NRIAG JOURNAL OF ASTRONOMY AND GEOPHYSICS
2020, VOL. 9, NO. 1, 168–175
https://doi.org/10.1080/20909977.2020.1728955

Groundwater aquifer potential using electrical resistivity method and porosity calculation: a case study

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ABSTRACT

This study uses aquifer characteristics such as the aquifer thickness, depth to the aquifer, and the subsurface porosity calculated from 1-D vertical electrical sounding data to evaluate groundwater potential. Thirty geoelectric investigations were carried out using Schlumberger-vertical-electrical -sounding (VES). The VES data were plotted against their respective current electrode spacing (AB/2) and presented as curves. The curves were interpreted quantitatively by partial curve matching and 1-D computer-assisted forward modelling using the WINRESIST version1.0 software. Isopach and isoresistivity maps of aquifer units in the area were generated from 1-D vertical electrical sounding data. The investigated area was subdivided into three zones of high (C); medium (B) and low (A) groundwater potential. Zone A overburden thickness <20 m has 30%, zone B with overburden thickness <30 m, which is the most predominant occupies 55% while 15% overburden thickness for zone C is <40 m. The subsurface porosity is calculated using Archie's Law. The aquifer in the northeastern and southeastern parts of the study area were determined to be of good quality and can yield reasonable quantities of water that can serve the community.

ARTICLE HISTORY
Received 13 February 2019
Revised 29 January 2020
Accepted 9 February 2020

KEYWORDS
Aquifer; porosity; groundwater; yield; electrical resistivity

1.1. Background to study

The basement complex rocks are characterised by crystalline igneous and metamorphic rocks with low porosity and negligible permeability. However, fracturing and weathering activities of basement complex rocks may lead to appreciable secondary porosity and permeability of the rocks, thereby making them suitable aquifers (Dan-Hassan and Adekile 1991). Odo-Ayedun, which is the study area, occurs within the Precambrian basement complex of southwestern Nigeria and, therefore, should be expected to have groundwater problems unless there is/are evidence(s) of fracturing and weathering activities on the rocks constituting this area. Also, the degree or extent of these activities would determine the quality of aquifers. Highly productive water wells are obtained by drilling in a rock that is broken along joints and small fractures.

Over the years, the people of this community have suffered enormous problems of water supply, either surface or groundwater. These problems have been noticed to be much more severe at the peak of the dry season when ironically, demand for water is most significant, and most of the surface sources dry up completely. Before now, a more substantial majority in the community relied on such sources as streams and ponds, especially during the dry seasons when hand-dug wells would have dried up. This situation led to the outbreak of water-borne diseases like cholera, diarrhoea, guinea worm that seriously threatened lives in the community in the '80s running through the early '90s. Also, valuable time could be wasted in water fetching and trekking long distances to and from water points.

Although efforts have been made in recent times to enhance the groundwater potentiality of this area. Hand-dug wells and boreholes have been drilled in different parts of the study area, but observation has shown that very few ones out of the boreholes, and hand-dug wells are functioning perfectly well with a considerable volume of water production throughout the year. The major problem associated with the unproductive wells has been identified to be an inadequate geological and geophysical survey which reveals the proper understanding of the hydrogeological characteristics before drilling of boreholes and hand-dug wells in the area.

1.2. Location and accessibility of the study area

Odo Ayedun-Ekiti, the study area, is located in Ayedun Ekiti, Southwestern Nigeria (Figure 1). Odo Ayedun is one of the twenty-four towns and villages constituting Ikole L.G.A. Oke Ayedun is located at 7.782533° N – 5.565667° E. It can be accessed through a network of roads most especially Oye-Ilupeju-Itapa-Osi-Ikole. The study area is accessible through various footpaths.

1.2.1. Relief, climate, and vegetation

The topography of the study area is gently undulating. Typical of these are the identified series of valleys within the study area. The study area falls within the tropical rain forest of southwestern Nigeria with distinct wet

