Geoelectric Appraisal of Groundwater Occurrence and Overburden Protecting Capability in Part of Federal University of Agriculture Abeokuta Campus, Southwest Nigeria

***Ganiyu, S. A., Olurin, O.T., Adeleke, O. O., Aluko, T. J., Aikhuele, D. O., and Lasisi, R.A.**

Department of Physics, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria
***Corresponding Author** Email: adekunsa@yahoo.com, ganiyusa@funaab.edu.ng

ABSTRACT

Groundwater exploration in areas underlain by basement complex can be a bit challenging, Delineation of its prospective zones and valuation of possible exposure to pollution are imperative, as its remediation when polluted is enormously challenging. The present study is carried out with the aim of delineating the groundwater prospective sections and evaluating the aquifer protective capability of the overburden layers in College of Physical Sciences, Federal University of Agriculture Abeokuta, Nigeria. Thirteen (13) VES stations were probed utilizing Schlumberger electrode array mode with half maximum current electrode separation (AB/2) of 110 m. The VES survey was done with the aid of Campus Tigre resistivity meter. The field VES data were processed using both partial curve matching and computer-assisted iterations (WINRESIST software) in order to generate geologic models of true resistivities and thicknesses. The obtained geo-electric parameters were used to calculate Dar Zarrouk parameters (longitudinal conductance (S), transverse resistance (T), reflection coefficient (RC) and coefficient of anisotropy (λ). Thematic maps of delineated geoelectric and derived Dar Zarrouk parameters were created using surfer 10.0 with a view to displaying their spatial variations. The results of VES data interpretation disclose 3 to 4 geo-electric horizons comprising topsoil, weathered basement (clayey soil/ saturated clay/sandy clay), fractured /partially fractured basement, and fresh basement. The VES results further discloses two sounding curves (H and QH) with dominance of H-curve (92.3%) relative to QH-curve (7.7%). The weathered and fractured basements constitute the aquiferous units in the area with the overburden thickness (OT) and resistivity ranging from 2.3 to 36.5 m and 12.0 to 915.0 Ωm, respectively. The total longitudinal conductance (S) ranges between 0.22 and 0.58 Ω^{-1}; T ranges between 331 and 2792 Ωm^2; RC varies from 0.51 to 0.99 while λ varies from 1.00 to 2.75. Based on RC and OT values used to infer groundwater yield status, 30.8% of total VES points had moderate to high groundwater yield whereas 69.2% exhibit very low to low groundwater potential. According to S values of the overburden units, three marked aquifer protecting capability zones were pinpointed namely: the poor (15.38%), weak (46.15%) and moderate (38.47%). The identified moderate to high groundwater yield zones (VES stations 8, 9, 11 and 12) with their associated moderate protective capability were along the northwest and west sides of the study area, and thus suggested for drilling. The thematic maps of OT and RC further corroborate the productivity of these VES points. Conclusively, majority of the investigated VES Stations (69.2%) had very low to low groundwater potential with poor to weak protective capability. The outcomes of this study present essential information that can assist in achieving optimum management of sustainable groundwater sources.

Keywords: Basement complex terrain, Groundwater prospective sections, Dar Zarrouk parameters, Aquifer protective capability, Schlumberger electrode array

INTRODUCTION

Water used by human beings for sustenance of life and preservation of ecosystem comes from different sources such as rivers, lakes, streams and aquifer units (Emenike et al., 2017; Adagunodo et al., 2018; Soomro et al., 2019). The predominant sources of water in most African countries include river, stream, spring, shallow wells, boreholes and pipe-borne water (though inadequate) (Okogbue and Omonona, 2013; Ganiyu et al., 2022). Groundwater is the water found in the voids of geological structures beneath the earth surface (Bello et al., 2019; Gaikwad et al., 2021). It is an important natural resource used by human beings to quench thirst, for cooking, washing amongst other various daily uses ranging from domestic agricultural, commercial to industrial purposes (Obiora et al., 2017; Oladunjoye et al., 2019: Olatinsu and Salawudeen, 2021; Agyemang, 2022). Groundwater quality is relatively guaranteed than that of surface water, as the latter is more prone to contamination from nearby anthropogenic activities (Olorunfemi and Oni, 2019; Sunkari et al., 2021; Awosika et al., 2020).

Groundwater can be polluted by contaminants released from nearly anthropogenic effects such as the use of soak-away pits, burning of refuse, washing, indiscriminate disposal of solid wastes, use of chemical formulations, presence of animal wastes among others beside the aquifer source (Anosike et al., 2019; Ganiyu et al., 2021a; Gaikwad et al; 2021). These contaminants infiltrate through the geological features and voids of the substances materials into the water table and ultimately affects groundwater potability (Mbaka et al., 2017; Anosike et al., 2019; Arunbose et al., 2021). It is imperative for hydrologists and relevant stakeholders to guide assiduously the available groundwater sources (Singh and Singh, 2018; Ganiyu et al., 2022). Geophysically, the Aquifer Protective Capacity (APC) characterization depicts the ability of groundwater abstraction source to curtail the leaching of contaminants into it (Adabanija &Ajibade, 2020; Oyeyemi et al., 2020; Khan et al., 2021). Therefore, apart from searching for points/stations of promising aquifer potential in a survey area, one must also consider the aquifer protective capacity rating of the study location (Okogbue and Omonona, 2013; Gaikwad et al., 2021).

The demand for groundwater by the populace in Africa Continent is increasing due to rise in population, urbanization, industrialization, climate change and continuous loss of surface water quality to pollutants (Soomro et al., 2019; Wu et al., 2020: Agyemang 2021). Inadequate supply of tap water by the government to the populace necessitates the reason why individuals and organizations embark on drilling of alternative groundwater sources such as shallow well and deep bore holes (Ganiyu et al., 2022). However, it must be noted that the existence and distribution of groundwater in a particular area are influenced by factors such as topography, climate conditions, underlying rock types, geological structures, land use activities and their interaction with the hydrological features (Perrone and Jasechko, 2017; Oladunjoye et al., 2019: Wu et al., 2020; Arunbose et al., 2021).

A cost-efficient geophysical survey needs to the carried out before the commencement of drilling for productive groundwater source at a particular site (Oyeyemi et al., 2020). This will provide needed geological information about the subsurface features beneath the study points, thus assist in proper selection of drilling points that can assure of sufficient groundwater yield (Abu Heen, 2017; Oyeyemi et al., 2020). Several non-invasive geophysical methods such as electrical, electromagnetic, magnetic, gravity and seismic refraction have been used either as a stand-alone method or in integrated form for locating groundwater potential zones (Adeoti et al., 2012; Handayani et al., 2018; Olorunfemi & Oni, 2019; Awosika et al., 2020; Sunkari et al., 2021). Electrical resistivity survey (particularly vertical electrical sounding (VES)) is the most widely used in groundwater exploration (Oyeyemi et al., 2018; Olorunfemi and Oni, 2019: Arunbose et al., 2021; Zayed, 2021). The VES measure the vertical contrast of the subsurface resistivity distribution based on the field measurements of the potential difference (Choudhury et al., 2017; Aizebeokhai & Oyeyemi, 2018). This is achieved by injecting electric current into the ground through the metallic current elctrodes while the resulting potential differences are measured via the potential electrodes (Olorunfemi and Oni, 2019: Agyemang 2021.) The VES techniques allow a quantitative assessment of heterogeneous subsurface geologic layers in terms of resistivity, thickness and depth (Kayode et al., 2016: Arunbose et al., 2021). For groundwater exploration purpose, electrical resistivity survey helps to make intelligent selection on where and depth that must be drilled to reach the aquifer units within the investigated areas (Abu Heen, 2017). The success rate of the selection made still depends greatly on the scientific and geological knowledge of the analyst. Among the useful information provided by electrical geophysical method concerning groundwater exploration includes resistivity distribution, thickness and depth of the geo-electric layers to the aquifer units as well as derived overburden protective capacity rating of the surveyed area (Bayewu et al., 2017; Oladunjoye et al., 2019; Oyeyemi et al., 2020).

In a complex geological setting, such as basement complex of Nigeria, prognosis of zones with appreciable groundwater yield is difficult due to heterogeneity and anisotropy in bedrock systems (Earon et al., 2015: Obora et al., 2017; Olatinsu and Salawudeen, 2021). Furthermore, basement complex rocks are naturally characterized by low porosity and negligible permeability (Oyeyemi et al., 2018; Olorunfemi and Oni, 2019). In fact, the problem of groundwater supply in areas underlain by basement complex terrain is visibly noticed during the dry season when most of the shallow hand-dug wells dry off due to intricacy of the basement terrain (Bayewu et al., 2017: Adagunado et al., 2018; Fajana 2020). Published reports by Olorunfemi & Oni (2019); Awosika et al. (2020); and Sunkari et al. (2021) averred that aquifer unit is mainly found in secondary porosity induced structures like fractures (faults, joints) or weathered parts of basement complex terrain under significant hydrostatic pressure (Fajana, 2020a; Agyemang, 2021). In some cases, combination of weathered and fractured layers is required for optimum groundwater accumulation (Olorunfemi & Oni, 2019: Fajana 2020b; Agyemang, 2021).

The accessibility, accretion and distribution of groundwater beneath the surface at a specific site are swayed by factors such as porosity, permeability, degrees of water saturation host rocks, predominant geological features, resistivity distribution, thickness of the geo-electric horizons and depth to the fresh bedrock (Aizebeokhai and Oyeyemi, 2018; Bello et al., 2019; Arunbose et al. 2021). Specifically, the capacity of the basement complex rock to store, convey and yield appreciable volume of groundwater is dictated by the nature, extent, thickness and continuity of the secondary porosities arising from faults/joints as well as connectedness of these geological features within the weathered regolith (Olorunfemi and Oni, 2019; Awosika et al., 2020: Olatinsu and Salawudeen, 2021). According to Olorunfemi & Oni (2019); aquifer units in the basement complex domain are discontinuous and, on most occasions, restricted in lateral and depth extent. Furthermore, it was reported that in a basement complex terrain, the thicker the overburden, the more feasible the groundwater exploration becomes in such domain (Adagunodo et al., 2018; Olorunfemi and Oni, 2019). Therefore, there is a need to carry out geophysical survey that provides information about the essence of the subsurface geological structures associated with groundwater occurrence and distribution before embarking on groundwater prospecting and extraction in an area underlain by basement complex (Obiora et al., 2017: Oyeyemi et al., 2020; Olatinsu and Salawudeen, 2021).

Electrical resistivity survey serves as an efficient geophysical method that increases the comprehension of the subsurface features linked to groundwater exploration, "thus assist in pinpointing productive aquifer with higher correctness and also aids in devising right groundwater management for the greater good of the populace (Oyeyemi et al., 2020; Arunbose et al., 2021).

Scientists have made use of electrical resistivity techniques for range of environmental investigations (Inim et al, 2020; Adabanija & Ajibade 2020, Gaikwad et al: 2021; Niculescu and Andrei, 2021). For instance, Inim et al. (2020) used combined ID and 2D electrical resistivity method to monitor the dynamics of saltwater intrusion within the coastland surrounding Ibese, Southeast Nigeria. They found out that high resistivity values depict saturated freshwater zones while low resistivity regions depict saturated saltwater. Ganiyu et al. (2021b) investigated the causes of unceasing road failures along busy Camp-Alabata Road, Nigeria through the delineation of geo-electric layers underlying the road with the use of combined VES and 2D electrical resistivity tomography (ERT) as well as soil analysis. Their results revealed that failed road sections were characterized by topsoil with <20 Ωm coupled with differential settlement of subgrade materials. Adabaniji and Ajibade (2020) investigated the groundwater corrosion and protective capability of the overburden units in a crystalline basement area utilizing VES data and in-situ measured TDS, respectively. They reported that overburden protective capacity ranged from excellent to good, fair and poor whereas the groundwater points in the southwest part of Ogbomoso North revealed strongly corrosive state while those in the northwest and south-eastern parts of the study area revealed non-corrosive groundwater. Gaikwad et al. (2021) identified groundwater potential zones (GPZ) in complex bedrock geological terrain with the use of VES technique and its derived Dar-Zarrouk parameters. Their results indicated that the VES points sited in the central part of the

Karli River Basin serve as the worthiest sites for GPZ.

This present study is aimed at identifying the groundwater potential zones within the environs of College of Physical Sciences (COLPHYS), Federal University of Agriculture Abeokuta, Nigeria through the utilization of VES technique. COLPHYS conducts innovative research in the field of chemistry, physics as well as biology apart from providing routine strategic supports to other colleges within the University. Groundwater is used by both students and staff for various purposes such as cooking & laundry (for boarders), cleanings of classroom/lecture theatres, laboratory uses among others. The increasing population of students coupled with that of staff has imposed a lot of stress on the available water supply projects in the University. Furthermore, most of the available boreholes within the Campus had history of being failed or not working properly while few exciting shallow wells are only relatively productive during the wet season and at best of low yield during the dry section. The objectives of the study include: (i) delineation of subsurface lithologies linked to groundwater development potential in the surveyed area (ii) identification of the essence of the subsurface geoelectric horizons (iii) evaluation of the probable groundwater yield of the sounding points via Dar Zarrouk parameters & overburden thickness and (iv) determination of the overburden protective capacity of the deciphering aquifer points.

