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Qualitative and Quantitative Interpretation of the Filtered Real Component of VLF-EM Data: Case Study of Solid Waste Dumpsite of Precambrian Basement Complex Rocks.

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ABSTRACT:*A Very- Low-Frequency electromagnetic (VLF-EM) survey was conducted on an open dumpsite in Kaduna metropolis, Kaduna State, Northwest Nigeria. The aim and objectives were to detect and delineate subsurface structures and locate possible Leachate plumes intrusion into the shallow ground water in the study area. VLF Data were acquired at 5 m intervals along six (6) profiles with maximum length of sixty-five (65) meters in the East-West direction. Linear inversion of the Electromagnetic measurements involved application of the Fraser filter on the measured real components of the field data and generation of the 2D resistivity models. The objective of the inversion is to obtain a subsurface distribution of the electrical resistivity, which generates a response that fits the field data within the limits of data errors. The Fraser filtered real components of the processed VLF data detected anomalous zones that are suspected fractured zones/ lithological boundaries that may possibly serves as conduits for the movement of the solid waste contaminants into the groundwater. However, the filtered real component peaks are reversed possibly due background noise in the study area. The resulting vertical resistivity distribution from the 2D resistivity inversion of the VLF-EM data revealed the general features of the subsurface structure matching quite well with the Fraser filtered responses of the VLF data. The 2D resistivity model shows dipping and steeply dipping linear conductors (Fractures) in the crystalline basement rocks. It was thus perceived that the solid waste pollutants could infiltrate through the soil and reach the shallow aquifer in and around the waste disposal site and endanger the ground water quality in the vicinity of the dumpsite.*

Keywords: *Aquifer, Dump site, Fracture, Leachate, Pollutant,*

I. INTRODUCTION

Waste dumps around Kaduna metropolitan area are one of the major sources of environmental pollution. The oxidation of sulphide and other hydrocarbons within the waste materials in the presence of oxygen and water may produce various toxic elements. The transportation of these elements into the groundwater flow systems through fracture zones could have serious impact on the receiving environment. Most of these contaminations undergo only limited degradation in the subsurface and persist for long periods while slowly releasing soluble organic constituent to ground water through dissolution. The potential long-term impact of these pollutants on the groundwater quality, proper detection and delineation is critical. Therefore, in order to develop appropriate environmental water management plan in the polluted area, it is important to detect the extension of pollution plume in the vicinity of such dumps. The integrated geophysical investigations have been found useful applications in many geological studies ranging from shallow engineering studies, ground water and mineral deposit exploration as well as in variety of geo-environmental studies like investigation of contaminated sites or waste disposal areas. High urbanization rate and urgent need for natural resources on one hand had necessitated the use of non-invasive application of the geophysical methods such as Geo-electrics and Electromagnetic, which have been found to be cost-effective [1]. The various metals produced by oxidation processes in the groundwater flow system may change considerably the conductivity of the polluted zone; hence the Geo-electric and Electromagnetic (EM) geophysical methods could effectively be used to map these zones [2]. In spite of the effective use of these methods, the cost and the required operational time are considerably very high. To overcome this problem, the VLF-EM method can economically be used. The VLF-EM method uses radio signals in the bandwidths of 15 – 30 KHz and is powerful tool for quick detection of near surface structures. Because of the easy operation of the instrument, speed of field survey and low operation cost, this method is suitable for rapid preliminary surveys and has been widely used in many geophysical investigations [3]; [4]. The existence of fracture zone in a geological medium can assist in creating ground water conduit medium and aids groundwater accumulation. Therefore, the use of VLF as geophysical tool is very crucial as it is very sensitive to changes in lithology and can detects zones of relatively low conductivity (fractures). The results can serve as primary information for the relevant ministries to set overall picture of migrating Leachate plume which will go a long way in preserving the abundant natural ground water as well as safe guarding the health of the nation, thereby preventing waste of public funds.

In this paper, six profiles (A-F) were investigated using VLF-EM method in an open dumpsite in Kaduna metropolis, Kaduna State, Northwest Nigeria with the aim of delineating subsurface structures (e.g. fractures) that may enhance hydraulic contact between Leachate and ground water.

II. THEORY OF VLF TECHNIQUE

VLF-EM signals propagate as surface waves (a type of ground wave) that travel thousands of miles. When traveling over and near the earth surface, the magnetic field induced by the displacement current is defined as the primary magnetic field. The primary EM field shifts in phase when a conductive body is encountered, and the conductive body then becomes the source of the secondary field. By measuring the secondary field and comparing it with the primary, the electric characteristics of the subsurface bodies can be determined [5]. In fact, the VLF data recorded in the field is a combination of the primary and one or more secondary fields, depending on the geologic conditions. The resultant is a polarized elliptical field rotating in space and varying in magnitude as it propagates [6]. The minor axis of the ellipse is not necessarily perpendicular to the earth surface. In fact, the minor axis is inclined at an angle θ to the vertical. If it is assumed that the primary magnetic field H is horizontal and the cylindrical secondary magnetic field S oscillates relative to the primary with a phase lag Φ and is inclined to the plane of the primary field at an angle α, then the inclination θ of the polarized elliptical field, sometimes called the tilt angle, is

