International Research Journal of Pure and Applied Physics, 11 (1),98-131, 2024
ISSN 2055-009X(Print)
ISSN 2055-0103(Online)
Website: https://www.eajournals.org/
Publication of the European Centre for Research Training and Development -UK

Preliminary Terrain Electromagnetic Method of Geophysical Investigation as Aids to Groundwater Development in Oru-Ijebu South-West Nigeria

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doi: : https://doi.org/10.37745/irjpap.13vol11n198131 Published October 29, 2024

Citation: Ishola, S. A. (2024) Preliminary Terrain Electromagnetic Method of Geophysical Investigation as Aids to Groundwater Development in Oru-Ijebu South-West Nigeria, *International Research Journal of Pure and Applied Physics*, 11 (1),98-131

ABSTRACT: *An electromagnetic method of geophysical investigation for preliminary stage of groundwater development was carried out using conductivity measurement for the purpose of locating fractured/fissured zones and associated groundwater media at Oru-Ijebu, South-West Nigeria. The area is typical basement complex rocks of South-West, Nigeria with the local geology predominantly dominated by granite gneiss with associated comprising of granite, banded gneiss, pegmatite, and undifferentiated migmatite and these have been intruded by quartz veins and pegmatite veins. Measurements of the ground conductivity were carried out with Geonics EM 34-3 along 10 traverses whose profile lengths varied between 160 and 200 m. Intensive geophysical fieldworks were performed utilizing Frequency Domain Electromagnetic Method (FDEM) using Geonics-EM-34 to determine the vertical and lateral variations of subsurface conductivity. The EM data were acquired at 500 m intervals along 20 profiles (2 on each traverse) with acquired data further processed and interpreted. The processed data were further presented as horizontal and vertical plots on a line graph. In the 10 m coil spacing, the highest and lowest subsurface conductivity is exhibited by EMORU1 and EMORU6 with the values of 164mmho/m and 68mmho/m respectively in HDM. The highest and lowest conductivity is exhibited by EMORU4 and EMORU10 with the values of 139mmho/m and 70mmho/m respectively in VDM. Also, in 20m inter coil spacing, the highest conductivity is jointly observed in EMORU2 with 190mmho/m and 200mmho/m in HDM and VDM respectively. The lowest conductivity is equally observed in EMORU6 with values of 56mmho/m and 80mmho/m for HDM and VDM respectively with the analysis identified key lateral distances for groundwater prospecting, particularly between 72 m to 154 m along the profiles. This study has therefore investigated and characterized the study area for possible groundwater exploration, with varying conductivity values with locations of high conductivity reflection points and cross-over points are prospective sites for groundwater exploration while locations of similar trends in both HDM and VDM possess the same lithology. The qualitative interpretation of EM results identified areas of hydrogeologic importance and forms a predictive and suggestive basis for Vertical Electrical Sounding (VES) investigation; points of positive EM anomalies were considered as priority area for electrical resistivity* *sounding and prospective groundwater development, since they suggest lithological variations within the unconsolidated overburden and/or water–filled fissures in the bedrock. The identified major geological interfaces were suspected to be of weathered zones.*

Keywords: electromagnetic survey, true conductivity, dipole, fissures, geonics, regoliths.

INTRODUCTION

Detection of groundwater zones and their associated quantity measure and in many instants the quality of the groundwater is a challenge for most part of Africa and Nigeria in particular. Despite the immense supply of rainfall in African Continent with an annual average of 744 mm coupled with accompanied low withdrawals of groundwater for its major water sectors like agriculture, industry, community water supply among others (Nazifi et al., 2016). Patterns of economic growth and societal development in many world regions, particularly in the developing regions of Africa are largely determined not only by the availability but also the accessibility of freshwater (Reinhard, 2006). Oru is a community whose population is continuously on the increase by the daily influx of biological population mostly students due to its proximity to Olabisi Onabanjo main and mini campuses. The inhabitants of Oru community are battling with the problems of inadequate availability of potable water for their daily activities due to the progressive population growth that has led to severe shortage of potable water for the area which in turn poses a great challenge to both the indigenes, students and the government staffs. To meet the needs of this aforementioned growing population, it is quite necessary to source for further and alternative water supply sources. The households and residents of Oru-Ijebu community are mostly depending on shallow hand-dug wells most of which are uncovered for household activities. These water sources are susceptible to pollutions due to their exposure to environmental activities like dust, surface run-off from nearby dumpsites and so on. The continued use of water directly from these sources may lead to water borne diseases like cyclosporiasis, amoebiasis, hepatitis A, cholera, diarrhoea, bilharzias among others. Furthermore, women, children, students, spend a lot of time and effort everyday going to the nearby wells sites to fetch water. These practices affect the productivity of these women, children, students and entire community at large. Sometimes students waste precious school hours outside classrooms in search of water at the expense of their academic engagement. The principal methods use for groundwater exploration in Nigeria include; the review of archival reports, interpretations of topographical, geological and structural maps, survey of existing boreholes and other water sources and discussions with residents of the communities. These methods may not necessary be the best but they serve are some of the earlier methods widely applied in groundwater investigation in Nigeria (Reinhard, 2006).

One of the most difficult tasks ever encountered by man has been the pathway to the understanding of the earth; it is principally based on what can be observed, how well the observer can perceive and interpretion given to his observation per time. The subtle characterization and inhomogeneities of the subsurface with the abrupt changes in lithology, electrical electrical conductivity and variable thicknesses of weathered bedrock materials often have great impacts on the interpretation of EM data (Ishola., 2019; Ishola et al., 2021). The geophysical investigation involving the use of electromagnetic (EM) method was carried out in the study area as a preliminary investigation for the groundwater developmentof the area. Electromagnetic (EM) profiling is a widely used geophysical method in the delineation of overburden formation rocks and clay regolith and location of fissured media and associated zones of deep weathering of the basement complex rocks and consolidated sedimentary terrains (Beeson, et al., 1988., Olayinka, 1990, Olayinka, et al., 2004; Ishola et al., 2023). In many instances, EM surveys are used as reconnaissance survey for locating aquiferous zones such as fractures, faults and joints. Geophysical methods play increasing significant roles in the search for suitable and productive groundwater reservoirs (Ishola et al., 2021). Electrical resistivity method has been used routinely in exploration for groundwater. However, several other geophysical methods have been applied successfully either singly or in combination, for prospecting for groundwater resources in varying geologic situations. Over the years, The electromagnetic method has found useful applications in groundwater prospecting in both Basement and sedimentary terrains, most especially as a reconnaissance tools to understanding the nature and groundwater development feasibility of a suspected aquiferous zone (Palacky et al., 1981; De Jong et al., 1981; Amadi and Nurudeen, 1990; Olorunfemi et al., 2001; Egwebe et al., 2004; Ariyo et al., 2009; Okafor and Mamah, 2012; Ishola., 2019; Ishola et al., 2021). The principal advantage of the EM- methods is that they do not require contact with the ground directly unlike in Direct Electrical methods (DCERM) of geophysical exploration making the speed with which EM can be made is much greater than the electrical method. In the areas where groundwater occurrences are structurally controlled, it is suitable to use a method that is sensitive to fractures. Among widely used geophysical methods, EM methods have been identified as good for detecting and delineating fracture zones (Chegbeleh *et al*., 2009). Aquiferous zones are characterized by high conductivity and they often show anomalies, which may be high or low depending on the quantity/quality of water in the aquifer. It can also be used to detect buried metal objects, ore bodies, and fluid-filled features to map deeper groundwater contaminant plumes. Therefore, the EM- measurement can be conducted in a faster way than the (DCERM) measurement making it a very useful application for rapid assessment together with other seemingly more accurate geophysical techniques. EM does not accept any individual reading if it is significantly different from adjacent readings and build a subsurface image based on all the readings along the survey line and adjacent lines (Ishola, 2019). Electromagnetic methods can be used as a preliminary investigation tools for locating area of anomalous zones which can in turn serve as a guide for the integration of other investigation tools for deeper probing where points on the electromagnetic profiles that show adequate conductivity were considered for electrical resistivity sounding. Also, Electromagnetic method can be applied singly or together with other geophysical techniques such as gravity, seismic refraction, and electrical resistivity methods during the search for groundwater depending on whether the search is on a regional or local scale (Nazif et al., 2016; Ugwu and Nwosu, 2009; GEONICS, 1990a; McNeil, 1980a). This study is focused on assessing the groundwater prospect of the study area, and more importantly, providing information on the hydrogeologic framework of major aquifer units, and delineation of areas suitable for drilling and installation water wells.

Study area

Location and Accessibility

The study area is bounded by latitudes 6˚ 56' 56.80" N to 6˚ 57' 4.87" N and longitudes 3° 56' 32.29" E to 3°56' 24.38" E. It is located in Oru and its environs. Oru-Ijebu is a semi-urban town located in Ijebu North local government area of Ogun State, South-Western Nigeria. It is accessible by minor and major roads that connect to towns such as Ago-Iwoye, Imope, Awa, Ilaporu, Ijebu-Igbo. Notable landmarks within the study area are Be Happy fueling station and Light Crown Hotel. In terms of relief form and drainage the study area can be said to have an undulating relief form. The undulating terrain is characterized by hills and valleys, influenced by the landscape's gentle slopes and depressions. Water flows through the landscape in a complex network of streams and rivers shaped by the terrain's ups and downs. Water flow changes seasonally, with more rapid flow during rainy season and reduced flow during the dry season.

Geology of the Study Area

The study area, Oru, and its environs lie within the Basement Complex of southwestern Nigeria. It forms part of the Pan African mobile belt which lies to the east of West African Craton. The major rock types in the area of study include granite gneiss, granite, banded gneiss, pegmatite, and undifferentiated migmatite and these have been intruded by quartz veins and pegmatite veins. Granite gneiss is the major rock that dominated the study area. They are typically medium-grained in texture and the minerals present include quartz, biotite, plagioclase, orthoclase, and other accessory minerals. There is a considerable variation in the amount of mafic and felsic minerals. Granite gneiss stretches from the eastern part to the northwest of the area (Ishola et al., 2023). Generally, it is grey and texturally medium-grained. Mineralogically, it consists of quartz, plagioclase, feldspar, biotite, and hornblende. Granite is the second most abundant rock type in the area covering the entire eastern and northwestern region. The colour is grey and texturally medium-grained. Banded Gneisses are foliated and the rocks consist of alternating bands of light and dark minerals. The light band is composed of felsic minerals mainly quartz and feldspar while the dark band consists of mafic minerals. Mineralogically, banded gneiss contains both felsic and mafic minerals. Pegmatite is located in the western part of the area of study. The entire Oru Township is underlain by pink pegmatite. Pegmatite is a very coarse-grained minor igneous rock; they are formed from the residual magma that is rich in volatile and fugitive elements. They occur as massive intrusions in Oru. Texturally, it ranges from medium to coarse-grained. Mineralogically, feldspar, mica (muscovite dominating over biotite), and quartz are the most abundant minerals while muscovite and tourmaline occur as accessory minerals (Ishola and Olufemi, 2024). Figure 2.2 below shows the Geological Map of the study area

