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Application of Integrated Geophysical Methods for Groundwater Exploration in Iworoko-Ekiti, Southwestern Nigeria

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Abstract
Electrical Resistivity and Electromagnetic Methods were adopted to probe the subsurface formation of the Isaba Garri processing Industry environment as a result of challenges experienced in groundwater production. The environment falls on a big outcrop of land where proximity of locating a position for a borehole has been difficult. The Impact method, Electromagnetic method using gradient array method and Three Vertical Electrical Soundings were established along a single 120 m traverse orientated in a north-south direction. The Electromagnetic approach served as a pre-study for the establishment of the VES. The EM and VES methods revealed different geologic formations which are; topsoil, weathered layer, fresh basement and fractured basement with resistivity range of 96 – 976, 1396 – 2380, 4546 – 28594 and 126 ohm-m, and thicknesses range of 1.2 – 2.9, 5.3 – 6.2, 4.1 to infinity and 10.7 m respectively. The result revealed that VES 1 located at the southern part of the study, is good enough for borehole drilling for the successful running of the Industry.

Keywords: Basement Complex, Electromagnetic, Electrical Resistivity, Groundwater, Iworoko-Ekiti

Introduction
The increasing need for groundwater as a primary freshwater source has driven research into efficient exploration methods, especially in areas where surface water is not abundant (Carrard et al., 2019; Katsanou and Karapanagioti, 2017; Dao et al., 2024 and Scalon et al., 2023). Groundwater, essential for domestic, industrial, and agricultural uses, often requires extensive geological and hydrogeological knowledge to locate, especially in complex terrains like hard rock areas (Ishola et al., 2023, Li et al., 2021and Ejepu et al., 2022). Differentiating between saturated and unsaturated zones aids in determining groundwater potential. Geophysical methods, particularly Vertical Electrical Sounding (VES) and Electromagnetic methods, have proven valuable for assessing aquifer depth, thickness, and water yield (Opoku et al., 2024, Ubaidullah et al., 2021 and Stanly et al., 2021). This study focuses on the Isaba Garri industry area in Nigeria’s Basement Complex, characterized by fractured and weathered rock formations that serve as primary aquifers. A well-coordinated investigation of this area will help delineate aquifer zones, assess groundwater conditions, and support sustainable water supply planning.

Aim and Objectives of the Study
The aim of this study is to use an integrated geophysical method for groundwater development in the study area.

The objectives of this study are to:

i. carry out reconnaissance survey of the environment by inspecting the study area.
ii. take water samples from hand dug wells, boreholes and stream within the study area.
iii. employ electrical resistivity method using schlumberger array and electromagnetic geophysical method using gradient array.
iv. delineate the subsurface structures and formations using the integrated method such as topsoil, weathered, fractured and fresh basement.
v. use (i-iv) to determine a suitable location for groundwater development in the study area.

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Description of the Location

The study area, located in Ifelodun/Irepodun Local Government, Ekiti State, Nigeria, lies within the Precambrian Basement Complex of Southwestern Nigeria, dating back to the Archean-Proterozoic era. The area experiences a tropical sub-equatorial climate with a bimodal rainfall pattern, peaking between May and October, with an annual rainfall of 1200-1400 mm. The dry season spans from November to March. Global warming has slightly altered the traditional onset and end of rains. The settlement is nucleated, with residents primarily engaged in farming and hunting. The mean temperature is 27°C, with February and March being the hottest months. Groundwater occurs mainly within weathered rock or fractures. The topography features low relief, with dome-shaped hills, boulders, and a varied elevation that influences drainage patterns.

Geological Setting

The study area lies within the Precambrian Basement Complex, part of the West African Craton, featuring rocks influenced by significant geological events like the Liberian, Eburnean, Kibarian, and Pan-African orogenies. This complex is shared with regions extending into Ghana, Togo, and the Dahomey region, and it includes crystalline basement rocks that cover approximately half of Nigeria's surface. The Precambrian basement complex rocks in Nigeria are classified into four main lithologic units: Migmatite-Gneiss-Quartzite Complex, Schist Belts, Pan-African Granitoids, and minor unmetamorphosed rocks. Locally, Iworoko Ekiti's geology comprises primarily banded gneiss, migmatite-gneiss, and granite-gneiss, with charnockite and granite occurring in close association(Cooray 1972, 1975, Olanrewaju 1981, and Olanrewaju 1987). . Both rock types are thought to be nearly contemporaneous, with charnockites potentially forming shortly after the granites (Rahaman, 1981).

