



Characterizing gully-prone zones using geophysical and geotechnical approaches: a case study of Njaba South-Eastern Nigeria

O. C. Akakuru¹ · A. I. Opara¹ · G. O. Aigbadon² · A. Usman³ · S. I. Ibeneme¹ · K. O. Iheme⁴ · A. O. Njoku⁵ · B. E. B. Akudinobi⁵

Received: 11 April 2022 / Revised: 24 September 2023 / Accepted: 16 October 2023

© The Author(s) under exclusive licence to Iranian Society of Environmentalists (IRSEN) and Science and Research Branch, Islamic Azad University 2023

Abstract

Over the years, Njaba has been known to be bedeviled with worrying gully erosion challenges. This is attributed to the geologic makeup of the soil and other environmental factors. Geophysical and geotechnical characterization of the soil within Njaba and its environs has been carried out with the aim of determining the potentials in the development and enhancement of gullies within the area. 23 vertical electrical sounding were conducted using Schlumberger array configuration with maximum current electrode spacing of 350 m, while two soil samples were also collected for geotechnical studies. The first layers were used to categorize the soils into competence and corrosive soils. Qualitative interpretation reveals that the sites are characterized by six (6) resistivity type curves, namely; 6-HK, 2-AK, 3-KH, 2-QH, 4-KK, 2-AH. The results from the iso-resistivity showed that the resistivities of the layers increased progressively with depth as the maximum electrode spacing increased. The transverse resistance calculated varies from 1408950 to 30987 Ωm , and the longitudinal conductance varies from 0.03163 to 0.00099876 mho. From the competence and corrosivity rating, the soils were categorized from highly competent to moderately competent for the competence categories with varying resistivities of 2800 to 154 Ωm and for the corrosivity category, soils were categorized from essentially non-corrosive to mildly corrosive soils with varying resistance of 182.0 to 154.0 Ωm . The coefficient of anisotropy determined averages 1.25, 1.14 and 1.06 at three different sites. The results of the compaction tests indicate that the Optimum Moisture Content ranged from 11.1–11.5% is required to achieve Maximum Dry Density of the samples ranging from 0.18–2.15 mg/m^3 . From the study, it can be ascertained that the soil is of low compressibility. The study suggests among others that surface and subsurface flows and drainage should be controlled by directing water through concrete channels into lined artificial reservoirs or straight into lakes or river plains.

Keywords Geophysical Analysis · Azimuthal Resistivity · Competence and Corrosivity · Gully Erosion · Geotechnics

Introduction

Soils assume a fundamental part for humankind since they give the crucial biological system administrations expected for human existence principally for the development of food by giving the climate to establish development (Sebastian et al. 2014; Okorafor et al. 2017). The significant reason for land degradation all over the planet is soil disintegration by gully erosion (Nampak et al. 2018; Rizzei et al. 2016; Ogbonnaya et al. 2020). Gully erosion which is a profound channel that is shaped by concentrated water stream, which in the process eliminates surface soils and materials is potential reason for decrease and conceivably control the gully. The nations of sub-Saharan Africa are blockaded by genuine natural debasement bringing about desert infringement, draft and soil disintegration due to either wind sway or

Editorial responsibility: Maryam Shabani.

✉ O. C. Akakuru
obinna.akakuru@futo.edu.ng

¹ Department of Geology, Federal University of Technology, Owerri, Imo State, Nigeria

² Department of Geology, Faculty of Sciences, Federal University Lokoja, Lokoja, Kogi State, Nigeria

³ Department of Physics, Geology, and Geophysics, Alex Ekwueme Federal University, Ndufu-Alike, Ikwo, Ikwo, Ebonyi State, Nigeria

⁴ Department of Geology and Mineral Science, University of Ilorin, Ilorin, Nigeria

⁵ Department of Geological Science, Nnamdi Azikiwe University, Awka, Nigeria



exceptionally high serious precipitation bringing about high runoff and soil loss. The issues have unfavorably impacted farming efficiency and in this manner projecting uncertainty of food security in the zone (Amos and John 2017; Ocheli et al. 2021). The environmental and group environments in the zone are frequently contorted some of the time prompting misfortunes in human and material capitals. In Nigeria, desertification and aridity are the major natural issues of the Northern areas of the country, while the high heavy precipitation of the southern Nigeria establishes empowering climate for disastrous soil disintegration in the area (Amagu et al. 2018; Nnam 2019; Amah et al. 2020).

The inherent danger to the natural settings of southeastern Nigeria is the progressive yet consistent analyzation of the scene by soil disintegration by water. One thing common to the known erosion sites in the country is that most of them begin as rills along slopes and develop gradually with no time into gullies (Nwankwoala and Igbokwe 2020a, b; Ocheli et al. 2021). Most of the times, the erosions get accelerated through human and cultural activities which appear to interfere negatively with natural processes and degrade landforms. Soils of the southeastern Nigeria have high soil erodibility and are classed as structurally unstable (Idowu and Oluwatosin 2008; Okorafor et al. 2017) in this way disintegration frames a significant sort of soil degradation nearby.

Gully erosion has gradually become a serious problem in Njaba and its neighboring communities as it has rendered many homeless, caused destruction to properties and most times create unfavorable changes to the landscape of the environment; unfavorable such that they wash away most surface cash crops thereby reducing food production, destroy important facilities, and also destroy roads hence making them inaccessible (Amangabara and Otumchere 2016; Okwu-Delunzu et al. 2018; Ocheli et al. 2021). The need to understand the dynamics and the textile strength of the geologic material within the researched area cannot be over emphasized since it will help in address the issue of gulling. Therefore, there is great need for a good understanding of the lithologies in the area so as to know erodibility strength of the geologic materials in the area (Emeh and Igwe 2017; Amos and John 2017; Nnam 2019).

Several studies have been carried out to assess gully erosion. Choubin et al (2019) worked on the application of fuzzy analytical network process model for analyzing the gully erosion susceptibility. Mosavi et al. (2020) worked on susceptibility mapping of soil water erosion using machine learning models. Locally, several studies have been done within Nigeria, especially erosion prone areas to ascertain the level of devastation and also proffer remedial measure. Amangabara and Otumchere (2016) x-rayed several factors and processes of the Umuagwo -Urualla Gully Erosion in Ideato North LGA of Imo State; Emeh and Igwe (2017)

determined the variations in soils derived from an erodible sandstone formation and factors controlling their susceptibility to erosion and landslide; Obi and Okekeogbu (2017) examined erosion problems and their impacts in Nanka, Anambra State of Nigeria; Amos and John (2017) used geophysical and geotechnical methods in the evaluation of erosion sites in Ebem-Ohafor Area of Abia State, Southern Nigeria; Amagu et al. (2018) integrated geological and geotechnical approaches in the evaluation of gully erosion at Nguzu Edda, Afikpo Sub-Basin, Southeastern Nigeria; Okwu-Delunzu et al. (2018) evaluated gully erosion and its environmental impact in Eke, Udi Local Government Area of Enugu State; Nnam (2019) assessed the magnitude of the magnitude of gully erosion in Enugu Urban area using revised universal soil loss erosion model (RUSLE); Egboka et al (2019) assessed the gully erosion and landslides in southeastern Nigeria and also determined the causes, consequences and control measures; Amah et al. (2020) studied the dynamics of soil erosion using rusle2 modeling and geo-spatial tool in Edda-Afikpo Mesas, South Eastern Nigeria; Nwankwoala and Igbokwe (2020a, b) assessed and mapped gully erosion geo-hazards in Agulu—Nanka, southeastern Nigeria using integrated geotechnical and GIS approaches; Ocheli et al. (2021) used geology and geotechnical methods in the investigations of part of the Anambra Basin, Southeastern Nigeria and also assessed its implication for gully erosion hazards.

The aim of this study is to study the Geotechnical properties that make soils susceptible to gully erosion, in order to understand and procure mitigation processes and correction procedures. The objectives of this study is to:

1. Ascertain erosion causing factor in the area by carrying out a detailed geoelectrical survey using Vertical Electrical Sounding (VES) and Azimuthal Resistivity Sounding (ARS),
2. Determine the index properties of the soil such as Atterberg limit (liquid limit, plastic limit and the shrinkage limit and their indices such as plasticity index, liquidity index, shrinkage index), bulk density, moisture content, specific gravity, grain size distribution and relative density.
3. Determine the engineering properties of the soils such as shear strength, compaction and California Bearing ratio test.

Materials and methods

Geology of the area

The study area is Njaba and its environs south-eastern Nigeria and lies between latitudes 5°47' and 6°00' and longitude



6°15' and 7°33' (Fig. 1). Njaba is bounded by Oru East, Isu, Mbaitoli, Orlu and Nkwerre. The main river that drains the study area is Njaba River which flows through the communities around Okwudo and Amucha. Flanking the Northern part of the study area around Mgbee community is the Orashi River. Geologically, the study area is underlain by the Coastal Plain Sands (Benin Formation), Ogwashi/Asaba Formation and Ameki Formation (Fig. 2). Basically, the study area lies within the Niger Delta basin. The stratigraphic sequence of the Niger Delta comprises three broad lithostratigraphic units namely; the Benin Formation—a coastal marine sequence of alternating sands and shales, Agbada Formation and a basal marine shale unit—the Akata Formation. The greater part of the study area is underlain by the Benin Formation (Akudinobi et al. 2018; Eyankware et al. 2022a, b). The Formation which is Pliocene to Miocene in age consists of Coastal Plain Sands with minor clay beds. The Formation contains some isolated gravels, conglomerates, and very coarse sandstone in some places. The Benin Formation comprises of a thick sequence of poorly consolidated to unconsolidated sandstones that are friable with sorting ranging from poorly to fairly sorted (Onyeagocha 1980). The Ogwashi–Asaba Formation which is Miocene to Oligocene in age consists of variable sequence of clay,

sandstones and thick seams of lignite (Onyekuru et al. 2021; Akakuru et al. 2021a,b, 2022). It is made up of white-pinkish clay, crossbedded sandstones, carbonaceous black shales, lignites and coal. Reyment (1965) stated that the thickness of the lignite seams is more than 6 m in some areas. Apart from being one of the mappable lithostratigraphic equivalents of the Agbada Formation of the subsurface stratigraphic unit in the Niger Delta Basin, the Ameki Formation overlies the impervious Imo shale group of Paleocene age, which is characterized by lateral and vertical variations in lithology (Akaninyene, 2012; Urom et al. 2021; Akakuru et al. 2022).