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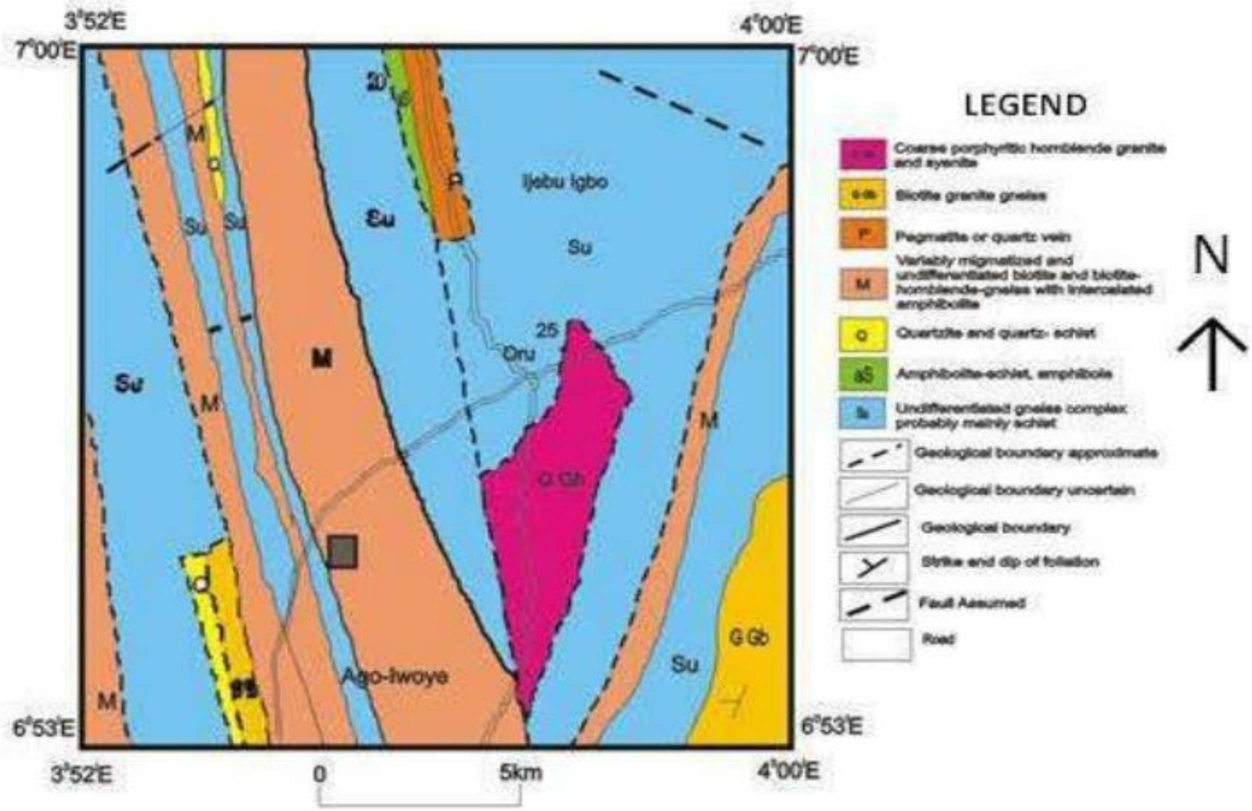

Figure 1: Geological Map of the Study Area. (Adekoya et al., 2017)

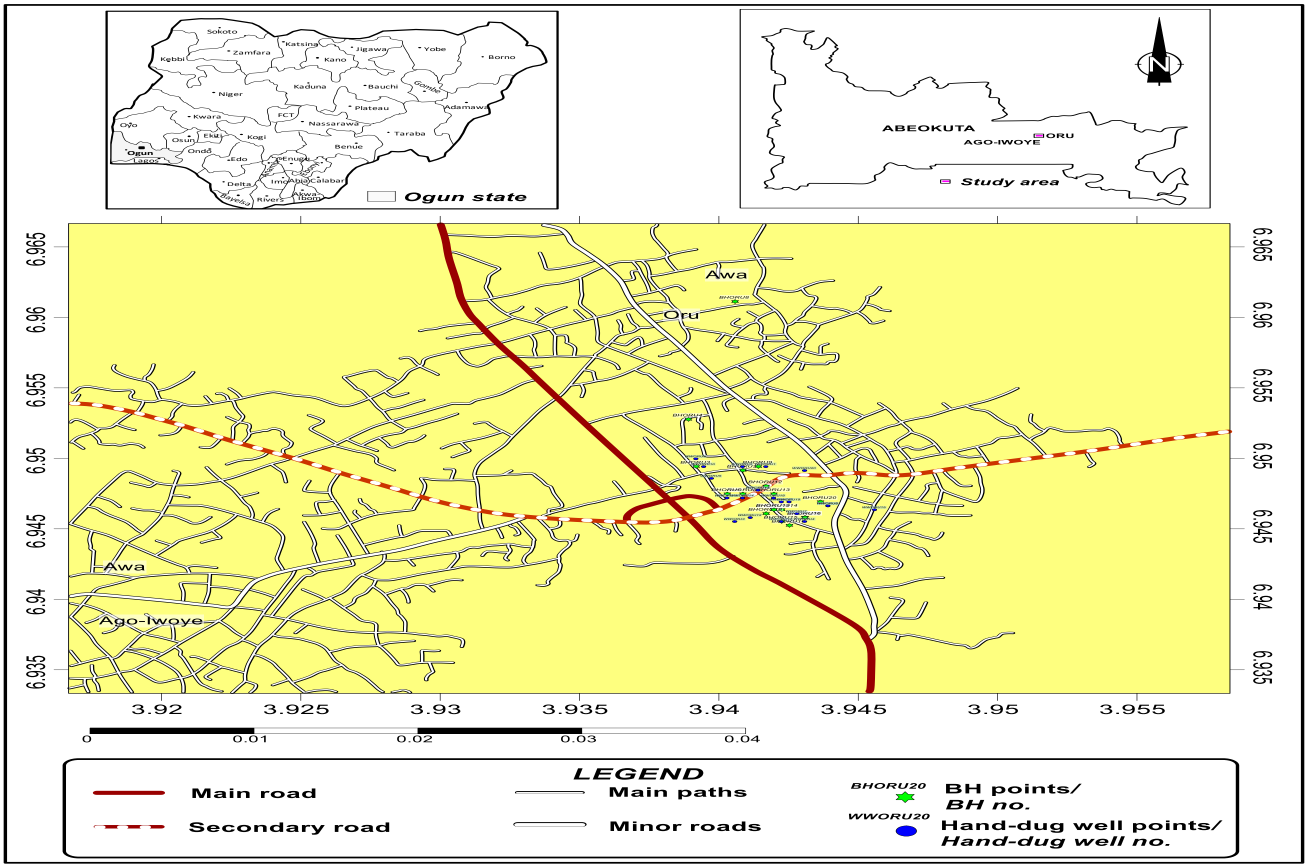

Figure 2: Location and accessibility map of the study area (Ishola, 2024)

MATERIALS AND METHODS

Theoretical Background

Electromagnetic method utilized the site response to the propagation of electromagnetic fields (Ishola *et al.*, 2023). Electromagnetic field comprised of an alternating electric intensity and magnetizing force. The speed at which EM can be made to propagate is much greater than the electrical method justifying the fact that electromagnetic method does not require contact with the ground. Therefore, an electromagnetic field can be developed by generating an alternating current through either a small coil comprising many turns of wire or a large loop of wire (GEONICS, 1990b; Ishola *et al.*, 2023). The concept of electromagnetic field is better be defined in terms of four significant vector functions namely E, D, H and B, where:

E is the electrical field in V/m; D is the dielectric displacement in Coulomb/m²; H is the magnetic field intensity in A/m and B is the magnetic induction in Tesla (Ishola, 2019; Ishola et al., 2023). Maxwell's equations adopting Faraday's law Experimental evidence reveals that all electromagnetic phenomena are subject to the following four Maxwell equations.

$\nabla E = -\frac{\partial B}{\partial t}$ ……………………………………(1) (Ishola, 2019; Ishola *et al.*, 2023)

Faraday's law shows us how a time varying magnetic field produces an electrical voltage.

Maxwell's equations using Ampere's law

Ampere's law revealed how an electric current and/or a time varying electric field generate a magnetic field.

$\boldsymbol{\nabla} H = J+\frac{\partial D}{\partial t}$ ………………………………………… (2) (Ishola, 2019; Ishola *et al.*, 2023)

Maxwell's Equations infer that lines of magnetic induction are continuous and there are no presence not even a single magnetic poles.

div B = 0 …………………………………………… (3) (Keary et al., 2002; Ishola *et al.*, 2023)

It also infers that electrical fields can begin and end on electrical charges.

div D = q ………………………………………....(4) (Keary et al., 2002; Ishola *et al.*, 2023)

Subsidiary equations and wave equation

By applying the following subsidiary equations,

$D = \boldsymbol{\epsilon}E$, $B = \boldsymbol{\mu}H$, $J = \boldsymbol{\sigma}E$ ………………………… (5) (Keary *et* al., 2002; Ishola *et al.*, 2023)

where J = electrical current density in A/m² ; q = electric charge in Coulomb/m³; ϵ = electrical permittivitiy; μ = magnetic permeability; σ = electrical conductivity (Ishola, 2019; Ishola et al., 2023). From these four Maxwell equations the electromagnetic wave equation can hereby be derived.

Primary and Secondary Fields

There is no significant difference between the fields propagated above the surface and the ones penetrated through the subsurface (only slight reduction in amplitude is recorded). If a conductive anomalous body is present, alternating currents (Eddy currents) are induced within the conductor by the the magnetic component of the incident EM wave as displayed in Figure. 5. The eddy currents generate their own secondary EM-field which travels to the receiver and the receiver equally detects the primary field which travels through the air (Ishola *et al.,* 2023). The resultant of the arrival of the primary and secondary field is authenticated and registered by the responds of the receiver (Ishola *et al.,* 2023). As a result of this field interaction, the measured response will differ both in phase and amplitude relative to the unmodulated primary field (Ishola, 2019; Ishola *et al.,* 2023). The detection of the presence of the encountered conductor as well as the necessary information on its geometry and electrical properties are revealed by these aforementioned differences between the transmitted and received electromagnetic fields. The depth of penetration of an electromagnetic field is dependent on the frequency as well as electrical conductivity of the medium through which propagation is made (McNeil, 1980b; Ishola *et al.*, 2023). Electromagnetic fields are therefore attenuated during their passage through the ground (GEONICS, 1990; Ishola et al., 2021; Ishola *et al.,* 2023). The amplitude of EM-radiation serves as a function of depth relative to its original amplitude A_0 is given as

$A_d = A_0 e^{-1}$ …………………………(6) (GEONICS, 1990; Ishola, 2019; Ishola *et al.*, 2023)

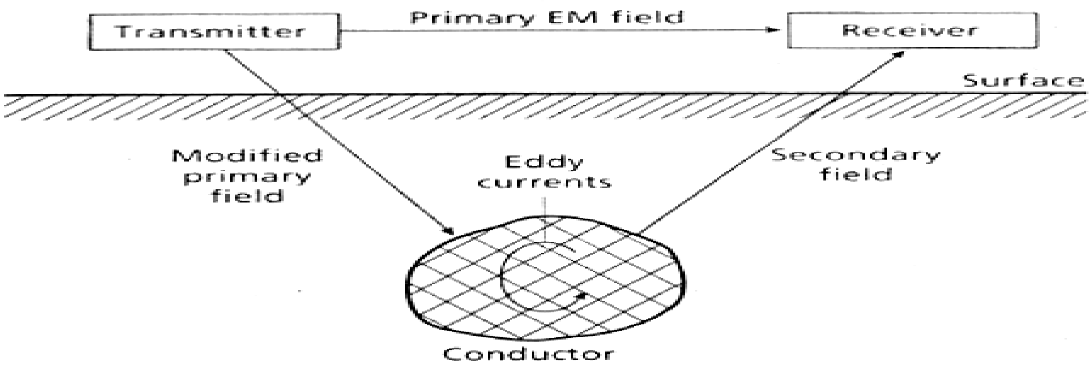

Fig. 3: General Principle of Electromagnetic Surveying (Ishola et al., 2023)

The depth at which the amplitude of the field A_d is decreased by the factor e^{-1} compared with its surface amplitude A_0 is defined as the depth of penetration d given as

$d = \frac{503.8}{\sqrt{\sigma f}}$ ………………………… (7) (GEONICS, 1990; Ishola, 2019; Ishola *et al.,* 2023)

where d is in metres, the conductivity s of the ground is in Sm^{-1} and the frequency of the field is in Hz.