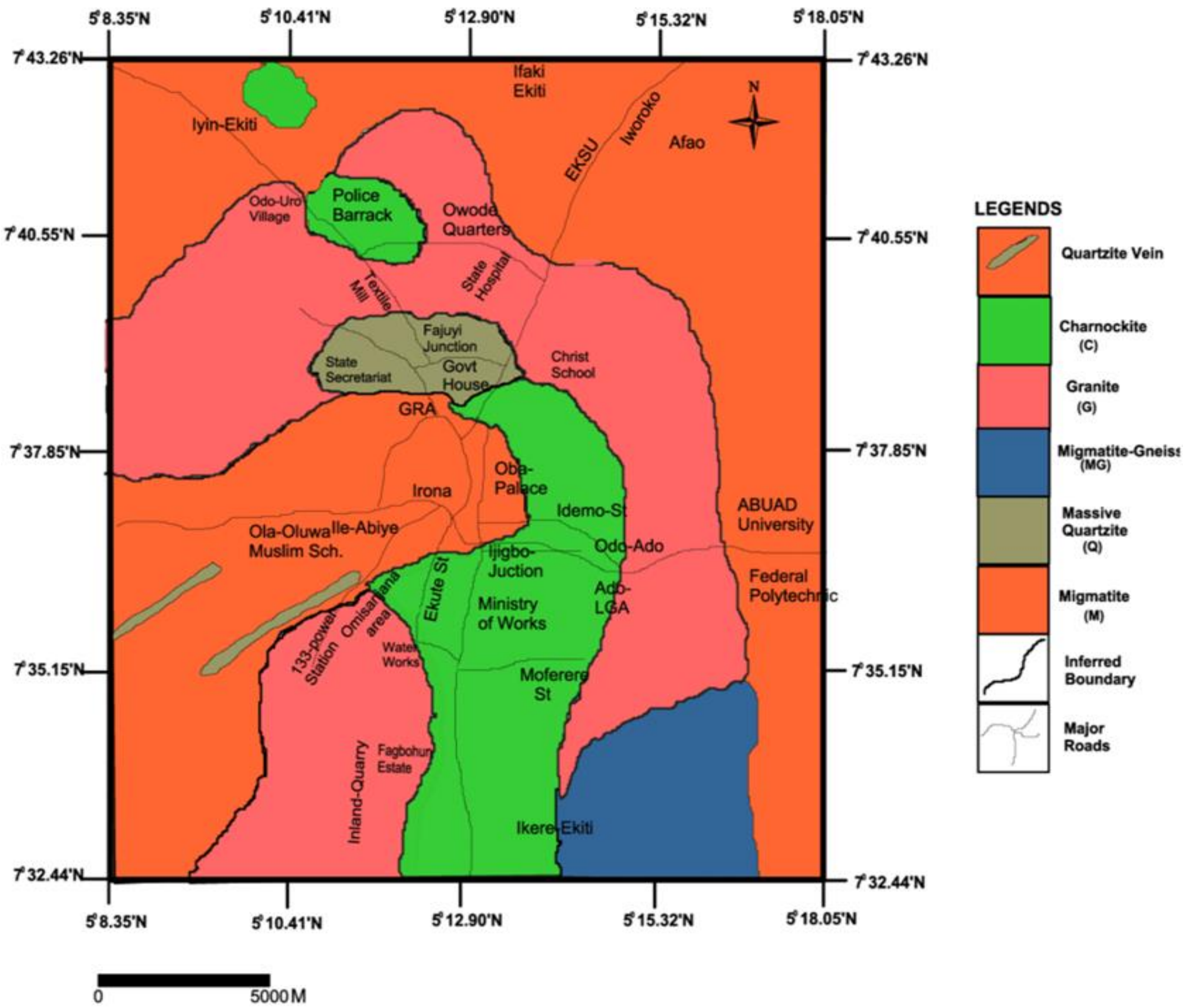

Figure 1: Geological map of the study area and its environs (Akintorinwa *et al., 2020*)

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Materials and Methods

Groundwater potential and quality at Isaba Garri Industry in Iworoko Ekiti were assessed using Electromagnetic (EM) and Vertical Electrical Sounding (VES) methods. EM mapping detected lateral conductivity variations efficiently, while VES provided vertical resistivity profiles to locate potential aquifer zones. PQWT 300NC equipment was used with a 70m traverse, producing 2D geoelectric profiles. Conductive zones identified by EM informed VES locations, with a Schlumberger configuration across three sites and a 130m spread. Field materials included GPS for location accuracy, thermometer for water temperature, and tape for depth measurements. Water quality indices such as WQI, SAR, and MAR were calculated, showing quality influenced by rock-water interaction, weathering, and leaching. pH values ranged from 5.1 to 7.3, indicating mildly acidic to slightly alkaline conditions, with localized acidity in densely populated areas. Data interpretations, presented in profiles and maps, support effective groundwater management and planning.

