



3D geophysical mapping of the subsurface to support urban water planning: a case study from Simawa, Nigeria

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ABSTRACT

Simawa town, Ogun state, lacks the required water infrastructure for rapid urban development. This study seeks to use the geoelectric method – taking into account the geology and hydrogeology of the study area – to determine the groundwater potential of the town. Fifteen Vertical Electrical Sounding (VES) stations were spread across the town to characterise the subsurface layers. Interpretation of the VES data yielded five geoelectric layers. A lithology log from a prior borehole was used as a geologic control to confirm the validity of the VES results. The five geoelectric layers correspond to the topsoil (layer 1), Akinbo clay (layer 2), Akinbo shale (Layer 3), Ewekoro limestone (Layer 4), and Abeokuta sandstone (layer 5). The Abeokuta sandstone represents the main aquifer unit, a confined aquifer that can serve as a suitable source of potable water. Boreholes drilled in Simawa town should target the confined sandstone aquifer at a minimum depth of 80 m.

ARTICLE HISTORY

Received 6 September 2021
Revised 30 November 2021
Accepted 8 January 2022

KEYWORDS

Groundwater exploration;
geoelectric method; 3D
subsurface modelling;
hydrogeology

1. Introduction

Simawa town, Ogun State, is a community plagued by a severe shortage of potable water suitable for domestic, industrial, and agricultural purposes. Most hand-dug wells in the community dry up during the dry season or produce turbid water. Residents depend on surface water sources that are difficult to access and susceptible to pollution. Rapid urban development and industrialisation require a sustainable source of potable water (Huisman et al. 1983).

Groundwater is a suitable and sustainable source of potable water because of its quality, reliability, and accessibility (UN/WWAP 2003). Groundwater is free of contaminants, except in unusual cases where it is contaminated because of poor waste management. Its quality makes it more suitable for urban development than open water sources. However, despite abundant reserves, groundwater development has not kept pace with urban growth in the region (Oteze 2006).

The geoelectrical method provides a rapid and cost-effective means of assessing the groundwater potential (Alabi et al. 2010). Subsurface electrical resistivity can distinguish between fresh and saltwater; sandy aquifers and clayey material; hard rock porous/fractured aquifers and low-permeable clay stones and marlstones; and water-bearing fractured rock and its solid host rock (Kirsch and Yaramanci 2009). The geoelectrical method is best suited for hydrogeological assessments because of the established relationship between the electrical and hydraulic properties of aquifers (Mazac et al. 1985). When integrated with geological data, the electrical

resistivity method has been proven to be a successful technique in groundwater exploration studies (Mohamaden 2016; Younis et al. 2016; Abd El Hameed et al. 2017; Mohamaden and Ehab 2017).

Vertical Electrical Sounding (VES) is a geoelectrical technique for measuring vertical variations of electrical resistivity in the subsurface. The method is best suited for the hydrogeological study of sedimentary basins. This study seeks to develop a hydrogeological model using the geoelectrical method for further water development planning and infrastructure in the town.

1.1. Geological setting

Simawa town is in the sedimentary environment of the eastern Dahomey basin, a broad arc-shaped area of about 600 km² with a maximum width of 130 km (Figure 1). The Dahomey basin was formed by the separation of the African and South American tectonic plates during the Jurassic-Cretaceous period (Omatsola and Adegoke 1981). The basin's tectonic structure is simple, forming a monocline against the basement outcrop to the North. Sedimentation shows an east-west trend and is roughly parallel to the ancient coastline (Okosun 1998a).

1.2. Stratigraphy

The stratigraphic formations in the study area trend NW–SE, with a shallow dip of about 1 degree. The formations form a monocline structure against the basement (Figure 2).

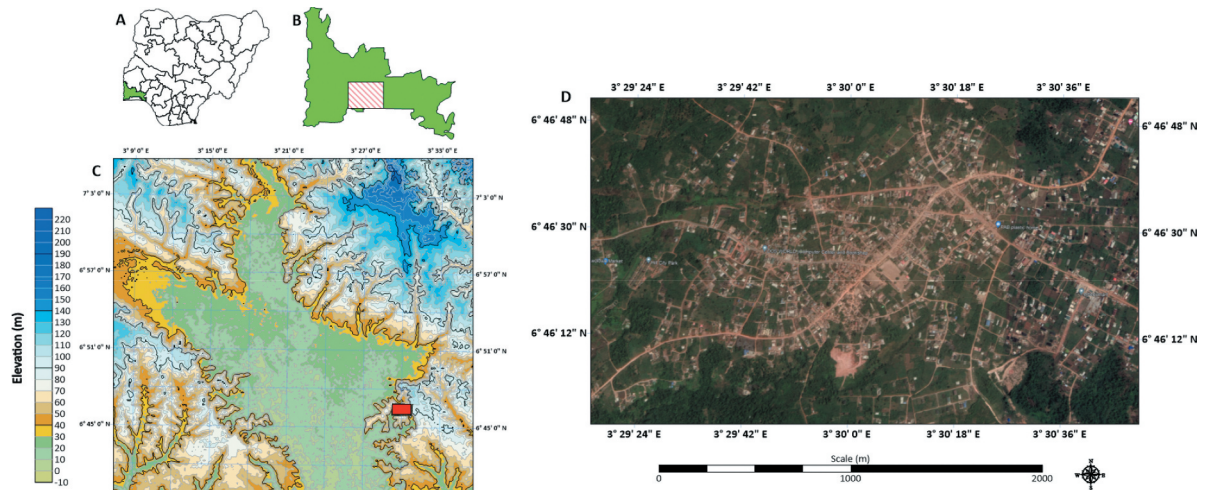


Figure 1. (a) The map of Nigeria shows Ogun state. (b) The map of Ogun state shows the Ogun River basin (c) The topographic map of Ogun River basin shows study area (red rectangle). (d) The map of study area.

The Abeokuta Formation, deposited over the basement complex during the Upper Cretaceous, has an approximate thickness of 260 m onshore. It comprises mainly sand and sandstone, with siltstone, mudstone, and shale interbeds (Omosanya et al. 2012). A thin basal conglomerate consisting of angular quartz pebbles in a sandstone matrix occurs at the lower boundary. It is overlain by coarse-grained, clayey, micaceous, and poorly sorted sand and sandstone (Omosanya et al. 2012). Outcrops show the shale content to increase upwards (Okosun 1990).

The Ewekoro Formation consists of fossiliferous limestone that becomes arenaceous at the base. The structure and chemical composition of the limestone

suggest a shallow marine depositional environment under tropical littoral to neritic conditions (Jan de Chine 1980). The formation is Palaeocene in age (Ehinola et al. 2016) with a maximum thickness of 47 m. In some areas, it is enveloped by the black shales of the Akinbo formation (Adebiyi 2014).

The Akinbo Formation is mainly greyish-black shales with occasional fine-coarse grained sand interbeds at the top. The shale is fissile, thinly laminated, and locally calcareous at the base. The formation has a maximum thickness of 178.4 m (Adebiyi 2014). The Ewekoro limestone was deposited under marine conditions during the Late Palaeocene to Early Eocene (Okosun 1998b).

