Integrated Geophysical Investigation of Gully Erosion in Ukpor Metropolis, Southeastern Nigeria Using Vertical Electrical Sounding and Electrical Resistivity Tomography Methods

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DOI: https://doi.org/10.51244/IJRSI.2024.1108010

Received: 06 July 2024; Accepted: 19 July 2024; Published: 28 August 2024

ABSTRACT

This research investigates the geophysical aspects of gully erosion in Ukpor Metropolis using Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) methods. We identified distinct subsurface lithological layers by interpreting resistivity curves and geoelectric sections across multiple sites, including clayey sands, dry sands, water-saturated sands, kaolinite clays, and shales. The resistivity data reveal a complex stratigraphy with varying aquifer depths and thicknesses, such as 39.5 meters and 97.3 meters. The study found that high resistivity values near the surface, indicative of porous and air-filled structures, significantly contribute to the area's susceptibility to erosion. Soils with resistivity over 50 Ωm have an 87% probability of being highly erodible, which correlates with the gully-prone zones identified. The ERT results depict unstable heterogeneous zones, particularly those with sand lithology, prone to gully formation and potential landslides. Conversely, areas with consolidated kaolinite sand exhibit higher resistivity and lower susceptibility to erosion due to compaction and cement deposition in the sand's pore spaces. The findings of this study underscore the critical role of subsurface lithology and resistivity characteristics in gully erosion processes. The study highlights the need for targeted erosion control measures and sustainable land management practices to mitigate the impact of gully formation in Ukpor Metropolis.

Keywords: Geophysical Investigation, Gully Erosion, Vertical Electrical Sounding, Electrical Resistivity Tomography, Ukpor

INTRODUCTION

Gully erosion in Anambra state, South East Nigeria, has continued challenging geoscientists and environmental scientists. The menace has taken its toll on the socioeconomic well-being of the people living in the affected area and the country at large such that lands used for aesthetic, agricultural and industrial purposes, ancestral homes, crops, livestock and other infrastructure are every day lost to the hazard at an alarming rate [1]. These problems are referred to as onsite effects of erosion. Soil erosion also leads to environmental pollution. Furthermore, downstream erosion leads to flooding, sedimentation of water reservoirs, and poor water quality.

Gullies significantly lead to loss and degradation of agricultural lands, biodiversity loss, pollution of water, and threat to lives and properties [2]. A decrease in soil quality invariably leads to a decrease in water quality and, often, air quality [3]. These are the offsite effects of erosion.

The study area is Ukpor, a town in southeastern Nigeria, which houses the Local Government Secretariat of Nnewi South Local Government Area of Anambra State, comprising nine villages. It is notable for its exclusively hilly topography and geologically rich structural exposures. Furthermore, the culturally rich heritage of the people, together with the series of diverse annual festivals, has made the towns a centre of tourism, especially Nigerians based in the diaspora. Additionally, kaolin's economic deposits within the area make it quite significant as a primary source of industrial raw materials. Kaolin is used in various industries, such as brick, pottery, ceramics, fiber, plastic, fertilizer, and glass. With about 66 million metric tons of kaolinite, the town is one of the significant regions of interest to these industries operating within eastern Nigeria [4].

Several geoscientific and geophysical methods have investigated gully erosions [3]. Near-surface site characterisation using geophysical methods yields important information related to the soil characteristics and can also provide insight into the processes that control the geomorphic evolution of landscapes [5], [6]. Electrical Resistivity Tomography (ERT) has become a widely used geophysical method in fields such as geology, environmental science, geotechnical engineering, and archaeology [7], [8], [9]. [10]. The erosion rate or erodibility of soil depends on many soil characteristics, including plasticity, water content, grain size, percentage of clay, compaction, and shear strength. These characteristics also influence soil in situ bulk electrical resistivity (ER) measurements [11]. Vertical electrical sounding has also been used to evaluate erosion sites [5], [12].

Several studies have successfully used Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) methods for gully erosion investigations. [13] and [14] used integrated electrical resistivity methods, including VES and ERT, to investigate gully erosion in parts of the Enugu North zone, Southeastern Nigeria. The study found that the methods effectively identified subsurface structures and properties contributing to gully erosion, such as loosed soil materials, silt, clay, and bedrock. Alile et al. [15] applied ERT to investigate erosion sites in Oredide Village, Auchi, in Etsako West LGA of Edo State, Southern Nigeria. The study used the technique to identify subsurface resistivity distributions and delineate subsurface lithology, which helped understand erosion processes. These studies demonstrate the effectiveness of VES and ERT methods in investigating gully erosion and identifying subsurface structures and properties that contribute to the erosion process.

This study aims to investigate gully erosion in the Ukpor metropolis using Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) methods to identify the subsurface structures and properties contributing to the erosion processes in the area. The results of this investigation will provide valuable insights for developing effective control measures and strategies for mitigating gully erosion in the region.

Geology and Structural Setting

The study area is located in the outcropping lithostratigraphic units of the Niger Delta Basin and is underlain by two major geologic formations; the Ameki and Ogwashi-Asaba Formations (Fig. 1). The Eocene Ameki Formation is a part of the Ameki Group and has the Nanka and Nsugbe Sandstones as its lateral equivalents. It comprises sandstones, shales, siltstones, thin ironstone bands, and nodules [16]. Thick kaolinite deposits occur towards the top of the Ameki sequence and the basal units of the overlying Ogwashi Asaba Formation. The Ameki Formation is unconformably overlain by the continental sandstones of the Ogwashi-Asaba Formation. The Oligocene-Miocene Ogwashi-Asaba formation consists of coarse-grained sandstone, clay-sized sediments, and carbonaceous shale. It also contains lignite seam intercalations, which can be observed in its outcrops.

Depth to the water table varies spatially and seasonally. During the rainy season, the area receives enormous amounts of downpours of rain, and the water table rises. The water table falls during the dry season due to hydraulic head decay. This results in decreased flow rates and an increase in the depth of the saturated zone. During the dry season, gulling activities are minimal.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XI Issue VIII August 2024

