	007°52'4.8"	003°50'27.6"	9.81	12.70	306.17	691.84
5	007°51'39.6"	003°51'18"	54.1	3.64	587.31	48.99
6	007°52'22.8"	003°50'16.8"	22.5	9.50	1529.35	424.94
7	007°51'43.2"	003°49'12"	117	5.82	1518.61	29.59
8	007°52'44.4"	003°51'10.8"	52.9	11.00	718.14	123.44
9	007°52'57.6"	003°50'45.6"	1091	0.35	396.11	1.36
10	007°52'15.6"	003°48'54"	9.85	2.46	1541.95	143.21
		Average	142.38	7.29	832.40	214.14

3.4 Identification of Groundwater Potential Zones in Terms of Transmissivity

The calculated transmissivity of the study area is presented in **Table 2.** These values varied from 1.35 to 691.83m^2/day while its mean value was 214.14 m^2/day. The highest value of 691.83 m^2/day occurred at Oranyan while the least value of 1.35 m^2/day occurred at Elegbo. The calculated values of the transmissivity of the study area were interpreted based on the aquifer classification by Offodile (1983), **Table 3.** Using this classification, only ten percent (10%) (Oranyan) of the study site will yield high groundwater potential, sixty percent (60%) (Sakutu, Niresa, Akodudu, Saabo, Elere, and Oroki) were of moderate potential; twenty percent (20%) of the study area (Ajegunle and Alasela) were of low potential and ten percent (10%) (Elegbo) of the area was of very low potential as shown in **Table 4. Figure7** showed the 2D spatial distribution of the aquifer transmissivity. This figure indicated that the very least groundwater potential occurred at the south eastern part of the study site while the high aquifer yield occurred at North central of the study site. The study area was generally of moderate groundwater potential.

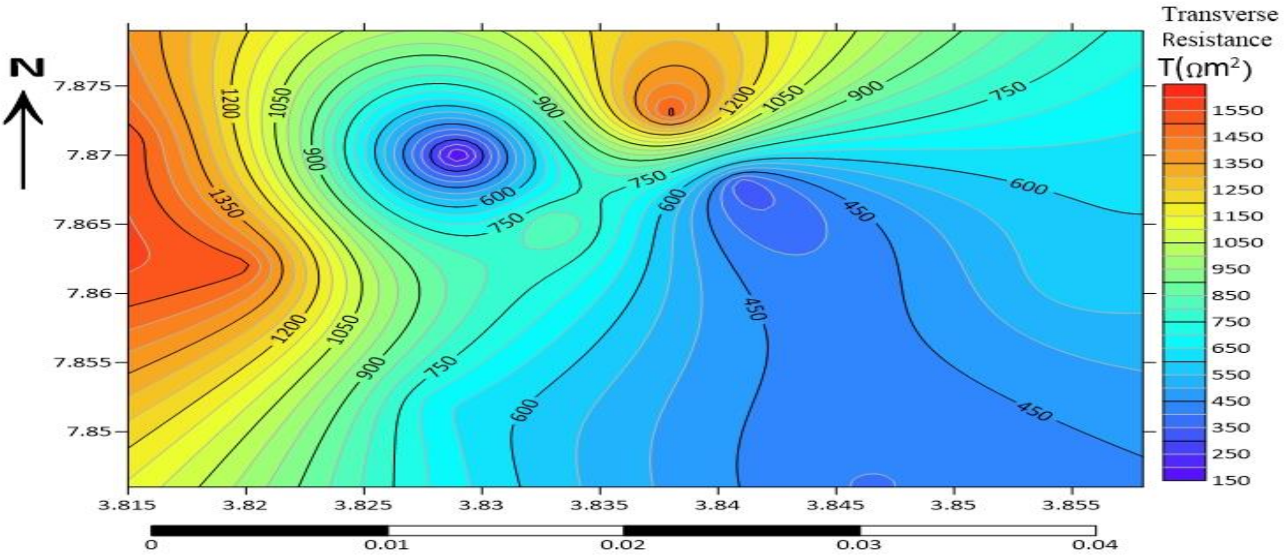

Figure 6: The Spatial distribution of Transverse Resistance of the study site.

