

Investigation of the Source of Groundwater Contamination Near a Farmland Using the VLF-EM and Magnetic Methods

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Abstract
Groundwater pollution continues to be a major problem in society where there is high level of urbanization, industrialization and conventional/inorganic farming. A detailed ground magnetic survey and VLF-EM was carried out on a site just beside a farmland to investigate the possible causes of the groundwater contamination in the area which lies within the Precambrian Basement Complex of Southwestern Nigeria. The survey was carried out using a proton precision magnetometer kept at a constant height during the survey, accompanied by Very Low Frequency - Electromagnetic Method (VLF-EM). Data for the two methods were acquired on five (5) traverses with the length of 100 m each. The distance between each traverse (inter traverse spacing) is 5 m. The VLF-EM data were interpreted qualitatively, using the Fraser and the Karous–Hjelt filters. The Fraser filtered data and relative current density pseudosections from the VLF-EM data indicate the presence of shallow and deep conductive zones that cross the farmland which are indicative of fractures. The quantitative interpretation of the data was done with a 2-D code that performs the inversion of the data. Magnetic maps were generated using Oasis Montaj, and profiles were plotted using Microsoft Excel software. From the results obtained, some major geological features were identified while linear features suspected to be fault/fractured zones, weathered zones, and bedrock depressions were delineated. Low magnetic intensity indicating presence of weak and incompetent zones were discovered. Earlier chemical analysis of both surface and groundwater collected at some depth on the farmland confirms the presence of water contamination. This knowledge supported the interpretation of the anomalies detected by VLF-EM and magnetic data as a possible cause of the contaminated groundwater flowing in connected fractures. The study concluded that the groundwater contamination originates from the farmland where some samples of the soil were found to contain nitrate chemicals resulting from fertilizer and pesticide used to enhance plant growth.
Keywords: Nitrate contamination, groundwater pollution, multiple fractures, contaminant transport, fractured zone, inorganic farming
DOI: 10.7176/JEES/12-6-04
Publication date: June 30th 2022

1. INTRODUCTION

The most serious water contamination observed in agricultural areas is mainly caused by fertilizer and pesticide application on farmland. When rain falls, this results in chemical runoff from the agricultural fields into surface waters which then percolates into groundwater (Jia, 2021). Nitrate contamination of groundwater has been identified as a significant pollution in agricultural areas. Thus, because of the abundance of fractures in the basement complex environment, multiple groundwater basins have the tendency of being affected by discharges of waste from farmlands, leachates from landfill and decayed buried objects in contact with surface or ground water. Pollution of the environment arises from several technological advancement and improper application of some of the resources. This usually bring about little consideration for the effects they have on the groundwater and surface water (Cairl et al., 2003; Isiuku & Enyoh, 2020; Oladeji et al., 2016).

A good irrigation planning, and proper inorganic farming management could help prevent the effects of chemical runoff from fertilizers on groundwater. The agrochemicals and sediment released through subsurface drainage and surface runoff could create an adverse environmental impact on groundwater supply in a community (Eyinla & Oladunjoye, 2014). Thus, various studies (e.g., Allred et al., 2017; A. K. Benson et al., 1997; R. C. Benson, 1993; Eyinla & Oladunjoye, 2014; Jones & Hockey, 1964) have reported that geophysical methods can be applied to the study of subsurface water flow patterns and can also help to monitor the soil suitability for maximum agricultural production which would eventually reduce the need for fertilizers on farmland. A recent study presented by Isiuku & Enyoh (2020) described the effects of nitrate and phosphate concentration found in water bodies in some parts of Southeastern, Nigeria. These effects could range from being minimal to life threatening.

Certain problems associated with landfill and its leachates, and how these can serve as potential sources of environmental contamination have been presented in earlier studies (e.g., Azeez & Eyinla, 2014; Clarke et al., 2015; Eyinla & Eyinla, 2017; Pinel-Raffaitin et al., 2008). Geophysical methods and geochemical analysis often aim at detecting and determining the extension of the polluted area by identifying some properties of the rock and that of the fluids they contain (Azeez & Eyinla, 2014). Similarly, the application of resistivity and electromagnetic geophysical methods for studying groundwater pollution provide possible means of evaluating the extent of the contamination. These studies are possible because the presence of organic and inorganic chemicals could result in a significant variation, mostly a decrease in the electrical resistivity of the rock.

An important Geophysical tool for environmental and groundwater study is the Very Low Frequency Electromagnetic Method (VLF-EM). VLF instruments can be used to study large areas very quickly because of its lightweight and portability. Thus, VLF method has been applied in the exploration of fractured zones, groundwater exploration and groundwater contamination (e.g., Adelusi et al., 2014; Al-Tarazi et al., 2008; Jamal & Singh, 2018; Ohwoghere-Asuma et al., 2020; Sharma & Baranwal, 2005; Sundararajan et al., 2007). A special quality that makes the VLF-EM very useful is that it is very sensitive to ground water quality and can detect conductive geological materials easily as it is able to determine the electrical characteristics of rocks in the shallow zone (Sharma & Baranwal, 2005; Sundararajan et al., 2007). The tool can be integrated with the electrical resistivity method to delineate aquifer contamination (Ohwoghere-Asuma et al., 2020). However, magnetic method is more versatile as it can detect deep and shallow targets. For the shallow investigation, the magnetic tool can characterize sediments above the bedrock and the bedrock topography can be defined. The main application of the magnetic method in groundwater investigation includes mapping of bedrock topography, locating basement fault and fractures and identifying zones of crustal weaknesses which may help to infer fluid flow path (Olorunfemi & Oni, 2019). It can also be used to map bedrock topography, especially when combined with other methods for correlation.

Thus, this study integrates the VLF-EM and magnetic methods to delineate the possible causes of groundwater contamination in the study area. The study area is a local community whose main usage of water is for domestic purposes and relies on hand-dug wells and boreholes. A farmland is located within the area where fertilizers have been continuously applied for plant growth. Geochemical analysis conducted on some samples of water taken from the surface and at shallow depth on the farm site revealed the presence of nitrate chemical in the water sample. The objectives of the study include identification of weak (conductive) zones within the area, and delineation of geologic structures such as faults, fractures, depressions, and joints which could serve as pathway for the contaminated fluid to flow from surface water into the groundwater.

2. LOCATION AND GEOLOGICAL SETTING OF THE STUDY AREA

This study was carried out in Akure, Southwestern Nigeria, and is underlain by Precambrian Basement Complex rocks (Figure 1). It lies within Northings 797600 mN and Eastings 751800 mE, UTM Minna Zone 31. The average elevation in the area is about 369 meters (1211 feet), and there are several outcrops with some hills which imply that the place is of high relief. The topography of the area indicates a downward slope trending N-S. The drainage pattern of the area is dendritic, and it is heavily dissected by rivers and streams. The flow pattern in the river is averagely North-South direction, which is supported by the topography of the area.