Description of the Study Area and its Geology

The Federal University of Agriculture, Abeokuta (FUNAAB), Nigeria was established as a specialized institution in January 1988 and located within Ododa local government area of Ogun State, Southwest Nigeria (Ganiyu et al., 2020). The land area of the University cover about 10,000 hectares. The University has 9 colleges housing 40 academic departments in addition to several institutes and units. Presently, the population of both students and staff in FUNAAB is approximately 19,000. Groundwater is used by both students and staff for various purposes such as cooking & laundry (for boarders), cleanings of classroom/lecture theatres, laboratory uses among others. The increasing population of students and staff has imposed a great stress on the available water supply projects in the University. Therefore, it will not be out of place for each college in the university to have productive boreholes/shallow wells all year round. This study serves as a step in the right direction. We carried out electrical resistivity survey at vicinity of College of Physical Sciences (COLPHYS) in order to delineate points of promising groundwater potential. The COLPHYS provides teaching and laboratory services to students in other disciplines of the university at the foundational levels.

The study area is located at latitudes 7° 13′40.278" to 7°13'40. 318"N and longitudes 3° 26'9.373" to 3°26'9.992"E. The mean temperature in Abeokuta varies from 27°C to 34°C in January and from 21°C to 29°C in August (Ganiyu et al., 2020). The rainy session in Abeokuta starts from April and ends in October whereas the dry season runs from November to March (Akanni, 1992; Alabi et al., 2021). Yearly rainfall amount in Abeokuta and its environs ranged from 750 to 1000 mm during the wet season and from 250 to 500 mm in the dry season (Akani, 1992; Ganiyu et al., 2020). Geologically, FUNAAB is located within the Pre-Cambrian Basement Complex terrain of southwest Nigeria (Ganiyu et al., 2021a). Locations within the basement complex terrain had challenges with regard to groundwater potential estimation (Obiora et al, 2017; Oladunjoye et al., 2019). Though, areas within basement complex of Southwest Nigeria receive relatively adequate rainfall during the wet season, most still faced problem of insufficient groundwater supply, chiefly due to insufficient weathered and fractured zones of the underlying rocks (Oladunjoye et al., 2019; Fajana, 2020a, b). The study locations (virgin land adjoining COLPHYS) are largely underlain by migmatite as shown in Figure 1.

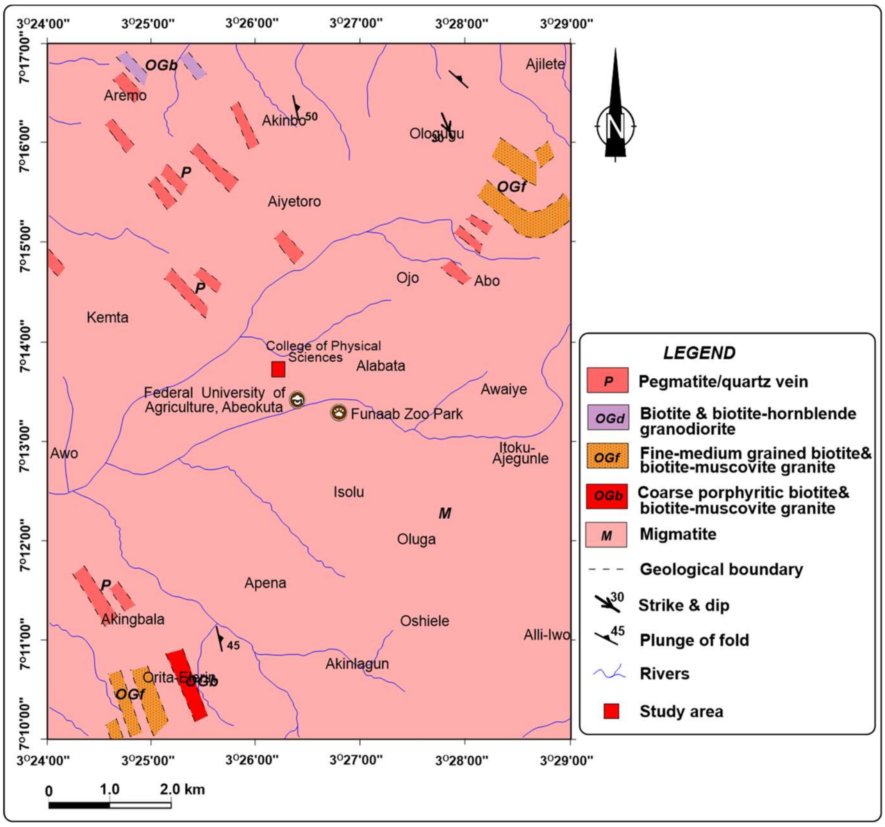


Figure 1: Geological map showing the rock type that underlies the study area (modified after NGSA, 2016)

Vertical Electrical Sounding (VES) Survey

The VES method was adopted for this study as it offers superior vertical resolution, uncomplicated field logistic, simple data analysis and excellent depth sensitivity (Soupios et al., 2007; Fajana, 2020a, Arunbose et al., 2021). A total of thirteen (13) VES points were established across the study area (Figure 2) utilizing the Schlumberger electrode configuration. The advantages of Schlumberger array over other configurations used in VES profiling include fewer personnel needed, less cumbersome field deployment, better vertical resolution, greater probing depth and relatively high signal to noise ratio (Vasantrao et al., 2017: Soomro et al., 2019: Khan et al 2021; Sunkari et al., 2021). The maximum half-current-electrode separation (AB/2) used in the survey was 110 m. The VES data (field Resistance (R_a)) were acquired with the use of Campus Tigre resistivity meter which was set to take the readings at 4-cycles.The spacing of AB/2 started at 1m and then increased whereas that of potential electrode spacing (MN/2) was fixed at a point until AB/2 become large when an increase in potential became necessary (Oyeyemi et al., 2020: Arumbose et al., 2021). Details of the theory and field set up of the VES survey using Schlumberger electrode configuration can be found in Obiora et al. (2017); Soomro et al. (2019) and Sunkari et al. (2021).

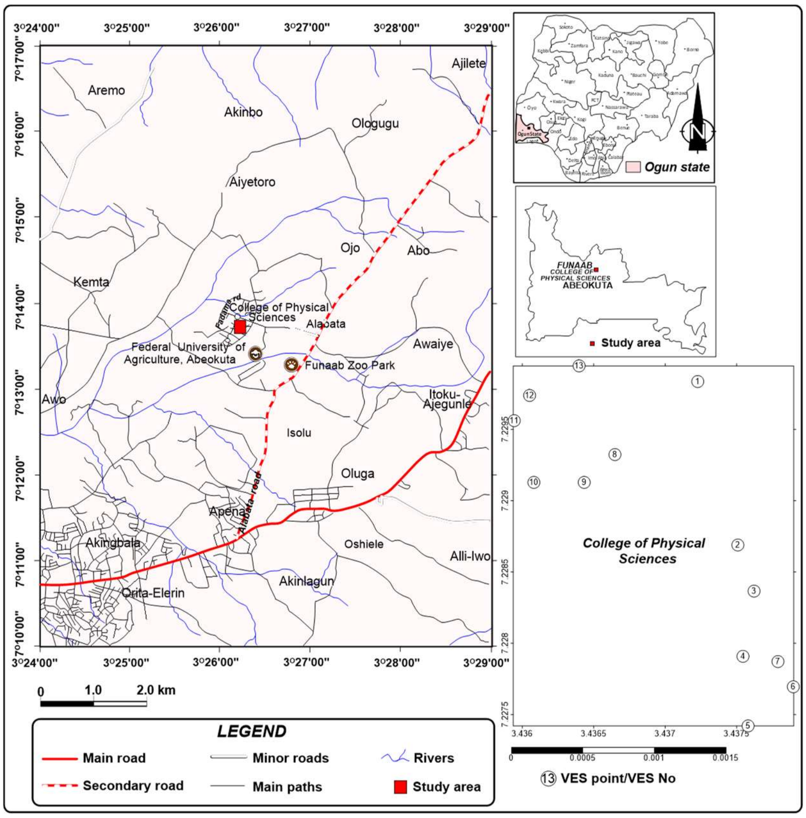


Figure 2: Location map of the study area

The apparent resistivity (ρ_a) values of VES points were later obtained by multiplying the field resistance (R_a) values with appropriate geometric factor (Obiora et al., 2015a, b, Vasantrao et al., 2017; Arunbose et al., 2021). The obtained VES data (i.e. ρ_a data) were firstly processed by plotting the ρ_a values against half- current electrode spacing (AB/2) on bi-logarithm graph paper and presented as sounding curves (Aizebeokhai et al., 2016; Obiora et al., 2017; Oyeyemi et al., 2020). Afterwards, quantitative interpretation of the obtained VES curves was done by partial curve matching, followed by computer-assisted 1D forward modelling technique using WINRESIST software (Obiora et al., 2015b; Oyeyemi et al., 2020). These quantitative processes provide true resistivity, thickness and depth of the deciphering geoelectric layers (Aizebeokhai et al., 2016: Khan et al., 2021).

Dar-Zarrouk parameters (total longitudinal conductance (S), total transverse resistance (T), reflection coefficient (RC), and coefficient of anisotropy (λ) that aid to explain the nature of the subsurface lithology and its structural behaviour with less ambivalence were derived from the thickness and resistivity values of model geologic layers obtained from iterated VES data (Obiora et al., 2017; Olayinka and Oyedele, 2019: Khan et al., 2021; Agyemang, 2022).

Consider a number of geologic horizons with resistivity values $\rho_1, \rho_2, \rho_3, \rho_4$ …….. ρ_n (in unit of Ωm) and thicknesses of h_1, h_2, h_3, h_4 ………… h_n (in meters). The total longitudinal conductance (S) in unit of Ohm^{-1} is given by the relation:

$$S = \sum_{i-1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \frac{h_4}{\rho_4} + \ldots\ldots\ldots\ldots\ldots + \frac{h_n}{\rho_n} \qquad \text{(i)}$$

The total transverse resistance (T) in unit of ohm m^2 is given by the relation:

$$T = \sum_{i=1}^{n} \rho_i h_i = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \rho_4 h_4 + \ldots\ldots + \rho_n h_n \qquad \text{(ii)}$$

where n in equations (i) and (ii) represents the number of geo-electric layers of a particular sounding point.

The coefficient of anisotropy (λ) is given by the relation:

$$\lambda = \sqrt{\frac{\rho_T}{\rho_S}} \qquad \text{(iii)}$$

where ρ_T is the average transverse resistivity and ρ_S refers to the average longitudinal resistivity.

The RC of each sounding point was calculated by the relation proposed by the Bhattacharya and Patra (1968) and have been used by Loke (1999); Sunkari et al. (2021) and Arunbose et al. (2021) as:

$$RC = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \qquad \text{(iv)}$$

where ρ_n refers to the resistivity of the nth geologic layer and ρ_{n-1} stands for the resistivity of the geologic horizon overlying the nth geologic layer (Obiora et al., 2015b; Arunbose et al., 2021).

The Aquifer Protective Capacity (APC) refers to the capability of the overburden unit to retard and filter infiltrating contaminants/effluents entering the aquiferous unit (0kogbue and Omonona, 2013; Adabanija and Ajibade, 2020; Khan et al., 2021). In this study, the APC was assessed based on total longitudinal conductance (S) value of each VES point using the APC rating of Table 1.

Table 1: APC rating modified after Henriet (1976): Oladapo and Akintorinwa (2007); Adabanija and Ajibade (2020)

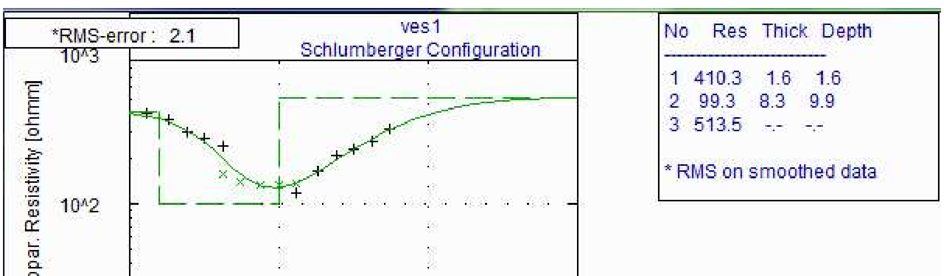
Longitudinal conductance (S) in Ohm^{-1}	APC Rating
< 0.10	Poor
0.10 - 0.19	Weak
0.20 - 0.69	Moderate
0.70 - 4.90	Good
5.00 - 10.00	Very good
>10.00	Excellent

The geo-electric cross sections for the sounding points were generated from the geo-electric layers parameters. Furthermore, Surfer 10.0 was also used to generate the thematic maps of geo-electric layer parameters as well as that of derived Dar-Zarrouk parameters for all the sounding points in the study area.