$$\theta = \approx tan^{-1}\left[\left(\frac{S}{H}\right)\sin\alpha\cos\phi\right] \cong \left(\frac{S}{H}\right)\sin\alpha\cos\phi \qquad (1)$$

ifθ is small (Paterson and Ronka, 1971). The eccentricityε, the ratio of the minor axis to the major axis of the polarization ellipse, is

$$\varepsilon = \frac{Y}{X} \approx \frac{S\sin\alpha\sin\phi}{H} \qquad (2)$$

whereY/X equals the ratio of the minor-axis signal to the major-axis signal. Because $S/H\sin\alpha$ indicates the vertical component of the ratio of the secondary to the primary field, equation 1 implies that the inclination θ approximates the real part of that component. It is sometimes called the in-phase measurement, becauseϕ is the phase lag of the secondary field relative to the primary field; it contains the ${}^{\pi}/_{2}$ phase lag caused by inductive coupling between the transmitter and the subsurface structure plus the additional phase lagϕ' caused by the electric properties of the subsurface structures. The eccentricity, therefore, approximates the imaginary part of the vertical component of the ratio of the secondary to the primary field and is referred to as the imaginary measurement. The VLF instrument measures the inclinationθ and the eccentricity ε by reading the magnetic signals detected by a pair of orthogonal coils, i.e., a reference coil and receiving coil at right angles to the signal coil. When the signal coil is tilted parallel to the minor axis of the ellipse and the reference coil is parallel to the major axis of the ellipse, a minimum signal is received. The signal from the minor-axis coil (signal coil) when shifted 90° in phase is used to balance out the signal in the major-axis coil (reference coil), and the ratio of the minor axis signal to the major-axis signal(Y/X in equation 2) can be a positive or negative percentage [7]. The signal measuring techniques in most modern VLF-EM systems have been modified; for example, two kinds of equipment—the Scintrex ENVI System and the GSM-19V—collect the in-phase and imaginary VLF data as a percentage of the primary-field strength to minimize the effect of fluctuations in the primary field and to circumvent the complicated units of the data. All VLF sensors in these two instruments consist of three orthogonal coils, i.e., two coils mounted horizontally and one mounted vertically. Other modern systems may measure the in-phase and imaginary data directly [8]

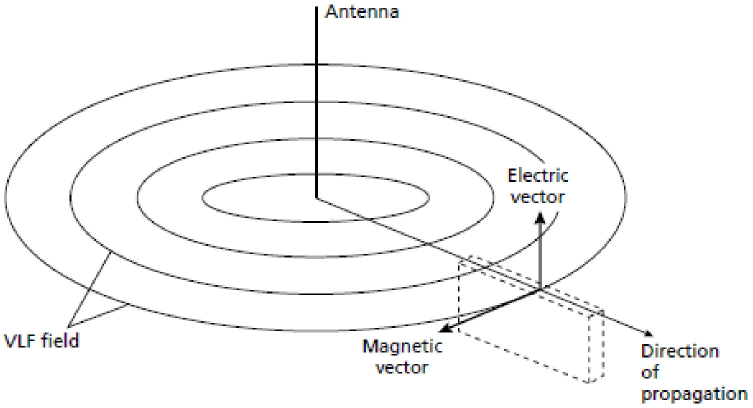

Fig1: Principle of VLF method. Dashed lines show a tabular conductor striking towards the antenna which is cut by the magnetic vector of the EM field.

III. GEOLOGIC AND HYDROGEOLOGIC SETTING OF THE STUDY AREA

The study area (Fig 2) with elevation 590 m above sea level is located between longitudes 007.24. E and latitude 10.30. It is among the forty (40) notorious dump-sites according to the Kaduna sate ministry of Environment and Natural Resources within Kaduna Metropolitan Local governments. It is located along Kankia road off Nnamdi Azikwe express way Western Bye-pass. It is adjacent to Abubakar Gumi collage and directly opposite old cemetery Sabon-Gari, Tudun-Wada Kaduna. The heap of the dump usually reaches about three (3m) meters high but is periodically evacuated. The dump site is surrounded by highly densely populated areas that mostly rely on well waters as their source of water. Therefore, the detection and delineation of such structural features may facilitate the location of ground water prospect zones in the study area. The study area is underlain by rocks of the Basement Complex consisting of biotite gneiss, and older granites. The rocks have been subjected to laterization. There are also the occurrences of laterite and rocks of the basement complex at different locations within the local government area and at different sections of Kaduna River. The area is far from the sea and has a typical continental climate. This type of climate according to [9] is characterized by dry and wet seasons. The dry season usually set in around mid-October and last to about late march or early April. The wet seasons starts around March ending and last to middle of October [10].One of the major sources of recharge in the study area is from river Kaduna. The river is a long tributary of the River Niger and is about 550km (140 miles) long .Other source is the rain water which is seasonal. The area is being discharged through river, ditches to river Kaduna [11].