Geophysical

Three strategies were incorporated for this reason for assessing the soil structure and anisotropic sort. The three includes a detailed geological mapping of the area; direct current resistivity survey using the vertical electrical sounding method, and Azimuthal resistivity survey was for the purpose of portraying electrical anisotropies as far as the nature, heading, and coefficient of electrical anisotropy. The geologic mapping of the study area involved the use of geologic map, topographic map and physical investigation

Fig. 1 Location map of the study area

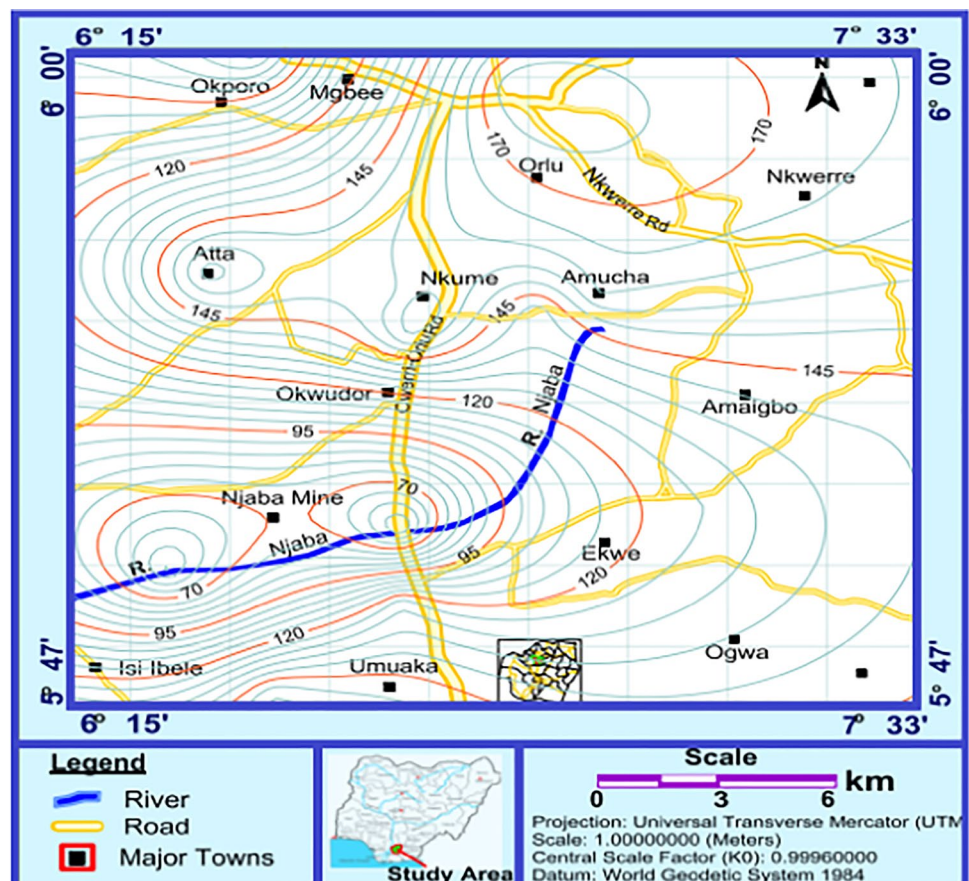
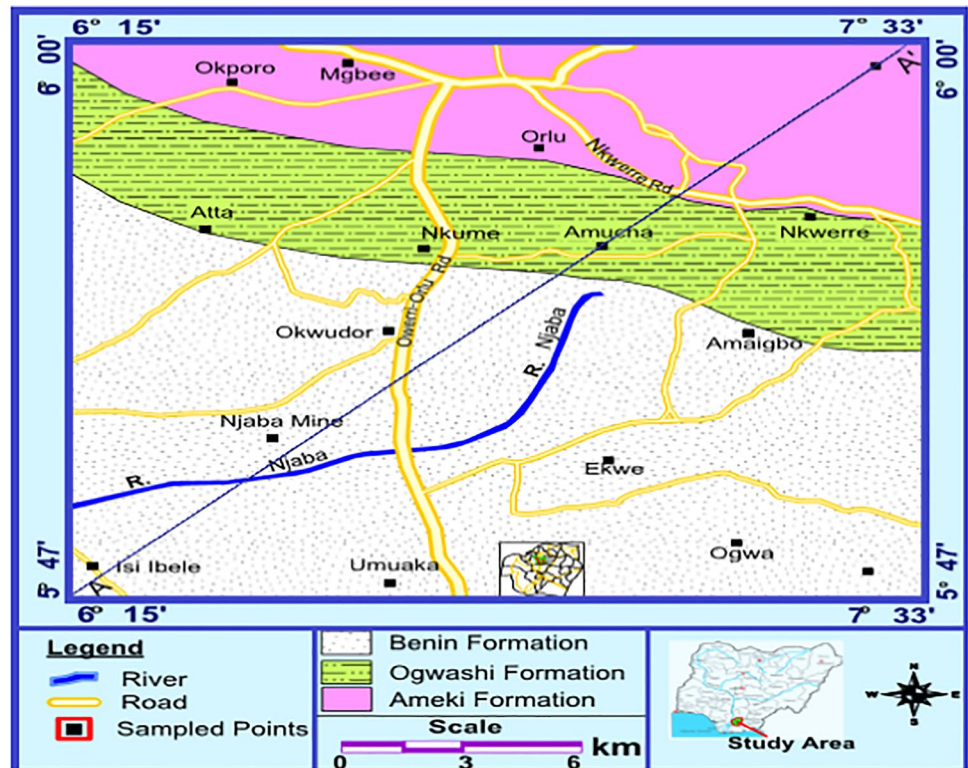


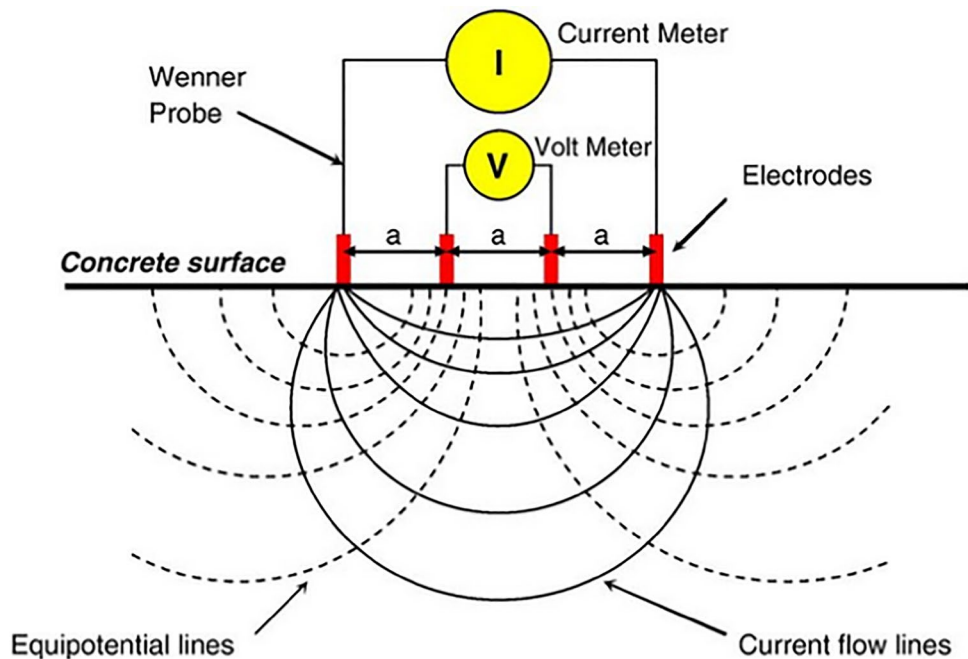
Fig. 2 Geologic map of the study area



to acquire geological information of the area and is also to describe the rock succession. Geomorphological activities such as weathering, erosion processes and denudation were also observed during field mapping (Fig. 2).

The general principle involves passing current into the subsurface using two electrodes. The lines of current flow adapt to the subsurface resistivity pattern so that the potential difference between equipment surfaces can be measured where they intersect the ground surface (Fig. 3). VES

Fig. 3 Diagrammatic representation of a basic resistivity set up (Eyankware et al. 2022b)



furnishes information concerning the vertical succession of different conductive zones and their individual thickness and resistivities. For homogeneous and on a level plane separated earth, VES results address just resistivity variety across the layers up to the most extreme profundity of test. For all intents and purposes, as the separating between the current cathodes is expanded about a middle, the absolute volume of earth remembered for the estimation likewise increments both in an upward direction and on a level plane (Eyankware et al. 2022b; Aniwetalu and Akakuru 2015; Usman et al. 2015; Obasi et al. 2020).

When a current I is passed through a cylinder causing a potential drop $-\partial V$ between the ends of the element, Ohm's law relates the current, potential difference and resistance conventionally as;

$$-\partial V = I\partial R \quad (1)$$

For a conducting cylinder of resistance ∂R , length ∂L and cross-sectional area ∂A , the resistivity ρ is given by

$$\rho = (-\partial R\partial A)/\partial L \quad (2)$$

Combining the two equations, we have

$$E = j\rho \quad (3)$$

where E is the potential gradient $V/\partial L$, j is the current density $I/(\partial A)$, ρ is the resistivity of the material.

Azimuthal electrical studies were done utilizing the Omega promoter Resistivity meter, with the Offset Wenner cathode design. Cathode developments of 10, 20 to a limit of 60 m were embraced. Estimations were made by turning the exhibit about a middle point at 45° additions in four Azimuthal bearings. The opposition $R(\omega)$ information got from the estimations were changed over to comparable clear resistivity ρ_a (Ωm) values for ensuing information examination.

Geotechnical

Geotechnical investigation was employed to obtain information on the physical properties of the sediments. These geotechnical investigations include both field and laboratory studies. The samples were obtained with the aid of a shovel at depths of 1 m from the ground surface and collected in sampling bags and sent to the laboratory. The soil samples were taken to the laboratory to test for both index and engineering properties. Index properties are the simple physical properties of the soils which were used for classification of soils for various engineering applications. They indicate a qualitative behavior of soil when subjected to various types of loads. The index properties analyzed were the Atterberg

limit (which includes the liquid limit, the plastic limit and the shrinkage limit and their indices such as plasticity index, liquidity index, shrinkage index), bulk density, moisture content, specific gravity, grain size distribution and relative density. The engineering properties of the soils are those properties which can be used for quantifying the engineering behavior of the soils. The engineering properties analyzed include shear strength, compaction and California Bearing ratio test. The tests were carried out at the Agricultural Engineering (A.G.E) lab II, Federal University of Technology, Owerri.

Results and discussion

Geoelectric sections

Geoelectric sections of the VES sites captured from the cross sections, A–A', B–B', and C–C' across the study area were developed. Cross section A–A' (Fig. 4) showed the geoelectric sections of NJ14, NJ21 and NJ3. This reveals that the top soil at NJ14 is clay of about 5 m thickness, whereas at NJ21 and NJ3, the top soils are silt of 10 m thickness. Underneath these top soils lies sandstone at NJ14 and sand at both NJ21 and NJ3.

Cross section B–B' (Fig. 4) shows the geoelectric sections of NJ12, NJ17, NJ23 and NJ8. This reveals that the top soils at NJ12 and NJ17 are clay of about 5 m thickness, silty sand of 10 m thickness at NJ23, and sand of about 2 m thickness at NJ8. Underneath the top soils at NJ12, NJ17 and NJ23 lies sand, whereas at NJ8 sandstone lies beneath the sand.