Notably, groundwater development in a typical basement complex environment is found in two main aquifer units, which are the weathered zone and the fractured basement aquifers (Falowo et al., 2019; Olagunju et al., 2017; Olorunfemi & Oni, 2019). Chemical alteration of the minerals produced the weathered aquifer layer while the fractured rock system originates from tectonic activities. It is possible for the aquifer to be in the weathered layer or in combination with the fractured rock. However, the continuous mining processes and agricultural activities make the water table to be directly exposed at the uppermost part. Consequently, this becomes vulnerable to both surface and near surface pollution arising from leachate from dump sites and chemicals wash from fertilizers on farmland (Falowo, 2018).

As shown in Figure 1, there are seven different rock units found in the area, which includes Migmatite-Gneiss, Quartzite, Charnokite, Biotite granite, Pelitic Schist, Granite Gneiss, and Granite as reported by (Falowo, 2018; Falowo et al., 2019). However, the dominant rock types found at the vicinity of the study location are Biotite Granite with some intrusion of Quartzite and Migmatite Gneiss. There are some observable structures in the rocks such as foliation, faults, joints, fractures, and fold of different types. The structural trend in the area is NNW-SSE and NNE-SSW.

For this study, data were collected along 5 traverses cutting across the sections of the farmland as shown on the bottom image in Figure 1. The topography of the area is a downslope such that there is a flow of water running beside the farmland in N-S direction.

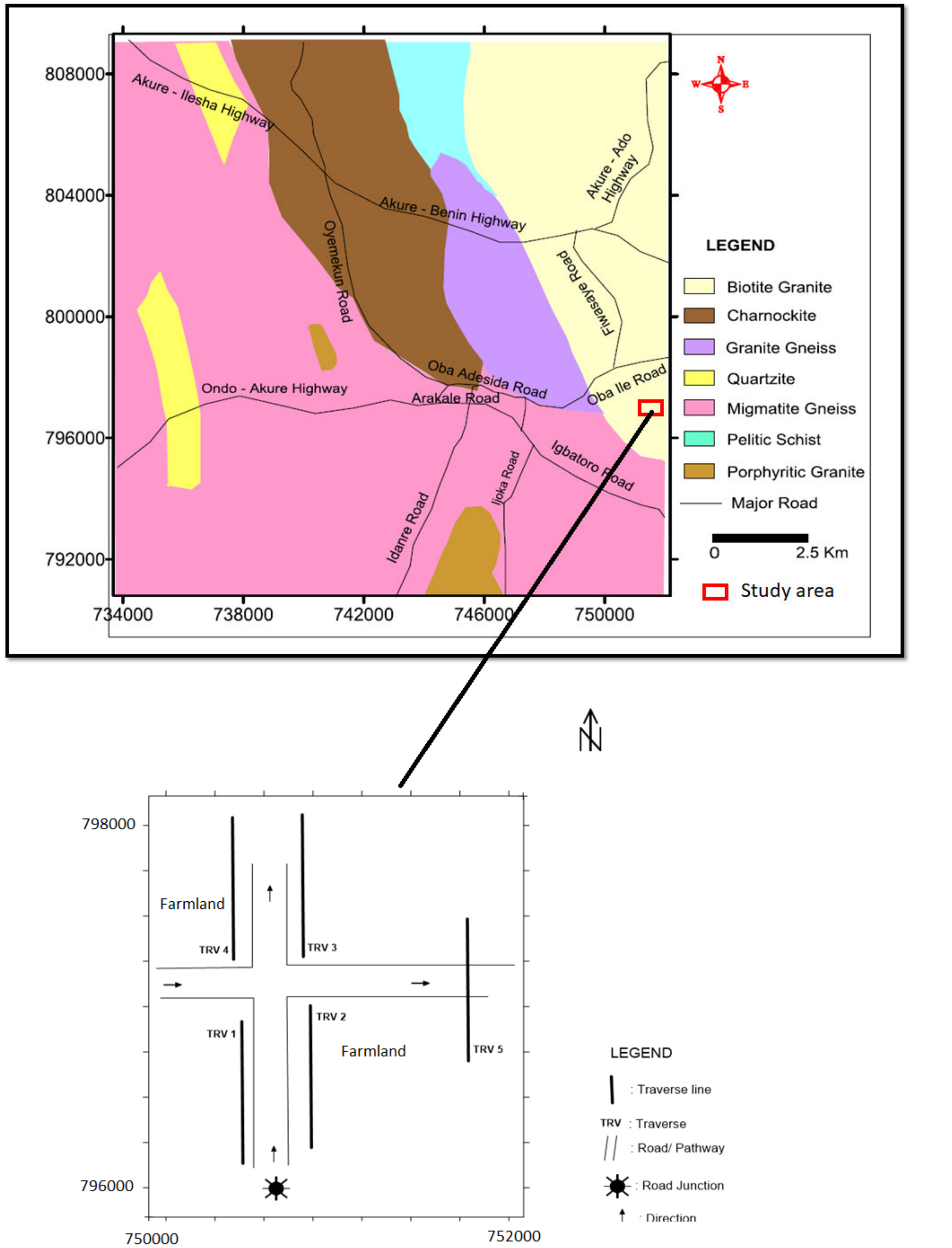

Figure 1: Geological map of Akure and environs showing the rock types in the study area and the layout of traverses in the study location (modified after Falowo et al., 2019).

3. MATERIALS AND METHODS

3.1 MAGNETIC METHOD (PROTON MAGNETOETER)

Magnetic method is the oldest geophysical exploration method used in prospecting. It measures the variation in the Earth's magnetic field caused by changes in the subsurface geological structure or the differences in near-surface rocks' magnetic properties (Salvatore et al., 2018). The relationship between magnetic fields and the magnetization within materials is expressed by:

$$B= \mu_O(H+M) \quad (1)$$

$$\mu = 4\pi \times 10^{-7} Wb/Am^{-1} \quad (2)$$

where B, the magnetic induction is the total flux of magnetic field lines through a cross-sectional area of a material, μ_O is the permeability of free space (4π×10−7 Wb/Am), H is the magnetic field applied to the material and M is magnetization or response of the material to the applied magnetic field. Magnetic susceptibility (k) is another important parameter, and the relationship between magnetic induction B, magnetizing force Hand susceptibility k is given as:

$$B= \mu_O H(1+K) \quad (3)$$

Where B is in tesla, H is given in amperes/meters and k is dimensionless in SI units (Nabighian et al., 2005). Magnetic traverses were carried out along N-S direction. Magnetic stations were established at 10 m intervals with a length of 100 m. Magnetic data were corrected for diurnal variation and offset using standard method. Magnetic data were presented as profiles which for qualitative interpretation. The total field obtained from the land magnetic data can be the sum of a regional field and the anomaly due to the point source (Nabighian et al., 2005). Consequently, correction is necessary to remove all causes of magnetic field other than those arising from the local magnetic effect of the subsurface. These corrections include the drift correction and geomagnetic correction. Also, noise from local sources can perturb the magnetic field such that spikes are observed on this drift corrected values. A three-point moving average filter is applied in this case to iterate the spiky field so that the resulting values can be residualized using trend analysis on MS Office Excel. Residualization of the magnetic field is done to remove the regional component of the field such that the net component is a representative of the local magnetic field of the area of study.