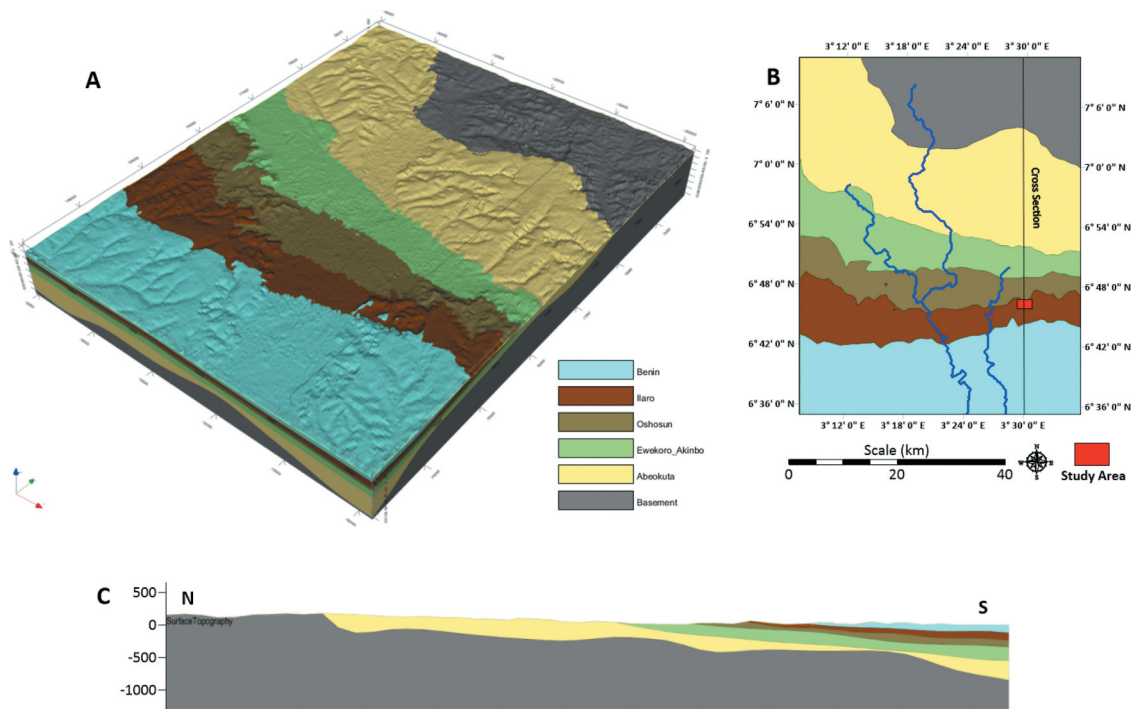


Figure 2. (a) 3D geological model of Ogun River basin (modified after (Persits et al. 1997)). (b) The geological map shows the cross-section and major rivers. (c) N-S geological cross section.

The Oshosun Formation is composed of clay, shale, unconsolidated sand, and sand with shale intercalations. The shale is laminated with thick calcareous intercalation at the base. The upper part is much sandier. The Oshosun Formation was deposited in a marine environment, probably in fairly deep water, during the Medial Eocene (Lutetian) Age (Adebiyi 2014). It is not easily distinguishable from the Akinbo Formation

The Ilaro Formation consists of grey-green sandy clays, sandy claystone, and sandstones. The sandy facies at the top of the formation are whitish-brown, medium to coarse-grained, and unevenly developed; they are also absent in some areas. The age of the formation is middle to late Eocene (Nton et al. 2009).

The Benin Formation is also called the Coastal Plain Sands. It consists of poorly sorted crossbedded sand with lenses of clay that show a near-shore to continental distinctiveness. The formation is Miocene to Holocene in age (Omatsola and Adegoke 1981).

1.3. Hydrogeology

The study area has two major climatic seasons: dry season from November to March and rainy season between April and October. Average annual precipitation is above 1700 mm (Adebiyi 2014). The area is drained by the tributaries of the Ogun River (Figure 3). The area is densely vegetated, so evapotranspiration is expected to be high.

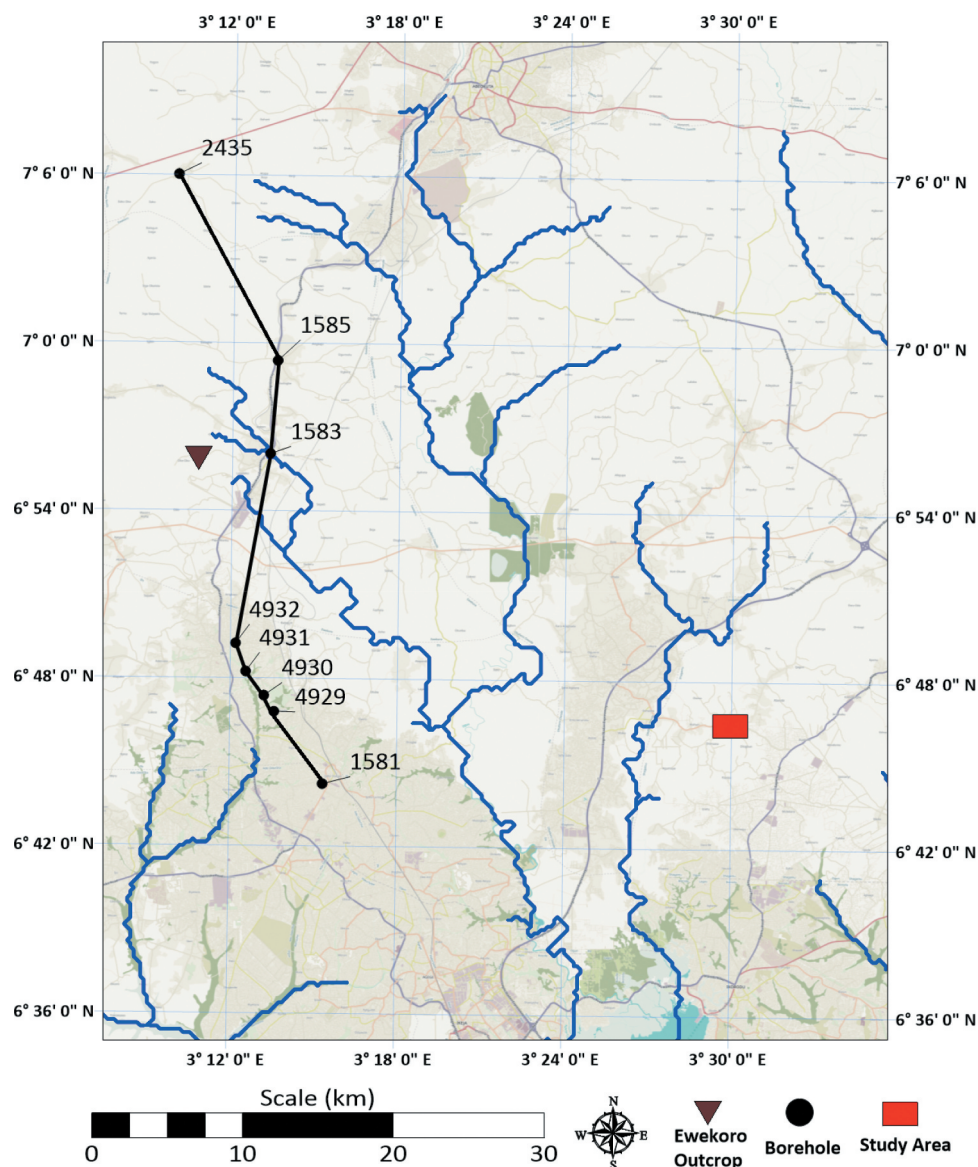


Figure 3. The drainage map of Ogun River basin shows outcrop and borehole locations.