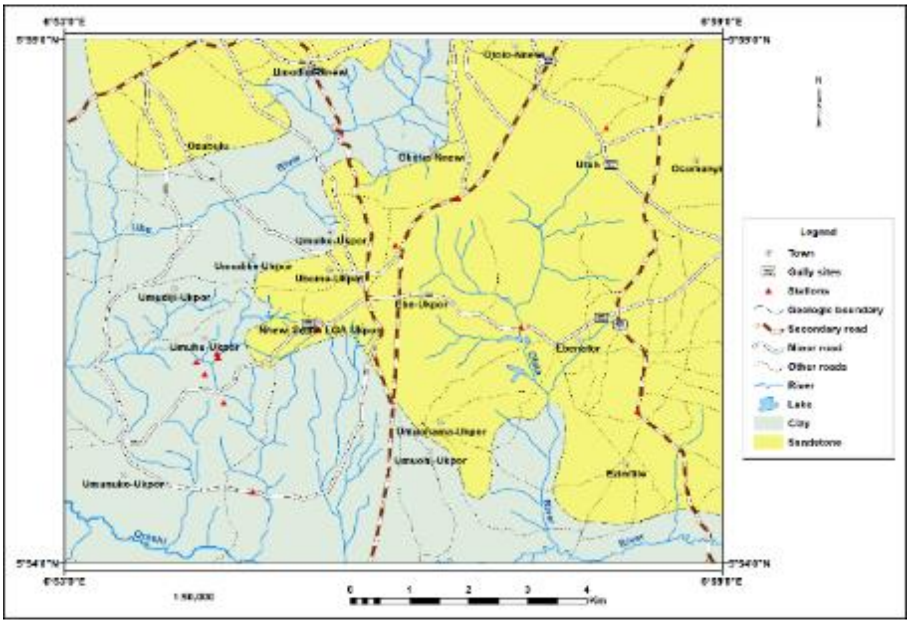


Fig. 1: Lithologic map of the study area showing gully sites and locations for VES and ERT surveys

MATERIALS AND METHODS

Basic Theory

lectrical Resistivity Methods

This method involves the introduction of an electric current of known intensity into the ground with the help of two electrodes (known as current electrodes, AB) and measuring the electric potential difference with another two electrodes (known as potential electrodes, MN) (Fig.2) [17]. This enables the determination of resistance and resistivity of probed formations.

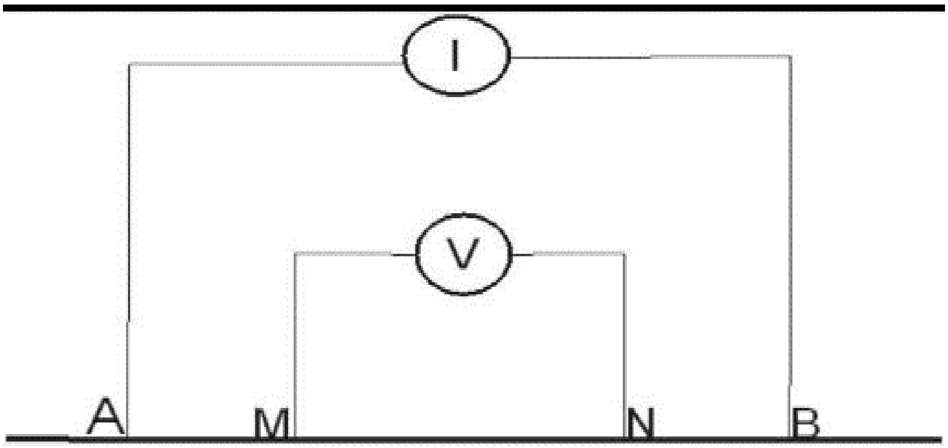


Fig. 2: The generalised electrode configuration in resistivity method (Kearey et al., 2002)

Electrical Resistivity (ER) is an intrinsic soil property that indicates a material's ability to oppose current flow. ER imaging (ERI) is a near-surface geophysical technique to collect bulk continuous ER measurements for a fixed depth. Several common factors influence the ER of soil and soil erodibility, including mean particle size, particle size distribution, soil unit weight, and water content [18, [19], [20].

Electrical Resistivity Tomography (ERT)

The ERT measurements were carried out using the Omega-48 resistivity meter (Fig. 3). Total of 6 Electrical Resistivity Tomography (ERT) was run at different sites within the study area: 3 at gully sites, one at a sand

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XI Issue VIII August 2024

mine, one at a kaolinite sand mine and 1 in an open field. The ERT survey in the open field serves as a control to understand the subsurface geology perfectly. The Wenner α array was employed to deploy the 6 ERT. Omega-48 Resistivity meter was used for data acquisition, and 20 electrodes were employed for the multi-electrode survey with the smallest electrode spacing of 5 meters. Wetting of the ground with salt water was ensured when the ground surface contact was not found sufficiently moist. The ratio of voltage and current measured in the field were converted to apparent resistivity and processed using RES2DINV, an inversion software for ERT, to get the pseudo-sections.

Fig. 3: Geophysical survey equipments

Vertical Electrical Sounding

A total of 8 Vertical Electrical Soundings using the Schlumberger array configuration with a maximum half current electrode spacing (AB/2) of 160 m were conducted to evaluate the geoelectrical setting of Ukpor and its environs. This geophysical survey method was chosen due to its simplicity in data acquisition and interpretation, high signal-to-noise ratio, great probing depth, and high efficiency in delineating subsurface lithologies and fluid-saturated zones. Using the OMEGA 48 resistivity meter, the apparent resistivities were measured along profile lines and recorded. The apparent resistivity distribution data was analysed and modelled using Microsoft Excel and IPI2WIN software to produce geo-electric sections of the surveyed points with layer thicknesses and depths. Subsurface geologic models and interpretations derived were constrained by data obtained within the study area, especially those close to the VES points, as well as the knowledge of the general geology of the study area. The geo-electric sections were then correlated to determine the vertical, horizontal distribution, and lateral continuity of lithologic units (aquifer and overburden) of interest. Data obtained from the modelling and interpretation of the VES survey were used to infer which lithologies are more prone to erosion than the other.

RESULTS AND DISCUSSIONS

Electrical Resistivity Tomography (ERT)

The 2D ERT investigation along all six sites is presented in Figures 4 – 9. The geologic implication of the depicted rock types from the resistivity value is evidence of a possible gully effect or landslide at the heterogeneous zones characterized by sand lithology. The heterogeneous zones are unstable and, hence, prone to gully erosion and are pronounced in Figures 5 - 7. Figure 8 shows relatively high resistivity values. These high values were likely due to the occurrence of consolidated kaolinite sand. Dry and consolidated sediments generally have high resistivity values. Figure 9, which serves as a control survey, is further evidence from the resistivity values that sand is the predominant rock type within the study area. It also highlights the anomaly with high resistivity within the study zone as consolidated kaolinite sand. The zones where the kaolinite sand occurs, like in Figures 4 and 8, will not be as gully-prone as the heterogeneous zones because of the compaction and cement deposition in the sand's pore spaces.