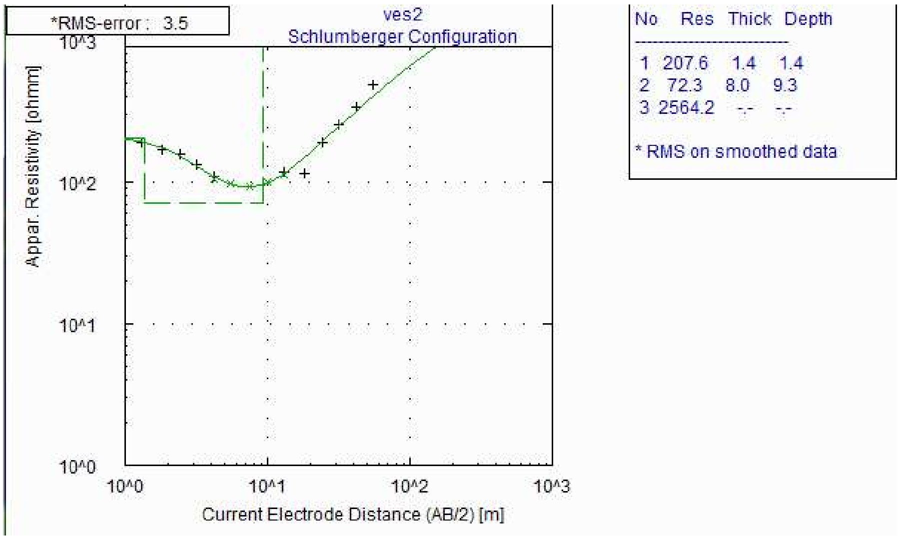
RESULTS AND DISCUSSIONS

The VES curves generated from the iterated VES data in the study area are shown in Figures 3a-k. The percentage distributions revealed that H-curve type constitutes 92.3% while the remaining 7.7% of total VES points (i.e. VES 11) constitutes QH- curve type. The dominancy H-type sounding curve in the study area concurs with similar result obtained by Ganiyu et al. (2020) in their investigation of soil moisture content over a cultivated farmland within FUNAAB Campus. The interpretation of the subsurface geologic layers according to the generated VES curves show 3 to 4 geo-electric horizons (Table 2). The first layer is the top soil, having a resistivity range of 128 to 927 Ωm, with a thickness range of 0.4 to 2.0 m. The relatively high resistivity values in the topsoil might be due to the reworking activities on the grassland (Ganiyu et al., 2020; Oyeyemi et al., 2020). The second layer with an inverse model resistivity range of 12 to 126 Ωm and the thickness range of 1.9 - 36.0 m is interpreted to be weathered basement (clayey/saturated clay/sandy clay). The lithologic distribution of the weathered horizon is noticed to be discernible by dominant clayey soil. Similar result of dominant clayey soil as weathered basement on similar area underlain by migmatite terrain was also reported by Akanbi (2018). The inverse model resistivity values of the third geo-electric horizons range from 370 to 915 Ωm and interpreted to be fractured basement. Fully fractured basement columns were delineated beneath VES stations 1, 3, 9, 11 and 12 with resistivity values ranging between 370 and 530 Ωm whereas partially fractured basement was traced beneath VES 7. The fourth layer is the fresh basement with resistivity values ranging between 410 to 5349 Ωm and were delineated under VES points 2, 4, 5, 6, 8, 10 ad 13.

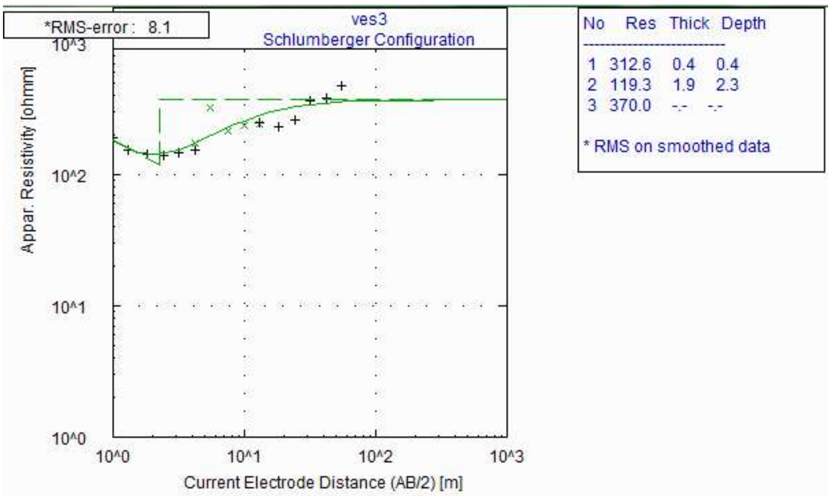
3(a)



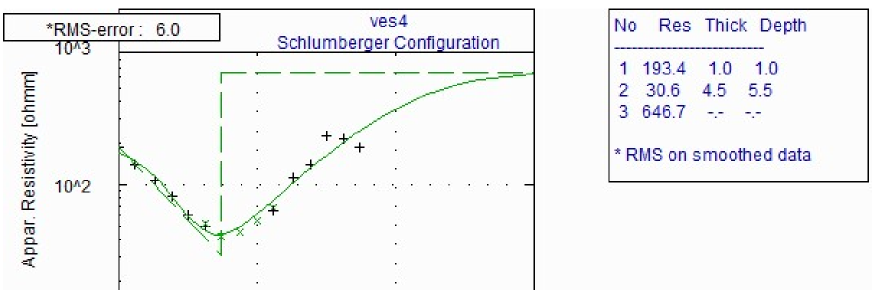
3(b)


*RMS-error : 3.5
ves2
Schlumberger Configuration
Appar. Resistivity [ohmm]
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 207.6 1.4 1.4
2 72.3 8.0 9.3
3 2564.2 -.- -.-
* RMS on smoothed data

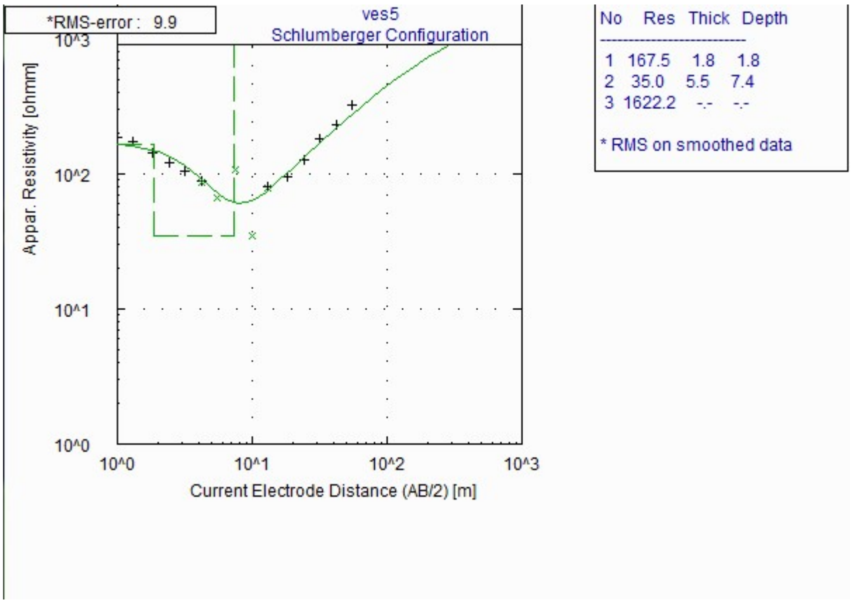
3(c)


*RMS-error : 8.1
ves3
Schlumberger Configuration
Appar. Resistivity [ohmm]
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 312.6 0.4 0.4
2 119.3 1.9 2.3
3 370.0 -.- -.-
* RMS on smoothed data

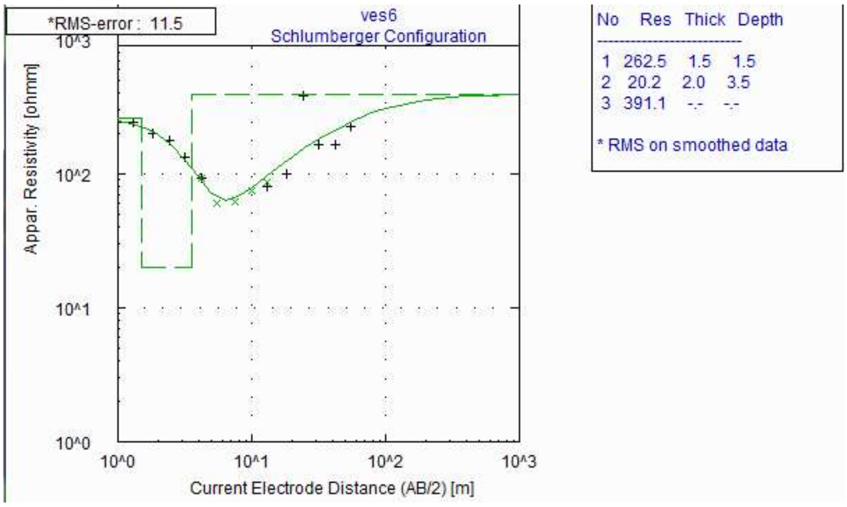
3(d)


*RMS-error : 6.0
ves4
Schlumberger Configuration
Appar. Resistivity [ohmm]
No Res Thick Depth
1 193.4 1.0 1.0
2 30.6 4.5 5.5
3 646.7 -.- -.-
* RMS on smoothed data

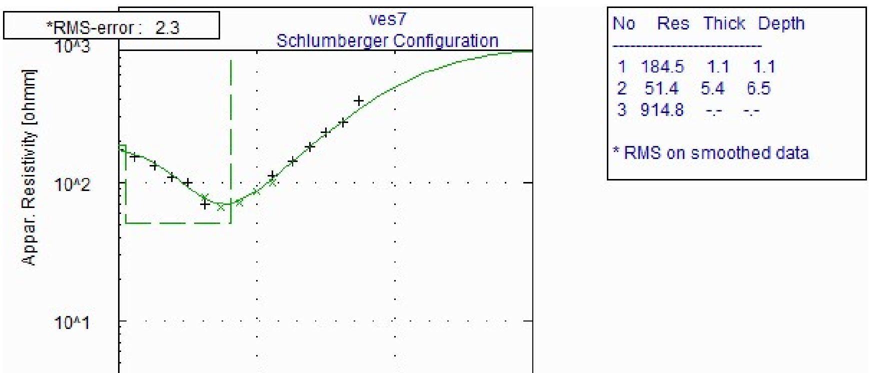
3(e)


*RMS-error : 9.9
ves5
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 167.5 1.8 1.8
2 35.0 5.5 7.4
3 1622.2 -.- -.-
* RMS on smoothed data

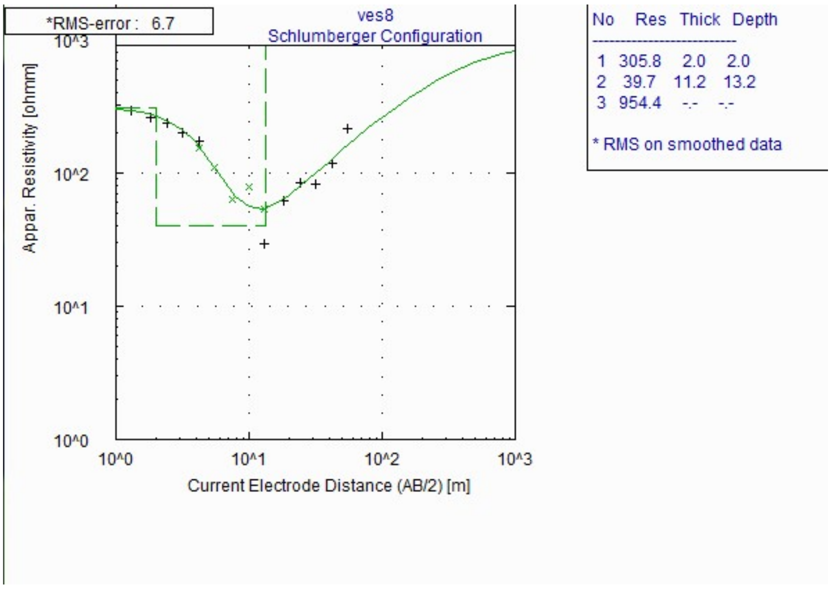
3(f)


*RMS-error : 11.5
ves6
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 262.5 1.5 1.5
2 20.2 2.0 3.5
3 391.1 -.- -.-
* RMS on smoothed data

