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# CONDUCTIVE ZONES CHARACTERIZATION USING VLF-EM TECHNIQUE AROUND A LANDFILL ON BASEMENT COMPLEX FORMATION OF SOUTHWESTERN NIGERIA

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## ABSTRACT

The conductive zones in the vicinities of the Saje dumpsite in Abeokuta metropolis, Ogun State, Southwestern Nigeria, were characterized employing the Very Low Frequency-Electromagnetic (VLF-EM) geophysical technique. The subsurface spatial distributions were mapped, and the migration and accumulation of leachate plumes in the fault lines or fractures were indicated. The survey traverses ranging from 140-200 m were laid from the dumpsite to the residential area with station intervals between 5 and 15 m using the ABEM WADI VLF meter. Nine traverses were created in the North of the dumpsite in the W-E direction, while five traverses were laid in the western region of the dumpsite in the N-S direction. The VLF meter's in-built filtering program and Fraser and Karous-Hjelt program filtered the real signatures obtained. The results were shown as 2D Karous-Hjelt pseudo-sections and Fraser anomaly curves, which depicted features with varying degrees of conductive and resistive regions in different directions. The anomaly curves showed prominent conductive signatures, which indicated massive accumulations of contaminants from the dumpsite. Also, the orientations of the conductive dwarf peaks of the signatures suggested appreciable massive contaminant regions. Furthermore, several cavities of both conductive and resistive responses were observed across the 2D Karous-Hjelt models to a depth of about 30 m. The results generally revealed conductive zones to distances of 35 and 75 m on the western and northern regions of the dumpsite, respectively. The regular patterns of conductive responses indicated fault lines as significant leachate plume trackways in the dumpsite subsurface.

**Keywords:** Dumpsite, VLF-EM, Conductive, Contaminants, Migration, Distance.

## INTRODUCTION

Leachate contaminant plume generation is the main challenge from municipal waste disposal locations, and it causes a significant threat to soil, groundwater, and surface water, making them unsuitable for both agricultural and domestic purposes (Nila *et al.,* 2020; Ojo *et al.,* 2020). Leachates are generated when rainwater dissolves the decomposing wastes and chemically and biologically reacts with them. Oladunjoye *et al.* (2011) stated that gravity had been identified to be a significant cause of leachate movement through the underlying soil until it reaches the aquifer. As the contaminant plumes move down into the subsurface, they pollute the water in soil pore spaces, and the mix migrates through the groundwater run track. The leachate contaminant plumes first enter the unsaturated region and later the saturated region before being transported to the aquifer. The pollutants influence the groundwater portability, exposing the inhabitants to adverse health risks.

Geophysical techniques such as electrical resistivity profiling, vertical electrical sounding, induced potential, and electromagnetic methods have proven highly efficient in mapping conductive zones and contaminant plume pathways. Ojo *et al.* (2020) used Very Low Frequency-Electromagnetic (VLF-EM) and 3D electrical resistivity profiling to delineate contaminant plumes at the Oke-Diya open dumpsite in Sagamu, Nigeria. Also, Raji and Adeoye (2017) used VLF-EM, vertical electrical sounding (VES), and 2D electrical resistivity to map leachate contaminant plumes around a solid waste disposal site in north-central Nigeria. Electromagnetic prospecting techniques have been instrumental in delineating conductive fluids and buried metals at shallow depths (Telford *et al.,* 1990; Ikhifa and Umego, 2016; Rahmatun *et al.,* 2019; Ohwoghere-Asuma *et al.,* 2020). In its usual form, the technique is most suitable for locating conductive bodies at shallow depths of the subsurface and applicable in the evaluation of mineral resources, groundwater prospecting, contaminants plume mapping, investigation of geothermal resources, geological fault location, and detection of natural and artificial cavities (Al-Tarazi *et al.,* 2008; Sunmonu *et al.,* 2017; Nila *et al.,* 2020).

In electromagnetic studies, conductivity responses of the subsurface are usually measured in terms of horizontal distances and depths. The adequate depth at which conductive bodies can be detected depends on the frequency and spacing between the receiver and the transmitter loops. Thus, electromagnetic techniques can be used similarly to resistivity techniques to obtain depth soundings and horizontal profiles within a few hundred meters (Telford *et al.,*1990; Ohwoghere-Asuma *et al.,* 2020). Measurements are obtained much simpler and faster than the resistivity technique, where metal electrodes are placed on the ground surface (Oladunjoye *et al.,* 2011; Ojo *et al.,* 2020). Currently, two types of electromagnetic survey are adopted: frequency-domain electromagnetic surveys, which are used predominantly for mapping lateral changes in subsurface conductivity, such as contaminant plumes migration, and secondly, time-domain electromagnetic surveys, which are commonly used for depth soundings (Telford *et al.,* 1990). Results of electromagnetic surveys are generally presented in profile form. Measurements may be made at one or several frequencies, and the interpretation is usually accomplished by modelling (Al-Tarazi *et al.,* 2008; Magawata *et al.,* 2019).

In recent times, the VLF-EM techniques have been widely employed in the delineation, evaluation, and characterization of conductive zones indicating leachate contaminant plumes (Ohwoghere-Asuma *et al.,* 2020; Ojo *et al.*, 2020; Nila *et al.,* 2020; Ighrakpata *et al.*, 2023; Alao *et al.*, 2024). The technique used radio waves from the worldwide network transmitters, operating between 5 and 30 kHz. The VLF method has been considered one of the most used electromagnetic techniques in geological mapping and conductive target detection (Fischer *et al.,* 1983). Then, the primary use was applied to mineral rocks and related geological structures investigations (Ramesh *et al.,* 2007). Also, it is well used for groundwater exploration, detection and mapping of groundwater contamination, delineation and detection of faults, fractures, and sedimentary cover (Al-Tarazi *et al.,* 2008; Sunmonu *et al.,* 2017; Rahmatun *et al.,* 2019; Magawata *et al.,* 2019; Ohwoghere-Asuma *et al.,* 2020). This present study used the VLF-EM geophysical technique to map the conductive zones as leachate plume pathways around the Saje dumpsite in the Abeokuta metropolis. By identifying regions prone to water and soil contaminations, the study's findings can guide policy decisions, underlining the significance of this research in shaping future waste management and environmental protection policies.