Cross section C–C' (Fig. 4) shows the geoelectric sections of NJ18, NJ2 and NJ7. The top soils at NJ18, NJ2 and NJ7 are silt, clay and silt, respectively, with respective thickness of 5 m, 20 m and 10 m. Beneath the top soil at NJ18 lies sand, and beneath the sand lies sandstone which is underlain by 60 m column of sand followed by continuous clay. At NJ2, clay of 5 m thickness lies beneath the clay which is underlain by sandstone, followed by sand underlain by a 140 m column of silty sand which is underlain by continuous sandy clay. At NJ7, 50 m column of sandstone underlies the silt, followed by sand and this underlain by continuous sandy clay.

Iso-resistivity

With the assumption that the effective depth of transmission is 2/3 of half current electrode separation, $AB/2$, the downward continuation of the resistivity value at the VES points across the study area gave rise to iso-resistivity map



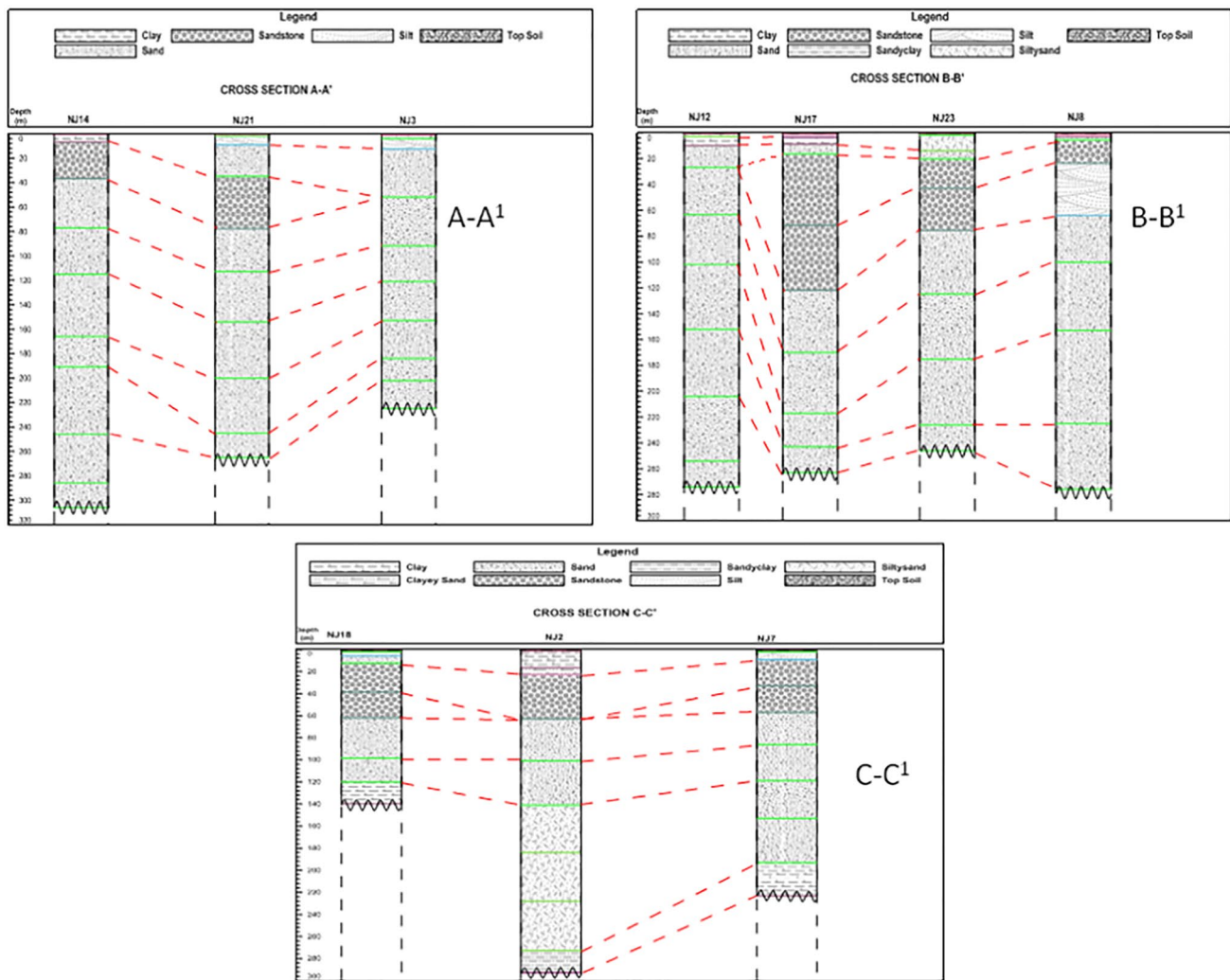


Fig. 4 Geoelectric sections of VES sites from cross section A–A' (NJ14, NJ21 and NJ3), B–B' (NJ12, NJ17, NJ23 and NJ8), and C–C' (NJ18, NJ2 and NJ7)

which showed variations of resistivity at specified interval of $AB/2 = 5$ m, $AB/2 = 20$ m, $AB/2 = 50$ m, $AB/2 = 100$ m, $AB/2 = 150$ m, $AB/2 = 200$ m, $AB/2 = 250$ m, $AB/2 = 300$ m, $AB/2 = 400$ m and $AB/2 = 500$ m. Table 1 summarizes the result of the downward continuation across the area of study.

The summary of Table 1 showed progressive increase in the resistivity of each layer in majority of the stations as depth of penetration increases. The iso-resistivity map (Fig. 5) is indicative of a depth of 3.3 m using the thumb's rule of $2/3 \cdot AB/2$. From Fig. 5A, B, it shows an increase in resistivity with depth. It is also important to note that the southern part of the map is highly resistive more than the other parts, while the northern part is conductive. The iso-resistivity maps also revealed that the study area is divided into three distinct and distinguishable zones. This is also in

line with the geology of the area which concludes that the study area is underlain by Ameki, Ogwashi-Asaba and Benin Formations.

Aquifer hydraulics (Da-Zarrook parameters)

Table 2 displays the aquifer hydraulic parameters of the study area; the aquifer resistivity ranges from 990 Ωm at VES NJ19 (Community borehole, Umuodiri) to 28700 Ωm at VES NJ9 (Umuokwara, Ihebinowere); the aquifer conductivity ranges from 0.0000348 to 0.00027 S/m; the aquifer depth falls within 75.2 m to 122 m, with 75.2 m being the shallowest and occurring at VES NJ11 (Acharaji, Akah); and the aquifer thickness ranges from 23.4 to 50.5 m. By applying Da-Zarrook parameters of transverse



Table 1 Iso-resistivity probe

Location	Longitude	Latitude	AB/2 = 5 m	AB/2 = 20 m	AB/2 = 50 m	AB/2 = 100 m	AB/2 = 150 m	AB/2 = 200 m	AB/2 = 250 m	AB/2 = 300 m	AB/2 = 400 m	AB/2 = 500 m
Ndiuhu Achara Umuaka Njaba, LGA	E7°00.837	N5°39.995	650	1200	1390	3700	4000	5750	6000	6200	6400	6500
Obinwame Umuaka, Njaba LGA	E7°00.437	N5°32.787	600	790	1800	2900	3800	4000	4200	4200	3700	3800
General Hospital Okwudor N/A, LGA	E7°00.649	N5°43.557	3500	3900	6000	8000	8700	9000	8000	7800	7500	7000
Comprehensive High School Umuaka, Njaba, LGA	E7°00.338	N5°40.296	300	800	1300	2200	3400	3600	3800	4100	3600	4500
Umunneke Ihebineowerre Okwudor, Njaba, LGA	E6°59.315	N5°42.335	2300	2500	4000	7000	8300	9800	10400	11100	9300	10000
Umuudara Ubokoro Alta, Njaba, LGA	E6°59.759	N5°45.548	1400	1500	2600	4000	4500	5000	5100	5500	5500	5400
Umuhezime Nkume, Njaba, LGA	E7°01.163	N5°44.615	1200	900	1800	3800	4000	4100	4500	4600	4100	3500
Duruevuru Amucha, Njaba LGA	E7°02.951	N5°44.471	150	290	1050	1800	2500	3000	3300	4000	4200	4500
Umuokwara Ihebinowerre, Njaba, LGA	E6°59.843	N5°42.533	900	1500	2500	5000	7000	9000	10000	11500	16000	17500
Umuokwara Ihebinowerre, Njaba, LGA (1)	E6°59.113	N5°43.089	800	900	2200	3800	4900	6600	6400	5400	5100	5000
Acharaji Akah, Njaba LGA	E7°01.180	N5°39.330	3900	3300	3950	5100	5900	6000	5900	6100	5800	4500
Nduhu Duruevuru Amucha, Njaba, LGA	E7°03.314	N5°44.651	1400	950	2000	3500	4400	4800	5500	5950	6000	7000
Acharaji Akah, Njaba L.G.A	E 7° 01.188	N 5°39.346	3900	3300	3950	5100	5900	6000	5900	6100	5800	4500
Isiozi Akah, Njaba L.G.A	E 7° 01.661'	N 5° 40.758	250	640	1600	2500	3200	3400	4000	4100	3800	3700
Umuete Amazano Njaba L.G.A			1000	1950	3000	5000	6500	7000	7000	7000	5550	5000
Umuolu Obekpu Njaba L.G.A (2)	E 6° 59.211	N 5°40.113	700	990	2450	3900	6000	7300	8500	9900	10000	11300



Table 1 (continued)

Location	Longitude	Latitude	AB/2 = 5 m	AB/2 = 20 m	AB/2 = 50 m	AB/2 = 100 m	AB/2 = 150 m	AB/2 = 200 m	AB/2 = 250 m	AB/2 = 300 m	AB/2 = 400 m	AB/2 = 500 m
Umuolu Obe- akpu Njaba L.G.A (1)	E 6°59.549	N 5°39.927	1800	2800	3100	5000	6000	6900	7000	7000	6500	5000
Christ the King Parish, Okwudor	E 7°00.782	N 5°43.950	800	900	2000	3500	4000	4500	4500	4000	3500	2500
Community Borehole Umuodiri			1500	1500	1300	1000	970	1000	1250	1300	1400	1600
Umuokpurufu Amakor, Njaba L.G.A	E 6°59.373	N 5°40.145	1900	2300	4800	9000	11100	13200	13150	13220	12500	11150
Umuocha Umuolem Okwudor, Njaba L.G.A	E 7°00.089	N 5° 43.908	1800	1950	2300	4000	4500	5500	5500	5500	5000	4800
Ndihu Ubah Umuakah, Njaba L.G.A	E 7°00.791	N 5°40.471	115	480	1100	2000	2500	3200	3500	4000	5000	4800
Umuodim Umu- ele Amazano, Njaba L.G.A	E 6°59.051	N 5°39.564	1700	1500	2800	5000	5500	6000	7000	7000	6500	6000

resistance and longitudinal conductance, the hydraulic characteristics of the aquifer were determined. The transverse resistance is the product of the aquifer thickness and the aquifer resistivity for each layer, while longitudinal conductance is the quotient of the aquifer conductivity with aquifer thickness. The results show very high transverse resistance from 1408950 to 30987 Ωm at VES NJ17 (Umuolu, Obeakpu 1) and VES NJ19 (Community borehole, umuodiri), respectively. Longitudinal conductance ranges from 0.031613 to 0.00099876 mho at VES NJ19 and VES NJ9. The high transverse resistivity values in the study area indicate high hydraulic transmissivity of the aquiferous zones in the area (Figs. 6, 7, 8).