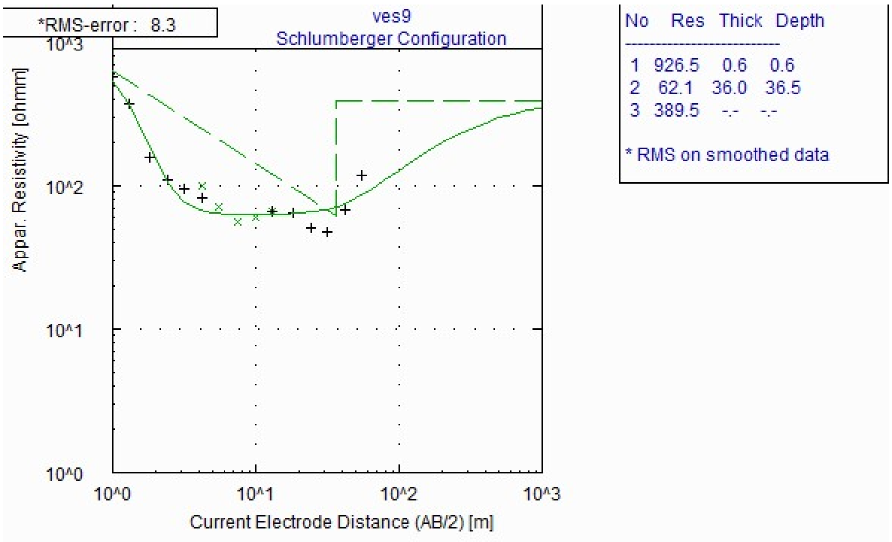
3(g)


*RMS-error : 2.3
ves7
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
No Res Thick Depth
1 184.5 1.1 1.1
2 51.4 5.4 6.5
3 914.8 -.- -.-
* RMS on smoothed data

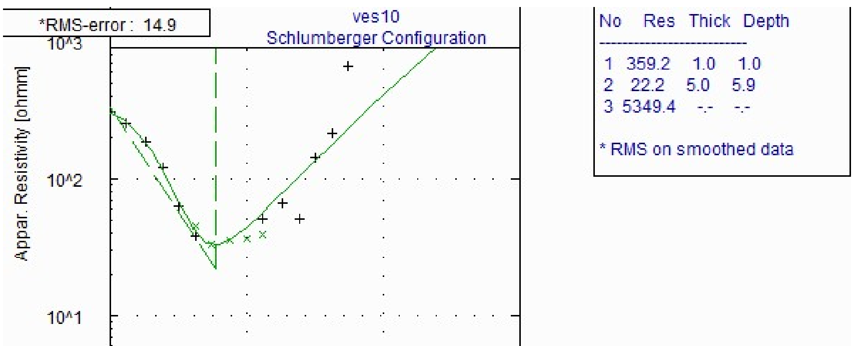
3(h)


*RMS-error : 6.7
ves8
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 305.8 2.0 2.0
2 39.7 11.2 13.2
3 954.4 -.- -.-
* RMS on smoothed data

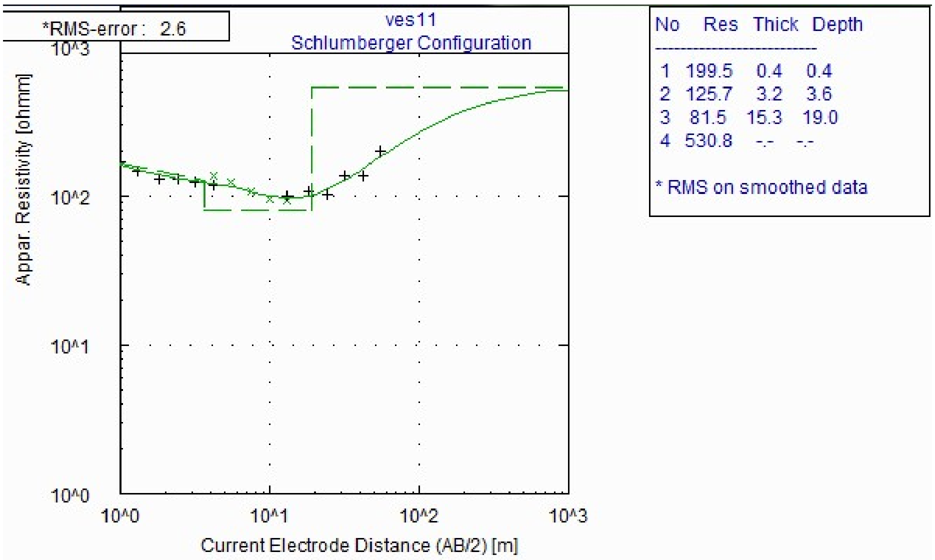
3(i)


*RMS-error : 8.3
ves9
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 926.5 0.6 0.6
2 62.1 36.0 36.5
3 389.5 -.- -.-
* RMS on smoothed data

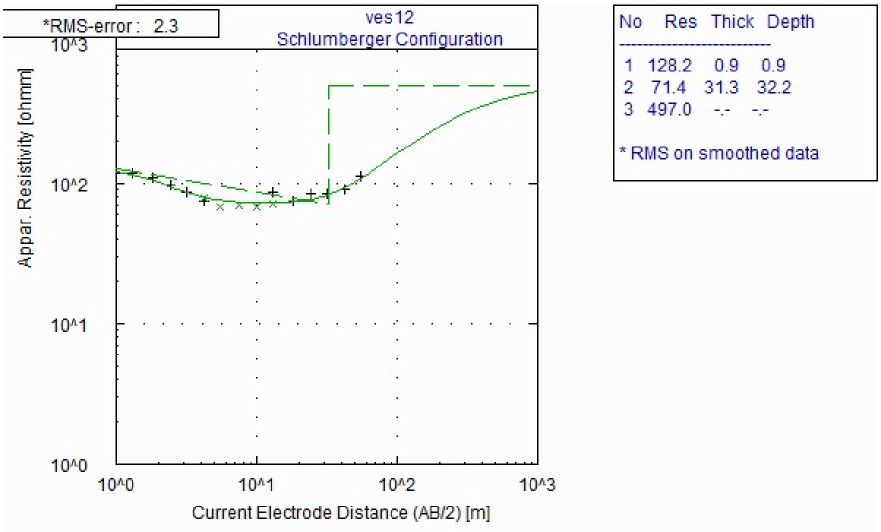
3(j)


*RMS-error : 14.9
ves10
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
No Res Thick Depth
1 359.2 1.0 1.0
2 22.2 5.0 5.9
3 5349.4 -.- -.-
* RMS on smoothed data

3(k)


*RMS-error : 2.6
ves11
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 199.5 0.4 0.4
2 125.7 3.2 3.6
3 81.5 15.3 19.0
4 530.8 -.- -.-
* RMS on smoothed data

3(l)


*RMS-error : 2.3
ves12
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
Current Electrode Distance (AB/2) [m]
No Res Thick Depth
1 128.2 0.9 0.9
2 71.4 31.3 32.2
3 497.0 -.- -.-
* RMS on smoothed data

3(m)

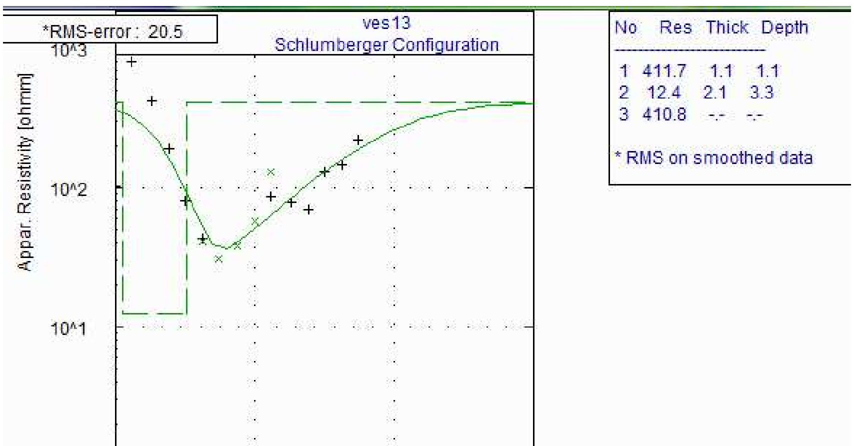

*RMS-error : 20.5
ves13
Schlumberger Configuration
Appar. Resistivity [ohmm]
10^3
10^2
10^1
No Res Thick Depth
1 411.7 1.1 1.1
2 12.4 2.1 3.3
3 410.8 -.- -.-
* RMS on smoothed data

Figure 3a-m: Layer Model Interpretations for VES 1 to VES 13

Table 2: Summary of the geo-electric parameters

Station	Layer No	Resistivity value (Ωm)	Thickness(m)	Depth (m)	Curve Type	Reflection Coefficient	Probable Lithology
VES 1	1	410	1.6	1.6			Top soil
	2	99	8.3	9.9	H	0.68	Weathered basement {clayey soil)
	3	514	-	-			Fractured basement
VES 2	1	208	1.4	1.4			Top soil
	2	72	8.0	9.3	H	0.95	Weathered basement (clayey soil)
	3	2564	-	-			Fresh basement
VES 3	1	313	0.4	0.4			Top soil
	2	119	1.9	2.3	H	0.51	Weathered basement (sandy clay)
	3	370	-	-			Fractured basement
VES 4	1	193	1.0	1.0			Top soil
	2	31	4.5	5.5	H	0.91	Weathered basement (saturated clay)
	3	647	-	-			Fresh basement
VES 5	1	168	1.8	1.8			Top soil
	2	35	5.5	7.2	H	0.96	Weathered basement (clayey soil)
	3	1622	-	-			Fresh basement
VES 6	1	263	1.9	1.9			Top soil
	2	20	2.0	3.5	H	0.90	Weathered basement (saturated clay)
	3	210	-	-			Fresh basement
VES 7	1	185	1.1	1.1			Top soil
	2	51	5.4	6.5	H	0.89	

	3	915	-	-			Weathered basement(clayey soil) Partially fractured basement
VES 8	1	306	2.0	2.0			Top soil
	2	40	11.2	13.2	H	0.92	Weathered basement(clayey soil)
	3	954	-	-			Fresh basement
VES 9	1	927	0.6	0.6			Top soil
	2	62	36.0	36.5	H	0.72	Weathered basement(clayey soil)
	3	390	-	-			Fractured basement
VES 10	1	359	1.0	1.0			Top soil
	2	22	5.0	5.9	H	0.99	Weathered basement(saturated clay)
	3	5349	-	-			Fresh basement
VES 11	1	200	0.4	0.4			Top soil
	2	126	3.2	3.6	QH	0.73	Sandy clay
	3	82	15.3	19.0			Weathered basement(clayey soil)
	4	531	-	-			Fractured basement
VES 12	1	128	0.9	0.9			Top soil
	2	71	31.3	32.2	H	0.84	Weathered basement(clayey soil)
	3	497	-	-			Fractured basement
VES 13	1	412	1.1	1.1			Top soil
	2	12	2.1	3.3	H	0.94	Weathered basement(saturated clay)
	3	411	-	-			Fresh basement

Geo-electric Section along VES 2, 3, 6 and 7

The resistivity of the topsoil ranges from 185 to 313 Ωm while that of the weathered basement ranges from 20 to 119 Ωm (Figure 4a). The weathered layer (clayey soil) with resistivity value <80 Ωm in both VES 2 and VES 7 are identical whereas that of VES 6 belongs to saturated clay with resistivity of 20 Ωm. However, a clayey sand (weathered basement) was noticed at shallow depth of 2.3 m beneath VES3. The fractured of basement resistivity values range from 370 to 915 Ωm. (Figure4a). The topography of this section is uneven with thickness range of 1.9 - 5.4 m and depth range of 2.3 to 9.3 m. The fractured basement is much closer to the surface with a depth of 2.3 m occurring at offset 40 m towards the NNW axis. Fresh basement horizon was noticed beneath VES 2 and VES 6, with its resistivity value beneath VES2 > 2000 Ωm whereas its value was <500 Ωm beneath VES6 (Figure 4a). The overburden thickness has a mean of 5.7 m along this transverse. Thus, this traverse is not good for groundwater prospect.

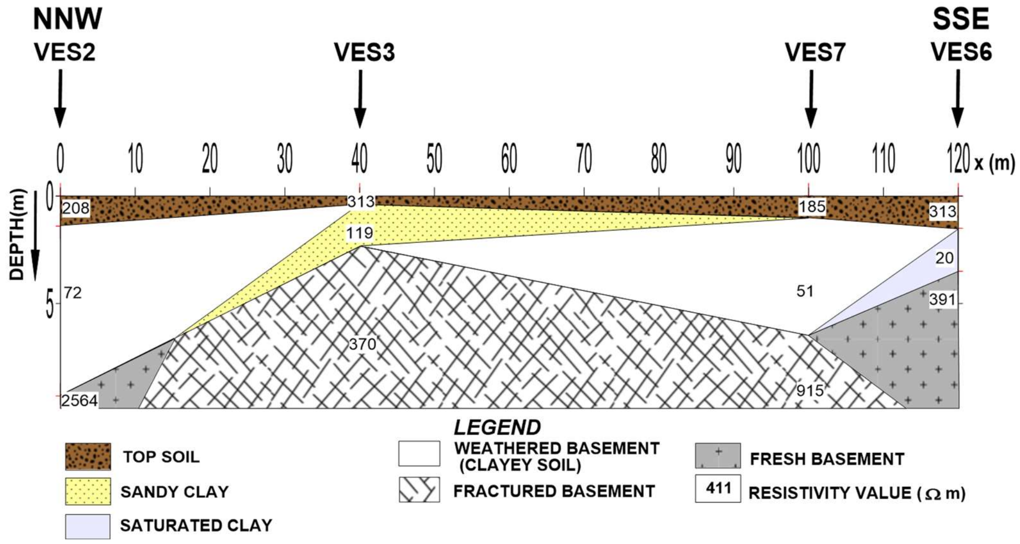


Figure 4a: Geo-electric section across VES 2, 3, 6 and 7

Geo-electric section along VES 3, 4 and 5

The geo-electric section shows that the sequence consists of shallow topsoil that has resistivity values ranging between 168-313 Ωm. The weathered basement has resistivity between 31 and 119 Ωm. The weathered layer (clayey soil) with resistivity value < 50 Ωm beneath VES 4 ad VES 5 are similar, whereas that of VES 3 belongs to clayey sand at a shallow depth 2.3 m to the surface (Figure 4b). The fractured basement had resistivity of 370 Ωm beneath VES3. The underlying bedrock (fresh basement) has resistivity that varied from 647 to 1622 Ωm. The highest resistivity of fresh basement (1622 Ωm) occurs at VES 5. The depth to the bedrock along this profile ranged from 2.3 to 7.2 m with a mean of 5.0 m (figure 4b). This profile is also not promising for groundwater potential.