IV. FIELD METHODS AND DATA COLLECTION

VLF-EM data were collected along profiles and measurements were made with a station separation of 5 m using the Scintrex Envi meter in the VLF-EM mode (i.e. measuring the ratio of the polarized magnetic field).The Scintrex Envi meter utilizes the magnetic component of the electromagnetic field generated by military radio transmitters that use the VLF (Very Low Frequency) band, that is, 15 to 30 KHz commonly used for low distance communication. The Scintrex Envi meter measures this field strength and phase displacement around a fracture zone or any conductive body in the rocks [5]. It detects the ratio (in percent) between the vertical and the horizontal components. The VLF transmitter HWU located in La Blanc, France, operating at a frequency of 18.3 kHz with co-ordinates 46N37-001E05 was selected as the source for the entire VLF survey because it provided a field which is approximately perpendicular to the direction of the strike of the envisaged geological structure beneath the ground surface (N-S Fractures).The lengths of the profiles vary from 65 to 60 m and are separated by 5 m. The in-phase and imaginary data were presented as single profiles. To locate the anomalies, measured data were processed using Fraser filtering and Quantitative interpretation of the single frequency VLF-EM data was achieved using the inversion code of [12] to yield subsurface resistivity distributions of the structures. The linear filtering technique developed by [13] converts somewhat noisy, non-contourable in-phase components to less noisy, contourable data, which ensures greatly the utility of the VLF-EM survey. The filtering process simply involves a four point weighted average using the weights of -1, -1, +1, +1.

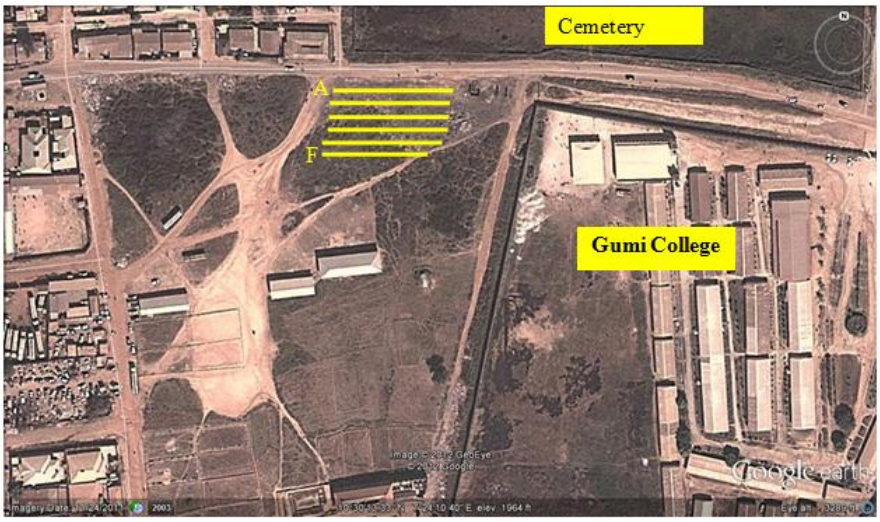

Fig.2: Satellite Imagery of the survey area showing location of the investigated profiles

This simple digital filter operator passes over the in phase component and when plotted generally peaks over the top of the conductor. According to [14] the advantages of the Fraser filter include: (1) complete removal of DC bias and great attenuation of long wavelength signals; (2) complete removal of Nyquist frequency related noise; (3) phase shifts in all frequencies by 90° and (4) having the band-pass centered at a wave length of five times the station spacing. Fraser filtering converts somewhat noisy, non-contourable in-phase components to less noisy, contourable data, which ensures greatly the utility of the VLF-EM survey. The filtered profile data were then subjected to 2D inversion operation. The VLF-EM modeling is implemented using an algorithm and software developed by [12] for in-phase and out-of-phase components based on a 2D regularized inversion approach by [14] Assuming a 2D conductivity distribution with strike along the x-direction and the y-direction as the measuring profile direction, the VLF-EM instruments measure the in-phase and out-of-phase components of the vertical magnetic field (Hz), using the local horizontal magnetic field (Hy) as the phase reference. At each measurement site it is possible to define a scalar *tipper* B given by

$$Hz = BHy. \qquad (3)$$

The *tipper* B is a complex quantity originated by the time lag between horizontal and vertical components of the magnetic fields due to the electromagnetic induction phenomena. The *tipper* does not exist over a homogeneous earth (or over a layered earth). Over a 2D earth, the *tipper* varies along the measuring profile showing the strongest variations in the vicinity of resistivity contrasts. The real and imaginary (or in-phase and imaginary) components of the *tipper* in the case of the VLF-EM method are usually expressed as percentage [15]In this paper, INV2DVLF software [12] was used to interpret VLF-EM data quantitatively. Two resistivity profiles employing Wenner array were performed on profiles C and D to generate an initial model proportional to 150 ohm- m.