Soil corrosivity and competence

From Table 3 and control Table 4, using only the resistivity of the first layer of each VES station, corrosivity and competence of soils were defined. The corrosivity of the soils in the study area ranges from the essentially non-corrosive categories in VES stations (NJ1, NJ3, NJ5, NJ6, NJ7, NJ9, NJ11, NJ12, NJ13, NJ15, NJ16, NJ18, NJ19, NJ20, NJ21, and NJ23) with resistivity values varying from 2800 to 218 Ωm at depths of 0.9–0.4 m, respectively, to mildly corrosive soils at VES station NJ2, NJ4, NJ8, NJ10 and NJ22 with varying resistivity values of 182.0–154.0 m at varying depths of 1.8–0.4 m, respectively. An exception is seen in an area with moderately corrosive soil at VES station NJ14 with resistivity of 78.5 Ωm at 0.5 m depth. The competence categories with varying resistivities based on the level of erodibility at each station falls within a range of highly incompetent to incompetent to moderately competent soil in VES stations (NJ1, NJ2, NJ3, NJ4, NJ5, NJ6, NJ7, NJ8, NJ9, NJ10, NJ11, NJ12, NJ13, NJ15, NJ16, NJ17, NJ18, NJ19, NJ20, NJ21, NJ22, NJ23) with resistivity values ranging from 2800 to 154 Ωm . An exception was seen in VES station NJ14 with resistivity value of 78.5 Ωm which is categorized as a competent soil.

Azimuthal resistivity sounding

The aftereffects of the geoelectric overview were plotted as radii to create anisotropy figures. The figures are elliptic in shape, demonstrative of the presence of electrical anisotropy and displayed conspicuous pinnacles which are portrayed respectably high to short tomahawks proportions regular of plunge anisotropy. At Comprehensive Secondary School, Okwudor, the lines of weakness were pronounced in the NE-SW, E-W, NW-SE, and N-S directions predominantly with NE-SW line of weakness being more dominant as it is repeated at depths of AB/2 = 15, AB/2 = 25 and AB/2 = 55. This indicates a poly-modal anisotropy with NE = SW being dominant in this region. This implies that any gully



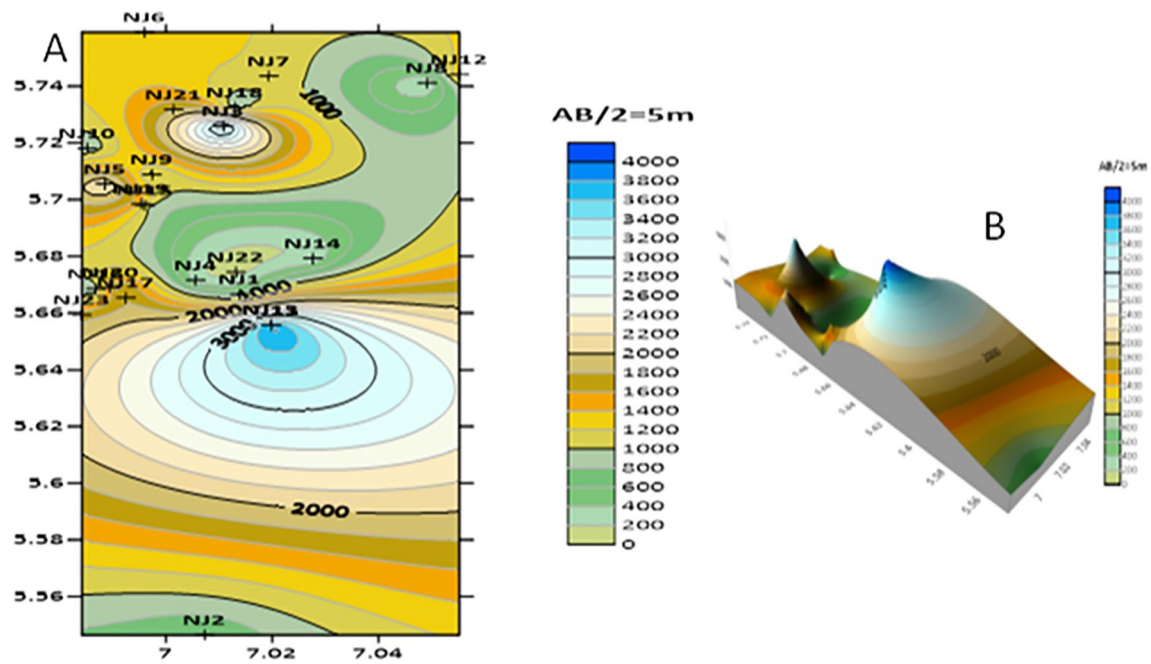


Fig. 5 Iso-resistivity map of the study area showing: **A** 2D Iso-resistivity map of $AB/2 = 5$ m **B** 3D Iso-resistivity map of $AB/2 = 5$ m

Table 2 Summary of aquifer hydraulic parameters

Longitude	Latitude	Elevation (Ft)	Aquifer resistivity (Ω m)	Aquifer conductivity (S/m)	Aquifer depth (m)	Aquifer thickness (m)	Transverse resistance = ρh (Ω m ²)	Longitudinal conductance $L_c = \sigma h$ (Ω^{-1})
E7°00.837	N5°39.995	551.0	24000	0.0000416	83	35.5	852000	0.0014768
E7°00.437	N5°32.787	508.0	4020	0.000248	101	38	152760	0.009424
E7°00.649	N5°43.557	532.0	6930	0.000144	91.9	40	277200	0.00576
E7°00.338	N5°40.296	522.0	9600	0.000104	115	48.4	464640	0.0050336
E6°59.315	N5°42.335	1339.0	18200	0.0000549	114	41.7	758940	0.00228933
E6°59.759	N5°45.548	610.0	6060	0.000165	111	48.5	293910	0.0080025
E7°01.163	N5°44.615	585.0	4770	0.0002096	86	29	138330	0.0060784
E7°02.951	N5°44.471	646.0	7770	0.000129	100	36.1	280497	0.0046569
E6°59.843	N5°42.533	499.0	28,700	0.0000348	84	28.7	823690	0.00099876
E6°59.113	N5°43.089	542.0	5720	0.000175	90	26.9	153868	0.0047075
E7°01.180	N5°39.330	505.0	7260	0.000138	75.2	37.8	274428	0.0052164
E7°03.314	N5°44.651	361.0	11000	0.0000861	102	38.7	425700	0.00333207
E 7° 01.188	N 5°39.346	505	7260	0.000134	75.2	37.8	274428	0.0050652
E 7° 01.661	N 5° 40.758	567	4150	0.000241	77.2	40.4	167660	0.0097364
			19700	0.000051	83.7	46.2	910140	0.0023562
E 6° 59.211	N 5°40.113	502	8200	0.000122	96	23.4	191880	0.0028548
E 6°59.549	N 5°39.927	551	27900	0.0000356	122	50.5	1408950	0.0017978
E7°00.782	N5°43.950	403	5000	0.0002	98.5	36.5	182500	0.0073
			990	0.00101	84.8	31.3	30987	0.031613
E 6°59.373	N 5°40.145	495	9800	0.000107527	77.9	29.7	291060	0.003193548
E 7°0.089	N 5° 43.908	479	9300	0.00011	77.6	42.6	396180	0.004686
E 7°00.791	N 5°40.471	538	3700	0.00027	106	47	173900	0.01269
E 6°59.051	N5°39.564	538	13500	0.000074	75.5	32.7	441450	0.0024198



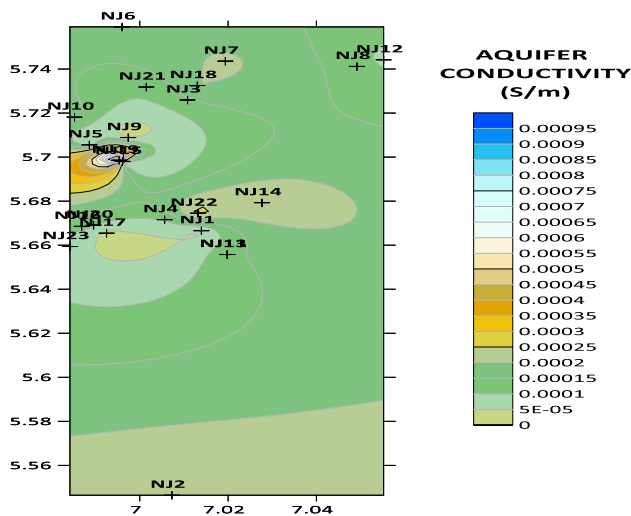


Fig. 6 2D map of aquifer resistivity in the study area

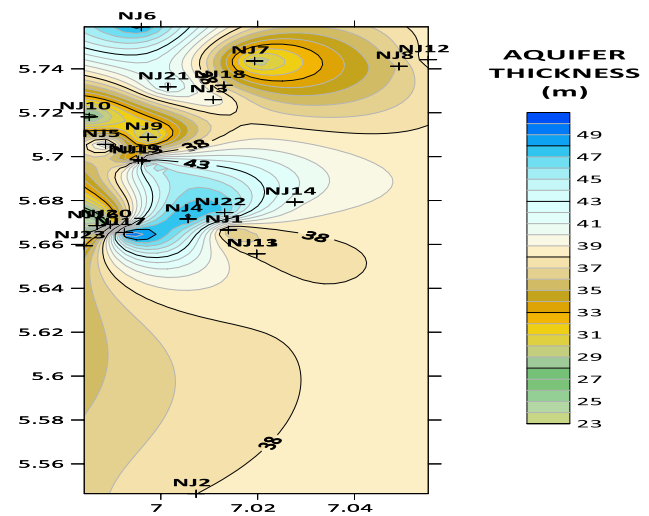


Fig. 8 2D aquifer thickness map of the study area

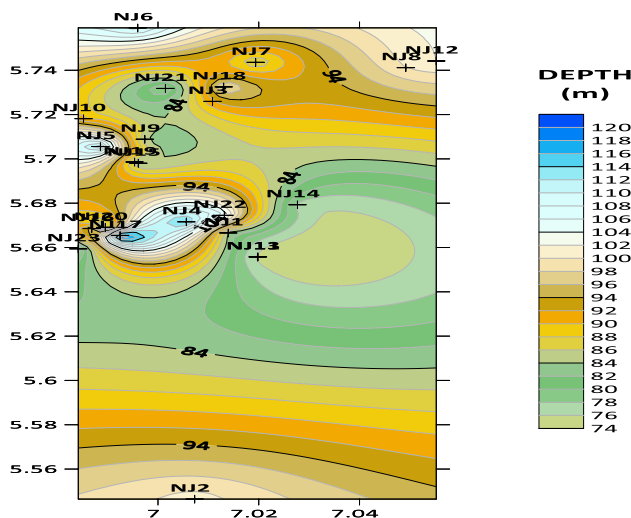


Fig. 7 2D map of aquifer depth in the study area

activities in the area will always take the trend of maximum anisotropy. The anisotropy diagrams obtained from Okwudor Gully Erosion Site have double peaks showing electrical anisotropy in the NE–SW and N–S directions, with the one at NE–SW direction being the deepest structural line of weakness from the azimuthal data collected. The E–W and NW–SE fracture sets seem to be weakly developed in this locality as indicated by the anisotropic dimensions. This indicates a bi-modal anisotropy. At Njaba Gully Erosion Site, the predominant structural lines of weakness were observed in the NE–SW and NW–SE, with the one at NE–SW direction being the most predominant.

