



## Case Study

# Delineation of aquifer storage potential in response to regional groundwater development

Joseph Omeiza Alao<sup>1</sup>  · Hamed A. Lawal<sup>1</sup> · Momohjimoh Abdulsalami<sup>2</sup> · Fahad Abubakar<sup>2</sup> · Obanero O. Abduwahab<sup>1</sup> · Ekwu Tongha Mary<sup>1</sup> · Mumeen Adebayo Yusuf<sup>3</sup>

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## Abstract

Developing aquifers as part of sustainability efforts toward groundwater development is a tactical approach to meeting water demand and management objectives. Delineation of aquifer storage potential (ASP) and longitudinal conductance ( $S_L$ ) is a good approach to protect and manage groundwater resources. A Schlumberger configuration was applied to delineate fifteen (15) vertical electrical sounding (VES) stations alongside a 2D electrical resistivity imagery (ERI) profile and regional borehole data to characterize the regional ASP. The results of the study show that the layer resistivity and thickness values of the regional aquifer unit range from 39.9–105  $\Omega\text{m}$  and 15–44 m, respectively, while the overburden thickness overlays the regional aquifer unit varied between 5–10 m corresponding to the regional borehole data. The weathered/fractured basemen, which constitute the regional aquifer unit were delineated, which consists of shallow, moderate, and deep aquifer zones. The deep aquifer zones fall within the depth of 30–44 m and are considered suitable for groundwater prospective. The weathered layer with appreciably low resistivity values with thick aquifer regolith has also been identified as most suitable for borehole siting. The weathered/fractured encountered within thick aquifer regolith were mapped as the region with a high ASP for groundwater development. In addition, the values of longitudinal conductance,  $S_L$  and transverse resistance,  $R_T$  estimated from aquifer parameters vary between 0.21 – 0.85  $\Omega^{-1}$  and 1695 – 3124  $\Omega\text{m}^2$ , respectively. The  $S_L$  values show that the study area falls within moderate (0.20 – 0.69  $\Omega^{-1}$ ) and good (0.7 – 4.9  $\Omega^{-1}$ ), which invariably determined the regional aquifer protective capacity. Thus, the DC geoelectrical approach has been successfully employed in a lateritic-based environment to delineate aquifer-promising zones for regional groundwater development.

**Keywords** Regional groundwater · Aquifer storage potential · Aquifer regolith · Weathered/fractured · Longitudinal conductance

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✉ Joseph Omeiza Alao, [alaojosephomeiza@gmail.com](mailto:alaojosephomeiza@gmail.com); Hamed A. Lawal, [haadeniyilawal@gmail.com](mailto:haadeniyilawal@gmail.com); Momohjimoh Abdulsalami, [abdulsalamim@custech.edu.ng](mailto:abdulsalamim@custech.edu.ng); Fahad Abubakar, [abubakarfahad1@gmail.com](mailto:abubakarfahad1@gmail.com); Obanero O. Abduwahab, [oziobanero@gmail.com](mailto:oziobanero@gmail.com); Ekwu Tongha Mary, [tonghamary@gmail.com](mailto:tonghamary@gmail.com); Mumeen Adebayo Yusuf, [asiribo.ma@unilorin.edu.ng](mailto:asiribo.ma@unilorin.edu.ng) | <sup>1</sup>Department of Physics, Air Force Institute of Technology, Kaduna, Nigeria. <sup>2</sup>Department of Geoscience, Confluence University of Science and Technology, Osara, Okene, Nigeria. <sup>3</sup>Department of Geology and Mineral Sciences, University of Ilorin, Ilorin, Nigeria.