V. RESULTS AND DISCUSSIONS

The VLF electromagnetic profiling data are presented as plots of filtered real and filtered imaginary (in %) against station position. Figure 2(a) shows the VLF profile data (in-phase and imaginary) along traverse A. Both the real (In-phase) and the imaginary components are predominantly positive with values ranging from +0.1% to +69.3%. The magnitude of the unfiltered imaginary component is small towards the west side of the traverse and increase to its peak at location of 35m, which then reduced to almost zero at location 65m towards the Eastern part of the traverse. These patterns of the imaginary component are suggestive of shallow conductive structure underlying this traverse [16] The real data was then subjected to filtering using Fraser filter, Fig3 (b). The real data became enhance and more definitive after the filtering process and one anomalous zone located at station 45 m was delineated which probably suggest the presence of a fracture or a lithologic boundary. The highest negative peak of the in-phase data is due to presence of metal gate of the Abubakar Mahmud Gumi College. Fig 3 (c) illustrates the 2D resistivity model obtained by the inversion of the VLF-EM data. Resistivity decreases downward except at the extreme western section which shows high resistivity value at the surface which reflects the metal gate of the Gummi College. For this model, although the presence of the overburden masks the information of the structure, the overall apparent resistivity still pronounces the structure well i.e., the presence of conductive body beneath the traverse. Zones with resistivity values > 30 ohm-m represent contaminant zones.

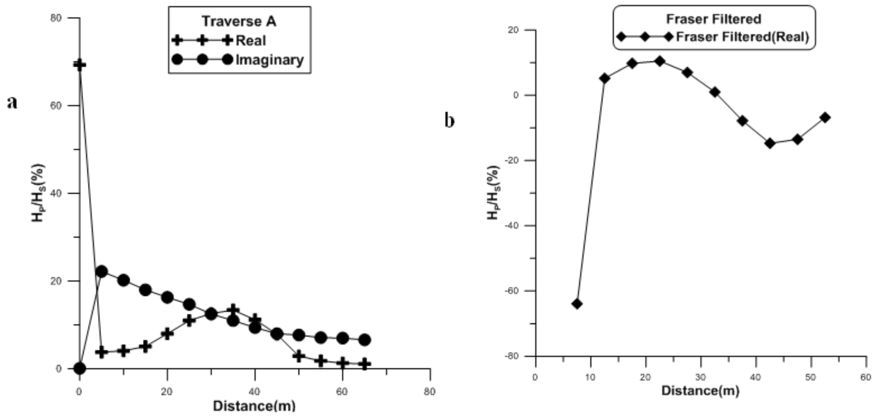

Fig.3 Traverse A: (a) Unfiltered Real and Imaginary data (b) Fraser Filtered (Real) data

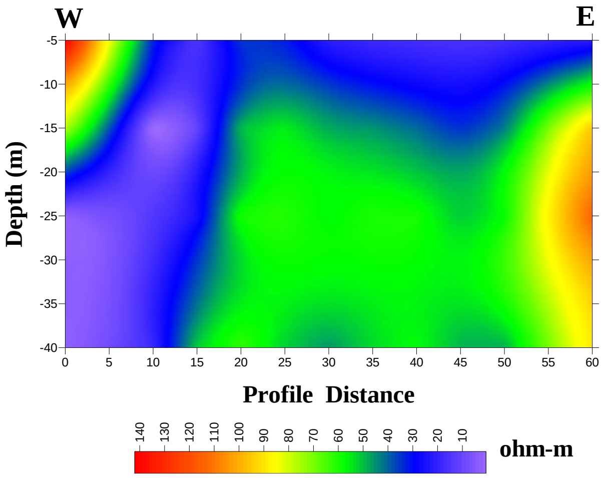

Fig. 3(c): 2D Resistivity model

Fig 4(a) shows the unfiltered data (Real and Imaginary) obtained along traverse B. The unfiltered real component begins with – 0.1% and rise gradually until it reaches its maximum at +12.3%. The imaginary component is predominantly positive with values varying from +3% to +34.6%. The magnitudes of the unfiltered imaginary measurements are high at western end of the traverse then gradually drop to minimum in the eastern end of the traverse. The magnitude of the real unfiltered data is low and negative at western end of the traverse with cross-over at station10m. Fig 4 (b*)* is the Fraser filtered (real) data which revealed two anomalous zones indicative of fractures and or lithologic boundary at locations 43m and 60 m. Figure 3C shows the 2D resistivity model. The anomalous zones identified in the Fraser filtered of the real component (Fig 4b) were also masked by the low resistive weathered basement. The fractures that could serve as contaminant pathway is incline (boundary between the blue and green color).