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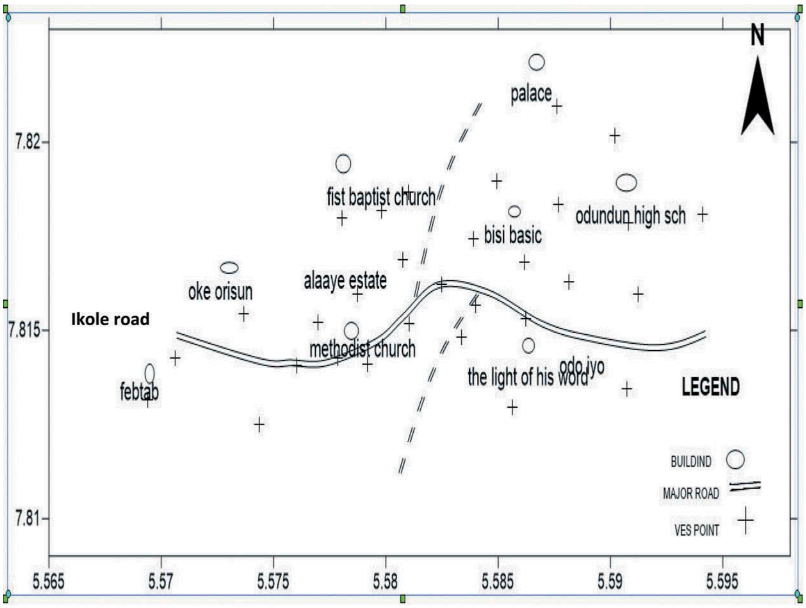

Figure 1. Base map of the study area.

and dry seasons. The dry season comes up between November and April, while the wet season prevails between May and October. The mean monthly temperature is about 28°C, while the mean humidity is over 70%. The mean annual rainfall is about 1800 mm. (http://ekitistate.gov.ng/about-ekiti/overview/). The vegetation of the study area is greatly influenced by the climate and relief of the city. It is the evergreen forest type that comprises palm trees, timbers, and grass. Human activities, such as farming and hunting are prevalent in the study area.

1.3. Aim and objectives of the study

This study aims to use the subsurface porosity of the area calculated from 1-D vertical electrical sounding data to evaluate the groundwater potential of the area.

(a) carry out a reconnaissance survey of the study area and also acquire geographical coordinates of some Landmarks in the study area to generate the base map;
(b) acquire and interpret 1-D Vertical Electrical Sounding data for structure and subsurface geologic sequence delineation respectively;
(c) Use the acquired and interpret 1-D Vertical Electrical Sounding data to calculate the subsurface porosity of the area;
(d) Use (c) to evaluate the groundwater potential of the study area.

2.1. Local geology of the study area

The study area is underlain by the Precambrian rocks of the Basement Complex of Southwestern (Figure 2) Nigeria, which covers about 50% of the land surface of Nigeria. The major lithological units include the granite gneiss, migmatites gneiss, and charnockite (Olayinka et al. 2004). The Basement rocks show significant variations in grain size and mineral composition. The rocks are predominantly quartz gneisses and schists consisting mainly of quartz with small amounts of white micaceous minerals. Ingrain size and structure; they vary from very coarse-grained pegmatite to medium-grained gneisses.

2.2. Hydrogeology of the basement complex

The rocks of the basement complex terrain are relatively impermeable and lack primary porosity, i.e. interconnected pore spaces that are formed during rock formation. The porosity and permeability of a rock help to determine the hydrogeologic properties, which in turn depend on the size, shape, and arrangement of the grains and the mineralogy of the rocks. The presence of fractures (secondary porosity) and the nature and thickness of the material overlying the rocks are factors that control groundwater storability and potential. Fractures in the rock are mainly caused by tectonic activities within the crustal rocks. These are important in basement rocks as it increases weathering activities. The mineralogy of a rock type also determines the degree of weathering. Rocks rich in ferromagnesian minerals and feldspars are subjected to a high degree of weathering to give clay minerals which are impermeable than rocks rich in silica that offers permeable water-bearing sandy and gravely medium (Offodile 1983). Recoverable groundwater in the basement complex often occurs in the weathered layer and fractured basement. The detection/or delineation of hydrogeological structure usually facilitate the location of groundwater prospective zones in typical complex settings (Omosuyi et al. 2007).