3.2 VERY LOW FREQUENCY (VLF) – ELECTROMAGNETIC METHOD

VLF-EM method utilizes Very Low Frequency radio communication signals to determine electrical properties of near-surface soils and shallow bedrock. The technique is applicable in mapping steeply dipping structures such as faults, fracture zones and areas of mineralization. In the reconnaissance mode, VLF profiles can be run quickly and cheaply to identify anomalous areas which may require further investigation through other detailed geophysical methods and/or drilling and sampling. These factors have given the VLF method wide applications in many geophysical studies including environmental, groundwater, mining and engineering survey. VLF can detect long conductors such as electric cables, pipelines, and certain bedrock fractures (Gnaneshwar et al., 2011). The radio signals used in the VLF-EM method is in the bandwidths of 10–30 kHz, and the equipment serves as a powerful tool for quick reconnaissance of near surface structures. It may be used wherever an electrical conductivity contrast is present between geological units. This may include Fault mapping, Groundwater investigations, Overburden mapping, Contaminant mapping, and Mineral exploration (Fraser, 1969; Gaafar, 2015; Gnaneshwar et al., 2011; Karous & Hjelt, 1983; Khalil & Santos, 2011a, 2011b). Electrically conductive features include fault zones, and zones of mineralization which tend to be more conductive than the surrounding bedrock or host rock. These significant differences make it suitable for mapping geologic structures and interface between difference rocks. Depth of investigation is controlled 35 by the electrical "skin depth" of the local geology. It varies from 40-60 meters in highly resistive soils to 4-5 meters in conductive soils. Productivity of the equipment depends on the terrain and vegetation. Depth of penetration of VLF signals is directly proportional to the resistivity of the material (Santosh et al., 2009).

VLF receiver measures the current density due to the primary (transmitted) and secondary (induced) magnetic fields. Structures such as water-saturated fracture zones, mineralized zones, metallic ore bodies, and conductors such as electric cables or pipelines may be detected through these measurements. The ability to detect water-filled bedrock fracture zones makes this type of survey method useful for bedrock water supply development and for site investigations that involve groundwater contamination (Gnaneshwar et al., 2011).

A good way of interpretating VLF-EM data is by qualitative methods based on filtering procedures. The two most applied processing methods are the Fraser and Karous–Hjelt filtering methods (Fraser, 1969; Karous & Hjelt, 1983). In the Fraser filter methods, the zero-crossing points is transformed into peaks which enhances the signals of the conductive structures.

4. RESULTS AND DISCUSSIONS

4.1 MAGNETIC PROFILES, VLF-EM PROFILES AND 2D PSEUDOSECTIONS

The results from the magnetic geophysical investigation are presented as profiles, and the results of the VLF as profiles and 2D pseudo sections. The ground magnetic survey generated high resolution images that showed major lithologies and structural features that are present in the study area. These profiles helped to identify the change in magnetic properties and to predict possible geologic structures. Anomalous high magnetic zones and low magnetic area suspected to have resulted from changing properties of the rock. The profile data has been reduced to the equator, with International Geomagnetic Reference Field, IGRF = 32,0000 nT subtracted from the ground magnetic reading. The magnetic profile represents the total magnetic intensity along all the profiles after all the steps of data processing have been applied. The vertical axis represents the magnetic intensity in Nanotesla (nT) while the horizontal axis represents the distance of stations along each profile.

In the VLF-EM method, the data obtained in the field were interpreted qualitatively using the Fraser and the Karous–Hjelt filters. The Fraser filtered data and the relative current density pseudosections obtained clearly reveal the presence of various shallow and deep conductive zones in the area.

Figure 2 shows the magnetic profile for traverse one. The vertical axis represents the magnetic data in nanotesla (nT) while the horizontal axis represents the station distance (m). A major part of the profile shows magnetic intensities which are assumed to be made up of higher magnetic minerals and materials. These are interpreted to be the competent zones where the rock mass in still intact. The main portion of the profile where low magnetic readings have been observed is the interval from 75m to 90m. These areas with low magnetic values are areas with non-magnetic minerals and are interpreted to be the faulted or fractured zones. These areas are likely to contain water due to the presence of fractures making them susceptible to accommodate and allow free passage of water. Figures 3a and 3b show the VLF result for traverse one. The section with low magnetic readings in Figure 2 also correlate with the section where there is high conductivity. The profiles show positive peaks of different intensities and sharpness which suggests the presence of shallow and deep conductor. The fracture zones lies between distance 75m to 90m which align with the point where there are magntic lows on the magnetic profile. These zones appear to be well fractured, and are suspected to contain conductive fluids.

The plot of the magnetic readings in the second traverse is shown in Figure 4. The rocks in these zones are not well fractured. While there are a few peaks, they generally do not have low magnetic values which could be interpreted as faulted zones or fractured zones. Figures 5a and b show the VLF results for traverse two. There are a few intervals of high conductivity, but the values are lower than those in traverse one. Thus, these are possibly intervals with partially weathered zones containing some amount of water.

Figure 6 presents the magnetic data for the third traverse. This profile has several intervals with high and low peaks which also correlate with the low and high conductivities in the VLF-EM profile in Figures 7a and b. Since the intervals with low magnetic readings also match the areas where high peaks of conductivity are observed, it is deduced that these are the faulted or fractured zones with conductive fluids. A similar trend is observed in Figure 8 showing the magnetic profile of traverse 4, and the corresponding VLF-EM plots in Figures 9a and b from the same traverse.

In the fifth traverse, the result of the magnetic data obtained is plotted in Figure 10. The profile shows two major low magnetic zones at intervals 30m and 55m. Seemingly, these points correspond to the high conductivity peak values on the VLF-EM profile in Figure 11a. These intervals interpreted as highly fractured zones with conductive fluid. Overall, the entire area contains multiple fracture system which are connected, and they could serve as flow pathway for contaminated water flow from the soil to the groundwater. The negative peak where materials are more resistive are regarded as intact materials with nonconductive basement rocks.

The pseudosections of the VLF-EM data in Figures 3b, 5b, 5b, 7b, 9b and 11b show contours of high and low conductive zones. Zones with red colour contours are intervals with high conductivity. These features have been interpreted as fractured rocks with conductive fluids which in this case could be the water flowing from the surface through the fractures down to the water table.