These anisotropically resolved headings concur with the predominant proliferation tomahawks of gully exercises in the particular destinations which confirm the way that gullying is connected with subsurface primary components. The coefficients of anisotropy (still up in the air from the destinations fluctuate from 1.25 for Comprehensive Secondary School, 1.14 for Okwudor Gully and 1.06 for Njaba Gully. These qualities are moderately higher than the worth of one (1) for a homogenously isotropic Earth medium demonstrative of anisotropic subsurface. The land Formations inside the destinations get soaked effectively due to their lithological construction, and more surface spillovers along underlying and plunging patterns down slant. This clarifies why these regions contain gorges of disturbing extent. Gully erosion follows the axes of structural weakness through the subsurface. These axes of structural weakness are geologically referred to as fault zones and serve as conduits for water saturation. The axis of greater current flow during radial sounding will therefore indicate the direction of anisotropy through the subsurface as water content more than any other factor influences electrical resistivity especially in a locality where the mineralogical symbols are uniform to semi-uniform such as the one obtainable in this locality. According to Habberjam (1975), and Opara et al. (2023) the length of the major axis of the ellipse is numerically equivalent to the transverse resistance P_t , while the length of the minor axis is numerically equivalent to the longitudinal resistivity P_l . The coefficient of anisotropy, λ , is the root of the ratio



Table 3 Summary of corrosivity and competence values

Ves. no	Location	Longitude	Latitude	Elevation (Ft)	Resistivity (Ωm)	Conductivity (S/m)	Layer depth (m)	Layer thickness (m)	Lithology	Competence	Corrosivity
					ρ_i	σ_i	d1	h1			
NJ1	Ndihu Achara, Umuaka Njaba, LGA	E7°00.837	N5°39.995	551.0	495.0	0.00202	3	3	Clayey sand	Competent	Essentially non-corrosive
NJ2	ObinwannE Umuaka, njaba LGA	E7°00.437	N5°32.787	508.0	178.0	0.0056	1.1	1.1	Sandy clay	Moderately competent	Mildly corrosive
NJ3	General Hospital Okwudor NJA, LGA	E7°00.649	N5°43.557	532.0	1300.0	0.00077	0.9	0.9	Sand/lat-erite	Highly competent	Essentially non-corrosive
NJ4	Comprehensive High School Umuaka, Njaba, LGA	E7°00.338	N5°40.296	522.0	182.0	0.00549	1.8	1.8	Sandy clay	Moderately competent	Mildly corrosive
NJ5	Umuneke Ihebineowere Okwudor, Njaba, LGA	E6°59.315	N5°42.335	1339.0	1000.0	0.001	0.5	0.5	Sand/lat-erite	Highly competent	Essentially non-corrosive
NJ6	Umudara Ubokoro Atta, Njaba, LGA	E6°59.759	N5°45.548	610.0	514.0	0.001946	0.4	0.4	Clayey sand	Competent	Essentially non-corrosive
NJ7	Umuezime Nkume, Njaba, LGA	E7°01.163	N5°44.615	585.0	321.0	0.00312	0.4	0.4	Sandy clay	Moderately competent	Essentially non-corrosive
NJ8	Duruewuru Amucha, Njaba LGA	E7°02.951	N5°44.471	646.0	199.0	0.00503	1.4	1.4	Sandy clay	Moderately competent	Mildly corrosive
NJ9	Umuokwara Ihebinowerre, Njaba, LGA (1)	E6°59.843	N5°42.533	499.0	373.0	0.00268	1	1	Clayey sand	Competent	Essentially non-corrosive
NJ10	Umuokwara Ihebinowerre, Njaba, LGA	E6°59.113	N5°43.089	542.0	154.0	0.006494	0.4	0.4	Sandy clay	Moderately competent	Mildly corrosive
NJ11	Acharaji Akah, Njaba LGA	E7°01.180	N5°39.330	505.0	2800.0	0.000357	0.9	0.9	Sand/lat-erite	Highly competent	Essentially non-corrosive
NJ12	Nduhu Duruewuru Amucha, Njaba, LGA	E7°03.314	N5°44.651	361.0	306.0	0.003268	0.5	0.5	Sandy clay	Moderately competent	Essentially non-corrosive
NJ13	Acharaji akah, Njaba L.G.A	E 7° 01.188	N 5°39.346	505	2800	0.000357	0.9	0.9	Sand/lat-erite	Highly competent	Essentially non-corrosive



Table 3 (continued)

Ves. no	Location	Longitude	Latitude	Elevation (Ft)	Resistivity (Ωm)	Conductivity (S/m)	Layer depth (m)	Layer thickness (m)	Lithology	Competence	Corrosivity
					ρ_1	σ_1	d1	h1			
NJ14	Isiozi Akah, Njaba L.G.A	E 7° 01.661	N 5° 40.758	567	78.5	0.012739	0.5	0.5	Shale/clay	Incompetent	Moderately corrosive
NJ15	Umuale Amazano Njaba L.G.A				500	0.002	0.6	0.6	Cayey sand	Competent	Essentially non-corrosive
NJ16	Umuolu Obeakpu Njaba L.G.A (2)	E 6° 59.211	N 5° 40.113	502	583	0.001715	0.8	0.8	Clayey sand	Competent	Essentially non-corrosive
NJ17	Umuolu Obeakpu Njaba L.G.A (1)	E 6° 59.549	N 5° 39.927	551	281	0.003559	1.0	1.0	Sandy clay	Moderately competent	Essentially non-corrosive
NJ18	Christ the King Parish, Okwudor	E 7° 00.782	N 5° 43.950	403	218	0.004587	0.4	0.4	Sandy clay	Moderately competent	Essentially non-corrosive
NJ19	Community Borehole Umuodiri				1460	0.000685	30.0	30.0	Sand/laterite	Highly competent	Essentially non-corrosive
NJ20	UmuokpuRUFO Amakor, Njaba L.G.A	E 6° 59.373	N 5° 40.145	495	246	0.004065	0.5	0.5	Sandy clay	Moderately competent	Essentially non-corrosive
NJ21	Umuocha Umualem Okwudor, Njaba L.G.A	E 7° 0.089	N 5° 43.908	479	850	0.001176	0.5	0.5	Sand/laterite	Highly competent	Essentially non-corrosive
NJ22	Ndihu Ubah, Umuakah, Njaba L.G.A	E 7° 00.791	N 5° 40.471	538	157	0.006369	1.1	1.1	Sandy clay	Moderately competent	Mildly corrosive
NJ23	Umuodim Umuale Amazano, Njaba L.G.A	E 6° 59.051	N 5° 39.564	538	411	0.002433	0.5	0.5	Clayey sand	Competent	Essentially non-corrosive



Table 4 Chart showing competence and corrosivity rating of soils

Soil resistivity (Ωm)	Lithology	Competence rating
Rating of subsoil competence using resistivity values ^a		
< 100	Clay	Incompetent
100–350	Sandy clay	Moderately competent
350–750	Clayey sand	Competent
> 750	Sand/laterite/crystalline rock	Highly competent
Soil resistivity (Ωm)		Competence rating
Soil corrosivity rating ^b		
> 200		Essentially non-corrosive
100–200		Mildly corrosive
50–100		Moderately corrosive
30–50		Corrosive
10–30		Highly corrosive
< 10		Extremely corrosive

^aSources Akakuru et al. (2023) and Oli et al. (2022)^bSources Bhattarai et al. (2015), Aigbadon et al. (2023) and Chiaka et al. (2019)

$\frac{P_i}{P_j}$ The high values of electrical anisotropy in association with deep gullies suggest that the network of fractures serves mainly as channels for surface runoff, rather than zones of groundwater infiltration Table 5, 6 Fig. 9.

Geotechnical results

Plots of dry density versus moisture content are presented in (Figs. 10, 11). The compaction curves show that the dry density increases with increasing water content up to a maximum and later decreases. The result of the compaction tests indicates that the range of OMC from 11.1–11.5% is required to achieve MDD of the samples ranging from 0.18–2.15 mg/m³. The order of the OMC is in the order: OKW1 > OKW2, while the reverse is the case for MDD. Less value of OMC in the study area can be a direct link to

the various gully erosions encountered. At reduced OMC, slope failure is inevitable and soils become instable, hence, erosion occurrence. Obaro (2019) who studied geotechnical properties of sediments around the study area, reported similar results.

Compaction Test Results for OKW1

Volume of Ring = 923.4 cm³, Natural Moisture Content = 11.64% Tables 7, 8.

Compaction test results for OKW2

Plots of dry density versus moisture content are presented in the figure below (Figs. 10, 11). The compaction curves show that the dry density increases with increasing water content up to a maximum and later decreases. The result

Table 5 Field data from Comprehensive Secondary School, Okwudor

S/N	AB/2	MN/2	K	N-S	E-W	NW-SE	NE-SW	N-S	E-W	NW-SE	NE-SW
1	10	2.5	58.93	93.82	4.77	4.55	4.54	5528.8	281.1	268.13	267.542
2	15	2.5	137.50	39.05	39.08	43.06	47.38	5369.4	5373.5	5920.8	6514.75
3	20	2.5	247.50	24.87	25.09	22.8	20.24	6155.3	6209.8	5643	5009.4
4	25	2.5	388.93	16.79	18.07	16.82	19.09	6530.1	7028	6541.8	7424.67
5	30	2.5	561.78	11.01	14.84	15.62	11.79	6185.2	8336.8	8775	6623.39
6	35	2.5	766.01	8.66	13.14	12.9	8.92	6633.6	10065	9881.5	6832.81
7	40	2.5	1001.79	7.11	9.98	10.06	8.17	7122.7	9997.9	10078	8184.62
8	45	2.5	1268.93	5.86	10.53	6.01	6.51	7435.9	13362	7626.3	8260.73
9	50	2.5	1567.50	5.08	8.55	7.53	5.55	7962.9	13402	11803	8699.63
10	55	2.5	1897.50	3.71	6.28	5.28	11.22	7039.7	11916	10019	21290



Table 6 Coefficient of anisotropy and root mean square from Table 5

AB/2 (m)	Coefficient of anisotropy (λ)	Root mean square (ρ_{rms})
10	4.53	1216.22
15	1.10	5914.40
20	1.11	5577.38
25	1.07	6963.05
30	1.19	2329.67
35	1.23	8171.31
40	1.19	8472.48
45	1.34	9967.82
50	1.30	10330.52
55	1.74	12242.36

of the compaction tests indicates that the range of OMC from 11.1–11.5% is required to achieve MDD of the samples ranging from 0.18–2.15 mg/m^3 . The order of the OMC is in the order: OKW1 > OKW2, while the reverse is the case for MDD. Less value of OMC in the study area can be a direct link to the various gully erosions encountered. At reduced OMC, slope failure is inevitable and soils become unstable, hence, erosion occurrence. Obaro (2019), who studied

geotechnical properties of sediments around the study area, reported similar results.