## 1 Introduction

Groundwater is a hidden natural resource and it is very vital to human existence due to its crucial role in all aspects of life. The high water scarcity rate in urban and rural Nigeria is becoming worrisome due to several factors such as frequent borehole failures, water pollution, climate change, etc. [1]. This is because groundwater resources account for a good percentage of the water supply in both rural and urban Nigeria [2]. However, the frequent borehole failure remains one of the major causes of water scarcity [3], which according to several sources is attributed to the fact that most boreholes and hand-dug wells were not sunk based on good hydro-geological/geophysical information, but are drilled at locations pre-determined by their owners [1, 4, 5]. Some studies observed that groundwater plays an all-important role in nation-building [6–9]. In 2011, a study estimated that one hundred and three (103) million Nigerians still lack basic sanitation facilities, and sixty-nine (69) million Nigerians do not have access to improved sources of water [10]. This is a far larger number than most countries in the developing world and a significant portion of the population in Africa. In addition, these wide disparities in the number of the populace without sanitary water persist across many zones within Nigeria, especially in rural areas and some urban communities, which aggravates the situation leaving more children and women vulnerable to sickness and poverty. Most of the water required for domestic and agricultural use is sourced from seasonal streams, rivers and shallow hand-dug wells, especially in rural and semi-urban Nigeria [7, 11]. These sources most often do not provide the needed good quality supply as they are highly prone to contamination by human activities.

The continuous deterioration in the quality of drinking water supplies in Nigeria due to several human activities such as solid wastes, wastewater, oil spillage etc. has generated serious challenges to human health [6, 12, 13]. These interactions between surface contaminants and the surface/groundwater have led to recent negative environmental impacts and public health risks [14–16]. However, the rural regional water supply does not face serious pollution threats compared to the cities. Therefore, the major water challenges in rural settlements may be unconnected to unproductive boreholes also known as borehole failures. Unproductive borehole is a common phenomenon in both rural and urban Nigeria as reported by several studies [3, 4] (Table 1). Several geophysical investigations have been conducted to ensure that the challenges of unproductive boreholes are resolved. However, these efforts have not yielded the required results and expectations as many boreholes continue to fail [1]. According to several surveys, the high rate of unproductive boreholes in Nigeria has been attributed to inadequate geophysical investigation of the concerned locations [5, 17]. According to some remarkable studies, more than 30% of the boreholes dug within the complex basement reportedly failed, while the so-called successes were not encouraging due to low yield [1, 3, 4].

In addition, a remarkable study noted that to ensure adequate water security and sustainability, there is a need to install multiple boreholes in geophysical identified groundwater-promising zones where the aquifer occurs in deep zones and fractured [1]. This is because most remarkable studies conducted in the complex basement rock noted that the weathered/fractured units are largely responsible for the regional groundwater-bearing capacity [1, 14, 18, 19] due to the existence of preferential flow pathways from secondary flow features like faults, joints and bedding planes [20]. These situations make this type of investigation a *prima facie* for the precise location of fractured zones for productive borehole sites. Therefore, this study aims to apply the electrical resistivity method to delineate the weathered/fractured zones alongside the computed aquifer parameters to identify the regional aquifer storage potential for groundwater development. To achieve this, the study: (i) determines subsurface geoelectric parameters such as layer resistivity and the thickness of the sequence layers. (ii) identify geological structures such as weathered/fracture zones as the regional ASP; (iii) Compute Dar Zarrouk Parameters to estimate the regional aquifer protective capacity of the study area.

**Table 1** Brief history of unproductive borehole and the possible causes in Nigeria

SN	Borehole installed	Unproductive	Percent-age failure	Possible cause(s)	Source(s)
1	69	16	30	Poor lack of geophysical investigation	[4]
2	50	31	62	Poor design and construction, lack of geophysical survey & poor maintenance	[5]
3	256	59	23	Seasonal variations in water level and lack of geophysical investigation	[3]
4	60	12	20	Aquifer depletion, equipment failure, poorly well design and construction	[17]