## THE STUDY AREA

Saje solid waste disposal site, located on an old quarry in Abeokuta metropolis, Ogun State, Southwestern Nigeria, is a matter of environmental concern. It covers an estimated area of 119,000 $m^2$ (Ojo *et al.,* 2022) and is situated within the latitude N07°11.201' - N07°11.480' and longitude E003°21.001' - N003°22.250' on a basement complex of igneous and metamorphic origin (Figure 1). The study location is distinguished by the overlay of sedimentary layers on the southwestern Nigeria basement rocks, which are composed of folded schist, quartzite, gneiss, older granite, and amphibolites or mica schist (Obaje, 2009; Eludoyin *et al.*, 2023). Saje dumpsite, the largest within Abeokuta, is flanked by igneous rocks to its east, residential buildings to the west and north, and a perennial stream drained by River Ogun to the south. The aquifer level is significantly affected by seasonal variations, with a depth of about 10 m during the dry season and shallow depths during the wet period (Acworth, 1987).

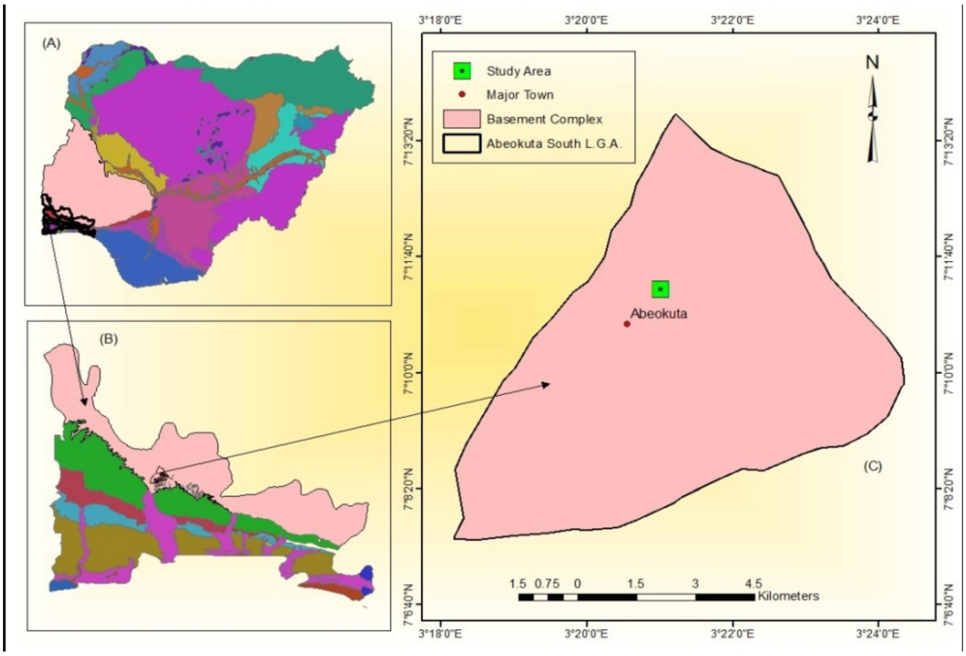

**Figure 1:** Geological Map of the Study Area (Ojo *et al.,* 2022).

## METHODOLOGY

The surveys were conducted using an ABEM WADI VLF meter to map out the conductive regions that give information about the sub-surface's conductivity directly related to leachate plume contaminations around the study area. Fourteen traverses were established with station intervals ranging from 5-15 m near the Saje dumpsite (Figure 2), with their orientations at high angles to the transmitter's direction. The length of each traverse ranged from 140-200 m, depending on the presence of residential buildings. Traverses 1-5 were measured west of the study area in the N-S bearing, while traverses 6-14 were mapped north of the study area in the W-E orientation.

The VLF-EM meter measured the imaginary and real parts of the induced vertical magnetic field as a percentage of the lateral primary field. The real component data, usually more diagnostic of linear features, were processed for qualitative interpretation. The data were processed using an in-built VLF-EM meter filtering program (Telford *et al.,* 1990) and two key filters - the Karous-Hjelt (K-H) and the Fraser (Fraser, 1969). These filters play a crucial role in enhancing data quality. The Fraser filter converts crossover points into peak responses by 90° phase shifting, and this process removes the direct current bias that reduces the random noise between consecutive stations resulting from the VLF component of sharp, irregular responses; it also removes Nyquist frequency-related noise and the long spatial wavelengths to improve the resolution of local anomalies (Ohwoghere-Asuma *et al.,* 2020). The K-H filter uses the linear fit theory to simplify the current density integral equation assumed to be in a thin horizontal sheet of varying apparent current density everywhere at a depth equal to the distance between measurement stations (Gnaneshwar *et al.,* 2011; Ojo *et al.,* 2020). The results of the VLF-EM investigation were presented as 2D pseudo-sections, which distinctly indicated both conductive and resistive signatures.

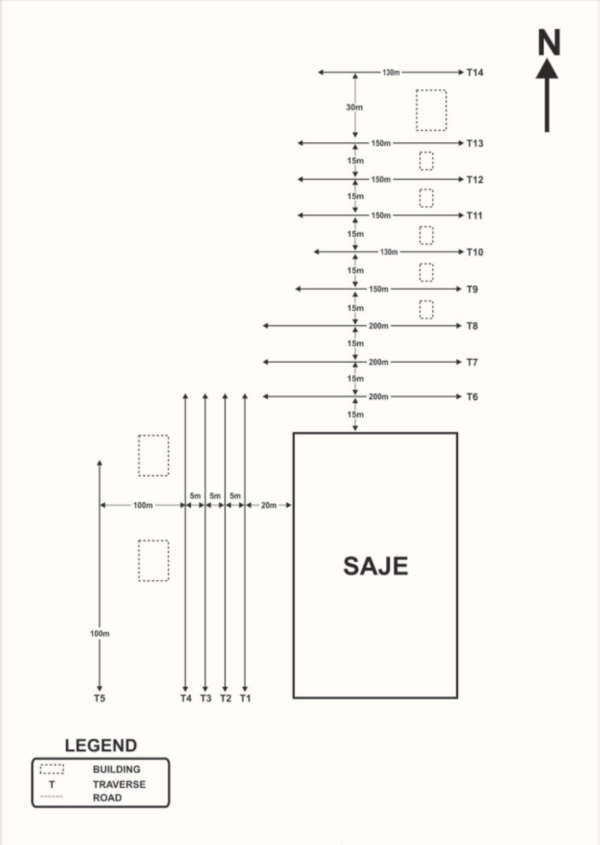

**Figure 2:** VLF-EM Survey Field Data Acquisition Layout.

## RESULTS AND DISCUSSION

Fraser curves and 2D K-H sections are used to differentiate between the conductive and resistive anomalies qualitatively. As revealed by Sunmonu *et al.* (2017) and Al-Tarazi *et al.* (2008), these methods effectively present variations in apparent current densities with depths. Figures 3-16 show the scalar measurements of the VLF-EM data as Fraser anomaly curves and 2D K-H models.