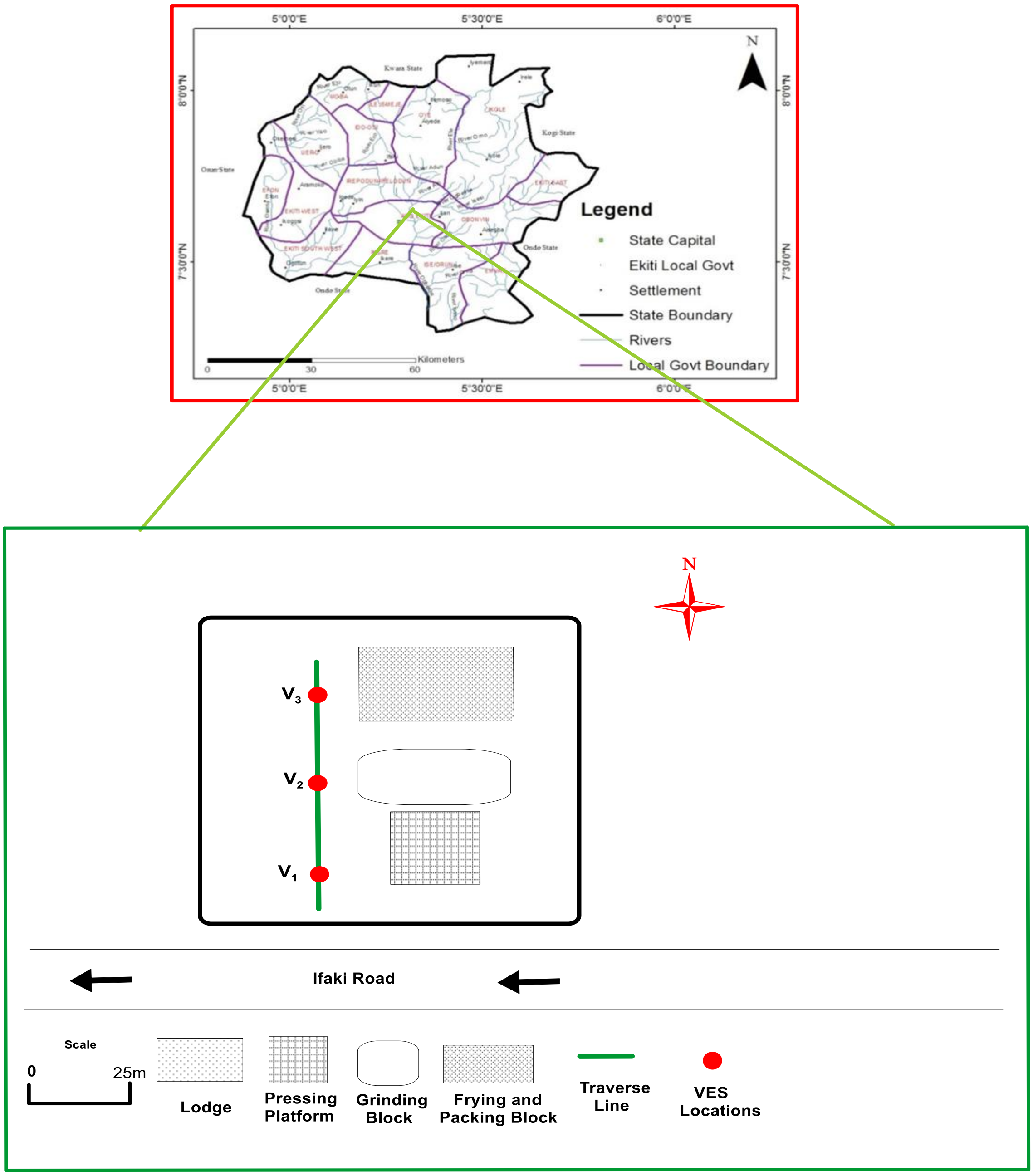

Figure 2: VES location in the study location

Basic Principles and Results

A 70 m traverse was set up for data acquisition along the north-south direction, with an inter-traverse spacing of 2m and electrode spacing of 10 meters (MN). The midpoint between MN indicates the probable subsurface location within the traverse. The PQWT-TC300 Electromagnetic instrument was used for the survey. The starting point was marked at 0 meters, and the MN two non-polarizing electrode and connecting cable and transducer bar