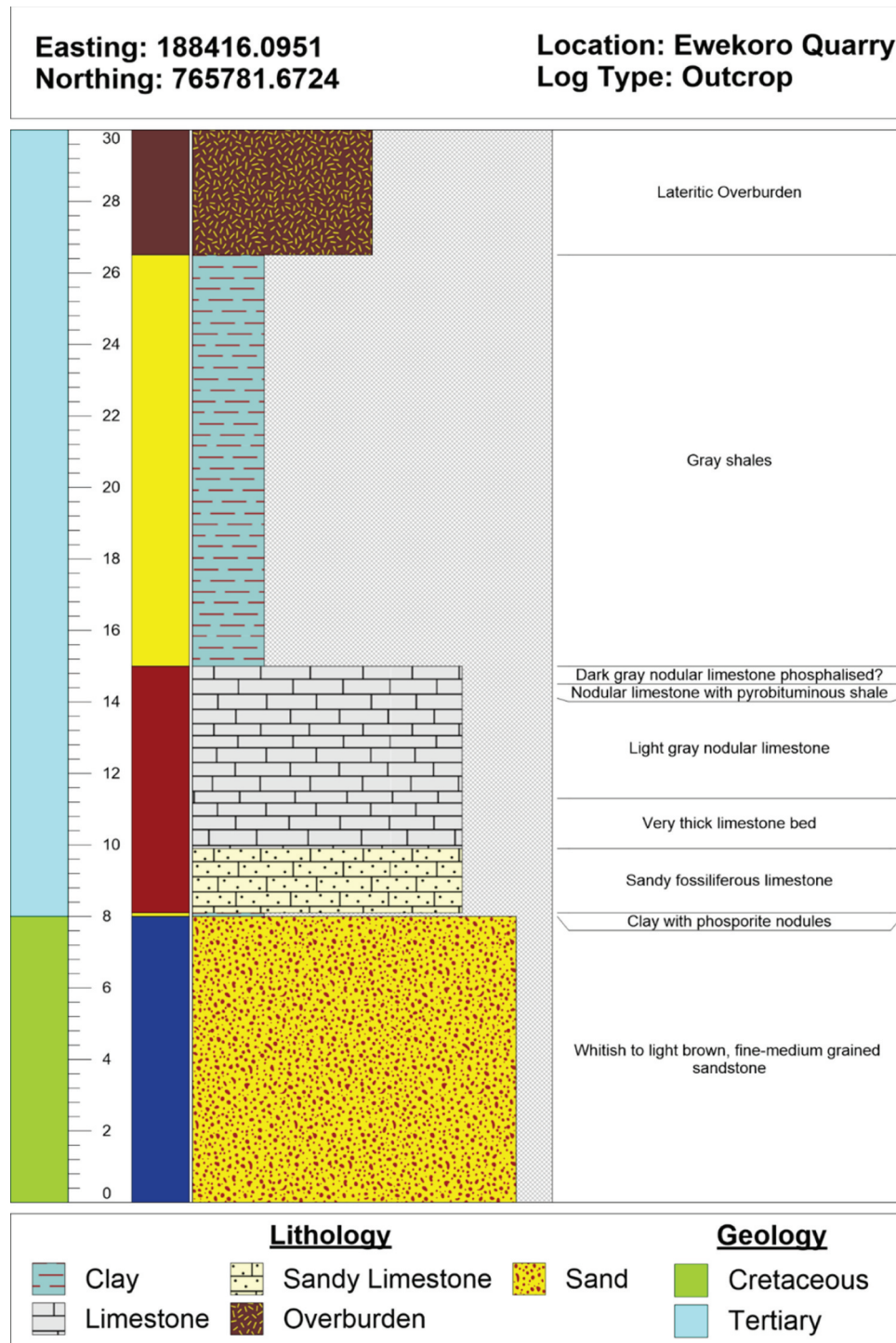


Figure 4. Litho-stratigraphic section exposed at Ewekoro Quarry.

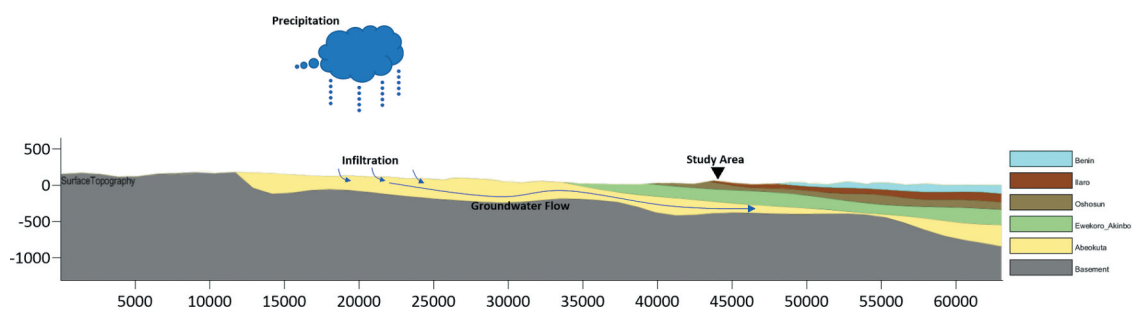


Figure 5. The N-S cross-section shows the groundwater recharge of the sandstone aquifer.

The major hydrogeological unit is the Abeokuta sandstone aquifer. Outcrops at Ewekoro quarry show the sandstone aquifer to be fine to medium-grained (Figure 4). The aquifer is confined by the Ewekoro limestone and Akinbo shale, respectively. Groundwater recharge occurs in the north, where the formation is exposed. Precipitation is the major source of groundwater recharge in the area (Figure 5). Geothermal water may be expected in the southernmost parts of the study area where the aquifer is deepest.

Records of 8 boreholes west of the study area show the occurrence of minor aquifers within the Oshosun and Ilaro formations. The aquifers are

confined or leaky and comprise sandy and sandstone horizons (Figure 6). The Ewekoro and Akinbo Formation are aquicludes which separate the regional Abeokuta sandstone aquifers from the localised Oshosun and Ilaro aquifers.