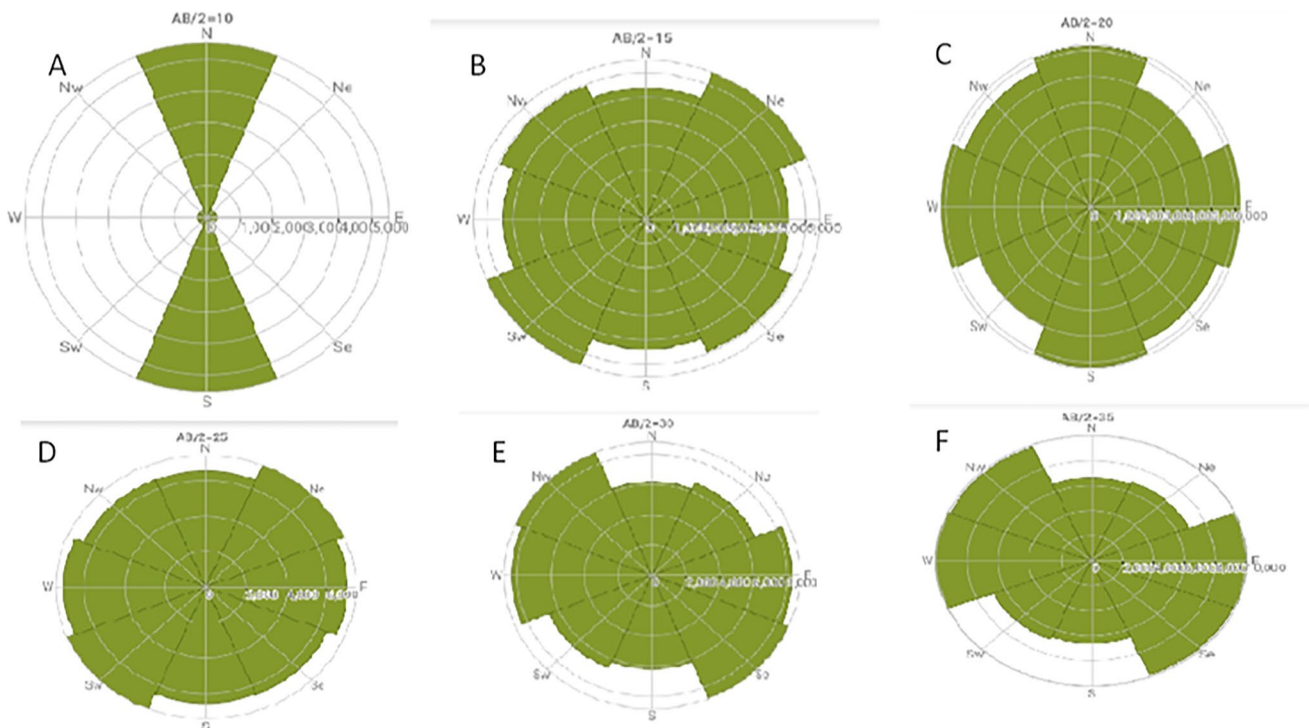
Volume of Ring = 923.4 cm^3 , Natural Moisture Content = 13.0% Tables 9, 10, 11.

Liquid and plastic limit test results for OKW1

Liquid limit is the water content where the soil starts to behave as a liquid. Liquid limit is measured by placing a clay sample in a standard cup and making a separation (groove) using a spatula. The cup is dropped till the separation vanishes. The water content of the soil is obtained from this sample. The test is performed again by increasing the water content. Soil with low water content would yield more blows and soil with high water content would yield less blows. On the other hand, Plastic Limit (PL) is the water content at the change from a plastic to a semi-solid state. This test involves repeatedly rolling a soil sample into a thread until it reaches a point where it crumbles. The results of liquid and plastic limit determination are shown in Tables 12, 13 Fig. 12.

Liquid and plastic limit test results for OKW2

Based on Table 17, it can be ascertained that the soil is of low compressibility. Also, the value indicates that the

**Fig. 9** Representative of the Azimuthal Plots from Soundings **A** AB/2 = 10 **B** AB/2 = 15 **C** AB/2 = 20 **D** AB/2 = 25 **E** AB/2 = 30 **F** AB/2 = 35

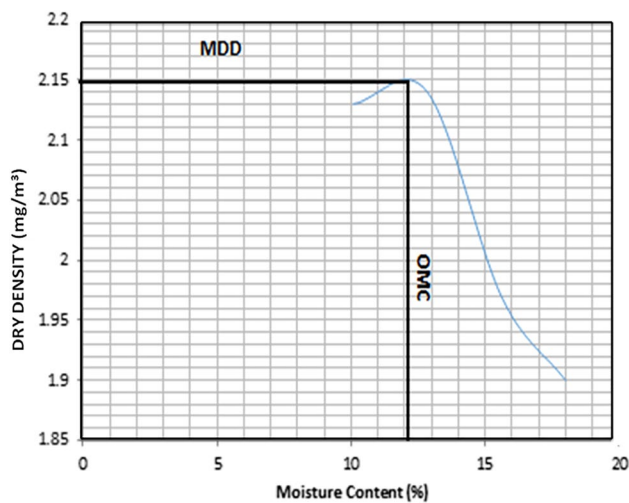


Fig. 10 OKW1 MDD versus OMC

soil has little or no cohesive properties and will easily crumble when dry. They will also show high dispersive behavior upon the action of river current. Under full saturation, the sediments will be collapsible. This is in line with the findings of Onu (2006), who reported that most of the collapsing sediments have liquid limit below 40% and plastic limit below 25%. These results showed that the gullies occurring in the study area are as a result of the properties of the soil. Gully erosions in the study locations can also be attributed to the non-plastic nature of the soils Tables 14, 15, 16, 17 Fig. 13.

Table 7 Bulk density determination

Trial numbers	1	2	3	4
Weight of ring + soil (g)	3980	4000	3940	3900
Weight of ring (g)	1800	1800	1800	1800
Weight of soil (g)	2180	2200	2140	2100
Bulk density (mg/m ³)	2.36	2.38	2.32	2.27

Table 8 Dry density/moisture content determination

Can identification	S	L1U5	A2	A3
Weight of wet soil + can (g) W2	91	101	144	115
Weight of dry soil + can (g) W3	84.5	91.5	126.5	101.5
Weight of can (g) W1	20	17.5	22	19
Weight of dry soil (g) W4	64.5	74	105.5	82.5
Moisture loss (g) W5	6.5	9.5	16.5	13.5
Moisture content (%) (W5/W4)*100	10.08	12.84	15.6	18
Dry density (mg/m ³)	2.13	2.14	1.97	1.90

Wet sieving results for OKW1

Weight of soil before washing and drying = 156 g, Weight of soil after washing and drying = 114 g, Mass of soil loss to washing = 42 g, % of fines = 26.92% Table 18 Fig. 14.

Wet sieving results for OKW2

Weight of soil before washing and drying = 164 g, Weight of soil after washing and drying = 109 g, Mass of soil loss to washing = 55 g, % of fines = 33.53% Table 19 Fig. 15.

Fig. 11 OKW2 MDD vs OMC

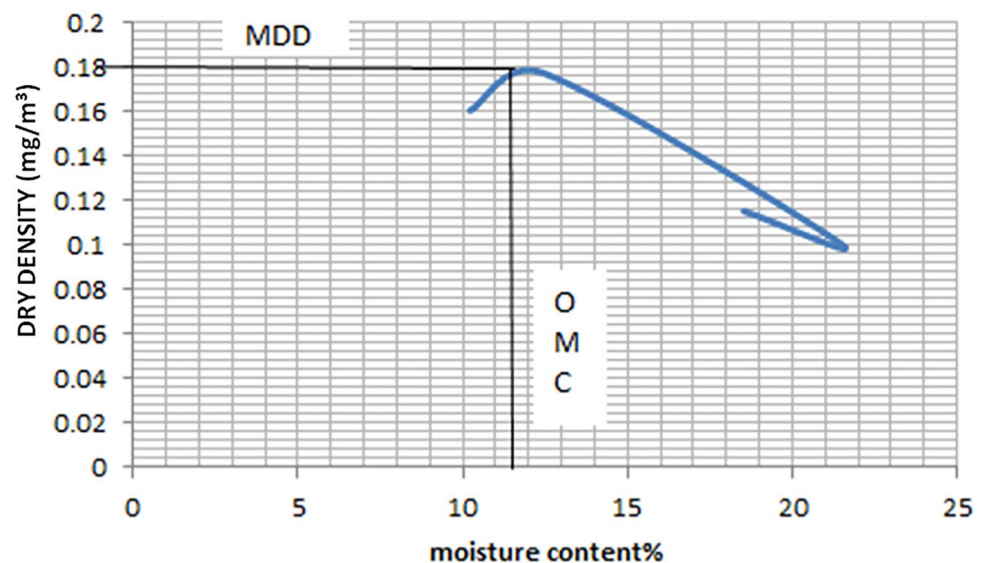


Table 9 Bulk density determination

Trial nos	1	2	3	4
Weight of ring + soil (g)	3550	4000	3900	3880
Weight of ring (g)	1800	1800	1800	1800
Weight of soil (g)	1750	2200	2100	2080
Bulk density (mg/m ³)	1.9	2.38	2.27	2.25

Table 10 Dry density/moisture content determination

Can identification	F2	P2	X2	Z3
Weight of wet soil + can (g)	85	105	103	109
Weight of dry soil + can (g)	79	95.5	88	95
Weight of can (g)	20.3	19	18	19.4
Weight of dry soil (g)	58.7	76.5	70	75.6
Moisture loss (g)	6	9.5	15	14
Moisture content (%)	10.22	12.42	21.41	18.52
Dry density (mg/m ³)	0.16	0.177	0.101	0.115

Table 11 Summary of proctor compaction test

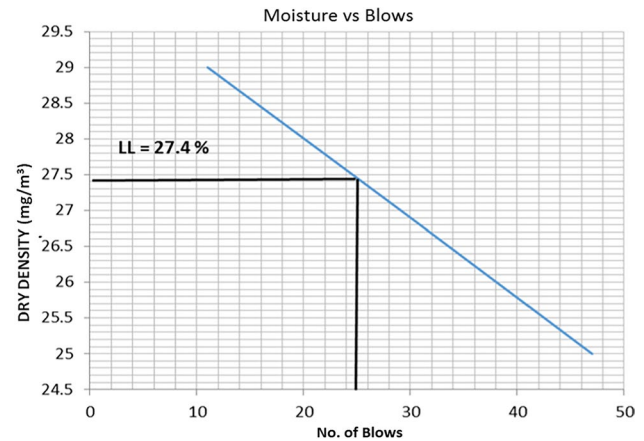
Sample	MDD (mg/m ³)	OMC
OKW1	2.15	11.1
OKW2	0.18	11.5