Table 3: Aquifer Classification based on Transmissivity Values of Offodile (1983)

Transmissivity (m²/day)	**Classification of Well**
>500	High potentials
50-500	Moderate Potential
5-50	Low Potential
0.5-5	Very Low Potential
< 0.5	Negligible potential

Table 4: The Aquifer Classification of the study area using transmissivty

VES Location	**Transmissivity**	**Classification**
Sakutu	317.44	Moderate
Niresa	249.98	Moderate
Akodudu	110.61	Moderate
Oranyan	691.83	High Potential
Ajegunle	48.99	Low Potential
Saabo	424.94	Moderate
Alasela	29.58	Low Potential
Elere	123.44	Moderate
Elegbo	1.35	Very low potential
Oroki	143.21	Moderate

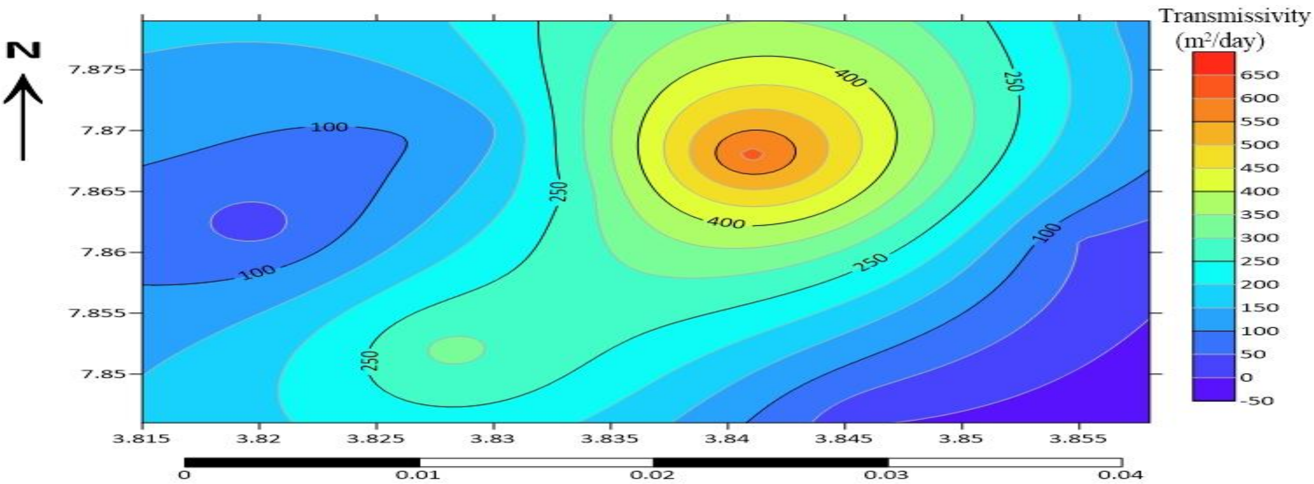

Figure 7: The Spatial distribution of the Transmissivity of the study site.

3.5 Identification of Groundwater Potential Zones in Terms of Hydraulic Conductivity

The hydraulic conductivity which is a measure of aquifer ability to transmit the groundwater was calculated using **Eqn. 20** (Heigold et al. 1979)**.** The calculated hydraulic conductivity values of the study area ranged from 0.56 m/day (Elegbo) to 48.94 m/day (Oranyan). The average hydraulic conductivity value was 21.84 m/day thus confirming the hydraulic conductivity of fine, coarse and gravel (Bouwers, 1978) which were found in the study area. Hydraulic conductivity is proportional to effective permeability. Permeability is a fundamental quantity in the study of aquifer because it determines the rate at which water is able to flow into and through porous storage rocks in aquifers (Hefferan *et al.*, 2010). Four zones (Oranyan, Oroki, Akodudu, Sakutu and Saabo) had high hydraulic conductivity values of 48.94, 45.03, 37.75, 29.86 and 20.84 m/day respectively, and were most likely to have good aquifer recharge capability. Hydraulic conductivity provides an indication of the ease with which water moves through the subsurface, a higher value represents the ease with which that happens. The highest hydraulic conductivity value of 48.94 m/day occurred at Oranyan toward the north-west direction of the study site while the least value of 0.56 m/day occurred at Elegbo in the south-east direction of the study site. To show the spatial distribution of the hydraulic conductivity of the study site, 2D contour map **(Figure 8)** was prepared using the values of hydraulic conductivity in **Table 2.**