2. Materials and methods

2.1. Data acquisition

Using the Schlumberger array, 15 VES stations were spread across the town (Figure 7). An electrode spread of 700 metres was used to ensure current flows to an expected depth of 100 m. We chose the direction of the

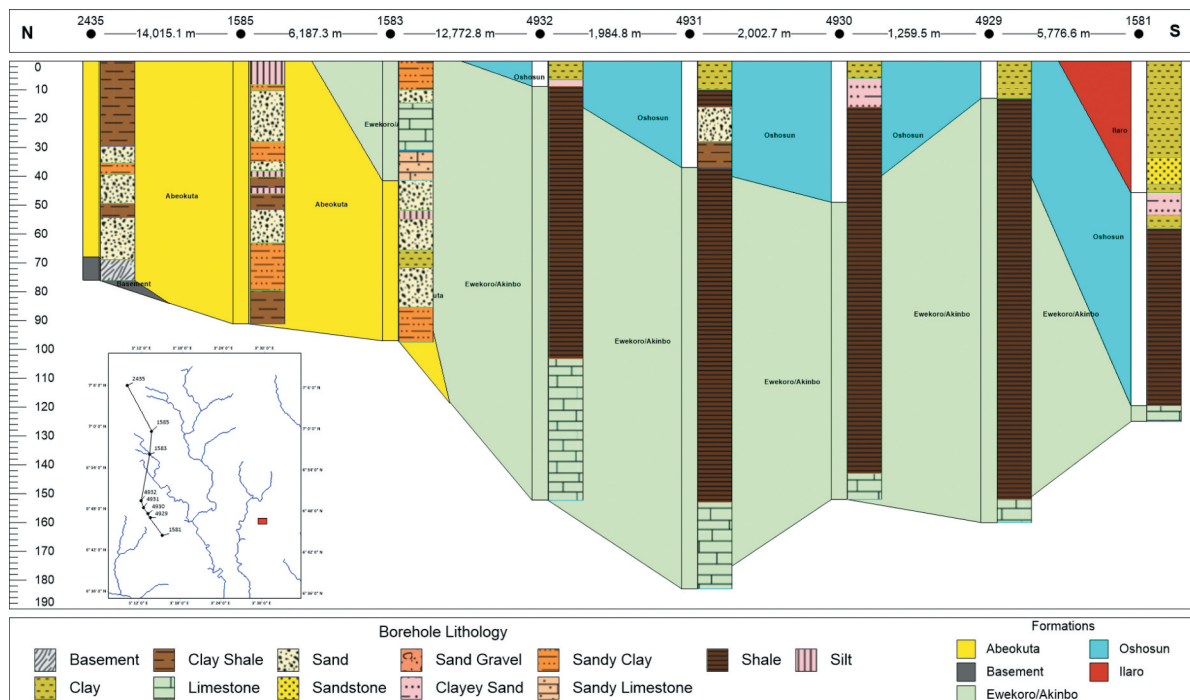


Figure 6. Borehole cross section showing minor sand and sandstone aquifers modified after (13).

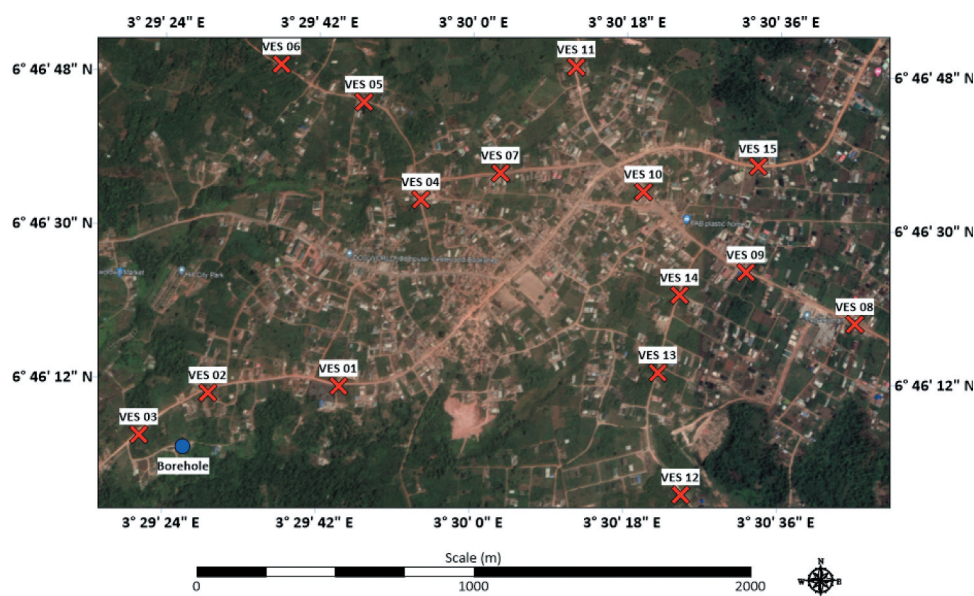


Figure 7. The base map shows VES stations and borehole location.