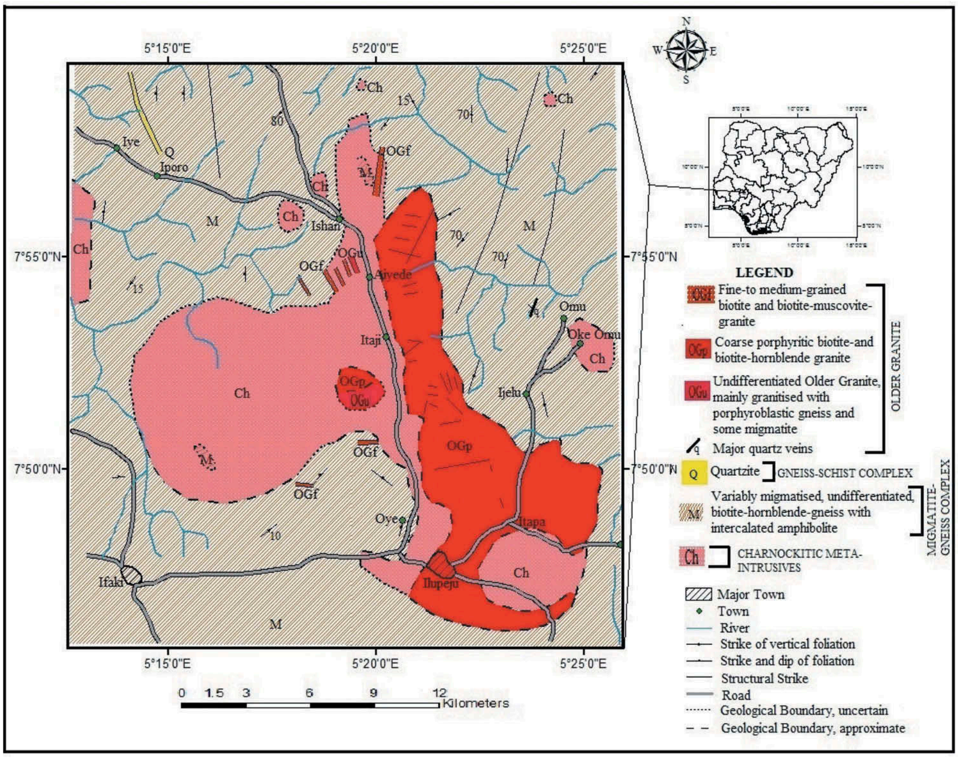

Figure 2. Geological Map of the Area Around Odo Ayedun, Southwest Nigeria.

3.1. Methodology

The electrical resistivity method was adopted in the study. Thirty (30) VES stations were evenly distributed within the study area (Figure 3). The VES technique utilising the Schlumberger array with maximum current electrodes spread (AB) of 200 m was used for the VES data acquisition with the aid ABEM SAS 300C Resistivity Metre. The VES data were plotted against their respective current electrode spacing (AB/2) on a log-log graph and presented as VES curves. The curves were interpreted quantitatively by partial curve matching and 1-D computer-assisted forward modelling using the WINRESIST version1.0 software.

The porosity of the subsurface's materials (ϕ) may affect the resistivity value. The porosity can be calculated using,

$$\phi = \sqrt{\rho w/\rho f} \tag{1}$$

Where ρw is the resistivity of the water in the formation, and ρf is the resistivity of the formation. The resistivity of water in the formation is derived by inverting the measured conductivity of the water from the formation. The resistivity of the formation is obtained from the acquired and interpreted 1-D vertical electrical sounding. These parameters are used to derive the porosity using equation 1 and subsequently generate the porosity map of the area.

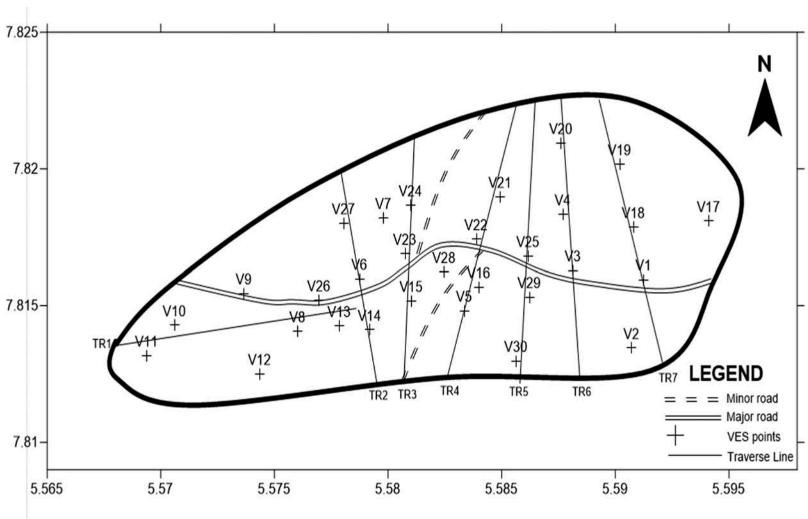

Figure 3. Geophysical Data Acquisition Map of the Study Area Showing the VES Location.

4. Results and discussion

The results of the geophysical investigation were presented as VES curves, table, and evaluation of groundwater potential in terms of overburden isopach, isoresistivity, and porosity maps.