### West of Saje Dumpsite

Traverse 1 (Figure 3) Fraser filtering anomaly curve revealed high conductive regions with a positive response of about 27 units at 100-110 m traverse lengths. These zones indicated fault lines that were probably pathways for leachate plumes in the subsurface. The resistive peaks of about -17 and -16 units were also observed at traverse lengths 90-100 and 110-120 m, respectively. Positive and negative dwarf peaks were widely distributed across the traverse, indicating weak conductive and resistive zones at different depths. The 2D K-H model revealed features of varying degrees of conductive regions across the pseudo-section to a depth of about 30 m. Highly conductive zones had patterns indicating fault lines filled with conductive media at traverse lengths 90-110 m. Traverse 2 (Figure 4) Fraser filtering curve revealed alternations of both conductive and resistive peaks at traverse lengths 50-200 m. The conductive response of amplitude 24 units was observed at traverse lengths 20-25 m, and a negative amplitude of about -10 units was also observed at traverse lengths 25-50 and 75-100 m. The highly conductive responses indicated fault lines that harboured conductive materials. The 2D K-H section revealed highly conductive zones at 20-25 m traverse lengths within 0-10 m depth. Weak conductive media were observed across the section at lengths 50-70 and 100-120 m and depths 15-30 m.

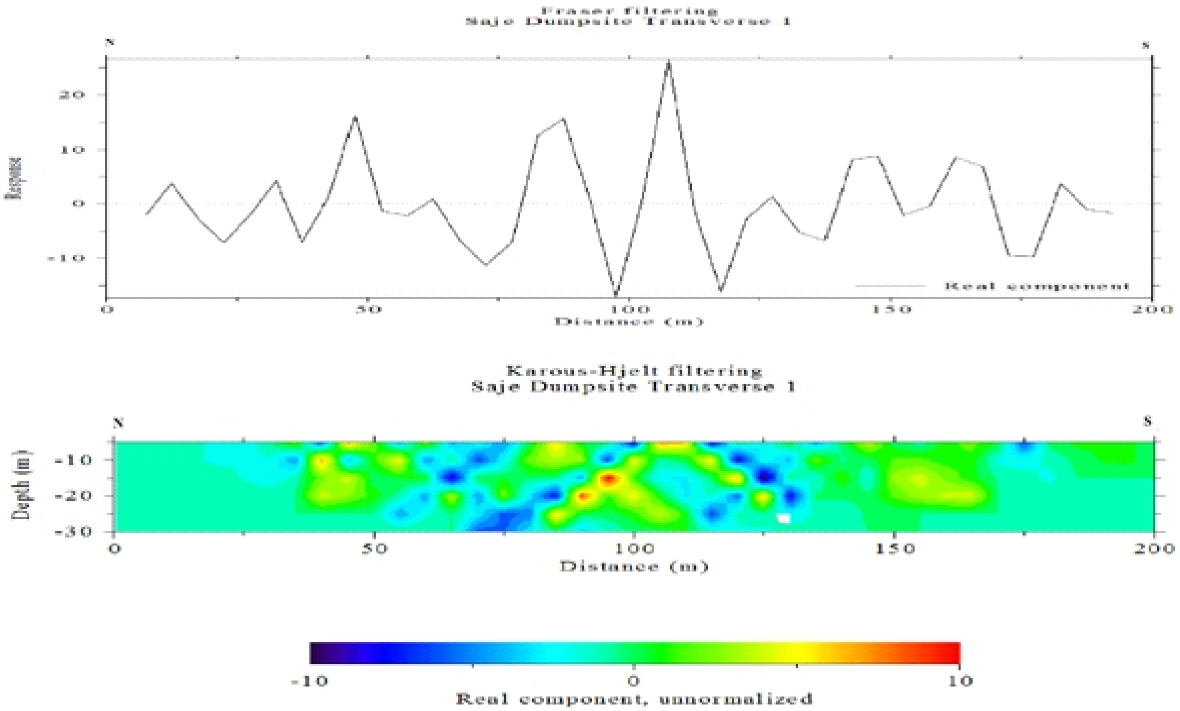

**Figure 3:** Traverse 1 Fraser anomaly curve and 2D K-H filtering section.

Traverse 3 (Figure 5) Fraser curve revealed two positive peaks of conductive responses 10 and 13 at traverse lengths 10-20 and 50-70 m, respectively. Also, two negative peaks of responses -8 and -11 were observed at traverse lengths 5-50 m. Conductive and resistive dwarf peaks were observed across the curve at 65-200 m traverse lengths. The 2D K-H filtering section revealed less pronounced conductive faults at 50-80 m traverse lengths and 0-30 m depths. These regions, which might increase in size over time, indicated the presence of leachate contaminant plumes in fault lines. Also, resistive zones were noticed at traverse lengths of 10-20 m and approximated depths of 0-12 m. Traverse 4 (Figure 6) Fraser anomaly curve revealed an alteration of positive and negative high gradient peaks at its centre. A high positive peak with a response of about 20 was observed at 100-110 m traverse lengths. A high negative peak of response -25 was also observed at traverse lengths 75-100 m. Positive and negative dwarf peaks were observed across the curve towards the southern region. The 2D K-H section revealed high conductive zones at 125-130 m traverse lengths and 0-30 m depths. These regions indicated fault lines with highly conductive plumes, as observed on traverse 3. These faults were towards the southern region of the section and could be aiding the migrations of contaminant plumes.