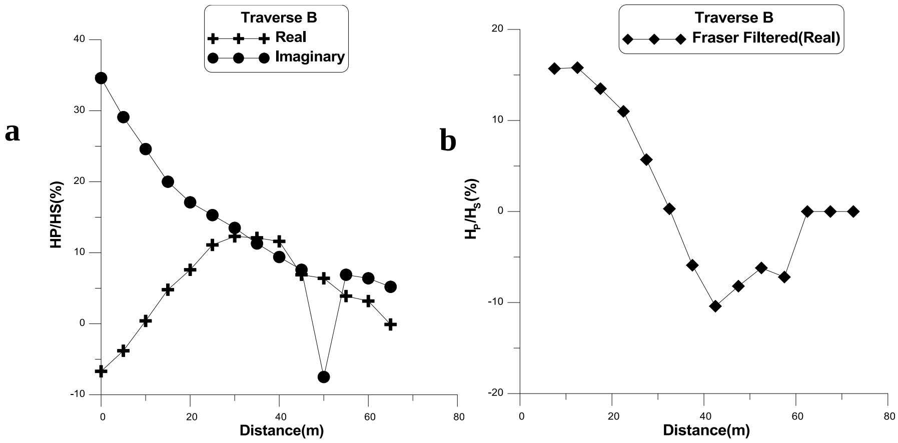

Fig. 4: Traverse B (a) Unfiltered Real and Imaginary data (b) Fraser Filtered (Real) data

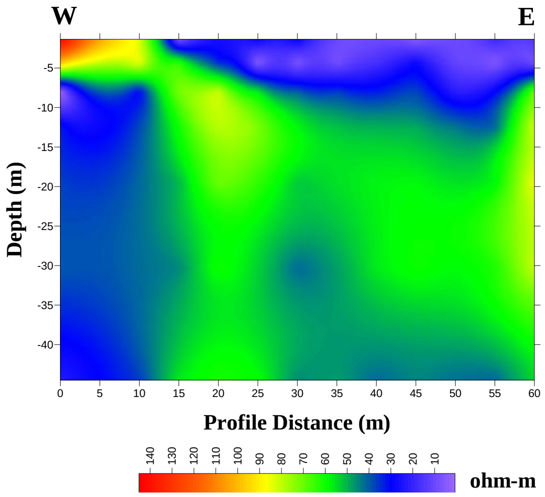

Fig. 4(c): 2D Resistivity model

Fig 5 (a) shows the unfiltered data obtain along traverse C. The values of the unfiltered real components begin from +3% at station 0 m then drop drastically to -10% at station 5m and then increase to +13% at 6m on the western part of the traverse. The imaginary components steeply increases from +10% to its peak of +40% at station 10m then gradually decreased to minimum of +5% at station 65m on the eastern end of the traverse. The unfiltered real data is highly variable with two distinct lows occurring at station 5 m and 20 m, respectively. The filtered real data (Fig 5b) delineate two anomalous zones along this traverse. These anomalous zones which are indicative of fractures and or lithologic boundary occur at station 18 m and 58 m respectively.

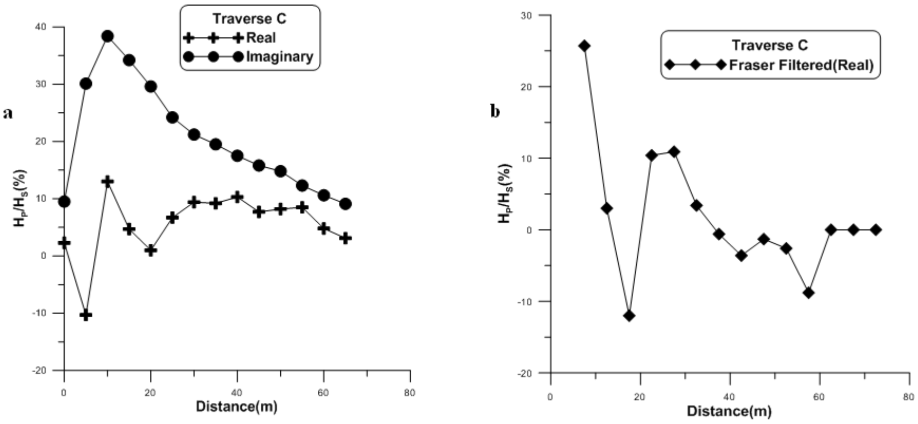

Fig: 5. Traverse C: (a) Unfiltered Real and Imaginary data (b) Fraser Filtered (Real) data