4.1. VES type curve

The resistivity sounding curve-types obtained from the surveyed area range from 3-layer (H) to 4-layer (KH) or 5-layer (HKH). The 4-layer curve-types is predominant in the study area. Figure 4(a,b) are typical 1D resistivity curves of sampled VES stations showing observed apparent resistivity, calculated apparent resistivity, and computed model. Summary of the formation of layer parameters and classification of the resistivity sounding curves are presented in Table 1. These type-curves, HA, A, KA, and KH can be interpreted in terms of the subsurface lithology (Olayinka et al. 2004).

4.2. Isopach and isoresistivity maps of aquifer units in the area

The isopach and isoresistivity maps of the study area are shown in Figures 5–7. The thickness of the overburden and the resistivity are important hydrogeologic considerations in groundwater development in the basement terrain. The reason for this is that water flows into the saturated zone through the overburden.

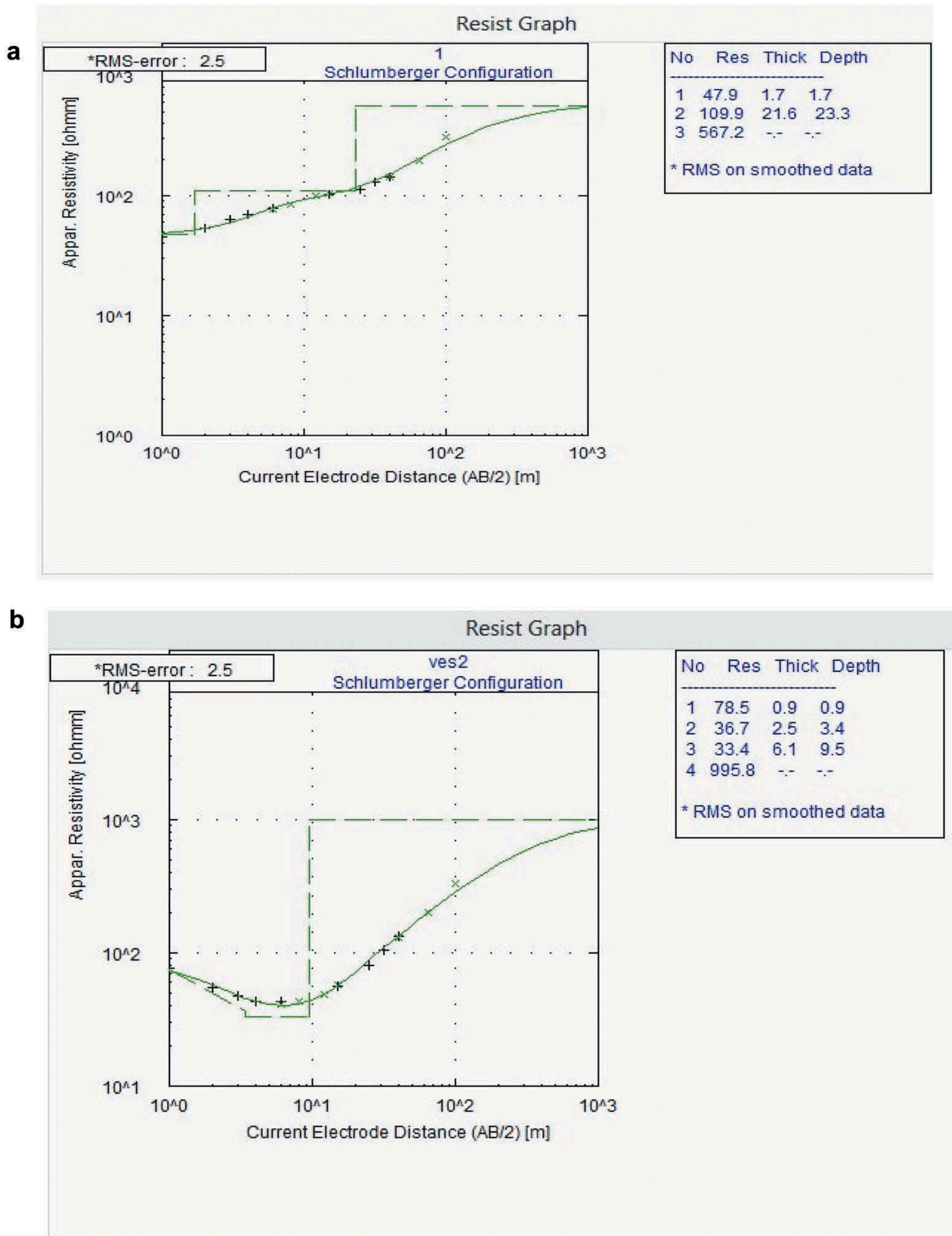

Figure 4. (a) A-TYPE (b) HA-TYPE.