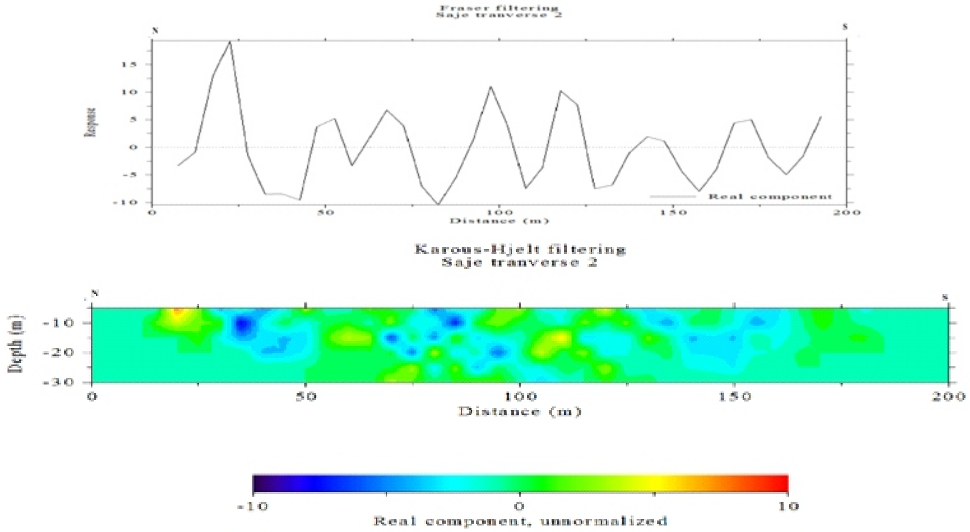

**Figure 4:** Traverse 6 Fraser anomaly curve and 2D K-H filtering section.

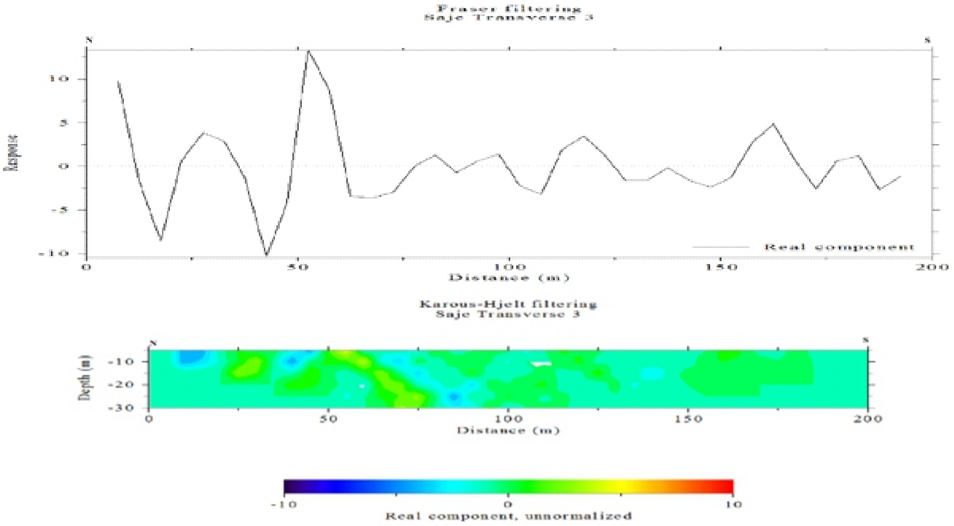

**Figure 5:** Traverse 3 Fraser anomaly curve and 2D K-H filtering section.

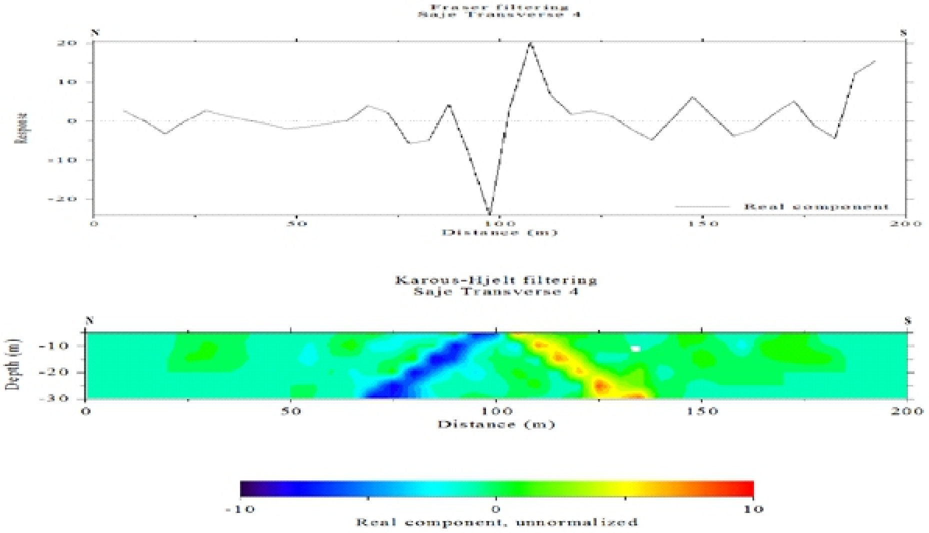

**Figure 6:** Traverse 4 Fraser anomaly curve and 2D K-H filtering section.

The control traverse (Figure 7) anomaly curve showed a positive peak of about 9 units, which was relatively low (weak conductive regions), at traverse lengths 75-85 m and a negative peak of about -22 units at lengths 90-93 m. In the northern region, the amplitudes of the peaks were low, indicating weak conductive zones. The 2D K-H section revealed relatively low conductive zones, which could result from water retention by clayey soil. High resistive zones were observed at 60-70 m traverse lengths and depths of about 12 m. Generally, this traverse indicated the absence of fault lines and contaminant migrations.

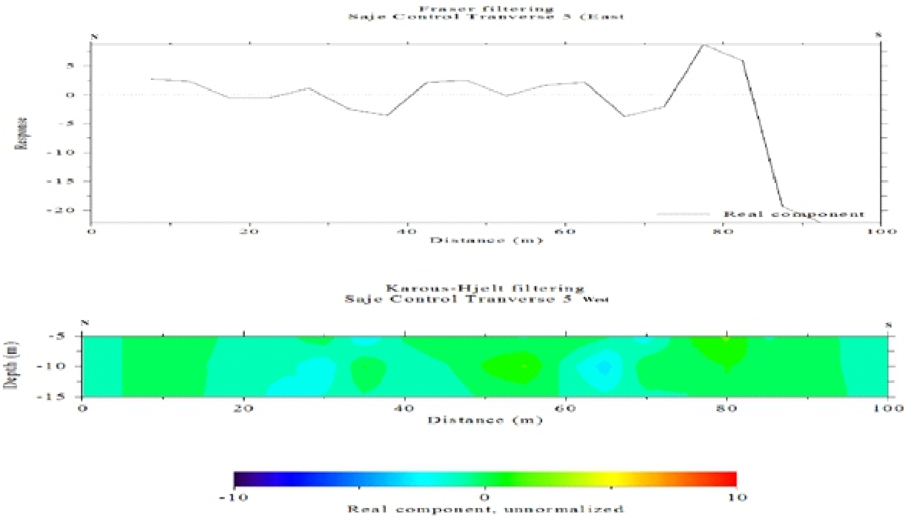

**Figure 7:** Traverse 5 (Control) Fraser anomaly curve and 2D K-H filtering section.

**North of the Study Area**

Traverse 6 (Figure 8) Fraser's filtering curve revealed two positive peaks in the western region with amplitudes 15 and 17 and at 10-30 m traverse lengths. These regions indicated fault lines that probably harbour contaminant plumes. At traverse lengths 120 and 170 m, negative peaks of responses -12 and -13 were observed, respectively. The alternations of both the conductive and resistive low amplitudes were observed across the curve. The 2D K-H section revealed closures of conductive zones at traverse lengths 10-30 m and approximated depths 0-12 m. Low resistive responses were also observed at depths 25 and 30 m along traverse lengths 45-55 and 100-125 m, respectively. Traverse 7 (Figure 9) Fraser curve revealed high peaks of both positive and negative responses of amplitudes 28 and -29 at traverse lengths 30-50 and 20-40 m, respectively. The broad base of these peaks revealed extensive conductive and resistive regions. The 2D K-H section showed highly conductive regions embedded within the resistive background at approximated depths of 0-10 m and a traverse length of about 20 m. Conductive zones, which indicated fault lines filled with contaminant plumes, were observed at 30-60 m traverse lengths and 0-25 m depths. Resistive materials were embedded at approximated depths of 13 and 25 m at traverse lengths 8-15 and 22-40 m, respectively.