## 2 Site description

The study area lies between latitudes  $09^{\circ}50'586''$  N and  $09^{\circ}50'565''$  N and longitudes  $07^{\circ}27'562''$  E and  $07^{\circ}27'054''$  E respectively, with an average height of 562 m above the sea level. It falls within the Basement Complex terrain of Nigeria (Fig. 1). The site is designated for irrigation farming and requires continuous water during the dry periods. The relief of the terrane study is characterized by undulating plain, gentle slopes, and consists of peneplains with eroded flat tops capped by layers of indurated laterites [7]. The rocks of the area are capped by laterites; the laterites are usually consolidated at the surface and sometimes weathered into lateritic nodules mixed with silty and sandy clays [2], while the rocks overlying the basement rocks sometimes act as recharge materials, especially where they are underlain by a weathered basement [2, 18]. In general, the geology of Nigeria consists of two main lithological units (Fig. 1). These are the Precambrian Crystalline Basement and Cretaceous-Tertiary sedimentary rocks [21]. Deep chemical weathering and fluvial erosion, influenced by the environment's bioclimatic nature, have developed the characteristics of high undulating plains with subdued interfluves [21]. The crystalline basement complex is composed mainly of metamorphic rocks [21]. Generally, studies have shown that the main aquifer components of the basement complex of Nigeria are weathered and fractured basements and water yielding capacities of wells drilled to these components always vary from place to place [1]. The water-bearing units (aquifers) in basement rocks occur within the weathered residual overburden (the regolith) and the fractured bedrock [2].

## 3 Material and methods

The materials used to carry out the study include but are not limited to ABEM Terrameter SAS 400, range poles, cable, hammers, electrode selector, 48 electrodes, global position system, and field book.