Table 1. Summary of layers parameters.

VES NO	LAYERS	RESISTIVITY (Ωm)	DEPTH (m)	VES CURVE	LITHOLOGY
1	1	47.9	1.7	A	TOPSOIL
	2	109.9	23.3		WEATHERED LAYER
	3	567			FRESH BASEMENT
2	1	78.5	0.9	HA	TOPSOIL
	2	36.7	3.4		CLAY
	3	33.4	9.5		WEATHERED LAYER
	4	995			FRESH BASEMENT
3	1	66.4	1.8	A	TOPSOIL
	2	181.1	21.3		WEATHERED LAYER
	3	384			PARTLY WEATHERED
4	1	118.7	1	HA	TOPSOIL
	2	94.6	2.7		CLAY
	3	115.4	37.4		WEATHERED LAYER
	4	1283			FRESH BASEMENT
5	1	117	3.5	A	TOPSOIL
	2	236.2	20.4		WEATHERED LAYER
	3	1633.7			FRESH BASEMENT
6	1	223.6	3.5	A	TOPSOIL
	2	263.4	20.4		WEATHERED LAYER
	3	580.6			PARTLY WEATHERED

4.2.1. Assessment of groundwater potential in terms of overburden thickness

Depth to the fresh basement (overburden thickness) at each VES sounding station was gridded and contoured and shown as isopach map of the overburden (Figure 5). The overburden includes the topsoil, weathered layer, and partly/weathered basement. The overburden thickness varies from 7.8 to 38.9 m. The map has been subdivided into three zones of high (C); medium (B) and low (A) groundwater potential. In Figure 5, zone A shows that overburden thickness <20 m has 30%, zone B with overburden thickness <30 m, which is the most predominant occupies 55% while 15% overburden thickness for zone C is <40 m.

4.2.2. Assessment of groundwater potential using isoresistivity maps

4.2.2.1. Isoresistivity map of weathered layer. The groundwater potential could also be zoned into high, medium, and low potential based on weathered layer resistivity. The isoresistivity map of the weathered layer is shown in Figure 6. Zones, where resistivity ranges from 100 to 250 Ωm, is classified as high groundwater potential, zones with resistivity range from 250 to 500 Ωm are classified as medium groundwater potential while zones with resistivity > 500Ωm are classified as low groundwater potential (Akintorinwa 2015).

4.2.3. Isoresistivity map of weathered basement

The resistivity values of the weathered basement at the various VES stations occupied in the study area were contoured and presented as isoresistivity map of the weathered basement (Figure 7).

The resistivity values range from 33.4 to 494.5Ωm. This indicates that the material composition is mainly clay/sandy clay/clayey sand.

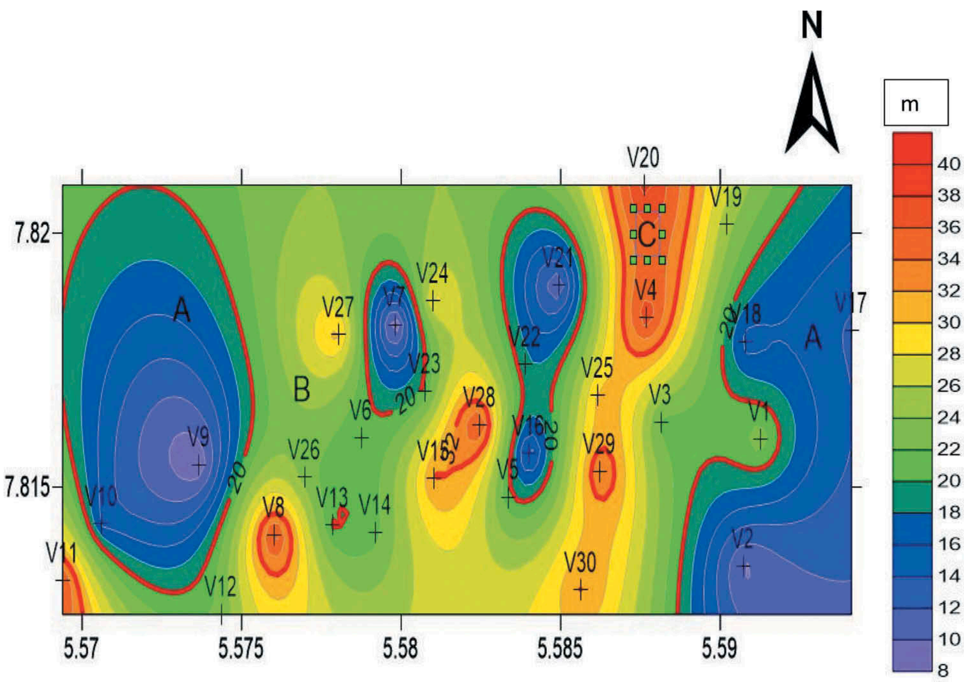

Figure 5. Isopach map of the overburden thickness in the study area.