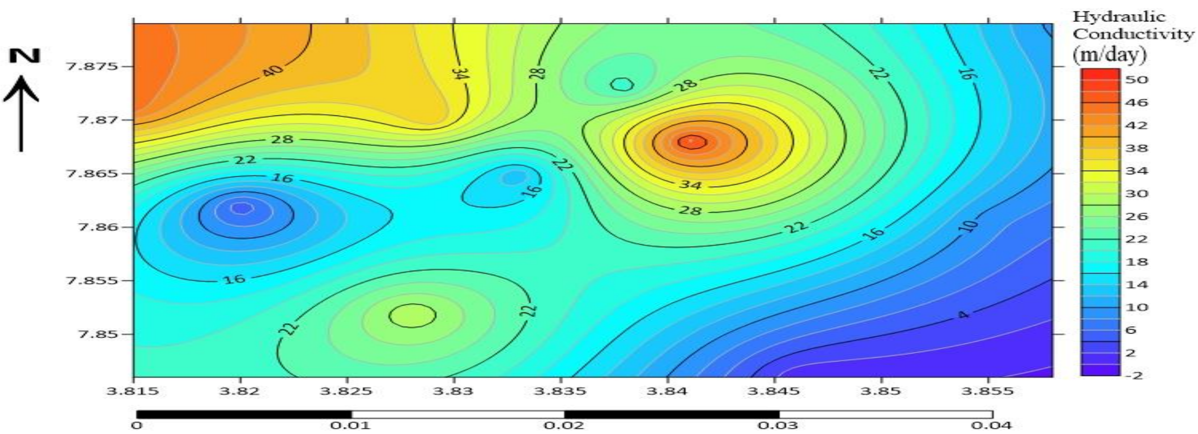

Figure 8: The Spatial distribution of Hydraulic Conductivity of the study site.

The area of high hydraulic conductivity value correlates with the high transmissivity value of the study area. It can be inferred that groundwater flow potential increases as transmissivity and hydraulic conductivity increase. The zones of high hydraulic conductivity and transmissivity are zones of water bearing potential and provision of local water supply for private consumption is possible in these zones. In addition to the above parameters, other groundwater potential indices that can provide insight into groundwater potential zones which were considered and calculated include Coefficient of Anisotropy (λ), Reflection coefficient (R_c), Resistivity contrast (F_c), Transverse resistivity (ρ_l) and Longitudinal resistivity (ρ_L) (**Table 5**).

Table 5. Other Groundwater Potential Zone Indices

VES Location	Hydraulic Conductivity (m/day)	Reflection Coefficient $R_C = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}}$	Resistivity Contrast $F_c = \frac{\rho_n}{\rho_{n-1}}$	Coefficient of Anisotropy $\lambda = \sqrt{\frac{\rho_l}{\rho_L}}$	Resistivity of Formation $\rho_m = \sqrt{\rho_T \rho_L}$
Sakutu	29.86	0.999	1344.773	1.825	34.324
Niresa	12.36	0.997	778.198	1.019	41.923
Akodudu	37.75	0.999	5023.782	1.581	28.557
Oranyan	48.94	0.839	11.417	1.416	15.289
Ajegunle	9.19	0.834	11.017	1.242	88.729
Saabo	20.84	0.954	42.409	1.407	53.295
Alasela	4.48	0.833	10.983	1.386	170.794
Elere	9.39	0.750	6.994	1.096	49.814
Elegbo	0.56	- 0.726	0.159	2.647	187.727
Oroki	45.03	0.999	3433.807	6.233	77.797
Average		0.748		1.985	74.825