Table 12 Liquid limit

Sample	MDD mg/m ³	OMC%
OKW1	2.15	11.1
OKW2	0.18	11.5

Table 13 Plastic limit

Can Id	Non-plastic
Weight of can + wet soil (g)	
Weight of can + dry soil (g)	
Weight of can (g)	
Weight of dry soil (g)	
Weight of moisture loss (g)	
Moisture content (%)	

**Fig. 12** Liquid limit plot OKW2**Table 14** Liquid limit

Can Id	L4	2020	L1U6
Wt. of can + wet soil (M2) (g)	49	49	88
Wt. of dry soil + can (M3) (g)	48	44	77
Wt. of can (M1) (g)	19	8.8	24.1
Wt. of dry soil (M3-M1) (g)	29	35.2	52.9
Wt. of moisture (g)	1	5	11
Moisture content (%)	3.45	14.20	20.79
No. of bumps	41	17	11

Table 15 Plastic limit

Can Id	Non-plastic
Weight of can + wet soil (g)	
Weight of can + dry soil (g)	
Weight of can (g)	
Weight of dry soil (g)	
Weight of moisture loss (g)	
Moisture content (%)	

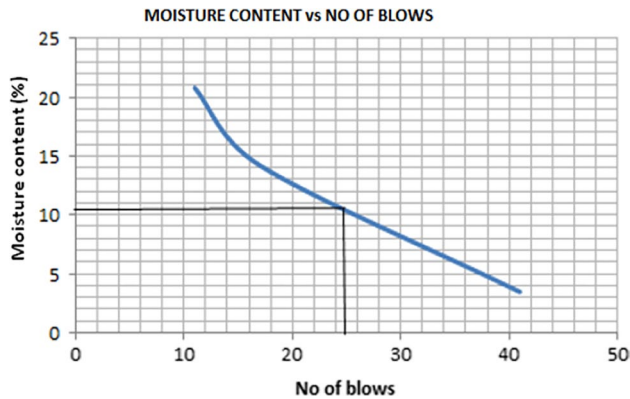
Table 16 Summary of plastic and liquid limit results

Sample	Wn%	LL%	PL%
OKW1	10.4	27.4	NP
OKW2	13.0	10.5	NP



Table 17 Liquid limits and compressibility (Venkatramaiah, 2006)

Range of LL%	Compressibility
< 30	Low
30–50	Medium
> 50	High

**Fig. 13** Liquid limit plot for OKW2**Table 18** Wet Sieving

Sieve size (mm)	Soil retained (g)	Mass passing (g)	% Passing
2.00	1	113	99.12
1.18	2	111	97.36
0.850	9	102	89.47
0.600	20	82	71.92
0.425	18	64	56.14
0.300	27	37	32.45
0.150	29	8	7.01
0.125	5	3	2.63
Pan	1	0	0

Based on the outputted results of the wet sieving, it can be seen that 26.92% of the samples obtained from about 1 m depth is made up fines, while the rest is sand; also, about 33.53% of the samples obtained at depth 2.5 m is made up of fines and the rest is sand. High percentage of sand in the sampled regions can be a cause of constant erosion since friable sands are easily eroded.

Conclusion

Gully erosion is caused due to the underlying geology and severity of the surface processes operating in the surface geology and soil cover coupled with the fact that gully erosion is predominant in sedimentary terrains. It is also observed that drainage, topography and lithology play a huge role in the genesis and formation of gulying in the study area. They tend to enhance the rate at which materials are being carried by moving water thereby causing erosion. From the competence and corrosivity interpretation, it was observed that from 23 VES stations, 22 stations were made up of sandy lithologies at the first layers which directly suggests the susceptibility of the area to gully erosion since wearing away of sediments starts from the surface. The azimuths of the major axes of the anisotropy diagram correlate significantly with the major strikes of the geologic formations. These azimuthal plots show that there is more to gulying within Njaba and its environs has been attributed to soil texture, compaction and rain-fall. The consistency in the structural lines of weakness as observed from the plots points to a structural deformation in the subsurface which in turn enhances a surface expression (gully) of the weaknesses underneath when exposed to the agents of erosion.

The result of the geotechnical studies such as percentage of fines, optimum moisture content, maximum dry density, liquid limit and plastic limit has been outputted. The result of the compaction tests indicates that the range of OMC from 11.1–11.5% is required to achieve MDD of the samples ranging from 0.18–2.15 mg/m³. From the study, it can be ascertained that the soil is of low compressibility. Also, the value indicates that the soil has little or no cohesive properties and will easily crumble when dry. They will also show high dispersive behavior upon the action of river current. Under full saturation, the sediments will be collapsible. The soils of the review region were seen to be loss and non-impervious to disintegration. They are additionally inadequately reviewed and practically without sediment and earth particles which would go about as concrete. The examples have a place with the fourth class based on the morsel (erodibility) test. Based on the interpretation made out of the results of this study and the investigations, the objectives of this study strongly have been achieved and it suggest the following control measures for gully erosion control in the study area;



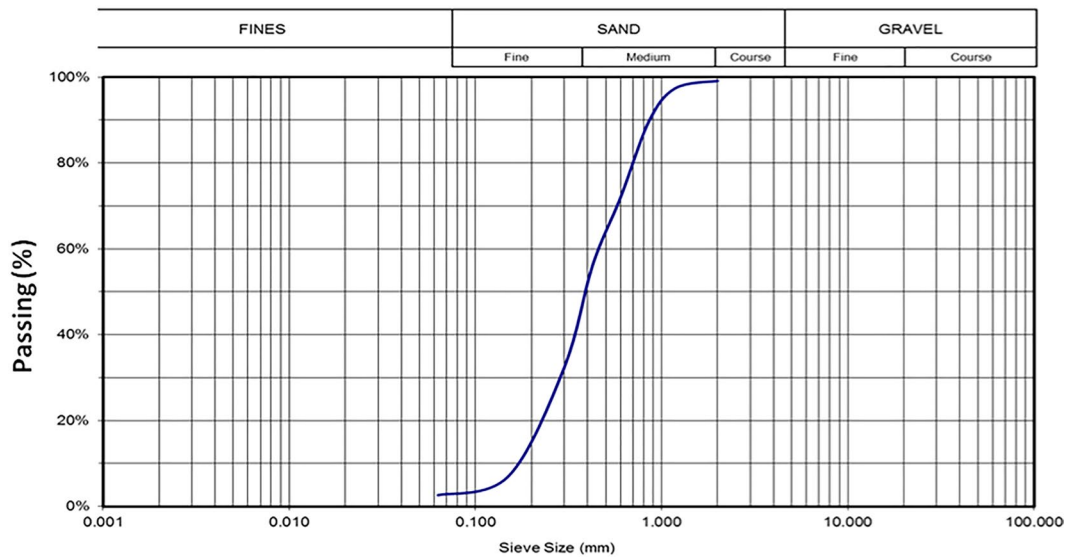


Fig. 14 Wet sieving plot for OKW1

Table 19 Wet sieving

Sieve size (mm)	Soil retained (g)	Mass passing (g)	% Passing
2.00	1	108	99.08
1.18	2	106	97.24
0.850	10	96	88.07
0.600	18	78	71.55
0.425	17	61	55.96
0.300	26	35	32.11
0.150	26	9	8.25
0.125	5	4	3.66
Pan	4	0	0

1. Surface and subsurface flows and drainage should be controlled by directing water through concrete channels into lined artificial reservoirs or straight into lakes or river plains;

2. Human activity and agricultural practices that enhance erosion should be controlled and their effects reduced to a minimum;
3. As a general rule of thumb, 70% groundcover is needed to protect soil in areas of high water flow and this needs to be thicker, up to 100% cover. In areas where rain is likely to increase rate of erosion, a higher percentage of groundcover will help reduce run-off and prevent erosion; and
4. Deep-rooted perennial grasses are recommended for planting in and on the sides of ephemeral waterways that have the potential to become gullies and since groundwater is slightly acidic, acid resistant construction materials should be used.



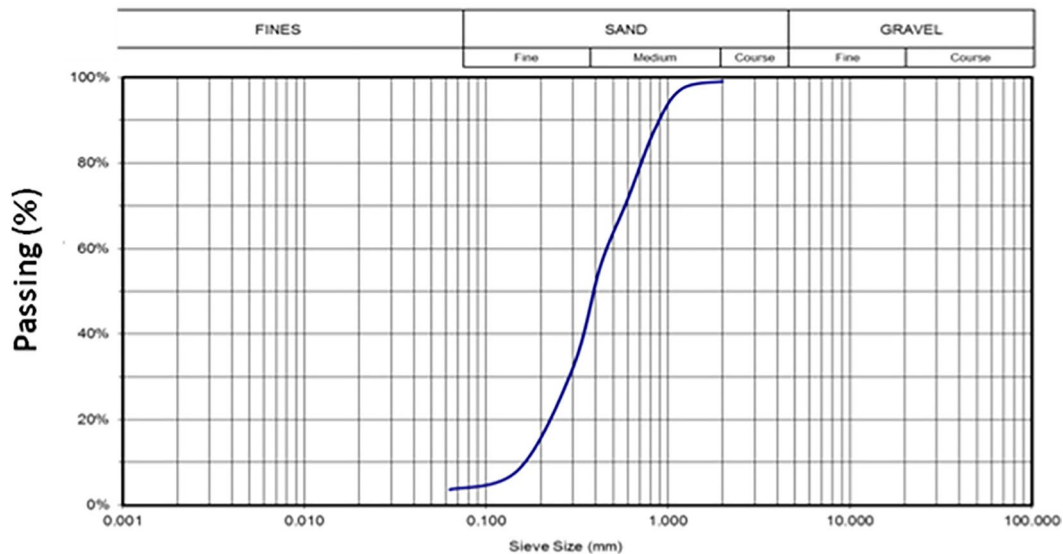


Fig. 15 Wet sieve plot

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval As per the literature review, this is neither a repetition of any work nor a copied key data from another's work. The methodology, findings, and conclusions made here belong to original research work as per our knowledge and belief.

Human or animal rights This research work is carried out in compliance with transparency, moral values, honesty, and hard work. No human participation or animals are involved in this research work.

Informed consent Every step of processing for publication is informed to all co-authors of this paper at the earliest, and everything is carried out with collective decision and consent.