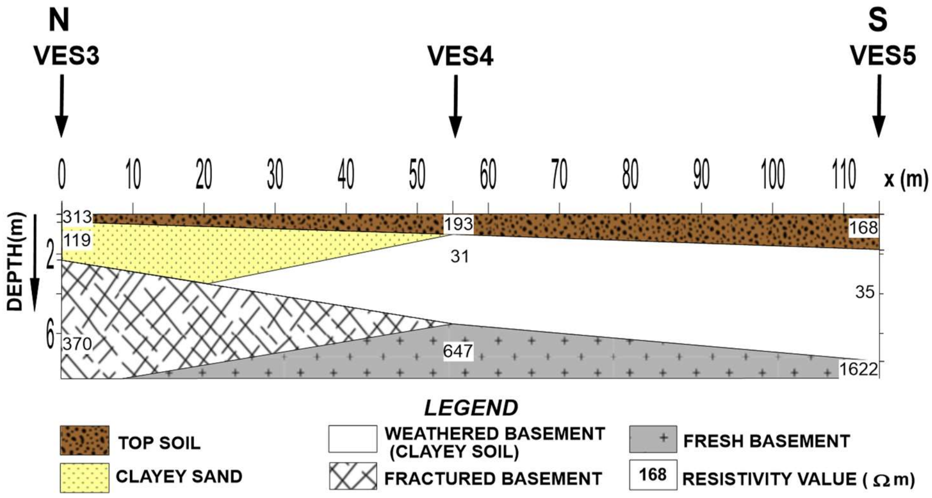


Figure 4b: Geo-electric section across VES 3, 4 and 5

Geo-electric section along VES 1, 8, 9, and 10

The topsoil has resistivity values between 306 and 927 Ωm with thickness varying from 0.6 to 2.0 m (Figure 4c). The weathered horizon has resistivity between 22 and 99 Ωm, and it comprises of clayey soil beneath VES 1, 8 and 9 whereas it manifested as saturated clay under VES 10 at shallow depth (< 6 m). The fractured basement resistivity values ranged from 390 to 954 Ωm. The depth to the fractured basement is maximum (36.5 m) under VES 9. Thus, VES 9 has high prospect for groundwater exploration. Fresh basement column was delineated beneath VES 10 along this profile with resistivity value of 5349 Ωm at the southwest axis of the section (Figure 4c).

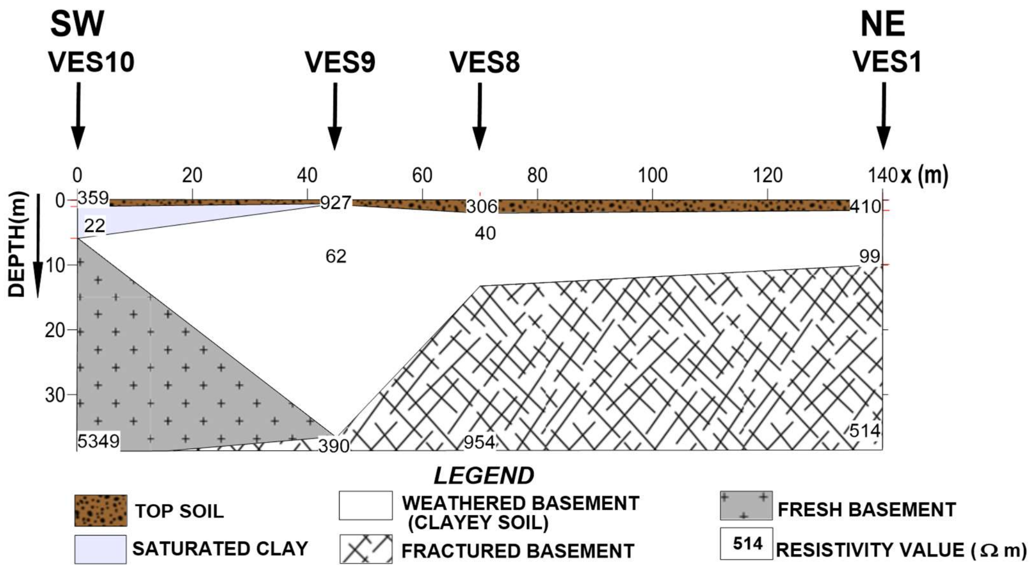


Figure 4c: Geo-electric section across VES 1, 8, 9 and 10

Geoelectric section along VES 11, 12 and 13

The thin topsoil has resistivity values between 128 and 412 Ωm whereas the weathered horizon has resistivity values that range from 12 to 82 Ωm (Figure 4d). The weathered horizon (clayey soil) of resistivity <100 Ωm beneath VES 11 and 12 are identical while that of VES 13 belongs to saturated clay with resistivity value of <20 Ωm. The depth to the fresh bedrock ranges from 3.3 to 32.2 m with a mean of 18.2 m along his profile. Furthermore, it was observed that the overburden thickness (OT) is maximum (32.2 m) beneath VES 12 along this profile. Therefore, VES 12 is another point considered worthy for groundwater exploration. Fresh basement with resistivity <500 Ωm closer to the surface was noticed beneath VES 13 (Figure 4d).

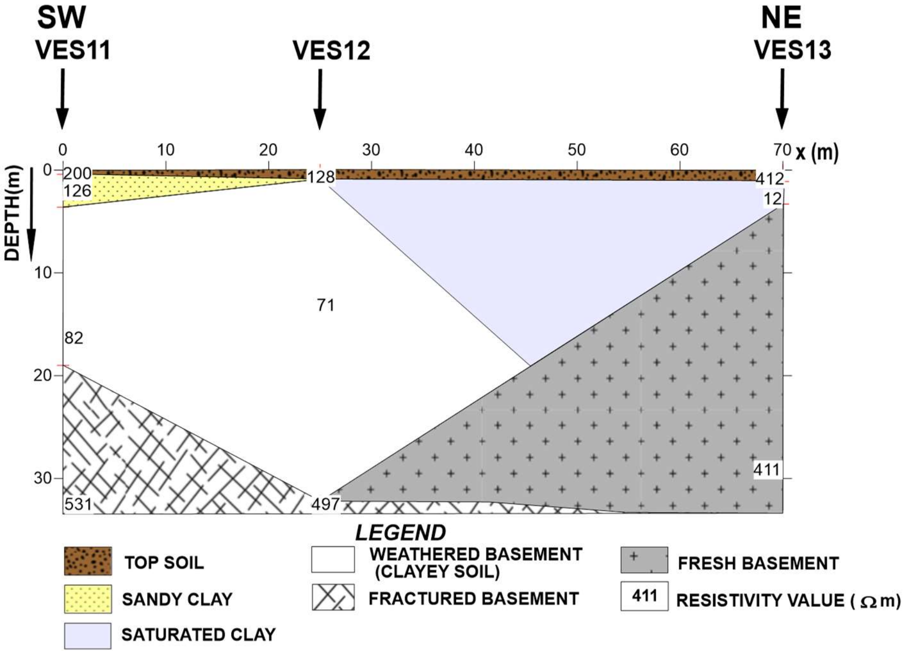


Figure 4d: Geo-electric section across VES 11, 12 and 13

Appraisal of Groundwater Potential Zones

Three key criteria were taken into consideration for the identification of groundwater potential zones in the study location namely, the overburden thickness, presence/absence of fractured weathered horizons and reflection coefficient (RC) values of the sounding points (Bayewu et al., 2017; Arunbose et al., 2021). According to Bayewu et al. (2018) and Arunbose et al. (2021), RC< 0.8 signify extremely weathered or fractured basement that encourage more for high groundwater potential. Therefore, combination of RC and OT can also be used satisfactory to delineate groundwater potential zones (Patra et al., 2016; Arunbose et al., 2021; Agyemang, 2022). Using the criteria of RC and OT as adopted by Srinivas et al. (2014); Bayewu et al. (2018); Arunbose et al. (2021) & Agyemang (2022) to identity GPZ, where VES stations with OT > 13 m and RC< 0.8 were categorized as promising high yield aquiferous zones; stations with OT> 13 m and RC $\geq$ 0.8 were characterized. as medium yield aquiferous zones: sounding points with OT < 13 m and or with RC > 0·8 were categorized as low yield groundwater zones while stations/ points with OT <13 m and RC< 0.8 were characterized as very low yield aquiferous zones. According to the aforementioned criteria, 15.38% of the VES points (VES 1 and VES 3) fall under very low groundwater potential, 53.86% of the total VES points (VES stations 2, 4, 5, 6, 7, 10 and 13) indicated low groundwater yield; 15.38% (VES 9 and VES 11) showed high groundwater potential and the remaining 15.38% (VES 8 and VES 12) depict medium groundwater potential zones. Table 3 summarizes the aquifer potential and vulnerability rating across the VES points in the study area.

Aquifer Protective Capability of the VES points

Table 3 presented the summary of the protective capability rating of each sounding point based on total longitudinal conductance (S) value. From Table 3, none of the VES points had good, very good to excellent protective capability status. The 13 VES points were categorized into moderate, weak, and poor using Table 1 categorization. Specifically, the total longitudinal conductance (S) values of the VES stations range from 0.017 to 0:5801 Ω^{-1}. The VES stations 1 and 3. (i.e. 15.38% of total VES points) are of poor protective capability; 46.15% (VES stations 2, 4, 5, 6, 7 and 13) exhibit weak protective capacity whereas 38.5% (VES stations 8,9,10.11 and 12), are characterized as having moderate protective capability (Okogbue and Omonona 2013: Arunbose et al., 2021).

Generally, it was observed that majority of the VES stations (61.5%) had poor/weak protective capacity while the remaining 38.5% of the VES points are characterized by moderate protective capability. This shows that 61.5% of the VES station are liable to contamination of aquifer unit. The least value of S obtained in VES 3 (Table 3) might be due to its thin and shallow overburden while the relatively high S values in VES 8 -12 may be due to the existence of relatively clayey overburden and thick sequence of the subsurface horizons (Arunbose et al., 2021).

Table 3: Groundwater potential and aquifer vulnerability rating across the 13 VES points

Station	RC	OT (m)	Presence of fractured/ weathered basement	Groundwater yield	S (Ω^{-1})	Protective capacity rating
VES 1	0.68	9.9	Yes	Very Low	0.087	Poor
VES 2	0.95	9.3	No	Low	0.117	Weak
VES 3	0.51	2.3	Yes	Very Low	0.017	Poor
VES 4	0.91	5.5	No	Low	0.152	Weak
VES 5	0.96	7.2	No	Low	0.168	Weak
VES 6	0.90	3.5	No	Low	0.105	Weak
VES 7	0.89	6.5	Yes	Low	0.111	Weak
VES 8	0.92	13.2	No	Medium	0.289	Moderate
VES 9	0.72	36.5	Yes	High	0.580	Moderate
VES 10	0.99	5.9	No	Low	0.228	Moderate
VES 11	0.73	19.0	Yes	High	0.215	Moderate
VES 12	0.84	32.2	Yes	Medium	0.445	Moderate
VES 13	0.94	3.3	No	Low	0.172	Weak

Thematic Maps of the Study Area

The spatial variation of RCs of sounding points in the study area are represented in Figure 5a. The values of RC range from 0.50 to 0.99 with an average of 0.84. The VES points with RC < 0.8 as shown in Figure 5a are VES 1, VES 2, VES 9 and VES 11. Figure 5b shows the overburden thickness map with thickness values raging between 2.0 m (at VES 3) and 37.0 m (at VES 9) with an average of 11.9 m. The thickness range of 13 to 36.5 m was evident at the nearly central/towards the west (VES 8 and 9) and part of the NW (VES 11 and 12) of the study area. This is an indication that high/medium groundwater potential zone is probable along the western and northwest part of the area using Figures 5a and 5b. Relatively thin overburden thickness (<13 m) stations were noticed at part of the NNW (VES 1), NW (VES 13), eastern (VES 2 and 3), south-eastern (VES 4, 5, 6 and 7) and part of the west side of the study area (VES 10). The thin overburden thickness in conjunction with the RC values (Figure 5a) could results to low/very low groundwater potential (Arunbose et al., 2021; Agyemang, 2022).