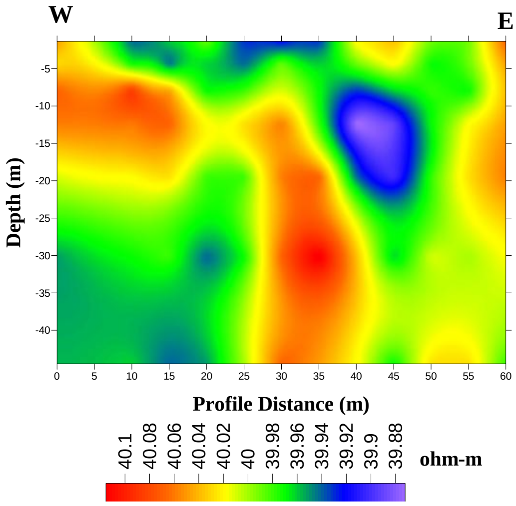

Fig. 5(c): 2D Resistivity model

Fig 6 (a) shows the unfiltered data along traverse D. The unfiltered real component varies from–2.7% to +40% while imaginary component varies from – 25% to +34%. Crossover from negative to positive values on the imaginary component occurred at station 20m. After filtering the real data, three anomalous zones were delineated (Fig.6b). These anomalous zones coincide with stations 18 m, 38 m and 55 m and they indicate fractured zones. The 2D resistivity model shown in Figure 5c is dominated by low resistivity values from the surface down to depth of 40 m except at the extreme eastern section. This represents contaminated soil since this traverse was conducted on top of the evacuated solid waste. Information of the anomalous zones identified in Figure 5b was also masked by the low resistivity weathered basement.

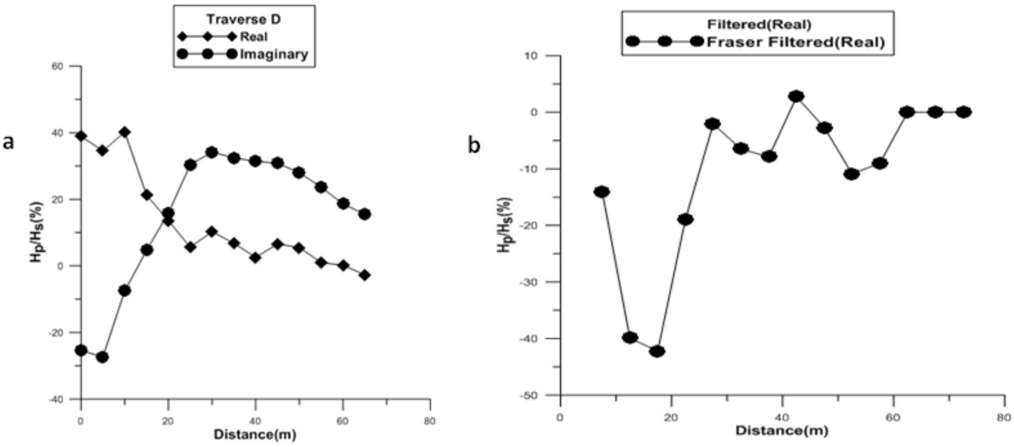

Fig. 6: Traverse D :(a) Unfiltered Real and Imaginary data (b) Fraser Filtered (Real) data

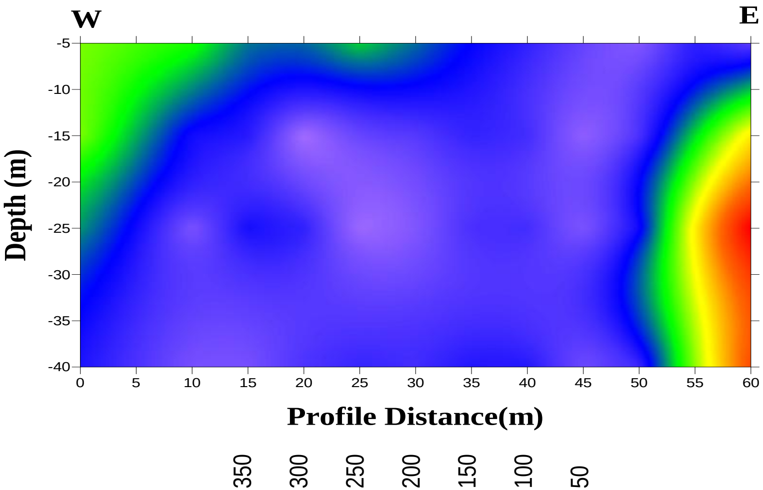

Fig. 6(c): 2D Resistivity model

Fig 6(a) shows the unfiltered data along the traverse E. The unfiltered real component varies from – 10.9% to +30.8% and the imaginary component varies from - 36.5%. to +35.4%. The magnitudes of the unfiltered imaginary measurements are relatively high at the western part of the traverse, while the real component is low and negative. This is an indication of lithological boundary between two rocks types having different physio-chemical properties. The presence of crossover point on the imaginary part and a reverse crossover on the real part at station 50 m indicates the presence of a conductor in the subsurface [16]. The non-zero signature pattern of the imaginary component of the EM fields suggests that the overburden is moderately to highly conductive. The real data is then filtered (Fig 6 (b) and the high and negative signal observed in the unfiltered real measurement between station 15 – 45 diminished to small negative values from station 37.5 – 47.5 m. Two anomalous zones were delineated in the filtered real component which corresponds to station 28 m and 52 m respectively. The anomalous zones suggest presence of fractures underlying this traverse. The 2D resistivity model (Fig 7c) shows similar pattern of the 2D resistivity model along traverse D i.e. lateral distribution of low resistivity values from the surface down to depth of 40 m from station 20 m to the end of the traverse.