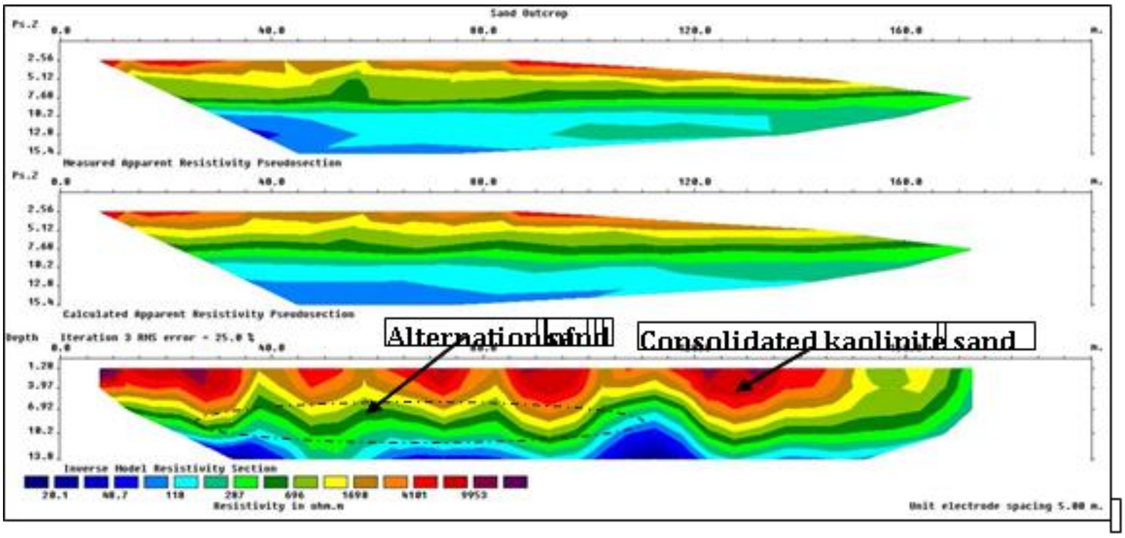


Fig 4: 2D Electrical Resistivity Tomogram of Abandoned Sand Quarry Ukpor

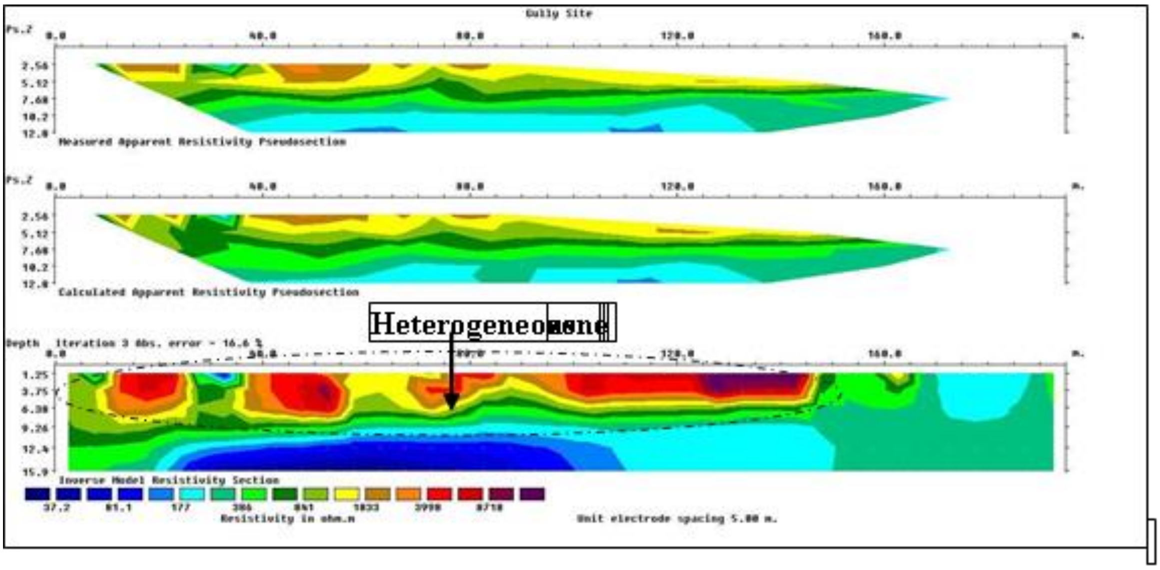


Fig 5: 2D Electrical Resistivity Tomogram of Massive Gully site, Ebenator

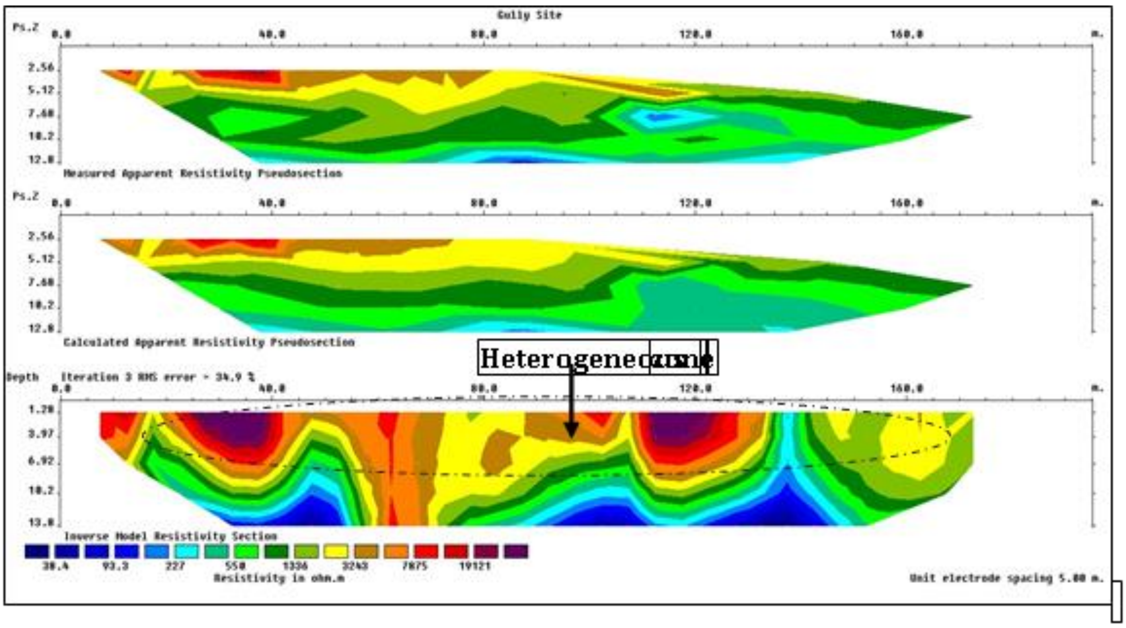


Fig 6: 2D Electrical Resistivity Tomogram of Gully site, Umudim Nnewi

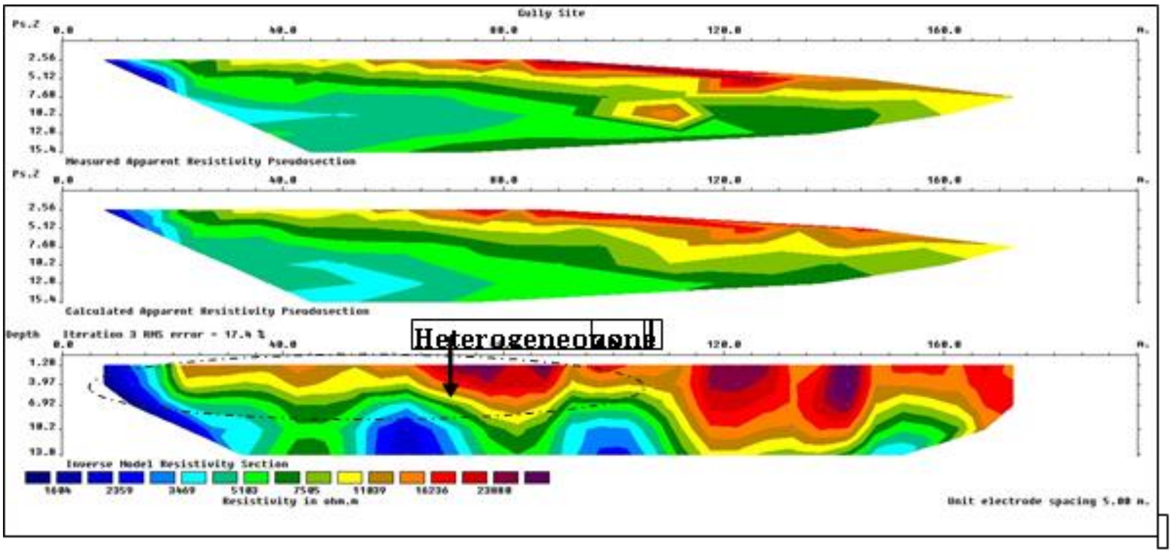


Fig. 7: 2D Electrical Resistivity Tomogram of Gully Site/Abandoned Kaoline quarry, Ukpor

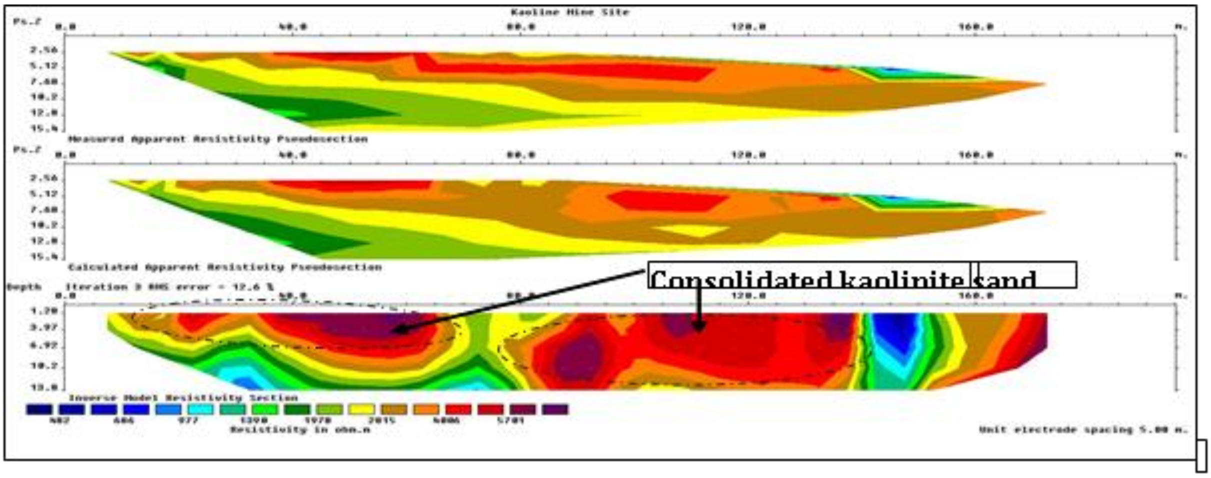