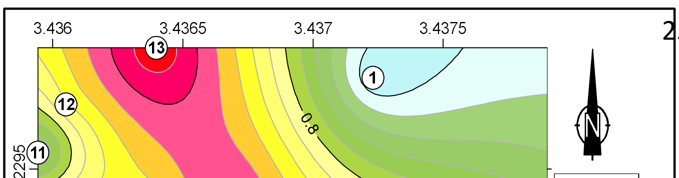
From the weathered basement resistivity map (Figure 5c), the resistivity values of the weathered horizon varied from 12 (at VES 13) to 120 Ωm (at VES 3). Relatively higher resistivity values of weathered layer > 60 Ωm were found in the NNW (VES 1), eastern part (VES 2 and 3) and some parts of the NW (VES 11 and 12). However, the nearly central VES points (VES 8 and 9); stations at the southern part of the study area (VES 4, 5, 6, and 7), VES 10 (at the west) and VES 13 (part of the northwest) are characterized by low resistivity (<60 Ωm) weathered horizon.

The weathered layer thickness map (Figure 5d) shows that the weathered basement thickness varied from 2 to 36 m with an average 9.6 m. Figure 5d reveals that thick aquifer unit >20 m was observed at VES 9 and VES 12 whereas the remaining part of the study area is dominated by < 20 m thickness. Figure 5e is the basement resistivity map with resistivity values ranging from 210 to 5400 Ωm. Groundwater yield is intensified by the presence of fracture within the basement (Olayinka et al., 1997; Awosika et al., 2020). According to Olayinka et al. (1997) and Oladunjoye et al. (2019) grouping of groundwater potential as a function of the basement rock, good aquifer potential is characterized by an area with <750 Ωm (evidence of intensely fractured basement). Therefore, 6.15% of VES points had basement resistivity <750 Ωm. Specifically, VES 7 and VES 8 had basement resistivity in the range of 750-1500 Ωm, thus belonging to medium aquifer potential; basement resistivity of VES 2 and VES 5 lie in the range 1501 – 3000 Ωm, thus belong to low aquifer potential (Oyedele and Olayinka, 2012; Oladunjoye et al., 2019). However, VES 10 had basement resistivity value > 3000 Ωm and thus belong to negligible aquifer potential (Oladunjoye et al., 2019). Conclusively, VES 9 and 11 with low basement resistivity (<750 Ωm), thick overburden (>13 m) and RC < 0.8 belong to high groundwater yield zones based on Figures 5a, 5b and 5e and concur with remark on Table 3.

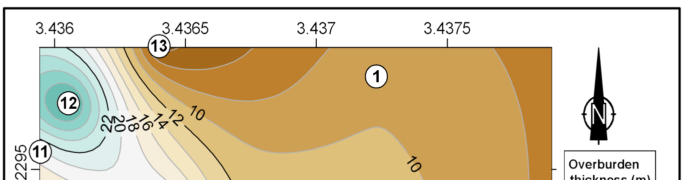
Figure 5f shows the spatial variation in the total longitudinal conductance (S) across the VES points which varied from 0.02 (at VES 3) to 0.58 (at VES 9) Ω^{-1} with an average of 0.21 Ω^{-1}. The mean value of S obtained in this study is similar to the average value of S (0.23 Ω^{-1}) reported by Akanbi (2018) in his evaluation of groundwater recharge potential across the migmatite terrain of Ibarapa region, southwest Nigeria. The VES points 1 and 3 with S < 0.1, an evidence of poor protective capacity stations can be observed in part of NNW (VES 1) and eastern (VES 3) regions of the study area. However, 46.2% of mapped area had S values in the range of 0.10 to 0.19, indicating weak protective capacity. These weak points can be seen on parts of southern (VES 6), eastern (VES 2), southeast (VES 4 and 7), SSW (VES 5) and northwest (VES 13) of the study area (Figure 5f). Furthermore, VES points 8 - 12 located towards the north west and western parts of the study area had S values in the range of 0.20 - 0.69 Ω^{-1}, an indication of moderate protective capacity (Arunbose et al., 2021; Agyemang, 2022). This is akin to remark on APC rating of these VES points in Table 3.

Figure 5g shows the variation of total transverse resistance (T) across the sounding points. The T values ranged from 300 (at VES 4) to 2800 Ωm² (at VES 9) with a mean of 1024 Ωm². Braga et al. (2006) classified aquifer transmissivity in terms of T as follows: T<400 Ωm² are categorized as having poor to negligible transmissivity; T values between 400 -1000 Ωm²are regarded as weak aquifer transmissivity; T values in the range of 1000 to 2000 Ωm² as moderate transmissivity, whereas T values > 2000 Ωm² characterized good aquifer transmissivity. Using this categorization in Figure 5g, the southern and southwestern parts of the surveyed area (i.e. VES stations 3, 4, 5, 6 and 7) as well as part of the Northwest (VES 13) and western (VES 10) regions of the study area had poor to weak transmissivity according to their T values. Furthermore, VES 1 (at the NNW) and VES 8 (towards the west) showed moderate transmissivity whereas VES 9 and VES 12 (towards the west) had good transmissivity as their T values were greater than 2000 Ωm² (Braga et al., 2006; Shailaja et al., 2016; Oladunjoye et al., 2019). Figure 5h shows the coefficient of anisotropy (λ) map with the λ values ranging from 1·00 to 2.75. The average of λ for the VES points is 1.37. The mean value of λ obtained in this study suggests that the rock unit underlying the area is metamorphic rock (migmatite) (Rao et al., 2003). Further observation of figure 5h reveals that VES 6 (at the south), VES 10 (towards the west) and VES 13 (towards the northwest) had λ values > 1.50 while the rest of the mapped area had λ values < 1.50. Stations with λ <1.50 are considered as areas with high permeability and porosity, consequently good potential zones for groundwater development (Rao et al., 2003; Shailaja et al., 2016; Agbemuko et al., 2021). Figure 5i shows the variation in topsoil resistivity across the VES points, with top soil resistivity values ranging from 128 to 927 Ωm with an average of 313 Ωm. From Figure 5i, only VES 9 has topsoil resistivity greater than 500 Ωm whereas the remaining VES points had topsoil resistivity <500 Ωm. Specifically, lowest topsoil resistivity value (128 Ωm) was recorded at VES 12. Figure 5j is the topsoil thickness map and revealed that the sounding points 1, 5, 6, 8 and 10 had topsoil thickness > 1.5 m whereas the remaining VES points had topsoil thickness <1.5 m.

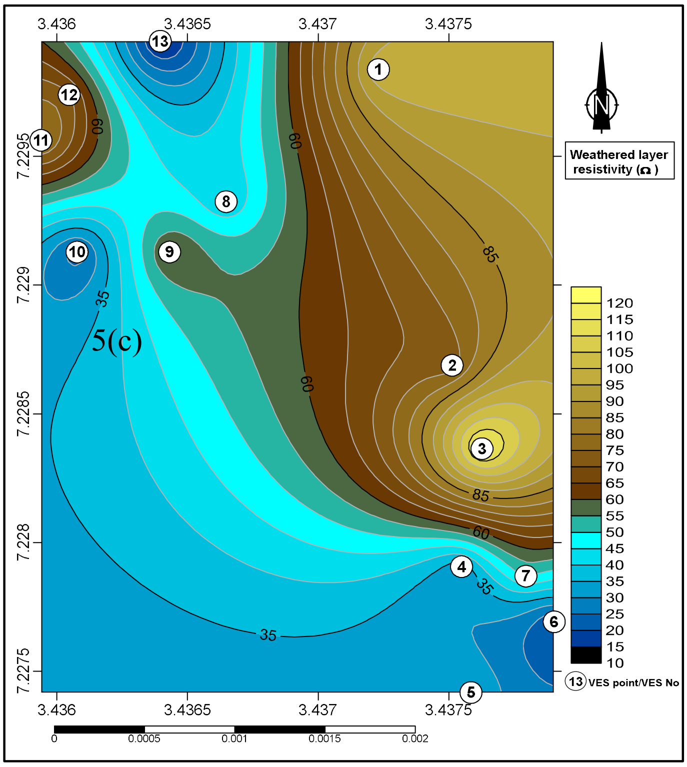
(a)



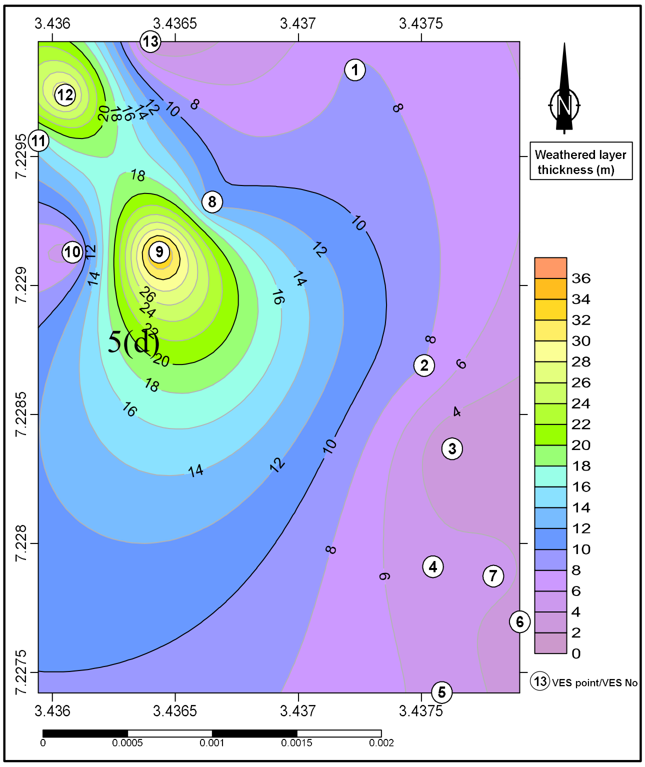
(b)



(c)



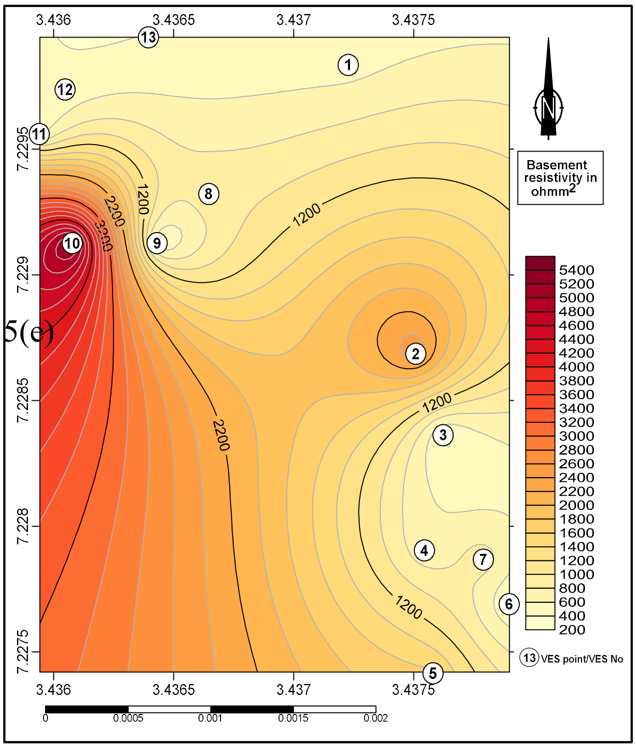
(d)



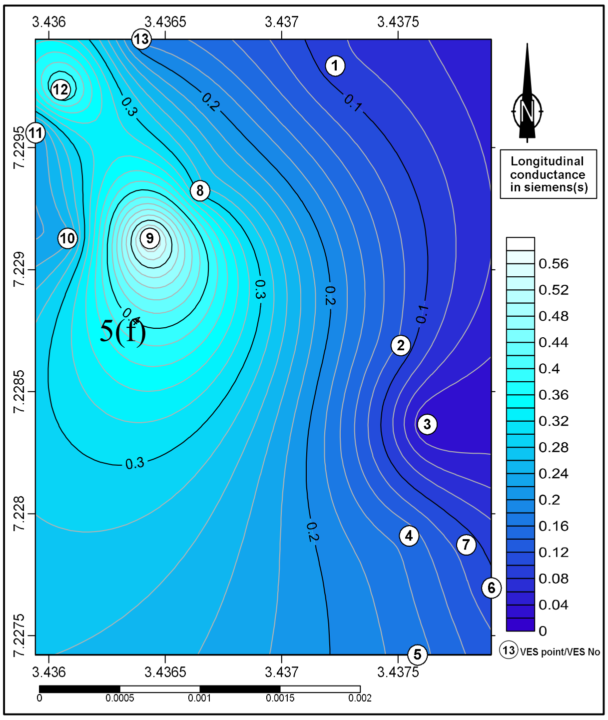
Figures 5a-d: Thematic maps of the study area