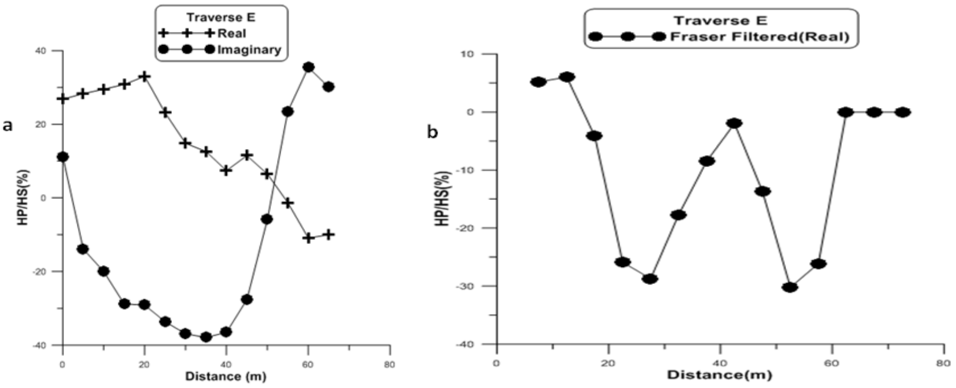

Fig. 7: Traverse E :(a) Unfiltered Real and Imaginary data (b) Fraser Filtered (Real) data

Fig 8 (a) shows the unfiltered VLF-EM data obtained along traverse F. The real component shows positive signatures with values varying from +14.5 % to +31.5% and the imaginary component shows negative signatures with values gently decreasing from -5% to – 47.4 %. The magnitude of the unfiltered imaginary measurements is small and negative with the lowest value (-47.4%) corresponding to station 55 m, while that of the real component are positive, relatively high and variable. The Fraser filtered of the real component fig 8 (b) delineate the presence of anomalous zones that are either indicative of a fracture zone or lithological boundary. These zones were located at stations 22 m and 42 m respectively.The2D resistivity model along profile E (Fig 8c) shows low (10 – 40 ohm-m) to moderate (40 90 ohm-m) resistivity zones from profile position 10 m to the end of the Eastern part of the investigated area. These zones clearly correspond to the anomalous zones on the Fraser filtered of the real component (Fig 8b) which is interpreted as blithologic boundary that can serve as conduit for transportation of contaminants.

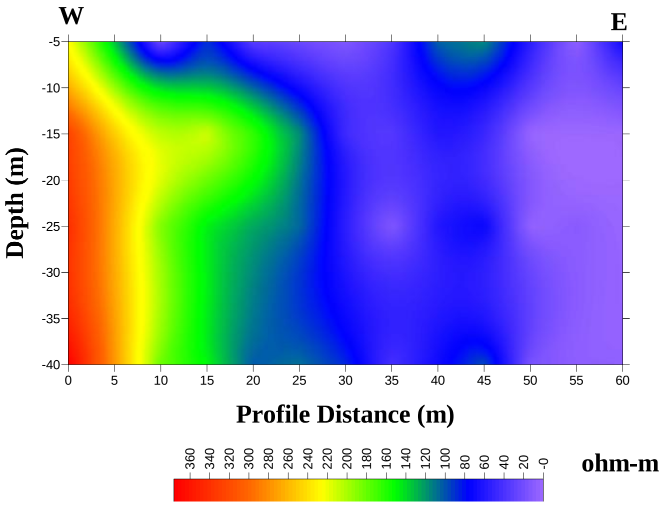

Fig7(c): 2D Resistivity model

Fig 9 shows the contour Fraser filtered data for the entire study area for both the real and imaginary components. The red line shows the anomalous zones suspected to be either fracture zones or lithological boundary trending in the East-West direction.

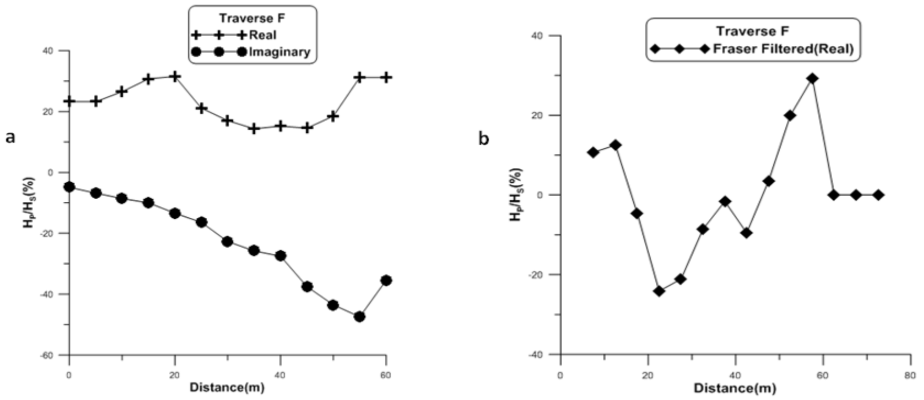

Fig. 8: Traverse F: (a) Unfiltered Real and Imaginary data (b) Fraser Filtered (Real) data