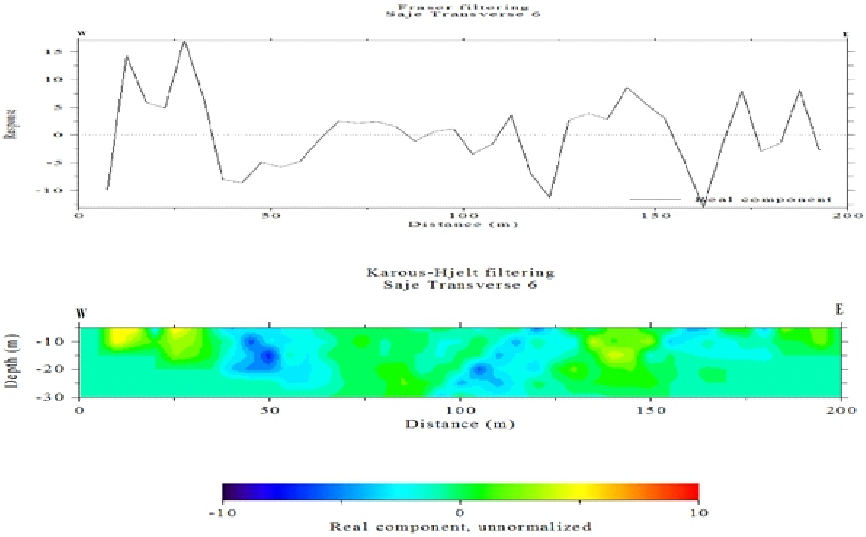

**Figure 8:** Traverse 6 Fraser filtering curve and 2D K-H filtering section.

Traverse 8 (Figure 10) Fraser curve revealed regions of high conductive and resistive peaks with amplitudes 35 and -30 at traverse lengths 50-60 and 40-50 m, respectively. The positive and negative dwarf peaks extended from the centre of the curve to the eastern region, and their orientations revealed that they were extensive. The 2D K-H section revealed highly extensive conductive zones at traverse lengths 50-80 m from the surface of the section to depths above 30 m. These regions indicated fault lines probably filled with contaminant plumes. Resistive zones were observed at traverse lengths 30-50 m to an approximated depth of 20 m from the surface of the section.