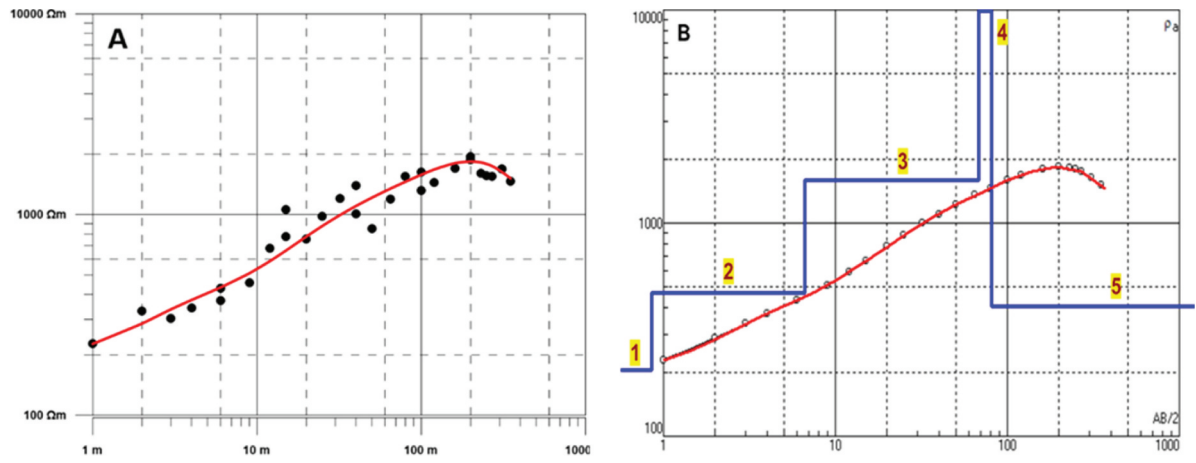


Figure 8. (a) Sounding curve for VES_01 and (b) geoelectric model for VES_01

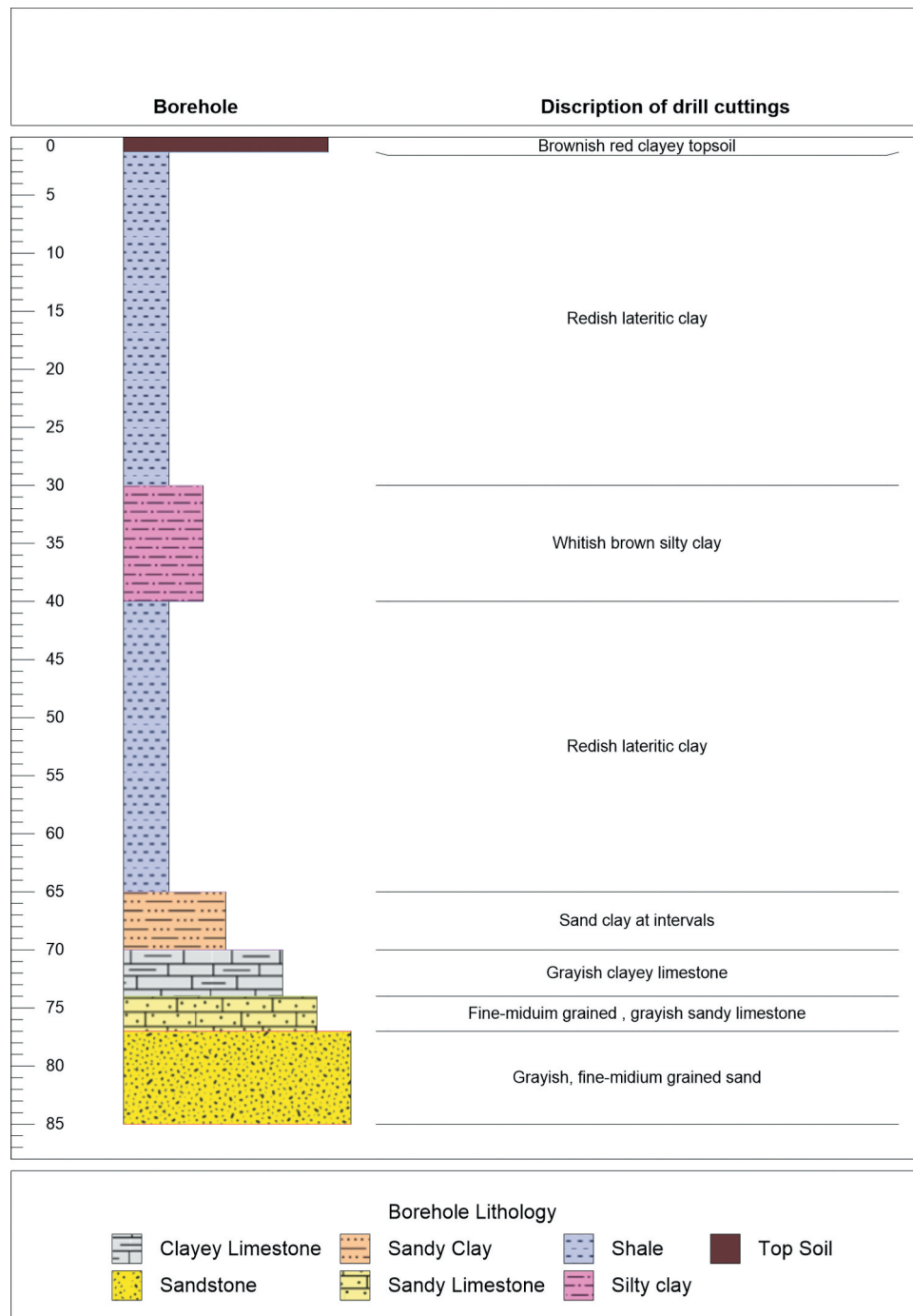


Figure 9. Borehole lithology (Simawa town).

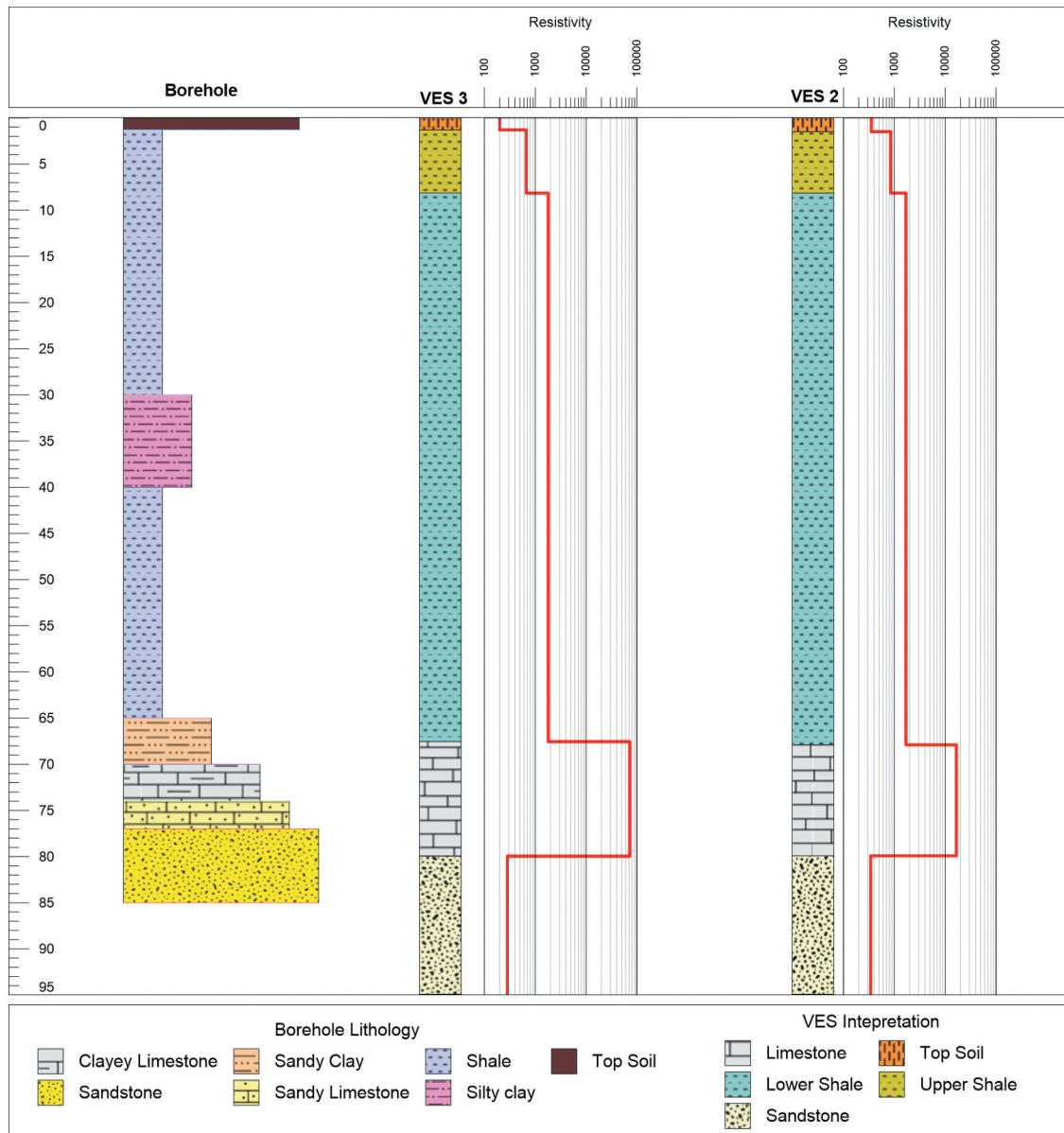


Figure 10. Litho-correlation between VES and borehole data.