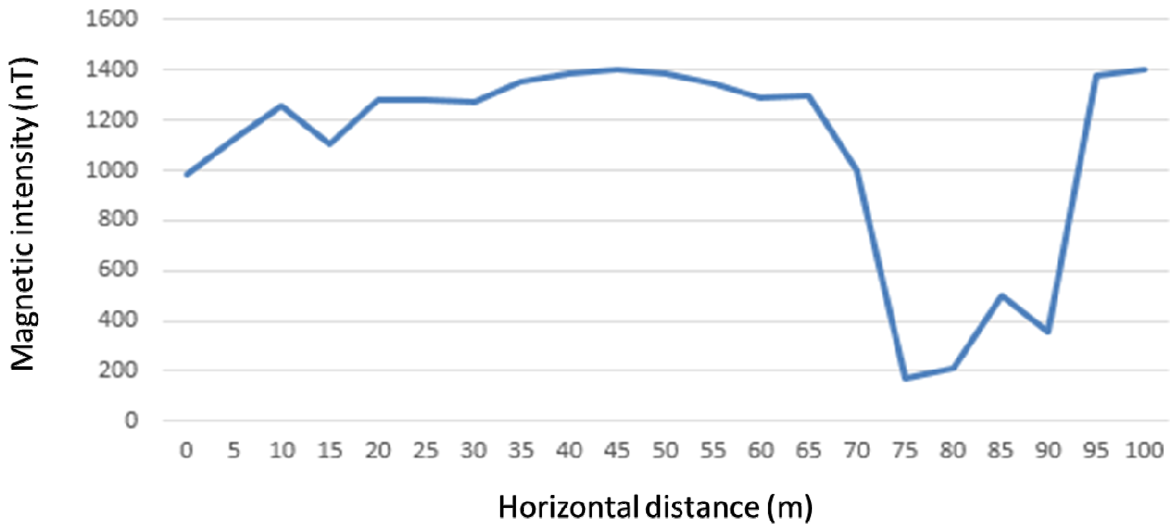

Figure 2: Profile showing the magnetic result for the magnetic data obtained for the first traverse

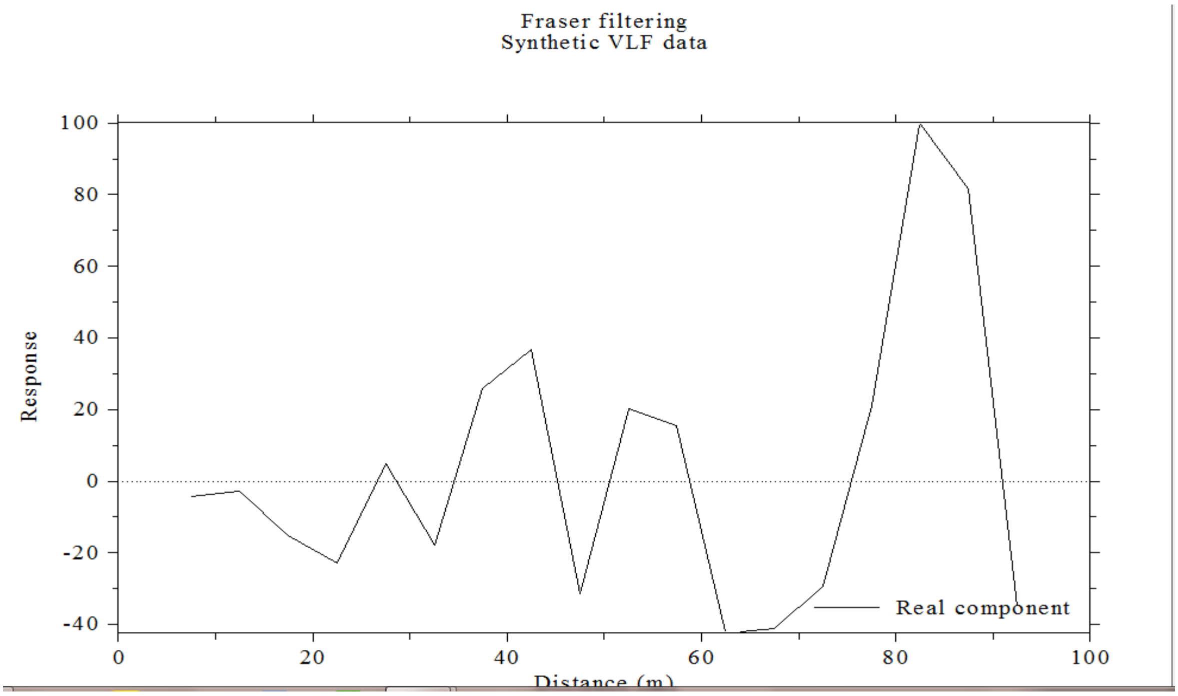

Figure 3a: profile showing the VLF result of the VLF data obtained for the first traverse

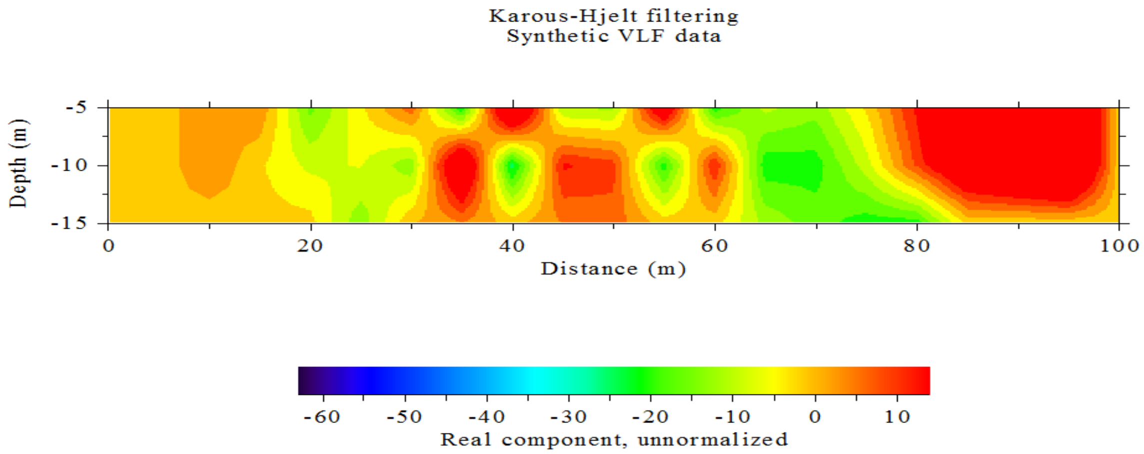

Figure 3b: Profile showing the VLF result of the pseudo-section for the VLF data obtained for the first traverse