Fig 8: 2D Electrical Resistivity Tomogram of Kaoline Quarry, Ugwupower Ukpor

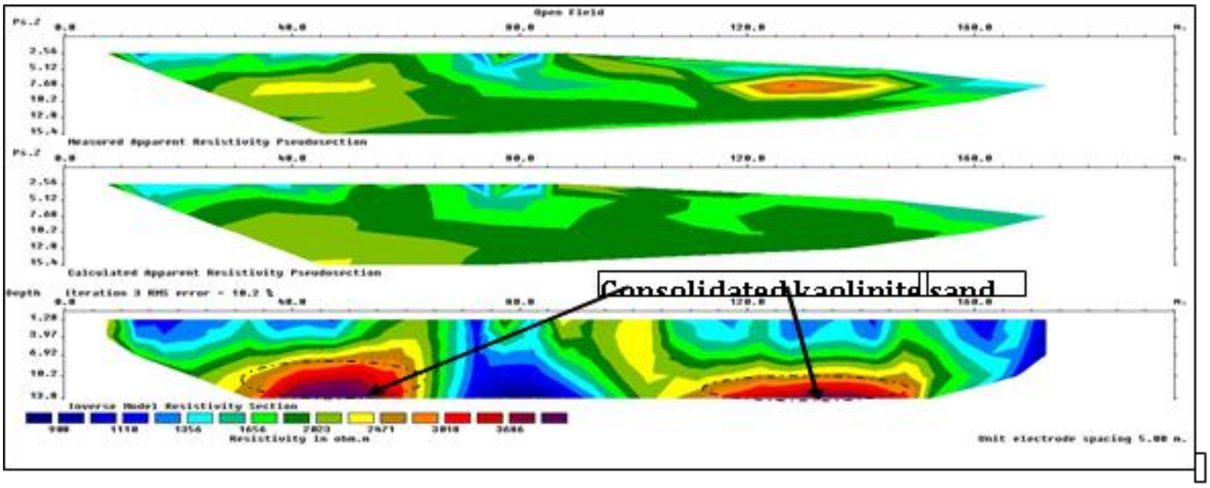


Fig 9: 2D Electrical Resistivity Tomogram of Open Field, Umuhu Ukpor.

Vertical Electrical Sounding

Vertical Electrical Sounding (VES) for subsurface lithologic studies was conducted at eight locations in the study area. Maximum current electrode spacing (AB) of 160m was used throughout the survey, and the apparent resistivity values of all obtained VES readings were appropriately computed and interpreted.