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were placed equidistantly at 10 meters. After each reading, the MN distance increased by 2 meter. VES was performed with a Schlumberger array to determine depths and layer characteristics based on resistivity contrasts. Using resistivity meter readings, field resistivity values were adjusted with a geometric factor to derive apparent resistivity. This data was plotted and interpreted with IPI2Win and WinResist software, providing detailed layer resistivity profiles and reducing error. The combined methods facilitated accurate subsurface characterization for identifying groundwater resources.

Results

Electromagnetic method

Figure 3 revealed the Frequency response curves or varying magnetic field sent into the subsurface at varying Frequencies. A total number of 19 different magnetic field generated at frequency range of 5Hz to 30Hz were deployed. The low trends synchronized profiles indicate the conductive layers within subsurface as shown in distance 0 – 5, 6 - 8 and 60 – 70 m. While the highly indurated or resistivity zones possess upward trends as visualize between distances 9 – 55 m within the subsurface (figure 4) The geo-electric section generated by the instrument also revealed highly conductive zones with distance 0 - 5 m to a depth of around 50 m; and 60 – 70 m distance to a depth of around 230m with bluish coloration (figure 4). The conductive zones at distance 60 – 70 m shows existence of fractured formation which would be good enough for ground water development (figure 4). This position was also used to establish VES 1.