Just as both the frequency of the electromagnetic field and the conductivity of the ground decrease, the depth of penetration thus increases (Ishola *et al.,* 2023). Therefore, equation (7) represents a theoretical relationship. Whereby the frequency used as a result of the EM survey can be tuned to a desired depth range in any particular medium. Empirically, an effective depth of penetration z_e can be defined as the depth as the maximum depth at which a conductor may lie and still produce a considerable electromagnetic anomaly as shown in equation 8.

$z_e = \frac{10}{\sqrt{\sigma f}}$ …………………………..… (8) (GEONICS, 1990; Ishola, 2019; Ishola *et al.*, 2023)

Penetration is dependent on factors such as the nature and magnitude of the effects of near-surface variations in conductivity, the geometry of the subsurface conductor and instrumental noise making this relationship an approximate one. Constraints are placed on the EM method due to the dependence of the depth of penetration on frequency. Very low frequencies are normally difficult to develop and measure and the maximum penetration attainable in the field is usually of the order of 500m (McNeil, 1980b; Keary et al., 2002; Omosuyi et al., 2007; Ishola, 2019). 10m spacing are f = 10 Hz, d =503 m; f =100 Hz, d = 159 m and f = 1000 Hz, d = 50.3 m; are examples of different Depths of penetration and their corresponding frequencies**.**

Principle of Operation and Interpretation Technique of EM 34-3

The Electromagnetic Ground Conductivity Survey Method utilized in this work is based on a well established applied geophysical method. EM 34-3 terrain conductivity meter manufactured by Geonics Limited was obtained from the Department of Geosciences, University of Lagos, South-West Nigeria. A direct reading of the apparent conductivity (σa) of the ground in units of millimhos per metre (SI equivalent units are millisiemens per metre (mS/m) was provided by a change in conductivity of 5.0 mS/cm assumed to be measurable with the instrument. induction number has been defined as the ratio of the intercoil spacing (s) divided by the skin depth (δ) (Ishola, 2019; Ishola et al., 2021). In FDEM method, a GEONICS EM-34 meter possesses separate coils that were connected by a reference cable which provided the basis of the system in lengths of 10m, 20m and 40 m long. The effective depths of investigations are 7.5 m (HD) and 15 m (VD); for a frequency of 6.4 KHz and separation of 10 m**;** for a separation of 20 m and frequency of 1.6 Hz, is obtained a depth investigation of 15 m (HD) and 30 m (VD); for the separation of 40 m and frequency of 0.4 Hz, the investigation (GEONICS, 1990; Ishola et al., 2021; Ishola *et al.*, 2023).

The instrument operates on the measurements at Low Induction Number providing a direct reading of the quadrature as the apparent conductivity in mS/m. The secondary magnetic field is a complicated function of the inter-coil spacing, (s), the operating frequency (f), and the ground conductivity (σ). However, the technical definition is stated as “operation at low values of induction number” the very simple function of these variables in secondary magnetic field is incorporated in the design of the EM 34- 3 (Ishola, 2019; Ishola *et al.,* 2023). The product of s and the skin depth d, known as the induction number, is far less than unity. Therefore, the ratio of the intercoil spacing (s) divided by the skin depth is known as the induction number B where the induction number is less than one, then the ratio of the secondary to the primary of magnetic fields at the receiver is directly proportional to apparent conductivity. The ratio of the secondary (Hs) to primary (Hp) magnetic fields at the receiver at low induction n umbers (B<<1) is given by (Ishola, 2019; Ishola *et al.,* 2023).

$$\frac{H_s}{H_p} = \frac{i\omega\,\mu\beta\sigma S^2}{4} \quad \text{...}(9)$$

Equation (9) provided the apparent conductivity as recorded by the instrument (Ishola *et al.*, 2023).

$$\sigma = \frac{i\omega\ \mu\beta\sigma S^2}{4}\left(\frac{H_S}{H_p}\right) \text{...} \quad (10)$$

where: H_s is the amplitude of the secondary electromagnetic field at the receiver coil; H_p represents the amplitude of the primary electromagnetic field at the receiver coil; ω is the angular frequency (ω = $2\pi f$); f is frequency (Hertz); µB is the magnetic permeability of vaccum or free space (1.2566×10-6 m kg C^{-2}); σ represents the measured ground conductivity (mho/m); s is the inter coil spacing (m) while the presence of $i = \sqrt{-1}$ depicts that the quadrature component is measured (Ishola, 2019; Ishola *et al.*, 2023). Therefore, the ratio of H_s/H_p is proportional to the ground conductivity σ. Since depth d depends on the product of estimation of the maximum probable value of σ allows the selection of f such that the above condition of low induction number is satisfied. The depth of penetration is independent of the conductivity distribution of the subsurface but depends upon σ (Okafor and Mamah, 2012; Ishola *et al.*, 2023). Measurements taken at low induction number thus provide an apparent σ_a given by (McNeill, 1980b; Ishola, 2019; Ishola *et al.*, 2023).

$$\sigma_n = \frac{1}{\rho_a} = \left(\frac{4}{\omega\ \mu_0 S^2}\right)\left(\frac{H_s}{H_p}\right)q \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The above relationship enables the construction of elecromagnetic instruments that procures a direct reading of ground conductivity down to predetermined depth. The measuring system is also predesigned so as to ensure that with the selection of frequency f, for a given inter-coil separation (s), a designed response of Hp for a given transmitter, the only unknown Hs which is measured by the instrument with the subscript q denoting the quadrature phase (Ishola, 2019). Therefore, to measure the terrain conductivity in the field the search coil is either held horizontally (measurement in vertical dipole moment) or vertically (horizontal dipole mode). The results obtained from this field operations are generally displayed in the form of conductivity profiles. Today, inductive electromagnetic survey methods are widely harnessed to map near-surface geology by mapping variations in the electrical conductivity of the ground. These variations are generally functions of certain factors like changes in soil structure, clay content, porosity, resistivity of the soil water, and degree of water- saturation in the soil (GEONICS, 1990; Ishola, 2019; Ishola *et al.*, 2023).

Field Data Acquisition (Electomagnetic Terrain Conductivity Survey)

Electromagnetic profiles were selectively created in autonomous communities within Papalanto District for the primary purpose of outlining shallow conductive hydrogeological structures that could possibly be connected water circulation of the local hydrogelogic units of the area (Okafor and Mamah, 2012; Ishola *et al.,* 2023). The outcome of this investigation would be highly significant in in the future delimitation of a protected zone from contaminant infiltration (Ishola et al., 2021). The investigated area has been a natural environment engaged agrarian and commercial activities and has served as abode for students of Olabisi Onabanjo University who stay outside the university campuses. The myriads of these activities have led to the increase in human and biological population which in turn increase the demands for more water supplies and has consequently necessitated the need for preliminary investigation to meet the current challenge. The data was acquired along 5 North-South profiles with 2 electromagnetic measurements made along each traverse. The lengths of each traverse varied between 160 m and 200 m to show conductivity changes with distance and depth for each location with an intercoil spacing of 10m, and 20 m. The distance between the beginnings of each measurement points to the beginning of another measurement point was 500 m. At each site two measurements were made using both horizontal and vertical dipole mode. The main conductivity contrasts, can now be interpreted roughly as the shallow expression of fractures within the sedimentary filling of the hydrogeological structure of the area (Macdonald et al., 2005; Ishola et al., 2021; Mamah, 2012; Airen and Osifo, 2023) Ishola *et al.,* 2023).

The procedure of the field operation involves An AC electric current is applied to a transmitter coil, the transmitter Tx is energised with an alternating current at a specific frequency, audio frequencies (100 - 5000 Hz), depth is 30 m (HD) and 60 m (VD) (GEONICS, 1990). Usually three frequencies are used seeking for different investigation depths; this generates a primary electromagnetic (EM) field in the coil. The primary time varying magnetic field generated from the transmitter and arising from this effect induces small current in the subsurface which is assumed uniform. These currents generate a secondary magnetic field, (Hs) which is sensed or detected, together with the primary field, (Hp) by the receiver coil, in the form of total field (HT) (Ishola *et al.,* 2023)**;** both magnetic fields are sensed by the receiver coil and a reading of apparent conductivity is given. The value of apparent conductivity depends on many factors. These are porosity, conductivity of pore fluid, pore surface area, degree of saturation of subsurface sediments, temperature, and (when present) clay content; the transmitter and receiver, are located vertically upward with the axis of the coil being horizontal to the subsurface; in the second mode (vertical magnetic dipole mode, VDM) the coils were placed lying flat horizontally with axis of the coil being vertical to the subsurface. Profiles with 10m and 20m of separation between transmitter and receiver were performed, using 6.4 KHz and 1.6 KHz respectively in order to probe at varying depth and resolution**;** In either of the modes, the transmitter operator stops at the measurement station, the receiver operator (the researcher) then moves the receiver coil backwards or forwards until the meter indicates correct inter-coil spacing. At this point the receiver operator reads the terrain conductivity from a second meter. The procedure takes about 10 - 20 seconds. The measurement is first carried out in the horizontal coil orientation (vertical dipole mode) and later the corresponding vertical coil orientation (horizontal dipole mode) along the same profile. The vertical coil orientation gives information about the shallow subsurface while the horizontal coil orientation penetrates deeper into the subsurface (Ishola *et al.,* 2023); the apparent conductivity readings were taken at each station along the traverses and recorded in mmho/m (milli mho per metre) while other features and artifacts that could alter or affect the reading such as metals, vehicles and so on were noted against the station. The result of the vertical and horizontal dipole apparent conductivity for both traverses is determined from the plots. Figure 4 shows the data acquisition map of the study area while figure 5 is the image map showing the traverse lines in the study area.

Data Processing and Interpretation

The acquired data were qualitatively checked by observing if negative apparent conductivity was recorded. Field note was used particularly as a guide to identify if certain anomalously high apparent conductivity values due to artifacts were present. The precautionary measures taken in the field among others using EM-34 transverses were restricted to areas far away from the overhead and underground utility cables and buried iron pipelines (Macdonald et al., 2005; Okafor and Mamah, 2012; Ishola *et al.,* 2023). The apparent conductivity reading of the horizontal dipole orientation on each traverse was plotted against station midpoint. This was also carried out separately for the vertical dipole orientation. The crossplots of apparent conductivity on the different spacing enabled a view of how the conductivity varies with depth. Qualitative analysis and interpretation were further carried out on the plotted data.