3.6 Identification of Groundwater Potential Zones in Term of Coefficient of Anisotropy

Bayewu *et al.* (2013) and Olasehinde and Bayewu (2011) had established that rocks in Basement Complex exhibit anisotropy (λ) due to their heterogeneous nature. This nature may be as a result of varying extent of weathering, near surface effects and existence of features such as faults, joints and foliation (Bayewu *et al.*, 2013).The presence of these features in basement rocks also creates secondary porosity and thus effective porosity. Coefficient of anisotropy (λ) measures the anisotropism extent of an aquifer system and its value increases with increase in hardness of rock (Balasubramanian *et al.*, 1986). Generally, it had been shown that the coefficient of anisotropy (λ) is in the range of 1 and does not exceed 2 in most geological conditions (Olorunfemi *et al.*, 1991) and that compact rock at shallow depth increases the coefficient of anisotropy (Keller and Frischknecht, 1966); hence, these areas can be associated with low porosity and permeability. The values of the coefficient of anisotropy of the study area varied from 1.019 (Niresa) to 6.233 (Oroki). Zones such as Niresa, Oranmiyan, Ajegunle, Saabo Alasela and Elere whose coefficient of anisotropy values ranged from 1.019 to 1.416 were considered to be of good groundwater potential zones since they have high overburden thickness. Zones such as Sakutu, Elegbo and Oroki had their coefficient of anisotropy to be greater than 1.5 were considered to be zones of low groundwater potential zones since the overburden thickness of these zones were thin (Olayinka and Oyedele 2019) (**Table 5**). Zones with coefficient of anisotropy values of 1.0 and less than 1.5 were typical of Basement Complex and are considered as high groundwater potential zones (Rao et al., 2003). The 2D contour map of the distribution of Coefficient of anisotropy is as shown in **Figure 9.** The anisotropic values ranging from 1.019 (Niresa) to 1.416 (Oranyan) observed may be an indication of been porous and permeable as well as of high-density water filled aquifer zones. Zones such as Sakutu, Akodudu, Elegbo and Oroki with anisotropic values greater than 1.5 to 6.233 may be impermeable and not porous so they were classified as poor groundwater potential zones.

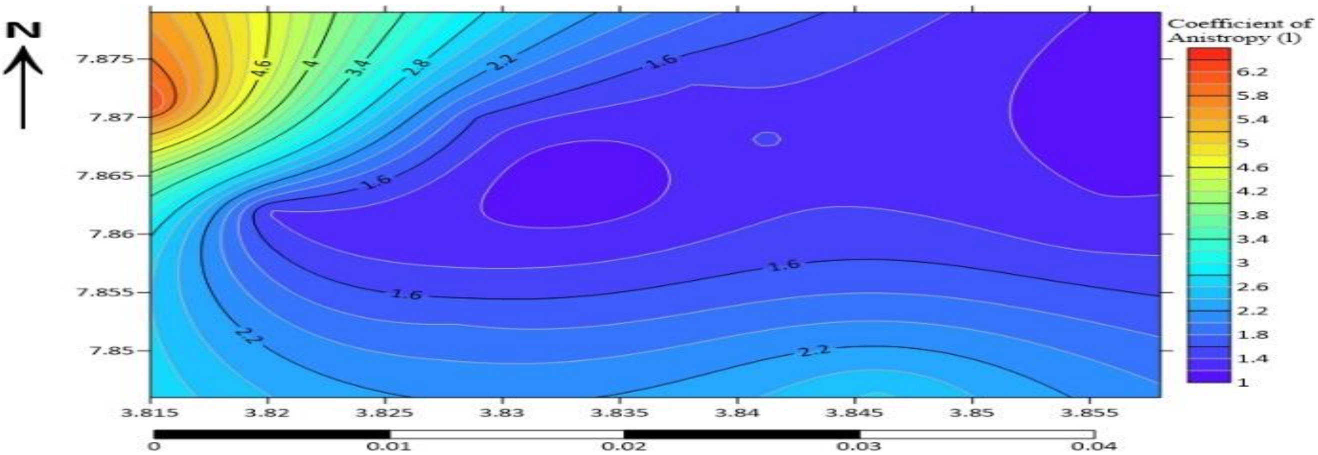

Figure 9. The Spatial distribution of Coefficient of Anisotropy of the study site