electrode spread along fairly straight and flat roads to avoid topographic effects on the sounding curve. The electrical current was generated via a direct current (D.C) motor battery (PASI P 100.2 Energiser). The apparent resistivity was measured using the resistivity metre (PASI G-16).

2.2. Data processing

The apparent resistivity values were plotted against their respective half current electrode spacing values ($AB/2$) on a log-log graph to produce a sounding curve. The sounding curves were smoothed to eliminate noisy data caused by the effects of lateral heterogeneities and other signatures (Figure 8a). The curves were then inputted into the IPI2Win computer program for evaluation in terms of a layered earth model (Figure 8b). More attention was paid to the

conformity of the layers than to the fitting error, but the fitting error was maintained below 2%. Due to the inherent problem of equivalence (Hill and Webb 1958), the sounding curves were constrained using prior stratigraphic information.

3. Results

Cuttings from a prior drilled borehole show the local stratigraphy to comprise: a sandstone aquifer, a limestone-confining unit, and a thick clay overburden (Figure 9). The sandstone aquifer is fine to medium grained and occurs at a depth of 77 m. An 8 m thick limestone layer that becomes sandy at the base confines the sandstone aquifer. The reddish-brown clay overburden has a 10 m thick silt clay layer at a depth of 30 m and a 4 m thick sandy clay layer at a depth of 66 m.

3.1. Correlation between borehole lithology and geoelectric sections

The borehole lithology was correlated with the geoelectric layers (Figure 10). The topsoil corresponds to the first geoelectric layer. The clay overburden correlates to the second and third geoelectric layers. The limestone layer matches the fourth geoelectric layer and the fifth geoelectric layer was likened to the sandstone. The silty clay layer was probably suppressed due to the low resistivity contrast across the layer boundaries. The sandy clay layer could not be resolved at that depth.

3.2. Geoelectric characteristics of stratigraphy layers

The geoelectric sections shown in Figures 11 and 12 consist of five geoelectric layers of conforming thickness and depth. The topsoil has a resistivity range of 144–768 Ωm . Low resistivity indicates mud-rich topsoils, and high resistivity indicates sand-rich topsoils.

The shale overburden has two distinct geoelectric layers that may correspond to the Akinbo Formation. The average resistivity of the upper

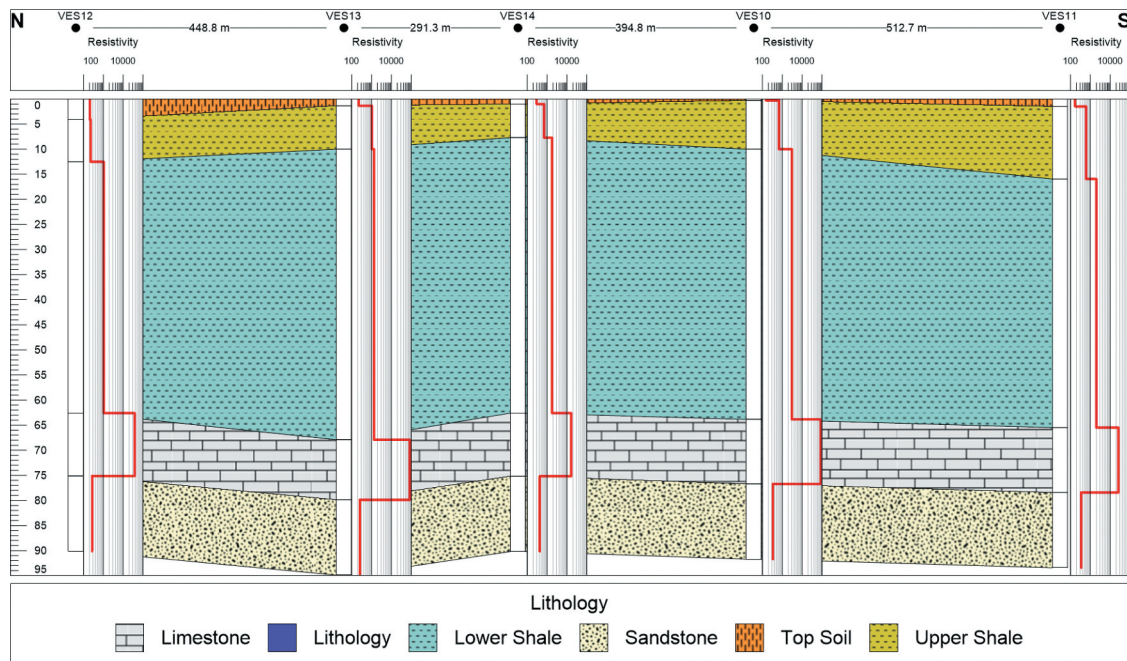


Figure 11. N-S geoelectric section.