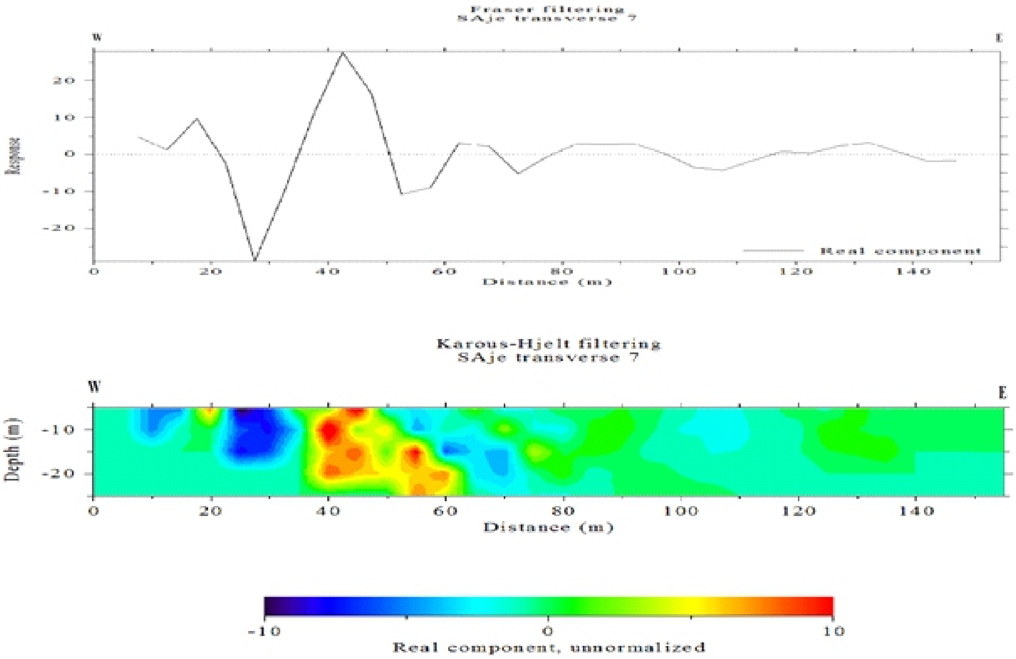

**Figure 9:** Traverse 7 Fraser filtering curve and K-H filtering section.

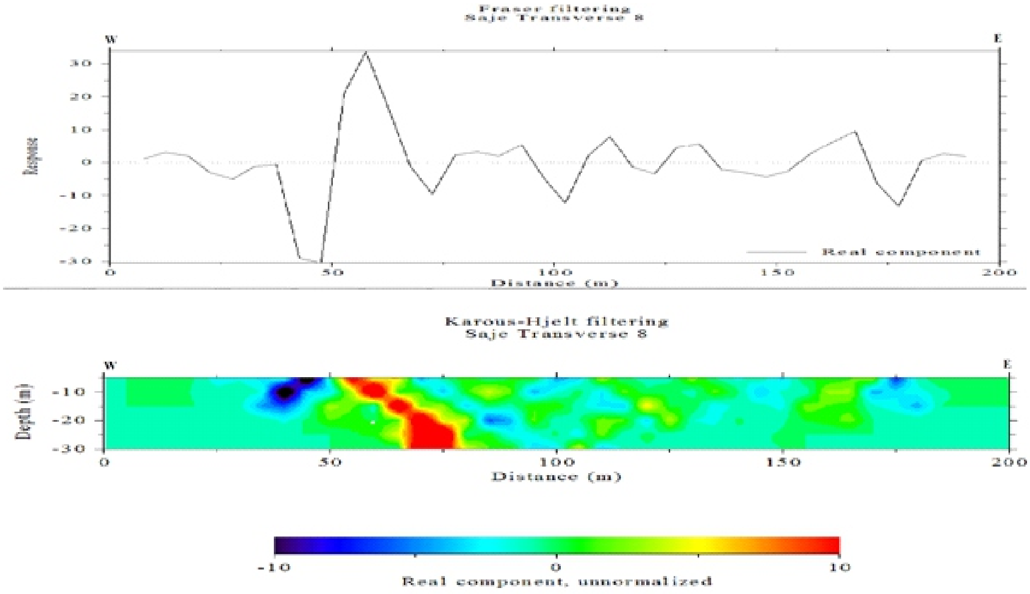

**Figure 10:** Traverse 8 Fraser filtering curve and 2D K-H filtering section.

Traverse 9 (Figure 11) Fraser curve revealed three prominent conductive peaks of amplitudes 30, 32, and 25 at traverse lengths 18-25, 95-105, and 120-130 m, respectively. Two negative peaks of amplitude -17 were also observed at traverse lengths 105-110 and 143 m. Dwarf peaks were observed across the curve at 30-90 m traverse lengths. The 2D K-H section revealed highly conductive zones from the surface of the section to approximated depths 20, 25, and 10 m at traverse lengths 20-30, 70-105, and 120-130 m, respectively. These regions probably indicated fault lines filled with contaminant plumes. Resistive zones were observed from the surface of the section to approximated depths of 15, 22, and 25 m at traverse lengths 5-20, 25-90, and 100-120 m, respectively. These regions indicated embedded high resistive media.

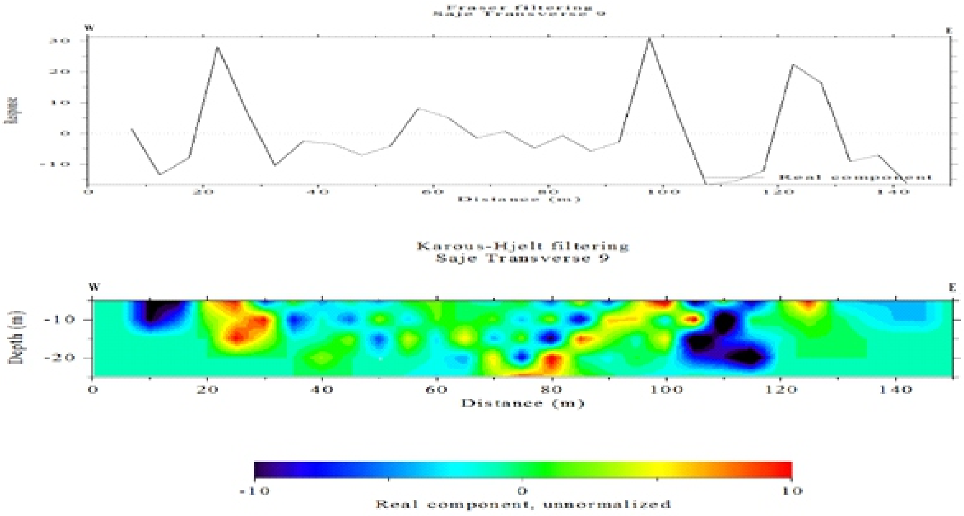

**Figure 11:** Traverse 9 Fraser filtering curve and 2D K-H filtering section.

Traverse 10 (Figure 12) Fraser anomaly curve revealed a broad-based positive peak response of about 22 at 70-90 m traverse lengths. Two highly extensive positive dwarf peaks were also observed at traverse lengths 40-50 and 100-110 m, and their wide bases indicated the massive and extensive presence of conductive media. The 2D K-H section revealed two regions of highly conductive responses from the surface of the section to depths of about 13 and 18 m at traverse lengths of 40-50 and 80-90 m, respectively. The pattern of these conductive zones suggested migration and accumulation of contaminants in the fault lines. Traverse 11 (Figure 13) Fraser curve also revealed wide-based positive and negative peaks. Positive peaks of amplitude 24 were observed at traverse lengths 60-90 and above 120 m, while a higher negative peak of amplitude -26 was observed at traverse lengths 90-100 m. Dwarf peaks were observed at lengths 20-60m. The 2D K-H section showed two extensive conductive zones at 20-30 and 60-80 m traverse lengths. The pattern of these conductive zones suggested fault lines with fewer contaminant migrations. Also, two highly resistive zones were observed at traverse lengths 50 and 90-120 m.

Traverse 12 (Figure 14) Fraser anomaly curve revealed high positive and negative peaks with responses 17 and -14, respectively, at 90-95 m traverse lengths. At the western region of the curve, widely distributed dwarf peaks were observed at traverse lengths 10-70 m. The 2D K-H section revealed a widely spread conductive zone to depths above 20 m from the surface of the section at traverse lengths 65-85 m. The conductive zone pattern indicated conductive media migration in the fault lines. Traverse 13 (Figure 15) Fraser curve revealed two positive peaks of approximated amplitudes 20 indicating conductive zones at traverse lengths 10-20 and 60-75 m. Also, two negative peaks of responses -10 and -15 were observed at traverse lengths 35-45 and 85 m. The 2D K-H filtering section showed low conductive zones at traverse distances 45-75, 100, and 115-150 m to depths above 20 m from the surface of the section. Also, resistivity regions were observed from the surface of the section to depths above 20 m at traverse lengths 15-45 and 80-90 m.