(e)

(f)

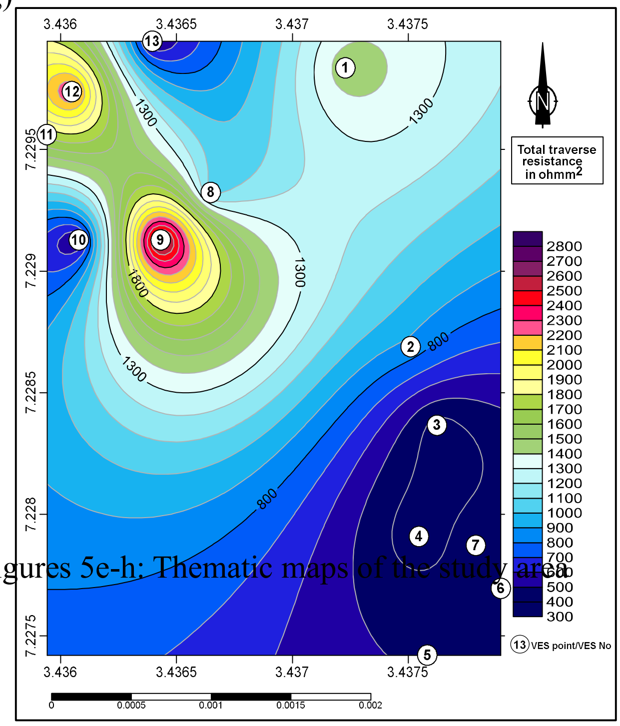


5(e)

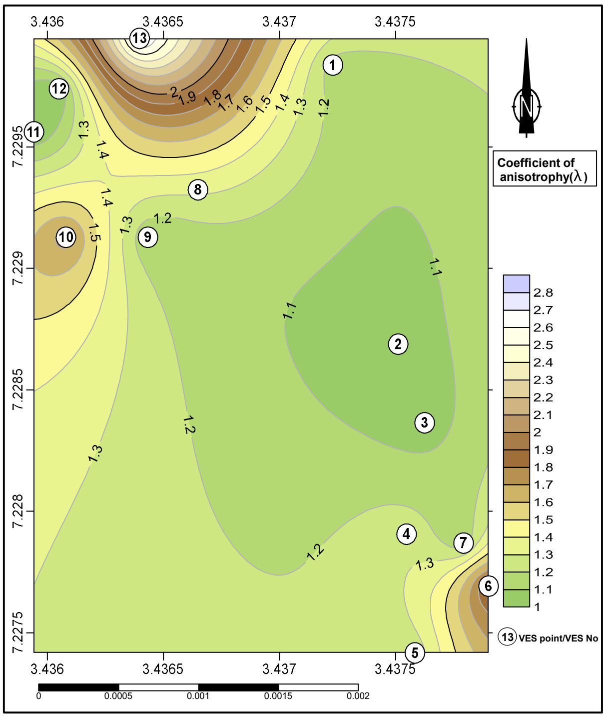


5(f)

(g)

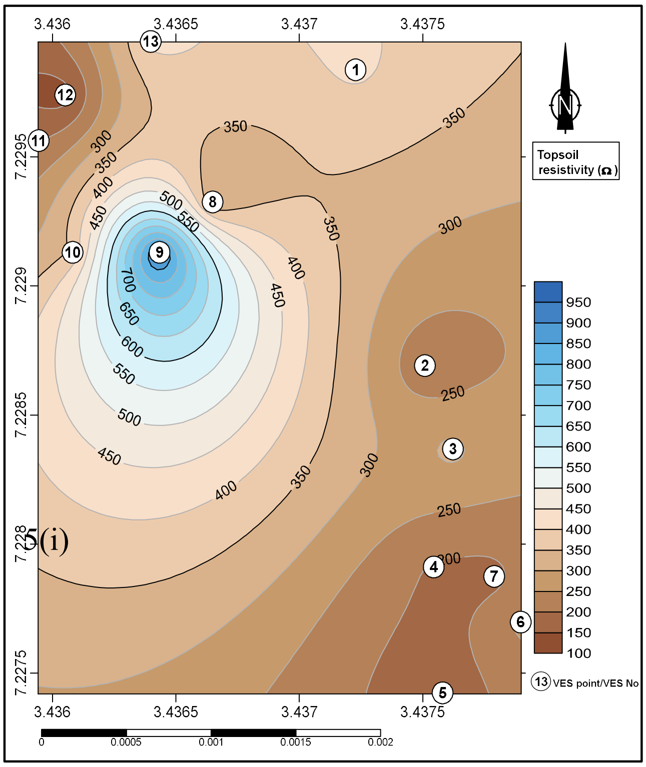


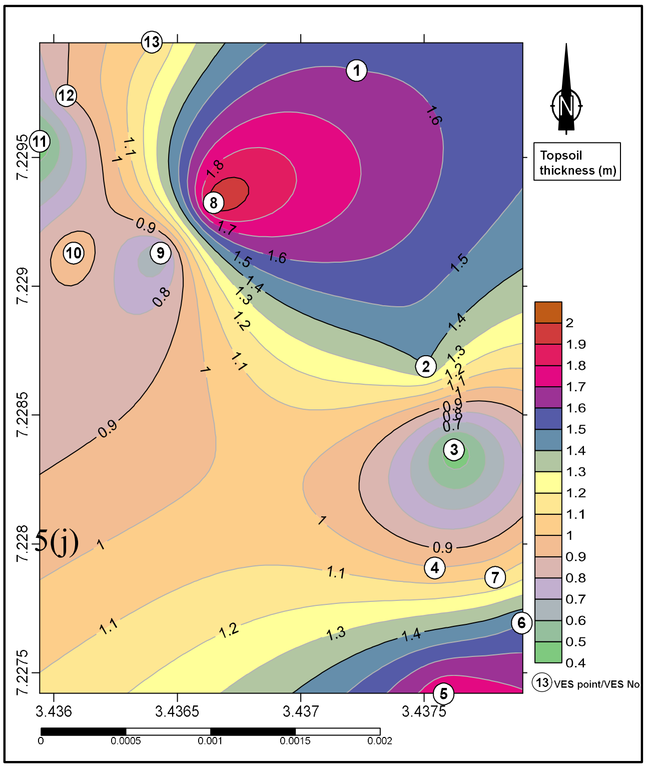
(h)



Figures 5e-h: Thematic maps of the study area

(i) (j)





Figures 5a-j: Thematic maps of the study area

CONCLUSION

Geoelectrical survey involving VES was carried out within a portion of university campus underlain by Basement Complex in order to delineate groundwater prospective sections and evaluate aquifer protective capability across the surveyed area. The results of the processed VES data specified the dominancy of H-curve type relative to QH-curve type. The interpretation of the VES results further discloses 3 to 4 geologic horizons viz: topsoil weathered basement (clayey/ saturated clay/sandy clay), fractured and fresh basement. The weathered and fractured basement constitute the aquifer units According to RC and OT values, the study area was categorized into definite groundwater potential regions namely very low, low, medium and high. Based on total longitudinal conductance (S) values, majority of the sounding stations had weak-to-poor aquifer protecting capability and thus more susceptible to surficial pollution. The remaining are characterized as having moderate protective capacity. The identified moderate-to-high groundwater potentiality zones (VES stations 8, 9, 11 and 12) with their associated moderate protective ability were along the northwest and western side of the study area and thus recommended for drilling. Conclusively, the outcomes of this study revealed that majority of the investigated VES points (69.2%) had low to very low groundwater potential with

REFERENCES

Abu Heen, Z.H. (2017): Use of Electrical Resistivity Methods (2D and VES) in proposed landfill site investigation- A case study of Al Fukhari landfill, southeastern Gaza strip, Palestine. Journal of Environment and Earth science, 7(3):119-127.

Adabanija M.A., Ajibade R.A. (2020): Investigating groundwater corrosion and overburden protective capacity in a low latitude crystalline basement complex of Southwestern Nigeria. NRIAG Journal of Astronomy and Geophysics, 9(1):245-259. https://doi.org/10.1080/20909977.2020.1723867.

Adagunodo, T.A, Akinloye, M.K., Sunman, L.A., Aizebeokhai, A.P., Oyeyemi, K.D., Abodunrin, F.O. (2018): Groundwater exploration in Aaba residential area of Akure, Nigeria. Frontiers in Earth Science, 6:66. DOI:10.3389/feart.2018.00066.

Adeoti, L., Alile, O.M., Uchegbulam, O., Adegbola, R.B. (2012): Seismic refraction prospecting for groundwater; A case study of Golden Heritage Estate, Ogun State. Research Journal of Physics 6 (1):1-18. DOI: 10.3923/rjp.2012.1.18.

Agbemuko, O.S., Abam, T.K.S., Tamunobereton-Ari, I. (2021): A further application of coefficient of anisotropy and reflection coefficient as indices in delineating groundwater potential in Basement Complex of Ado Ekiti, southwestern Nigeria. The International Journal of Science and technoledge, 9(11):1-10. DOI:10.24940/theijst/2021/v9/i11/ST2111-004.

Agyemang, V.O. (2021): Hydrogeophysical characterization of aquifers in Upper Denkyira East and West Districts, Ghana. Applied Water Science, 11:132. https//doi.org/10.1007/s13201-021-01462-w.

Agyemang, V.O. (2022): Geophysical investigation of groundwater potential and aquifer protective capability in selected communities within Cape Coast municipality, Ghana. Applied Water Science, 12:23. https://doi.org/10.1007/s13201-021-01558-3.

Aizebeokhai, A.P., Oyeyemi A.P., Oyeyemi, K.D., Joel, E.S. (2016): Groundwater potential assessment in a sedimentary terrain, Southwestern Nigeria. Arab J Geosciences, 9:496. DOI: 10.1007/s12517-016—2524-5.

Aizebeokhai, A.P., Oyeyemi, K.D. (2018): Geoelectrical characterization of basement aquifers; the case of Iberekodo southwestern Nigeria. Hydrogeol J, 26(2): 651-664.

Akanbi, O.A. (2018): Hydrogeological characterization and prospect of basement aquifers of Ibarapa region, southwestern Nigeria. Appl Water Sci, 8:89. https://doi.org/10.1007/s13201-018-0731-9.

Akanni C.O. (1992): Relief, drainage, soil and climate of Ogun State in maps (pp 6-20). In: Onakomaiya, S.O., Oyesiku, O.O. Jegede, F.J. (eds) Ogun State in maps. Rex Charles Publication, Ibadan.

Alabi; A.A., Ganiyu, S.A., Idowu, O.A., Ogabi, A.F., Popoola, O.I. (2021): Investigation of groundwater potential using integrated geophysical methods in Moloko-Asipa, Ogun State Nigeria. Applied Water Science, 11:70. https://doi.org/10.1007/s13201-021-01388-3.

Anosike, S., Ibuot, J.C., Obiora D.N., Ugbor, D.O. (2019): Geophysical and Physicochemical investigation of groundwater repositories in Njaba LGA of Imo State, Eastern Nigeria. Int J Env Sci and Tech.

https://doi.org/10.1007/s13762-019-02366-8.

Arunbose, S., Srinivas, Y., Rajkumar, S. (2021): Efficacy of hydrological investigation in Karumeniyar river basin, southern Tamil Naidu, India using vertical electrical sounding techniques: A case study. MethodsX, 8:101215. https://doi.org/10.1016/j.mex.2021.101215.

Awosika, D.D., Ariyibi, E.A., Adebayo, A.S., Dasha, O.A., Shode, O.H., Adenika, C.I., Olagunju, E. (2020): Evaluation of groundwater potential zones using integrated geophysical approach in Obun-Ewi, Ondo East local government, Southwestern Nigeria. Sustainable water Resources Management. 6:63. https://doi.org/10.1007/s40899-020-00418-3.

Bayewu, O.O., Oloruntola, M.O., Mosuro, G.O., Laniyan, T.A., Ariyo, S.O., Fatoba, J.O. (2017): Geophysical evaluation of groundwater potential in part of southwestern Basement Complex terrain of Nigeria. Appl Water Sci, DOI: 10.1007/s13201-017-0623-4.

Bayewu, O.O., Oloruntola, M.O., Mosuro, G.O., Laniyan, T.A., Ariyo, S.O., Fatoba, J.O. (2018): Assessment of groundwater prospect and aquifer protective capacity using resistivity method in Olabisi Onabanjo University Campus, Ago-Iwoye, Southwestern Nigeria. NRIAG J Astron Geophys, 7(2):347-360. DOI: 10.1016/j.nriag.2018.05.002.

Bello, H.I., Alhassan, U.D., Salako K.A., Rafiu, A.A., Adetona, A.A., Sheu, J. (2019): Geoelectrical investigation of groundwater potential at Nigeria Union of Teachers Housing estate Paggo, Minna, Nigeria. Appl Water Science, 9:52. https://doi.org/10.1007/s13201-019-0922-z.