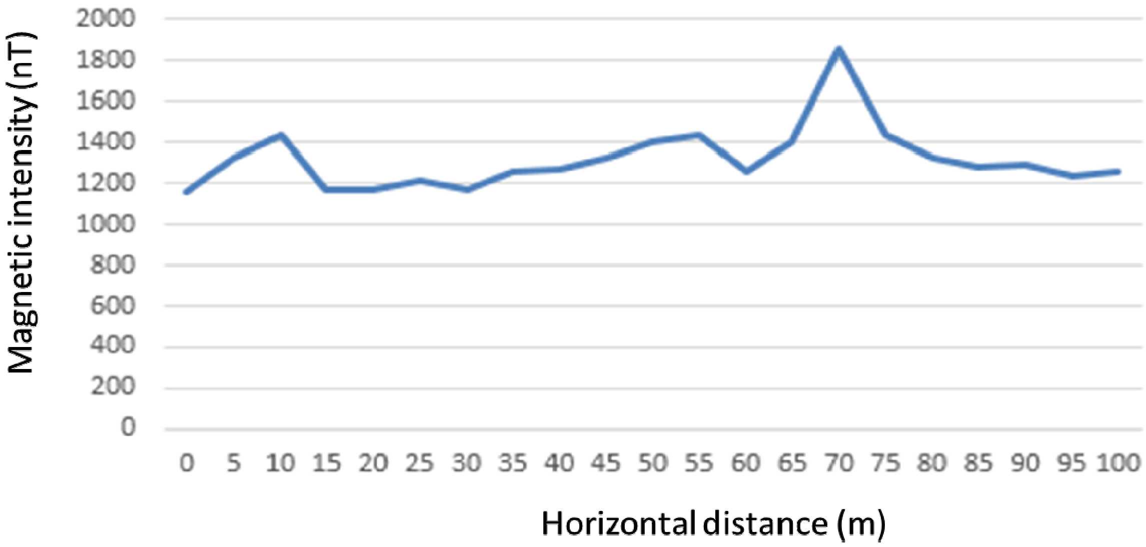

Figure 4: Profile showing the magnetic result for the magnetic data obtained for the second traverse

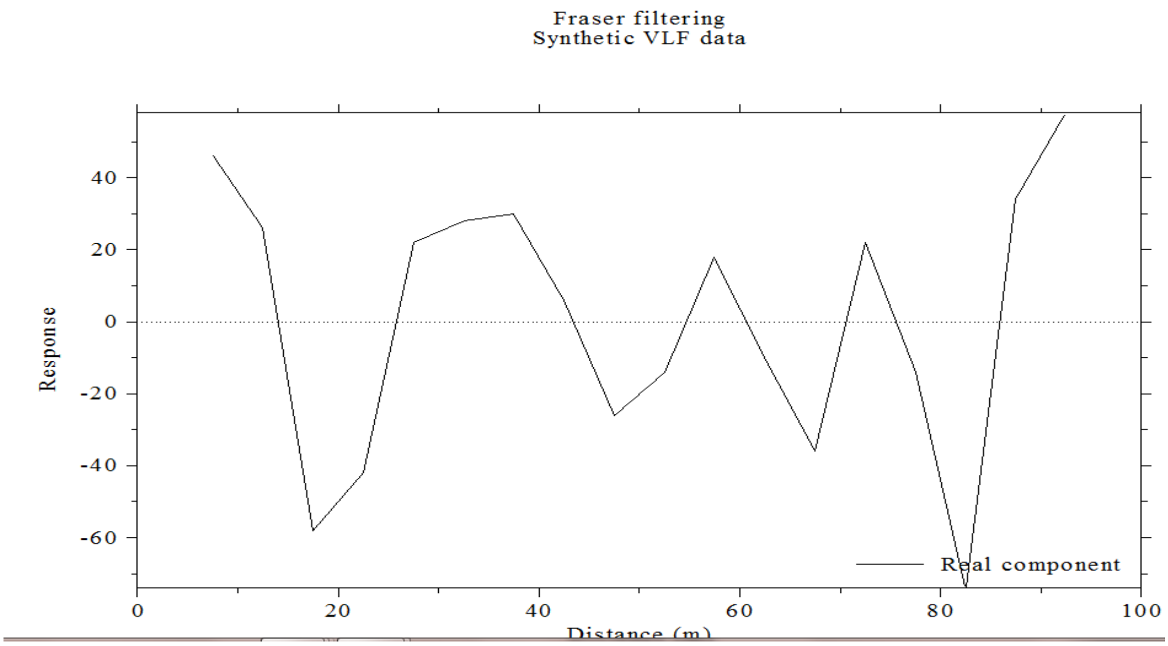

Figure 5a: Profile showing the VLF result for the VLF data obtained for the second traverse

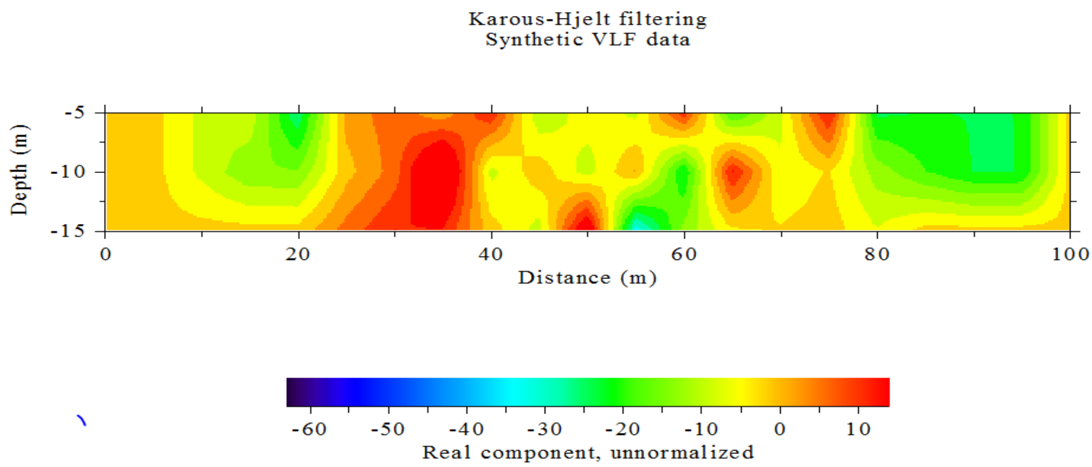

Figure 5b: Profile showing the VLF result of pseudo-section for the VLF data obtained for the second traverse