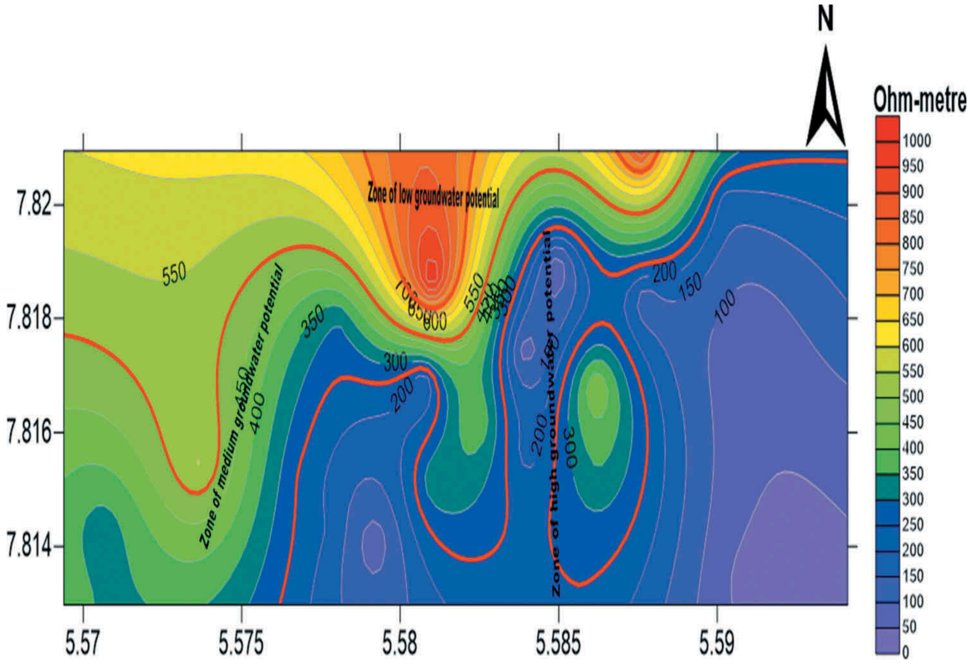

Figure 6. The weathered layer resistivity distribution map of the study area.

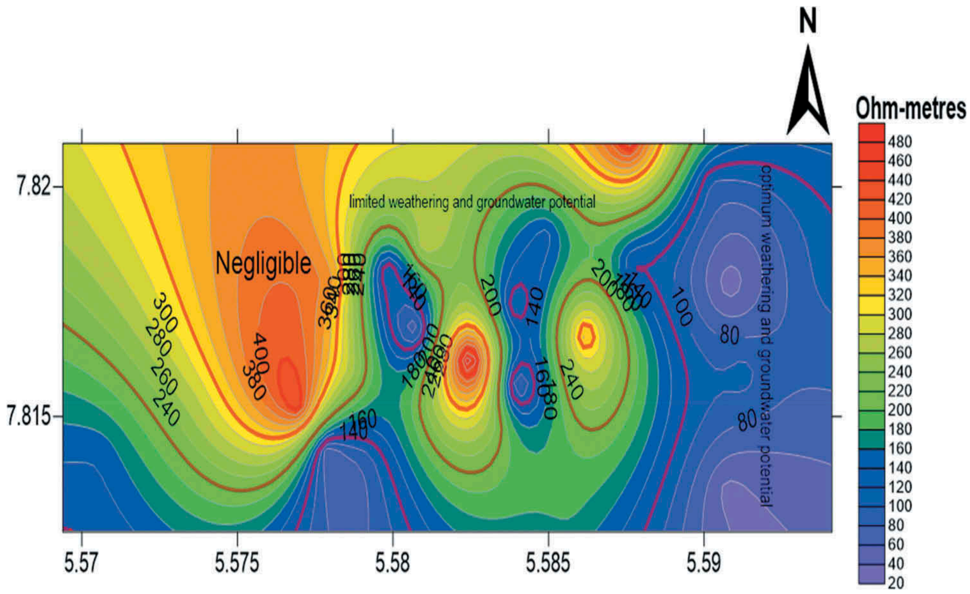

Figure 7. The weathered basement resistivity distribution map of the study area.