INTERNATIONAL JOURNAL OF RESEARCH AND SCIENTIFIC INNOVATION (IJRSI)
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XI Issue VIII August 2024

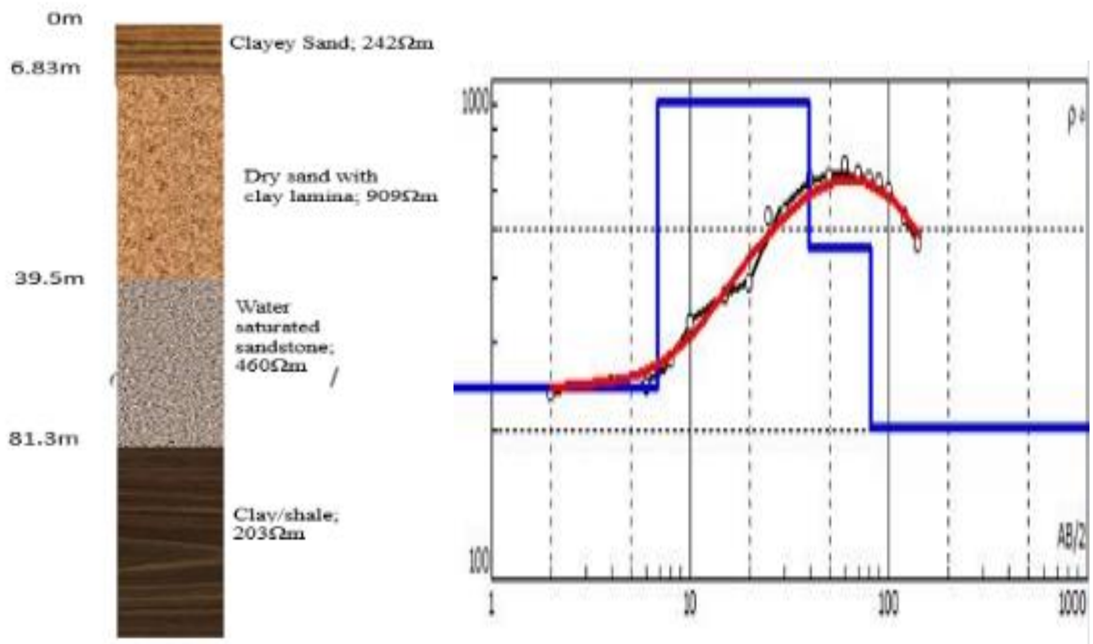
Table 1: Locations and Coordinates of the Vertical Electrical Sounding (VES) Stations.

S/N	Station	Location	Latitude	Longitude	Elevation(M)
1	Umudim Gully Site	Umudim	05° 58' 35.6" N	006° 55'18.78" E	97.00
2	Nnewi-South Local Government Area Headquarters Gully Site.	Ukpor	05°56'12.31" N	006° 55'11.95" E	158.00
3	Kaoline Mine	Ugwu Power	05°54'41.31" N	006° 54'37.54" E	68.00
4	Road-Cut Gully Site	Ebenator	05° 56'4.52" N	006°58' 37.00" E	111.00
5	Umuhu Ukpor	Umuhu	05^0 56' 16.71" N	006^0 53' 22.70" E	64.00
6	Otolo Nnewi	Otolo	05° 58.775' N	006° 57.419' E	132.00
7	Ebe Umudim Ukpor	Ebe Umudim	05° 57.139' N	006° 56.119' E	125.00
8	Umuohama Ukpor	Umuohama	05°56'48.03" N	006° 55' 8.73" E	63.00

The geophysical data presented above (resistivity and AB/2) were plotted using the IP12WIN and Microsoft Excel software and matched to appropriate theoretical curves to obtain the depth and thickness of aquifer bodies within the study area. This helped understand the subsurface geology and was useful in delineating the aquiferous units underlying the study area. The geo-electric sections obtained from this process are presented below.

Ves Station 1: Gully Site, Umudim-Nnewi – 97m

From the interpretation of the curves below, four layers were interpreted, with the first layer having an average apparent resistivity of 242 Ωm, which was interpreted to be clayey sand, the second layer interpreted as dry sand with clay lamina with an average apparent resistivity of 909 Ωm, the third layer interpreted as sandstone (water saturated) with an average apparent resistivity of 460 Ωm and the fourth layer interpreted as clay/shale with an average apparent of 203 Ωm (Fig. 10). The depth of the aquifer is 39.5 metres, with a thickness of 41.80 meters.



(a) *(b)*

Fig. 10: (a) Geoelectric section of Station 1 (b) VES Curve of Station 1

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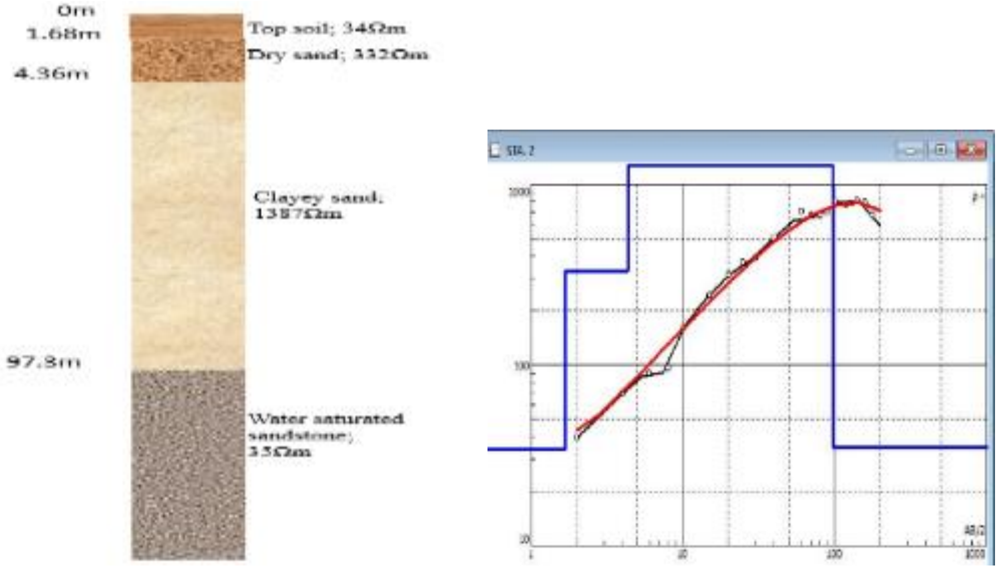
Ves Station 2: Gully Site, Nnewi South Local Government Headquarters, Ukpor

From the interpretation of the curves and geoelectric section (Fig. 11), four layers were interpreted, with the first layer having an average apparent resistivity of 34 Ωm, which was interpreted to be topsoil; the second layer interpreted as dry sand with an average apparent resistivity of 332 Ωm; the third layer interpreted as dry clayey sand with an average apparent resistivity of 1387 Ωm and the fourth layer interpreted as sandstone (water saturated) with an average apparent of 35 Ωm. The depth of the aquifer is 97.3 meters.