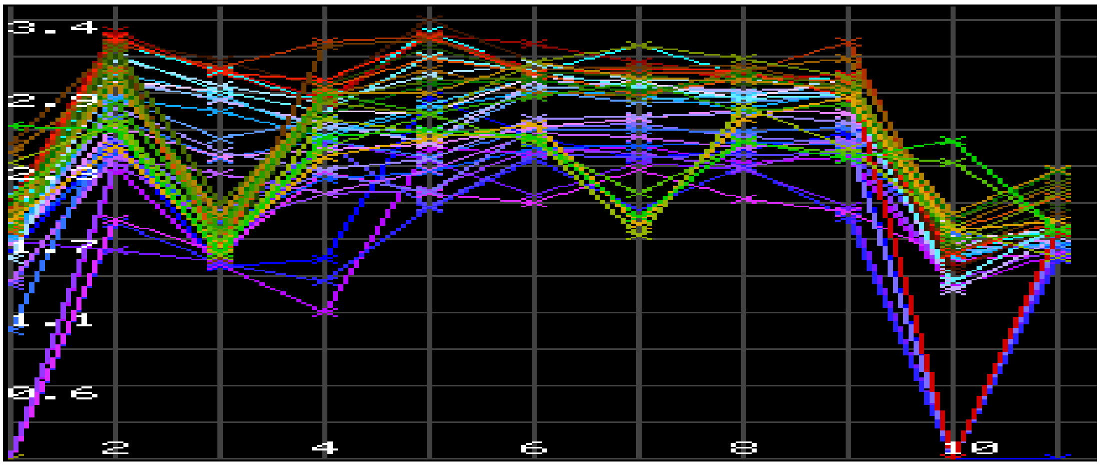

Figure 3: VLF-EM anomaly Curve for Isaba Garri Industry

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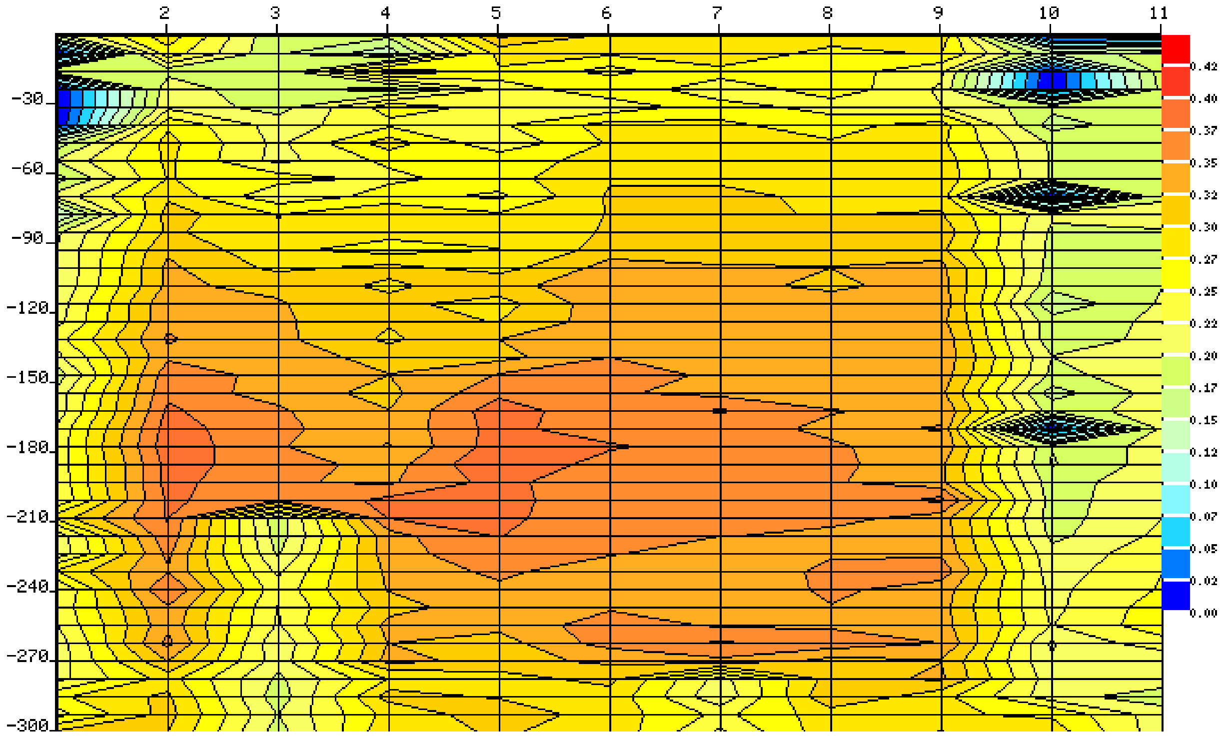

Figure 4: Geosection of traverse 2

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TABLE 1: Summary of Interpreted VES Curves

VES	RESISTIVITY (Ωm)	THICKNESS (m)	DEPTH	CURVE TYPE	NO OF LAYERS	REMARK
1	96	1.2	1.2			TOPSOIL
	1396	4.1	5.3			FRESH BASEMENT
	126	10.7	11.0	KH	4	FRACTURED ZONE
	4546	-	-			FRESH BASEMENT
2	367	2.9	2.9			TOPSOIL
	1733	5.3	8.2			WEATHERED LAYER
	7544	-	-	A	3	FRESH BASEMENT
3	976	1.2	1.2			TOPSOIL
	2380	6.2	7.4	A		WEATHERED LAYER
	28594	-	-		3	FRESH BASEMENT