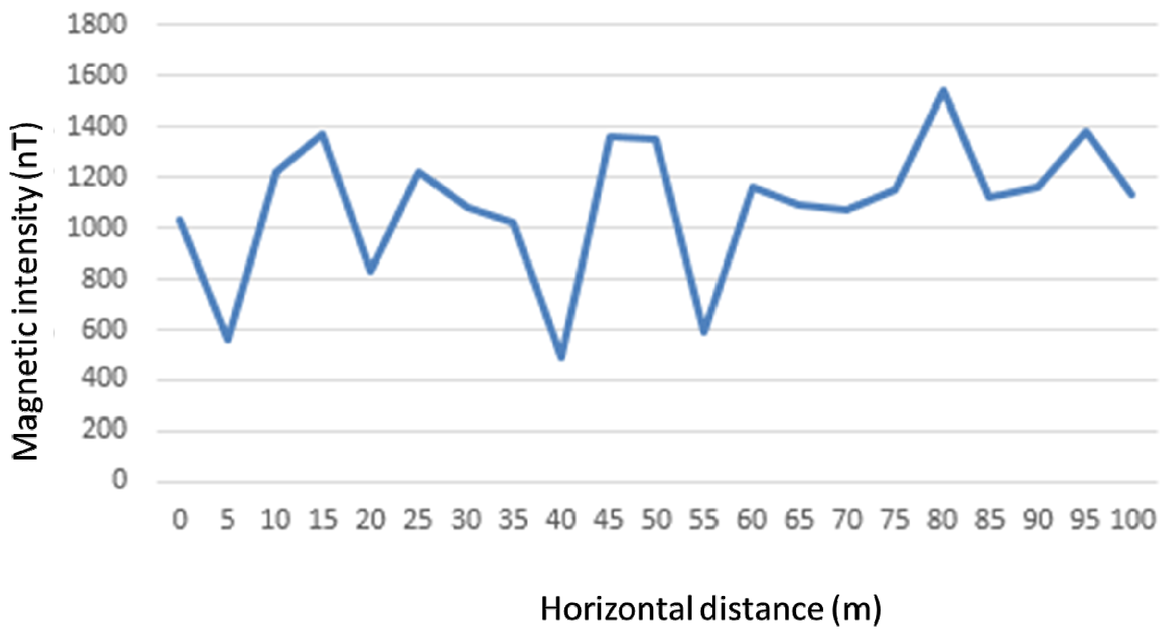

Figure 6: Profile showing the magnetic result for the magnetic data obtained for the third traverse

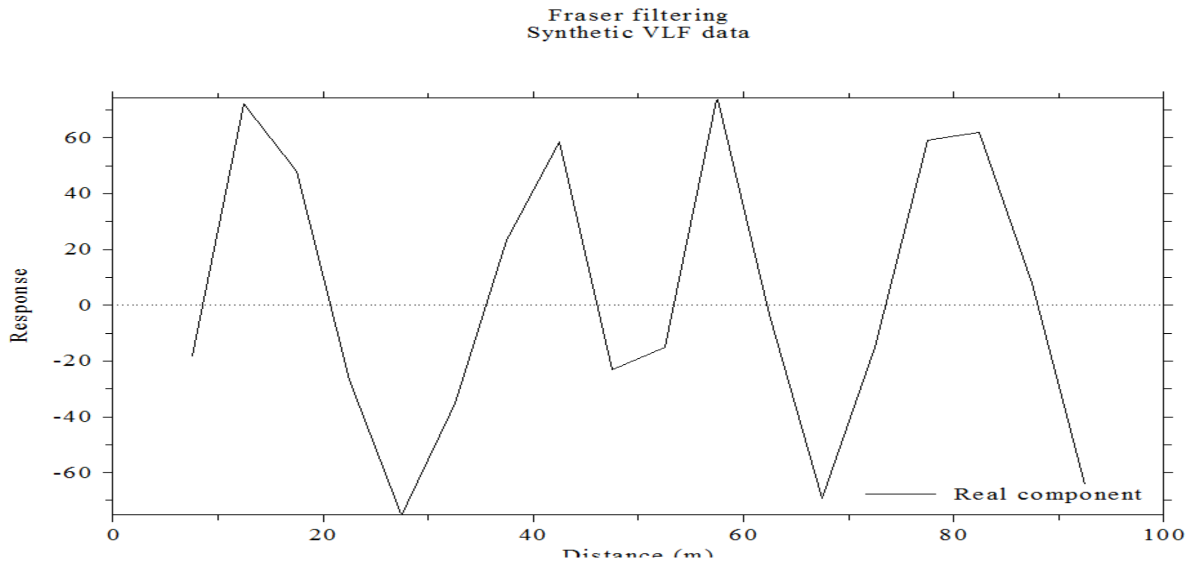

Figure 7a: Profile showing the VLF result for the VLF data obtained for the third traverse

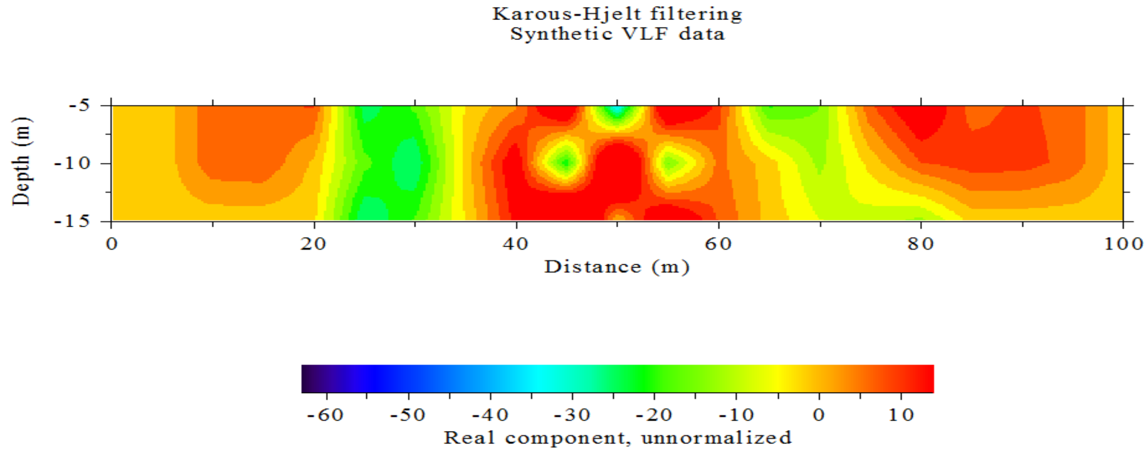

Figure 7b. Profile showing the VLF result of the pseudo-section for the VLF data obtained for the third traverse

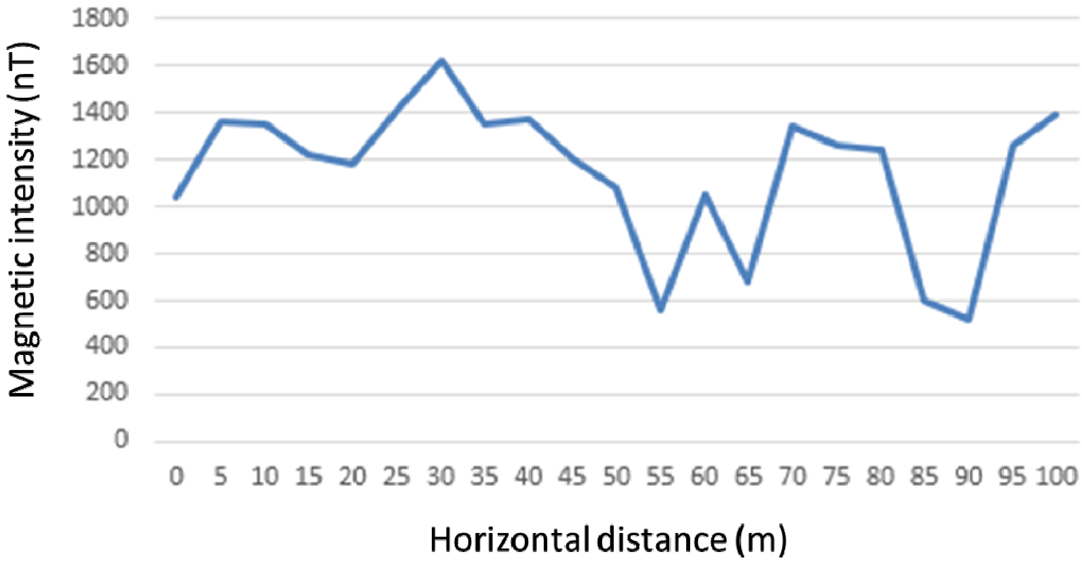

Figure 8: Profile showing the magnetic result for the magnetic data obtained for the fourth traverse