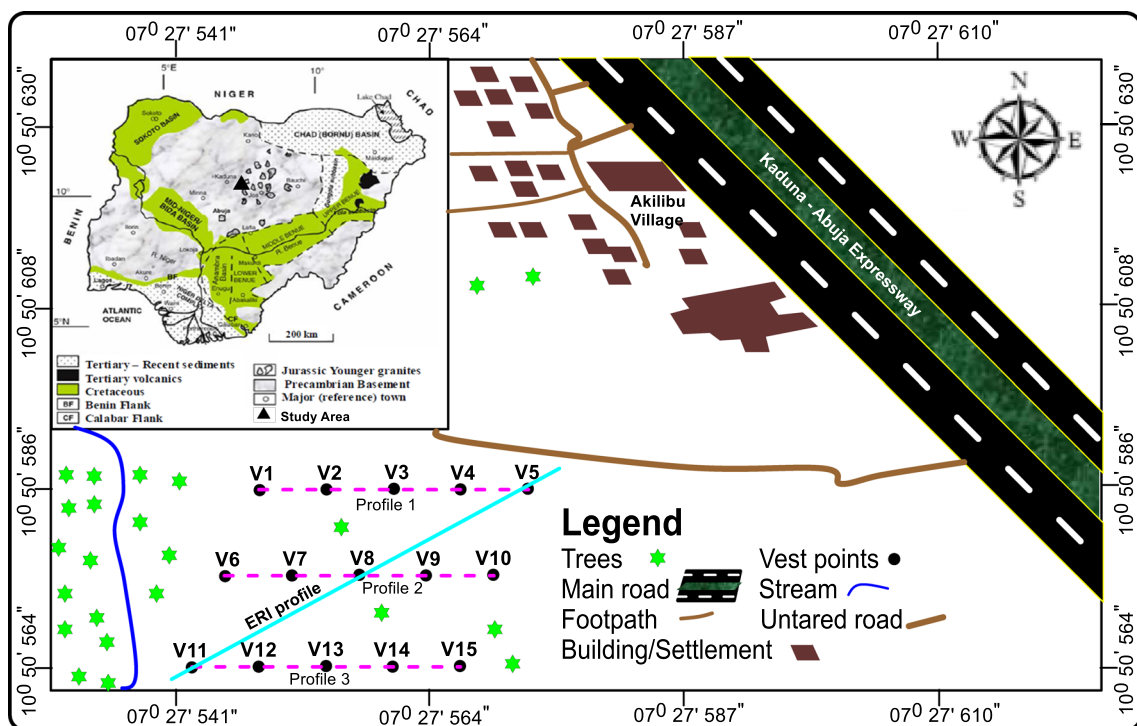


Fig.1 The map showing the study area with vertical electrical sounding points

### 3.1 Data acquisition

The electrical resistivity was used to acquire the field data. Electrical resistivity is a geophysical method in which an electrical current is injected into the ground to measure the electrical properties of the subsurface. The electrical properties of the subsurface are measured based on the response of the subsurface material to the current flow through electrodes to the subsurface [22–24]. In this survey, fifteen (15) Vertical Electrical Sounding (VES) points were conducted using an Omega Resistivity Meter. The VES was performed using a Schlumberger array with a maximum current electrode spread of 200 m, while a 2D ERI was performed with a Wenner-alpha configuration. The electrodes were laid along the profile in a single line with a 5.0 m electrode spacing, connected to a central control unit (ABEM Terrameter SAS 400) using electrical cables to obtain subsurface layer resistivities. The VES was performed using a Schlumberger array with a maximum current electrode spread of 200 m. A typical Schlumberger array electrode arrangement with 4 electrodes is shown in Fig. 2a. The potential ( $V_C$ ) at an internal electrode C is the sum of the potential contributions ( $V_A$ ) and ( $V_B$ ) from the current source at A, and the sink at B [25].

$$V_C = V_A + V_B \quad (1)$$

The potential gradient associated with this current density is

$$\frac{\partial V}{\partial r} = -\frac{\rho I}{2\pi r^2} = -\rho I \quad (2)$$

The potential ( $V_r$ ) at distance  $r$  is then obtained by integration

$$V_r = \int \partial V = -\int \frac{\rho I \partial r}{2\pi r^2} = \frac{\rho I}{2\pi r} \quad (3)$$

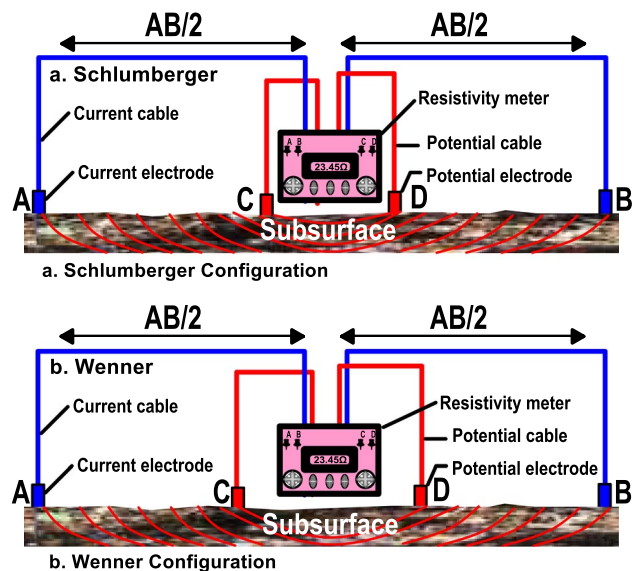
From (3);

$$V_C = \frac{\rho I}{2\pi} \left[ \frac{1}{AC} - \frac{1}{CB} \right] \quad (4)$$

The potential difference is then given by;

$$\Delta V = V_C - V_D = \frac{\rho I}{2\pi} \left[ \left( \frac{1}{AC} - \frac{1}{CB} \right) - \left( \frac{1}{AD} - \frac{1}{BD} \right) \right] \quad (5)$$

**Fig. 2** Electrical resistivity configurations



$$\rho_a = \frac{2\pi\Delta V}{I} \left[ \left( \frac{1}{AC} - \frac{1}{CB} \right) - \left( \frac{1}{AD} - \frac{1}{BD} \right) \right]^{-1} \quad (6)$$