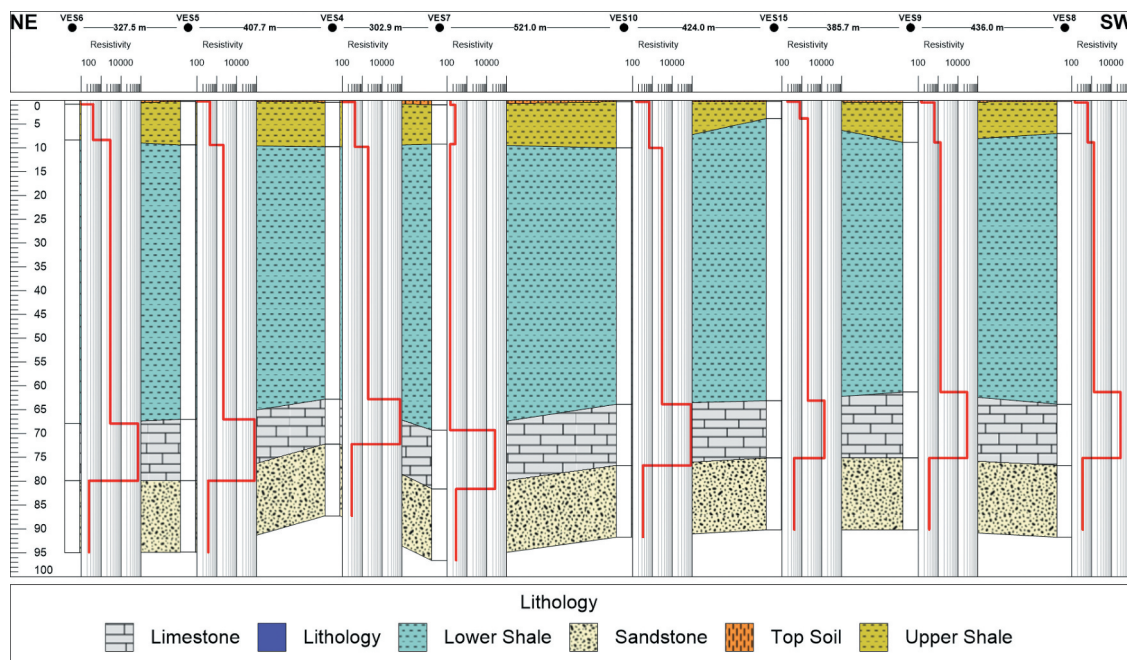


Figure 12. NE-SW geoelectric section.

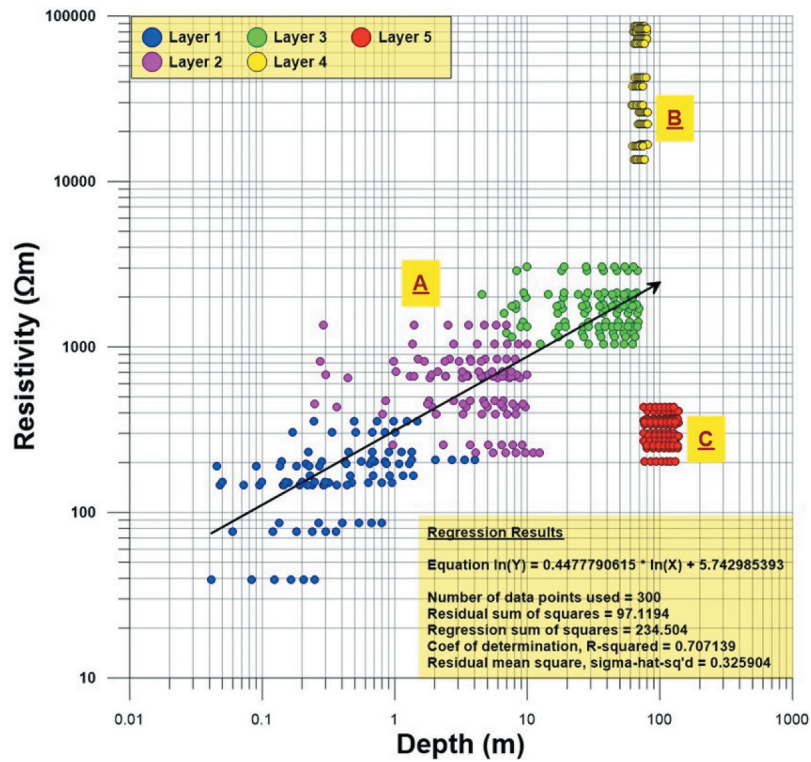


Figure 13. The cross plot shows the facies clusters and regression line.

Table 1. Statistical summary of the regression analysis.

Geoelectric layers	Formation	Lithology	Measured resistivity (Ωm)	Model Resistivity (Ωm)	Resistivity Anomaly (%)	Facies
2	Akinbo	Clay	643.35	686.77	-8.78	Facies A
3	Akinbo	Shale	1767.53	1854.22	-5.01	
4	Ewekoro	Limestone	49,725.93	2657.24	+171.10	Facies B
5	Abeokuta	Sandstone	314.54	3177.83	-163.87	Facies C

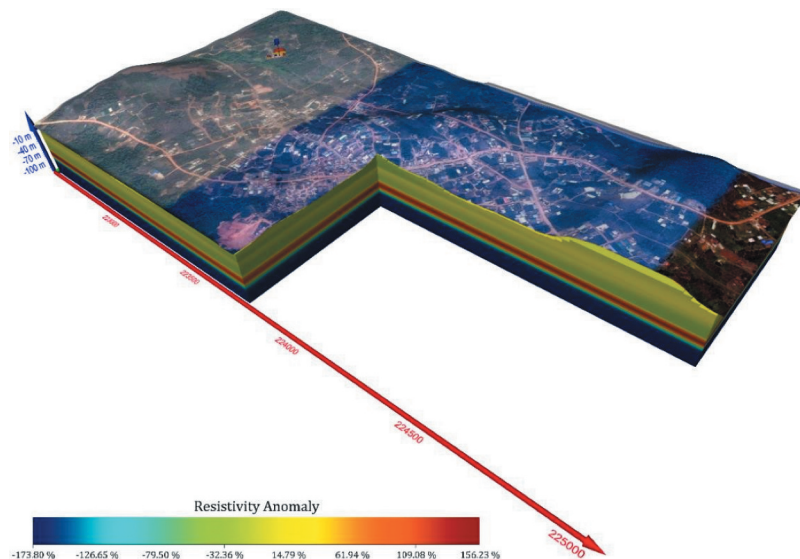


Figure 14. 3D resistivity anomaly model.

and lower shale layers is 643.35 Ωm and 1767.53 Ωm respectively. The higher resistivity of the lower layer shows increased compaction and consolidation.

The Ewekoro limestone layer has an average resistivity of 49.7 kΩm. The anomalously high resistivity results from the low porosity of the limestone (Van Overmeeren 1989).

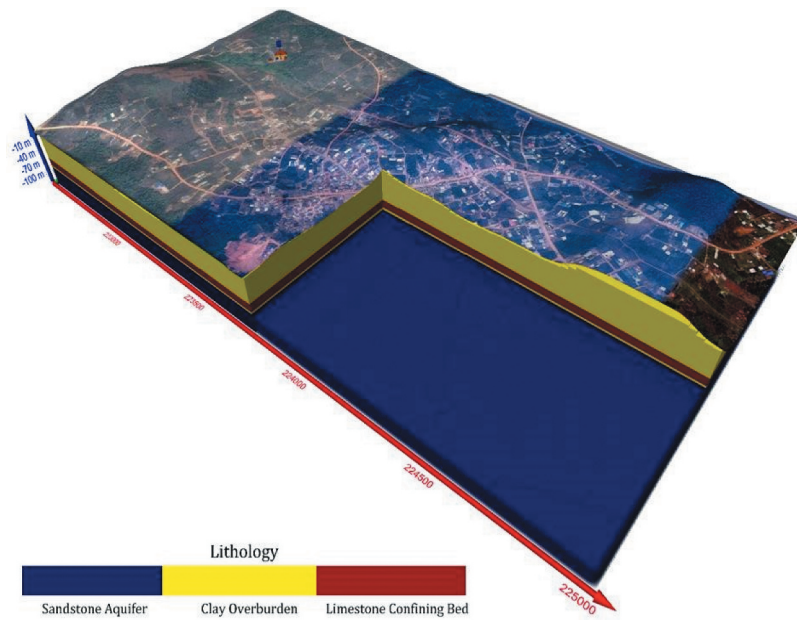


Figure 15. 3D hydrogeological model.