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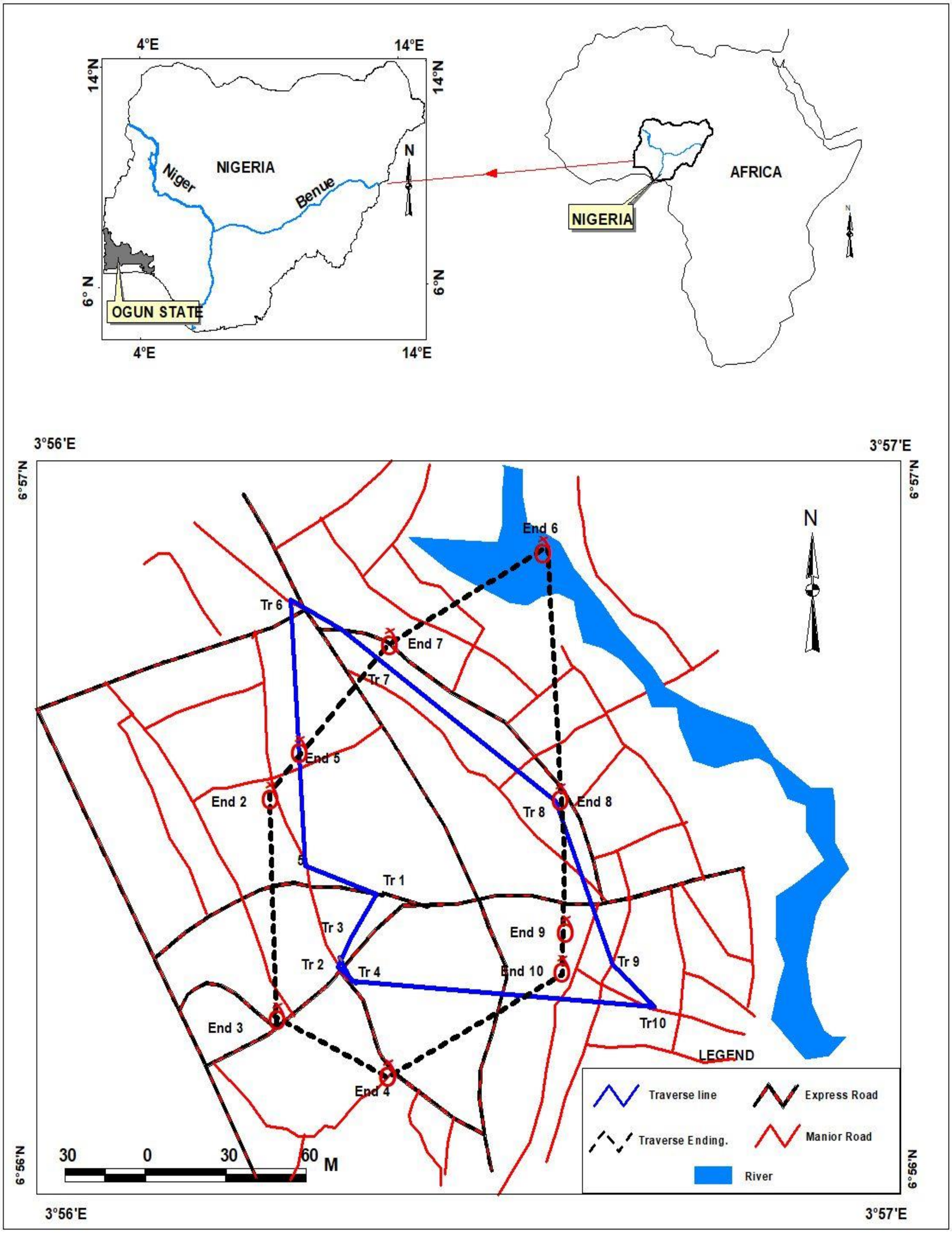

Figure 4: Data Acquisition Map of the Study Area

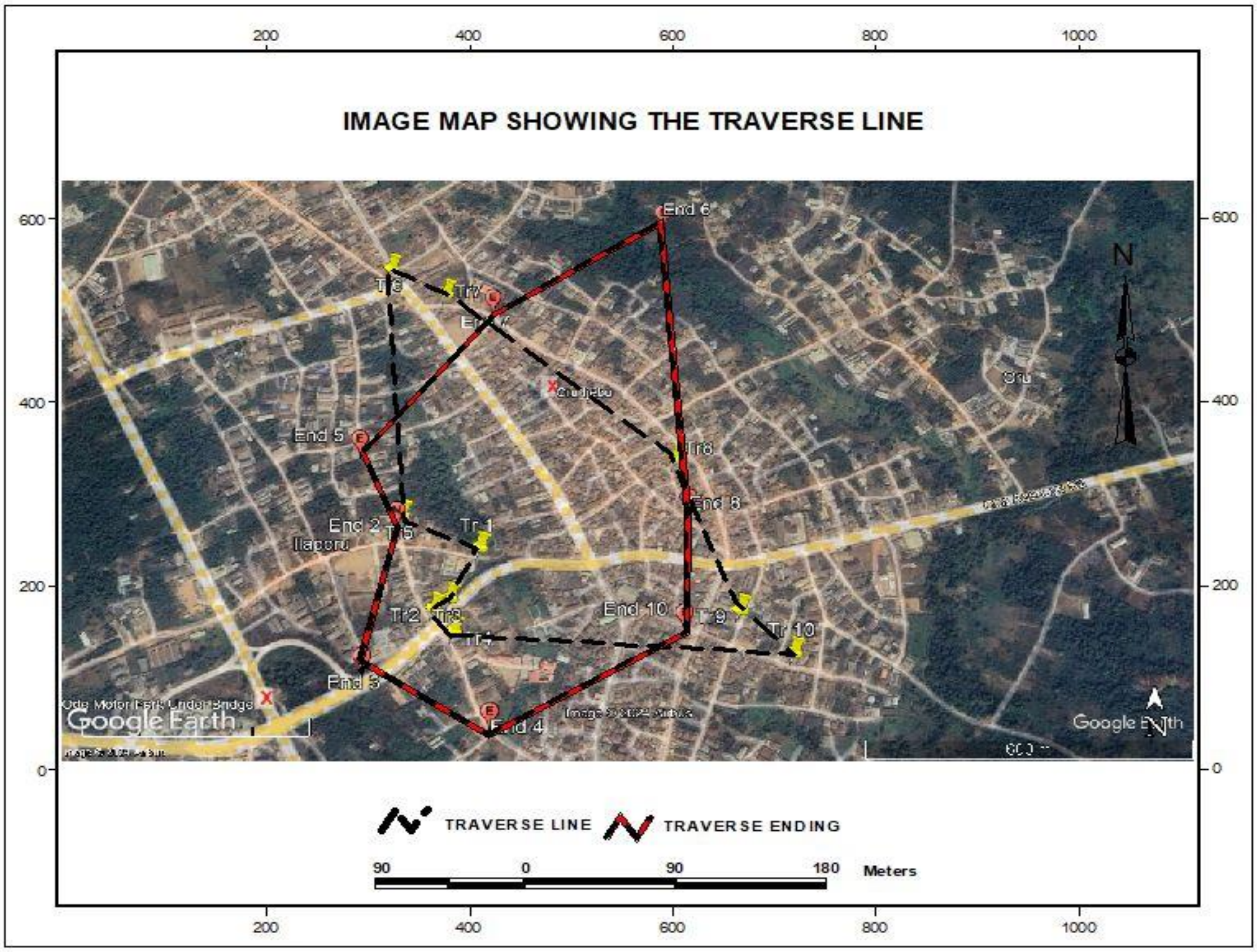

Figure 5: Image Map of the Traverse Lines

RESULTS AND DISCUSSION

The results of the EM-34 electromagnetics method are hereby presented as plots of horizontal dipole (H_D) and vertical dipole (V_D) against the mid station as shown in Figure 4.1. The plots are indicative of the subsurface conductivity (vertically and horizontally) concerning a certain depth.

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU1

Figure 4.1 represents the plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10 m coil spacing and a total of 200 m length was covered. The plot showed gentle or low curves that are indicative of the subsurface being made of the same or similar lithology. The low to gentle conductivity region along this profile is indicative that the subsurface has no good fracture zone/weathered layer that could serve as a good aquifer unit for groundwater exploration. However, a high apparent conductivity zone (+ peak) suggestive of a possible fractured zone of water accumulation was observed along the profile line at a lateral distance of 135m to 154m as shown in Figure 4.1. Also, two (2) cross-over points were identified at a lateral distance of 72m and 110m suggestive of possible fractured or zones of groundwater accumulation. Also, Figure 4.2 represents the plot for the 20m coil spacing along profile 1. The plot showed similar results but investigated deeper than that of the 10 m coil spacing. From the plot, a high conductivity zone suggestive of a possible fractured zone was identified at lateral distances of 110m to 130m respectively. Thus, both results revealed that there is a prospect zone at lateral distances of 72m, 110m, and 135m to 154m respectively. These zones could be favorable for groundwater accumulation.

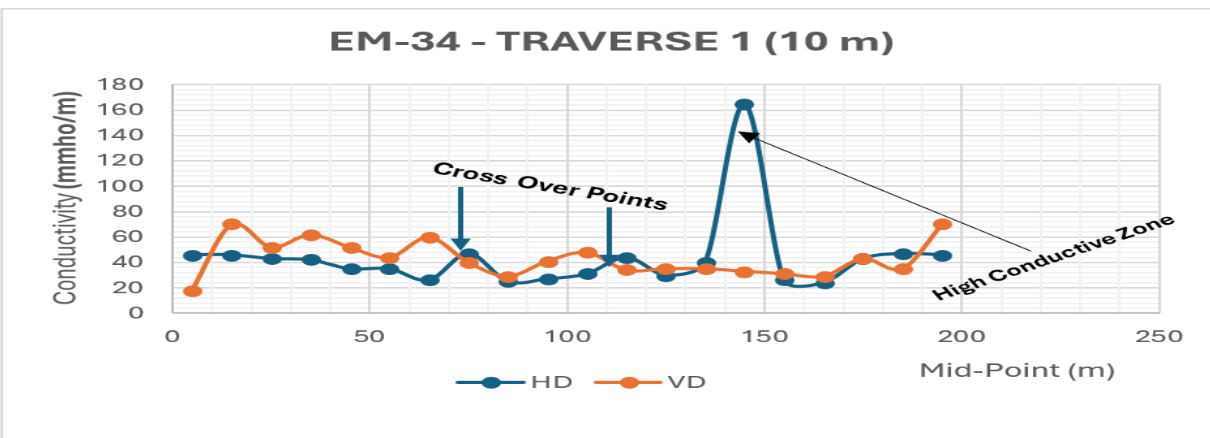

Figure 4.1: Plot of HD and VD along Traverse 1 (10 m Spacing)

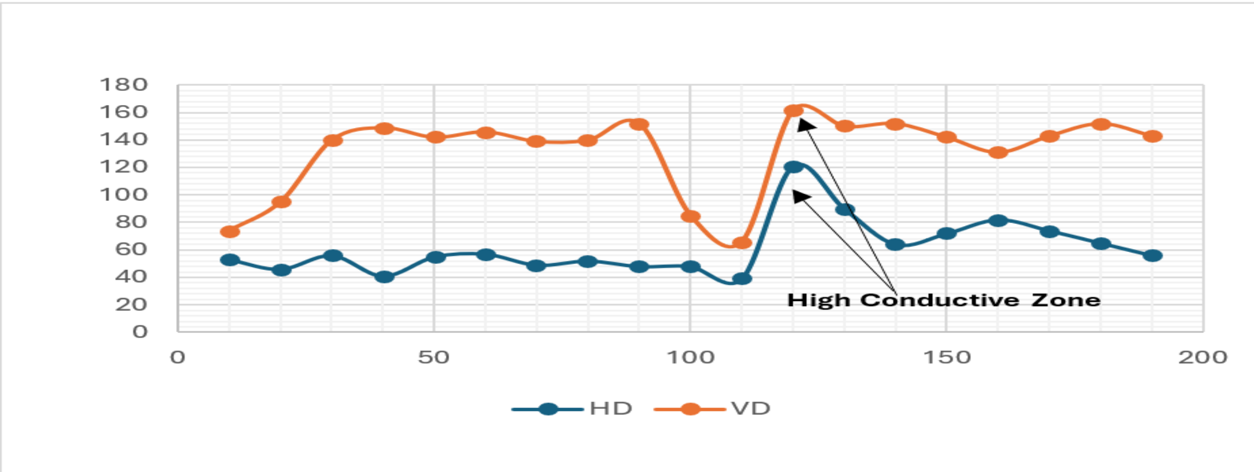

Figure 4.2: Plot of HD and VD along Traverse 1(20 m Spacing)

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU2

Figure 4.3 represents the plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10 m coil spacing and a total of 200 m length was covered. The plot showed varying conductivity signatures along the profile. However, the EM profiles show similar signatures, with a wide separation between the vertical and horizontal dipoles. These zones are identified at lateral distances of 73m to 90m, 90m to 109m, and 122m to 152m respectively. These zones are suggestive of possible fractured zones for groundwater exploration. Also, Figure 4.4 represents the plot for the 20m coil spacing along profile 2. The plot showed similar results but investigated deeper than that of the 10m coil spacing. The result of the 20m coil spacing further confirms the occurrence of possible fractured zones/groundwater occurrence at lateral distances of 90m to 120m. These zones could be favorable for groundwater accumulation.