Hence,

$$\rho_a = RK \quad (7)$$

where

$$K = \frac{2\pi}{\left( \frac{1}{AC} - \frac{1}{CB} \right) - \left( \frac{1}{AD} - \frac{1}{BD} \right)} \quad (8)$$

From Fig. 2b, the k-factor for Wenner-apha configuration can be expressed by Eq. (9), when  $AC = BD = a$  and  $CB = AD = 2a$ , So that Eq. (8) becomes:

$$K = 2a\pi \quad (9)$$

Equations (8) and (9) can be used to compute the K-factor for Schlumberger and Wenner-apha configurations, respectively. In general, if  $(AC) = (BD) = a$  and  $(BC) = (AD) = 2a$ ; the K-factor from Eqs. (8) and (9) becomes

$$K = \pi \frac{(AC)(AD)}{(CD)} \quad (10)$$

### 3.2 The Dar Zarruk parameters

Geo-electric subsurface layers are usually described by two basic parameters: their subsurface layer thickness ( $h_a$ ) and apparent resistivity ( $\rho_a$ ) [14]. The Dar Zarruk parameter's concept was first proposed in 1947, with the fact that the layer apparent resistivity and thickness of subsurface layer lithologic can be calculated to predict the hydraulic properties [26, 27]. The Dar Zarruk [DZ] parameters such as the longitudinal conductance,  $S_L$  and transverse resistance,  $R_T$  use these parameters to estimate the regional aquifer protective capacity and target areas' aquifer hydraulic properties [14, 28]. For consecutive homogeneous, isotropic, and horizontal layers of resistivity ( $\rho_a$ ) and thickness (h) values, the DZ parameters can be expressed in Eqs. (11) and (12) respectively [26, 27]:

$$S_L = h_a / \rho_a \quad (11)$$

$$R_T = h_a \cdot \rho_a \quad (12)$$

High or low values of  $R_T$  and  $S_L$  reflect succession layer thickness and should be considered a top priority in terms of groundwater protective capacity evaluation [14]

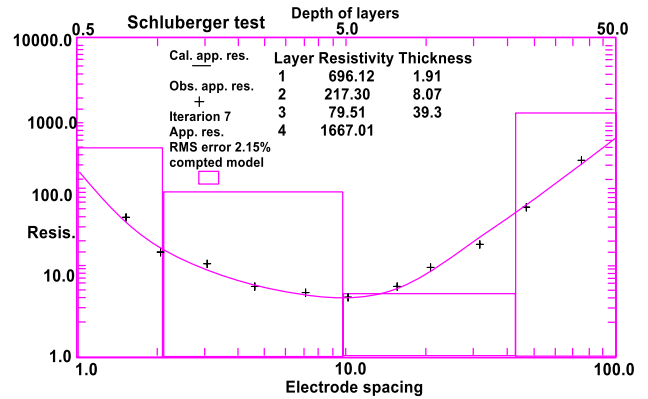
### 3.3 Data processing

The data collected by Schlumberger and Wenner-apha arrays were processed using the Res 1D version 1.00.07 Beta and Res 2DINV modelling software, respectively. The Res 1D and 2DINV software were used to perform resistivity curve and 2D ERI inversion with its quality fitness expressed in terms of the absolute root mean square (RMS) error [22]. Figure 3 is the typical resistivity curve with subsurface parameters after quantitative interpretation for all VES points along the three profiles. Figure 6 presents the 2D ERI inversion model along the orthogonal three profiles of VES points with an RMS error of 4.6% for Wenner-apha arrays.