Omosuyi et al. (2007) developed a scheme for ranking of groundwater potential as a function of saprolite (weathered basement) resistivity, as presented in Table 2. This classification shows that resistivity range 20–100 Ωm is related to excellent weathering and groundwater potential, while resistivity range of 101–150 Ωm is suggestive of medium aquifer conditions and potential. When the weathered basement resistivity falls within the range of 151–300 Ωm, it is indicative of limited weathering and poor potential. Through this classification, 30% of the study area Figure 7 is characterised by optimum weathering and groundwater potential, with 50% of the study showing limited aquifer conditions and potential. The weathered basement resistivity values >300 Ωm represents 20%. This region offers no appeal for groundwater development unless it is overlain by thick overburden.

Table 2. Aquifer potential as a function of saprolite resistivity of the study area.

Saprolite resistivity (Ωm)	Aquifer characteristics
<20	Clayey; limited aquifer potential
20 – 100	Optimum weathering and groundwater potential
101 – 150	Medium aquifer conditions and potential
151 – 300	Limited weathering and poor potential
>300	Negligible

Modified after Omosuyi et al. (2007).

4.3. Bedrock resistivity distribution map of the study area

Aquiferous units in the basement complex terrain are mainly found in the thick and porous weathered overburden (saprolite zone) and the fractured part of the bedrock. The presence of these fractures further supports the groundwater potentials of those zones (Shemang 1993; Aboh and Osazuwa 2000; Mallam 2004). Fractures influence the groundwater yield more than weathered layer probably because of the relatively high permeability. (Olorunfemi and Fasuyi 1993; Bala and Ike 2001). The fractured/fresh bedrock resistivity values of the study area vary from 38.8 – 1675Ωm (Figure 8). High fractured permeability as a result of weathering is delineated at the eastern part with resistivity values <600 Ωm, an indication of high aquifer potential.

4.4. Groundwater potential

Olayinka and Olorunfemi (1992), proposed values of overburden thickness ranging between 20 m and 30 m for productive wells. Similarly, they also prescribed a minimum overburden thickness of 25 m for viable groundwater abstraction. In the surveyed area, the depth to the fresh basement (total overburden) varies from 7.8 to 38.9 m. Overburden thickness of between 20 m and 40 m occurred in 60% which thus suggests that the water-bearing horizon across the area is generally significantly thick and can support productive groundwater abstraction (Figure 5)

The thick weathered layer (containing less percentage of clay) above the basement rock constitutes a water-bearing layer. 60% of the area falling within medium groundwater potential (100 to 250Ωm) and high groundwater potential (>250Ωm), according to Akintorinwa 2015.

The weathered basement resistivity values range from 33.4 to 494.5Ωm, with the thickness varying from 8.1 to 36.7 m. The ranking of groundwater potential as a function of saprolite

Resistivity (Wright 1992; Mallam, 2004) showed that 30% of the study area with 20 to 100 Ωm is characterised by excellent weathering and groundwater potential while 50% of the study area with a resistivity between 151 and 300Ωm exhibited medium aquifer conditions and potential.

Bedrock fractures contribute substantially to groundwater yield in a typical basement complex area. High fractured permeability as a result of weathering is observed at the eastern part with resistivity values <600 Ωm, an indication of high aquifer potential. However, the fractured zone covered <30% of the study area. It is significant that the three main essential characteristics, namely overburden thickness, weathered layer resistivity, and weathered basement resistivity, generally support one another in the groundwater potential evaluation.

4.5. Subsurface porosity map of the area

Porosity determination is applied in measuring the ability of the rock materials to hold and store water. The porosity of the subsurface materials was determined to verify the aquifer identification in the study area. The porosity of the area is divided into two parts, the zone of high porosity and low porosity (Figure 9). The Northeastern and southeastern parts of the area are highly porous. Again, classifications agree with the