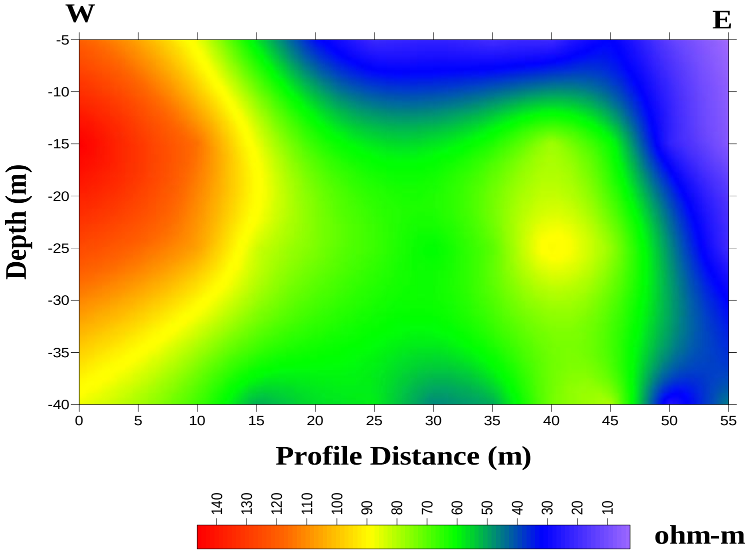

Fig. 8(c): 2D Resistivity model

VI. CONCLUSION

Surface geophysical method was used as part of the process of detecting and delineating fracture and as well as assessment of ground water contamination in the study area. Six (6) parallel traverses located at the dumpsite were surveyed using VLF-EM method. The non-zero signature pattern of the imaginary component of the EM fields suggests that the overburden is moderately to highly conductive. Though the results from the filtered real curves show the presence of vertically dipping conductive features which were interpreted to be fracture zones filled with Leachate, it is interesting to note that the amplitude peaks of the Fraser filtered in-phase profiles are reversed. One possibility is that the data are strongly affected by the background noise [YihJeng, personal communications, 2016]. The asymmetry of the conductive anomaly indicates a west dipping conductive sheet and these subsurface structures probably act as conduits for conveying contaminated plumes into the surrounding ground water. The 2D resistivity model generated from the VLF data correlates quite well with the Fraser filtered responses of the VLF data. In most of the 2D resistivity models, information of the anomalous zones was masked by low resistivity weathered basement. Based on the result of this research, it is apparent that contamination of the ground water in the study area is in progress. Thus, there is an urgent need to address further contamination in order to safeguard the health of the people.

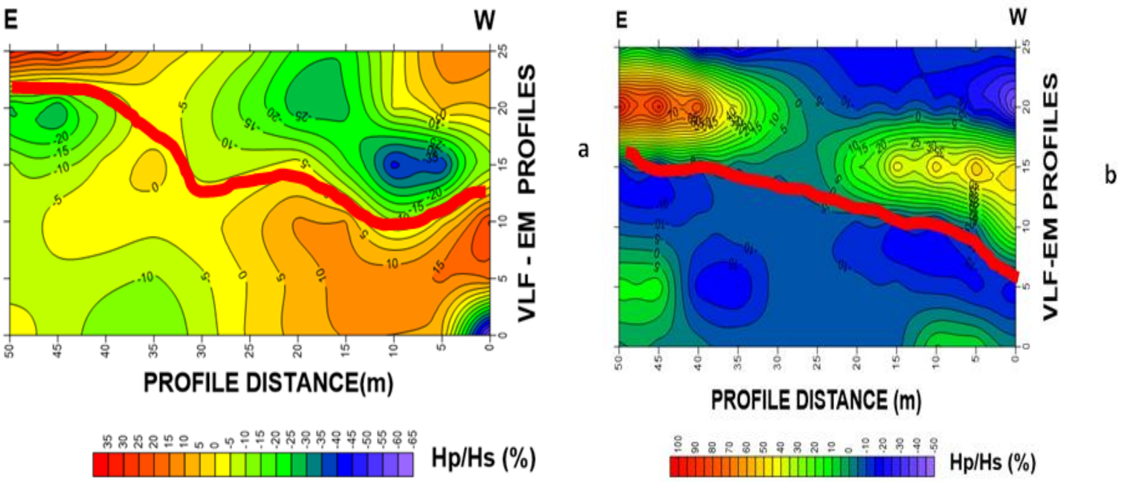

Fig 9: Contour Fraser filtered data: (a) Real component (b) Imaginary component

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