3.7 Identification of Groundwater Potential Zones in Term of Reflection Coefficient

The quantity 'reflection coefficient' is a measure of the degree of fracture in an area. It could also be an indication of the density of formation in an aquifer. In this study, the reflection coefficient values varied from - 0.726 to 0.999 with the average value of 0.748. In the findings of Olayinka (1996), zones whose reflection coefficient value is low will exhibit fracture of the basement rock and hence has a higher water potential, therefore zones such as Elegbo, Oranyan, Ajegunle, Alasela, Elere and Oroki whose reflection coefficient values were less than 0.9 may be indicative of high-density water filled fracture (Anudu *et al.*, 2011; Olayinka *et al.*, 2000). Others such as Sakutu, Niresa, Akodudu, Saabo and Elegbo had their reflection coefficient greater than 0.9 so they were considered as poor groundwater productive zones. The 2D contour map of the distribution of the reflection coefficient is as shown in **Figure 10.**

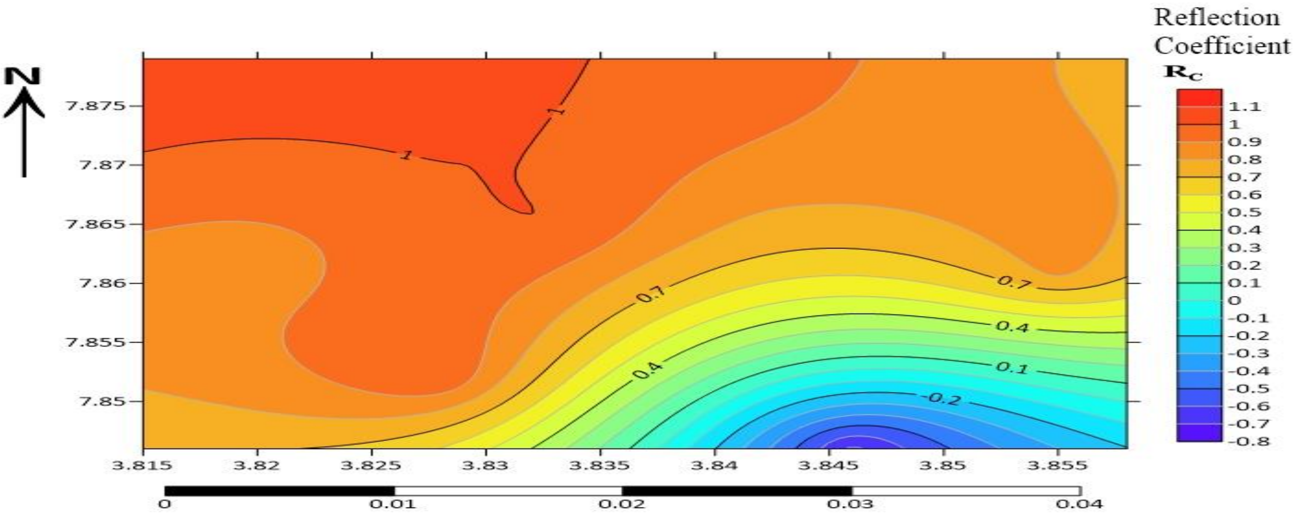

Figure 10. The Spatial distribution of Reflection Coefficient of the study site

3.8 Identification of Groundwater Potential Zones in Term of Resistivity Contrast

Resistivity contrast at fresh basement rock can provide deep perception into the aquiferous nature of the basement rocks. In the findings of Olayinka (1996), low resistivity contrast value indicates the presence of fracture of the basement rock and hence a high-water potential. In this study, fifty percent (50 %) of the study area (Oranyan, Saabo, Ajegunle, Alasela, Elere and Elegbo) had their resistivity contrast values between 0.159 and 11.417 (< 12.00), an indication of high-density water filled fracture. Zones such as Sakutu, Niresa, Akodudu, Saaabo and Oroki whose resistivity contrast ranged from 5023 to 778.198 were considered as non-productive zones for groundwater potential. The determined average value of resistivity contrast in this study was 1066.354. The 2D contour map of the spatial distribution of this parameter is as shown in **Figure 11** with high values of the resistivity contrast of Sakutu, Niresa, Akodudu, Saabo and Oroki were toward the northwestern direction.