## 4 Result presentations

The final model geoelectric parameters of RES 1D were used to construct the geo-electric/geologic section (Fig. 4) of the terrane to reveal the variation in resistivity, depth to the basement (overburden thickness) and thickness of the underlain layer. The results show that the terrane is underlain by four to five distinctive lithological units

**Fig. 3** Typical resistivity curve VES 1



Scale	Existing Regional Borehole Data			The Delineated Regional Groundwater Data		
	Depth (m)	Lithology	Driller Description	Geology Interpretation	Lithology	Geology infer
0		Topsoil, Laterite, Lateritic clay	Soft and hard Overburden		Overburden	399Ωm–922Ωm
10		Granite, gravel, Brownish fine sand, Quartz	Weathered fresh basement		Weathered layer	40Ωm–105Ωm
20						
30						
40		Gap	Fractured basement		Fractured basement	499Ωm–911Ωm
50		Granite	Fresh basement		Bed rock	1211Ωm–5200Ωm

**Fig. 4** Geological well-logs of the Region (courtesy of NWRI 1&2) [10]

**Table 2** Typical subsoil layer resistivity and thickness values compiled from different locations within a 20 km radius of the study area [1, 14, 29], and of the current study for comparison

Soil and rock types	Subsurface layer Parameters of the previous studies		Subsurface layer Parameters of the current study	
	Resistivity (Ωm)	Thickness (m)	Resistivity (Ωm)	Thickness (m)
Topsoil (lateritic/clay)	300–5000	1.5–10	133–3922	2.5–7.5
Weathered lateritic/clay, silty	100–450	2–8	399–922	3–7
Weathered basement	30–370	5–51	39.9–105	9.5–36
Fractured basement	450–1100	5–15	499–911	6–10
Fresh crystalline basement rock	> 1000	Infinite	1211–5200	Infinite

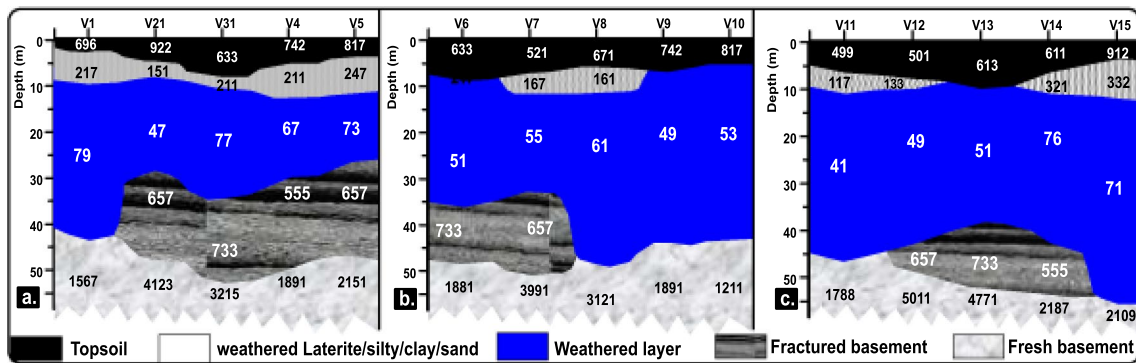
interpreted as topsoil (first layer), which comprises lateritic-clay and laterite; the second layer was interpreted as sand/silty-clay/weathered laterite; the third and fourth layers were interpreted as weathered/fractured basement layer and fifth/last layer was interpreted as fresh basement (Table 2). The resistivity and thickness values of the topsoil range from 499–912 Ωm and 2.0–10 m respectively. The weathered layer is interpreted to have resistivity and thickness values (39.9–105 Ωm and 15–44 m). The bottom layer with resistivity ranging from 1211–5200 Ωm is interpreted to be a fresh basement of an infinite layer thickness with an average overburden thickness of 31 m. All other aquifer parameters including the estimated DZ parameters are presented in Table 3, while Table 4 was used

**Table 3** The summary of computed Dar-zarrouk parameters estimated from the geoelectric parameters across all the 15-VES stations of the study area