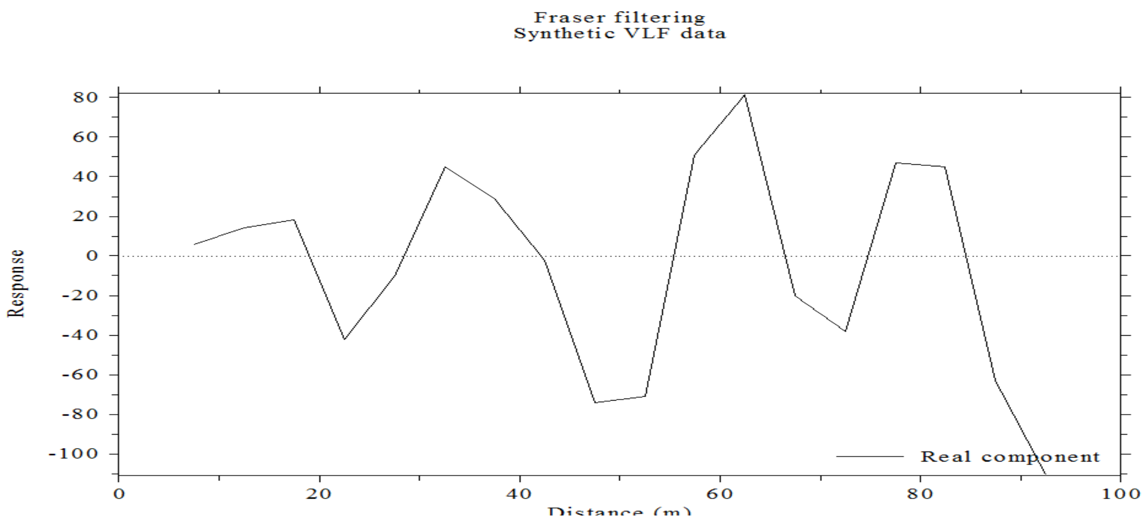

Figure 9a: profile showing the VLF result for the VLF data obtained for the fourth traverse

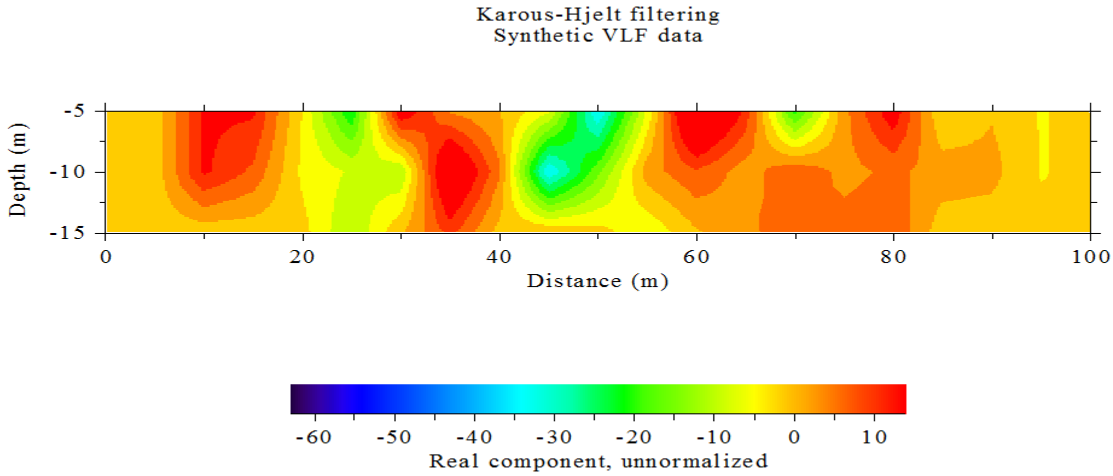

Figure 9b: Profile showing the VLF result of the pseudo-section for the VLF data obtained for the fourth traverse

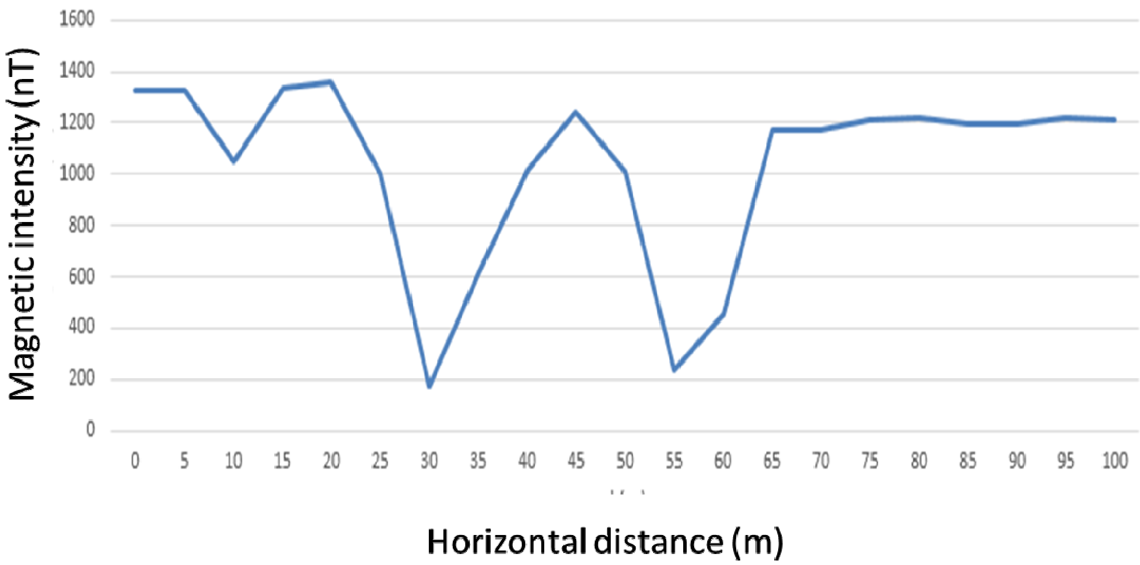

Figure 10: Profile showing the magnetic result for the magnetic data obtained for the fifth traverse