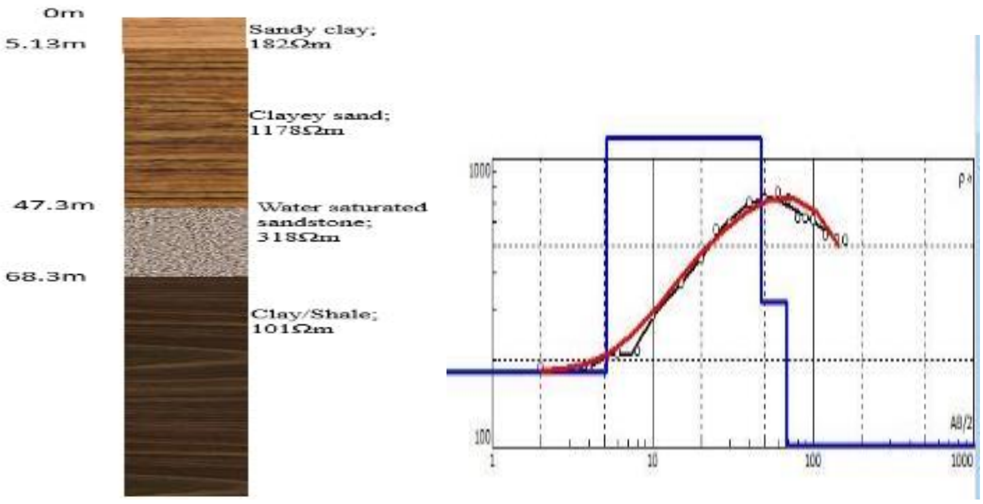
Ves Station 3: Ugwu Power, Umunuko-Ukpor

Fig. 12 shows the geoelectric section and curves of the VES study at Ugwu Power. From the interpretation of the curves below, four layers were interpreted, with the first layer having an average apparent resistivity of 182 Ωm, which was interpreted to be sandy clay, the second layer interpreted as dry clayey sand with an average apparent resistivity of 1178 Ωm, the third layer interpreted as water saturated sandstone with an average apparent resistivity of 318 Ωm and the fourth layer interpreted as clay/shale with an average apparent of 101 Ωm. The depth to the aquifer is at 47.3m. The thickness of the aquifer is 21m.



(a) *(b)*

Fig. 11: (a) Geoelectric section of Station 2 (b) VES Curve of Station 2



(a) *(b)*

Fig. 12: (a) Geoelectric section of station 3 (b) VES Curve of station 3

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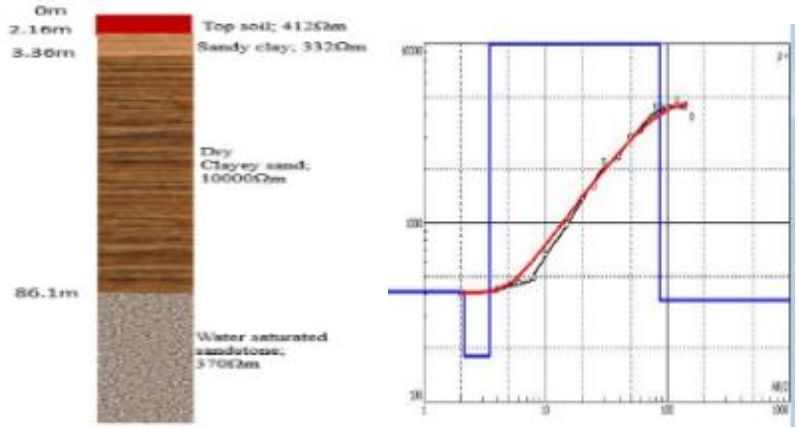
Ves Station 4: Gully Site, Ezinifite Road, Ebenator

Fig. 13 shows the geoelectric section and VES curve of the gully site at Ebenator. Four layers were interpreted from the curve, with the first layer having an average apparent resistivity of 412 Ωm, which was interpreted to be topsoil, the second layer interpreted as sandy clay with an average apparent resistivity of 332 Ωm, the third layer interpreted as dry clayey sand with an average apparent resistivity of 10000 Ωm and the fourth layer interpreted as sandstone (water saturated) with an average apparent resistivity of 370 Ωm. The depth of the aquifer is at 86.1 meters.



(a) *(b)*

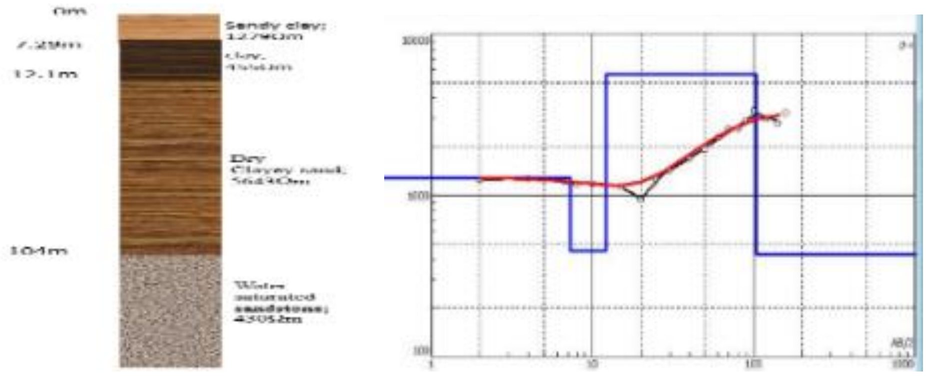
Fig. 13: (a) Geoelectric section of Station 4 (b) VES Curve of Station 4

Ves Station 5: Umuhu-Ukpor

From the interpretation of the curves and geoelectric section shown in Fig. 14, four layers were interpreted, with the first layer having an average apparent resistivity of 1278 Ωm, which was interpreted to be sandy clay, the second layer interpreted as clay with an average apparent resistivity of 455 Ωm, the third layer interpreted as dry clayey sand with an average apparent resistivity of 5647 Ωm and the fourth layer interpreted as sandstone (water saturated) with an average apparent of 430 Ωm. The depth to the aquifer is at 104meters.