SN	VES Pts	Aquifer resistivity $\rho$ ( $\Omega$ m)	Aquifer thickness D (m)	Transverse resistance R ( $\Omega$ m <sup>2</sup> )	Longitudinal conductivity S ( $\Omega$ <sup>-1</sup> )
1	V1	78.9	29.7	2370.1	0.38
2	V2	47.3	19.7	940.3	0.43
3	V3	76.7	21.2	1616.7	0.27
4	V4	67.2	17.2	1138.8	0.25
5	V5	73.3	15.4	1094.5	0.21
6	V6	50.5	27.8	1427.8	0.55
7	V7	54.6	17.8	990.1	0.32
8	V8	61.4	37.9	2318.2	0.621
9	V9	48.8	34.6	1715.2	0.71
10	V10	53.2	35.3	1855.3	0.66
11	V11	41.4	35.1	1434.5	0.85
12	V12	49.1	30.3	1470.0	0.61
13	V13	58.7	28.2	1652.0	0.47
14	V14	75.6	29.8	2280.1	0.39
15	V15	70.7	44.1	3124.3	0.62

**Table 4** Protective capacity rating [30, 31]

Protective Capacity (mhos)	Rating
< 0.1	Poor
0.1–0.19	Weak
0.2–0.69	Moderate
0.7–4.9	Good
5.0–10	Very good
> 10	Excellent



**Fig. 5** Geoelectric and Geology Section for all the Profiles. **a** Profile 1, **b** profile 2 and **c** profile 3

to rate the regional aquifer performance. Figure 4 presents borehole data acquired by the National Water Resources Institute (NWRI) around the study area [10]. The six-inch diameter vertical cylindrical borehole data provides a fundamental insight into the regional geology for critical analysis.

## 5 Discussion

The resistivity and thickness values of the aquifer unit and the overburden are presented in Fig. 5a–c. These values are considered important parameters for evaluating the regional groundwater potential for this study. The interpreted data reveals that the study area is underlain by weathered/fractured zones, which are largely responsible for the regional groundwater potential according to the previous studies [1, 2, 14, 18, 19]. However, the observed thickness nature and resistivity values of the weathered/fractured basement layer project the regions as promising zones for groundwater development for both domestic and industrial water supply. Figure 5 shows the resistivity and thickness values of the subsurface rocks obtained in the course of the interpretation which were used to estimate the aquifer storage capacity. According to previous studies, a region of basement rocks with low resistivity values ( $< 1200 \Omega\text{m}$ ), may have probably been heavily weathered, faulted or fractured and could be considered for groundwater development [1, 14]. From the apparent electrical resistivity values varying between 499–911  $\Omega\text{m}$ , which were interpreted as the fractured basement rocks overlying the fresh basement rocks (Figs. 5 and 6), more than 95% of the region possesses high aquifer potential. Studies have shown that the regions of crystalline basement complex terrains with adequate aquifer storativity and transmissivity are areas where groundwater exploitation can be guaranteed [1, 14]. Therefore, the study area is largely productive for groundwater development qualitatively and quantitatively in almost all the VES stations including the orthogonal 2D ERI profile. However, the VES stations where the aquifer basement rocks are fractured show stronger aquifer potential units.

The study further evaluated the aquifer potential and its protective capacity from aquifer resistivity and thickness values using estimated DZ parameters. Previous studies show that regions with a shallow overburden thickness ( $< 5$ ) overlying the aquifer regions ( $< 12 \text{ m}$ ) may be very susceptible (vulnerable) to surface contaminants that may arise from human activities [1, 14, 32, 33]. From the data interpretation (Figs. 5 and 6), the study area is relatively protected against contamination from near surface activities such as solid waste and sewage with overburden thickness overlying the aquifer extending beyond 9 m. The longitudinal conductance,  $S_L$  and transverse resistance,  $R_T$  estimated from aquifer parameters vary between  $0.21 - 0.85 \Omega^{-1}$  and  $1695 - 3124 \Omega\text{m}^2$  respectively. The longitudinal conductance values show that the study area falls within moderate ( $0.20 - 0.69 \Omega^{-1}$ ) and good ( $0.7 - 0.49 \Omega^{-1}$ ) aquifer protective capacity. However, there are other factors such as depth to the water table, contaminant nature, and geological factors like faults or vents that enhance contaminants infiltration into the subsurface down to the groundwater zone.