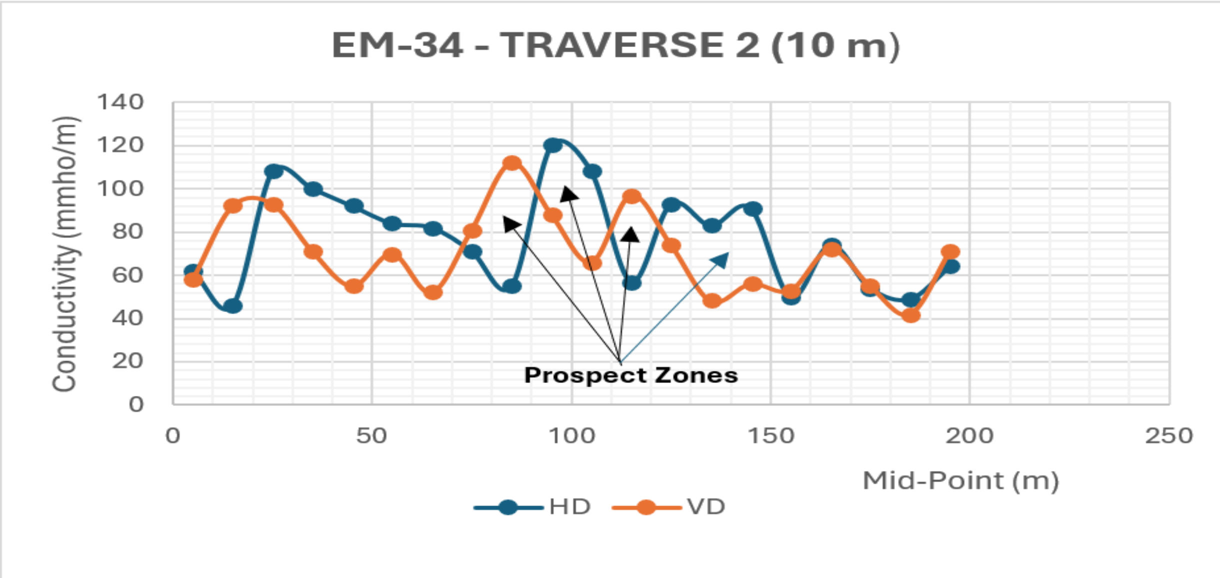

Figure 4.3: Plot of HD and VD along Traverse 2 (10m Spacing)

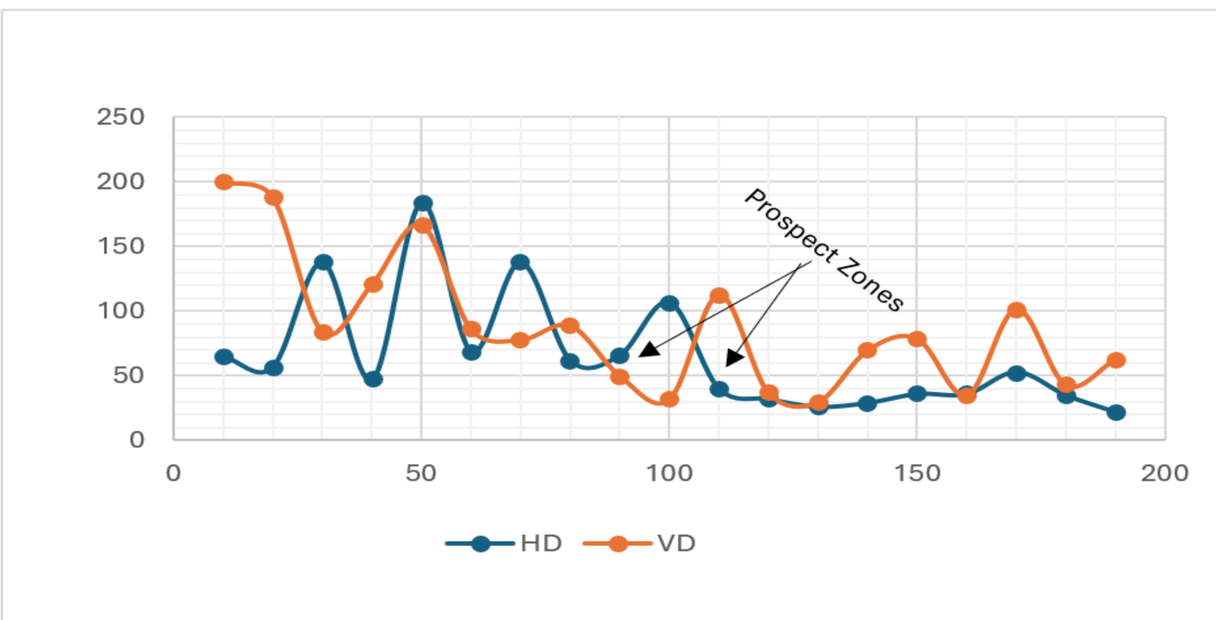

Figure 4.4: Plot of HD and VD along Traverse 2 (20m Spacing)

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU3

Figure 4.5 represents the plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10 m coil spacingand a total of 100 m length was covered. The plot showed varying conductivity signatures along the profile. However, the EM profiles show three cross-over points with one high conductivity zone along the profile lines. These zones are identified at a lateral distance of 22m 32m and 42m, while the high conductivity zone was identified at a lateral distance of 36 m to 68 respectively. These zones are suggestive of possible fractured zones for groundwater exploration. Also, Figure 4.6 represents the plot for the 20m coil spacing along profile 3. The plot showed similar results but investigated deeper than that of the 10m coil spacing. The result of the 20 m coil spacing further confirms the occurrence of possible fractured zones/groundwater occurrence at lateral distances of 32m and 56m to 75m. More so, a high conductivity zone was also identified at a lateral distance of about 10m to 18m. These zones could be favorable for groundwater accumulation.

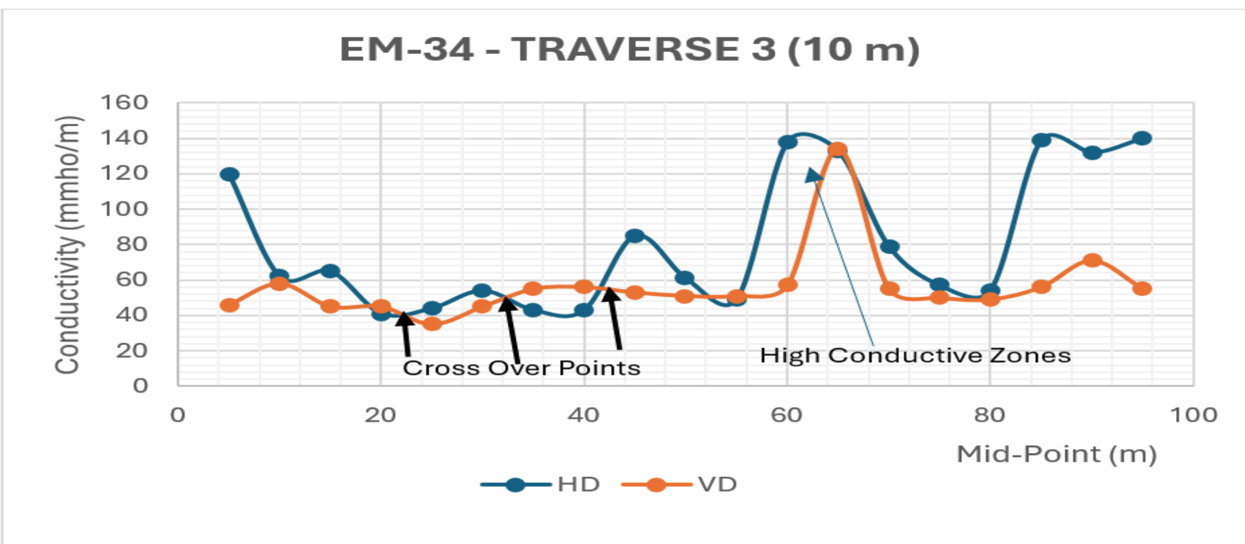

Figure 4.5: Plot of HD and VD along Traverse 3(10m)

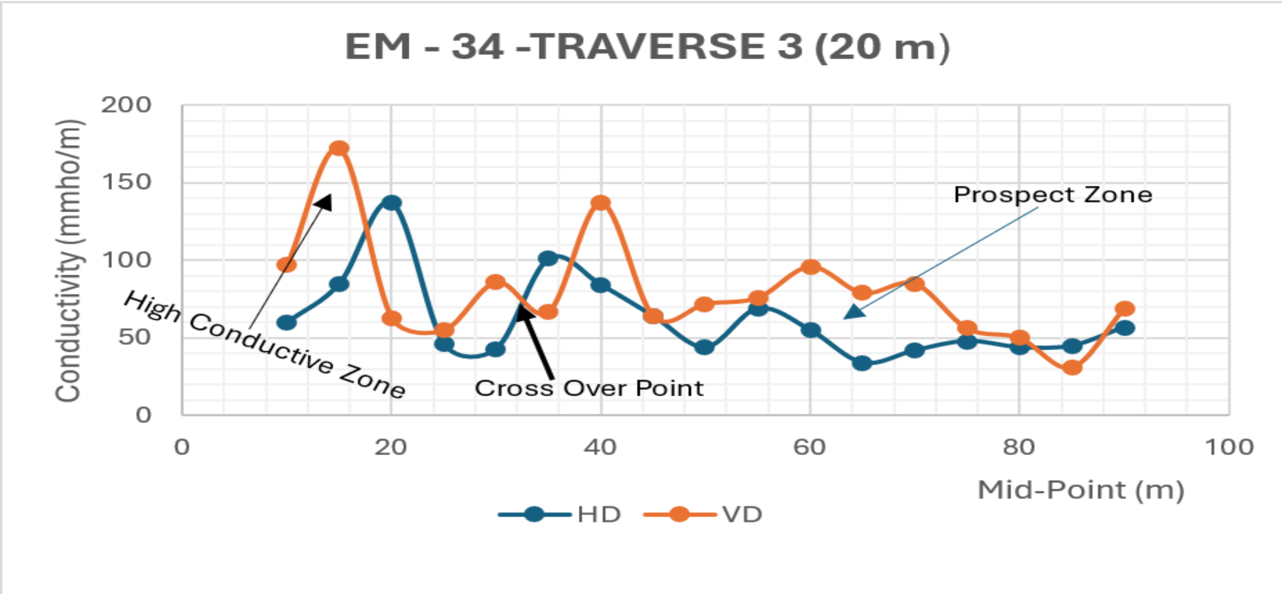

Figure 4.6: Plot of HD and VD along Traverse 3(20m Spacing)

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU4

The plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10 m coil spacing along traverse 4 is presented in Figure 4.7. The result covered a total distance of 200m. The plot showed a gentle conductivity signature from the beginning of the plot to a lateral distance of about 60m. However, a low conductivity zone suggestive of a high resistive region was identified at a lateral distance of 68m to 130m. This low conductive zone could not be favorable for groundwater prospecting. Varying conductivity signatures along the profile revealed the plot for the 20m coil spacing along profile 4 showing the prospective zone at a deeper depth as presented in Figure 4.8. The plot showed varying conductivity signatures which resulted in three prospecting zones. These prospect zones show wide separation between the H_D and V_D plots at lateral distances of 32m to 64m, 77m to 95m, and 95m to 105m. These zones could be favorable for groundwater accumulation.