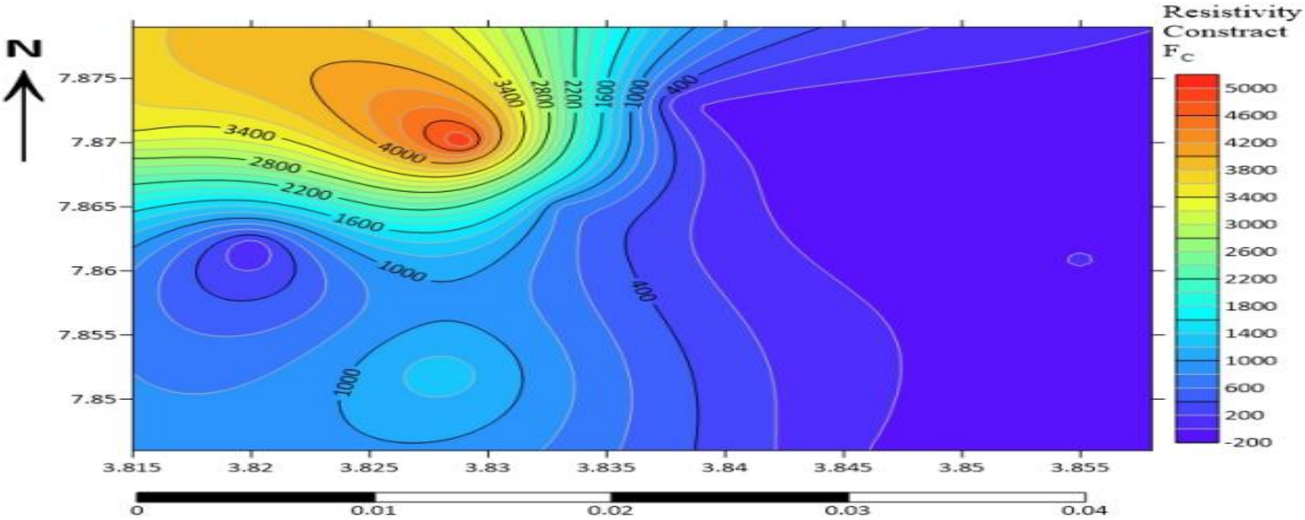

Figure 11. The Spatial distribution of Resistivity Contrast of the study site

3.9 Identification of Groundwater Potential Zones in Term of Resistivity of Formation

Rocks with void spaces can only become connected when fluids occupy them and they can either become conductive or nonconductive. So, the electrical properties of any rocks depend on the void space geometry and the types of fluid it contained. The measurement of the influence of pore structure on the resistance of sample is called Resistivity of formation. When the mineral grains of rocks is not a conductive one, the electrical current can only flow through the fluid in the pores of the rock. When salt water is present in void spaces of any rock, it becomes conductive resulting in low values of resistivity of formation. But the values of the resistivity of formation become high if hydrocarbon or gas is present. In the study areas, the resistivity of formation values ranged from 15.289 to 187.727 Ωm typical of sand clay/clayey sand. The groundwater potential zone of the study areas may be low. The 2D spatial distribution of resistivity of formation of the study areas is as shown in **Figure12.**

3.10 Zones of Groundwater Potential

Having considered the various literatures for the analysis of all the groundwater potential zones, it was observed that Oranyan zone was found to be of high groundwater potential zone since it occurred seven times in the considered groundwater indices out of the eight. Ajegunle, Alasela, Elere, Saabo and Oroki zones were considered to be of moderate productive zones for groundwater because their frequency of occurrence were four times each out of the eight groundwater potential indices considered as shown in **Figure 13.** Zones such as Elegbo and Niresa whose frequency of occurrence were three times each out of eight groundwater potential indices were considered to be of low productive zones of groundwater. The frequency of occurrence of Akodudu and Sakutu in the considered groundwater indices was just two each and they were tagged as very low productive zones of groundwater. **Table 6** illustrates the frequency of occurrence of each zone in the result and discussion of the considered eight groundwater indices while **Figure 13** is the plot of the frequency of occurrences against the various zones in the study area.