## 6 Conclusion

The geoelectric investigation of the study area revealed that the area is underlain with four to five distinctive geological layers. The aquifer is interpreted as having low resistivity (39.9–105  $\Omega\text{m}$ ) and high thickness ranging from 15–44 m. The overburdened thickness (thick topsoil) overlying the regional aquifer has resistivity and thickness values ranging from 499–912  $\Omega\text{m}$  and 2.0–10 m respectively thereby providing the aquifer protective capacity of the region. A weather/fractured basement layer is interpreted from 5.5 m to 55 m and is considered positive for groundwater development.

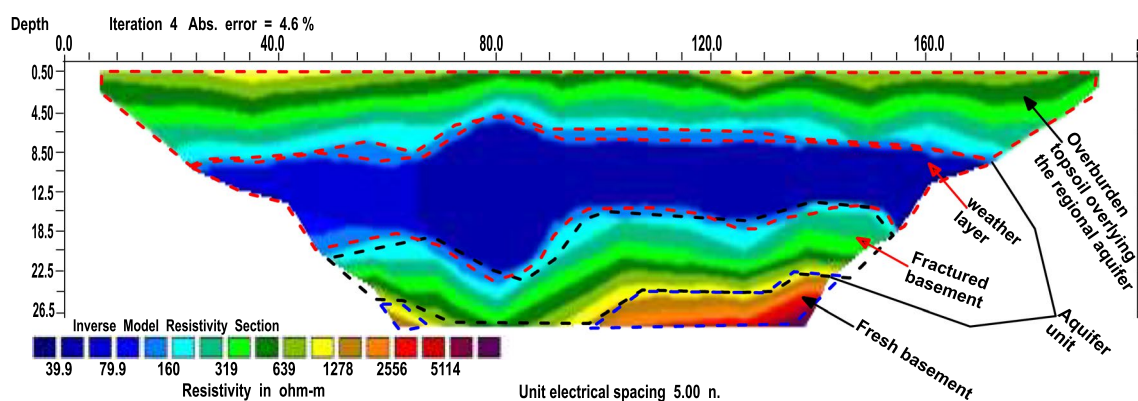


Fig. 6 2D ERI Inversion of the study area



The weathered layer with appreciably low resistivity values with thick regolith has also been identified as most suitable for borehole siting. The weathered/fractured zones are the regions identified as potential targets for siting boreholes. Because the entire investigated area is essentially positive for groundwater exploitation for both individual and industrial water supply quantities and qualities, the fractured zones are considered the most promising zone for siting boreholes most especially for industrial-scale water wells. The weathered/fractured encountered within thick aquifer regolith indicates the aquifer's high storage capacity. That is, the viable aquifers wholly within the region often occur in a weathered/fractured basement layer. For a basement aquifer to produce effectively, the development of the bedrock component requires interactions with storage available in overlying or adjacent saturated regolith, or other suitable formations such as the fractured and thick aquifer regolith. The study has successfully delineated the ASP as a measurement of groundwater potential, which can be evaluated from the aquifer properties such as resistivity, nature and thickness. Hence, the dc-resistivity method has proved very successful in delineating aquifer storage capacity or aquifer deep zones for groundwater development.

**Author contributions** OJA conceived and designed the work, while Investigation, Data acquisition, Data processing, Analysis, Resources, Writing and editing of the manuscript, were done by all the authors (JOA, HAL, MJA, FA, OOA, ETM, and MAY).

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**Data availability** The datasets generated during and/or analyzed during this study are available on request.

## Declarations

**Competing interests** The authors have no relevant financial or nonfinancial conflicts of interest to disclose.

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