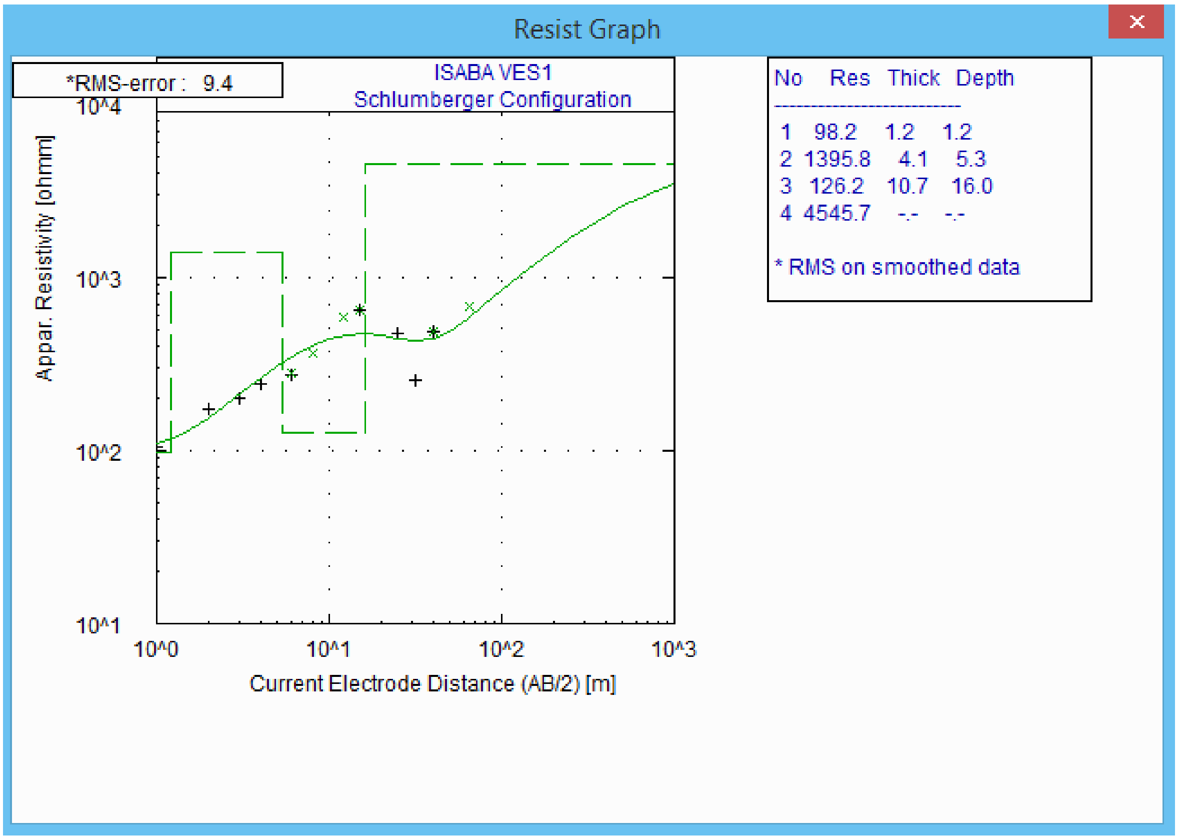

Figure 5: Curve VES 1

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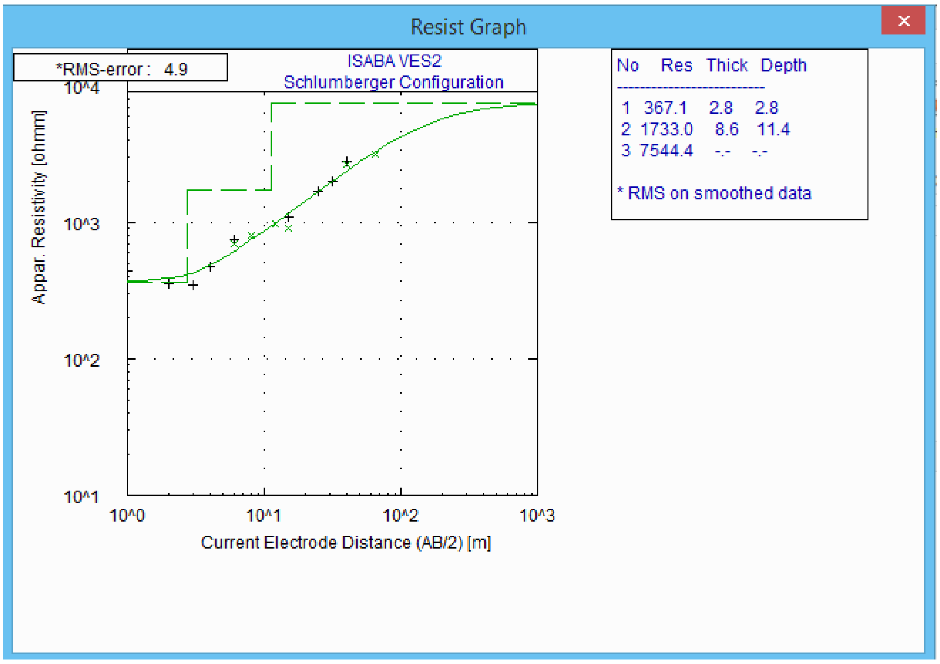