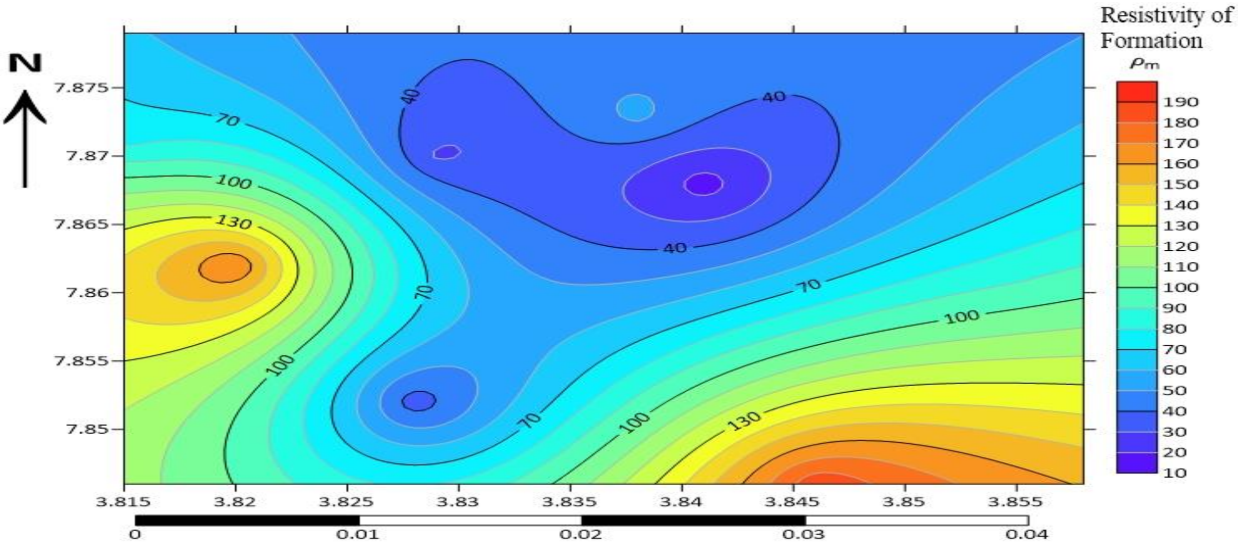

Figure 12. The Spatial distribution of Resistivity of Formation of the study site