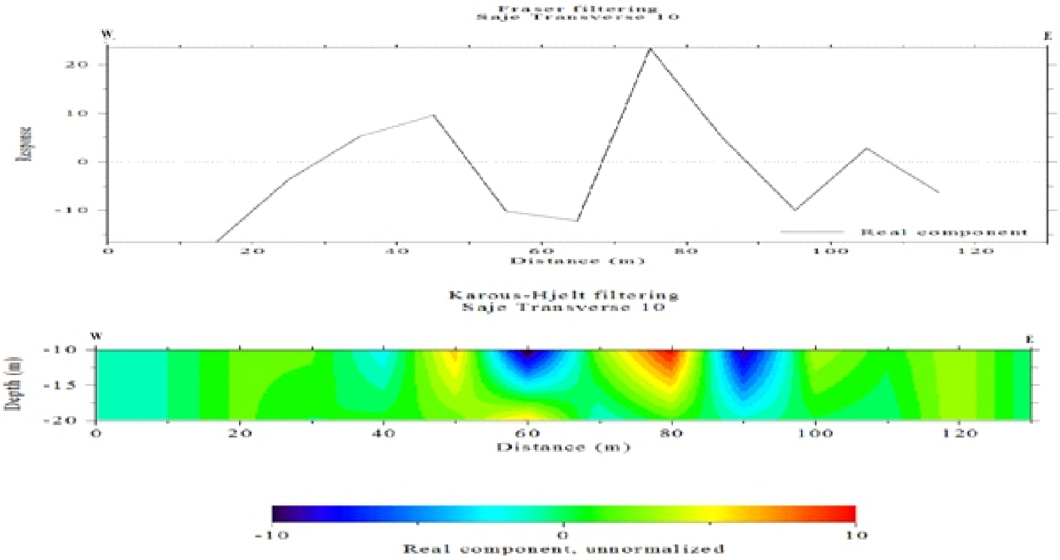

**Figure 12:** Traverse 10 Fraser filtering curve and 2D K-H filtering section.

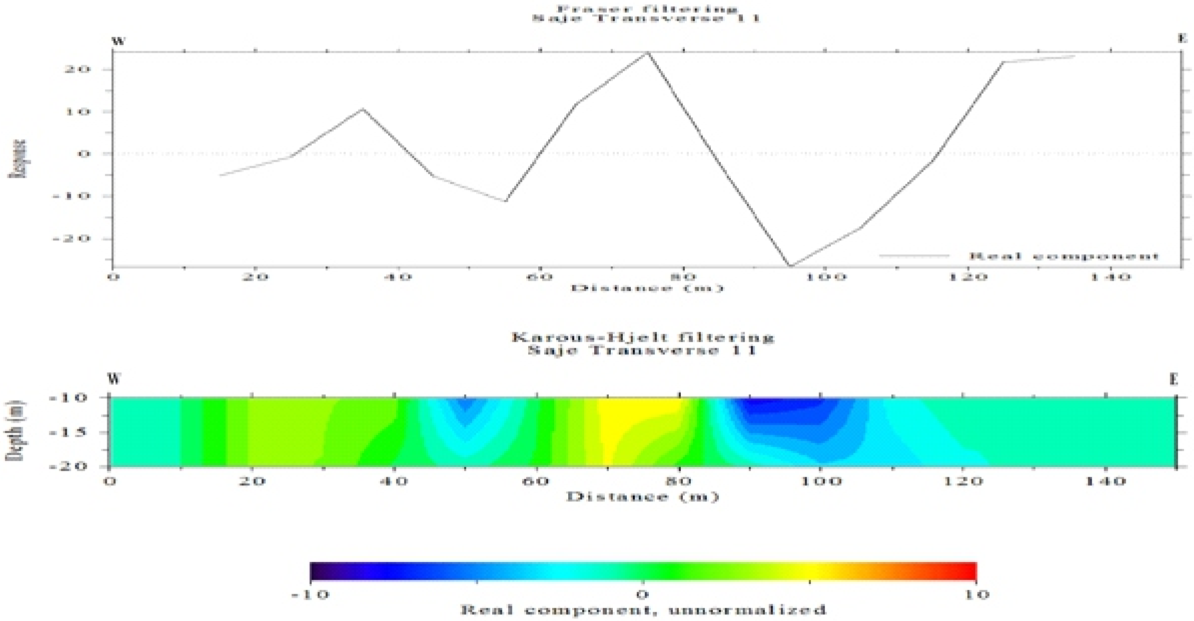

**Figure 13:** Traverse 11 Fraser filtering curve and 2D K-H filtering section.

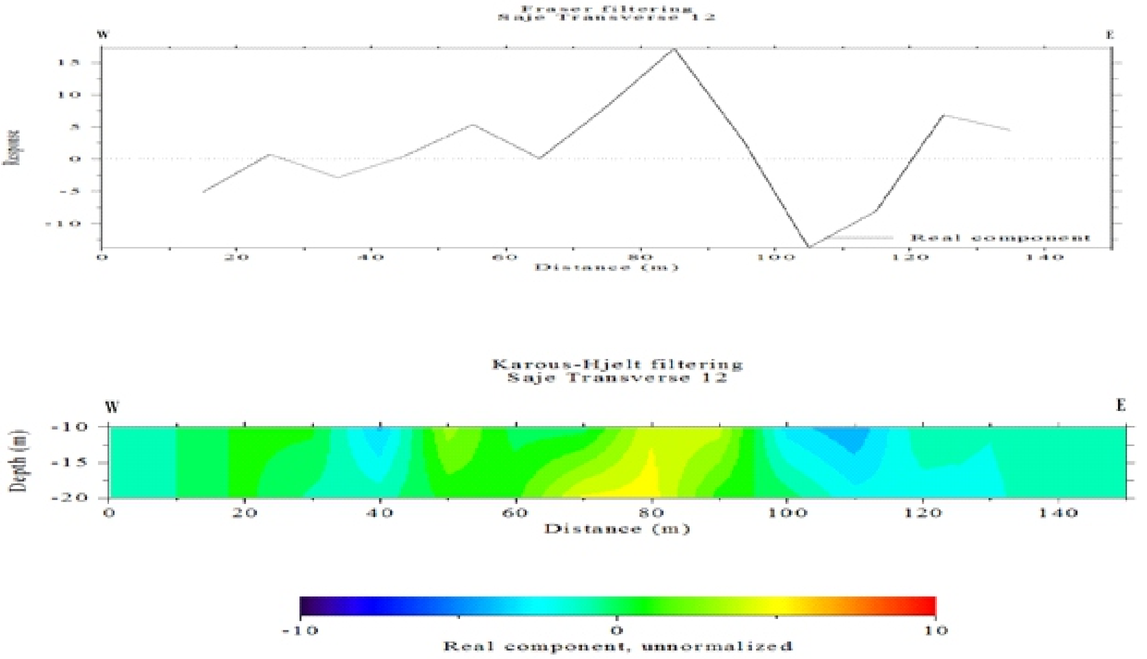

**Figure 14:** Traverse 12 Fraser filtering curve and 2D K-H filtering section.

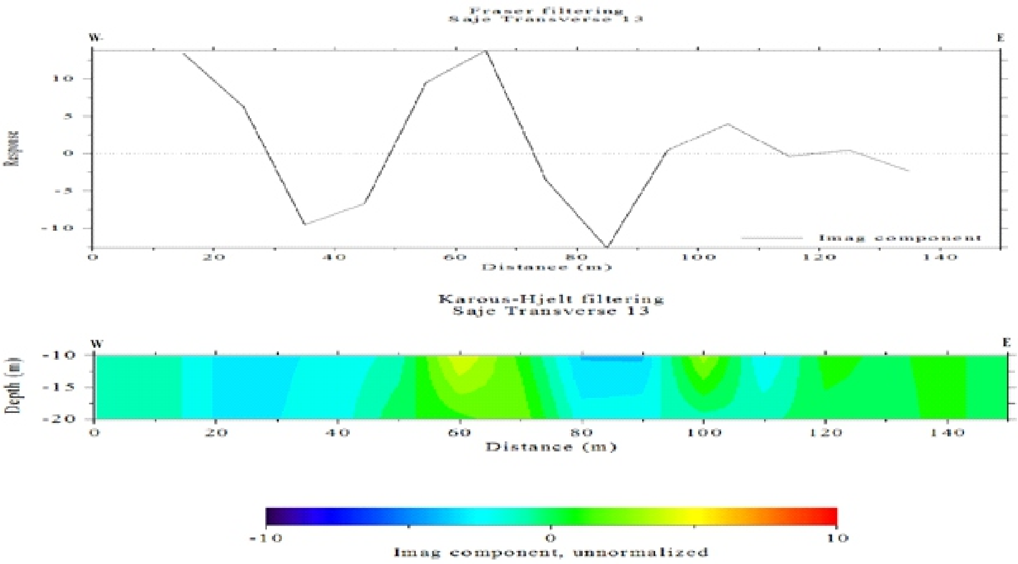

**Figure 15:** Traverse 13Fraser filtering curve and 2D K-H filtering section.

The control traverse (Figure 16) revealed low positive and negative peaks on the Fraser filtering anomaly curve. This traverse indicated low conductive zones and revealed prominent regions of resistive anomalies. The 2D K-H filtering section revealed low conductive areas, which probably indicated the absence of conductive media in the fault lines. The resistive zones were observed at 50-65 and 80 m traverse lengths.

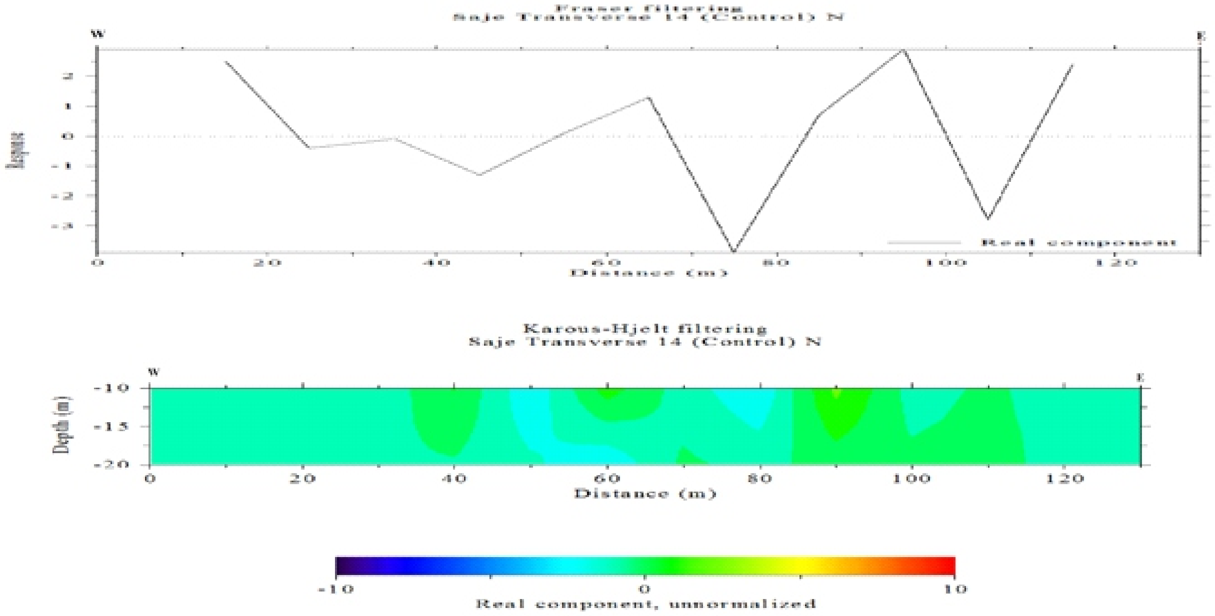

**Figure 16:** Traverse 14 (Control) Fraser filtering curve and 2D K-H filtering section.

On the west of the Saje dumpsite, high conductive zones were observed about 35 m away from the waste disposal site (traverses 1-4), and these conductive zones with responses between 9 and 24 indicated fault lines with saturated leachate contaminant plumes. The control section (traverse 5) with positive and negative amplitude responses of 12 and -25, respectively, revealed very low or absence of conductive zone at a distance of about 135 m from the dumpsite. On the north of the Saje dumpsite, the conductive responses ranged between 3 and 35. Traverses 6-10, distances 0-75 m from the study location, revealed high conductive regions, which could be zones with saturated leachate contaminant plumes in the fault lines. Traverses 11-13, distances 75-120 m, showed zones with low conductive media, which could be interpreted as regions with unsaturated leachate contaminant plumes. Finally, the control section (traverse 14), with conductive and resistive responses 3 and -4, respectively, was laid about 150 m away from the dumpsite and revealed the absence of conductive zones.