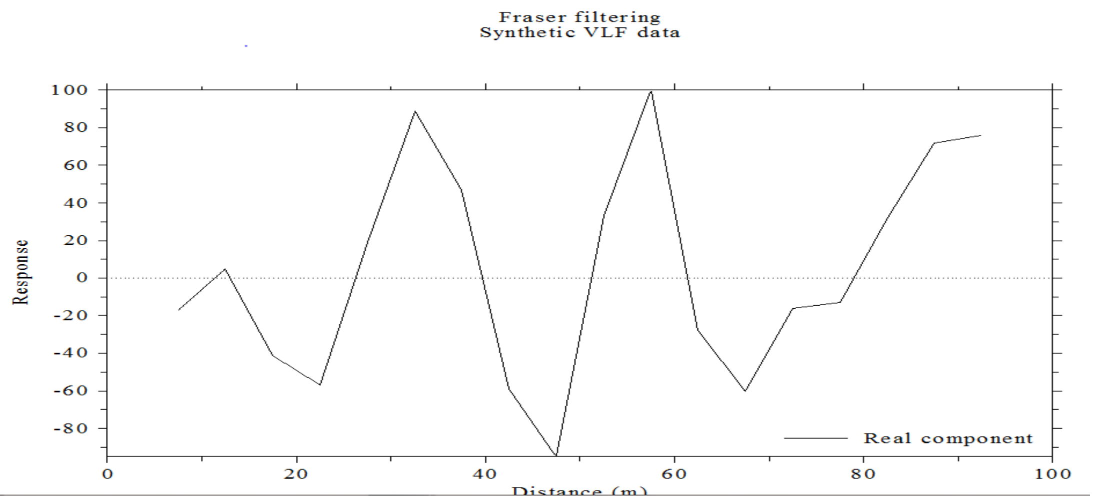

Figure 11: Profile showing the VLF result for the VLF data obtained for the fifth traverse

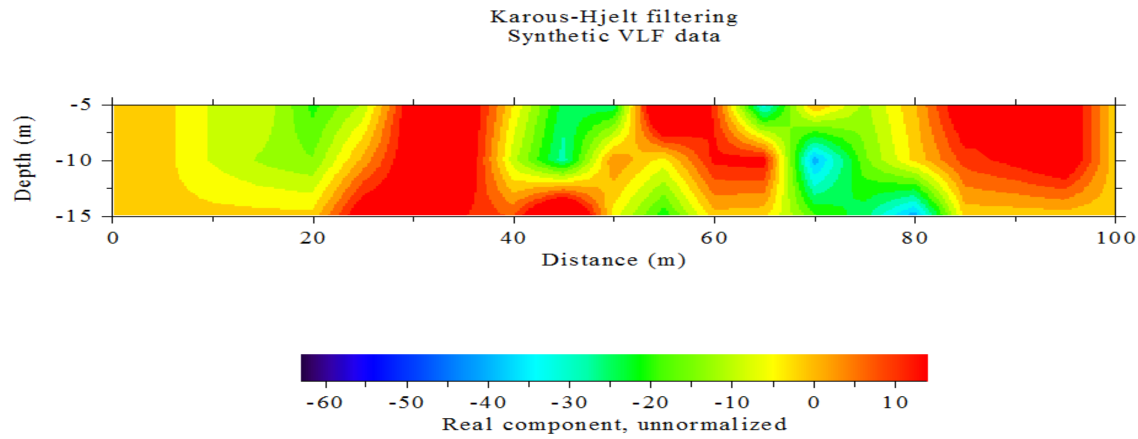

Figure 11b: Profile showing the VLF result of the pseudo-section for the VLF data obtained for the fifth traverse.

4.2 DISCUSSIONS

The outcome of the geophysical investigation carried out on the study area revealed a good correlation between the results from the Magnetic method and the VLF method. Along the first traverse, very low resistivity zone is located between distance 75m to 95m. This interval also corresponds to the weak zones identified in the magnetic result at 75m to 95m. The second traverse is laid cross the farmland where some predetermined fracturing directions have been identified during literature study and geological survey of the area. The VLF-EM profile shows some highly conductive zones which are indicative of water-filled fractures. From the magnetic profile of the traverse two, it was observed that these intervals have low magnetic materials. Clearly, there a scientific deduction from the low magnetic intensity zones corresponding with the high conductivity zones observed through VLF profiles. The findings of this study show similar observations in the earlier studies presented in literature (e.g., Adelusi et al., 2014; Al-Tarazi et al., 2008; Gaafar, 2015; Gnaneshwar et al., 2011; Jamal & Singh, 2018; Khalil & Santos, 2011b, 2011a; Sundararajan et al., 2007).

The geochemical analysis conducted on samples from the soil water on the farm at shallow depth indicate some nitrate concentration that is above the WHO guide limit of 45 mg NO3/L.

Thus, since the direct source of nitrate in groundwater are mainly from wastes or commercial fertilisers applied to the land surface (Adelana, 2006), the overall deduction from the combined results of the two methods is that as a result of the identified water-filled fractures within and around the farmland in the study area, the source of the groundwater contamination is mainly due to the chemical runoff from the nitrate of the fertilizers applied to the farm. Here, the presence of connected fractures, cracks, and weathered rocks in the subsurface serve as passage for the flow of contaminated fluid. The nitrate could easily mix with subsurface and surface water on the farmland would likely flow through the fractures to connect to the aquifer and pollute the groundwater. Also, because there are streams near the farm and the area falls within the tropical rain forest, there is continuous recharge of the surface water (streams) and the groundwater. The water in the near surface pores also allows the dilution of concentrated chemical in the soil which then percolates into the groundwater. Thus, the geologic structures allow the passage of contaminated water from the surface to the water table.

5 CONCLUSION

Groundwater contamination in the site was studied to investigate the possibility of a fracture-controlled contaminant transport from a farmland to the groundwater in the area. The two methods combined for this study are VLF and ground magnetic survey. From the VLF results, it was observed that there are highs and lows resistivity values at various points. The low resistivity (high conductivity) zones are indictive of the presence of fractures, faults, cracks and weathered rocks. The results of the magnetic survey identified these low resistivities (high conductive) zones as the intervals corresponding to low magnetic intensity. Although this trend was not found to be uniform across the five traverses and at all intervals, but at most of the intervals where low resistivities readings were recorded, there is a corresponding low magnetic intensity on the magnetic profiles. The rocks in the area showed very highly fractured basement rocks which indicates that conductivity of the rock could be linked to the presence of fractures or fault and the fluids they contain. Overall, the basement rock in the area shows some stages of weathering, and this makes the application of VLF-EM and magnetic methods very suitable for this study.

Overall, the highly conductive materials have low magnetic intensity and are observed to be either fractured or weathered materials with conductive fluids. And most evidently, these are the areas serving as pathways for the contaminated fluids to move from the surface to the groundwater. It is easier for chemicals in the soil to be diluted by surface water through rainfalls or stream flow.

Thus, this study has facilitated a better understanding of the possible danger caused by water quality degradation in agricultural areas where leaching from fertilizer can result in runoff of chemicals into surface waters through fractures and faults. The most prominent effect of this occurs when the polluted fluid percolate into groundwater in the area.

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