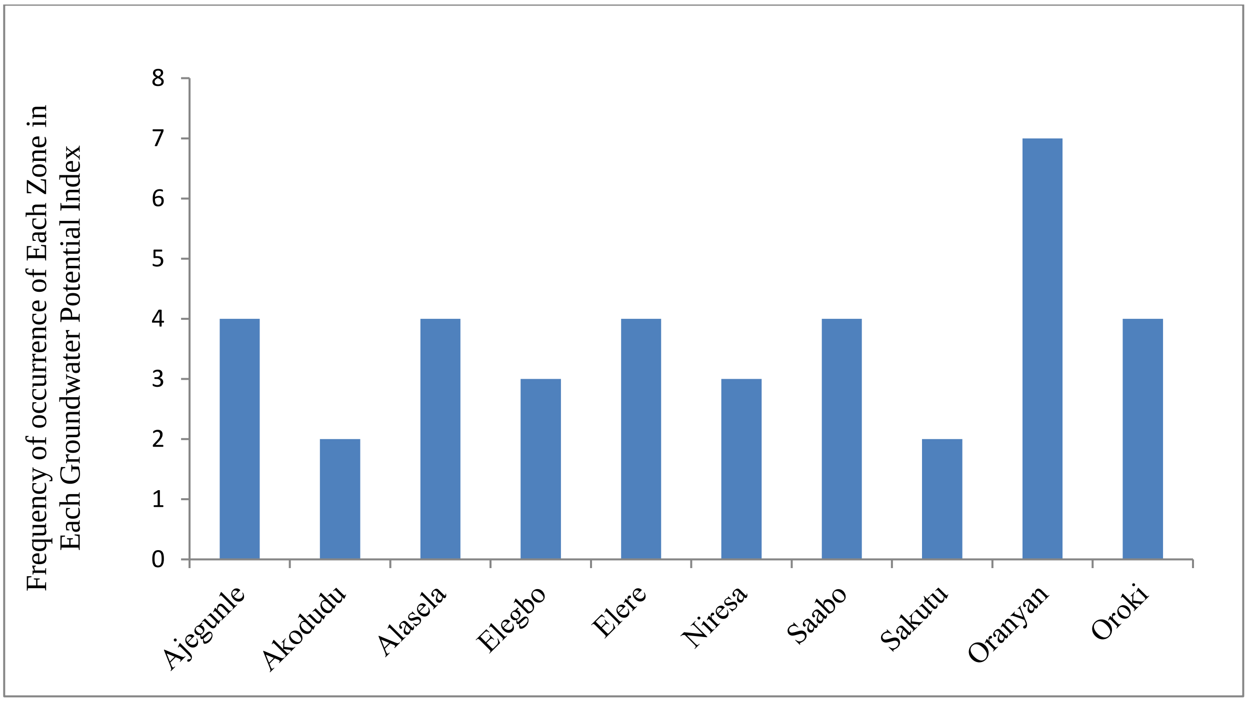

Figure 13. Frequency of Occurrence of Zones in Groundwater Potential Indices

Table 6. Frequency of zones in Groundwater Indices

SN	Groundwater Indices	The Occurrence of Zone in the Analisis of Groundwater Indices	Frequency of zone with Groundwater Potential	Zone with Highest Frequency
1	Aquifer Thickness	Niresa, Oranyan, Elere	4	Ajegunle
2	Transverse Resistance	Saabo, Alasela, Oroki	2	Akodudu
3	Transmissivty	Oranyan	4	Alasela
4	Hydraulic Conductivity	Oranyan, Oroki, Akodudu, Sakutu, Saabo	3	Elegbo
5	Coefficient of Anisotropy	Niresa, Oranyan, Ajegunle, Saabo,Alasela,Elere	4	Elere
6	Reflection Coefficient	Elegbo, Oranyan, Ajegunle, Alasela, Elere, Oroki	3	Niresa
7	Resistivity Contrast	Oranyan,Saabo, Ajegunle, Alasela, Elere, Elegbo	4	Saabo
8	Resistivity of Formation	Sakutu, Niresa, Akodudu Oranyan, Ajegunle, Saabo, Elere, Elegbo, Oroki	2	Sakutu
9			7	Oranyan
10			4	Oroki

Conclusion

This study has been able to identify, predict and rate the various zones of the study area as higher, moderate, low and very low groundwater potential for borehole siting using the analysis of the aquifer thickness and seven groundwater indices. The analyses of these groundwater indices revealed that the Oranyan zone had the highest groundwater potential, occurring seven (7) times out of the eight groundwater indices. Ajegunle, Alasela, Elere, Saabo, and Oroki zones had moderate groundwater potential, occurring four (4) times each. The Elegbo and Niresa zones had low productive potential, occurring three (3) times each in the analysis of various parameters of groundwater indices. The Sakutu and Akodudu zones were adjudged to have very low groundwater potential, occurring only twice (2) out of the eight groundwater potential parameters. The results of this study can serve as a baseline for groundwater resources management, facilitating water supply for domestic, industrial, and agricultural purposes.

Disclosure statement

Conflict of Interest: The authors declare that there are no conflicts of interest

Compliance with ethical Standards: This article does not contain any studies involving human or animal subjects.

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