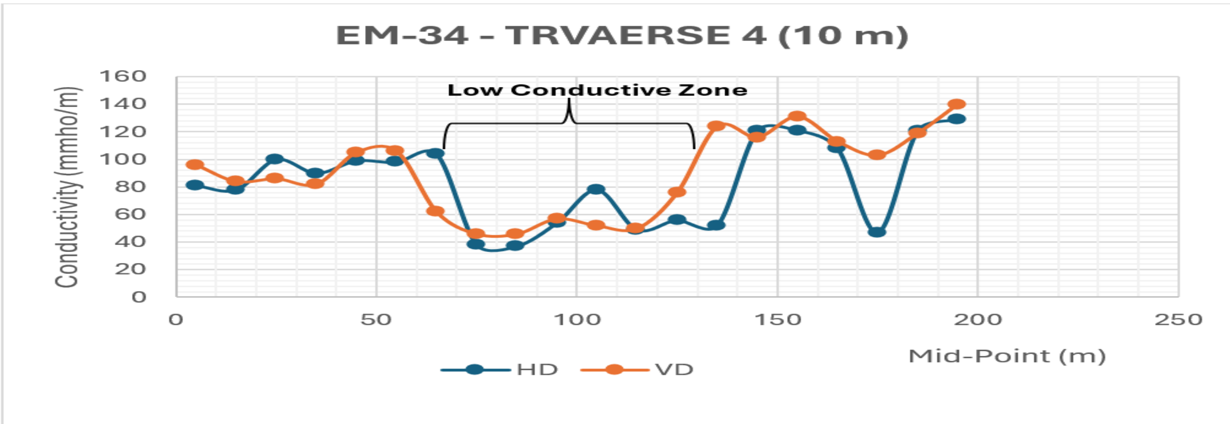

Figure 4.7: Plot of HD and VD along Traverse 4 (10m Spacing)

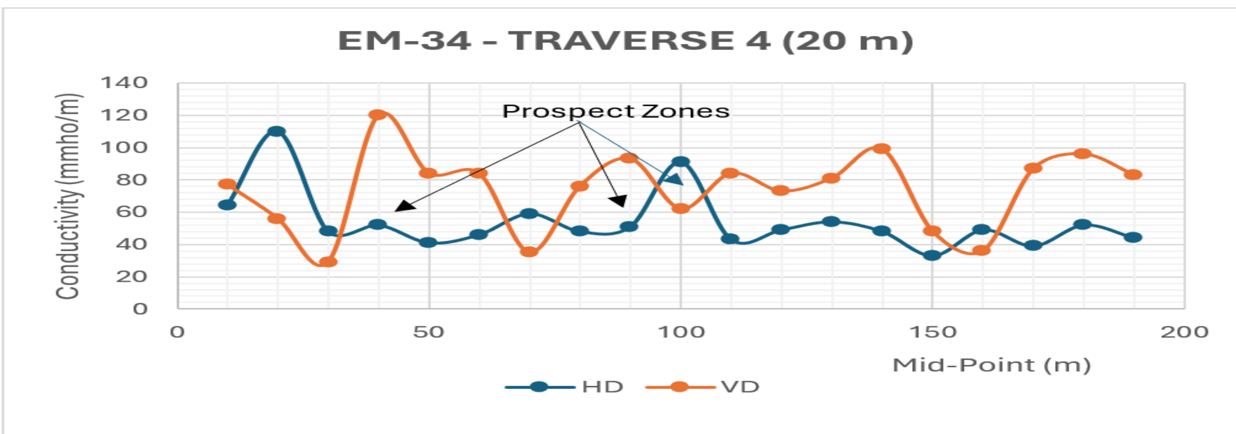

Figure 4.8: Plot of HD and VD along Traverse 4 (20m) Spacing

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU5

The plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10 m coil spacing along traverse 5 is presented in Figure 4.9. The result covered a total distance of 200m. The plot showed varying conductivity signatures across the entire profile. However, three (3) cross-over points suggestive of a possible fractured or weathered layer (aquifer) were identified at lateral distances of 38m, 82m, and 110m. These zones could have a favorable groundwater supply. The result of the 20 m coil spacing is presented in Figure 4.10. The

International Research Journal of Pure and Applied Physics, 11 (1),98-131, 2024
ISSN 2055-009X(Print)
ISSN 2055-0103(Online)
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result showed two (2) more anomalous zones for possible groundwater accumulation at deeper depths. These zones are identified at lateral distances of about 52m to 80m and 130m respectively.

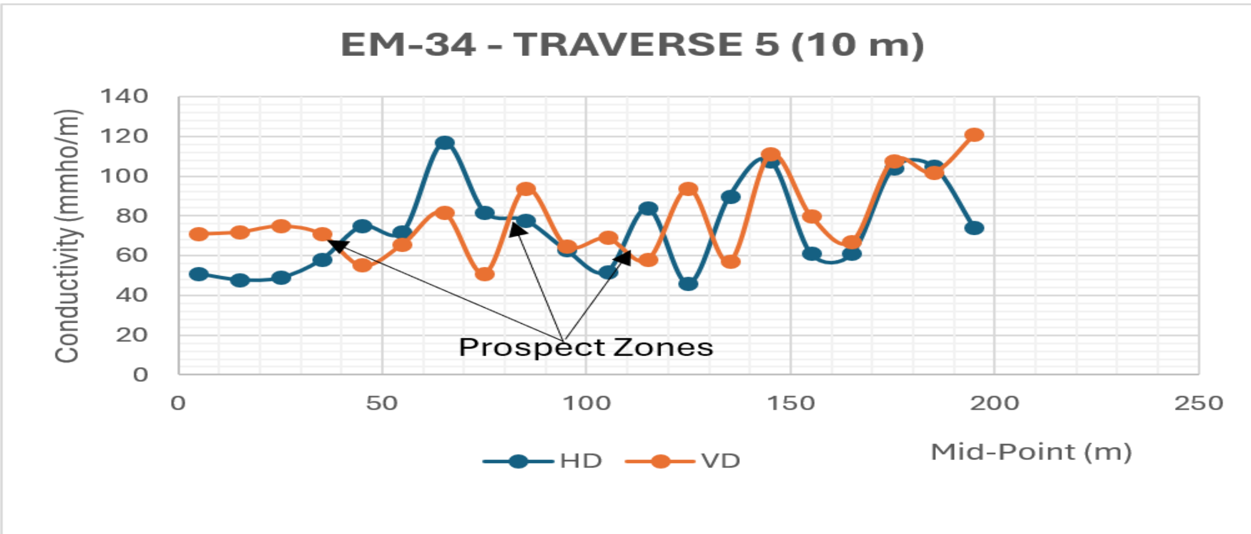

Figure 4.9: Plot of HD and VD along Traverse 5(10m) Spacing

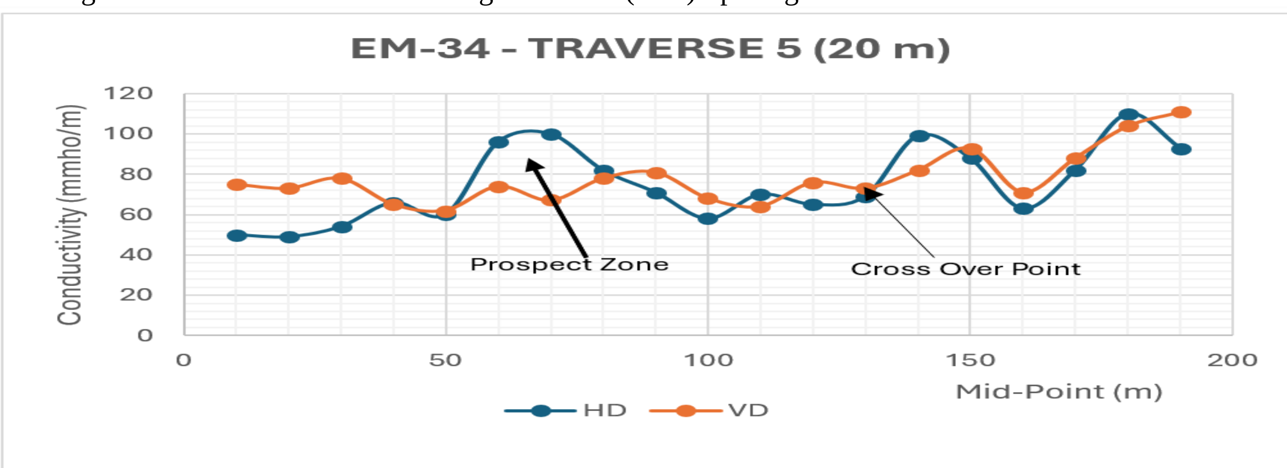

Figure 4.10: Plot of HD and VD along Traverse 5 (20m) Spacing

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU6

The plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10 m coil spacing along traverse 6 is presented in Figure 4.11. The result covered a total distance of 200m. The plot showed varying conductivity

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ISSN 2055-0103(Online)
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signatures across the entire profile. However, four (4) cross-over points suggestive of a possible fractured or weathered layer (aquifer) were identified at lateral distances of 20m, 48m, 78m, and 135m. These zones could have a favorable groundwater supply. The result of the 20 m coil spacing is presented in Figure 4.12. The result showed two (2) more anomalous zones for possible groundwater accumulation at deeper depths. These zones are identified at lateral distances of about 50 m to 98 m and 103m- 137m respectively. Thus, prospect zones were identified along this profile line at lateral distances of 20m, 48m, 78m, and 135m at shallow depth and lateral distances of 50m to 98m and 103m to 137m at moderate depth for further investigation.

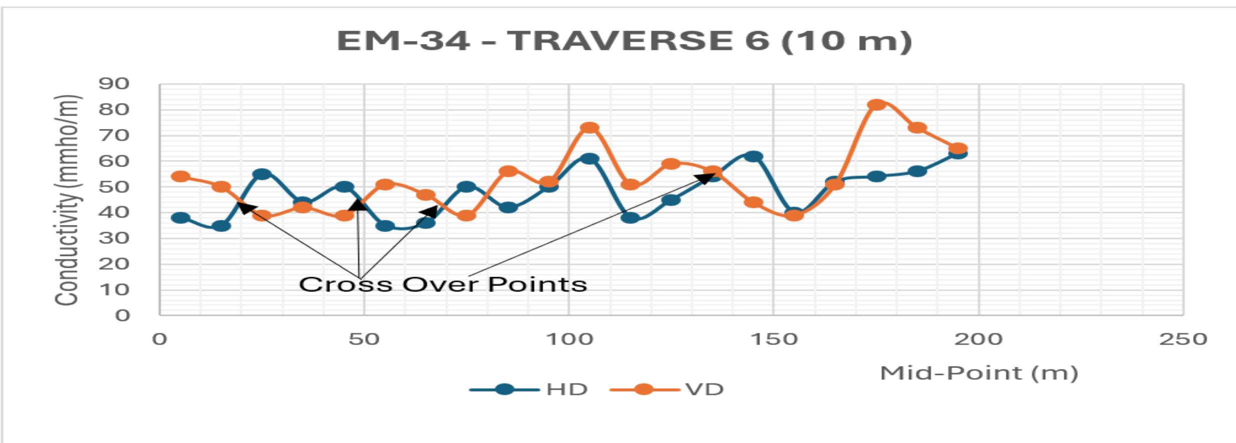

Figure 4.11: Plot of HD and VD along Traverse 6 (10m Spacing)

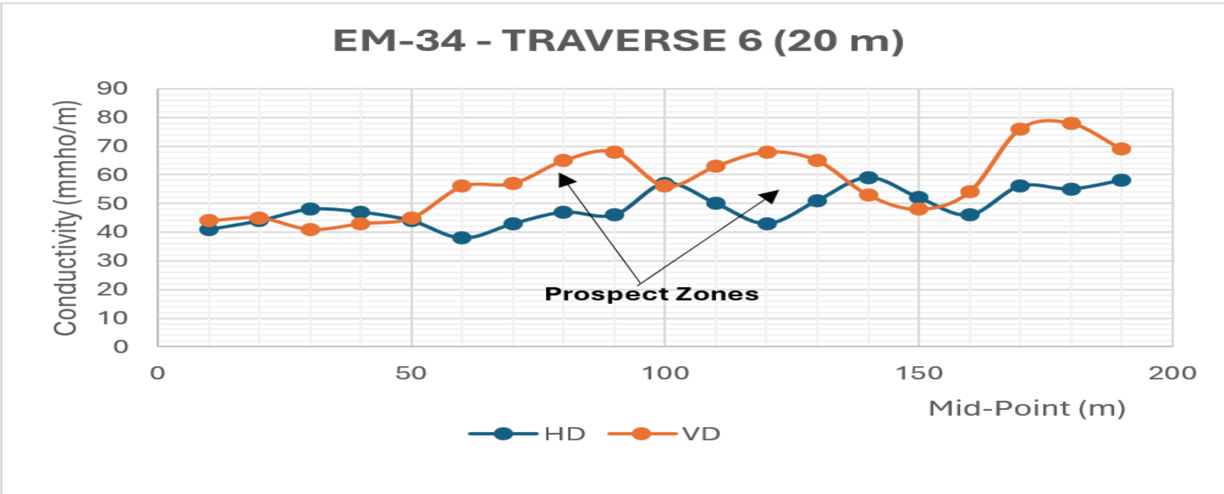

Figure 4.12: Plot of HD and VD along Traverse 6 – 20m Spacing

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU7

The plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10 m coil spacing along traverse 7 is presented in Figure 4.13. The result covered a total distance of 200 m. The plot showed varying conductivity signatures across the entire profile. However, four (4) cross-over points suggestive of a possible fractured or weathered layer (aquifer) were identified at lateral distances of 35m to 55m, 100m to 110m, 11m to 121m, and 163m to185m. These are zones for possible groundwater supply. The result of the 20 m coil spacing is presented in Figure 4.14. The result showed a similar result to that of the 10 m coil spacing but further confirmed the possible occurrence of the fractured zones identified at lateral distances of 40m to 60m and 160m to 190m. Thus, prospect zones identified along this profile line were identified at lateral distances of 35m to 60m, 100m to 110m, 112m to 121m, and 135m to 190m for further investigation.