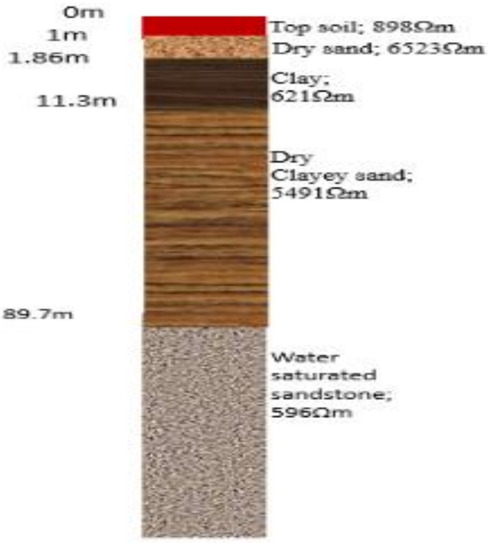
Ves Station 6: Gully Site, Otolo-Nnewi

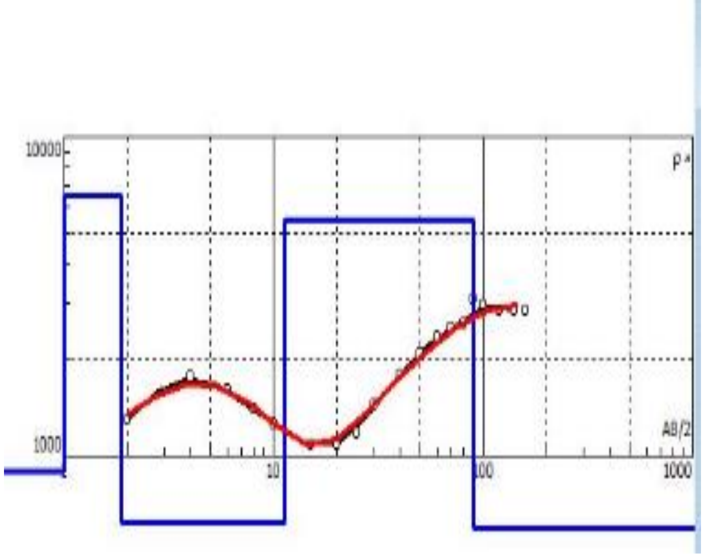
From the interpretation of the curves and geoelectric section shown in Fig. 15, five layers were interpreted, with the first layer having an average apparent resistivity of 898Ωm which was interpreted to be topsoil, the second layer interpreted as sand with an average apparent resistivity of 6523 Ωm, the third layer interpreted as clay with an average apparent resistivity of 621 Ωm, the fourth layer interpreted as water dry clayey sand with an average apparent resistivity of 5491 Ωm and the fifth layer interpreted as sandstone (water saturated) with an average apparent of 596 Ωm. The depth of the aquifer is 89.7 meters.



(a) *(b)*

Fig. 14: (a) Geoelectric section of station 5 (b) VES Curve of station 5



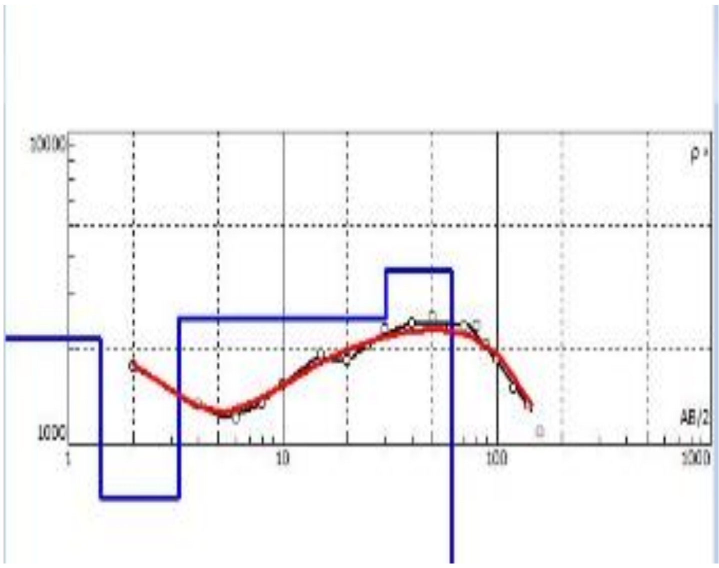


(a) *(b)*

Fig. 15: (a) Geoelectric section of station 6 (b) VES Curve of station 6

Ves Station 7: Ebe-Umudim Ukpor

Fig. 16 shows a five-layer curve and geoelectric for VES Station 7 at Ebe-Umudim Ukpor. The first layer had an average apparent resistivity of 2161Ωm, interpreted as topsoil. The second layer was interpreted as sandy clay with an average apparent resistivity of 672 Ωm, the third layer was interpreted as dry clayey sand with an average apparent resistivity of 2526 Ωm, the fourth layer was interpreted as water sandstone (water saturated) with an average apparent resistivity of 3599 Ωm and the fifth layer interpreted as clay/shale with an average apparent of 88.5 Ωm. The depth to the aquifer is 30.2 meters. The thickness of the aquifer is 31 meters.



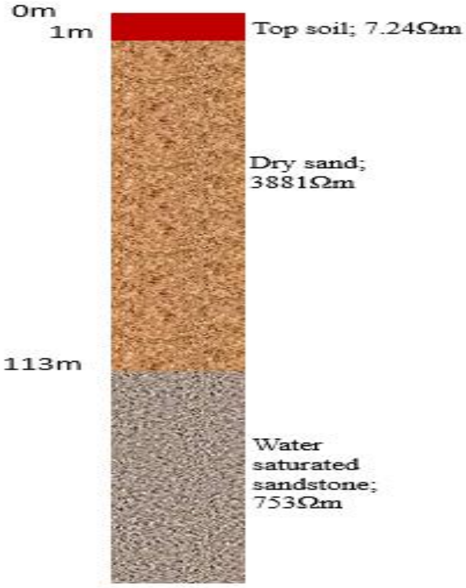
(a) *(b)*

Fig. 16: (a) Geoelectric section of Station 7 (b) VES Curve of station 7

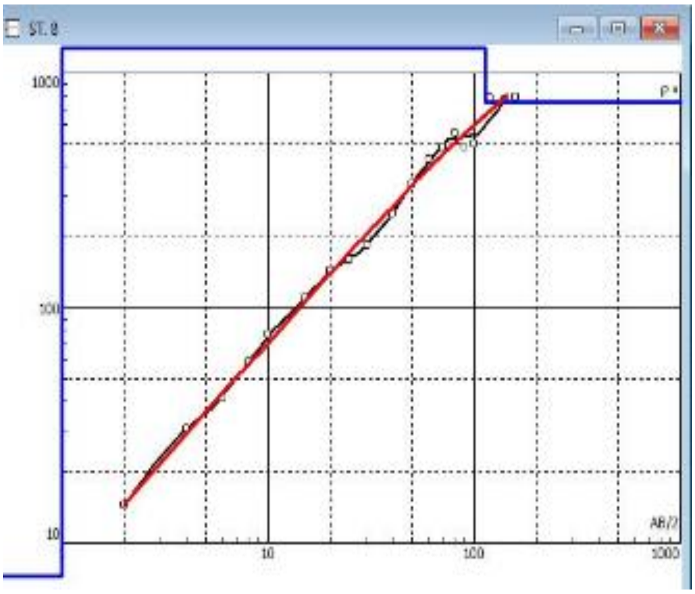
Ves Station 8: Umuohama Ukpor

From the interpretation of the curves below (Fig. 17), three layers were interpreted, with the first layer having an average apparent resistivity of 7.24 Ωm, which was interpreted to be Topsoil, the second layer interpreted as dry sand with an average apparent resistivity of 3881Ωm and the third layer interpreted as sandstone (water saturated) with an average apparent of 753 Ωm. The depth of the aquifer is at 113 meters.

INTERNATIONAL JOURNAL OF RESEARCH AND SCIENTIFIC INNOVATION (IJRSI)
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XI Issue VIII August 2024



(a)



(b)

Fig. 17: (a) Geoelectric section of station 8 (b) VES Curve of Station 8

Table 4.8 below provides a summary of the interpreted VES information. It reveals that the depth of the aquifer in the study area ranges from 30 – 113m, with the thickness of the aquifer ranging from 21 – 42m. The aquiferous unit in the study area is generally sandstone.