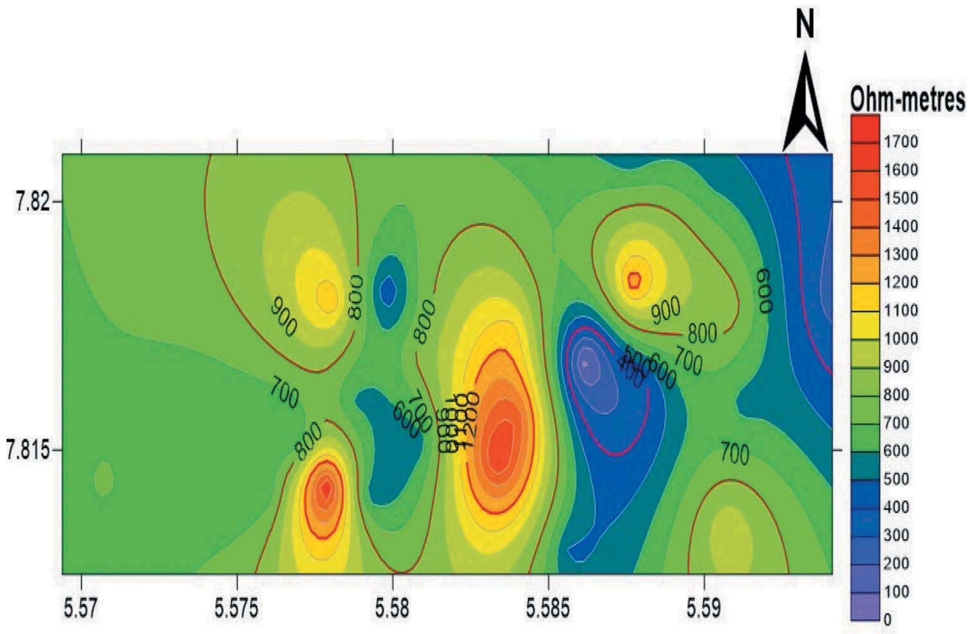

Figure 8. Bedrock resistivity distribution map of the study area.

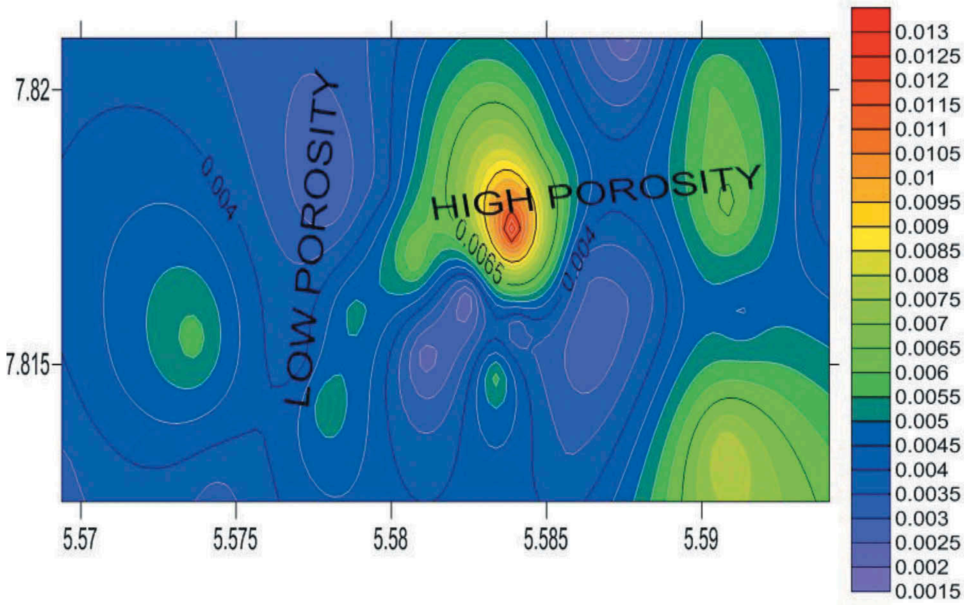

Figure 9. Subsurface Porosity (ϕ x 10^4) map of the area.

previous overburden thickness (Figure 5) and weathered layer resistivity (Figure 6) assessments. In any hard rock terrain, generally, two types of zones are recognised. The first one is the weathering rock mantle near the ground surface, which occurs as more or less a granular material. Here, the porosity is intergranular, and this zone behaves like a granular aquifer medium. This zone is underlain by the bedrock, where the fracture porosity is the controlling factor. This zone is generally unaltered and devoid of water-bearing capacity. However, the network of horizontal and vertical joints and fractures make up the aquifer system. Although clay materials have high porosity, the permeability is low. The area with low porosity is a good seal rock as it prevents water from flowing out, trapping water within the rock fractures.

5. Conclusion

The isoresistivity maps showing resistivity distribution of the aquifer layers (weathered layer, weathered basement, and basement) had proven useful in promising mapping areas for groundwater abstraction. The porosity of the subsurface materials in the study area also helps in delineating the aquifer since the saturated zone of the aquifer area has high porosity. In the study area, the groundwater potential is relatively high for exploitation. Northeastern and southeastern parts of the study area are showing high porosity, indicating that they can hold a lot of water, therefore, revealed areas of the excellent groundwater aquifer.

Disclosure statement

No potential conflict of interest was reported by the author.

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