Figure 6: Curve VES 2

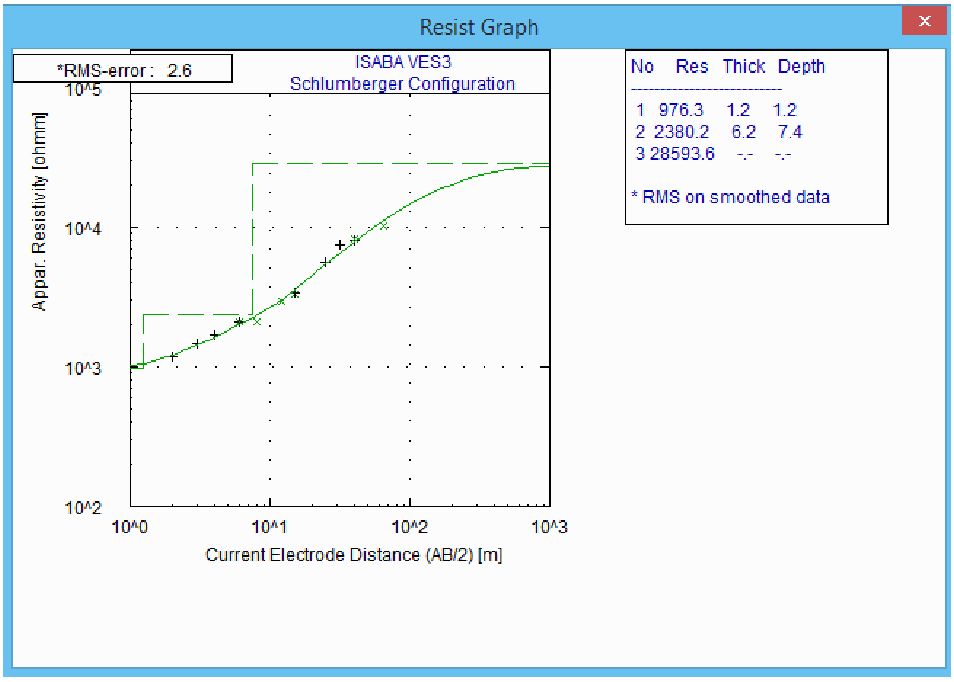

Figure 7: Curve VES 3

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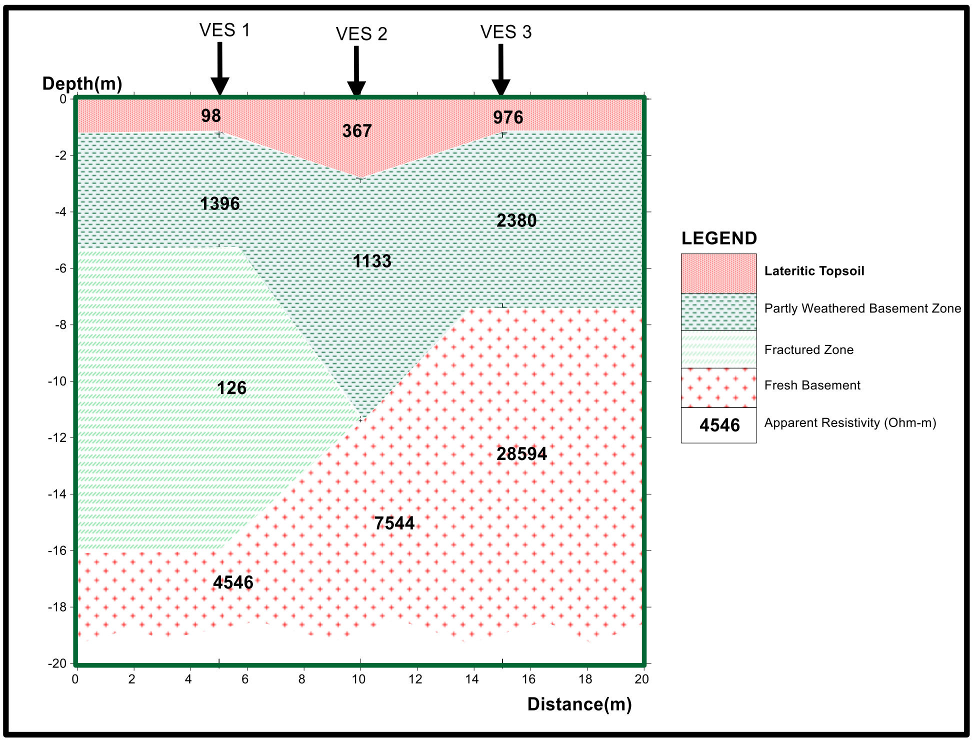