Generally, the conductive zones become less prominent with distance from the study area. The amplitudes of the positive response peaks were higher in most cases than the negative response peaks, indicating that the fault lines in the subsurface were filled with conductive fluids than the resistive materials. The patterns, orientations, and nature of the conductive zones' migrations, as observed on the curves and pseudo-sections, were similar to the movements of contaminant plumes in some previous studies on basement formations (Raji and Adeoye, 2017; Ikhifa and Umego, 2016).

## CONCLUSION

The patterns and distributions of conductive zones in the subsurface of the Saje waste site on an old quarry in Abeokuta, Southwest Nigeria, were mapped to a depth of 30 m using the VLF-EM geophysical method to identify regions prone to water and soil contaminations, according to one of the objectives of the National Environmental Regulations for contaminations due to quarry site operations in Nigeria (NER, 2013). The conductive zones, which could be attributed to fault lines filled with contaminant plumes, decreased with distances away from the dumpsite, and fault lines had been identified as a significant leachate contaminant plumes pathway in the study area subsurface. In addition, boreholes and hand-dug wells should not sink within 35 and 75 m on the west and north of the study area, respectively, as these areas had been identified to be saturated with contaminant plumes.

## POTENTIAL CONFLICT OF INTEREST

The authors do not have any form of potential interest or relationship that could influence the work or study.

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