Bhattacharya, P.K., Patra, H.P. (1968): Direct current geoelectric sounding: Principles and Interpretation. In: Methods in Geochemistry and Geophysics: Series 9. Elsevier Publishing Company. p135.

Braga D.C., Filho, W.M., Dourado, J.C. (2006): Resistivity [DC] methods applied to aquifer protection studies. Brazilian Journal of Geophysics, 24(4):547-581.

Choudhury, J., Kumar, K.L., Nagaiah, E., Sonkamble, S., Ahmed, S., Kumar, V. (2017): Vertical electrical sounding to delineate the potential aquifer zones for drinking water in Niamey city, Niger, Africa. J Earth Syst Sci, 126:91. DOI: 10.1007/s12040-017-0860-9.

Earon, R., Dehkordi, S.E., Olofsson, B. (2015): Groundwater resources potential in hard rock terain: a multivariate approach. Groundwater, 53(5):748-758. https://doi.org/10.1111/gwat 12265.

Emenike C.P., Tenebe, I.T., Omole, D.O., Igene, B.U., Oniemayin, B.I., Omeje M. (2017): Accessing safe drinking water in sub–Saharan Africa: Issues and challenges in south west Nigeria. Sustain Cities Soc, 30: 263-272.

Fajana, A.O. (2020a): Groundwater aquifer potential using electrical resistivity method and porosity calculation: a case study. NRIAG Journal of Astronomy and Geophysics, 9:168-175. DOI:10.1080/20909977.2020.1728955.

Fajana, A.O. (2020b): Integrated geophysical investigation of aquifer and its groundwater potential in Phases 1 and 2, Federal University Oye Ekiti, South western basement complex of Nigeria. Model Earth Syst Environ, 6(3):1707-1725. https://doi.org/10.1007/s40808-020-00785-y.

Gaikwad, S., Pawar, N.J., Bedse, P., Wagh, V., Kadam, A. (2021): Delineation of groundwater potential zones using vertical electrical sounding (VES) in a complex bedrock geological setting of the west coast of India. Modelling Earth System and Environment. https://doi.org/10.1007/s40808-021-01223-3.

Ganiyu, S.A., Olurin, O.T., Oladunjoye, M.A., Badmus, B.S. (2020): Investigation of soil mixture content over a cultivated farmland in Abeokuta Nigeria using electrical resistivity methods and soil analysis. Journal of King Saud University-Science, 32:811-821. https://doi.org/10.1016/j.jksus.2019.02.016.

Ganiyu, S.A, Mabunmi, A.A., Olurin. O.T., Adeyemi, A.A., Jegede, O.A., Okeh, A (2021a): Assessment of microbial and heavy metal contamination in shallow hand dug wells bordering Ona River, southwestern Nigeria. Environ Monit Asses, 193: 126.https://doi.org/10.1007/s10661-021-08910-9.

Ganiyu, S.A., Oladunjoye, M.A., Olabadola, M.O., Aizebeokhai A.P., Badmus, B.S. (2021b): Investigation of incessant road failure in parts of Abeokuta, southwestern Nigeria using integrated geoelectric method and soil analysis. Environ Earth Sci, 80:133. https://doi.org/10.1007/S12665-021-09446-4.

Ganiyu, S.A., Oyadeyi A.T., Rabiu, J.A., Jegede, O.A. (2022): Hydrogeochemical categorization and quality assessment of shallow groundwater sources in typical urban slum and peri-urban areas of Ibadan, southwestern Nigeria. Environ Earth Sci 81:111. https://doi.org/10.1007/s12665-022-10237-8.

Handayani, L., Wardhana, D.D., Hartanto, P., Delinom, R., Sudaryanto Bakti, H., Lubis, R.F. (2018): Gravity survey of groundwater characterization at Labuan Basin. IOP Conf Series Earth and Environmental Science, 118:012015. DOI:10.1088/1755-1315/118/1/012015.

Henrietta, J.P. (1976): Direct application of Dar Zarrouk parameters in groundwater survey Geophys Prospect, 24:344-353.

Inim, I.J., Udosen, N.I., Tijani, M.N., Affiah, U.E., George, N.J. (2020): Time-lapse electrical resistivity investigation of seawater intrusion in coastal aquifer of Ibeno, southeastern Nigeria. Applied Water Science, 10; 232. https://doi.org/10.1007/s13201-020-01316-x.

Jones, M.J. (1985): The weathered zone aquifers of the basement complex areas of Africa. Q.J. Eng Geol, 18:35-48. https://doi.org/10.1144/GSL.QJEG.1985.018.01.06.

Kayode, J.S., Adelusi, A.O., Nawawi, M.N.M., Bawallah, M., Olowolafe, T.S. (2016): Geo-electrical investigation of near surface conductive structures suitable for groundwater accumulation in a resistive crystalline basement environment: a case study of Isuada, southwestern Nigeria. J Afric Earth Sci, 19:289-302. DOI: 10.1016/j.jafrsci.2016.04.009.

Khan, S., Nisar, U., Ehsan, S.A., Farid, A., Shahzad, S.M., Qazi, H.H., Khan, M.J., Ahmed, T. (2021): Aquifer vulnerability and groundwater quality around Brahma Bahtar Lesser Himalayas Pakistan. Environ Earth Sci, 80:454. https://doi.org/10.1007/s12665-021-09739-8.

Loke, M.H. (1999): Time-lapse resistivity imaging inversion. In: Proceedings of the 5th meeting of the Environmental and Engineering. Geophysical Society European Section. Eml.90pp.

Mbaka, P.K., Mwangi, J.K., Kiptum, C.K. (2017): Assessment of water quality in selected shallow wells of Keiyo highlands, Kenya. Africa J Sci Tech Innov Devt. https://doi.org/10.1080/2042/1338.2017.1327476.

NGSA (2016) Geological and Mineral Resources Map of Ogun State, Nigeria. Nigerian Geological Survey Agency, Abuja, Nigeria

Niculescu, B.M., Andrei, G. (2021): Application of electrical resistivity tomography for imaging seawater intrusion in a coastal aquifer. Acta Geophysica. https://doi.org/10.1007/s11600-020-00529-7.

Obiora D.N., Adeolu E.A., Ibuot, J.C. (2015a): Evaluation of aquifer protective capacity of overburden unit and soil corrosivity in Makurdi, Benue State, Nigeria using electrical resistivity method. J Earth Syst Sci, 124(1): 125-135.

Obiora, D.N., Ibuot J.C., George N.J. (2015b): Evaluation of aquifer potential, geoelectric and hydraulic parameters in Ezza North, southeastern Nigeria using geoelectric sounding. Int J Environ Sci Tech. DOI: 10.1007/s13762-015-0886-y.

Obiora D.N., Ibuot J.C., Alhassan, U.D., Okeke F.N. (2017): Study of aquifer characteristics in Northern Paiko, Niger state, Nigeria using geoelectric resistivity method. Int J Environ Sci Tech. DOI: 10.1007/s13762-015-1612-8.

Okogbue C.O., Omonona, O.V. (2013): Groundwater potential of the Egbe-Mopa basement area, Central Nigeria. Hydrological Sciences Journal, 58:4:826-840. DOI:10.1080/02626667.2013.775445.

Oladapo, M.I., Akintorinwa, O.J. (2007): Hydrogeophysical study of Ogbese southwestern Nigeria. Glob J Pure Appl Sci, 13(1):55-61.

Oladunjoye, M.A., Korede I.A., Adefehinti, A. (2019): Geoelectrical exploration for groundwater in crystalline basement rocks of Gbongudu community, Ibadan, southwestern Nigeria. Global Journal of Geological Sciences, 17:25-43.

Olatinsu, O.B., Salawudeen S.Y. (2021): Integrated geophysical investigation of groundwater potential and bedrock structure in Precambrian basement rock of Ife southwestern Nigeria. Groundwater for sustainable Development, 14:10016. https://doi.org/10.1016/j.gsd.2021.100616.

Olayinka A.I. Oyedele E.A.A. (2019): On the application of coefficient of anisotropy as an index of groundwater potential in a typical basement complex of Ado Ekiti, southwest Nigeria. Phys Sci Int J, 22 (1) 1-10. https://doi.org/10.9734/psij/2019/v22il30119.

Olayinka A.I., Akpan E.J., Magbagbeola, O.A. (1997): Geoelectrical sounding for estimating aquifer potential in the crystalline basement area around Shaki, Southwestern Nigeria. Water Resources Journal of NAH, 8(1&2):71-78.

Olorunfemi, M.O., Oni, A.G. (2019): Integrated geophysical methods and techniques for siting productive borehole in basement complex terrain of southwestern Nigeria. Ife Journal of science, 21(1):013-026. https://dx.doi.org/10.4314/ijsv21il.2.

Oyedele E. A., Olayinka, A.I. (2012): Statistical evaluation of groundwater potential of Ado-Ekiti, southwestern Nigeria. Transnational Journal of Science& Technology, 2(6):110-127.

Oyeyemi, K.D., Aizebeokhai, A.P., Metwaly, M., Oladunjoye, M.A., Bayo-Solarin, B.A., Sanuade, O.A., Thompson, C.E., Ajayi, F.S., Ekhaguere, O.A. (2020): Evaluating the groundwater potential of coastal aquifer using geoelectrical resistivity survey and porosity estimation: A case in Ota, SW Nigeria. Groundwater for Sustainable Development. https://doi.org/10.1016/j.gsd.2020.100488.

Oyeyemi, K.D., Aizebeokhai, A.P., Sanuade, O.A., Ndambuki, J.M., Olofinnade, O.M., Adagunodo, T.A., Olaojo, A.A. (2018): The use of geological based geophysical surveys for groundwater distribution in crystalline basement terrain, SW Nigeria. IOP Conf. Sci. Earth Environ Sci. 173(1):012029. DOI:10.1088/1755-1315/173/1/012029.

Patra, H.P., Adhikari, S.K., Kumar, S. (2016): Groundwater Prospecting and Management Springer Hydrogeology. DOI: 10.10071978-981-10-1148-1.

Perrone, D., Jasechko, S. (2017): Dry groundwater wells in the western United States. Environ Res Lett, 12:104002. https://doi.org/10.1088/1748.9326/aa8acO.

Rao, P.J., Rao, B.S., Rao, M.J., Harikrishna, P. (2003): Geoelectrical data analysis to demarcate groundwater pockets and recharge zones in Champavathi River Basin, Vizianagaram District, Andhra Pradesh. J Indian Geophys Union, 7(2):105-113.

Shailaja, G., Lavminarayana, M., Patil, J.D., Erram V.C., Suryawanshi, R.A., Gupta, G. (2016) Efficacy of anisotropic properties in groundwater exploration from geoelectric sounding over trap covered terrain. J Indian Geophys Union, 20(5):453-461.

Singh, A.L., Singh, V.K. (2018): Assessment of groundwater quality of Ballia district, Uttar Pradesh, India with reference to arsenic contamination using multivariate statistical analysis. Appl Water Science, 8:95. https://doi.org/10.1007/s1320/018-0737-3.

Soomro A., Qureshi A.L., Jamali, M.A., Ashraf, A. (2019): Groundwater investigation through vertical electrical sounding at will area from. Nooriabad onward Karachi Acta Geophysica. https://doi.org/10.1007/s11600-019-00247-9

Soupios, P., Kouli, M., Vallianatos, F., Vafidis, A., Stavroulakis, G. (2007); Estimation of aquifer parameters from surficial geophysical methods. A case study of Keritis Basin in Chania (Crete- Greece). Journal of Hydrology, 338:122-131. DOI: 10.1016/j.jhydrol.2007.02.028.

Sunkari, E.D., Kore, B.M., Abioui, M. (2021): Hydrogeophysical appraisal of groundwater potential in the fractured basement aquifers of the Federal Capital Territory, Abuja, Nigeria. Results in Geophysical Sciences, 5:100012. https://doi.org/10.1016/j.ringps.2021.100012.

Vasantrao, B.M., Bhaskarrao, P.J., Makund, B.A., Baburao, G.R., Narayan, P.S. (2017): Comparatives study of Wenner and Schlumberger electrical resistivity method for groundwater investigation: a case study from Dhule District (MS), India. Appl Water Sci, 7(8): 4321-4340. https://doi.org/10.1007/s13201-017-0576-7.

Wu, W.Y., Lo, M.H., Wada, Y., Famiglietti, S., Reager, J.T., Yeh, P.J.F., Ducharne, A., Yang, Z.-L. (2020): Divergent effects of climate change on future groundwater availability in key mid-latitude aquifer. Nat Commun, 11:3710. https://doi.org/10.1038/s41467-020-17581-y.

Srinivas, Y., Oliver, D.H., Stanley Raj, A., Chandrasekar, N. (2014): Delineation of groundwater potential zones along the coastal parts of Kanyakumari district, Tamilnadu. J Indian Geophys Union, 18(3):356-362.

Zayed, M.A. (2021): Geoelectrical exploration of groundwater by using vertical electrical sounding techniques at Wadi Morra, South Sinai. Egypt. Austin Journal of Earth science, 4(1):1025.