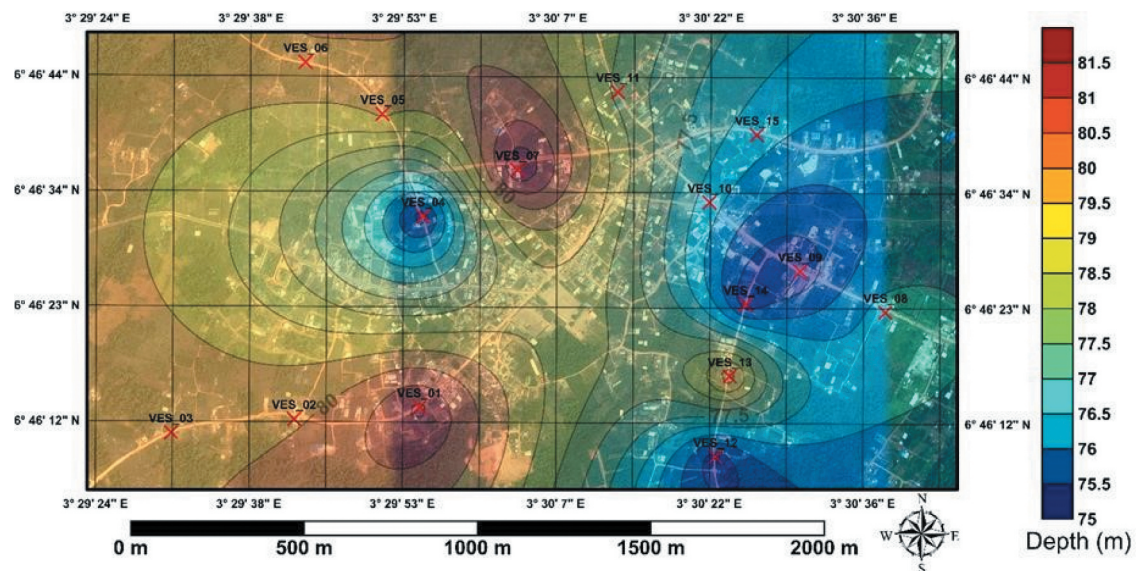


Figure 16. The structural map shows depth to the sandstone aquifer.

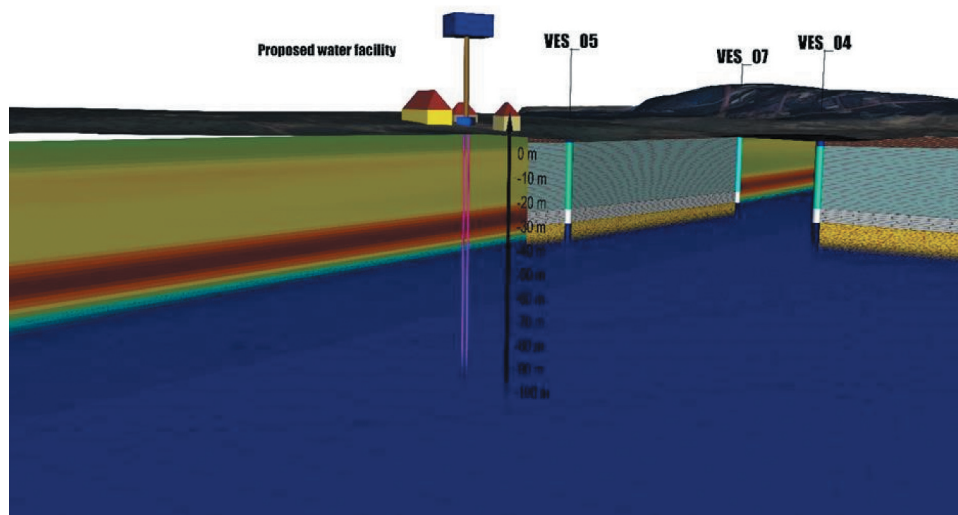


Figure 17. Proposed groundwater facility.

The fifth geoelectric layer is the sandstone aquifer; its resistivity ranges from 204 Ωm to 443 Ωm . Since aquifer resistivity is inversely proportional to the porosity (Badmus and Olatinsu 2009), low resistivity shows increased porosity favourable for groundwater exploitation.

4. Discussion

4.1. Facies modelling

The geoelectric layers are grouped into three facies (Figure 13). Facie A represents the shale and clay overburden of the Akinbo formation. Facie B is the Ewekoro limestone formations. Facie C is the Abeokuta sandstone aquifer.

A linear regression analysis of the cross plot was conducted. The results were used to calculate a model resistivity value (Equation 1), which was then compared to the measured resistivity to identify anomalous zones. The percentage difference between the measured and model resistivity was used to quantify the resistivity anomaly (Equation 2). In a sandstone environment, a low resistivity anomaly

will be the target.

Table 1 shows the statistical summary of the regression analysis. The clay and shale overburden of the Akinbo formation show no significant percentage difference between the measured and model resistivity. The average resistivity anomaly of the Ewekoro limestone layer is +171%. The high anomaly indicates unfavourable hydrogeological characteristics. The average resistivity anomaly of the Abeokuta sandstone layer is -163%. The low anomaly shows the presence of groundwater (Figure 14).

$\text{Ln}(\text{Model Resistivity}) = 0.45 * \text{Ln}(\text{depth}) \times 5.74$
Equation 1

$\text{Resistivity Anomaly} = [(\text{Measured resistivity} - \text{Model resistivity}) / (\text{Measured resistivity} + \text{Model resistivity})] \times 100$
Equation 2

4.2. Hydrogeological framework

The resistivity anomaly model was used to construct a hydrogeological model of the study area (Figure 15). The main water source in the Abeokuta sandstone occurs at an average depth of 80 m (Figure 16). The impermeable Ewekoro limestone formation confines the sandstone aquifer. A thick clay and shale overburden, which belongs to the Akinbo formation, overlies the confined aquifer system.

5. Conclusions

Simawa town requires a constant supply of potable water for urbanisation. Fifteen VES, together with outcrop and borehole data, were used to evaluate the

town's groundwater potential. The results of the VES interpretation revealed five geological layers: the topsoil, upper clay, lower clay, limestone, and sandstone. The borehole and outcrop logs showed a near-consistent correlation with the VES result.

The sandstone layer was identified as the major aquifer due to its low resistivity anomaly. It is an artesian aquifer confined by limestone at a depth of about 80 m. The contour map of the depth to aquifer should be used when sinking future boreholes. The proposed water facility (Figure 17) should target the artesian sandstone aquifer at a minimum depth of 80 m.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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