Table 2: Summary of VES Interpretation

Ves Point and Towns	No. of Layers	Aquifer Layer/Unit	Aquifer Thickness (M)	Aquifer Depth (M)	Aquifer Resistivity	Vadose Zone
1/Umudim-Nnewi	4	3/Sandstone	41.8	39.53	460	Sandstone
2/Nnewi-South LGA Hqtrs Ukpor	4	4/Sandstone	-	97.34	35	Clayey sand
3/Umunuko-Ukpor	4	3/Sandstone	21	47.33	318	Clayey sand
4/Ebenator	4	4/Sandstone	-	86.14	370	Clayey sand
5/Umuhu-Ukpor	4	4/Sandstone	-	104.00	430	Clayey sand
6/Otolo-Nnewi	5	5/Sandstone	-	89.74	596	Clayey sand
7/Ebe-Ukpor	5	4/Sandstone	31	30.24	3599	Clayey sand
8/Umuohama Ukpor	3	3/Sandstone	-	113	753	Sandstone

Correlation of the Interpreted Geo-electric Sections

Fig. 18 shows a regional correlation of geo-electric sections (VES 5, 8, 7 and 6) across the study area. The top is relatively thin in the study area. The top or weathered rock resistivity value was found to vary between 7.24 to 898 Ω-m while its thickness ranges between 1 to 2.16 meters. Other related geo-electric sections are dry sand

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XI Issue VIII August 2024

and clayey sand. The water-saturated sandstone is characterized by resistivity ranging from 430 to 3599 Ω-m. However, the base of the water-saturated sandstone across these correlated VES stations was not reached.

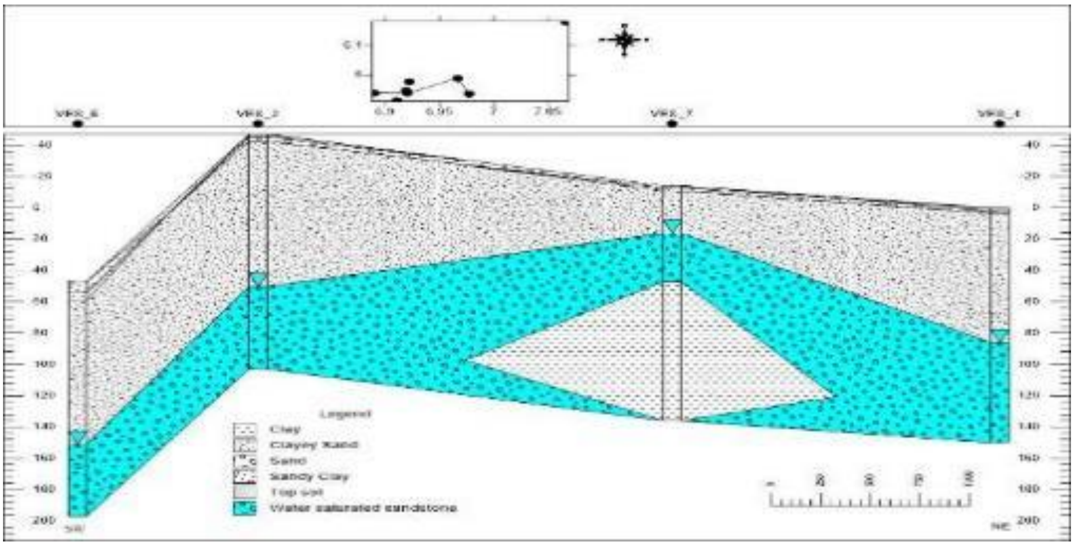


Fig. 18: Correlated geo-electric sections of Stations 5, 2, 7 and 4

The interpretation of the VES curves shows differing lithology consisting of clayey sands, dry sands and water-saturated sands overlying the kaolinite clays and shales, which when removed, results in the collapse of the overlying loose sands. Soils with ER over 50 Ωm have an 87% probability of being classified as highly erodible [11]. In addition, when the near-surface, which is mostly impacted by the erosion, is characterized by high resistivity values as it is across the study area, it implies that the near-surface is porous, the pores are then filled with air, and the air is infinitely resistive, thus the reason for the high resistivity values recorded near surface. This porous nature, therefore, hastens erosion across the study area. At deeper depths across the study area, the resistivity value is about half the resistivity value at the near-surface, implying that the erosional impact may decrease with depth.

CONCLUSION

The geophysical investigation of gully erosion in Ukpor Metropolis using Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) methods has provided comprehensive insights into the subsurface lithology and the factors contributing to erosion in the area. Interpreting the VES and geoelectric section across various sites reveals a complex subsurface structure of multiple layers. These layers include clayey sands, dry sands, water-saturated sands, kaolinite clays, shales, and consolidated kaolinite sand. The depth of the aquifer varies significantly across the study area, ranging from 39.5 meters to 97.3 meters. The aquifer's characteristics, including its thickness, are critical in understanding groundwater flow and its impact on erosion.

The near-surface layers exhibit high resistivity values, indicating a porous structure filled with air, which is infinitely resistive. This porous nature accelerates erosion as it weakens the soil structure, making it more susceptible to collapse and gully formation. At deeper depths, the resistivity values are approximately half those of the near-surface, suggesting a decrease in the erosional impact with depth. This highlights that the most severe erosion occurs near the surface.

Soils with resistivity values over 50 Ω m have an 87% probability of being classified as highly erodible. The study area predominantly consists of highly resistive and erodible soils, particularly in the heterogeneous zones characterized by sand lithology. The ERT results further corroborate the presence of heterogeneous zones prone to gully erosion. These zones are unstable due to the varying lithology, particularly the loose sand layers overlying kaolinite clays and shales. The 2D ERT investigations across six sites depict varying resistivity values, indicating different rock types and their susceptibility to erosion. High resistivity values correspond to dry and consolidated sediments, such as kaolinite sand, which is less prone to gully formation. Areas with consolidated kaolinite sand show relatively higher resistivity and are less erosion-resistant.

The geophysical methods employed in this study have effectively delineated the subsurface structures and identified the factors contributing to gully erosion in the Ukpor Metropolis. The presence of porous, highly resistive near-surface layers, combined with the heterogeneous nature of the subsurface lithology, significantly contributes to the area's susceptibility to erosion. The findings underscore the need for targeted erosion control measures, particularly in the highly erodible zones, to mitigate the impact of gully formation and ensure the stability of the region's landscape.

ACKNOWLEDGEMENT

We are grateful to the American Association of Petroleum Geologists (AAPG) for funding this research through the AAPG Grant-in-Aid program. This work has benefited from discussions from experts in the field of Geosciences.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

FUNDING

This research was funded by the AAPG Grant-in-Aid scholarship.

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ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XI Issue VIII August 2024

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