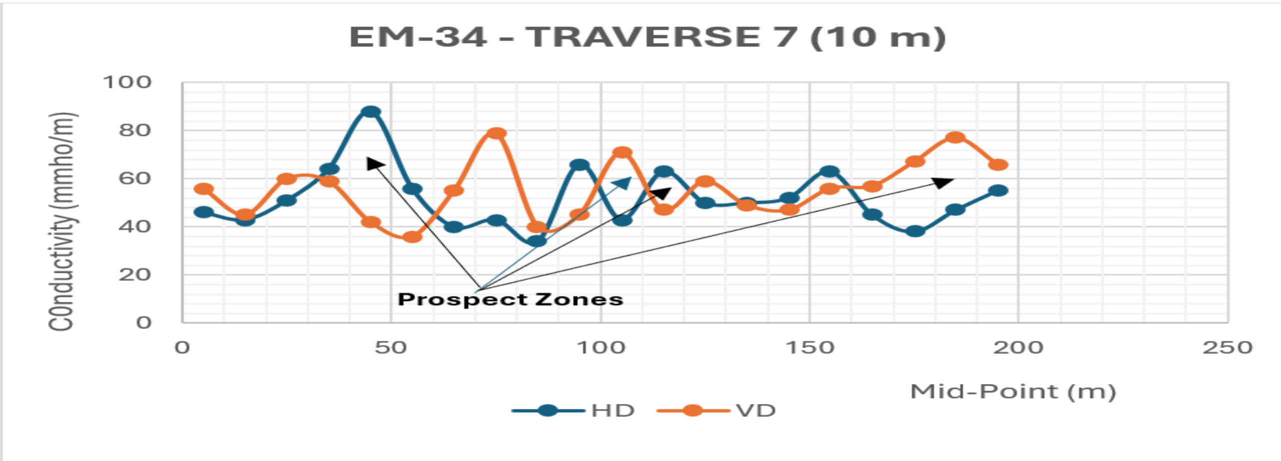

Figure 4.13: Plot of HD and VD along Traverse 7(10m) Spacing

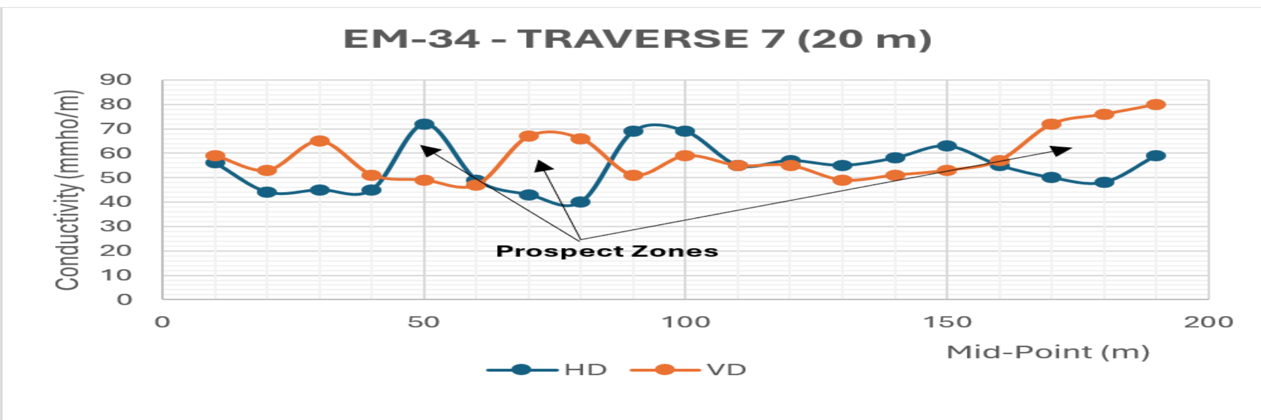

Figure 4.14: Plot of HD and VD along Traverse 7(20m) Spacing

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU8

The plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10m coil spacing along traverse 8 is presented in Figure 4.15. The result covered a total distance of 200m. The plot showed varying conductivity signatures across the entire profile. However, two (2) cross-over points suggestive of a possible fractured or weathered layer (aquifer) were identified at lateral distances of 110m and 132m. These are zones for possible groundwater supply. For the 20m coil spacing, the subsurface shows similar subsurface

International Research Journal of Pure and Applied Physics, 11 (1),98-131, 2024
ISSN 2055-009X(Print)
ISSN 2055-0103(Online)
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conductivity across the profile line as shown in Figure 4.16. However, the conductivity along this profile is therefore representative of an environment that has no good fracture zone or weathered layer at deep depth. Thus, the prospect zones were only identified along the 10m coil spacing.

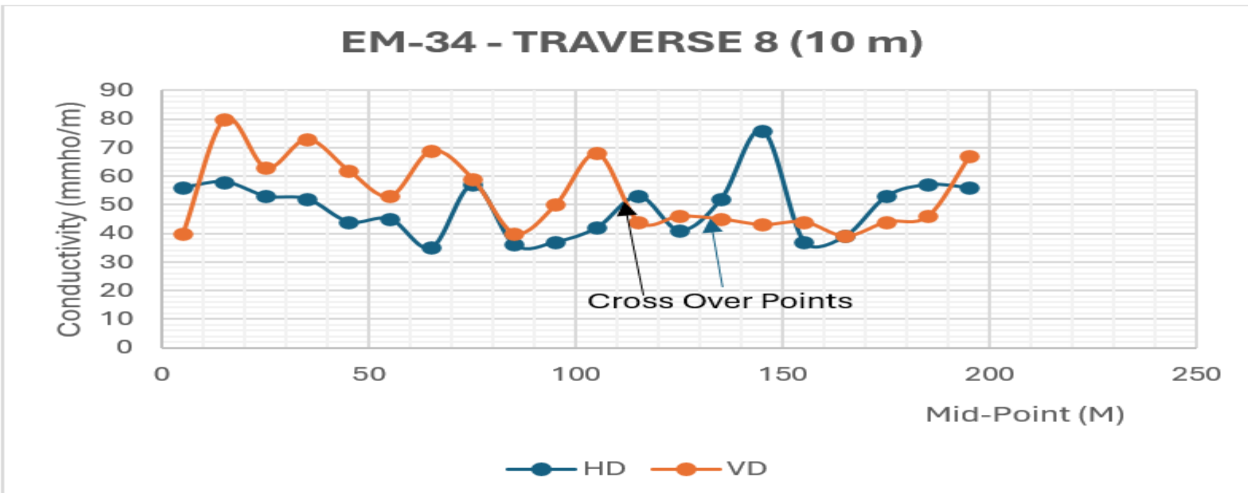

Figure 4.15: Plot of HD and VD along Traverse 8(10m Spacing)

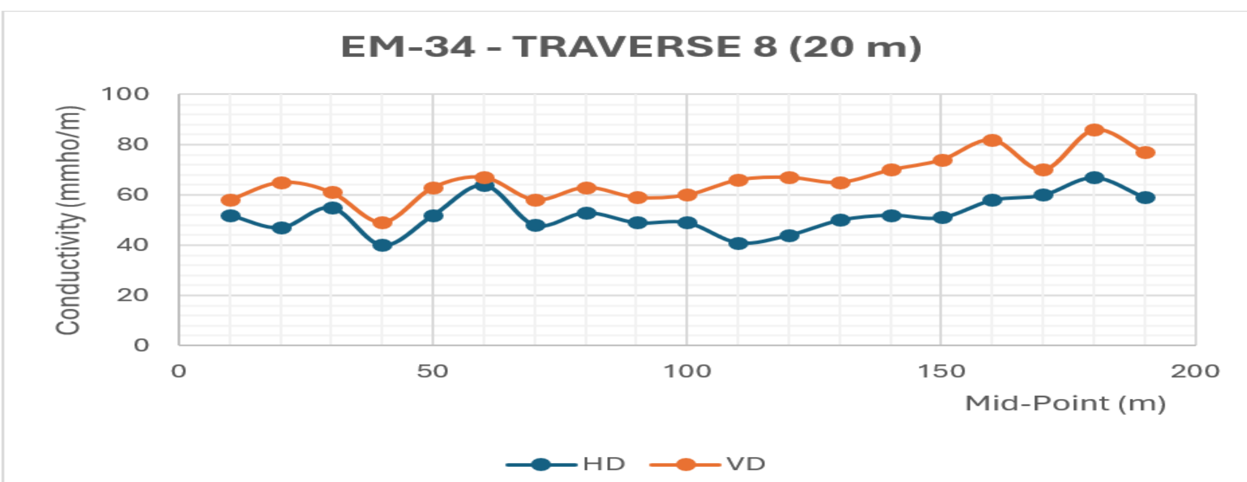

Figure 4.16: Plot of HD and VD along Traverse 8 (20m Spacing)

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU9

The plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10m coil spacingalong traverse 9 is presented in Figure 4.17. The result covered a total distance of 200m. The plot showed varying conductivity signatures across the entire profile. However, six (6) prospect zones suggestive of possible aquifer zones were identified at lateral distances of 40m, 70m, 70m to 100m, 108m to 125m, and 125m to 155m. These are zones for possible groundwater supply. For the 20m coil spacing, the subsurface shows similar subsurface conductivity across the profile line as shown in Figure 4.18. However, an anomalous zone suspected to be a zone for possible groundwater supply (aquifer) was identified at a lateral distance of 90m to 105m. The anomalous zone occurs at a deeper depth than that of the 10m coil spacing. Thus, the prospect zones were identified along the 10m coil spacing and only one prospect zone was delineated using the 20m coil spacing.