References

- Aigbadon GO, Igwe EO, Ocheli A, Overare B, Akakuru OC, Akudo EO, Obasi IA, Bala JAII, Aminu MB (2023) Sedimentary facies, paleoenvironments and paleogeography of the upper cretaceous succession in the southern Bida Basin, Nigeria. *Arab J Geosci*. <https://doi.org/10.1007/s12517-023-11390-5>
- Akakuru OC, Akudinobi B, Opara AI, Onyekuru SO, Akakuru OU (2021a) Hydrogeochemical facies and pollution status of groundwater resources of Owerri and environs. *Southeast Niger Environ Monit Assess* 193:623. <https://doi.org/10.1007/s10661-021-09364-9>
- Akakuru OC, Akudinobi BE, Nwankwoala HO, Akakuru OU, Onyekuru SO (2021b) Compendious evaluation of groundwater in parts of Asaba, Nigeria for agricultural sustainability. *Geosci J*. <https://doi.org/10.1007/s12303-021-0010-x>
- Akakuru OC, Eze CU, Okeke OC, Opara AI, Usman AO, Iheme OK, Ibeneme SI, Iwuoha PO (2022) Hydrogeochemical evolution, water quality indices, irrigation suitability and pollution index of groundwater (PIG) around Eastern Niger Delta. *Niger Int J Energy Water Res*. <https://doi.org/10.1007/s42108-021-00162-0>
- Akakuru OC, Onyeonwuna UB, Opara AI, Iheme KO, Njoku AO, Amadi CC, Akaolisa CCZ, Okwuosha OR (2023) Electro-geohydraulic estimation of shallow aquifer characteristics of Njaba and environs, Southeastern Nigeria. *Arab J Geosci*. <https://doi.org/10.1007/s12517-023-11378-1>
- Akaninyene OA, Igboekwe MU (2012) Preliminary Lithologic Deductions for Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria, using vertical electrical sounding method. *Arch Phy Res* 3(4):292–302
- Akudinobi BEB, Obasi PN, Akakuru OC (2018) Assessment of recharge and discharge areas in Abakiliki and environs using hydrologic parameters in shallow wells. *Asian J Environ Ecol* 6(4):1–9
- Amagu AC, Eze SN, Jun-Ichi K, Nweke MO (2018) Geological and geotechnical evaluation of gully erosion at Nguzu Edda, Afikpo Sub-Basin, Southeastern Nigeria. *J Environ Earth Sci* 8:148–158
- Amah JJ, Aghamelu OP, Omonona OV, Onwe IM (2020) A study of the dynamics of soil erosion using rusle2 modelling and geospatial tool in Edda-Afikpo Mesas South Eastern Nigeria. *Pak J Geol* 4:56–71. <https://doi.org/10.2478/pjg-2020-0007>
- Amangabara GT, Otumchere VN (2016) Understanding the Factors and Processes of the Umuagwo -Urualla Gully Erosion in Ideato North LGA of Imo State. *Niger J Sci Eng Res* 3:55–67
- Amos CU, John UJ (2017) Geophysical and geotechnical evaluation of erosion sites in Ebem-Ohafia Area of Abia State. *South Niger Adv Res* 10:1–14. <https://doi.org/10.9734/AIR/2017/31538>
- Aniwetalu EU, Akakuru O (2015) Granomeric analysis of mamu formation and enugu shale around ozalla and its environs evidence from field study. *IOSR J Appl Geol Geophys* 3(2):19–26
- Bhattarai M, Adhikari LB, Gautam UP, Laurendeau A, Labonne C, Hoste-Colomer R, Sèbe O, Hernandez B (2015) Overview of the



- large April 25th Gorkha, Nepal earthquake from accelerometric perspective. *Seismol Res Lett* 86:40–48
- Chiaka JC, Akakuru OC, Akakuru OU, Akudinobi BEB (2019) Geotechnical aspects of a gully site at ofekata ii autonomous community, Awo-omamma, Imo State, Southeastern Nigeria. *Int J Appl Natural Sci* 8(2):41–54
- Choubin B, Rahmati O, Tahmasebipour N, Feizizadeh B, Pourghasemi HR (2019) Application of fuzzy analytical network process model for analyzing the gully erosion susceptibility. In: Pourghasemi H, Rossi M (eds) *Natural hazards gis-based spatial modeling using data mining techniques, advances in natural and technological hazards research*. Springer, New York. https://doi.org/10.1007/978-3-319-73383-8_5
- Egboka BC, Orji A, Nwankwoala HO (2019) Gully erosion and landslides in southeastern nigeria: causes consequences and control measures. *Glob J Eng Sci* 2(4):1–11. <https://doi.org/10.33552/GJES.2019.02.000541>
- Emeh CO, Igwe O (2017) Variations in soils derived from an erodible sandstone formation and factors controlling their susceptibility to erosion and landslide. *J Geol Soc India* 90(3):362–370. <https://doi.org/10.1007/s12594-017-0725-5>
- Eyankware MO, Akakuru OC, Ulakpa ROE, Eyankware EO (2022a) Hydrogeochemical approach in the assessment of coastal aquifer for domestic, industrial, and agricultural utilities in Port Harcourt urban, Southern Nigeria. *Int J Energy Water Res*. <https://doi.org/10.1007/s42108-022-00184-2>
- Eyankware MO, Eyankware RO, Akakuru OC (2022b) Hydrogeophysical delineation of aquifer vulnerability in parts of Nkalagu and Ohofia Agba areas of Abakaliki, SE. Nigeria. *Sustain Water Res Manag*. <https://doi.org/10.1007/s40899-022-00603-6>
- Habberjam GM (1975) Apparent resistivity anisotropy and strike measurements. *Geophys prospect* 23(1):211–215
- Idowu OJ, Oluwatoshin GA (2008) Hydraulic Properties in relation to morphology of a tropical soil with hardened plinthite under time land use types. *Trop Sub-Trop Agro Ecosyst* 8(4):145–155
- Mosavi A, Sajedi-Hosseini F, Choubin B, Taromideh F, Rahi G, Dineva AA (2020) Susceptibility mapping of soil water erosion using machine learning models. *Water* 12(7):1995. <https://doi.org/10.3390/w12071995>
- Nampak H, Pradhan B, Mojaddadi Rizzei H, Park HJ (2018) Assessment of landcover and land use change impact on soil loss in a tropical catchment byusing multitemporal SPOT-5 satellite images and revised universal soil loss equation model. *Land Degrad Dev* 29(10):3440–3455
- Nnam V(2019) Assessment of the magnitude of gully erosion in enugu urban area using revised universal soil loss erosion model (RUSLE). *African Research Journal of the Environment*, 16–23. https://publishingrealtime.com/files/b6acb191_0122.pdf
- Nwankwoala HO, Igbokwe T (2020a) Assessment and mapping of gully erosion geo-hazards in Agulu - Nanka, southeastern Nigeria: an integrated geotechnical and gis approach. *Int Sci J* 146:236–254
- Nwankwoala HO, Igbokwe T (2020b) Assessment and mapping of gully erosion geo-hazards in Agulu—Nanka, Southeastern Nigeria: an integrated geotechnical and GIS approach. *Int Sci J* 146:236–254
- Obaro RI, Odediran OA, Itheme KO, Akakuru OC, Gbadebo AF (2019) Geotechnical evaluation of lateritic soil in Baba-Ode Area, Ilorin, North – Central Nigeria. *J Res Inf Civil Eng* 16(1):2595–2609
- Obasi PN, Ani CC, Akakuru OC, Akpa C (2020) Determination of aquifer depth using vertical electrical sounding in ihechiowa area. *Arochukwu South Niger EBSU Sci J* 1(1):111–126
- Obi NI, Okekeogbu CJ (2017) Erosion problems and their impacts in anambra state of Nigeria: (a case of Nanka community). *Int J Environ Pollut Res* 1:24–37
- Ocheli A, Ogbe OB, Aigbadon GO (2021) Geology and geotechnical investigations of part of the Anambra Basin Southeastern Nigeria: implication for gully erosion hazards. *Environ Syst Res* 10:1–6
- Ogbonnaya I, Ugwuoke II, Onwuka S, Ozioko O (2020) GIS- based gully erosion susceptibility modeling, adapting bivariate statistical method and AHP approach in Gombe town and environs. *Northe Niger Geoenviron Hazards*. <https://doi.org/10.1186/s40677-020-00166-8>
- Okorafor OO, Akinbile CO, Adeyemo AJ (2017) Soil erosion in South-eastern Nigeria: areview. *Sci Res J* 5(9):33–39
- Okwu-Delunzu VU, Iwueke NT, Aniagolu CO (2018) Gully erosion and its environmental impact in eke udi local government area of enugu state. *Environ Ecol Res* 6(5):507–517. <https://doi.org/10.13189/eer.2018.060511>
- Oli IC, Opara AI, Okeke OC, Akaolisa CZ, Akakuru OC, Osi-Okeke I, Udeh HM (2022) Evaluation of aquifer hydraulic conductivity and transmissivity of Ezza/Ikwo area, Southeastern Nigeria, using pumping test and surficial resistivity techniques. *Environ Monit Assess* 194:719. <https://doi.org/10.1007/s10661-022-10341-z>
- Onu DO (2006) Determinants of farm—level soil conservation and erosion control adoption and utilization behaviours in the ecologically vulnerable areas of Imo State. *Niger J Rural Dev* 24(4):521–543
- Onyeagocha AC (1980) Petrography and depositional environments of the benin formation. *J Min Geol* 17(2):147–150
- Onyekuru SO, Iwuagwu JC, Ulasi A, Adaeze Ibeneme SI, Ukaonu C, Okoli AE, Akakuru OC (2021) Calibration of petrophysical evaluation results of clastic reservoirs using core data, in the offshore depobelt, Niger Delta, Nigeria. *Model Earth Syst Environ*. <https://doi.org/10.1007/s40808-021-01285-3>
- Opara AI, Ireaja AN, Eyankware MO, Urom OO, Ikoro DO, Akakuru OC, Dioha E, Omoko NE (2023) Comparative analysis of techniques used for aquifer protective capacity studies in the South-eastern part of Nigeria. *Int J Energy Water*. <https://doi.org/10.1007/s42108-023-00251-2>
- Reyment RA (1965) *Aspects of the geology of Nigeria*. Ibadan University Press, Ibadan, pp 66–69
- Rizzei HM, Saharkhiz MA, Pradhan B, Ahmad N (2016) Soil erosion predictionbased on land cover dynamics at the Semenyih watershed in Malaysia usingLTM and USLE models. *Geocarto Int* 31(10):1158–1177
- Sebastian A, Bora L, Steve L, Bernd H (2014) Conventional and Organic Farming; Soilerosion and conservation potential for rowcultivation. *Geoderma* 12:23–32
- Urom OO, Opara AI, Usen OS, Akiang FB, Isreal HO, Ibezim JO, Akakuru OC (2021) Electro-geohydraulic estimation of shallow aquifers of Owerri and environs Southeastern, Nigeria using multiple empirical resistivity equations. *Int J Energy Water Res*. <https://doi.org/10.1007/s42108-021-00122-8>
- Usman AO, Omada JI, Omali AO, Akakuru OC (2015) Evaluation of the aquifer characteristics of nteje and environs, anambra basin, South Eastern. *Niger J Nat Sci Res* 5(14):99–114

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