Figure 8: Layer model interpretation for VES 1, 2 and 3

The geoelectric survey identified three subsurface layers: topsoil, weathered layer, and fresh basement. VES 1 revealed a four layer case of KH curve type with topsoil, fresh basement, fractured basement and fresh basement with layer resistivity of 98, 1396, 126 and 4546 ohm-m and thicknesses1.2, 4.1, 10.7 m and infinity respectively At VES 2, these layers have resistivity values of 367.1 Ωm, 1733.0 Ωm, and 7544.4 Ωm, with depths of 2.8 m and 11.4 m for the topsoil and weathered layer, respectively, while the fresh basement's depth is undetermined. The data produced an A-type curve ($\rho1 < \rho2 < \rho3$) for VES 2. For VES 3, resistivity values were 976.3 Ωm, 2380.2 Ωm, and 28593.6 Ωm, corresponding to topsoil, weathered layer, and fresh basement, respectively, with thicknesses of 1.2 m and 6.2 m for the first two layers. This also yielded an A-type curve, indicating aquifers in the weathered layer. The groundwater potential is evaluated based on the availability and thickness of the fractured zone, which constitutes the aquifer zone. The geoelectric section provides insights into the subsurface geology, with the curve type aiding in the interpretation of aquifer properties and the evaluation of groundwater resources. The comparatively very low resistivity value from VES 1 which corresponds with the fractured revealed zone of the EM-geosection has shown that it would be the most promising location for the groundwater development of that area.

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Conclusions

VES survey methods were used to conduct the geophysical investigation for groundwater research in Isaba Garri Industry, Iworoko Ekiti. These findings were confirmed by the VES interpretation, which showed that the topsoil, fresh basement, fractured zone, and weathered layer made up the subsurface structure of the area under investigation. Whereas VES 2 and VES 3 showed three layers, VES 1 showed four layers. At VES 1, four geoelectric layers were inferred, with resistivity values of 96, 1395.8, 126.2, and 4545.7 Ωm, respectively. These layers included topsoil, fresh basement, fractured zone, and fresh basement. The last layer's depth is unknown, although the first three layers' respective depths are 1.2, 5.3, and 16.0 meters. Topsoil, fresh basement, fractured basement, and fresh basement are the four geoelectric layers found in VES 1. At VES 2, three strata were also identified: topsoil, weathered layer, and fresh basement. The corresponding resistivity values for these layers were 367.1, 1733.0, and 7544.4 Ωm. The layers are 2.8 and 11.4 meters deep, respectively. With similar thicknesses of 1.2 and 6.2 meters, the geoelectric layers of VES 3 reveal that it is composed of three layers: topsoil, worn layer, and fresh basement. The layers' resistivity values are 976.3, 2380.2, and 28593.6 Ωm from topsoil to fresh basement. The geophysical investigation for groundwater potential in the study area, which combined VES and EM methods, showed a thin, shallow, and dry weathered layer with an average depth to bedrock of 20 m. Thick fractures were found in VES, and the electromagnetic study revealed that the deep-seated fractured zones are very thick and wide, making location 10 distance 60 m, which corresponded to VES 1, the best drill location. While machine digging targeted at a suspected aquifer to a total depth of 200m is good in the quest for groundwater exploration in the area, the use of other verifiable geophysical techniques, such as well logging, is recommended for further studies. These findings generally indicated a good groundwater yield with poor protective capacity of sandy overburden.

Recommendations

Location 10 at distance 60 m is hereby recommended to a total depth of 200m for good water production.

1. Continuous Monitoring: Ensuring the ongoing safety of drinking water sources demands a commitment to regular and systematic groundwater quality monitoring.
2. Source Identification: To address the issue comprehensively, further investigations should be carried out to pinpoint specific anthropogenic sources responsible for elevated nitrate levels. By gaining a precise understanding of these sources, targeted mitigation strategies can be devised and implemented.
3. Public Awareness: The dissemination of knowledge among the local population, particularly parents and caregivers of infants and children, regarding the potential hazards associated with nitrate-contaminated water is of utmost importance. Promoting awareness of safe water sources and the adoption of appropriate water treatment practices is essential for safeguarding public health.
4. Agricultural Best Practices: Acknowledging the significant contribution of agricultural activities to nitrate contamination, the promotion of responsible agricultural practices becomes paramount. This includes advocating for optimised fertiliser use and measures to reduce chemical runoff, thereby mitigating nitrate pollution at its source.
5. Collaboration: Effective management of groundwater nitrate concerns necessitates collaboration among local authorities, environmental agencies, and research institutions. Such cooperative efforts lead to informed decision-making and the implementation of precise interventions aimed at preserving water quality and protecting public health.

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