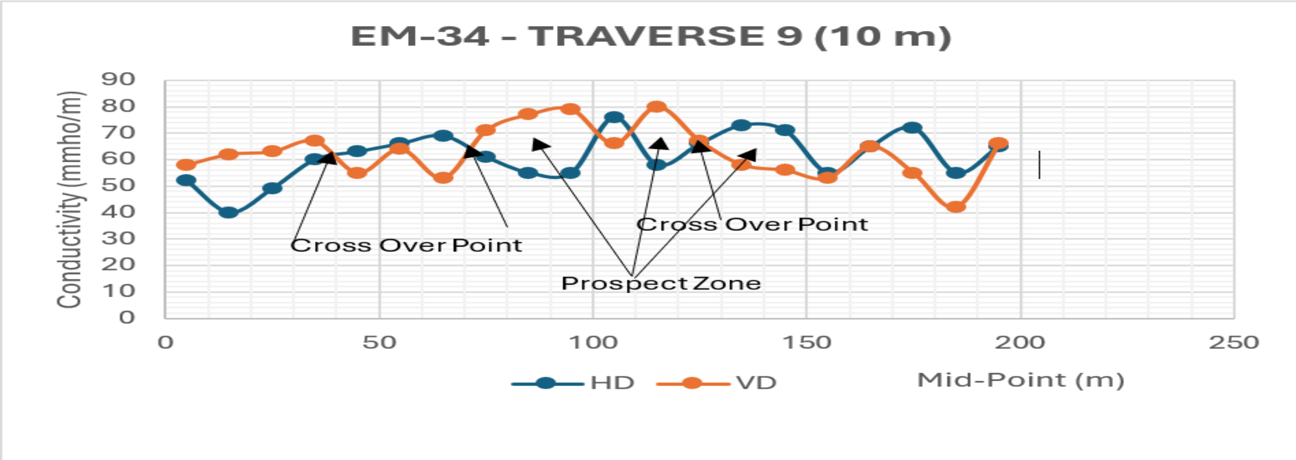

Figure 4.17: Plot of HD and VD along Traverse 9(10m Spacing)

International Research Journal of Pure and Applied Physics, 11 (1),98-131, 2024
ISSN 2055-009X(Print)
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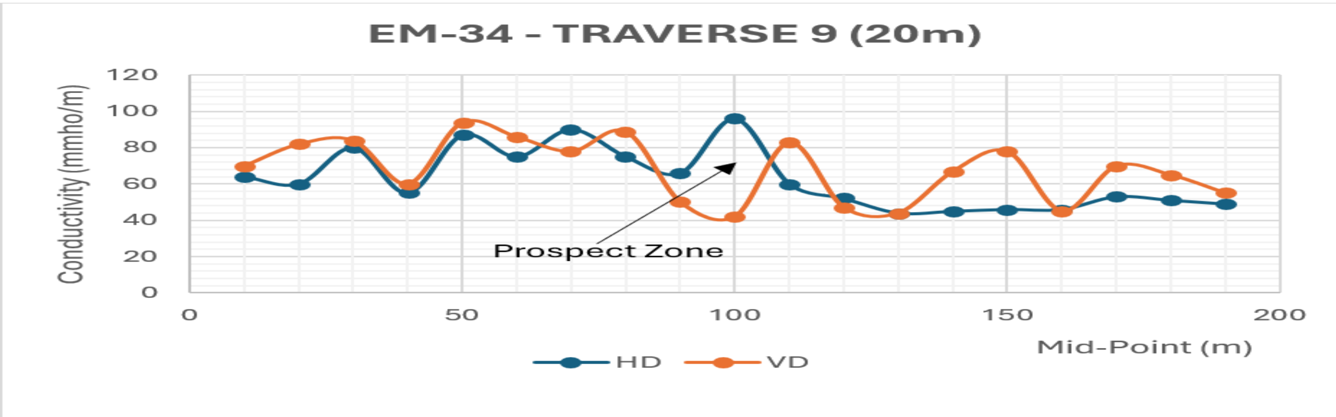

Figure 4.18: Plot of HD and VD along Traverse 9(20m Spacing)

EM Plot for Horizontal Dipole (H_D) and Vertical Dipole (V_D) along Traverse EMORU10

The plot of horizontal dipole (H_D) and vertical dipole (V_D) for the 10m coil spacing along traverse 10 is presented in Figure 4.19. The result covered a total distance of 100m. The plot showed varying conductivity signatures across the entire profile. However, two (2) prospect zones suggestive of possible aquifer zones were identified at lateral distances of 30m and 41m. These are zones for possible groundwater supply. The plot of the 20m coil spacing along traverse 10 is presented in Figure 4.20. The plot showed slightly similar subsurface conductivity across the profile line. Two (2) anomalous zones were identified suggestive of possible aquifer zones at lateral distances of 32m and 60m to 76m. The anomalous zone occurs at a deeper depth than that of the 10m coil spacing.

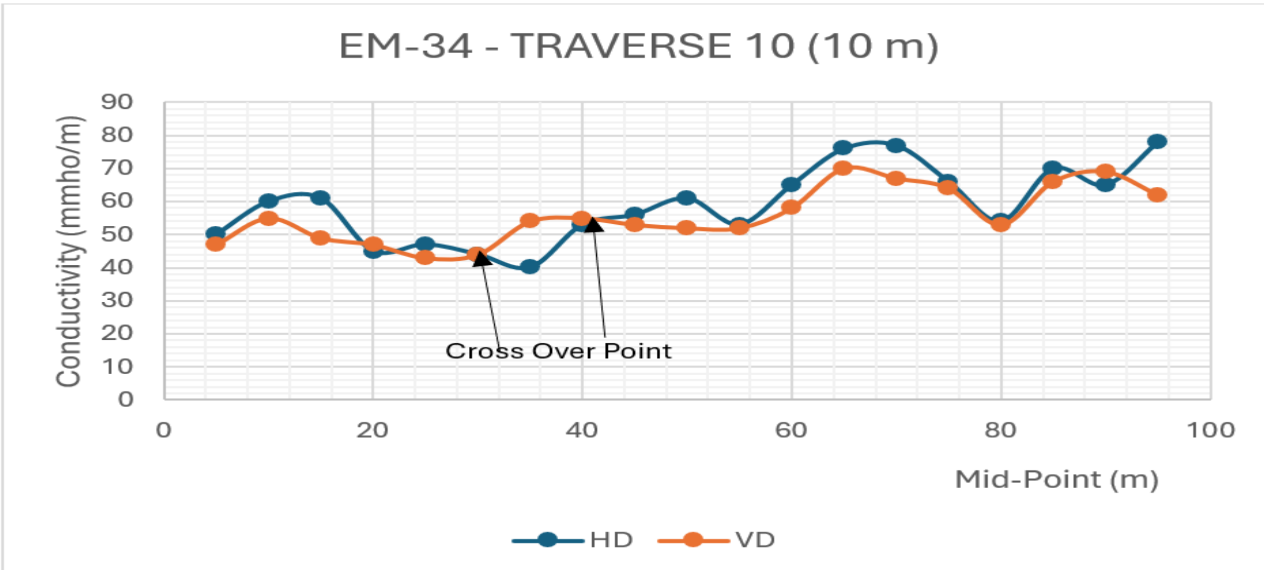

Figure 4.19: Plot of HD and VD along Traverse 10 (10m Spacing)

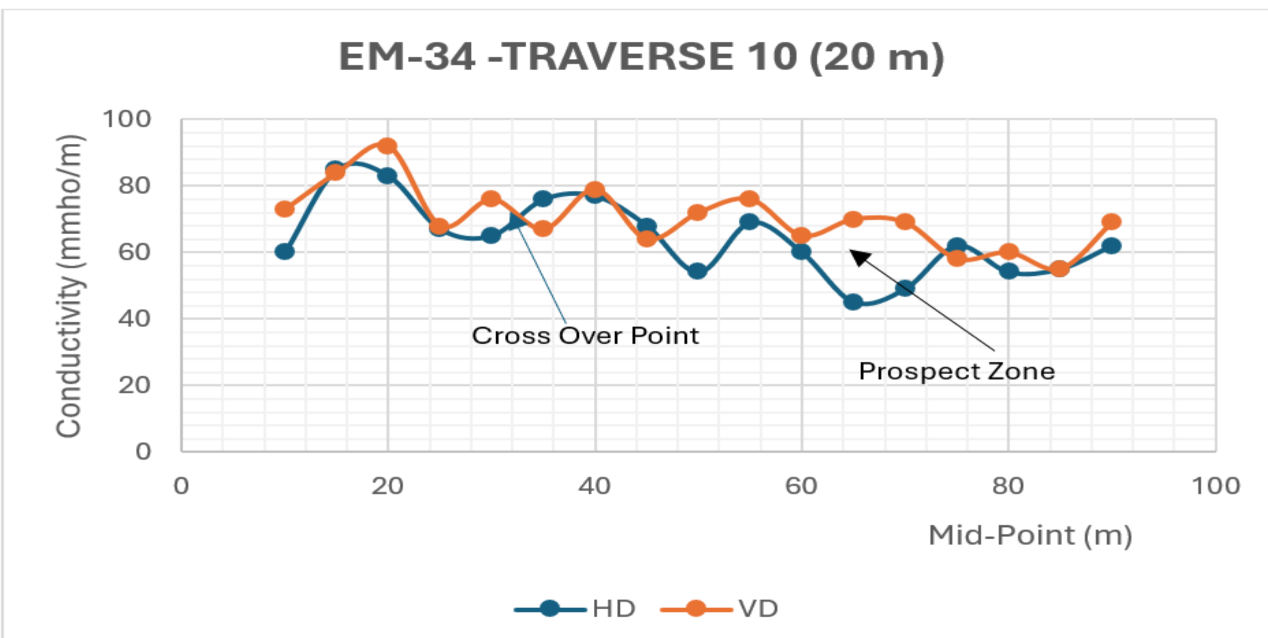

Figure 4.20: Plot of HD and VD along Traverse 10(20m Spacing)

CONCLUSION

A detailed electromagnetic method of geophysical prospecting was carried out to provide valuable insight into the variations in subsurface conductivity to assess the groundwater potential of the Oru-Ijebu community of Ogun State using the Geonics EM 34-3. The transmitter sends an electromagnetic (primary field) into the ground through a coil. The EM signal induces an electric current in the subsurface that flows and detects the subsurface anomaly (fractures or weathered basement, metal objects, subsurface contaminants, cavities) and generates a secondary magnetic field. Both the primary and secondary magnetic fields are detected by the receiver coil. The subsurface conductivity values in the horizontal and vertical dipole modes are read from the receiver. The EM data was acquired with the Geonics EM 34-3, along 5 North-South profiles with two distinct EM measurements separately undertaken along a profile with inter coil spacing of 10m and 20m, at station intervals of 100m and 200m. Points of high conductivity are prospective sites for further facilitation of groundwater development like borehole drilling to fully harness the groundwater resources of the area. Different traverses indicated areas with low conductivity, suggesting non-fractured zones, while specific high-conductivity zones were associated with potential water accumulation sites. The results of this study provide valuable insight into the subsurface conductivity variations associated with water-bearing geologic structures by assessing the various patterns of the EM signature. At each station, the subsurface conductivity reading was measured with the transmitter and receiver coils in the Horizontal Magnetic Dipole Mode (HDM) and Vertical Magnetic Dipole Mode (VDM). The processed data were further presented as horizontal and vertical plots on a line graph. In the 10 m coil spacing, the highest and lowest subsurface conductivity is exhibited by EMORU1 and EMORU6 with the values of 164mmho/m and 68mmho/m respectively in HDM. The highest and lowest conductivity is exhibited by EMORU4 and EMORU10 with the values of 139mmho/m and 70mmho/m respectively in VDM. Also, in 20m inter coil spacing, the highest conductivity is jointly observed in EMORU2 with 190mmho/m and 200mmho/m in HDM and VDM respectively. The lowest conductivity is equally observed

ISSN 2055-009X(Print)
ISSN 2055-0103(Online)
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in EMORU6 with values of 56mmho/m and 80mmho/m for HDM and VDM respectively with the analysis identified key lateral distances for groundwater prospecting, particularly between 72 m to 154 m along the profiles. This study has therefore investigated and characterized the study area for possible groundwater exploration, with varying conductivity values with locations of high conductivity reflection points and cross-over points are prospective sites for groundwater exploration while locations of similar trends in both HDM and VDM possess the same lithology. Qualitative interpretation of the EM results identified areas for successful borehole drilling and forms a predictive basis for Vertical Electrical Sounding for further investigation.

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